The Aluminum **Joining Manual**







ALUMINUM EXTRUDERS COUNCIL



2015 Aluminum Automotive Manual – Joining

Content

- 1. Introduction
- 2. Characteristics of aluminium in fusion welding
- 3. Arc welding
- 4. Beam welding
- 5. Resistance welding
- 6. Brazing
- 7. Solid state welding
- 8. Mechanical joining
- 9. Adhesive bonding
- 10. Hybrid joining
- 11. Joining dissimilar materials

1. Introduction

Joining is a most important fabrication technology in automobile manufacturing. The standard joining technique for the production of conventional steel car bodies has been resistance spot welding. With the advancement of new, innovative joining technologies and the simultaneous introduction of high and ultra-high strength steel grades, additional joining methods have found limited application. However, resistance spot welding still remains the dominating joining technique for steel cars.

On the other hand, joining of aluminium components by resistance spot welding of aluminium presents some problems. When substituting steel by aluminium, the sensitivity of the mechanical properties of work-hardened and age-hardened aluminium alloys to heat input generated during the welding process and their specific physical characteristics ask for specific attention in design and engineering as well as production planning (equipment and process parameters). Consequently, the growing application of lightweight aluminium solutions in automobiles posed significant challenges both for the automobile manufacturer as well as for the supplier of the aluminium materials and components. The key enabler for the use of aluminium in automotive applications proved to be the series application of non-heat involving joining techniques like mechanical joining and adhesive bonding.

Today, appropriate qualitatively outstanding and highly efficient joining methods are available for aluminium and will be described below in more detail. The integration of aluminium components and modules required the development and introduction of well adapted processing procedures and in some cases even novel joining techniques both for the realisation of aluminium to aluminium joints as well as for mixed material joints. Nevertheless the application-specific selection of the optimum joining method for technical performance and cost efficiency is still a challenging task. Also, there is a clear need for further developments in order to meet more and more demanding future quality and cost targets.



Modern automobile assembly line

(Source: BMW)

The technical feasibility of reliable and safe joints with highest process capability and optimum costefficiency is a prerequisite for the successful application of aluminium in automotive structures. The assembly tasks in automotive manufacturing range from the joining of individual aluminium components consisting of different alloys and product forms (stamped sheet parts, castings, machined extrusions, forgings, etc.) to multi-material joining of aluminium to steel, magnesium, plastic and

composite components. Mixed material designs present additional complications since the selection of the applicable joining method is often restricted and secondary factors such as different thermal expansion coefficients or potential galvanic corrosion effects have to be taken into account. On the other hand, especially the availability of high quality, cost-efficient mixed material joining technologies is a most important requirement for the continuing implementation of innovative lightweight aluminum solutions in automotive constructions.

Apart from the demanding technical performance requirements on the assembled structure, it is most important to consider also the economic aspects of the assembly operation. The joining processes applied in automobile assembly have been optimised over many years for steel designs. In addition, automobile assembly lines are today highly automatized, i.e. in particular in the body shop, most assembly tasks are carried out by robots. The vast existing experience in steel joint design and engineering cannot be simply transferred to aluminium and other materials. Furthermore, it is only possible to apply the standard steel joining equipment as well as the extensive processing knowhow in limited cases. Consequently, substitution of steel parts by lighter aluminium components requires often the development and introduction of new, innovative joining solutions as well as significant investments in suitable assembly equipment and training. On the other hand, these new developments also offer the chance for new lightweight designs and cost-efficient manufacturing solutions.



Assembly of an aluminium car body

(Source: Ferrari)

Basically, material joining is based on three main principles:

- Material coalescence where the materials are held together by atomic or molecular binding forces. In this case, the atoms and/or molecules must be placed in close proximity to each other e.g. by processes without the presence of heat (solid state welding or diffusion), processes based on the mixing in a liquid state (like fusion welding) or processes with addition of a third, generally hardening, liquid substance (e.g. soldering or adhesive bonding).
- **Interlocking joints** are formed by the interlocking of two materials or by the anchoring of additional elements into or inside the corresponding materials (i.e. mechanical joints).
- Frictional connections which are the result of friction between the involved materials, enhanced by the application of an external force (e.g. the shrinking of a hub onto a shaft).

Today, different joining technologies are used for the fabrication of aluminium components and modules in automotive applications and the number of aluminum joining options continues to grow in response to specific design and assembly challenges, e.g.:

- Aluminium car bodies assembled using adhesives in conjunction with punctiform joints (e.g. self-piercing rivets) equal or exceed chassis stiffness requirements.
- Non-critical joints, such as hood and deck lid flanges, can be joined using inexpensive, readily automated clinching methods, often combined with adhesive bonding.
- Other newly developed mechanical joining techniques for structural and non-structural applications offer additional advantages regarding joint quality or process speed.
- Resistance spot welding is increasingly attractive because of new processes, material, and equipment developments that extend tip life, enhance weld quality, and reduce welding power demands.
- Arc welding is also enhanced due to advances in equipment, such as solid-state power supplies and better wire-feed devices.
- Laser beam and combined laser/arc welding methods provide automotive body designers with even greater assembly options for closures and structural components.
- Friction stir welding is making inroad into the field of automotive aluminium applications.
- Brazing of aluminium is largely confined to the production of heat transfer components. It may, however, well find future applications in other, structural applications.

In the following, the different joining technologies used for the assembly of aluminium parts for automotive applications (including joining of aluminium with other materials) will be described. Due to the large variety of possible solutions, no performance values can be quoted here, please refer to product suppliers for more detail information.

More details, in particular regarding fundamental metallurgical aspects, can be found on the freelyaccessible aluMATTER website providing interactive e-learning resources for aluminium science and technology:

http://aluminium.matter.org.uk/content/html/eng/default.asp?catid=47&pageid=2144416963

Additional information on aluminium joining is offered by TALAT (Training in Aluminium Application Technologies), a comprehensive collection of training material for engineers and researchers in industries and universities:

http://www.alueurope.eu/talat/4000/4000.htm.

Much more information and other studies can also be found on the websites of the European Aluminium Association and the Aluminum Association:

http://www.alueurope.eu/applications/automotive/

http://www.drivealuminum.org/research-resources

Purpose

The intention of the present document is to provide information about the wide range of technologies applicable to join aluminium alloy components with other parts made from aluminium alloys or dissimilar materials, in particular for automotive applications. The list of the described joining methods is clearly not exhaustive, also keeping in mind the ongoing further developments. In addition, it should be kept in mind that the information provided about the different joining methods obviously can't be complete. If an actual application is envisaged, early contact with the supplier(s) of the respective processing equipment and auxiliary materials as well as your aluminium supplier is recommended.

The present document is not meant to be a guideline for design and engineering nor an actual manual for production purposes. Most of the described technologies are mature and proven in practical applications. However, there are also techniques still under development or in the qualification phase. For more detailed information, please contact the supplier(s) of the respective processing equipment and auxiliary materials as well as your aluminium supplier. The present document is also not an academic paper with specific references to the literature. Today, searching the internet offers the

possibility to get additional competent and up-to-date information, including references to scientific and/or technical papers.

Acknowledgment

The work to develop this Aluminium Automotive Joining Manual is a joint effort between the European Aluminium Association and the Aluminum Association. The chapters have been reviewed by experts from member companies of both these associations.

Disclaimer

The present publication is meant for informative purposes only. The information in this publication is general in nature and is not intended for direct application to specific technical or scientific projects. Neither the European Aluminium Association nor the Aluminum Association will be liable for any damage, costs or expenses resulting from the use of the information in this publication. Neither the European Aluminium Association nor the Aluminum Association makes any representations, warranties or endorsements of any kind whatsoever as to the publication or any of the information included therein and each of the European Aluminium Association and the Aluminum Association disclaims all warranties and conditions with respect to the publication and the information included therein, whether express or implied, statutory or otherwise.

Furthermore, some of the described joining technologies, processing equipment and auxiliary material may be proprietary, protected by patents and/or trademarks. This publication is owned by the European Aluminium Association. Unauthorized use of this publication is strictly prohibited.

For additional information, please contact your aluminium supplier to be able to discuss details directly with the relevant experts.

EAA Aluminium Automotive Manual – Joining

2. Characteristics of aluminium in fusion welding

Content:

- 2. Characteristics of aluminium in fusion welding
- 2.0 Introduction
- 2.1 Welding of aluminium
- 2.1.1 The aluminium oxide film
- 2.2 Weld preparation
- 2.3 The welding zone
- 2.3.1 Solidification in the fusion zone
- 2.3.2 Crack formation in the fusion zone
- 2.3.3 Gas absorption and pore formation
- 2.4 Filler materials
- 2.4.1 Selection of filler materials
- 2.5 Shielding gases for welding aluminium
- 2.6 Joint design for fusion welding
- 2.7 Characteristics of the weld zone
- 2.8 Imperfections in fusion welds
- 2.9 Work environment and safety
- 2.10 Simulation of fusion welding

2.0 Introduction

Fusion welding of wrought and cast aluminium components is a key joining technology in automotive engineering. Fusion welding is characterised by partial melting of the work pieces to form a molten metal pool that solidifies and results, after subsequent cooling, in a firm joint. For quality reasons, a filler material is added sometimes. Different energy sources are used to produce the weld, including electricity, laser, electron beam and friction. Various fusion welding processes have been adapted or specifically developed for fusion welding of aluminium which are described in subsequent chapters:

- 3. Arc welding
- 4. Beam welding
- 5. Resistance welding
- 6. Brazing
- 7. Solid state welding.

The present chapter considers some general aspects of the various fusion welding methods.

In order to achieve sound and efficient weld joints of aluminium parts, the choice of joint design, welding parameters, procedures and processes must consider:

- · Welding characteristics of the alloys to be joined
- · Characteristics of the applied fusion welding process
- Joint configuration and surface characteristics of the joining zone (weld preparation).



Weldability - a system approach

Weldability, i.e. the suitability of an aluminium part or component for welding, depends on:

- Base material quality (alloy composition, surface characteristics, ...)
- Design (suitability of design for welding, joint design, ...)
- Welding process (welding method, equipment, processing parameters, ...).

2.1 Welding of aluminium

Aluminium and its alloys are in general highly suitable for fusion welding. However, although many welding methods are possible, only selected fusion welding techniques are generally used in series production. Application-oriented refinements in welding tools, equipment and materials have resulted in the increasing acceptance of specific fusion welding methods for aluminium joining.

The physical properties of a material have a significant influence on the welding characteristics:

- Pure aluminum has a melting point of 660 °C, whereas the fusion range of the most common aluminium alloys is between 520 – 660 °C. Because there is no visible color change, it is difficult to judge when the metal approaches its melting point.

- Preheating may be necessary, particularly where thick sections are encountered. A comparison with steel shows a much higher thermal conductivity, a higher heat capacity, heat of fusion and thermal expansion. As a consequence, aluminium materials require high heat inputs to melt and may suffer from large deformations.
- When exposed to air, aluminum rapidly develops a tenacious surface oxide film, which – above all other factors related to aluminum welding – causes the most trouble. Unless the oxide film is destroyed or removed before and during welding, it will interfere with the coalescence of the work pieces and, if applicable, the filler material.

Aluminium alloys that are referred to as "non-weldable" have – as a consequence of their composition – an elevated tendency to solidification cracking and, in some cases, also an increased susceptibility to stress corrosion cracking in the as-welded condition. The following groups of "non-weldable" aluminium alloys are typically mechanically fastened and/or adhesively bonded rather than fusion welded:

Aluminium machining alloys

In many of these alloys, bismuth, tin, and/or lead are added in small quantities to facilitate machinability. The addition of low melting point metals seriously increase solidification cracking tendency. It must be noted that as a result of recent regulations, the addition of lead has been largely discontinued, specifically for automotive applications.

EN AW-2xxx series alloys containing aluminium-copper-magnesium

These alloys which are used for aerospace and other high performance applications can be susceptible to solidification cracking as well as stress corrosion cracking and premature failure after fusion welding. However, binary aluminium-copper alloys of the 2xxx series are considered to be weldable when using an Al-Cu filler metal.

EN AW-7xxx series alloys contaning aluminum-zinc-copper-magnesium

If these alloys (also used for aerospace and other high performance applications) are fusion welded, they may also fail for the reasons outlined above. Alloys based on the aluminiumzinc-magnesium system without copper, however, are considered to be weldable.

In the heat affected zone of the "non-weldable" EN AW-2xxx and -7xxx series alloys, low melting point intermetallic phases are preferentially precipitated at the grain boundaries which lowers and widens the solidification temperature range of the grain boundary. Consequently, when arc welding these types of base metals, the grain boundaries become the last to solidify and can easily crack due to solidification shrinkage stresses. In addition, the difference in galvanic potential between the grain boundaries and the interior of the grains is increased, making them more susceptible to stress corrosion cracking.

2.1.1 The aluminium oxide film

The thickness of the oxide layer covering technical aluminium surfaces is smaller than 0.01 mm. The melting point of aluminium oxide is about 2000 °C, in contrast to 660 °C of the aluminium metal. Due to its high melting point, the oxide film does not dissolve in the weld bath, but must be (locally) destroyed to obtain a fused bond line in the joint. The aluminium oxide film is relatively strong, it has a low electrical and thermal conductivity and can easily cause welding defects. In general, it shows an inhomogeneous structure and rough surface with a high affinity for gas adsorption and surface contamination, i.e. it is a potential source for gas porosity. Furthermore, the oxide density is higher than the density of molten aluminium and may form non-metallic inclusions in the fusion zone.



Constitution of oxide layer on aluminium alloys (schematic)

In order to form a proper weld, the oxide film has to be removed or cracked during the welding process to allow the fusion of the metal. This can be facilitated by the application of an appropriate surfaces treatment before welding. Proper cleaning of the aluminium surface is always necessary in order to achieve high quality welding results (see also 9.4).

Nevertheless, even after complete removal of the original oxide film, aluminium surfaces are immediately re-covered by a thin oxide film. Destruction of this oxide film is achieved for example in arc welding techniques by the cleaning action of the electric arc and of the shielding gases. Oxide removal is essentially caused by ion impingement and little (if any) by electron penetration through the oxide barrier. The efficiency depends on electrode polarity and is therefore influenced by the type of current:

- Positive electrode \rightarrow cracking of the oxide film by ion impingement,
- Negative electrode \rightarrow no oxide film removal by ion impingement.



In contrast to argon, helium provides also some cleaning action with negatively poled electrodes because of its higher ionisation energy and higher heat dissipation.

Removal of aluminium oxide by ion impingement (left) and electrode penetration through the oxide layer (right)

2.2 Weld preparation

The production of high-quality fusion welds between aluminium components depends strongly on the quality of the surfaces to be welded. Special care is required to limit porosity and other internal imperfections of the weld zone. The most important factors are:

- Correct storage of components, work piece, filler materials (dry as well as smut-, oiland dust-free environment)
- Minimize moisture condensation and absorption of water contamination during transport and storage
- Proper surface preparation of the areas to be joined, avoid ground or smeared surfaces.

The level of cleanliness and metal preparation required for welding depends on the desired weld quality level. Dirt, oil residues, moisture and oxides must be removed, either with mechanical or chemical methods. Surface films containing hydrogen bearing mixtures

represent the largest problem because they are broken down into atomic hydrogen in the arc, causing gas porosity in the weld. Normal shop practice is to mechanically remove the oxide layer by brushing, scraping or shot peening. Only light pressure should be used when brushing. Excessive pressure might lead to locally overheating and distortion of the metal surface.

Applicable chemical treatments include cleaning with alcohol or acetone, alkaline or acidic pickling or even more complicated chemical treatments. As an example, the amount of porosity in the weld seam decrease as result of the applied preparation technique of the joint surface in the following order:

- As-received state (sheared, plasma arc cut or laser cut)
- Milling
- Grinding
- Brushing with rotating CrNi steel brushes
- Etching
- Etching and scraping (only joint surface).

In critical applications, the cleaned surface produced by etching may be subsequently protected by a suitable conversion treatment. A suitable conversion treatment of the individual components ensures ideal welding conditions. However, this additional process step is generally not necessary provided that the components are properly stored and handled before welding.

2.3 The welding zone

Fusion welding produces a locally modified microstructure. Different zones can be identified as a result of local alloy composition changes and/or the temperature cycle during welding. Depending on the actual heat input and the geometry of the joint, the width of these zones can vary considerably.





The **fusion zone** is characterised by the presence of molten metal from both adjoin materials A and B and, if applicable also from the introduced filler metal. The solidification of the molten metal pool starts from the weld seam.

In the **transition zone**, (partial) melting of the eutectic phases at the grain boundaries will take place. Also, diffusion of alloying elements along the grain boundaries may occur.

In the **heat affected zone**, thermally controlled solid state processes (segregation effects, precipitation processes, recovery and recrystallisation processes) are possible, depending on the reached temperature level.

2.3.1 Solidification in the fusion zone

Solidification in the fusion zone is generally characterised by rapid cooling and solidification processes, i.e. a fine as-cast grain structure is formed. The resulting grain size can be controlled by an appropriate selection of the welding parameters.

Three types of weld pool solidification are being observed, i.e. without eutectic formation (pure aluminium), with a low fraction of grain boundary eutectic (in general with low alloyed aluminium alloys) and with a continuous grain boundary eutectic (i.e. for highly alloyed

aluminium alloys). As a result of these different types of solidification, there are various potential defects which form at the grain boundaries.



Solidification types of aluminium alloys

2.3.2 Crack formation in the fusion zone

Depending on the specific welding conditions (design, applied welding process and material combination), there is a risk for crack formation in the fusion zone. An important factor influencing the cracking sensitivity is the solidification range of the particular alloy (temperature difference between liquidus and solidus).

The risk for crack formation ("hot cracking") in the fusion zone increases with increasing solidification range of the alloy (or the alloy combination) to be welded:

Pure aluminium has no solidification range and is resistant to cracking.

Non-age hardening alloys (EN AW-1xxx, 3xxx and 5xxx series) have solidification • ranges below 50 °C and can be readily fusion welded provided the necessary measures are taken.

• The solidification ranges of EN AW-6xxx series alloys and 7xxx alloys of the AI-Zn-Mg system are about 50 °C and are thus sensitive to solidification cracking. Proper countermeasures are necessary to ensure an adequate weld quality.

In general, high strength alloys containing copper and magnesium as well as zinc (some EN AW-2xxx serie and 7xxx alloys) have solidification ranges larger than 100 °C and therefore show a high cracking sensitivity. Fusion welding is very difficult, if not impossible.

Solidification cracking is the result of the presence of high thermal stresses and the solidification shrinkage effect as the weld pool solidifies. It is determined by a combination of metallurgical, thermal, and mechanical factors. In practice, the cracking sensitivity within the fusion zone can be reduced by the use of a filler wire. The addition of the filler wire allows changing the alloy content in the fusion zone to an uncritical alloy concentration. If the correct filler metal is selected, the cracking can be avoided. Another way to reduce solidification cracking is to reduce transverse stress or to increase the amount of edge preparation.

As an example, two strategies to compensate the weld cracking propensity in Al-Mg-Si alloys are shown in the following figure:

- Alloving with Mg (R-5056A)

(possibility A) - Alloying with Si (R-4043A) (possibility B).

Under the assumption of a 50% mixture of parent and filler metal in the weld pool, the graphic indicates a significantly decreasing tendency for crack formation.



Weld cracking propensity in Al-Mg-Si alloys

Another type of cracking in fusion welded, precipitation hardenable aluminium alloys is liquation cracking. Liquation cracking may occur in the transition zone when the temperature is increased sufficiently above the melting point of low melting eutectic intermetallic phases present at the grain boundaries. A crack will develop if there is sufficient tensile stress in the joint and the molten eutectic may connect to the fusion zone. The combination of solidification shrinkage and insufficient molten metal feeding may then prevent the closing of the formed crack when the weld solidifies.

Higher heat input tends to expand the affected region. Therefore, the selection of filler alloy with a lower solidification temperature and improved fluidity will provide lower susceptibility to liquation cracking since the solidification shrinkage occurs at a lower temperature. Similarly, lower thermal input with higher current or higher travel speed can also mitigate this problem. Additionally, designing joints that improve filler metal dilution into the base material and mitigate solidification stresses will also decrease the sensitivity for crack formation.

A third type of cracking is due to alloy segregation where the centerline of the weld pool solidifies last due to solute segregation. This is similar to liquation cracking and can manifest itself as "crater cracks" that are star shaped in the center of the weld. Assuring proper filler metal dilution and applying techniques where additional wire can be fed into the weld, will reduce the susceptibility for segregation based cracking.

2.3.3 Gas absorption and pore formation

Pores caused by hydrogen are a characteristic phenomenon observed when welding aluminium and its alloys. The reason for the formation of hydrogen porosity during solidification is the ability of liquid aluminium to absorb a large amount of hydrogen. During solidification, the hydrogen solubility decreases by a factor of 20. Thus the excess gas is released and the hydrogen bubbles may become trapped and forms pores.

Depending on the solidification morphology of the alloy, two types of hydrogen porosity are observed:

- Pores distributed uniformly,
- Pores linked together in a chain-like fashion.

Low welding speeds (and high energy input) lead to a broad fusion zone and, as a result of the lower solidification rate, to an unfavourable porosity distribution.



Hydrogen gas absorption during welding

The high solubility of molten aluminium for hydrogen leads to the absorption of additional hydrogen in the molten metal pool during welding. Hydrogen may originate from moisture and contaminants (e.g. dirt, oil and grease) on the work pieces or the welding equipment (incl. filler wire) and the shielding gas or the surrounding atmosphere. Hydrogen and other gases causing porosity are absorbed by:

- Turbulences in the shielding gas envelope; the reason can be a too high or too low flow rate of the shielding gas.
- Unstable arc conditions,
- Unfavourable torch position, too high slanting angle,
- Entrance of air into the shielding gas nozzle,
- Impurities on the work piece surface, filler wire, or in the used shielding gases,
- Insufficient edge preparation.



Gas absorption during welding

2.4 Filler materials

Filler metals are generally introduced in the form of wires. The addition of filler metals has two goals:

- To avoid the formation of cracks in the fusion zone through an adjustment of the alloy composition of the molten pool
- To provide additional material for gap bridging.

Therefore, filler wire alloys have to be adapted to the alloy compositions(s) of the components to be welded and the required strength and formability (as well as other properties) of the weld zone have to meet the product requirements for the final assembly.

The composition of the most important filler metals for aluminium welding belong to the two groups:

- Si or Mg are the main alloying elements
- Depending on the specific alloy (combination), varying amounts of other elements (e.g. Mn, Cr, Ti and Fe) are used.

Filler metals based on the composition AI - 5 % Mg generally provide welds of the highest strength. On the other hand, filler metals based on AI - 5 % Si are more resistant with respect to solidification cracking and easier to use when welding age hardenable alloys.

Little development work has been done during the last decades to develop filler metals for aluminium welding. A heightened interest has been shown only during recent years due to the increased amount of welding performed on aluminium. Newly developed filler metals offer increased strength and reduced mismatch, which in turn reduces material consumption and enables new possibilities in design.

2.4.1 Selection of filler materials

Depending on the specific welding technique and material combination, the application of a filler wire is not necessary. However, if a filler wire is being used, it is most important to select the proper filler metal composition. The main factors which influence the filler alloy selection are:

- Prevention of hot cracking
- Weld metal strength and ductility
- Corrosion resistance
- Weld performance at elevated temperatures
- Weld metal fluidity
- MIG electrode wire feedability
- Weld metal colour match with base material after anodizing.

The filler metal as such is not hardenable, which implies that no hardening procedure can strengthen the weld after welding. When a good colour match is needed between the weld bead and the surface, Si-alloyed filler metals should be avoided. When anodising, the precipitated silicon particles impart a dark grey, almost black colour.

R-1050A R-1450 R-1450 R-3103 R-5356 R-3103	R-1050A R-1450 R-1450 R-3103 R-5356 R-3103	R-3103									
R-1450 R-3103 R-5356 R-3103	R-1450 R-3103 R-5356 R-3103	R-3103					and alloy combinations				
R-5356 R-3103	R-5356 R-3103	R-5356									
E COLO		R-3103	R-5356 R-6149				(first de	signate	ed filler	is prefe	erred)
K-5356	R-5356	R-5356 R-3101	R-5356	R-5356 R-5754							
R-5356 R-3101	R-5356 R-3101	R-5356 R-3101	R-5356 R-5149	R-5356 R-5754	R-5356 R-5149						
R-5356 R-3101	R-5356 R-3101	R-5356 R-3101	R-5356 R-5149	R-5356 R-5754	R-5356 R-5149	R-5183 R-5087 R-5356					
R-4043A R-5356	R-4043A R-5356	R-4043A R-5356	R-5356 R-5149	R-5356 R-5754	R-5356 R-5149	R-5183 R-5087 R-5356	R-4043A R-5356				
R-5356 R-5149	R-5356 R-5149	R-5356 R-3103	R-5356 R-5149	R-5356 R-5754	R-5356 R-5149	R-5183 R-5087 R-5356	R-5356	R-5183 R-5087 R-5356			
R-4043A	R-4043A	R-4043A	R-4043A	R-4043A	R-4043A	R-4043A	R-4043A	R-4043A	R-4043A		
R-4047A	R-4047A	R4047A	R-4047A	R-4047A	R-4047A	R-4047A	R-4047A	R-4047A	R-4047A R-4043A	R-4047A R-4046	
R-5356	R-5356	R-5356	R-5356	R-5356	R-5356	R-5356	R-5356	R-5356	-0000000	000000	R-5356
AW-1090 AW-1080A AW-1070A	AW-1050A AW-1200	AW-3103 AW-3003	AW-5005A AW-5051A AW-5052	AW-5754 AW-5019	AW-5454 AW-5251 AW-5049	AW-5086 AW-5083	AW-6060 AW-6005A AW-6082	AW-7020	AC-41XXX AC-42XXX	AC-43XXX AC-44XXX	AC-51XXX
	-5356 -5356 -3101 -5356 -3101 -4043A -5356 -5149 -4043A -4043A -4043A -5356 W-1090 W-1090A W-1070A	-5356 R-5356 -5356 R-5356 -53101 R-5356 -53101 R-5356 -5356 R-5356 -5356 R-5356 -5356 R-5356 -5356 R-5356 -5356 R-5356 -5356 R-5356 -54043A R-4043A -4043A R-4043A -4047A R-4047A -5356 R-5356 W-1080A AW-1050A W-1080A AW-1200	-5356 R-5356 R-5356 R-5356 -5356 R-5356 R-3101 -5356 R-3101 R-3101 -5356 R-5356 R-5356 -3101 R-3101 R-3101 -5356 R-5356 R-5356 -3101 R-4043A R-4043A -4043A R-5356 R-5356 -5356 R-5356 R-5356 -5449 R-5149 R-3103 -4043A R-4043A R-4043A -4047A R-4047A R4047A -4047A R-4047A R4047A	-5356 R-5356 R-5356 R-5356 R-5356 -5356 R-5356 R-5356 R-5356 R-5356 -53101 R-3101 R-3101 R-5149 -5356 R-5356 R-5356 R-5356 -63101 R-3101 R-3101 R-5149 -4043A R-4043A R-4043A R-5149 -5356 R-5356 R-5356 R-5356 -5149 R-5149 R-3103 R-5149 -5356 R-5356 R-5356 R-5356 -5149 R-5149 R-3103 R-5149 -4043A R-4043A R-4043A R-4043A -4047A R-4047A R-4043A R-4043A -4047A R-4047A R-4047A R-4047A -5356 R-5356 R-5356 R-5356 W-1090 AW-1020 AW-303 AW-5057 W-1070A AW-1020 AW-303 AW-5052	-5356 R-5356 </td <td>-5356 R-5356 R-5356<!--</td--><td>-5356 R-5356 R-5356<!--</td--><td>-5356 R-5356 R-5356 R-5356 R-5356 R-5356 R-5356 -5356 R-5356 R-5356 R-5356 R-5356 R-5356 R-5356 -5356 R-3101 R-3101 R-5149 R-5754 R-5149 -5356 R-5356 R-5356 R-5356 R-5356 R-5356 -3101 R-3101 R-5149 R-5754 R-5149 R-5087 -5356 R-5356 R-5356 R-5356 R-5356 R-5356 R-5356 -4043A R-4043A R-4043A R-6356 R-5356 R-5356 R-5356 R-5356 -5356 R-5356 R-5356 R-5356 R-5356 R-5356 R-5356 -4043A <t< td=""><td>63356 R-5356 R-5149 R-5754 R-5149 R-5149 R-5149 R-5149 R-5149 R-5356 R-5183 R-4043A R-4043A R-4043A R-6356 R-5356 R-5169 R-5356 R-5183 R-4043A R-4043A R-6356 R-5149 R-5356 R-5183 R-4043A R-4043A R-4043A R-6356 R-5149 R-5087 R-5356 45356 R-5356 R-5149 R-5356 R-5183 R-5087 R-5356 R-5356</td><td>6356 R-5356 R-5356</td></t<><td>6356 R-5356 R-5356</td></td></td></td>	-5356 R-5356 </td <td>-5356 R-5356 R-5356<!--</td--><td>-5356 R-5356 R-5356 R-5356 R-5356 R-5356 R-5356 -5356 R-5356 R-5356 R-5356 R-5356 R-5356 R-5356 -5356 R-3101 R-3101 R-5149 R-5754 R-5149 -5356 R-5356 R-5356 R-5356 R-5356 R-5356 -3101 R-3101 R-5149 R-5754 R-5149 R-5087 -5356 R-5356 R-5356 R-5356 R-5356 R-5356 R-5356 -4043A R-4043A R-4043A R-6356 R-5356 R-5356 R-5356 R-5356 -5356 R-5356 R-5356 R-5356 R-5356 R-5356 R-5356 -4043A <t< td=""><td>63356 R-5356 R-5149 R-5754 R-5149 R-5149 R-5149 R-5149 R-5149 R-5356 R-5183 R-4043A R-4043A R-4043A R-6356 R-5356 R-5169 R-5356 R-5183 R-4043A R-4043A R-6356 R-5149 R-5356 R-5183 R-4043A R-4043A R-4043A R-6356 R-5149 R-5087 R-5356 45356 R-5356 R-5149 R-5356 R-5183 R-5087 R-5356 R-5356</td><td>6356 R-5356 R-5356</td></t<><td>6356 R-5356 R-5356</td></td></td>	-5356 R-5356 </td <td>-5356 R-5356 R-5356 R-5356 R-5356 R-5356 R-5356 -5356 R-5356 R-5356 R-5356 R-5356 R-5356 R-5356 -5356 R-3101 R-3101 R-5149 R-5754 R-5149 -5356 R-5356 R-5356 R-5356 R-5356 R-5356 -3101 R-3101 R-5149 R-5754 R-5149 R-5087 -5356 R-5356 R-5356 R-5356 R-5356 R-5356 R-5356 -4043A R-4043A R-4043A R-6356 R-5356 R-5356 R-5356 R-5356 -5356 R-5356 R-5356 R-5356 R-5356 R-5356 R-5356 -4043A <t< td=""><td>63356 R-5356 R-5149 R-5754 R-5149 R-5149 R-5149 R-5149 R-5149 R-5356 R-5183 R-4043A R-4043A R-4043A R-6356 R-5356 R-5169 R-5356 R-5183 R-4043A R-4043A R-6356 R-5149 R-5356 R-5183 R-4043A R-4043A R-4043A R-6356 R-5149 R-5087 R-5356 45356 R-5356 R-5149 R-5356 R-5183 R-5087 R-5356 R-5356</td><td>6356 R-5356 R-5356</td></t<><td>6356 R-5356 R-5356</td></td>	-5356 R-5356 R-5356 R-5356 R-5356 R-5356 R-5356 -5356 R-5356 R-5356 R-5356 R-5356 R-5356 R-5356 -5356 R-3101 R-3101 R-5149 R-5754 R-5149 -5356 R-5356 R-5356 R-5356 R-5356 R-5356 -3101 R-3101 R-5149 R-5754 R-5149 R-5087 -5356 R-5356 R-5356 R-5356 R-5356 R-5356 R-5356 -4043A R-4043A R-4043A R-6356 R-5356 R-5356 R-5356 R-5356 -5356 R-5356 R-5356 R-5356 R-5356 R-5356 R-5356 -4043A <t< td=""><td>63356 R-5356 R-5149 R-5754 R-5149 R-5149 R-5149 R-5149 R-5149 R-5356 R-5183 R-4043A R-4043A R-4043A R-6356 R-5356 R-5169 R-5356 R-5183 R-4043A R-4043A R-6356 R-5149 R-5356 R-5183 R-4043A R-4043A R-4043A R-6356 R-5149 R-5087 R-5356 45356 R-5356 R-5149 R-5356 R-5183 R-5087 R-5356 R-5356</td><td>6356 R-5356 R-5356</td></t<> <td>6356 R-5356 R-5356</td>	63356 R-5356 R-5149 R-5754 R-5149 R-5149 R-5149 R-5149 R-5149 R-5356 R-5183 R-4043A R-4043A R-4043A R-6356 R-5356 R-5169 R-5356 R-5183 R-4043A R-4043A R-6356 R-5149 R-5356 R-5183 R-4043A R-4043A R-4043A R-6356 R-5149 R-5087 R-5356 45356 R-5356 R-5149 R-5356 R-5183 R-5087 R-5356	6356 R-5356	6356 R-5356

Selection of filler metal

A major factor towards producing good quality aluminium welds is the use of high quality filler rods and wires of the correct diameter and alloy specification. Moreover, the filler metal surfaces must be kept free from moisture, lubricants, and other contaminants.

2.5 Shielding gases for welding aluminium

The aluminium weld pool as well as the electrode must be protected from the atmosphere. The other role of the shielding gases is to provide a stable arc, to cool the electrode and to minimise the introduction of defects into the weld.

The most important selection criteria is the heat conductivity of the gas. For aluminium welding, the predominantly used inert gas is argon, but also combinations of helium and argon are applied. Effective mixtures have been found to lie between 30 - 70 % of each respective gas (typical mixtures are Ar/He: 30/70; 50/50 or 70/30). Compared to argon, helium offers a higher heat concentration and a higher melting rate, but also heat dissipation is higher and arc stability is lower. Because of its lower density, helium requires a higher flow rate than argon.

The advantages that can be reached with helium are the result of the higher arc power (due to the higher ionization energy of helium compared to argon) combined with its better heat conduction (nine times higher than that of argon). Helium raises the temperature of the arc which increases the heat delivered to the weld and weld zone. As a result, the weld penetration is deeper and broader than with argon, contributing to a reduced porosity in the weld bead. On the other hand, with a good heat transferring gas such as helium, a higher fraction of the heat (generated from the energy converted in the arc) will be lost to the environment. The most common solution is to use argon for MIG and AC TIG welding because the process is usually easier to control with argon.

As welds in aluminium are prone to the formation of oxide inclusions and voids, the shielding gas must meet strict purity requirements. Process gases and gas supply system must be clean and free from moisture because even minute traces of dirt or moisture can cause severe weld porosity. Argon and helium should have a minimum purity of 99.995 % and a dew point of - 60 °C or lower. It is very important that the purity of the gas is preserved all the way to the arc. If there is any leakage in the welding equipment, the gas will be contaminated.

Sometimes monomix shielding gases are used consisting of inert gases with minute amounts of active gases (O₂, CO₂, NO in less than 0.1 vol. %). Very small additions of oxidising components do not adversely affect the weld quality, but actually improve arc stability. They provide a slight, but measurable improvement of the energy transfer and consequently of the welding speed. Monomix shielding gases are also claimed to produce a smoother transition between weld and base metal, thus improving the fatigue properties of welded components. CO₂ is suitable for MIG welding of AIMg alloys, but cannot be used for TIG welding since CO₂ would rapidly destroy the tungsten electrode. The addition of 0.03 % NO can also be used for TIG and MIG welding in order to reduce ozone levels.

2.6 Joint design for fusion welding

The right choice of joint configuration depends on the

- material thickness
- accessible torch or beam positions
- technological requirements
- clamping possibilities
- required tolerances.



Joints for gas shielded arc welding

The joint configuration must be selected with respect to the principle stresses acting on the joint (i.e. tension, compression or shear loads). Some recommended joint configurations are given below. Shear stress should be largely avoided, because most joints are very sensitive to this kind of loading.



Recommended joint configurations

The aluminium extrusion technology offers some interesting possibilities to simplify the welding process. Examples of innovative, proactive aluminium profile design include edge preparation, material compensation, in-built fastening, integral root backing and the minimisation of the number of welds required are all examples of proactive.

Aluminium profiles can also be designed in a way that reduces the required number of welds. Furthermore, welds can be located in a low stress section of the cross-sectional area. This means fewer welds and improved strength. In addition, butt welds are used rather than the weaker fillet welds.



Edge preparation (and material compensation for strength reduction in the weld zone) integrated into the profile design

(Source: Sapa)





Placing welds in lower stress sections of the cross sectional area (left) and reduced number of welds

(Source: Sapa)

When the welding plan (i.e. the order in which the weld are performed) is established, minimum geometrical distortion of the assembled sructure must be envisaged. The key words In order to reduce geometrical distortions due to shrinkage, low heat input and symmetrical welding must be envisaged. The following recommendations can be made:

- Weld as little as possible.
- Use highly productive welding methods with maximum welding speed and the lowest possible heat input.
- Begin welding in the centre of the structure and proceed symmetrically outwards.
- If longitudinal and transverse joints meet, weld the transverse first. If butt and fillet joints meet, weld the butt joints first.
- Use fixtures that provide even cooling, if possible, allow free movement of the work pieces.

Even if the above mentioned measures are taken, it may be difficult to get welded parts completely free from distortions. An efficient and long-established method of correcting distorted parts is flame straightening. In flame straightening, an oxy-fuel flame is used to quickly heat a limited area of the component or assembly. For aluminium, the proper temperature range is 350 - 400 °C. Upon cooling, the material in the heated area contracts more than it expanded when heated and the component or assembly is straightened out. By using external restraining devices, the straightening effect can be reinforced.

Other possible measures to reduce thermal distortions during welding include the use of temporary backing strips that are applied to control weld penetration. They are removed after welding. Care must be taken to prevent melting the backing material into the weld pool. In addition, preheating to 100 - 200 °C can be used when welding large material thicknesses, in particular to reduce the thermal effects of the different material cross section when welding work pieces of dissimilar thickness. However, all these measures (flame straightening, temporary backing strips and preheating) add additional complications and should be avoided in series production by proper design of the welded structure and an appropriate welding schedule.

Attention to good joint fit-up (i.e. joint gap/root face combinations and plate mismatch) is important to ensure the production of high quality welds. Joint fit-up and edge preparation are

closely related. Inferior joint fit-up will produce poor welds, independent of the quality of edge preparation.

In addition to edge preparation and joint fit-up, joint accessibility becomes just an as important consideration. The aspect of accessibility (i.e. the sizes of the welding TIG torch or MIG gun and the arcing characteristics) is often overlooked during the initial design stage. Apart from the accessibility factor, the designer should always be aware that it is important to allow an unrestricted view of the arc within the preparation.

2.7 Characteristics of the weld zone

The fusion zone shows an as-cast structure with the respective physical characteristics. Most important in practice, however, are the related property changes within the heat affected zone. Every fusion welding process leads to the formation of a heat affected zone in the neighbouring parent metal where – depending on the original microstructure and the location – different thermally assisted microstructural processes can occur. The extension of the heat affected zone depends on the thermal input, which again depends on:

- the heat input of the specific welding technique,
- the welding speed and for multi-pass welding pass thickness, and
- the thermal conduction as determined by the work piece geometry and alloy composition.



Strength variation in the heat affected zone of a welded Al-Mg-Si alloy

(Source: Sapa)

In general, the heat affected zone is characterised by a local softening (reduction of strength). The resulting strength change depends on the alloy type, the original microstructural characteristics (local strengthening mechanisms) and the active softening mechanisms. In non-heat treatable aluminium alloys, the strength of work-hardened tempers (H tempers) is reduced due to recovery / recrystallisation processes whereas no (or relatively small) strength changes occur for soft (annealed) tempers.

When heat treatable aluminium alloys are welded, they lose a significant amount of their original mechanical properties in the heat affected zone. If the base metal being welded is in the -T4 temper, much of the original strength can be recovered after welding by proper postweld ageing. If the base metal is welded in the -T6 temper, it can be solution heat treated and aged after welding which will restore it to the -T6 temper. However, any post-weld heat treating and ageing may cause additional problems.

In Al-Mg-Si alloys (EN AW-6xxx serie), the strength of the original T4 or T6 tempers is reduced in the heat affected zone due to over-ageing. Full re-hardening would require a complete solution heat treatment followed by quenching and artificial ageing; as a result, the welded assembly will most likely be strongly distorted. Partial re-hardening after welding is possible up to about 40 % of the parent metal strength. Therefore, it is recommended:

 To keep the energy input per unit length of the weld as small as possible (→ reduce width of heat affected zone),

 To weld AIMgSi alloys in the T4 temper followed by age hardening of the complete assembly (if possible).

With extruded aluminium profiles, it is easy to compensate for the decreased joint strength by a local increase of the wall thickness. Furthermore, edge preparation can be directly incorporated into the cross section design.

In Al-Zn-Mg alloys (Cu-free alloys of the EN AW-7xxx serie), strength in the heat affected zone is reduced due to the re-solution of the precipitates. In this case, natural or – preferred – artificial ageing allows to restore more or less the original strength. As an example, the weldable EN AW-7020 offers unique possibilities due to:

- large solid solution range from 350 to 500 °C,
- low quench rate sensitivity,
- significant age-hardening effect at room temperature.

The heat affected zone reaches the original strength after 90 days of natural ageing.

Apart from strength, the corrosion resistance in the heat affected zone is probably the most important issue which has to be considered. As a rule, the heat input caused by the welding process often reduces the standard corrosion properties of aluminium alloys in the weld zone. The area next to the weld and the weld bead may lose corrosion resistance due to the creation of a coarse-grained structure. Furthermore, solidification cracks may promote the corrosive attack since can easily open the cracks. In addition, the potential formation of local residual stresses has to be considered in detail.

Among the "weldable" aluminium alloys, EN AW-6xxx and -7xxx alloys are most sensitive to corrosion problems after fusion welding. Pure aluminium and the non-hardenable alloys are more resistant or are not affected at all.

2.8 Imperfections in fusion welds

The presence of imperfections in a welded joint may not render the component defective in the sense of being unsuitable for the intended application (thus the preferred term is imperfection rather than defect). Welds that contain discontinuities serious enough to affect the weld strength, corrosion resistance or any other characteristic properties are considered as "defective welds". The defects may be the results of incorrect metal preparation, welding procedures or techniques. Common defect types include cracks (longitudinal, transversal or crater cracks), excessive porosity, incomplete fusion, undercuts and inadequate penetration. Incorrect weld size and shape are also considered as weld defects.

Imperfections can be distinguished with respect to their nature:

- Physical (e.g. cracks in fusion zone)
- Chemical (e.g. oxide inclusions)
- Geometrical (e.g. edge misalignment).

In industrial practice, however, imperfections in welds are rather divided into external and internal irregularities.



Examples of internal and external imperfections

Imperfections must be considered as irregularities in welded joints and, since they will always be present to some degree, it is necessary to define acceptable limits. There are various standards and guidelines for the description of external (e.g. misalignment of edges, notches and poor weld geometry) and internal (e.g. type and distribution of porosity, inclusions, cracks

and fusion defects) imperfections. The purpose of these standards and guidelines is to allow for a clear description of the observed defects.

The use of standardised terms also enables the establishment of application-oriented consistent quality specifications for welds. A subdivision into different evaluation classes enables the definition of limiting values, depending on the required geometrical tolerance and/or weld characteristics. This is done in appropriate guidance documents.

In design codes for welded structures, the imperfections are broadly classified into those produced during fabrication of the component or structure (external and internal imperfections as defined above) and those formed as result of adverse conditions during service (e.g. brittle fracture, stress corrosion cracking or fatigue failure). The application code will specify the quality levels which must be achieved for the various joints.

Welding procedure, joint features and access and welder technique will have a direct effect on fabrication imperfections.

a) Solidification cracking



TIG weld of the alloy EN AW-6061-T6 welded with 4043 filler metal (left) and without filler wire (right)

(Source: MAXAL)

The majority of aluminium alloys can be successfully fusion welded without cracking-related problems. Solidification cracking can be considered as a metallurgical weakness (see section 2.3.2), i.e. the result of a non-appropriate use of filler metal (no filler metal or wrong filler wire composition). It can also the result of not appropriately developed and tested welding procedures (e.g. too little filler metal in the weld, too small weld for the base material thickness or too low welding speed).

Solidification cracking (hot cracking) is a high-temperature cracking mechanism and is mainly a function of how metal alloy systems solidify. Aluminium crack sensitivity curve diagrams are a helpful tool to understand why aluminium welds crack and how the choice of filler alloy and joint design can influence crack sensitivity. The crack sensitivity curves show that with the addition of small amounts of alloying elements (Si, Cu Mg), the crack sensitivity becomes more severe, reaches a maximum, and then falls off to relatively low levels.

It can be seen that most of the aluminium alloys considered unweldable autogenously (without filler alloy addition) have chemistries at or near the peaks of crack sensitivity. In these cases, it is important that the composition of the weld, which is comprised of both base alloys and the filler alloy, lies in an area of low crack sensitivity.



Crack sensitivity curve of the most common weld metal chemistries

A further aspect to be considered are secondary cracking mechanisms. The filler metal choice has an effect on the shrinkage stress. Silicon filler metals (4xxx) have lower solidification and reduced cooling shrinkage rates than Mg filler alloys (5xxx). Therefore, 4xxx filler alloys have lower shrinkage stresses and produce reduced stress cracking.

b) Porosity

Porosity causes much concern despite the fact that, unless it is severe or aligned, it usually has less effect on weld strength than other defects. It is rather easily detected through standard radiography and thus has become a highly regulated defect.

Porosity is generally caused by hydrogen gas trapped in the metal as it cools (see section 6.3.3). The relevant sources of hydrogen that create porosity are:

- Hydrocarbons (in the form of paint, oil, grease, other lubricants and contaminants)
- Hydrated aluminum oxide (aluminum oxide can absorb moisture and become hydrated, the hydrated oxide will release hydrogen when subjected to heat during welding)
- Moisture (moisture within the atmosphere can be a serious cause of porosity under certain circumstances). Moisture from other external sources such contaminated shielding gas or from pre-cleaning operations must also be considered.

To control porosity, it is essential to eliminate moisture and contaminants by correct metal preparation and control of the welding procedure (i.e. the longer the weld remains fluid, the greater is the opportunity for the hydrogen to escape). The shielding gas, regardless of composition, should therefore have the lowest possible moisture and hydrogen content.

A specific type of internal imperfections are "mechanical pores" which are caused by the entrapping of air during welding. The formation of mechanical pores is favoured by the use of high energy welding processes (high welding speed), alloys with narrow solidification ranges and small tapering angle of the weld edges. This effect can be compensated by the creation of ventilation areas achieved by a narrow air gap between the work pieces, edge preparation with taper angles of 50 - 70° and reduction of welding speed to enable proper degassing.



Mechanical pore formation and prevention

c) Inclusions

Oxide inclusion in aluminium welds may be avoided by a proper surface treatment prior to welding (see section 2.2). More critical are metallic inclusions. The most common is tungsten, transferred through the arc when TIG welding. Nitrogen can also be a problem because it readily forms nitrides with aluminium which reduce the mechanical properties.

d) Incomplete fusion

Incomplete fusion is perhaps the most serious of the different defects, since it significantly weakens the joint and is difficult to detect. It is the result of weld metal failing to coalesce with the base metal or with other weld metal. Incomplete fusion results mainly from incorrect welding parameters (specifically insufficient current) and insufficient edge preparation / cleaning.

e) Incomplete root fusion or penetration

Incomplete root fusion is when the weld fails to fuse one side of the joint in the root. Incomplete root penetration occurs when both sides root region of the joint are unfused.

These types of imperfections are more likely in consumable electrode processes where the weld metal is "automatically" deposited as the arc consumes the electrode wire or rod. Correct welding parameters for the material thickness should give adequate weld bead penetration. In particular a too low current level for the size of root face will lead to inadequate weld penetration. It is also essential that the correct root face size and bevel angles are used and that the joint root gap is set accurately.

The following imperfections are related to poor geometric shape of the weld:

- Excess weld metal
- Undercut
- Overlap
- Linear misalignment
- Incompletely filled groove.

Penetration and fusion are controlled by the welder, the weld joint design, the weld procedure, the welding equipment, and the shielding gas characteristics.

f) Excess weld metal (overfill)

Excess weld metal is weld metal lying outside the plane joining the weld toes. This imperfection evelops when excessive weld metal is added to the joint, ie.e too much filler metal for the travel speed used. An increase in travel speed or voltage will help to reduce cap height.



Excess weld metal

(Source: TWI)

Most standards have limit for excess weld metal which is related to material thickness, but some also have a maximum upper limits. Moreover, most specifications state that a "smooth transition is required".

g) Undercut

An undercut is an irregular groove in the parent metal. A wide spreading arc (high arc voltage) with insufficient fill (low current or high travel speed) is the usual cause. This imperfection may be avoided by reducing travel speed and/or the welding current and by maintaining the correct arc length.



Undercut

(Source: TWI)

The figure shows undercut at surface of a completed joint but it may also be found at the toes of each pass of a multi-run weld. The latter can result in slag becoming trapped in the undercut region.

h) Overlap

Overlap is an imperfection at a toe or root of a weld caused by metal flowing onto the surface of the parent metal without fusing to it. It may occur in both fillet and butt welds.

The presence of the "overlap" imperfection is generally not allowed. It can be avoided by proper welding conditions, in particular by a reduction in weld pool size (reducing current or increasing travel speed). Adequate cleaning of the work pieces is also important.



Overlap (Source: TWI)

i) Linear misalignment

This imperfection relates to deviations from the correct position/alignment of the joint. It is primarily the result of poor component fit-up before welding. The consequence of linear misalignment can, when welding is carried out from one side, be lack of root or sidewall fusion to give a sharp continuous imperfection along the higher weld face toe.



Linear misalignment (Source: TWI)

j) Incompletely filled groove

This is a – continuous or intermittent – channel in the surface of a weld, running along its length. The joint has not been sufficiently filled due to insufficient filler metal (current or wire feed too low or too high a travel speed). The result is that the weld thickness is less than that specified in the design, which could lead to failure. Most standards will not accept this type of imperfection.



Incompletely filled groove (Source: TWI)

There are various other types of weld imperfections which are described in the different standards and guidance documents. For details, please refer to the appropriate application codes.

k) Weld discoloration, spatter and black smut

EN AW-4xxx series filler metals produce less weld discoloration, spatter and smut than EN AW-5xxx series filler metals. Magnesium in the Al-Mg-filler metal alloys preferentially vaporizes in the arc and condenses as a black powder next to the weld bead. It has a lower vapour pressure than either silicon or aluminium. The increased vapourisation causes some disintegration of the transfering droplet as separation from the tip of the electrode occurs. Increased black smut and spatter are therefore encountered next to a weld bead made with Al-Mg filler metal alloys.

Also oxygen and moisture causes weld discoloration and smut build-up. Thus the air content in the shielding gas should be minimized.

I) Detection of welding imperfections

There are several methods of detecting weld defects in aluminium. Visual inspection is by far the easiest and most inexpensive method. Frequent visual inspection during welding can often detect imperfections early enough to allow for corrective actions before a weld is welded completed, and thus minimize repair welding at a later stage. Radiographic, penetrant, ultrasonic or eddy current are all non-destructive detection methods that are readily used on aluminium. Ultrasonic testing is the most effective and most frequently used testing method.

Method	Incomplete fusion	Pores	Cracks	Incomplete penetration	Inclusion
Radiography	Х	Х		Х	
Penetrant			x		
Ultrsonic	Х	x	х	х	х
Eddy current			x		

Non-destructive testing methods for aluminium welds

2.9 Work environment and safety

Welding operations result in fumes and spatter and thus should be properly controlled to minimise spatter and dust formation. Appropriate personal protective equipment must be used to avoid inhalation. Aluminium metal is not particularly hazardous or toxic. Aluminium oxide dust is a nuisance dust. On the other hand, aluminium dust is pyrophoric and must be suitably handled.

When welding aluminium, the emission of particulate fume and gases depends on the welding method, the applied filler metal and the type of alloy. TIG welding produces less fume than MIG welding due to the lower energy of the arc and the fact that the filler metal is not placed in the extremely hot centre of the arc. The highest amount of fume is produced by using AI - 5 % Mg filler metal.

Dust is created in the form of fumes and particles. The particles are often large in size and fall down close to the workplace, but fume particles are smaller and can travel far from the workplace. Therefore, much effort is directed towards minimising air pollution. One of the largest problems encountered when welding is the formation of ozone. MIG welding of aluminium produces more ozone than TIG welding. The amount is also dependant on welding current, arc length, welding time and type of alloy. Silicon filler metals produces the largest amount of ozone, whereas ozone production is much lower when using magnesium alloyed filler wire. In order to reduce the ozone level, proper ventilation of the workplace is therefore essential. The second possibility is the use of a shielding gas that reacts with ozone, i.e. the addition of a small amount of nitric oxide (NO) to the shielding gas. NO dissociates the ozone molecules into oxygen and nitrogen dioxide (NO₂).

2.10 Simulation of fusion welding

Fusion welding of aluminium is today well understood and can be simulated by several specific software programs (e.g. SYSWeld[®] or WELDSIM[®]). The use of the computer to simulate the joining process often allows a reduction of the development cost by reducing the amount of experimental investigations.

The welding process includes several different non-linear physical phenomena which have an influence on the final properties of the welded joint. Their consideration in a single simulation model is unrealistic:

- The mathematical description of all these acting phenomena with their respective coupling is extremely difficult.
- The computational time of such a model would be unacceptable with the available computational resources.

In order to decrease the complexity of the model, simplifications and assumptions are therefore taken into consideration depending on the focus and the respective required accuracy of the investigated problem. Over the last 30 years, research in the area of welding simulation has converged to three main domains:

- Process simulation
- Material simulation
- Structure simulation.

The process simulation deals with the welding process itself. In comparison to the structure simulation that describes the process effects on the surrounding structure, the goal of a process simulation is the description of the molten pool formation (and the fluid flow dynamics inside the weld pool) as a function of the acting physical phenomena and the resulting local temperature field. The material simulation deals with the microstructural evolution during and after the welding process in and around the weld seam on a micro- and macroscopic scale including hot and cold cracking. Many computational thermodynamic and kinetic models have been developed in the last decades to predict these phenomena. The prediction of the thermal and mechanical material properties of alloys in dependence on their chemical composition also belongs to the material simulation. The structure simulation deals with the heat effects of the welding process, which are the global temperature field and the resulting residual stresses and distortions of the welded assembly.

In industrial practice, the definition of the welding sequence and the locations where the parts should be welded provides the basis for the correct completion of the welding assembly process. Numerical simulation allows the prediction and minimization of the resulting distortions, i.e. it enables an increase of the overall product quality as well as drastic cost saving.

The welding process is simulated with the aim to control the process in a way that minimizes the stress gradient as well as tensile / compressive surface stresses. As a result, the lifetime of the assembly under dynamic loads increases and corrosion risk decrases. Virtual manufacturing helps to optimize part geometry, materials and process parameters during the early stages of a new design cycle avoiding expensive engineering changes that could occur later. It also allows user-defined weld sequencing and control of the weld manufacturing parameters such as velocity, energy input and many others.



Virtual manufacturing ensures optimum weld quality

(Source: ESI)

Process modeling techniques can be also applied to optimize the functional requirements of a specific component at minimum costs. For welded aluminium structures, the load-bearing capacity of the welds is of major concern since the mechanical integrity of the welded component is generally poorer than that of the base material. As an example, the heat affected zone in Al-Mg-Si alloys represents the weakest part of the weld. Therefore, the design stress cannot exceed the minimum strength level in this zone. On the other hand, adding material thickness to increase the load-bearing capacity of the joint should be avoided because of the resulting weight and cost penalties.

The predicted weld thermal history can be used as input to a microstructure module that calculates the evolution of the particle size distribution with time. Advanced dislocation mechanics are then employed to convert the computed particle size distribution into an equivalent room temperature yield strength. The results from the microstructure module are then transferred to a mechanical module to obtain the actual residual stress and distortions.



Main inputs and outputs of WELDSIM®

Aluminium Automotive Manual – Joining

3. Arc welding

Content:

3. Arc welding

3.0 Introduction

3.1 Arc welding with consumable electrodes

3.1.1 Gas metal arc welding

- 3.1.1.1 MIG welding of aluminium
- 3.1.1.2 Pulsed MIG welding
- 3.1.1.3 Advanced control techniques for pulsed MIG welding
- 3.1.1.4 High performance MIG welding
- 3.1.1.5 Tandem MIG welding
- 3.1.1.6 Pulsed MIG welding with alternating current
- 3.1.1.7 Advanced MIG welding techniques using short-circuit ("dip") metal transfer
- 3.1.1.8 Advanced MIG welding techniques using reciprocating wire feeding
- 3.1.1.9 MIG spot welding

3.2 Arc welding with non-consumable electrodes

3.2.1 Tungsten inert gas (TIG) welding

- 3.2.1.1 Tungsten electrodes
- 3.2.1.2 Shielding gases
- 3.2.1.3 Effects of polarity on weld penetration
- 3.2.1.4 Square wave ("pulsed") and frequency controlled TIG (AC) welding
- 3.2.1.5 TIG welding equipment

3.2.2 Plasma arc welding

3.3 Arc stud welding

- 3.3.1 Arc stud welding with lift ignition
- 3.3.2 Arc stud welding with tip ignition
- 3.3.3 Arc element welding

3.4 Other arc welding techniques

- 3.4.1 Shielded metal arc welding
- 3.4.2 Oxyfuel gas welding

3.0 Introduction

Welding is a commonly used fabrication process to join metallic materials. A weld joint is accomplished by partially melting the work pieces to form a molten metal pool that solidifies and forms - after subsequent cooling - a firm, permanent connection. Sometimes, a filler metal is also added to the molten metal pool. Various fusion welding techniques are used in practice. Some general aspects which concern all the different methods are covered in section "2. Characteristics of aluminium in fusion welding". Please see this section for more details.

A most important welding method is arc welding. Arc welding is a fusion welding process which uses a power supply to initiate and maintain an electric arc between an electrode and the base material to create a molten metal pool at the welding point. Arc welding can be accomplished either with direct (DC) or alternating (AC) current. The welding region is usually protected by some type of shielding gas, vapour, or slag.

The different arc welding techniques are defined by the type of electrode:

- Arc welding with a consumable electrode
- Arc welding with a non-consumable (refractory) electrode.

For aluminium materials, three arc welding processes are most relevant:

- MIG welding (often referred to as GMAW (Gas Metal Arc Welding))
- TIG welding (often referred to as GTAW (Gas Tungsten Arc Welding))
- Plasma arc welding (PAW).

The weld region is shielded from the atmosphere by an inert gas.

Gas shielded arc welding processes with relevance to aluminium



further processes are known, but have no relevance to aluminium welding

Arc welding processes may be manual, semi-automatic, or fully automated. Manual welding is used for welding tasks where mechanisation/automation is not considered to be profitable. If applicable, a hand held rod may be used in TIG welding to add the filler metal to the weld pool whereas in MIG welding, the consumable electrode is always automatically fed from a reel.

In mechanised welding, the welding parameters are controlled mechanically or electronically, but can be manually adjusted during welding to ensure the required weld quality. In contrast, in automatic welding, manual adjustments of the welding parameters are not possible during welding, but may be made between welding operations. The result is a more consistent weld quality and weld bead appearance, provided that the welding parameters are properly defined. Generally a human operator prepares the materials to be welded.

For high production volumes, robotic welding is commonly used. The welding process is completely automated and robots both perform the weld and handle the parts.

3.1 Arc welding with consumable electrodes

3.1.1 Gas metal arc welding

Gas metal arc welding (GMAW) is a semi-automatic or automatic welding process where a continuously fed consumable wire acts as both electrode and filler material. The welding wire uncoils automatically from a reel to the welding torch. Heat is produced by an arc between the electrode and the base metal. It is a versatile welding process, suitable for practically all metals, quick and easy on thin as well as heavy gauge material and generally calls for little post weld finishing.

A differentiation can be made between metal inert gas (MIG) welding and metal active gas (MAG) welding. For steel welding, active gas mixtures (mainly argon-based gas mixtures which contain oxygen or carbon dioxide) are preferred. In contrast, for aluminium and most other metals, inert shielding gases (argon, helium or mixtures of these two) are exclusively utilized (see also section 2.5).

Although seldom used, flux cored wires can be applied as an alternative to shielding gases. In this case, evaporation of their casing in the arc creates a shielding gas environment.



Fundamental features of the gas metal arc welding (GMAW) process

3.1.1.1 MIG welding of aluminium

For MIG welding of aluminium, a direct current (DC) power supply with the electrode connected to the positive pole is usually used since this arrangement results in a very good removal of the aluminium oxide surface film (see section 2.1.1). The wider application of the MIG welding process with alternating current (AC) was only enabled by recent power source developments. This approach is particularly useful when welding thin aluminium materials since AC MIG welding reduces the heat input into the base material.

During the last years, significant improvements were made with respect to power source technology and weld process control. The welding current, arc length and electrode wire speed are controlled by the welding machine and set by the operator. The MIG process uses a continuous wire feed and, for the majority of welding operations, it is important that the rate at which the wire burns off in the arc is matched by the wire feed speed. Otherwise, an unstable arc and variable weld quality may result. In general, the feeder is of the push-pull type, i.e. the wire is pushed through a feed pipe and at the same time drawn by the gun. Wire feeding is provided either by an integrated wire drive inside the power source housing or an external wire-feed unit.

Conventional stepped power sources use a transformer to produce the desired welding voltage. A rectifier, positioned downstream from the transformer, generates the rectified

welding current from the supplied alternate current. An adjustable induction coil smooths out unwanted current peaks, thereby reducing the tendency to produce welding spatter.



Schematic of the MIG welding process

(Source: Miller Electric Mfg. Co.)

The welding current flows from the power source through the gun cable and welding torch (or welding gun) to the wire and across the arc. On the other side of the arc, the current flows through the base metal to the work cable and back to the power source. The filler wire is fed via two or four drive rollers into the welding torch, where the current is transferred either via a contact tube or a contact tip.



Schematic of a MIG welding gun (left) with current transfer at the tip (right)

(Source: Lincoln Electric Company)

The shielding gas flows through the gun and out the nozzle. The free wire end is concentrically surrounded by the gas nozzle. The shielding gas prevents chemical reactions between the hot work piece surface and the surrounding air and protects the weld pool from contamination. In addition to controlling the arc behaviour and deposition rate, the shielding gas is also partly responsible for the material transfer and the shape of the resulting weld seam.



Gas-cooled welding torches for manual (left) and robotic welding (center) with current transfer using a contact tube (right)

(Source: Fronius)

Manual and machine welding torches are available in gas-cooled and water-cooled versions. Gas-cooled welding torches are cooled by the shielding gas, while water-cooled welding torches offer more effective cooling. For welding currents of 300 A and above, water-cooled welding torches are standard.

In the standard DC MIG welding process, most of the heat developed in the arc is generated at the electrode (positive pole). The result is a high wire burn-off rate and an efficient heat transfer into the weld pool. The selection of wire diameter and wire feed speed determine the welding current as the burn-off rate of the wire will form an equilibrium with the feed speed.

The manner in which the filler metal transfers from the electrode to the weld pool largely determines the operating features of the process. There are three basic metal transfer modes in gas arc welding: short-circuiting, globular, and spray:



Types of metal transfer

In short-circuit (or dip) transfer welding, metal transfer occurs when an electrical short circuit is established. At low welding currents, the tip of the continuously fed wire may not melt sufficiently fast to maintain the arc, but can dip into the weld pool. An electrical short is created and the current spikes. The combination of surface tension forces and the magnetic pinch force created by the current spike cause the droplet to transfer to the weld pool and the arc is re-established. The cycle is repeated about 100 times per second.

Due to the low heat input, this metal transfer mode would be particularly useful for joining thin materials. However, the violent nature of the short-circuiting event results in relatively high spatter levels and the process has a tendency to generate incomplete fusion discontinuities when welding thicker materials. Thus for a long time, the short-circuit transfer process variant was not used for aluminium welding.

Only recently, new equipment developments enabled significant improvements in the control and stability of short-circuiting metal transfer. Several manufacturers now offer advanced versions of the MIG welding process for thin sheet and/or positional welding based on the short-circuit transfer mode (see section 3.1.1.6).

As welding current and voltage are increased, metal transfer takes on a different appearance. In the globular transfer mode, a molten metal ball builds up at the end of the electrode with a diameter which is usually greater than the wire itself. When the drop finally detaches either by gravity or short-circuiting, it falls onto the work piece producing high heat, an uneven weld surface and spatter. Due to its erratic nature, the globular transfer mode is not used for aluminium welding.

By raising the welding current and voltage still further, metal transfer changes from larger globules through small droplets eventually to a vaporised stream. In the spray transfer mode, small molten drops are detached from the tip of the wire and projected by electromagnetic forces towards the weld pool. The wire does not make contact with the weld pool, i.e. the arc is stable and little spatter is produced. On the other hand, the continuous spray of small molten droplets enables high deposition rates and deep penetration into the parent metal. The low melting point of aluminium and its alloys allows the application of the spray transfer mode even at relatively low currents. Thus for a long time, spray metal transfer was the preferred technique for aluminium welding.

A drawback of the spray arc welding method is its high thermal input, which means that it is best suited for welding thicker materials and for welding in flat and horizontal positions. When welding thinner aluminium components, the risk of burn-through and warping issues calls for careful control of the processing parameters. As a possible solution, the fine wire MIG welding process (with wire diameters < 1 mm) was considered. However, the soft, fine aluminium wires are difficult to feed and this approach proved to be not very successful.

Today, the pulsed spray method (see section 3.1.1.2), a variant of the spray transfer mode where metal transfer is achieved by applying direct current pulses, is normally applied, in particular for thinner aluminium work pieces.



Manual and automated MIG welding of an aluminium car body structure

(Source: Ferrari)

In MIG welding, the electric arc is dynamic, i.e. current and voltage are constantly changing. Current effects the consumption rate of the electrode, i.e. the higher the current level, the faster the electrode melts. Voltage controls the length of the welding arc and the resulting width and volume of the arc cone. As voltage increases, the arc length gets longer (and arc cone broader).



Effect of Arc Voltage

(Source: Lincoln Electric Company)

Many MIG welding power sources are designed with a constant voltage characteristic. This is most important in manual welding where a fixed arc length cannot be maintained during welding. When a constant voltage power source is used, a small increase in the arc length increases the arc voltage and therefore results in a large drop in arc current. Consequently the wire burn-off rate decreases, the tip of the wire moves back closer to the weld pool, decreasing the voltage and raising the current again. The result is a "self-adjusting arc" where arc length and filler metal deposition rate are maintained constant almost irrespective of the

torch movement, although weld penetration is not maintained constant because the current is varying. On the other hand, a constant current power source has also advantages. In this case, a large change in arc voltage results in only a small change in arc current. Heat input is reasonably constant, leading to more consistent weld penetration.

Just as it is possible to perform MIG welding using constant current or constant voltage power supplies, it is also possible to perform MIG welding using power supplies where the overall arc power is regulated. In the Power Mode[™] process variant, the wire feeding speed and the overall arc power are preset. The arc length is set by changing the arc power, i.e. increasing arc power increases the arc length.



Comparison of the constant current, constant voltage and constant power slopes

(Source: Lincoln Electric Company)

The power supply responds to changes in voltage sensed at the welding arc. However, unlike a constant voltage weld process, the Power Mode[™] will respond with less current change. The benefit of this type of control is most obvious in applications where energy and penetration must be closely monitored and consistent, i.e. it aids in the control of the arc's response to variations in stick-out. Spatter levels are usually lower than those obtained from constant voltage power supplies.

3.1.1.2 Pulsed MIG welding

Pulsed MIG welding is a further development of the standard MIG welding process. It was developed in the early 1960s, but wider adoption on the shop floor started only in the late 1970s. With the introduction of solid state electronics, pulsed arc welding became the standard MIG welding technique for aluminium.



Pulsed MIG arc welding features a controlled, short-circuit-free material transfer (Source: Fronius)

Characteristic of the pulsed arc technique is the controlled material transfer. Pulsed MIG welding maintains an arc at low current and superimposes short periodic pulses (30 - 300 Hz) of high current in order to detach and transfer single drops of molten metal from the electrode to the weld pool. In the background current phase, the energy supply is reduced to such an extent that the arc is only just stable and the surface of the work piece is preheated.

The peak current phase is used for targeted droplet detachment. A precisely controlled current pulse supplies the heat to melt the filler wire, but also to pinch off just one molten droplet for each pulse. The droplet size is adjustable. Although the metal transfer occurs at the high current levels necessary for spray transfer, the average current is reduced. The reduction of the overall heat input decreases the size of the weld pool and heat-affected zone. Furthermore, a thicker electrode can be used when welding thin material, i.e. the deposition rate (welding speed) can be increased.



Robotic MIG welding with through-arm (left) and external wire feeding (right) (Source: Lincoln Electric Company)

With the pulsed arc technique, an unwanted short circuit with simultaneous droplet explosion is ruled out as is uncontrolled welding spatter. There is less deformation of the work piece and less need for post-weld finishing. The smaller weld pool offers greater versatility, making it possible to weld in all positions. It also helps to bridge gaps when fit-up is less than optimal. Furthermore it provides the operator with excellent directional control over the weld pool, which improves bead appearance.



Robotically applied MIG weld joining the C pillar to a roof section on the Jaguar XK

(Source: Jaguar)

Pulsed MIG welding requires a power source which can supply the two different current levels. Modern microprocessor-controlled power sources allow to fine-tune arc conditions e.g. for material thickness, wire diameter or material type and have a built-in set of programs that automatically select the optimal welding parameters enabling perfect and reproducible results. Therefore practical application is much easier compared to older power source types where all pulse parameters had to be adjusted by the operator.



Microprocessor-controlled power source for short circuit, spray and pulse-spray metal transfer and a push-pull wirefeeder (left)

(Source: The Lincoln Electric Company)

3.1.1.3 Advanced control techniques for pulsed MIG welding

Further advancements of the MIG welding process were enabled in recent years by the increasing use of microelectronics and digital technology. The results are even lighter power sources, faster controlled arc movements and improvements in the ignition process. The latest developments are completely digitalized welding systems. The crucial difference compared to conventional computer-controlled power sources is the incorporation of a digital signal processor which carries out the welding process control. The new developments provide an even easier user guidance and further improved welding characteristics.

In pulsed MIG welding, the output of the power source is neither constant current nor constant voltage. Modern power sources rather monitor and change both voltage and current at extremely fast rates in order to maintain stable arc welding conditions. The continuously adjustable output current is constantly measured and kept within the ideal range. Also the pulse waveform is continuously adjusted by providing a fast or slow front edge on the pulse to transfer the droplet at the proper rate. The back edge falls at a controlled rate to add the required heat to wet the droplet to the molten metal pool.

Some specific control features that significantly improve pulsed MIG welding performance are described in the following. As an example, pulsed waveforms have been developed that use true constant current. The purpose of these waveforms is to eliminate the rapid variations of the arc length ("hunting") that is common when using 5XXX filler metals. This approach has been reported to be successful, with a more stable arc and no arc hunting.

Another example is the Profile Pulse[™] feature that significantly improves the weld bead appearance. It creates a TIG-like weld bead profile without having to weave or step the torch.



Typical consistently spaced ripple pattern of a MIG Profile Pulse[™] weld (Source: Miller Electric Mfg. Co)
The wire feed speed and arc power are modulated at a low frequency, thus producing a consistently spaced ripple pattern. The spacing of the ripple pattern can be changed by changing the switching frequency (usually from 0 to 5 Hz). Commonly used for highly visible welds, the Profile Pulse[™] program can also aid in out-of-position welding.

The same effect can be achieved without changing the wire feeding speed e.g. by superimposing a low frequency pulse over the normal pulse and adjusting the relative length of the high-current phase per cycle ("SynchroPulse" function) or the Pulse-On-Pulse[™] process which uses a sequence of varying pulse wave shapes. In the Pulse-On-Pulse[™] process, a number of high energy pulsed is followed by the same number of low energy pulses. The high energy pulses provide a hotter arc (longer arc duration) while the low energy pulses allow the weld pool to cool. As a result, heat input can be controlled even more precisely.



Pulse-On-Pulse[™] process

(Source: Lincoln Electric Company)

The high measuring and control speed of modern power sources also offer functions such as the penetration stabiliser and the arc length stabiliser feature. Arc-length control ensures that the arc length remains constant at all times, even when the stick-out changes. It maintains a consistently short arc, which allows to achieve higher welding speeds.



Constant arc length despite varying stick-out (left) and changing torch position (right)

(Source: Fronius)

Weld penetration can be kept constant by using current controls to adjust the heat so that changes in electrode extension do not affect heat input. Another possibility is to make use of an active wire control to compensate for the influence of the torch stand-off distance on the welding result.



The activated penetration stabiliser controls the wire feed speed instead of the welding current (left) and ensures constant weld penetration (right)

(Source: Fronius)

Significant improvements have been achieved also with regard to the start and stop phase. The ideal ignition sequence can be optimised and programmed with the ignition parameters precisely matched to the diameter and quality of the wire. A special ignition variant takes into account the good thermal conductivity of aluminium. In order to prevent fusion defects in the start-up phase, the base metal has to be melted right away. Thus, ignition is effected at considerably higher power. Once there has been sufficient heat input into the weld pool, the welding power is decreased. Furthermore, the ignition energy can be adapted to the actual wire temperature at the instant of arc initiation. The result is a quiet, jerk-free arc ignition.

Towards the end of the seam, there is a danger of the weld pool collapsing or dropping through as a result of the heat running ahead in the work piece. This is counteracted by reducing the welding power to an even lower value for filling the crater. At the end, a controlled current pulse sheds the last molten droplet, preventing a solid globule from forming at the tip of the electrode.



End of welding without burn-back pulse (left) and with burn-back pulse (right)

(Source: Fronius)

3.1.1.4 High performance MIG welding

There is only limited scope for translating higher arc power into higher welding speeds. When the power is increased, the arc pressure rises very rapidly, which makes the weld pool difficult to control. The result may be an irregular bead shape, porosity or excess penetration.

Nevertheless, there is an increasing demand for high quality MIG welding processes with increased productivity. By definition, high-performance MIG welding processes have one or more solid wires of 1.0 mm or 1.2 mm diameter with a wire feed speed of more than 15 m/min. Processes with a greater wire cross section may also count among the high-performance welding processes. The enhanced deposition rate can be used either for welding larger cross-sections (i.e. improved gap bridging) or for increased welding speeds.

The applied power source technology (as well as the wire feeding system and the welding torches) corresponds to that used in standard MIG applications, but in design and performance, the components are specifically adapted to the requirements of high-performance welding.

a) Large wire MIG welding

In principle, an enhanced deposition rate can be achieved by a longer free wire tip in the welding torch (greater "stick-out") and an increase of the wire feeding speed. However, particularly with aluminium, there is an upper limit for the wire feeding speed; the limiting values are approximately 18 m/min with 1.2 mm and around 11 m/min for 1.6 mm diameter wire.

The better option is the use of wires with a higher cross-sectional area. With round wires of up to 3.2 mm diameter, a maximum deposition rate of 5 kg/h could be achieved. However, the main disadvantage of larger wires is also the wire feeding process; the soft aluminium wires are difficult to feed as they lack column strength. Thus for aluminium, practical application of large wire welding is very limited.

b) Flat wire MIG welding

A more promising alternative is the use of a flat wire. When a flat strip wire is deflected by its wider side, it can be fed better than a round wire with the same cross-sectional area. The rectangular cross section of the wire also allows the transport of more current with less resistance due to the skin effect (current is best conducted around the outside of the welding wire).

The arc burns stable on the whole edge of the strip wire. At the strip wire, the arc has a pronounced elliptic shape, but becomes almost round at the welding site. Different welding results will be obtained, depending on whether the strip-wire is fed parallel or at right angles to the direction of welding. The wider arc leads to a lower arc pressure, resulting in decreased penetration and improved gap bridging. The maximum deposition rate reaches 4 kg/h for aluminium. MIG welding with a flat wire basically takes place under the same process conditions as those applicable to round wire.



Push-pull strip-wire MIG torch with water-cooled gas nozzle (Source: Fronius)

c) Twin wire MIG welding

A greater increase in deposition rate is offered by the application of a two-wire technology. Basically, two variants are possible:

- In **twin wire welding**, both wire electrodes are guided jointly through the same contact tube which means that both electrodes have same electrical potential on a continuous basis.

- In **tandem welding**, each electrode has a separate contact tube. The contact tubes are electrically insulated from each other, i.e. it is possible that the two electrodes have different electrical potentials.



Twin wire welding with a common contact tube (left) and tandem welding right) (Source: Fronius)

After initial successes with simultaneous melt-off from two wire electrodes in MAG welding of steel, efforts were made to transfer these results to aluminium MIG welding. However, the respective trials did not deliver the expected gain in welding speed. The small arc length repeatedly led to a short circuit between one wire electrode and the weld pool, which then caused arc extinction on the second wire electrode. Consequently, the high current density on the first wire electrode quickly broke the short circuit.

The result was an instability of both arcs owing to the wide fluctuations in arc length and a large amount of weld spatter. Although both the spattering and the instability could be reduced when the arc length was increased, the corrective measures also decreased the welding speed. Consequently, further development of the twin wire concept was discontinued.

The definitive solution for an increased deposition rate based on the two wire method proved to be the tandem MIG welding process where the two wires can be operated independently (see section 3.1.1.5).

d) Hybrid MIG welding

For even higher performance, the MIG welding process can be combined with other welding techniques. Relevant for practical application are the Laser MIG welding process (see section 10.3.1) and the Plasma MIG welding process (see section 10.3.2). In hybrid welding, both techniques act in the welding zone at the same time and influence each other. The results are beneficial synergy effects such as highest possible speed with the highest possible quality, process stability and spatter-free welding even at maximum speed, improved gap bridging and less geometrical distortion.

3.1.1.5 Tandem MIG welding

Tandem MIG welding systems comprise two wire feed units and power sources. Both wires - which are electrically isolated from each other - are continuously fed through a special welding torch and melt simultaneously in a common weld pool. Each wire is separately contacted, i.e. they can be operated independently with different wire diameters, current levels or operating modes.

Welding commonly takes place with the two wires in-line along the joint. However, the wires may be positioned also side by side or at any angle in between allowing precise control of bead width and gap filling.



Tandem MIG welding process (left) and torch cutaway (right)

(Source: Fronius)

Tandem MIG welding requires a special power source control that enables the stable operation of two independent welding arcs working in close proximity. The length of the two electric arcs is separately controlled which means that it is possible to ensure a stable arc and perfect drop release in both cases and thus achieve low spatter. Since the length of each of the two arcs can be kept short, the weld pool remains narrow. But the longer weld pool

produced by the consecutively placed arcs enables a significant increase of the welding speed.

The first electrode in-line is referred to as the lead electrode and the second electrode is the trail electrode. The function of the lead wire is to ensure that the base metal is thoroughly melted, i.e. to generate the majority of weld penetration and metal deposition. The trail wire controls the weld pool for bead contour and edge wetting; it also adds to the overall weld metal deposition rate. Furthermore, the trailing arc prolongs the weld-pool degasification time, i.e. it reduces pore-formation sensitivity.

The process would work with a large diameter lead wire and a small diameter trail wire (which therefore draws less current) using the same voltage for both electrodes. However, the lead and trail welding wires are generally specified to be the same diameter to satisfy inventory constraints and/or because the direction of welding must be reversed. Consequently, a slightly higher power is normally set for the leading arc.

The electrical insulation of the two electrodes allows the independent selection of the arc type (constant DC arc or pulsed arc). Thus there are four basic operating modes for tandem MIG welding:

- Pulsed arc in both electrodes

- Constant voltage mode ("standard arc") in the leading electrode / pulsed arc in the trailing electrode

- Pulsed arc in the leading electrode / standard arc in the trailing electrode
- Standard arc in both electrodes.

The first two operating modes are mainly used in practice as they address two critical demands: high speed thin metal welding and heavy gauge material welding. The "pulsed arc in the leading electrode / standard arc in the trailing electrode" mode has less relevance, but may be applied to achieve maximum welding speed and gap bridging. The "standard arc in both electrodes" mode is seldom used.

DC welding with a combination of a constant positive voltage in the leading electrode and a positive pulse in the trailing electrode is ideal for deep penetration. The lead electrode ensures a high deposition rate whereas the pulsed trail arc cools the molten metal pool and minimises electromagnetic arc interference. The independent control of the lead and trail arc parameters offers a wide operating range and allows to achieve an optimum balance between weld penetration and fill.



Main operating modes in tandem MIG welding

(Source: Lincoln Electric Company)

The "pulsed arc in both electrodes" configuration is used for optimally controlled metal transfer and to manage total process heat input on thin gauge material and other heat sensitive applications. The current in each wire is alternately pulsed to avoid magnetic interactions between the two arcs, leading to increased stability, minimal arc blow and reduced spatter. This requirement imposes strict operation constraints and the process must be carefully applied.



Tandem MIG welding with 180° phase-displaced pulsed arcs for optimum metal transfer

(Source: Lincoln Electric Company)

The ability to distribute the total welding current across two separate welding wires provides unique benefits for high-speed welding. On thin gauge materials, speed-limiting quality issues are either burn-through or insufficient gap filling characteristics. The tandem MIG welding process addresses both of these issues. It allows the lead wire to generate the required penetration while the trail wire creates added fill. Also, the trail arc acts as an additional force that pushes the molten metal for better follow and wetting capabilities.

Tandem MIG welding is typically used for mechanised or robotic welding in order to keep torch position precisely enough in relation to the weld seam. Wire movement is separately controlled for each arc, a synchronisation unit on the power sources ensures appropriate material transfer.

3.1.1.6 Pulsed MIG welding with alternating current

MIG welding with alternating current (AC) has existed for over 20 years, but has only been used in few applications. The limiting factor was the availability of a suitable power supply. A resurgence of AC MIG welding was only possible in the last few years when modern inverter, software-controlled power supplies enabled much better process control.



(Source: Lincoln Electric Company)

In the AC pulsed mode, both negative and positive polarity pulses are applied to the wire electrode. In the electrode positive (EP) mode, heat input into the work piece is high (i.e. high

weld penetration), along with cathodic arc cleaning. On negative polarity (EN), the heat input is lower, but the wire burn-off rate is greater. The overall lower heat input reduces geometrical distortion, allows thinner materials to be welded and larger gaps to be bridged without burn-through. In conjunction with pulse control and specific pulse adjustments, a significant improvement of the arc stability can be achieved and spatter can be reduced.



AC pulsed MIG welding allows control of heat input and the ability to bridge gaps

(Source: Miller Welding Automation)

Thus it is possible to optimally control the deposition rate, the formation of the weld and the bonding conditions between base material and filler metal. The applied AC frequencies vary over a range of approximately 50 – 400 Hz and the arc is usually running in the range of 10% EN/90% EP to 30% EN/70% EP. In most cases, the AC pulsed wave looks very similar to a conventional DC pulsed wave with a shorter EN pulse added at the end. Compared to DC pulsed MIG welding, the produced weld seams are of the same height and width, but since the heat input at the same wire feeding speed is lower, there is less "melt-through" or "read-through". The welds have low notches at the edge of the seam and a uniform weld scaling; there are no visual surface imperfections.

In response to the growing demand for heat-reduced arc welding processes, some manufacturers offer dedicated AC MIG welding power supplies. Other manufacturers manufacture a separate AC module that can be added to a current generation power supply at any time.



Conventional DC Inverter supply with an AC advanced module underneath (Source: Lincoln Electric Company)

3.1.1.7 Advanced MIG welding techniques using short-circuit ("dip") metal transfer

MIG welding using the short-circuit (or dip) metal transfer mode produces the lowest heat input, making this process variant particularly attractive for thin sheet applications where precise control of the weld pool is required. Thanks to advanced process control methods, properly controlled short-circuit transfer MIG welding can produce joints with a quality comparable to that of the TIG (GTAW) welding process, at production rates characteristic of the MIG welding process. The ability to generate welds with low and controlled heat input also enables successful welding of crack-sensitive materials.

In short-circuit metal transfer welding, the molten tip of the electrode contacts the weld pool and induces an electrical short. The resulting current spike increases the strength of the electromagnetic field surrounding the wire and creates a force which separates the molten part from the rest of the electrode ("pinch effect"). Surface tension forces draw the molten metal into the weld pool and the cycle begins again. The main difficulty associated with this type of metal transfer is the high spatter level. In order to balance maintaining a molten wire tip (for metal transfer) against an excessive current/pinch force (causing spatter), the most critical factor is the rate of current rise during the droplet detachment phase.



Short-circuit metal transfer causes high spatter levels

(Source: Fronius)

Advanced versions for a heat-reduced MIG welding process based on short-circuit metal transfer control the current profile throughout the various stages of the metal transfer cycle or use the reciprocating wire feed approach (see section 3.1.1.8). Further process variants synchronize both current and wire feed control during and/or before the short-circuit stage.

There have been numerous attempts to improve the arc behaviour during short-circuit metal transfer by closer control of the applied current cycle, especially in the re-ignition phase after the short circuit. As early as the 1980s, first trials were made to reduce the current immediately before the short circuit bridge breaks, followed by a high voltage pulse to ease arc re-ignition. Newer attempts introduced a closely controlled current increase to facilitate the separation of the molten metal ball in the short circuit phase, immediately followed by a rapid reduction of the welding current prior to the facilitated arc re-ignition. Since the current in the wire is reduced towards the end of the short circuit phase, the overall heat input is reduced and the weld pool is colder and less fluid.

The successful application of this control concept was made possible by the recent development of digitally controlled power sources. Welding equipment suppliers have come up with a number of solutions (e.g. EWM ColdArc[®], Fronius Low Spatter control (LSC), Lincoln Electric Surface Tension Transfer (STT), Miller Regulated Metal Deposition (RMD[™]), etc.) which are characterized by slightly different current profile characteristics. The welding process is regulated by continuous measurement and evaluation of the arc voltage. The power source instantaneously reacts to all phases of the weld metal transfer in accordance with the real situation of arc.

The proper control of the current waveform throughout the various stages of the metal transfer cycle enables smoother droplet transfer, precise bead placement, and reduced spatter levels. Since the advanced short-circuit metal transfer modes are insensitive to changes in the contact tip-to-work piece distance, they are ideally suited for automatic or semi-automatic operation.



Welding voltage and current in the individual metal transfer phases of the Lincoln Electric Surface Tension Transfer (STT) process

(Source: The Lincoln Electric Company)

In a first phase (which corresponds to the conventional short-circuit metal transfer process), the electric arc is burning between the end of electrode and the weld pool and a ball of molten material forms at the end of the electrode. When the size of the molten metal ball reaches the pre-determined size and contacts the weld pool, the welding current is rapidly reduced to a minimum to avoid any spatter or harsh arc behaviour. The current is then increased in accordance with a pre-determined curve to facilitate the separation of the ball. When the weld metal is about to separate from the end of the electrode and to transfer to the weld pool (i.e. the short breaks), the power source drastically reduces the welding current. Droplet transfer happens at minimum current and thus limits spatter and other effects caused by the dynamic activity during restart of arc. After completion of the metal transfer and re-establishment of the arc, a current peak is applied to produce a plasma force which pushes down the weld pool and prevents an accidental short. The current then tails out to regulate the overall heat balance and the cycle starts again.

3.1.1.8 Advanced MIG welding techniques using reciprocating wire feeding

The other possibility to realize a MIG welding process with reduced heat input based on the short-circuit metal transfer mode is the reciprocating wire feed (RWF) technique. The wire is reciprocated in and out of the weld pool in synchronization with the current waveform, i.e. the heating arc is automatically activated and deactivated in order to systematically heat and cool the welding wire.

The key to RWF MIG welding is an accurate digital process control where the detection of a short circuit initiates an immediate withdrawal of the wire, interrupting the arc load. The wire movement must take place at a very high frequency and extreme precision.



Functional principle of reciprocating wire feeding (Source: Fronius)

During the arcing phase, a droplet is formed on the end of the wire and the filler wire is advanced towards the weld pool. The shorting phase begins when the wire with its molten droplet comes into contact with the weld pool. When the short circuit is detected, the digital process control interrupts the power supply and initiates the retraction of the wire. The retraction of the wire, in combination with the surface tension forces, causes the droplet to detach. Due to the slight retraction of the wire electrode, the short-circuit bridge breaks more easily and the duration of the short circuit is reduced ensuring a clean, spatter-free material transfer. Once the ball is separated, the wire motion is reversed and the process starts again.

In the RWF mode, heat is only introduced very briefly in the arcing period, after which thermal input is immediately reduced and metal transfer is essentially current-free. Thus RWF MIG welding generates only a fraction of the heat produced in the standard MIG welding process and also less heat than advanced, current-controlled short-circuit MIG welding where droplet transfer is achieved through the combination of the pinch force imposed by an increased current level and surface tension forces.



Reciprocating wire feed MIG welding torch (CMT[®] process)

(Source: Fronius)

However, RWF MIG welding is more complex than the conventional MIG welding process and its advanced short-circuit metal transfer variants. Equipment manufacturers include Jetline Engineering (Controlled Short Circuit, CSC), Fronius (Cold Metal Transfer, CMT), SKS Systems (micro-Mig), and Panasonic (Active Wire Process, AWP). Since a highly dynamic wire drive is required, the RWF technique is commonly applied as an automated process and used in combination with welding robots (partly also as a consequence of the need to manipulate a larger, heavier torch). Many equipment manufacturers offer pre-defined programs that enable synergic control of all welding parameters.

The various systems mainly differ in the wire feeding concept. One possibility is a high speed, precision stepper motor incorporated into the torch that controls both feeding direction and wire speed as used for example in Jetline's CSC system. Another possibility is the two wire drive system used in the Fronius CMT[®] process. The rapid forward and back wire movement is ensured by a gearless wire drive directly on the torch which is designed for speed whereas the more powerful, slower main wire feeder is responsible for the continuous wire feed. A buffer is used to convert the superimposed, high-frequency wire movement into a continuous wire feed.

There are different options to exploit the potential of the RWF MIG welding technique. As an example, RWF and standard electrode positive pulsed MIG welding can be combined to produce more heat for thicker material welding. Introducing pulses in a controlled, adjustable way offers significant improvements in performance and flexibility.



Combination of RWF and pulsing cycles (pulsed-arc positive)

(Source: Fronius)

Another option is to operate the RWF MIG welding with alternating current (AC). The polarity of the welding current is made an integral part of the process-control and thus offers an even more tightly controlled thermal input. Polarity reversal takes place in the short circuit phase. Due to the negatively poled phase, the weld process achieves a higher deposition rate and better gap bridging. The positive cycles ensure controlled thermal input and precision droplet transfer. The relationship between the positive and negative cycles can be individually defined as required by each specific application.



Combination of RWF and AC cycles

(Source: Fronius)

RWF cycles can also be combined with negative electrode polarity alternating with positive polarity pulsing phases. During the negatively poled RWF phase, a higher deposition rate is obtained with lower thermal input. Pole reversal to the positively poled pulsing cycles takes place in the short circuit. In addition to the higher thermal input, the pulsing phase enables a non-short-circuiting droplet transfer. The relationship between the positive and negative process cycles is also freely selectable. This process variant achieves optimum arc control and absolute precision.



RWF process combining negatively poled cycles and positively poled pulsing cycles

(Source: Fronius)

Furthermore the RWF technique can be incorporated into a tandem MIG welding process.

Since material transfer in the RWF mode takes place with barely any current flow, light-gauge welding (0.3 - 0.8 mm) of aluminium sheets is perfectly feasible. At material thicknesses up to 3 mm, it outperforms conventional MIG and TIG welding processes by far. For seam welding, the work pieces are securely clamped and welded, and then any excess metal is removed by grinding. Most interesting is also the application of RWF MIG welding to join an aluminium component to steel using a special brazing process (see section 11.2.1.3).

Ultimately, RWF cycles can be combined with advanced current profile control methods. In this case, the current is programmed to squeeze the liquid bridge. When the welding system detects the necking sequence, the current is immediately lowered while the rearward movement of the wire assists in the droplet detachment, thus minimizing time in the short-circuit phase. The high precision of the droplet-detachment sequence ensures spatter-free metal transfer and guarantees that after every short circuit, a near-identical quantity of filler metal is melted off. The incorporation of the wire motion into weld process-control results in a higher process stability, offers the ability to bridge higher gaps and ensures a flaw-less weld appearance, specifically when welding thin-walled aluminium materials.



RWF MIG welding with advanced current control excels in the low thickness range

(Source: Miller Welding Automation)

Since the arc length is acquired and mechanically adjusted, the arc remains stable, independent of the work piece surface, the welding speed and the welding position. These advantages are obviously most interesting for robotic welding. Thanks to fully synchronized system components and consistent digitalization of the power source, robotic welding can be performed faster and with a higher degree of reproducibility. Information on the current status of the power source and on every weld seam can be used to monitor, analyse and document the welding process.



Fully digitized power source designed to meet the demands of robot-assisted welding

(Source: Fronius)

3.1.1.9 MIG spot welding

MIG spot welding may be used to lap weld sheets by melting through the top sheet and fusing into the bottom sheet without moving the torch. The equipment used for spot welding is essentially the same as that used for conventional MIG welding, using the same power source, wire feeder and welding torch. The torch, however, is equipped with a modified gas shroud that enables the shroud to be positioned directly onto the sheet surface. The shroud is designed to hold the torch at the correct arc length and is castellated such that the shield gas may escape. The power source is provided with a timer so that when the torch trigger is pulled a pre-weld purge gas flow is established, the arc burns for a pre-set time and there is a timed and controlled weld termination. The pressure applied by positioning the torch assists in bringing the two plate surfaces together.

The process may be operated in two ways: (a) by MIG spot welding with the weld pool penetrating through the top plate and fusing into the lower one or (b) by plug welding where a hole is drilled in the upper plate to enable the arc to operate directly on the lower plate so that full fusion can be achieved. MIG spot welding method can be used as an alternative to resistance spot welding where there is insufficient access for a spot welder.



Schematic of the MIG spot welding process

(Source: Miller Electric Mfg. Co.)

Argon is the preferred shield gas choice as it produces a deep, narrow penetration. Argon also provides better arc cleaning than helium. Proper surface cleanliness is crucial to achieve defect-free welds.

3.2 Arc welding with non-consumable electrodes

The tungsten inert gas (TIG) welding process – often referred to as gas tungsten arc welding (GTAW) process – was developed earlier than the MIG (GMAW) welding process. For many applications, TIG welding has been replaced nowadays by MIG welding, primarily because of the increased welding speed when welding thicker sections. However, TIG welding is still widely used to join aluminium alloy products. The small, intense arc provided by the pointed electrode is ideal for high quality and precision welding. TIG welding is especially useful for welding thin materials, but requires significant operator skill and can only be accomplished at relatively low speeds. Generally, little or no post weld finishing is required.



Common components of a TIG welding system (Source: Miller Electric Mfg. Co.)

TIG welding uses a non-consumable electrode made of tungsten and an inert shielding gas or gas mixture. The welding heat is generated by an electric arc between the tip of the electrode and the base metal. TIG welding is carried out with either alternating current (AC) or direct current (DC). For the majority of metals, TIG welding takes place using direct current with

negative electrode polarity (DC-EN). Aluminium, however, is generally welded using alternating current. Initially applied to all material thicknesses and joint types, TIG welding is today generally limited to join thin aluminium plates up to 7 mm thickness, although the DC-EN mode is suitable for welding thicknesses up to 25 mm.

A related process is plasma arc welding (see 3.2.2). Plasma arc welding also applies a nonconsumable tungsten electrode, but uses a plasma gas to make the arc. The greater energy concentration offers higher welding speeds and results in lower geometrical distortions. However, the more concentrated plasma arc makes transverse control more critical. Thus plasma arc welding is generally restricted to mechanized processes.

3.2.1 Tungsten inert gas (TIG) welding

At the core of a TIG welding torch is a non-consumable, temperature-resistant tungsten electrode through which the welding current is introduced to the weld zone. Between the pointed tungsten electrode and the work piece, the arc is formed in an inert atmosphere. The freely burning arc delivers the heat which is used to locally melt the base material and generate the weld. If applicable, it also melts the added filler metal.

Well prepared, close-fitting materials may need no filler metal to be effectively fused. But many aluminium alloys require the addition of filler material to maintain the metallurgical and mechanical properties of the weld (see 2.4). The filler wire is added separately to the weld pool, either manually or with a wire feed unit.

The shielding gas streams out of the welding torch through the collet body and is directed toward the weld by means of a nozzle which is fitted around the tungsten electrode. The shielding gas protects the hot tungsten electrode and the weld pool from chemical reactions with the surrounding air.

Ignition of the electrode normally takes place without the tungsten electrode touching the work piece. This requires a high-voltage source that temporarily switches on during ignition and provides an electric spark. The spark produces a conductive path for the welding current through the shielding gas and allows the arc to be initiated. An alternate way to initiate the arc is the "scratch start". Scratching the electrode against the work piece with the power on serves to strike an arc. However, scratch starting can cause contamination of the weld and electrode. Some types of TIG welding equipment offer a "touch start" mode where a spark is produced with a reduced voltage on the electrode (well below the limit that causes metal to transfer and contamination of the weld or electrode). As soon as a spark is detected, the power is immediately increased, converting the spark to a full arc.



TIG (tungsten inert gas) welding process

The TIG-welding method can be used manually, partly and fully mechanized as well as automatically. TIG welding generally provides a smooth weld bead with little undercut. In specific cases, MIG welded joints can be therefore dressed by TIG for improved fatigue life.

3.2.1.1 Tungsten electrodes

Tungsten electrodes are used when arc welding with the TIG or the plasma arc process because they can withstand very high temperatures with minimal melting or erosion. Tungsten electrodes usually contain small quantities (1 - 4 %) of other metal oxides which – compared to pure tungsten electrodes – can facilitate arc ignition, improve current-carrying capacity of the rod and increase arc stability as well as electrode life. The electrodes are produced by powder metallurgy and are formed to size after sintering.

Pure tungsten may be used in conjunction with transformer-based power sources for AC welding. For a broad variety of power source technologies, however, tungsten containing lanthanum, cerium, yttrium or zirconium oxides are primarily used. Thorium oxide has been used for many years and has been found most effective in reducing electrode degradation and increasing thermal efficiency. But legal requirements concerning the handling and utilization of radioactive thorium-containing materials impose high costs on manufacturers and their customers alike. Therefore, careful consideration should be given if the use of thoriated tungsten electrodes is justified. The general consensus is that cerium or lanthanum oxides are acceptable alternatives to thoriated tungsten.

It is important to select the correct electrode type, diameter and tip angle for the level of the applied welding current. For AC welding of aluminium, cerium oxide containing tungsten electrodes are commonly used. Electrodes with lanthanum or rare earth oxide additions are recommended for applications which require slightly higher performance. The electrode diameter is determined by the thickness of the work piece and the current magnitude. As a rule, the lower the current, the smaller the electrode diameter and the tip angle should be chosen.



Tungsten electrode tip prepared for AC use on an inverter welding power source (top) and slightly rounded after use (bottom)

(Source: Miller Electric Mfg. Co.)

It must be noted that AC welding can generate a large amount of heat at the tip of the electrode. As a result, it is not uncommon for the pointed tip of the electrode to assume a hemispherical profile. Overheating or underloading of the electrode will produce unsatisfactory tip geometries.



Formation of the correct electrode tip in alternating current welding with transformer based power sources

3.2.1.2 Shielding gases

Only inert shielding gases such as argon, helium or their mixtures can be used since the tungsten electrode is at a very high temperature and therefore prone to chemical reactions with the environment. The choice of the shielding gas, as well as the current type and polarity, influence the heat transfer of the arc and affect the profile of the weld seam. This is predominately due to the physical characteristics of the gases and their respective thermal conductivities which strongly determine the shape of the arc (see section 2.5).

The most-used shielding gas for TIG welding of aluminium with alternating current is argon. It optimises the ignition properties and offers a calm and stable metal transfer. Helium raises the temperature of the arc which leads to a higher thermal input into the work piece. This can be utilised either for welding thicker materials or for increasing the welding speed in thin material. There is also a lower tendency for porosity due to the hotter weld pool with lower viscosity and better degasification possibilities. A disadvantage of helium is, however, the less stable arc and difficult arc ignition. Additionally, due to its lower density compared to argon and the surrounding air, helium will require higher flow rates to ensure adequate coverage.



Profile of the TIG weld pool for different shielding gases (same welding conditions):

- 100 % Argon (left)
- 50 % Ar / 50 % He (centre)
- 100 % Helium (right)

A compromise between the two different gases offer argon-helium mixtures. Effective combinations of helium and argon have been found to lie between 30 - 70 % of each respective gas. Most commonly used is a mixture of 50 % argon and 50 % helium. In addition to classic argon and the argon-helium mixtures, more advanced gas mixtures may also contain very small amounts (150 – 300 ppm) of nitrogen for additional arc stabilization.

Pure helium or high helium content shielding gas mixtures are seldom employed except in TIG welding in the DC mode with a negative electrode where the increased heat is necessary to break up the oxide film. However, the DC-EN TIG welding technique is relatively seldom used in practice.

3.2.1.3 Effects of polarity on weld penetration

The form of the weld pool and of the weld seam can be influenced by current type and electrode polarity. Alternating current (AC) is the most popular TIG welding method of aluminium, but direct current (DC) power can be employed for some specialized applications. Three types of arc generation are feasible:

- Direct current, electrode negative (DC-EN) \rightarrow deep penetration
- Direct current, electrode positive (DC-EP) \rightarrow low penetration

- Alternating current (AC) \rightarrow medium penetration.



Effect of current type on weld penetration

TIG welding in the direct current electrode negative mode (DC-EN) results in relatively deep and narrow weld penetration, and very little, if any, arc cleaning during welding. About 80 % of the heat is generated in the base material and about 20 % at the electrode. Typically used with pure helium shielding gas, this method is capable of welding much greater material thicknesses. However, only mechanised welding is recommended since a short arc (< 1 mm) is required. Because of the absence of an arc cleaning effect, fusion of the joint faces occurs mainly by melting/break-up of the oxide film, i.e. there is an increased risk of welding discontinuities (oxide inclusions and fusion defects).

Using TIG welding in the direct current electrode positive mode (DC-EP), about 20 % of the heat is generated in the work piece and 80 % at the electrode, i.e. arc cleaning is excellent, but there is very shallow weld penetration. This is the least used TIG welding method as it places a heavy thermal load on the tungsten electrode. It requires large diameter electrodes with wide angled tips, but nevertheless often leads to excessive electrode heating.

The AC arc offers a compromise of the characteristics of positive and negative electrode polarity. It provides appropriate cleaning for most applications, extends the electrode lifetime, and divides the arc heat more evenly between electrode and weld pool, leading to medium weld penetration. Some power supplies enable the use of an unbalanced alternating current wave by modifying the exact percentage of time that the current spends in each state of polarity, giving even more control over the amount of heat and cleaning action.



TIG-AC welding process with periodic cleaning/melting actions

The respective application areas of the different TIG welding modes for aluminium are:

- TIG (AC) conventional TIG welding: Generally used for thicknesses up to 6 10 mm, provides good cleaning action of the arc.
- TIG-He (DC-EN): Requires pre-cleaned surfaces of the work piece and generally fully automatic welding because of the short arc length. It offers higher welding speeds, lower thermal stresses and lower thermal load of the electrode than TIG (AC).

• TIG (DC-EP): Only used for very thin gauge materials due to the large thermal load of the electrode in this polarity.

Historically, alternating current has posed an obstacle to TIG welding because the arc would frequently extinguish when the current reaches zero before reversing direction. Without any current passing between the tungsten electrode and the base metal, the arc simply goes out, i.e. it is necessary to start the arc at the beginning of each half cycle. Consequently transformer based technology requires a high frequency spark of several thousand volts which last for a few microseconds at the beginning of the positive and negative half cycles to encourage ignition. The high frequency sparks cause the electrode – work piece gap to break down ("ionize") and thus enable current flow.

The high frequency power source necessary for arc ignition, however, represents a potential hazard to the sensitive electronic equipment in the surrounding. This problem was eliminated with the introduction of advanced inverter-based power sources and the application of the pulsating square wave technique. Thus conventional AC TIG welding finds today much less application.



Arc burning process in TIG welding with alternating current

3.2.1.4 Square wave ("pulsed") and frequency controlled TIG (AC) welding

The square wave technology eliminates the tendency for the arc to extinguish when the current comes to a halt as it reverses direction by making the transition very quickly. This greatly improves the stability of the arc and makes the square wave technology the preferred method for TIG welding aluminium.

The most important weld parameters are the pulse current (l_p), the background current (l_G), the pulse current time (t_p), the background current time (t_G) and the pulse frequency $f_p = 1 / t_c$, where: t_c = duration of period.



Pulsating square wave AC welding

During the high current impulse, a large amount of heat is generated in the welding area which results in the fusion of the work material and, if applicable, the filler wire. In the impulse pause where a low current is preset, only a little heat is transmitted into the work piece, thus the weld pool stays comparatively cool. The low background current only serves to maintain the arc in order to avoid interruptions and ignition difficulties.

With square wave AC welding, the weld heat input can be considerably changed by the choice of times and current values, allowing significantly better control of the weld pool. Thus the application range of the TIG process can be extended to low power values, i.e. the material thicknesses can be reduced, weld drop-through can be prevented and the weld seam appearance can be improved. In the extreme case, a weld seam may even consist of fusion welding points which lie next to each other or overlap.

But the re-ignition of the arc by the utilization of a steep-sided, square wave has also disadvantages. The main problem is that the change to the arc column resulting from the current change causes an acoustic emission ("noise").

The recent introduction of inverter-based power sources enabled the development of advanced square wave techniques which further decrease the time it takes for the current to reverse direction. In addition, they also offer more possibilities for the selection and control of the current profile.

Modern power sources offer the selection between different waveforms which affect the arc and weld pool characteristics as well as the penetration profile in a different way. But also the resulting arc "noise" essentially depends on the waveform.



Different waveforms change the TIG welding characteristics

A very square wave (A) produces a smooth, stable arc with great directional control. It forms a fast-freezing weld pool with deep penetration and fast travel speeds. A common issue is porosity, especially on thick aluminium parts, because the molten metal pool solidifies too quickly. Slowing down the welding speed will normally resolve this issue. However, the noise level of a pure square wave is very high.

The "sinusoidal" (C) wave with fast transition through the zero amperage point offers a soft arc, i.e. similar to a conventional power source. It provides good wetting action and actually sounds quieter than any other waveform. The triangular wave (D) leads to quick weld pool formation, but reduces the overall heat input into the weld. It is especially beneficial for welding thin aluminium parts.

The soft square waveform (B) maintains the benefits of the true square wave, but the arc noise is reduced and control of the weld pool is improved. For most applications, this waveform is ideal. In practice, an appropriate adjustment of the soft square waveform is generally used to set the physically quietest arc for any specific welding current.

Furthermore, independent amperage (or amplitude) control allows the EP and EN current level to be set differently. A current waveform with greater EN than EP creates a narrow bead with deeper penetration and no visible cleaning action. A current waveform with greater EP than EN leads to a wider bead with less penetration and clearly visible cleaning action. Increasing EN while maintaining or reducing EP also takes heat off of the tungsten electrode and more precisely directs it into the weld.



Effects of independent current control in square wave AC welding

(Source: Miller Electric Mfg. Co.)

AC balance control adjusts the amount of time spent in the penetration (EN) and cleaning action (EP) portions of the cycle. Extending the EN portion narrows the weld bead, achieves greater penetration, and may permit increased travel speeds. It also reduces the excessive etching zone beyond the toes or edges of the weld. Reducing the EN portion of the cycle widens the weld bead. It produces a greater cleaning action and minimizes penetration, which may help prevent burn-through on thin materials.



Effects of AC balance for square wave AC welding

(Source: Miller Electric Mfg. Co.)

An increased EN portion also reduces the balling action, increases the lifetime of the tungsten electrode and may permit the use of a smaller electrode to more precisely direct the heat into the weld. Reducing the EN cycle increases the balling action because more heat is directed into the electrode. This creates a large ball at the end of the tungsten and causes the arc to lose stability, making it hard to control the arc weld pool.

Depending on the power source, the balance may be typically adjusted in the range of 50 - 75 % EN mode. The preferred range for clean aluminium work pieces is 68 - 75 % EN.

The introduction of inverter power sources also allowed to exploit the variability of the pulse frequency. Traditional power source frequencies are dictated by the input power (50 Hz in Europe, 60 Hz in the United States) while inverter power sources have a greater ability to transform the electricity to the desired output frequency. Adjusting the AC frequency provides excellent control over bead appearance and penetration profile.

	Waveform	Waveform Effect on Bead			
	60 Hz	Wider profile ideal for buildup work	Visible Oxide Removal (etching)		
	120 Hz	Narrower profile for fillet welds and automated applications	Visible Oxide Removal (etching) ©2015 Miller Electric Mfg. Co		

Effects of Frequency for AC GTAW

(Source: Miller Electric Mfg. Co.)

Up-to-date inverter-based power sources offer AC output frequencies between 20 Hz and 400 Hz. In general, 120 to 200 Hz provides an ideal frequency for most aluminium welding applications. The increased frequency causes the current to change direction more often and the arc cone has less time to expand. It produces a more focused arc with increased directional control and a narrower bead and cleaning area which improves performance when welding in corners, on root passes, and in fillet welds. An arc cone at 400 Hz is even tighter and more focused. The result is a significantly improved arc stability, ideal for fit ups requiring precise penetration and reduced distortion. On the other hand, a lower frequency softens the arc and results in a wider weld pool. This removes impurities well and transfers the maximum amount of energy to the weld piece, which speeds up applications requiring heavy metal deposition.

3.2.1.5 TIG welding equipment

An ideal TIG AC/DC power source possesses a virtually constant output current to control the length of the arc. A constant current power source is essential to avoid excessively high currents being drawn when the electrode is short-circuited on to the work piece surface. This may happen either deliberately during arc starting or inadvertently during welding. If a flat characteristic power source is used, any contact with the work piece surface would damage the electrode tip or fuse the electrode to the work piece surface.

Continuous current adjustment is required for proper adaption to different material thicknesses. Modern inverter power sources offer the additional advantage of a fast reaction to changes in the welding process. Many power sources also allow the user to select the current waveform and to properly adjust the specific current profile characteristics.



AC/DC power source for TIG welding offering tailored arc control (Source: Miller Electric Mfg. Co.)

Depending on the severity of the thermal load, TIG welding torches are either gas-cooled (for light duty applications) or water-cooled. For welding currents >100 A, water cooling of torch and current cable is commonly used. The gas nozzle is made of metal or ceramics and has to be insulated against electricity conducting parts. The electrode protrudes about 2 to 4 mm beyond nozzle. They are cooled by the shielding gas.



Gas-cooled TIG welding torch (Source: Miller Electric Mfg. Co.)

Gas-cooled welding torches are cooled by the shielding gas which flows through, while watercooled welding torches also require a pump and heat exchanger.



Water-cooled TIG welding torch (Source: Fronius)

The filler metal is added to the weld pool separately from the torch. There are also TIG welding torches with an integral device for mechanised wire feeding.

3.2.2 Plasma welding

The plasma welding process is basically very similar to the TIG process, but has a number of advantages which make it an interesting alternative to laser welding, especially on sheets and other components with a sheet thickness of up to 8 mm.

The difference is that in plasma welding, the arc consists of a plasma (i.e. a gas with positive charge carriers (ions) and negative charge carriers (electrons)). The plasma arc is constricted with the help of a water-cooled, fine-bore copper nozzle which squeezes the arc, increases its pressure, temperature and heat intensity and thus improves arc stability, arc shape and heat transfer characteristics. Additionally, plasma welding has greater torch standoff. Being enveloped in plasma gas, the tungsten electrode also has a longer service life than in TIG welding.



Plasma arc welding process

(Source: Fronius)

The process employs two separate inert gas flows. By positioning the electrode within the body of the torch, the plasma gas can be separated from the shielding gas envelope. The plasma gas flows through the orifice at relatively low pressure and flow rate; it becomes ionized and forms the arc plasma. The pressure of the orifice gas is intentionally kept low to avoid weld metal turbulence, but this low pressure is not able to provide proper shielding of the weld pool. Therefore a shielding gas flows through the outer nozzle at comparatively higher flow rates and shields the arc plasma as well as the molten weld from the atmosphere. These gases can be of the same or of differing composition. The plasma gas is normally argon, whereas for shielding, argon or argon/helium mixtures are used.

Filler metal may or may not be added. If a filler metal is necessary, an automated feed system is usually added to the torch.

Plasma arc welding process can be divided into two basic types:

- Non-transferred arc process: The arc is formed between the electrode (negative) and the water cooled constricting nozzle (positive). The arc plasma comes out of the nozzle as a flame. The arc is independent of the work piece and the work piece does not form a part of the electrical circuit. Compared to a transferred arc plasma, the non-transferred arc plasma possesses a lower energy density.
- **Transferred arc process:** The arc is formed between the electrode (negative) and the work piece (positive). A transferred arc possesses high energy density and plasma jet velocity, it is used for welding at high arc travel speeds. For initiation, a pilot arc is established between the electrode and the nozzle. This arc is then transferred to the metal to be welded and the main current starts to flow, thus igniting the transferred arc. The pilot arc system ensures reliable arc starting and, as the pilot arc is maintained between welds, it obviates the need for a high frequency pulse which may cause electrical interference.

The plasma exits the orifice at high velocities (approaching the speed of sound) and a temperature up to 28,000 °C or higher. Characteristic for the plasma arc is the strong temperature drop from the arc core towards the outside (in order to avoid melting of the constricting copper nozzle). Another difference compared to the TIG welding process can be observed visually: the TIG arc is conical and the plasma arc is cylindrical.

The plasma torch delivers a high concentration of heat to a small area, offering higher welding speeds and resulting in lower geometrical distortions. The size and the type of nozzle tip are selected depending upon the metal to be welded, weld shapes and desired penetration depth. With high performance welding equipment, the plasma process produces exceptionally high quality welds.

Three operating modes can be produced by varying bore diameter and plasma gas flow rate:

• Micro-plasma (0.1 to 15 A)

The micro-plasma arc can be operated at very low welding currents. It was traditionally used for welding thin sheets (down to 0.1 mm thickness). The needle-like, stiff arc minimises arc wandering and distortion.



Micro-plasma welding (Source: Fronius)

• Medium current (15 to 200 A)

At higher currents, the process characteristics of the plasma arc are similar to the TIG arc, but because the plasma is constricted, the arc is stiffer. Medium current plasma arc welding is an alternative to conventional TIG welding. The advantages are deeper penetration and greater tolerance to surface contamination including coatings. The major disadvantage is the bulkiness of the torch, making manual welding more difficult.

• Keyhole plasma (over 100 A)

By increasing welding current and plasma gas flow, a very powerful plasma beam is created which is used to melt completely through the base material, forming a "keyhole". The forward moving arc melts the leading edge of the keyhole, molten metal flows around the perimeter of the hole and solidifies behind the arc to form the weld bead under surface tension forces.

Compared with TIG arc welding, keyhole welding offers higher welding speeds and deeper material penetration. The normal method is to use the keyhole mode with filler metal to ensure a smooth weld bead profile with no undercut. The filler metal is added at the leading edge of the keyhole.

As the welding parameters, plasma gas flow rate and filler wire addition must be carefully balanced to maintain the keyhole and weld pool stability, this technique is only suitable for mechanised welding. The slope-out of current and plasma gas flow must be carefully controlled to close the keyhole without leaving a hole while terminating the weld in the structure.



Keyhole plasma welding

(Source: Fronius)

The plasma arc is normally operated with a DC power source. With a sine wave AC current, the plasma arc is not readily stabilised. However, for aluminium welding, the AC square-wave mode is commonly used and provides good results. Special modifications of waveform, i.e. a reduction of the duration of electrode positive polarity, allow to keep the electrode sufficiently cool in order to maintain a pointed tip and achieve arc stability.

In plasma arc welding, the electrode tip diameter is not as critical as for TIG welding. More critical is the plasma nozzle bore diameter. A bore diameter which is too small for the current level and plasma gas flow rate will lead to excessive nozzle erosion or even melting. On the other hand, a too large bore diameter may give problems with arc stability and maintaining a keyhole.

A further development is the variable-polarity plasma welding process. It combines the advantages of plasma arc welding with the additional benefits of arc cleaning, provided by periodic bursts of positive electrode energy. Variable polarity plasma welding has relatively low arc-travel speeds when compared to other arc welding methods and especially compared to MIG welding, but the fact that a single pass will replace multiple passes needed by other methods sometimes motivates its use.

3.3 Arc stud welding

Arc stud welding is a welding process in which a metal fastener (weld stud) is attached to a work piece by heating both parts with an electric arc. For welding, the fastener is positioned using a stud gun. When the operator activates the stud gun trigger, the sufficiently heated metal fastener is joined to the work piece without any filler metal. The welding time is less than one second, typically measured in milliseconds. One end of the fastener is prepared for welding. Shielding gases or flux may or may not be used to protect the weld.

There are two basic power supplies used to create the arc for welding studs. One type uses DC power sources similar to those used for gas-shielded metal arc welding ("arc stud welding"). The other type derives the heat from an arc produced by the rapid discharge of electrical energy stored in a bank of capacitors ("capacitor discharge stud welding"). The capacitor discharge method with its significantly shorter process time permits the welding of more dissimilar metals and alloys than arc stud welding. For either process, a wide range of stud styles is available.

The arc may be established either by rapid resistance heating and vaporization of a projection on the stud weld base ("gap ignition") or by drawing an arc as the stud is lifted away from the work piece ("lift ignition").

Stud welding produces full cross-sectional welded, high-quality attachment points that resist breaking or loosening. Bolts and similar attachments can be joined to aluminium sheets, extrusions or castings with single side access and without drilling holes or back-side support. However, conventional steel stud welders cannot be used for aluminium since its high heat dissipation asks for a power supply with a higher current capacity.



Arc stud welding using a spotter on aluminium (Source: Cebora)

3.3.1 Arc stud welding with lift ignition

Arc stud welding with lift ignition is also called drawn arc stud welding since the arc is drawn between the stud and the work piece. The necessary heat is developed by a DC arc between the stud (electrode) and the work piece. Welding time and plunging of the stud into the molten weld pool to complete the weld are controlled automatically.



Drawn arc stud welding process

(Source: HBS)

Drawn arc stud welding generates high-quality welds and is particularly suitable when high demands relevant to safety regulations are made on the welding quality. The actual welding process consists of three steps:

- The stud tip is placed in contact with the work piece.
- The stud is lifted off the work piece while the current is flowing, thus creating a secondary (pilot) arc between stud tip and work piece.
- After a pre-determined period, the main current is allowed to flow. The ignition of the main arc creates a molten surface between the stud and work piece.
- The stud is plunged into the molten pool and the welding current is switched off. The weld pool solidifies and a cross-sectional joint is formed.

A welding rectifier serves as energy source and provides the continuous welding current which can be regulated with respect to weld time and power. The welding time amounts to \leq 0.1 - 1 seconds.

Because arc stud welding time cycles are very short, the heat input into the base metal is very small compared to conventional arc welding. Consequently, the weld metal and heat affected zones are very narrow and distortion of the base metal at stud locations is minimal.



Illustration of the drawn arc stud welding process

(Source: Tucker)

A number of standard stud designs are commercially produced. Fasteners designed for arc welding often show a small tip which extends from the base of the fastener. This tip facilitates provides arc initiation and ensures precise weld time control for consistent, automatic welding. When selecting a stud, it is important to recognize that some of its length will be lost due to welding as part of the stud and the base metal melt. Molten metal is then expelled from the joint. When properly formed, the resulting flash indicates complete fusion over the full cross section of the stud base and suggests that the weld is free of contaminants and porosity.

Studs applied by arc stud welding often require a disposable ceramic arc shield ("ferrule") around the base. It surrounds the stud to contain the molten metal and to shield the arc. At the end, the ferrule is broken away and discarded. Aluminium studs, however, do not use a ferrule; they usually rely on an inert gas (argon or helium) to protect the molten metal from the atmosphere and to stabilize the arc. But this approach is normally limited to production type applications because a fixed setup must be maintained and the welding variables must be closer controlled. Shielding gas mixtures of argon and 25 - 50 % helium at 2 - 4 l/min are recommended. The rapidly cooling weld cannot be completely avoid porosity in the weld zone. However, the amount of porosity can be minimised by proper surface preparation and optimised gas shielding.

Another possibility to avoid the use of ferrules is short cycle welding. A high weld current is applied for a very short time to minimize oxidation of the molten metal. Short cycle welding (welding time < 0.1 s) is generally limited to small studs. Since no ceramic ferrules are required, short duration stud welding can be easier adapted to automatic processes.



Short cycle drawn arc stud welding

(Source: HBS)

For lift ignition stud welding, the minimum wall thickness of the substrate is 1 - 2 mm. Due to low thermal stresses, geometrical distortion of the substrate can be reduced to a minimum,

there is very little to the reverse side of the substrate. Nevertheless, drawn arc welding typically causes more reverse-side marking compared to stud welding with tip ignition.



Stud welding with lift ignition; studs and ferrules are available in a variety of shapes, sizes and materials

Various combinations of stud and substrate materials are possible. In case of aluminium substrates, prior removal of the oxide layer by mechanical (brushing, grinding) or chemical (alkaline etching) measures is necessary to avoid imperfect welds. Another possibility would be to reverse the plasma field to clean the surface and then reverse to the original polarity for stud welding.

3.3.2 Arc stud welding with tip ignition

In the process variant, the stud is positioned in a defined and adjustable distance above the work piece. After triggering the welding process, the stud is accelerated by a spring to the plate surface. As soon as there is contact between the ignition tip and the work piece, the current circuit is closed. The rapidly increasing current vaporizes the ignition tip and ignites the arc. During or immediately following the electrical discharge, pressure is applied to the stud, plunging its base into the molten pool of the work piece. As soon as the stud contacts the work piece, the current is cut and the molten zones join and solidify. Due to the extremely short welding times and the small amount of molten metal expelled from the joint, aluminium stud welding becomes feasible without using a shielding inert gas atmosphere or a ceramic ferrule.



Capacitor discharge stud welding with tip ignition (gap welding)

(Source: HBS)

For stud welding with tip ignition, the required energy is generally stored in a capacitor battery and discharged through the ignition tip of the welding elements within an extremely short time period (1 - 3 milliseconds).



Capacitor discharge stud welding unit (left) and stud welding gun (right)

(Source: HBS)

The capacitor discharge technology is mainly suited for applications requiring small to medium sized studs. Owing to the low weld penetration (approximately 0.1 mm), it can be used for stud welding on thin-walled aluminium sheets with a minimum thickness of 0.5 mm. No traces of welding such as geometrical distortion, pressure marks, discoloration or deformation are visible on the reverse side of sheet. Even a discoloration of a painted backside can be avoided.

3.3.3 Arc element welding

In arc element welding ("stud welding with an auxiliary joining part"), a short auxiliary joining part is used. The top sheet must be perforated. There is no direct joint between the top sheet and the bottom sheet, but the auxiliary joining part fixes the top sheet onto the carrier sheet in a mainly form-fitting and partially force-fitting joint. A welded joint is created only between the auxiliary joining part and the carrier sheet. Both drawn arc and tip ignition stud welding variants can be applied.



Arc element welding (with tip) processing scheme

(Source: LWF Paderborn)

This joining technique (which is still under development) is particularly suited to join different materials. The following figure shows a cross section through an arc element welded joint which connects a carbon reinforced fibre composite panel (top sheet, thickness 1.5 mm) to a high strength steel sheet (bottom sheet, thickness 2 mm).



Joint between dissimilar materials produce by arc element welding (Source: LWF Paderborn)

3.4 Other arc welding techniques

3.4.1 Shielded metal arc welding

Prior to the development of the inert gas welding processes, arc welding of aluminium was mainly restricted to shielded metal arc welding, also known as manual metal arc welding or stick welding. An electric current is used to strike an arc between the base material and a consumable electrode rod. The electrodes are straight lengths of aluminium alloy rod, coated with flux. During welding, the flux dissolves the aluminium oxide surface layer both on the base alloy and the welding rod. Some of the flux components vaporize in the arc to form shielding gases which help to stabilise the arc and shield the arc and the weld pool from the surrounding atmosphere. The electrode core itself acts as filler material.

The process is very versatile, requiring little operator training and inexpensive equipment. However, welding times are rather long since the electrodes must be frequently replaced. When welding aluminium, the process is rather limited due to arc spatter, erratic arc control and limitations on thin material. A major problems with shielded metal arc welding of aluminium is corrosion caused by flux entrapment and porosity of the resulting welds. Furthermore there are no electrodes available for welding aluminium alloys with high magnesium content. Also electrodes, once exposed to the air, begin to absorb moisture into the flux, which eventually corrodes the aluminium core and produces excessive porosity problems.



Shielded metal arc welding

Current welding codes and standards for aluminium structures do not recognise this welding technique as being suitable for production. Nevertheless it is today still used for small repair work.

3.4.2 Oxyfuel gas welding

One of the oldest welding processes is oxyfuel gas welding. It relies on the combustion of oxygen and acetylene. When mixed together in correct proportions within a hand-held torch or blowpipe, a relatively hot flame is produced with a temperature of about 3,200 °C. Welding is generally carried out using the neutral flame setting which has equal quantities of oxygen and acetylene.



Prior to the development of the inert gas welding processes, it was widely used for welding aluminium, but has only limited applications today. For aluminium, an active flux must be used to remove the surface oxide and shield the weld pool. One of the problems with this welding process is that the flux is hydroscopic and becomes corrosive to aluminium. Therefore, any flux residue must be removed after welding to minimise the corrosion risk. Another disadvantage is the excessive heat input, i.e. the mechanical strength of the welded joint tends to be lower, the heat affected zone is very wide and distortion tends to be extreme. Welding is only practical in the flat and vertical positions.

EAA Aluminium Automotive Manual – Joining

4. Beam welding

Contents:

4. Beam welding

4.0 Introduction

4.1 Laser beam welding

4.1.1 Laser sources 4.1.1.1 CO₂ lasers 4.1.1.2 Solid state lasers

4.1.2 Laser beam welding processes

4.1.2.1 Heat conduction welding
4.1.2.2 Deep penetration welding
4.1.2.3 Twin laser welding
4.1.2.4 Remote laser welding
4.1.2.5 Laser welding of tubes, profiles and tailored blanks
4.1.2.6 Laser deposit welding

- 4.1.3 Laser welding defects
- 4.1.4 Joint configurations
- 4.1.5 Addition of filler wire
- 4.1.6 Shielding gases for laser welding
- 4.1.7 Characteristics of laser welding of aluminium alloys

4.2 Electron beam welding

- 4.2.1 Vacuum electron beam welding
- 4.2.2 Non-vacuum electron beam welding
- 4.2.3 Electron beam welding of aluminium alloys

4.0 Introduction

This chapter provides a technical overview of the unique features of the beam welding processes:

- Laser Beam Welding (LBW) and
- Electron Beam Welding (EBW)

including several examples of automotive aluminium applications. Apart from welding, both process techniques are also used for cutting and for surface treatment of aluminium products.

Electron beam welding results in very deep, narrow penetration at high welding speeds. It is usually carried out in a vacuum chamber, but also non-vacuum welding machines are used. The low overall heat input of electron beam welding enables to achieve the highest as-welded strength levels in aluminium alloys. The high thermal gradient from the weld into the base metal creates only limited metallurgical modifications and is least likely to cause intergranular cracking in butt joints when no filler is added.

Laser welding offers similar weld characteristics, although the penetration depths as well as the welding speed are considerably lower. Because of the high reflectivity of aluminium alloys, effective coupling of the laser beam and aluminium requires a relatively high power density. With the advent of commercially available high-power laser systems, however, laser beam welding is today a most versatile applicable fusion joining process for aluminium. The speed of welding is proportional to the amount of power supplied, but also depends on the type and thickness of the work pieces.

Compared to the widespread applications of laser beam welding, electron beam welding has only found limited application. The main advantages of laser beam welding in comparison to electron beam welding in industrial application are:

- The laser beam can be transmitted through air (no need for a vacuum).
- The process can be easily automated using standard robots.
- There are lower requirements for occupational safety (no generation of X rays).
- The beam can be transmitted through a fibre optic cable and shared or switched between fibres or work stations.

4.1 Laser beam welding

The industrial application of lasers has been implemented successfully in the early 1970s. Since then, the laser became an increasingly used flexible tool. During the last two decades, laser welding has developed to a key assembly technology in the automotive industry. With its high processing speeds, its low heat input and resultant low distortion and its overall flexibility of application, it proved to be an ideal assembly technology, in particular in car body fabrication. Laser beam welding produces excellent quality joints; it offers high productivity and ease of automation.

Laser beam welding is a fusion welding technology using a laser beam as the primary heat source. The laser beam provides a localized high power density (of the order of 1 MW/cm² or more), allowing for narrow, deep welds and high welding speeds. The localized heat input in laser welding leads to small heat-affected zones and results in high heating and cooling rates.

When lasers were first tested on aluminium, using similar processing conditions to those applied for steel structures, the initial high surface reflectivity and thermal conductivity of aluminium and the volatilisation of low boiling point constituents caused numerous defects such as lack of penetration, blow holes, porosity and weld metal cracks in some alloys. These problems are now largely overcome with the advent of higher average laser powers, improved and innovative beam focussing systems and better beam qualities, resulting in a power density high enough to produce a stable keyhole for welding.

The laser welding system consists of several components: laser generator, beam delivery path (which can be open air or optical fibre), focusing optics (generally attached to a robot), shield gas supply, filler metal addition (if applicable), cooling equipment, and a work piece handling system. In general, fibre optic cables are applied to carry light along a light pipe that can range from 25 to 1000 μ m in core diameter, which in combination with the focusing optics dictates the size (power density) of the laser beam on the work piece.



Laser welding cell (Source: Trumpf)

In most automotive applications, the thickness of the applied wrought and cast aluminium alloy components is less than 4 mm. Laser beam welding in its various process variants is intensively used to weld such aluminium alloy components. Nevertheless, laser beam welding of aluminium still presents several challenges, including porosity, loss of alloying elements, and solidification cracking in some heat-treatable alloys.

In principle, laser welding is not different from any other fusion welding process where, depending on the envisaged application, the processing conditions must be properly adapted. Laser beam welding can be employed over all the relevant aluminium thickness range (typically 0.5 - 4 mm in automotive applications) at speeds ranging from 2 to > 10 m/min using industrial solid state lasers. But also welding joints requiring at least 10 mm of penetration can be realized. The spot size of the laser can vary between 0.2 mm and > 10 mm, though only smaller spot sizes are used for welding. The depth of penetration is proportional to the amount of power supplied, but is also dependent on the location of the focal point: penetration is maximized when the focal point is slightly below the surface of the work piece. The high reflectivity of aluminium alloys, especially when welding in the conduction mode, requires that the laser beam be oriented at a slight angle to the work piece to prevent damage to the optical components and laser, though some laser types are more resistant to back reflections than others.



High power diode laser beam welding of an aluminium car body structure (Source: Audi)

A very important topic is the additional level of personnel safety required by laser beam welding. Today's industrial solid state lasers produce laser light that is not visible to the human eye. Thus in class 4 (i.e. not enclosed) applications, special precautions, including administrative controls and personal protective equipment, must be taken to prevent exposure from laser beams. The largest threat is to the eyes due to direct or scattered reflection of laser energy. Thus operators are required to wear suitable eyewear or use special screens to avoid eye damage.

4.1.1 Laser sources

The two types of lasers commonly used for welding are solid state lasers and gas lasers. Lasers can further be grouped into several categories depending on various characteristics such as the wavelength and the quality of the light produced. A most important differentiation criterion is the mode of light emission:

Continuous wave mode

In this mode, the laser medium is pumped continuously and emits a continuous laser beam.

- Pulsing mode

In the pulsed mode, the gain medium is pumped in bursts to generate short laser pulses. Power, duration and frequency of the laser pulses are important parameters for material processing.

Different kinds of joints require different operation modes of the laser device. Selection of the appropriate laser type should be made in close coordination with the

Practical metal seam welding was only feasible in the early 1970s when multi-kilowatt, continuous wave CO_2 lasers were developed. In the 1980s, high power deep penetration keyhole welding of carbon steels with CO_2 lasers became a regular industrial practice. However, there was only limited application of CO_2 lasers for aluminium welding due to its very high reflectivity at the relatively long wavelength (10.6 µm). Practical application of flash-pumped Nd:YAG (neodymium doped-yttrium aluminium garnet) lasers, which emit a more suitable wavelength (1.06 µm), was not possible due to their low power and extremely poor efficiency at the time. In the mid-1990s, diode pumped Nd:YAG lasers were developed which offered kilowatt power and high efficiency. As a result, there was a growing interest in aluminium laser welding since the absorption of the laser beam energy in aluminium alloys at 1.06 µm is three times as much as it is at 10.6 µm. Nevertheless, the poor beam quality and high cost of diode pumped Nd:YAG lasers still hindered their acceptance in industry. In the early 2000s, with the arrival of the high power ytterbium fibre lasers, the disc and diode lasers, along with excellent beam quality and low maintenance cost, the advantages of laser welding aluminium components could be better realized.

Laser Name	Lasing Medium	Wavelength [µm]	Power	Beam Quality	Electrical Efficiency
CO ₂	Gaseous (CO ₂)	10.6	Medium / High	High / Medium	Low (10 %)
Fibre	Solid State (Yb-doped quartz fibre)	1.075	High	High	High (25 – 35 %)
YAG	Solid State (Nd:YAG)	1.064	Medium	Medium	Low / Medium (5 – 25 %)
Disk	Solid State (Yb:YAG)	1.030	High	High	High (25 – 35 %)
Diode	Solid State	0.9 - 1.07	High	Low	Highest (45 %)

Common industrial laser types and characteristics

The requirement of very high laser power for aluminium welding is not only due to its high reflectivity and heat conductivity. An important parameter is also the absorption spectrum. Generally, metals have relatively high absorptions in the ultraviolet (UV) end of spectrum and low absorptions in the infrared (IR) range of the spectrum. Unlike most other metals, iron and steel have relatively high absorption factors in the IR spectrum. These materials therefore show good weldability with both solid-state and CO_2 lasers. In case of aluminium, however, the decisive factor is the increase of the absorbed laser energy with decreasing wavelength. Thus for aluminium welding, solid state lasers are generally more efficient (except for welding depths > 6 - 8 mm where CO_2 lasers are better).
The various types of solid state lasers differ somewhat in the wavelength, but more important are the differences in the intensity of the laser radiation, the quality of the laser beam and the sensitivity to back reflection. The beam quality refers to the ability to produce a beam of true Gaussian energy distribution and how tightly the beam may be focused. It depends on the laser type, the other optical components in the system and any contamination of these components. Highest beam qualities are required for cutting, while welding can tolerate slightly lower beam qualities. Welding with filler may be possible with even lower beam qualities. Thus, depending on the specific application, the most cost efficient solution must be carefully evaluated.

4.1.1.1 CO₂ lasers

CO₂ lasers generally use a three-component gas mixture consisting of helium, nitrogen and CO₂ to generate the laser beam. High-voltage, low-current power sources supply the energy needed to excite the lasing medium. The purity of lasing gas must be extremely high in order to avoid any contamination of the laser components and thus an impaired laser performance. Moisture and hydrocarbons are particularly detrimental to the laser performance.

The wavelength of the laser beam is $10.6 \,\mu$ m, putting it in the far-infrared spectrum, i.e. invisible to the human eye. CO₂ lasers can operate in both continuous and pulsed mode. Fibre optic cables, which are made of quartz glass and absorb this wavelength, would be destroyed. Therefore a rigid lens and a carefully aligned and maintained mirror delivery system must be used.

Owing to their reliability and durability as beam sources, CO₂ lasers are well established in material processing. However, these machines require a large gas supply (except sealed CO₂ lasers), draw a lot of power and produce extremely hot gas that requires cooling, which explains why their wall plug efficiency is only 10 to 12 %.



CO₂ laser head (left) with mirror optic (right), the focusing mirror simultaneously deflects the laser beam by 90 degrees

(Source: Trumpf)

 CO_2 lasers typically provide a high-power, well-collimated beam of about 10 - 20 mm in diameter. While the infrared light is not well absorbed by most metals, the combination of high power (> 20 kW) and small, focussed beam diameter yields the power density necessary to initiate keyhole welding.

4.1.1.2 Solid state lasers

In solid state lasers, the light from a lamp or a series of diode lasers is focused ("pumped") into a crystal medium, which then emits a small, well-collimated beam of laser light in the near infrared. They operate at wavelengths on the order of 1 μ m, much shorter than gas lasers.

The power spectrum of solid state lasers typically ranges from 20 W to > 10 kW. Depending on the laser type, solid state lasers work in continuous operation or pulsed operation with pulse durations of milli- down to pico- or even femtoseconds, opening a vast range of possible applications. In order to deliver the laser beam to the weld area, fibre optics is usually employed.

Nd:YAG solid state lasers include a solid rod of material pumped with light from flash lamps or diodes. The basic configuration of flash lamp-pumped lasers makes them less efficient (electrical efficiency only 2 - 3 %) than diode-pumped lasers which are less complicated and have lower consumables cost (the lamps also must be replaced every few months). On the other hand, diode-pumped lasers show a higher initial purchase price. They are mostly used for conduction welding due to the combination of relatively poor beam quality and moderate power level.

Fibre lasers are conceptually like diode-pumped solid state lasers, but employ a glass fibre doped with ytterbium to generate the laser light. The laser energy is then transferred via another glass fibre to the point of use. Due to their high beam quality, they can be focused to a small spot and thus allow achieving also the power density necessary for keyhole welding. Fibre lasers produce narrow weld seams, they offer high process speeds and are increasingly used for robotic industrial welding, in particular for thin-sheet applications.

Diode lasers are a more recent development in the 1 μ m wavelength range. Based on high-power diodes, the diode laser achieves its high power output through the arrangement of many electronic components in a single block. By directly coupling the diodes to an output fibre increases the wall plug efficiency while providing high flexibility. The beam quality is comparatively low; nevertheless, diode lasers are popular for use in welding metals. They produce precise and visually perfect weld seams, are energy-efficient and extremely efficient in operation. Diode lasers are best-used for conduction welding of thin metals. Because of their small size, diode laser systems can be mounted directly on robot arms and moved relatively quickly. It also makes it easier to keep them cool.

Disk lasers use a small Yb:YAG (ytterbium: yttrium-aluminium garnet) disc pumped via diodes, the light is delivered via glass fibres to the point of use. They combine the advantages of solid-state and diode lasers. The use of a disk as the laser medium ensures a high beam quality and the diode laser as pump source provides the excitation energy. Disk lasers deliver high continuous power and thus maximum process performance. The excellent beam quality enables large working distances and applications with narrow focusing optics.



Optics design of a disk laser (left) and diode laser (right) (Source: Trumpf)

Solid state lasers can be placed independent of the processing location. Using flexible fibre cables, the laser beam is guided to the processing location and focused on the work piece with easy-to-integrate optics. The laser beam can traverse distances of over 100 m, without significant loss of power. However, the fibre cost, routing and handling logistic and spare part availability are considerations that limit the practical length of a fibre optic cable. Several processing stations can be supplied by a single laser.



Welding optics for solid state lasers (Source: Trumpf)

4.1.2 Laser beam welding processes

Two main laser welding methods can be distinguished: heat conduction welding and deep penetration (keyhole) welding. Heat conduction welding is characterised by lower energy intensity on the work piece leading primarily to surface melting. When the energy intensity is significantly increased, the material is heated above its boiling point forming a keyhole which contains metal vapour. As the laser moves relative to the work piece, a deep penetrating laser weld is produced. The beneficial characteristics of keyhole welding (i.e. large penetration depth and relatively small heat affected zone) attracted more industrial applications. However, conduction welding - where vaporisation of the material is insignificant - can be a viable alternative since it is a very stable process and it is easier to obtain high quality welds free of pores and spatter.

Both continuous and pulsed lasers can be applied for welding. The short, powerful pulses of pulsed lasers are ideal for spot welding, but can also be used for seam welding. The resulting "cold" welding process is suitable in particular for components where the amount of heat introduced and the degree of deformation must be very low. High power laser sources ensure that materials with a high melting point as well as materials with a high thermal conductivity can be successfully welded.

Laser beam welding facilities can be grouped into two types. Traditionally, the laser head is moved along the weld seam, usually with a robot. Nowadays, the remote laser beam welding technique is also often used. In this method, the laser beam is moved along the seam with the help of a laser scanner, so that the robotic arm does not need to follow the seam any more. The advantages of remote laser welding are the higher speed and the higher precision of the welding process.

4.1.2.1 Heat conduction welding

Heat conduction welding is the typical mode of operation at lower power densities. In heat conduction welding, the materials to be joined are melted by absorption of the laser beam at the material surface and the solidified melt joins the mating parts along a common joint. The weld penetration depth is generally below 1 to 2 mm, there is no vaporisation of the molten material. The maximum weld depth

is limited by the heat conductivity of the material. If the heat is not able to dissipate quickly enough, the processing temperature will rise above the vaporisation temperature, the welding depth increases sharply and the process turns into deep penetration welding.

Heat conduction welding is typically used to join thin wall parts (butt and lap joints). Also possible are closure welds and hermetic seals. Interesting examples are corner welds on visible surfaces. The laser produces a smooth, rounded bead that does not require any extra grinding or finishing. The width of the weld is always greater than its depth. The heat-affected zone is relatively wide and the transition from the fusion zone to the base metal is smooth and gradual.

Conduction welding works over a relatively large linear power range, i.e. the delivered power can be adjusted until the ideal process parameters for the particular application are found. The combination of power control and shallow penetration makes conduction mode welding most suitable for heat-sensitive, thin sheet applications. Furthermore, aluminium alloys containing volatile alloying materials (such as magnesium or zinc), which are difficult to keyhole-weld, can be successfully conduction-welded.



Heat conduction welding (schematic)

4.1.2.2 Deep penetration welding

Deep penetration welding requires extremely high power densities of about 10⁶ W per cm² or higher, depending on the type of metal. Once the metal temperature rises above its boiling point, metal vapour is generated and the vapour pressure opens a channel around the laser beam. Meanwhile, the surrounding material continues to melt. The result is a deep, narrow, vapour-filled capillary approx. 1.5 times the diameter of the focal spot of the laser beam, which is surrounded by molten metal. The hydrostatic pressure, the surface tension of the melt, and the vapour pressure inside the capillary reach an equilibrium, preventing the capillary – often referred to as the "keyhole" – from collapsing. The laser beam is reflected multiple times on the walls of the keyhole. The molten material absorbs the laser beam almost completely, allowing the laser to produce welds that are deep and narrow. Thus, keyhole welding also overcomes the high reflectivity issue when welding aluminium alloys. As the laser beam advances along the weld joint, the keyhole moves with it through the work piece. The molten metal flows around the keyhole and solidifies in its trail.

Deep penetration welding is distinguished by great efficiency and fast welding speeds. The result is a deep, narrow weld zone with a uniform internal structure. The weld depth may be up to ten times greater than the weld width. There is a relatively narrow heat-affected zone and minimum distortion. This process is used in applications requiring deeper welds or where several layers of material have to be welded simultaneously (i.e. for butt, corner, T, lap, and flange welds).

However, deep penetration welding is not without problems (e.g. beam instability, keyhole oscillation, and intermittent closure of the keyhole which may lead to porosity). In comparison, laser conduction welding is fairly stable and may often be the preferred alternative when laser welding aluminium and its alloys.



Deep penetration welding produces a vapour-filled capillary ("keyhole")

4.1.2.3 Twin laser welding

A possibility to increase the weld quality and the process stability is the use of two focused laser beams generated by one ("bifocal" method) or two lasers ("Twistlas" method). The result is a higher positioning and gap tolerance which is particularly useful for butt joint welding. Also the keyhole stability is improved, i.e. the time of opportunity for volatile constituents to exhaust through the keyhole is increased.



Laser welding with bifocal and Twistlas (Source: Trumpf)

4.1.2.4 Remote laser welding

Remote laser welding uses scan mirrors for positioning the beam precisely at the desired weld location and quick decoupling in between welds. It enables the realisation of highly productive and flexible production line layouts, making laser beam welding in series production faster, more accurate, and thus more cost-effective than traditional welding processes. The essential process advantages offered by remote laser welding are single-sided component accessibility and high processing speeds up to 15 times faster in comparison to resistance spot welding.



Scanner welding (Source: Trumpf)

The scanner technology offers an attractive alternative to moving the laser head or the work piece for beam positioning. Beam guidance is performed with mobile mirrors [1]. By changing the angle of the mirror, the beam can be moved in a controlled manner [4]. Using an additional lens system [2], the focus point can be moved in the Z direction. Thus three-dimensional components can be completely processed without moving either the processing head or the part. High-power disk lasers with good beam quality are used as beam sources. One or more flexible fibre optic laser cables lead the laser light from the laser unit to the processing station.

The processing field [3] determines which welds can be carried out. The processing speed and size of the focus diameter at the work piece depends on the imaging properties of the optic, the beam incidence angle, the laser beam quality and the material.

Compared to moving the work piece axes, the scanner technology enables significantly higher processing speeds with lower investment costs. The limiting factor in the scanner technology, however, is the size of the processing field. For welding applications, the spot size of the focused laser beam must be about 500 μ m in order to achieve the required energy density. Historically, this has been accomplished through the use of reflective or light-transmissive optics and focal lengths have been limited to 50 to 400 mm. As a consequence, only relatively flat components of limited dimensions could be processed.

A necessary condition for the widespread introduction of the remote laser welding method into industrial practice was therefore an increase of the work envelope by increasing the focal distance. Since the focused spot size is determined by the raw beam diameter and quality, a raw laser beam of high quality and enlarged diameter is necessary. For many years, this condition limited remote welding to high-power CO₂ lasers where the typical beam delivery system consists of reflective optical components. Thus the scan head had to remain stationary, limiting the working volume.

The high beam quality available with today's solid state (diode, disk or fibre) laser systems, combined with a fibre light transport system and a beam-expanding telescope, however, enables the realisation of the required focused spot diameter even with a focal length of 1.5 to 2.25 m. Because of the long focal length of the focusing lens, small deviations of the mirror now cause long paths in the plane, and

thus extremely fast positioning of the focal spot at different welding positions. Due to the very fast translation movements, beam-off time is nearly eliminated, and the laser unit can produce at close to 100% of the available fabrication time.

The scanner mirrors move the focus spot across the work piece along the X and Y axes. Focusing is either effected after the deflection unit via an optimized lens system or, like in the remote welding method, via a movable focusing lens in front of the scanner head. With a new highly dynamic drive unit, the movable lens can quickly position the spot in a precise location on the Z axis without moving the optics. This allows the laser to quickly move around in the third dimension, eliminating the problem of working in different planes and enabling the beam to reach weld spots in previously inaccessible locations.



The scanner principle with two mirrors allows precisely controlled laser beam movements

Using two mirrors, the laser beam can be placed at any predefined position within the process field or space, or it can be guided over any contour. This strategy uses a focus optic mounted to a linear drive axis to move the focal point in the vertical axis, and two deflection mirrors with cone angles of $\pm 20^{\circ}$ to move the focal point in the horizontal plane. Spot and seam welds can thus be made without moving the work piece or the focusing optics. Programming flexibility with remote welding allows the realisation of optimized weld paths and sequences, decreases processing times and enables the application of a better strategy for reducing thermal distortion of the work piece.

Furthermore, the programmable focusing optics can be also guided over a work piece with an industrial robot. The use of a robot increases the workspace significantly, permitting true threedimensional part processing. The "RobScan" process developed by Daimler combines the high speed and precision of scanner optics with the flexibility of a robot. A disk-laser is used as a beam source, thus allowing the laser beam to be routed to the laser head via flexible optical fibres. The positioning times between the weld seams can be reduced due to the simultaneous superimposition of the scanner mirror and robot movement, a process referred to as welding on-the-fly.



Robotic welding with a scanning head

(Source: Trumpf)

Mounted on the end of the robot arm, the scanning head uses two electronically controlled adjustable mirrors to move the tightly focussed laser beam from one welding spot to the next at a high speed. However, the system does not stop at each welding spot to make a seam before moving on a few centimetres to the next spot. Instead, the steel robot arm continually moves along the component while the scanner head simultaneously guides the laser beam across the component.



Remote welding of door panel showing linear stitches and staple shaped welds

(Source: Daimler)

Technological developments in remote laser welding are currently going on very rapidly. Another example is the "laser stir" welding technique developed by Volkswagen. Conventionally, a gap width of 0.2 mm has been considered as the upper limit for remote laser welding. The two mirrors inside the scan head enable to rapidly focus the laser beam on the work piece with a high degree of precision. This allows manipulating the beam into a circular motion it is guided along the gap. The resulting "wobble effect" causes the laser to stir the melt pool, which increases the volume of molten material and enables to bridge gaps of up to 0.5 mm.

In addition, remote laser welding decreases production tolerances. It subjects the parts to less heat input and mechanical stress than conventional welding processes, i.e. there is less geometrical distortion of the parts. The lower number of positioning and clamping devices also contributes to a greater dimensional stability of the welded components. On the other hand, additional complexities arise when a filler metal has to be added or a shielding gas has to be integrated in order to produce a high quality joint. The large focal distance prevents direct coordination of the laser beam movement

and wire feeding mechanism. A solution has been found with the development of a special multi-layer aluminium sheet material (see section 4.1.5) which already incorporates the filler metal functionality.

In summary, remote laser welding is a high speed metal joining technology that involves a multikilowatt laser beam, an industrial robot and a laser scanning system working in combination to rapidly produce a sequence of laser welds across a work piece with minimum non-productive time. The scanner permits a reduction of the time between each weld to fractions of a second, enabling more joints to be made within a given cycle time; the robot allows the scanner to be placed where needed around the parts to be welded, reducing the number of re-orientation operations of the part. The ongoing development activities ensure that this process will play an even more important role in future.

4.1.2.5 Laser welding of tubes, profiles and tailored blanks

Compared to conventional fusion welding techniques, longitudinal laser welding of tubes and profiles clearly benefits from the higher process speeds. But there are also qualitative improvements. The low heat input in laser beam welding leads amongst others to a narrow weld seam, a small heat-affected zone and little loss of alloying elements. The fine-grained microstructure of the welding seam allows subsequent forming processes with high deformation degrees, even without any heat treatment.



Endless laser welded tubes (Source: Trumpf)

Laser welding is also a preferred method for the production of high quality aluminium tailor welded blanks. In the past, laboratory tests have been carried out using various lasers. Excellent results have been achieved in particular with two-sided simultaneous welding using two diode lasers. The use of two lasers not only increases the process speed, but also offers qualitative advantages both regarding avoidance of defects (porosity, hot cracking, etc.) and optimization of weld seam geometry



Fabrication of aluminium tailor welded blanks with diode lasers (Source: ThyssenKrupp)

3.1.2.6 Laser deposit welding

During the laser deposit welding process, also known as laser cladding or direct metal deposition, a filler material such as a wire or a powder and the surface of the substrate material are melted by laser radiation. Thus, a metallurgically bonded surface layer can be produced.

Laser deposit welding enables the repair of surface defects on (semi-)finished components; it can also be used to apply protective layers to prevent wear and corrosion or to fabricate a near-net shape part ("additive manufacturing technology"). The laser beam produces a precise and high quality connection between the added filler material and the work piece. The low heat input, rapid heating and cooling, and precise control of laser beam energy help to minimize thermal loading of the work piece. Depending on the task, either manual or automated laser deposition welding is used.

a) Manual laser deposition welding

In manual deposition welding, the welder guides the filler material "by hand" to the area to be welded. A thin wire is primarily used as filler material. The laser beam melts the wire and the molten material forms a strong bond with the substrate which is also superficially melted. Argon gas shields the work process from the ambient air. Finally, the part can be restored to its original shape by grinding, milling, etc.





b) Automated laser deposition welding

In this case, a machine guides the filler material to the area to be welded. Although the filler material can also be a wire, this process primarily uses metal powders. Metal powder is "welded" in layers to the base material without pores or cracks. After cooling, the deposited metal layer can be machined. The laser is used to generate a molten bath on the substrate surface. Powdered material is guided through the nozzle into the melt pool and, step by step, the next layer can be deposited.



Automated deposition welding, the filler material is delivered in powder form

(Source: Trumpf)

The powder used in laser cladding is injected into the system by either coaxial or lateral nozzles. Moving the substrate allows the melt pool to solidify and thus produces a track of solid metal. This is the most common technique; however some processes involve moving the laser/nozzle assembly over a stationary substrate. The injected powder is normally of metallic nature; however, ceramic particles can be also used.

The same principle can be also used to improve the surface characteristics of aluminium components by laser surface melting. In this case, the laser radiation does not penetrate the material very deeply, but changes the surface structure and/or the properties of the surface layer. The technique principally involved are laser surface melting and laser surface alloying. Pure surface re-melting can be used to modify the surface topography on a microstructural scale or to create pressure tension in the surface. With the addition of suitable powders, the composition of the surface layer can be modified allowing for example significant hardening effects (e.g. by adding iron powder). Also the wear resistance can be drastically improved for example by introducing a fine dispersion of hard ceramic particles into the surface. A wide range of unique microstructures can be produced by these techniques resulting from the extremely high cooling rates when the relatively thin laser melted surface layer is allowed to solidify in contact with the virtually unaffected substrate which acts as a large heat sink.

4.1.3 Laser welding defects

Compared to the solidification rates encountered in conventional arc welding processes (10² to 10³ °C/sec), the solidification rates in laser welding are much higher (10⁵ to 10⁶ °C/sec). Consequently, the weld metal shows mostly a very fine grained microstructure.

Special care is necessary in process planning regarding the appropriate weld position as the low viscosity of highly fluid molten aluminium can result in dropping or sagging of the under bead. Apart from typical fusion welding defects like incomplete fusion, craters, expelled material, weld spatters and geometrical defect (misalignment, undercut, etc.), there are four types of internal weld defects in laser welding of aluminium which must be considered in more detail:

- porosity,
- cracking,
- inclusions and
- loss of alloying elements.

Most gas porosity in aluminium alloys can be attributed to hydrogen. Hydrogen porosity can be a bigger problem than in conventional arc welding since the high cooling rate has an unfavourable effect which hinders diffusion of the trapped hydrogen. A possible measure to avoid excessive formation and growth of hydrogen porosity is a lower welding speed. Another way to reduce hydrogen porosity would be to increase power density and thus the solidification time, allowing the hydrogen to escape. The best option, however, is to avoid the formation of hydrogen porosity beforehand by ensuring proper quality of the starting material, suitable material storage conditions, proper surface preparation and processing conditions, etc.

But even with proper material surface preparation, laser parameters, shielding gas and filler metal, aluminium alloys are susceptible to random porosities after keyhole laser welding. These types of pores have an irregular or tubular shape and are usually located in the keyhole path, whereas hydrogen pores are more or less evenly distributed. The highest level of process-related porosity is found in the regions where an unstable keyhole is formed. Consequently the keyhole must be kept as stable as possible; this can be achieved by welding at high speeds and the addition of filler wire

Many aluminium alloys also exhibit a strong tendency for weld crack formation because of their large solidification temperature range, high coefficient of thermal expansion, and large solidification shrinkage. The restrained contraction of a weld during cooling induces tensile stresses in the joint which may cause cracking. There are two types of hot cracking: cracking that occurs in the weld fusion zone during solidification (solidification cracking), and cracking that takes place in the immediately adjoining zone due to local liquation (liquation cracking). Hot cracking sensitivity can be often avoided by adding the appropriate filler wire, thereby altering the weld chemistry away from the most crack-sensitive compositions.



External and internal weld defects that can occur in laser welding

Oxides are the main type of inclusions found in laser welded aluminium alloys. During keyhole laser welding, the inherently unstable keyhole flow may entrap shielding gas or even air because of imperfect gas shielding. Therefore, some oxide particles may be formed in the keyhole vapour. Furthermore, some surface oxide film particles may be entrapped in the weld pool.

In addition, the high power density used for laser welding may cause selective vaporisation of alloying elements with a low melting point (e.g. magnesium or zinc) because of their higher vapour pressure than aluminium. Selective vaporisation of alloying elements can take place in both keyhole and conduction laser welding. The loss of alloying elements can be minimised by controlling the beam power density, which influences the temperature of the molten metal in the welding pool. Another way to reduce the loss of alloying elements is the use of a suitable filler metal. Laser welding of aluminium alloys with the addition of a filler metal may replenish the loss of alloying elements and also prevent solidification cracking.

When the vaporised elements escape through the keyhole, they can also pull molten material along with them, leaving weld voids and spatter in their wake. The solution is to choose either a large focused spot size or to reduce the welding speed in order to allow the vapours to exhaust without causing damage.

4.1.4 Joint configurations

The laser welding process is characterised by high welding speeds, deep penetration effect and low heat input. This makes the laser particularly suitable for welding overlap joints. The high welding speed is advantageous for long, one-dimensional welds. On the other hand, fast and precise beam movements in remote laser welding offer the possibility to exactly position the weld spots at the required locations. Depending on the required strength of the weld and the acceptable maximum amount of heat input into the component, continuous or individual welding spots, short lines (stitches) or small circles can be made. Another advantage is of laser welding that the high accessibility, it only needs single sided access and welds can be carried out in narrow places.

Two aspects are particularly beneficial:

- the reduced flange width (i.e. reduction of component size, weight and cost), and
- the increased strength and stiffness of the component as a result of the continuous joint and weld shape optimization for loading and stresses.

Laser welded joints can be also significantly smaller and thinner than their MIG (GMA) welded counterparts. The greatest advantages in costs and productivity compared to conventional welding can be achieved when the components are intentionally designed or re-designed to take advantage of the laser joining process.



Laser welding can reduce or eliminate flanges compared with resistance spot welding (left) or enable improved (reduced weight or increased strength) designs (right)

In order to get an acceptable joint profile and weld quality, a number of processing and fit-up conditions have to be satisfied. Some examples of sheet metal joint configurations suitable for laser welding are shown below.



Sheet metal configurations suitable for laser welding

(Source: Trumpf)

In a specific application, the joint configuration must be selected taking into account he principle stresses acting on the joint, i.e. tension, compression or shear loads. Shear stress should be largely avoided, because most joints are very sensitive to this kind of loading.



But there are also process-specific considerations. As an example, butt joints provide higher strength, higher welding efficiency (faster or less power) and reduced material usage, but require closer positioning tolerances and better edge geometry and fit-up. The smaller weld fusion area also reduces the size of the heat affected zone and distortion of the welded assembly. On the other hand, overlap joints provide greater process window regarding positioning, but generally yield lower strength, lower welding efficiency, and increased material usage.

Joint Configuration	Weld Fusion	Positioning
	 Area	Tolerance
Seam weld on butt joint	+	-
Lap weld on lap joint	-	+
Seam weld on T joint	+	-
Lap weld on T joint	-	+
Seam weld on flange	+	-
Lap weld on flange	-	+

Characteristics of laser joint configurations

The most important requirement for reliable laser welding is a close fit-up at the joint interfaces. If the welding interfaces are too far apart, there is insufficient weld material to bridge the gap or the weld will be undercut.

Butt joint configuration:

- Gap: 3-10% thickness of thinnest sheet
- Offset: 5-12% thickness of thinnest sheet

Overlap joint configuration:

Gap: 5-10% thickness of top sheet



Acceptable joint tolerances in laser welding

(Source: Trumpf)

However, the acceptable gap tolerance is always case specific. An improved fit-up can be achieved for example through precision shearing of the edges or the use of special clamping arrangements (such as rollers near the welding region). Furthermore, appropriate control of the laser beam can be used for better gap bridging, e.g. by increasing the spot size (if the laser source has sufficient power), by beam spitting (twin spot technique) or by weaving or wobbling the laser beam. Also possible is the addition of a filler wire or – as a last resort – the application of the laser MIG (GMA) hybrid welding method.

Another important factor is the positioning tolerance. The position of the joint under the laser must be precise enough such that the focused laser spot does not miss the joint. The tolerance of this misalignment is a function of the focused beam diameter and to a lesser extent the joint design. Seam tracking devices are therefore often used in practice.

Good weld fixtures using appropriate clamping devices is a prerequisite for success. When joining pre-fabricated components (e.g. formed and machined tubes or extruded profiles) or net-shaped parts (castings), even more possibilities exist as positioning aids or interlocking features can be integrated into the individual components.

4.1.5 Addition of filler wire

Laser beam welding is preferably carried out without the addition of a filler metal. However, in many cases, a filler metal must be added either for metallurgical reasons or to accommodate larger gaps. Due to the specific characteristics of laser welding, the addition of filler wire introduces a number of limitations to the process in terms of alignment, productivity (especially with remote laser welding), etc. The small laser spot and the narrow welding gap require very precise wire feeding. Thus, in practical application, sophisticated coordination between beam and wire feeding positioning mechanisms and the optical seam tracking device is necessary.

Solidification cracking is a concern when aluminium alloys are laser welded, especially in pulsed laser welding. While most non-heat treatable aluminium alloys can be welded without filler metal in the continuous wave mode, filler metal is necessary for welding heat treatable alloys. Proper filler metal selection is most important in preventing weld cracking and ensuring good mechanical characteristics of the weld (see also 2.4). In general, the filler metal alloys recommended for arc welding are also recommended for laser beam welding. Si-rich filler wires (e.g. EN AW-4043 and 4047) are typically used for laser welding of the standard automotive EN AW-6xxx alloys among each other or with EN AW-5xxx alloys (etc.). Structural EN AW-5356 or EN AW-4043. For the selection of suitable filler wire wires for other age hardening aluminium alloy systems, please see section 2.4.1).

In practice, the wire feeding mechanism is generally attached to a robot arm together with the laser head. In specific cases, the use of ancillary equipment to preheat the wire by resistance heating (hot wire) has shown to result in increased process stability (high quality and spatter-free welding) and increased welding speeds. In the laser hot wire method, the laser beam heats the base metal. The pre-heated wire is fed in, and welded with the base metal. In the laser cold wire mode, the laser beam heats both the base metal and the filler metal, and welds them together.



Laser welding with hot (left) and cold wire (right)

(Source: Fronius)

As an alternative, the filler metal can also be added in powder form using the laser metal deposition approach, i.e. the filler metal powder is directly injected into the melt pool.

In remote laser welding, both mechanisms for the addition of filler metal outlined above will not work because the distance between the laser head and the weld location is too large. A solution was found with the development of the laser remote weldable car body sheet alloy Anticorodal®-200 RW (Novelis Fusion[™] alloy 8840). It is a patented multi-layer AlMgSi sheet product suitable for outer body application based on the Novelis Fusion™ process. The application of this multi-layer alloy enables remote laser welding without using filler material which otherwise would not be possible for EN AW-6xxx type alloys. It also enables to bridge up to 4 mm wide gaps between the components to be welded. A wide variety of weld configurations (overlap, butt, edge, edge overlap, T joint, etc.) have been successfully tested. The multi-layer alloy can be also successfully welded to conventional (monolithic) aluminium sheet and extrusion alloys as long as the multi-layer alloy Ac-200RW (8840) is on top allowing easier flow of the extra clad alloy to into the weld joint.



Multi-layer Fusion[™] alloy 8840 is laser weldable without filler metal (Source: Novelis)

4.1.6 Shielding gases for laser welding

The primary function of the shielding gas during laser welding is the protection of the molten weld pool from oxidation and other environmental contaminations. For full penetration welds that require acceptable root weld profiles, the root should also be shielded with argon to prevent sagging, underfill and sharp angles. In addition, shielding gases are used to suppress plasma formation in case of CO₂ lasers (which can absorb laser power), to stabilise the process and to protect the laser optics against fumes and spatter.



Nozzles for shielding gas supply

Coaxial, annular or lateral (side-jet) nozzles can be used for delivering the gas to the weld region. Laminar flow is a prerequisite for proper shielding gas coverage. High shielding gas velocity causes turbulence which entrains atmospheric air with the gas flow.

The choice of the shielding gas can have a significant effect on both the weld quality and the process productivity. For laser welding of aluminium, the use of argon, helium or helium-argon mixtures (up to 50% argon) is recommended; although for specialised applications, mixtures may give enhanced performance.

Originally, pure helium was used for welding since helium offers optimum protections and its application is least critical. Today the shielding gases used in laser welding tend to be more like those used in gas metal arc welding (see 2.5).

4.1.7 Characteristics of laser welding of aluminium alloys

Today, laser welding of most wrought aluminium alloys presents little problems. In particular the EN AW-5xxx and the EN AW-6xxx series alloys which are commonly used in the automotive industry can be properly laser welded. The addition of a suitable filler metal (or the application of other appropriate measures) is, however, generally necessary to safely avoid hot cracking when EN AW-6xxx alloys are joined.

The mechanical properties of laser-welded aluminium alloys depend on joint configuration, face and root bead profiles, fusion zone composition (with or without filler metal), and the amount of weld heat input. In the weld zone, depending on the alloy system(s), some of the strength achieved in the base metal by work hardening and heat treating may be lost in the weld metal. The above mentioned issues with alloying element vaporization in alloys containing Mg and Zn may also degrade the strength of the weld metal. Some reduction in cross-weld tensile strength may be also caused by cross-sectional reductions caused by welding defects (e.g. undercut or porosity).

Laser welded joints in EN AW-5xxx series alloys retain their cross-weld tensile strengths to within 80 - 100 % of the strength level of the parent material and only show a small reduction in elongation-to-failure value. The reduction in cross-weld tensile strength is due to annealing effects resulting from the heat impact. EN AW-5xxx alloys are generally welded without filler metal although a filler metal (e.g. EN AW-5356)) can be introduced to improve the strength and ductility of the joint, if desired.

For the heat-treatable EN AW-6xxx (AIMgSi) alloys, a greater loss in cross-weld tensile strength and elongation-to-failure value occurs. This drop is caused by the local dissolution of hardening precipitates and the loss of strain-hardening. The heat affected zone is also softened by over-ageing during welding. Post weld aging of the heat-treatable alloys may be used to further increase the tensile strength.

Although no special surface treatment is required when welding aluminium, care has to be taken to avoid excessive porosity. The predominant cause for porosity is the evolution of hydrogen gas during weld metal solidification. This hydrogen can originate from lubricants, moisture in the atmosphere and surface oxides or the presence of hydrogen in the parent material. Good quality welds can be achieved for most alloys by cleaning the surfaces prior to welding and adequate inert gas shielding of the weld pool area.

Hydrogen content may, however, present problems when aluminium castings are laser welded. Whereas for example the MIG (GMA) arc welding method will still produce an adequate weld joint quality in conventional high pressure die castings, the faster laser welding process may lead to an irregular distribution of relatively large gas pores (i.e. an inacceptable joint quality). Only castings produced with high quality vacuum pressure die casting techniques are properly weldable using the laser welding process.



Gas porosity in laser welded aluminium pressure die castings

(Source: Alusuisse)

4.2 Electron beam welding

Electron beam welding is a joining method which uses a tightly focussed beam of high energy electrons. A tightly focused beam of electrons strikes the work piece with a power density of 10⁵ W/mm² or greater. The high power density causes vaporisation of the molten metal, leading to the formation of the "welding capillary" or "keyhole" that is characteristic of electron beam welding. Electron beam welding results in extremely narrow, deep penetration welds with a minimal heat affected zone, requiring minimal power input. The bulk of the assembly remains cold and stable.

Both high energy density laser and electron beam welding characteristically produce a deep, narrow weld bead. There are, however, significant differences between the two processes: lasers heat with photons of approximately 0.1 eV energy while electron beams use particles of the order of 10⁵ eV energy. The beam of laser light readily interacts with the free electrons in the plasma which is formed by vaporisation of the surface of the metal, and this interaction defocuses part of the incident beam. On the other hand, the electrons of an electron beam are too energetic to be deflected significantly by the plasma. As a result, it is possible to couple the energy much more efficiently using electron beam welding compared to laser welding.

The beam is produced and controlled by the electron beam generator. The electrons emerge from the cathode consisting of a tungsten filament heated to approximately 2'500 °C. Voltages of up to 150 kV between cathode and anode accelerate the electrons towards the work piece. An electromagnetic lens focuses the diverging electron beam to a spot with high power density. When the electrons hit the surface of the work piece, their kinetic energy is mostly transformed into heat; only a small part of the energy is emitted as X rays.

The concentrated energy of the narrow electron beam penetrates the aluminium to a great depth. In a first phase, the high energy concentration at the beam spot melts the material (A). Then the material in the centre vaporises and leads to a keyhole surrounded by molten metal (B). The beam penetrates deeper into the work piece through the vapour channel (C). When the beam moves forward, it melts the metal in front of the keyhole, which then flows to the rear of the keyhole and solidifies to form the weld (D).



Electron beam welding process

(Source: Steigerwald Strahltechnik)

The energy absorption on the work piece is nearly independent of the incident angle, the type of material and surface state. Consequently in electron beam welding, the electrical wall-plug efficiency is high (> 50 %, including all auxiliaries).

Various types of weld are distinguished depending on the basic geometric shape of the components; the welds can be made continuous, discontinuous or as a spot weld.



Vacuum (left) and non-vacuum (right) electron beam welding technology (Source: Steigerwald Strahltechnik)

4.2.1 Vacuum electron beam welding

Electron beam welding is traditionally performed with the component to be welded contained entirely within a vacuum chamber. The generator is mounted to the processing chamber. With a conventional beam generator, a vacuum better than 10⁻⁴ mbar must be achieved in the electron gun vacuum envelope. In industrial systems, the processing chamber pressure typically ranges from 10⁻² mbar to 10⁻⁴ mbar. Whilst in many applications a vacuum welding environment is attractive, for large parts and where high productivity is required, the need for an evacuated chamber can drastically hinder efficient work. The limiting factor is the pump cycle time which may be reduced by twin chamber machines.

Electron beam welds are usually either fully penetrating or partially penetrating. Electron beam welding creates high integrity joints with low heat input. The narrow melt and heat affected zones minimises distortion to the component as whole. Depth-width-ratios of 50:1 and welding depths up to 300 mm are possible. Deep weld penetration can be achieved in a single pass with a high welding speed (>>10 m/min). Normally the components are welded without filler materials, but are added when necessary. Welding in vacuum ensures in a clean and reproducible environment and protects the molten metal. The mechanised (or automated) operation guarantees reliability and reproducibility.

Electron beam welding under vacuum causes a low divergence of the electron beam. The power density with a beam power of 100 kW or more and a spot diameter between 0.1 and 1 mm is extremely high. The beam is moved over the work piece either by electromagnetic deflection or mechanical motion or both, enabling rapid changes of weld direction combined with high welding speeds. It is also possible to oscillate the beam by modulation of the frequencies of the free programmable deflector coils in order to improve out-gassing of the weld and gap bridging. It is important to maintain the cavity long enough for optimum degassing to keep porosity to a minimum.

The preferred joint geometries are lap joints and simple butt joints. Also used are weld pool supported joints, joints with positioning guides and special weld geometries for penetration improvement.



Butt Joint Geometries in Electron Beam Welding

4.2.2 Non-vacuum electron beam welding

Non-vacuum electron beam welding employs essentially the same equipment as vacuum electron beam welding except that the working chamber is replaced by an orifice system. The electron beam emerges from the gun column via a series of differentially pumped vacuum stages which are separated by small diameter orifices. Thus the need for evacuation time is eliminated, as the orifice system and the generator column are permanently kept under vacuum. The electron beam is guided to the atmosphere (1'000 mbar) from the high vacuum (10⁻⁴ mbar) in the electron beam generator over a soft vacuum (10⁻² mbar) and rough vacuum (< 1 mbar).

The other difference is that in vacuum electron beam welding, the working distance can be varied over a wide range (up to 2000 mm) by changing the lens current. In non-vacuum electron beam welding, the working distance is fixed. The electron beam is focused on the outer nozzle of the orifice system which has a diameter between 1 mm and 2 mm. This small nozzle makes sure that only a

small amount of vaporized material can reach the rough vacuum range and the beam generator. Additionally a cross-jet of the applied processing gas, crosswise to the beam direction, seals the orifice. Thus a steady welding operation is guaranteed. Differences in the working distance are equalized by moving the electron beam generator.

After leaving the nozzle, a diffuse and diverging electron beam is formed due to the interaction of the electrons with the gas molecules in the surrounding air. The power distribution of the electron beam allows keyhole welding within a distance of up to 25 mm working distance. A minimum working distance (> 5 mm) must be kept to prevent a thermal distortion of the orifice system.

In non-vacuum electron beam welding, the use of a shielding gas (He, Ar) to protect the weld pool is generally necessary. In addition, a working gas protects the nozzle and beam generator against pollution. Helium is the preferred working/shielding gas. With its small atomic diameter, helium minimises the expansion of the electron beam. The gas quantity and the working distance are important parameters apart from the beam parameters (beam current and acceleration voltage). They all influence welding velocity, welding depth and joint quality.

With non-vacuum electron beam welding, deep penetration welding with depth-width-ratios of 5:1 can be reached. Non-vacuum electron beam welding allows single pass welding of thick section at atmospheric pressure with weld characteristics similar to those produced by in-vacuum welding, i.e. low distortion and high weld quality. The diverging and high-energy electron beam permits a good gap bridging without using filler material and is insensitive to working distance variations and pollution. Gaps between 0.1 up to 1 mm can be tolerated depending on the joint design, material thickness and welding speed. If necessary, a filler material can be used. However, in this case, the welding velocity is reduced





(Source: Steigerwald Strahltechnik)

The classical application for non-vacuum electron beam welding is welding of thin metal sheets (< 5 mm). Flange and overlap joints are ideal joints for non-vacuum electron beam welding. Due to the presence of large material quantities, only coarse joint preparation is required and relative large gaps can be tolerated. The "tailored blank" joint allows gaps of a few tenth of a millimetre. In case of a butt weld, gaps with < 0.1 mm are only tolerated without filler metal.



Joint geometries for non-vacuum electron beam welding

(Source: Steigerwald Strahltechnik)

Most important in electron beam welding is proper protection from the emitted X rays. Whereas in vacuum electron beam welding, the vacuum chamber provides the necessary protection, the working area of a non-vacuum electron beam welding machine must be shielded by properly adopted lead walls.

4.2.3 Electron beam welding of aluminium alloys

Electron beam welding can be used to join aluminium alloys in a similar manner as laser beam welding. There are no electron beam-specific issues or problems. It also allows joining different types of materials, e.g. joining aluminium and steel. As the energy input can be precisely controlled, durable weld-solder joints can be made (in this case, the steel partner remains solid and the aluminium is fused to it).



Non-vacuum electron beam welding of a cross beam of the instrument panel support

(Source: Alusuisse)

For the application shown above, non-vacuum welding proved to be the optimum joining method in a comparative study. The structural beam is produced from two stamped half shells made from 2.5 mm thick EN AW-5754 sheets. The edge welds are manufactured at a welding speed of 12 m/min. A big advantage is the round shape of the weld which offers safe manual handling on the assembly line, no danger of scrubbing of electric wire insulation during service, etc.

EAA Aluminium Automotive Manual – Joining

5. Electric resistance welding

Content:

- 5. Electric resistance welding
- **5.0 Introduction**
- 5.1 Resistance spot welding
- 5.1.1 The resistance spot welding process
- 5.1.2 Resistance spot welding equipment
- 5.1.3 Electrodes and electrode maintenance
- 5.1.4 Joint configurations for resistance spot welding
- 5.1.5 Resistance spot welding of aluminium alloys
- 5.2 Resistance spot welding with process tape
- 5.3 Resistance seam welding
- 5.4 Projection welding
- 5.5 Resistance butt welding (flash welding)
- 5.6 Resistance element welding
- 5.7 Resistance stud welding
- 5.8 High frequency welding

5.0 Introduction

Electric resistance welding refers to a group of thermo-electric welding processes such as spot and seam welding. The weld is made by conducting a strong current through the metal to heat up and finally melt the metal at a localized point, predetermined by the design of the electrodes and/or the work piece to be welded. A force is always applied before, during and after the application of current to confine the contact area at the weld interfaces and, in some applications, to forge the work pieces.

The general heat generation formula for resistance welding is:

Heat = $I^2 \times R \times t$,

where I is the weld current through the work pieces, R is the electrical resistance of the work pieces and t is the weld time. The weld current and duration of current are controlled by the resistance welding power supply. The resistance of the work pieces is a function of many different factors, i.e. the electrical resistance of the work pieces and electrodes, the geometry of the work pieces, the surface conditions of both work pieces and electrodes, the electrode geometry, the electrode pressing force (i.e. the force used to hold the materials together), etc.

When the electrical current passes through the metal, heat is preferentially generated at the connecting or "faying" surfaces of the parts to be joined. When the welding temperature is reached, the parts are welded in spots at their contact points between the electrodes by the electrode force. In general, resistance welding methods are efficient (very short process time), require no consumables, are clean and environmentally friendly, but their application is limited to relatively thin materials and the equipment cost can be high.

Aluminium and its alloys have high thermal and electrical conductivity compared with steel and, as the process depends on resistance heating, they require much higher welding currents.

There are three basic types of resistance welding bonds:

- In a **solid state bond** (also called a thermo-compression bond), dissimilar materials are joined using a very short heating time, high weld energy and high force. There is little melting and minimum thermal impact on both materials, i.e. the materials are more or less bond while still in the "solid state". The joint typically exhibits good shear and tensile strength, but poor peel strength.
- In a **fusion bond**, either similar or dissimilar materials, both materials are locally heated to the melting point. The subsequent cooling (and combination of the two materials) forms a weld nugget. Typically, high weld energies at either short or long weld times, depending on physical characteristics, are used to produce fusion bonds. The bonded materials usually exhibit excellent tensile, peel and shear strengths.
- In a **reflow braze bond**, resistance heating of a low temperature brazing material is used to join either dissimilar materials or widely varying thick/thin material combinations. The brazing material must wet each part and possess a lower melting point than both work pieces. The resultant bond has definite interfaces with minimum grain growth. Typically the process requires a longer heating time at low weld energy. The resultant bond exhibits excellent tensile strength, but poor peel and shear strength.

In the following, the fusion bond approach will be considered in more details. Solid state resistance welding and resistance brazing are only relevant for very specific types of joints between aluminium and other materials.

5.1 Resistance spot welding

Resistance spot welding is a resistance welding process that utilizes the heat obtained by the resistance to the flow of electric current to the work pieces through electrodes that concentrate current and pressure at the weld area. The generated heat is used to melt and

solidify a nugget at the faying surfaces of a joint. The resistance spot welding process is characterized by a very fast welding operation which is readily adapted to automation.



Schematic of resistance spot welding process

The work pieces are overlapped and held together under pressure exerted by two shaped copper electrodes. The applied force presses the sheet surfaces into intimate contact. A large current is then passed through electrodes and work pieces for a very short time. The electrode faces concentrate the welding current into a small spot. Governed by Joule's law, heating is caused due to the bulk resistance of the work pieces and the contact resistances, which are determined by the surface condition of the work pieces (surface roughness, cleanliness, surface oxides and, if applicable, surface coatings). Welding times vary depending on the type of material, its thickness, the electrode force and the diameter of the electrodes.

5.1.1 The resistance spot welding process

Spot welding involves three stages. At first, the electrodes are brought in contact with the surface of the metal and a slight pressure is applied. On a microscopic scale, the metal surface is quite rough, i.e. when the metals are forced together, some peaks will make contact. Where the contact pressure is sufficiently high, the oxide layer breaks, forming a limited number of metal-to-metal bridges. The weld schedule must include sufficient time to build electrode force to 95% of the intended weld force prior to initiating current.

Then a high current flows for a short time. As it passes through the bulk metal, the weld current is distributed over a large area. However, as it approaches the interface, the current is forced to flow through the metallic bridges, which increases the current density and generates enough heat to cause melting. As the first of these bridges melt and collapse, new peaks come into contact, forming new bridges and additional current paths. The resistance of the molten metal is higher than that of the new bridges so that the current flow transfers primarily from bridge-to-bridge. This process continues until the entire interface is molten. The amount of heat (energy) delivered to the spot depends on the resistance between the electrodes and the magnitude and duration of the current. The amount of energy must be chosen to match the properties and thickness of the materials to be joined and the type of the electrodes. Applying too little energy will not melt the metal or will make a poor weld. Applying too much energy will melt too much metal, eject molten material, and make a hole rather than a weld.

After the current is removed, the electrodes the electrode force is maintained for a fraction of a second, while the weld rapidly cools. At the end of the cycle, solidification of the nugget is completed under the electrode force. Often the work piece is locally cooled via coolant holes in the centre of the electrodes. Typically, a circular nugget of diameter between 4 and 7 mm is produced. There is no protruding weld-bead on either side of the joint.

Since the resistance welding process relies on heating, some amount of heat affected zone (HAZ) is inevitable. In general, the goal in resistance welding is to minimize the HAZ. When the flow of current stops, part of the heat generated is lost to the surroundings by heat

transfer through solids, heat lost from exposed surfaces by air-cooling, and radiation. Heat balance is a function of part material and geometry, electrode material and geometry, polarity, and the weld schedule. The goal of good resistance welding is to focus the heat generated close to the weld interface at the spot where the weld is desired.

The applied pressure and the heat generation are localized by the form of the electrodes. The weld nugget size is usually defined by the electrode tip contact area, i.e. welding occurs without excessive heating of the remainder of the sheet



Typical steps in producing a resistance spot weld

(Source: EWI)

Modern welding equipment can accurately control the electrode force, the welding current and time. Thus any uncertainty in the resistance spot welding process comes from variability in the resistance term. For aluminium being such a good electrical conductor, the heat generated during spot welding is primarily obtained from the contact resistances at the faying surfaces and not from the bulk material resistance like in steel. The weld nugget will develop in the middle of the joint where the two oxide surfaces meet.



Total resistance is the sum of all resistances in the electrodes and work piece stack-up

Thus the key to successful resistance spot welding of aluminium is to guarantee reproducible and stable sheet surface characteristics. The surface contact resistance is determined by a combination of different materials-related factors:

- Surface topography
- Composition of oxide film (function of alloy type and processing route)
- Degree of any surface cleaning
- Type and amount of any chemical pre-treatments
- Type and amount of any residual lubricants, weld-through sealers or adhesives.

As a general rule, aluminium semi-finished products are spot weldable, but the inhomogeneous surface oxide leads to inconsistent weld performance and expulsion. Chemical or mechanical removal of the surface oxide film immediately before welding provides a consistent, but low surface resistance which, on the other hand, requires much higher welding currents that substantially increase electrode sticking. Some specially designed chemical surface treatments, often applied by the material supplier, provide a consistent, medium to high surface resistance and, thus good spot weldability can be ensured. Anodised surfaces or organic coatings (including dry lubricants) usually lead to very high resistance (sometimes even insulating) surface layers and are usually not spot weldable.

Optimised surface pre-treatments for spot welding generally include a cleaning step (mixed acid cleaning or electrolytic cleaning) followed by a conversion treatment (e.g. Alcoa 951 process, Ti or Ti/Zr fluoride treatment) or thin film anodizing in order to guarantee the required storage stability. But in the automotive industry, it is often also common practice to resistance weld lubricated aluminium sheet with no special surface treatments. Issues regarding inhomogeneous surface oxidation are addressed with improved mill controls, properly pre-lubricated aluminium materials and adapted transport and storage methods.



Resistance of aluminium and steel during spot welding

Characteristic for aluminium spot welding is a rapid fall of the electrical resistance in the beginning. Actually, the dynamic behaviour of the resistance value – which is determined by the breakdown of the contact resistances in the system – is more important than the initial (static) value. The weld current is initially concentrated by selective conduction through these fractured areas which explains the high initial contact resistance. Consequently, compared to steel, resistance spot welding of aluminium requires higher electrode forces. Higher force capability is also needed to control expulsion when welding thicker gauge aluminium materials.

In addition, in aluminium spot welding, short weld times are employed to generate the heat quickly and thus minimise the heat loss by conduction. Since the welding current must be two to three times higher than in case of steel and the welding time is only one third of the welding time of steel, the welding gun has to deliver high currents for very short times. This means the electric parameters (current and voltage) must be controlled more precisely in narrower time window.

5.1.2 Resistance spot welding equipment

The basic difference between the equipment required for aluminium spot welding compared to spot welding of steel is the force and current capability of the welding gun. An electrode force range of 0.2 to 4 kN and welding currents under 15 kA are usually sufficient for steel spot welding. For aluminium resistance spot welding, however, a force range of 0.2 to 8 kN and welding currents up to 40 kA are typically required.

A key element of an aluminium resistance spot welding system is therefore the power supply. Today, medium frequency direct current (MFDC) welding power supplies are mainly used. A particular benefit of MFDC power supplies is the flexibility to weld a variety of gauges and materials and the reduced size and mass of the welding transformer, enabling robot manipulation of the higher current guns needed for aluminium welding. This approach is further exploited by systems operating at even higher frequencies (up to 20kHz). More compact transformers offer particular benefit on long reach guns where the additional weight savings allow the use of a reduced robot size and also to reduce gun inertia.

But there are alternative power supplies that produce welds with the same quality as MFDC, i.e. single-phase alternate current (AC) and conventional direct current (DC) systems. These technologies offer a lower equipment cost, but will require larger robots and higher primary power. Typically, AC power supplies yield better electrode life performance compared to DC systems, but are less flexible whereas DC power supplies offer greater control of the short time welding pulse and thus improved weldability. Another possible power supply technology is the capacitor discharge (CD) method which is commonly used in the micro resistance

welding industry, but could also provide advantages for aluminium resistance welding applications.

Polarity effects must considered when using all power supply technologies. Nugget growth is offset slightly towards the positive electrode and this can be used to advantage when welding dissimilar thicknesses. In addition, the positive electrode is subjected to faster wear than the negative one. Also if any of the interfaces of a resistance weld is composed of dissimilar materials, that interface will heat or cool depending on the polarity of the applied potential. This effect is dominant only in the first few milliseconds of a weld, but significantly affects the weld quality and electrode wear. The effects of polarity can be minimized via the use of weld pulses of alternating polarity. Current stepping is an effective process control strategy that compensates for electrode growth and wear. There are also MFDC power supplies that can alternate polarity under development.



Resistance spot welding welding robot

(Source: T.J. Snow)

The other key elements used in the spot welding process are the tool holders and the electrodes. The tool holders provide the necessary electrode force and hold the electrodes firmly in place. They also support the (optional) water hoses which cool the electrodes during welding. Traditionally, pneumatic actuators have been employed in the automotive industry to apply the electrode clamping force. Today, electric servomotor actuators are usually installed. Unlike pneumatics, servo guns with force feedback control operate accurately at both low and high gun forces. They also offer the potential for faster cycle times by improved control of the electrode aperture and closing speed. Another interesting possibility is the ability to increase or decrease the electrode force during welding. Force stepping adds another degree of control since it maintains increased uniformity of the pressure – and ultimately current density distribution – across the welding interfaces. It may also reduce electrode erosion since it lowers the contact resistance at the electrode and sheet interfaces.



Servo-controlled spot welding gun

(Source: ARO)

An MFDC servo gun specified for welding aluminium is fully capable of welding steel, therefore a production cell set-up for aluminium resistance spot welding offers the flexibility to also weld the full range of automotive steels (but not the other way round).



Manual resistance spot welder (left) and robot spot welding system (right)

(Source: Elektron/ Kuka Systems)

5.1.3 Electrodes and electrode maintenance

The copper electrodes used for aluminium resistance spot welding are designed in different shapes and sizes depending on the application. Radius style electrodes are used for high heat applications, electrodes with a truncated tip for high pressure, eccentric electrodes for welding corners, offset eccentric tips for reaching into corners and small spaces, and finally offset truncated for reaching into the work piece itself.

A new development for aluminium resistance spot welding is GM's patented multi-ring domed electrode. The new welding technique works on sheet, extruded and cast aluminium and enables stronger welds because the multi-ring domed electrode head disrupts the oxide on the aluminium surface.



GM's proprietary multi-ring domed electrode head (Source: GM)

Recommended by the Resistance Welders Manufacturing Association are electrodes made from group A class 1 alloys. Group A class 1 alloys have the highest electrical conductivity. For the standard Al-Mg and Al-Mg-Si car body sheet alloys, electrodes A class 2 can be used too. Efficient cooling of the electrodes must be ensured; the coolant flow rate should be 5 - 10 litres per minute (more than in case of steel). It must be also noted that for aluminium welding, the electrode tip diameter and dome radius are bigger than for steel.



Schematic of an electrode for aluminium resistance spot welding

Newer studies showed that the face diameter D should be smaller than indicated in the figure above. It was found that for aluminium sheet thicknesses between 0.8 and 4.0 mm, a face diameter D between 5.0 and 10.0 mm promotes more uniform contact distribution at the electrode and interfacial surfaces, reduces undersized welds that occur intermittently and significantly increases electrode life.

The main problem connected with resistance spot welding of aluminium and its alloys is the short life time of the electrodes. The rapid deterioration of the tip surface of the copper electrode is the result of the high pressure, the high temperature and in particular alloying processes during welding. The accumulation of aluminium on the electrode face causes increased resistance heating at the electrode-aluminium interface and therefore even more aluminium melts and sticks to the electrode. Once significant aluminium accumulation has occurred, deterioration of the weld consistency and quality is rapid. Unless some sort of electrode maintenance is employed, typically only between 300 and 3000 aluminium spot welds can be achieved on a set of electrodes before the weld quality drops below a minimum threshold.

Numerous process and material strategies to increase the electrode life performance have been proposed in the past. Most concepts focused on reducing electrode erosion through a variety of surface coatings and treatments. Such techniques can enhance spot welding performance, but are often difficult to implement and expensive.

More efficient proved to be the introduction of a regular electrode cleaning step, ideally before electrode wear contributes to poor weld quality. Dressing allows the user to restore a worn electrode to a desired geometry, thereby eliminating changes in electrode topography and diameter due to pitting and erosion. The actual type and frequency of electrode cleaning, process times and tool designs are dependent upon the overall cleaning strategy. The process takes up to several seconds and is typically completed during the part transfer operation.

In many automotive resistance spot welding lines, electrode dressing has been introduced to extend electrode life time and improve weld consistency both for steel and aluminium. A wide range of commercially available electrode dressing equipment has been developed; including hand-held dressers for manual guns and stand-mounted systems for robots.



Hand-held dresser (left) and stand-mounted robot dresser with swarf tray (right)

(Source: University of Warwick)

A common feature of cutters designed for steel is the emphasis on reshaping the sides of the electrodes to remove mushrooming and thereby maintain welding current density. In aluminium resistance spot welding, mushrooming of the electrode does not occur and the main requirement of the cutter would be to take light cuts from the face to remove aluminium, oxides and pits. However, this is not the optimum solution because the required frequent electrode dressing may lead to substantial geometrical changes, i.e. the electrodes must be replaced early.

A more efficient solution for aluminium resistance spot welding proved to be the use of less aggressive electrode maintenance methods and to employ a dressing cutter only when the tip is badly damaged. The use of suitable abrasive wheels was found to be extremely effective at removing aluminium from the electrode face. An additional advantage is that the adaptable buffing wheels maintain the profile on domed electrodes.







Ring of aluminium on electrode removed by a short buffing operation

(Source: University of Warwick)

Using a polishing wheel enables the electrodes to be buffed clean within the component cycle time, with only a minimal change in electrode geometry even after hundreds of buffing cycles. Restoration of the original electrode geometry is less necessary for aluminium than for steels since there is little mechanical deformation during electrode wear. The effect of periodic buffing after a relatively short number of spot welds is a significantly improved consistency of the aluminium resistance spot welding process, reduced process cost (less electrode replacement) and increased productivity (less down-time for electrode changes).

5.1.4 Joint configurations for resistance spot welding

The joint configurations suitable for aluminium are essentially the same as for steel. Resistance spot welding is most often configured in way that requires access to both sides of the joint, so welding to closed sections is not generally possible. There are some single-sided variants of the resistance spot welding process, but these are largely unproven for aluminium.



A selection of joint configurations suitable for resistance spot welding

Two or more components are overlapped in the region to be joined. Typically, this is along a weld flange specifically incorporated on the components for the purpose of accommodating the spot welds. In order to minimise the possibility of edge-welds and uncontrolled weld expulsion, weld flanges must have an adequate width to provide a flat portion that is wider than the anticipated weld nugget diameter. For dissimilar thickness joints, the flange thickness ratio should be less than 3:1.



Typical flange for resistance spot welding

The recommended flange widths for aluminium are similar to those for steel. The weld flat dimension (F) must be several mm greater than the weld nugget diameter (D) and must include the usual tolerances for spot positioning and flange mismatches. The overall flange width (W) includes the allowance for the forming radius. Also, for reasons of accessibility, gun alignment and avoidance of current shunting, no part of the electrode (or its holder) is allowed to contact the corner radii or the up-flanged part of the component. Thus a certain distance (note A) must be kept to avoid any interference between electrode and work piece. Furthermore, nearby spot welds have a significant influence as they may offer lower resistance paths.

Production experience has shown that aluminium requires better part fit-up compared to steel. Poor sheet fit-up and off-angle electrode alignment affect the weld quality by overheating the joint, simultaneously promoting expulsion and small weld nugget sizes. Micro-movements at any of the surfaces (e.g. gun skidding, electrode rotation, or shear forces caused by asymmetric stack-ups or electrode geometries) must be minimised or avoided. An aluminiumspecific problem are the high electrode forces which may cause deflection of inadequately designed gun arms, leading to misalignment and skidding (micro-movement).

Contact resistance is directly related to the force applied at the surfaces. Poorly fitting parts reduce the effective force to contain the growing weld nugget. Thus the components to be welded must be formed within tight tolerances to avoid the need to use the welding equipment to force the flanges together, i.e. the closing force required to move the parts back into intimate contact must be minimised.



Effect of poor part fit-up

The electrodes must be kept as much as possible perpendicular to the sheet surfaces in order to maintain weld strength and to prevent cracking. Electrode designs with smaller radiuses on the face may improve weld quality under non-ideal fit-up conditions.





5.1.5 Resistance spot welding of aluminium alloys

For a given material combination and joining parameters (electrodes, joint configuration and electrode force), the weld lobe describes a region of acceptable welding parameters. The parameter axes are generally weld time and weld current while the electrode force is kept constant. The "lower" boundary is the parameter combination that produces a weld button of minimum acceptable dimensions. The "upper" boundary is defined by expulsion conditions. The area inside the lobe represents the "safe" welding window for new electrodes, i.e. it gives an idea of the parameter robustness.



Schematic of a typical weld lobe

The cross-section of an ideal aluminium spot weld shows good shape of the weld nugget, acceptable penetration, no cracks, and minimal porosity.


Ideal resistance spot weld between two aluminium sheets

The typical non-conformities of resistance spot welds are:

- cold welds or too small nuggets,
 - too big nuggets (often leading to expulsion and deep indentations of the welding electrodes),
 - cracks, porosity, pores, etc., inside the welding nugget.

Expulsion ("weld splash") is detrimental to weld quality and should be avoided. Some nugget porosity or cracking can occur, especially in sensitive alloy types. Small pores and other discontinuities located in the centre of the nugget do not significantly affect spot weld performance. However, if they are extensive or extend to the edge of the weld nugget where the influence of applied stresses is greater, unexpected and catastrophic failure through the weld nugget can occur when the structure is loaded.



Unacceptable welds: expulsion (left) and overheated weld with coarse defects (right)

5.2 Resistance spot welding with process tape

Resistance spot welding with an intermediate layer (process tape) is a further development of the conventional resistance spot welding process. The principle is based on a process tape running between the electrode and the work pieces, in the same rhythm as the spot-welding operation. Every time the "used" length of the process tape is moved out of the contact zone, i.e. exactly the same conditions are obtained for every weld spot. The presence of the intermediate layer enables - in combination with the servo-electric mechanical actuator and the powerful MFDC interactive process control - to form top-quality joints for different material combinations, even when there are different (and indeed only minimal) material thicknesses.



DeltaSpot[®] resistance spot welding process

(Source: Fronius)

Process tapes are available in a range of different alloys and coatings, with different electrical and thermal conductivities. The process tape performs several functions. It prevents direct contact between the electrode and the work piece, protecting the electrode from wear, contamination or other influences emanating from the surface of the work piece. Secondly, the constantly "new" electrode contact surface to the work piece prevents surface spatter and widens the process window. This results in an improved precision and reproducibility of the welding process, a consistent, high quality of the welding points and a significantly higher electrode service life.

Most important, however, is the possibility to directly and selectively influence the heat balance in the work piece. This is because the existing contact and material resistances are now augmented by the material and contact resistance of the process tape. When the current is switched on, the tape-related resistances generate additional heat which shields the joint against electrode cooling. The result is more heat in the work piece with lower electrical input power.



Principle of resistance spot welding with process tape

(Source: Fronius)

In the schematic representation shown above, the heat generation can be seen at the right side with (red curve) and without (black curve) the application of a process tape. By using process tapes made of different materials and with different coatings, the user can modify and optimise the overall heat balance and distribution of heat in the work pieces.

The process tape is a flexible tool for creating optimum conditions in each application. The same welding gun can be used to weld different sheet thicknesses, material combinations and multi-sheet joints simply by changing the process tape. Also the extra resistances allow to focus the added heat input onto the point being joined, reducing any shunt effects. Unwanted current transfer at other positions on the work piece hardly ever occurs. This is especially relevant for light-gauge sheets.

A difficult task for resistance spot welding is for example the realisation of a three-sheet joint including two thick sheets and one thin sheet. The welding point forms primarily in the area of the thicker sheet and does not cover the thin sheet sufficiently. The additional heat applied by

the process tape enables a targeted control of the welding point depth. Using a process tape with greater resistance, it is possible to compensate for the reduced amount of heat in the area of the thin sheet; the shape of the weld is symmetrical and shows increased volume in the area of the thinner sheet. Unlike in conventional spot welding where the weld-pool nearly always takes a nugget shape, the DeltaSpot[®] process creates a cylindrical weld shape if the boundary conditions allow. This is mainly due to the insulation against electrode cooling, and to the extra thermal input.



Spot weld joining three EN AW-5054 aluminium sheets (0.3 mm, 2.0 mm and 1.0 mm) produced using a coated process tape

(Source: Fronius)

The standard electrode used in resistance spot welding has a convex shape. Due to the slightly elastic process tape, this results in an optimally shaped circular contact area. However, a concave electrode with a ring-shaped contact area can offer alternative advantages, i.e. producing a higher current density on the "ring" (compared to a flat electrode) which results in higher process reliability. Another benefit of spot welding with process tapes is that the surfaces of aluminium sheets are barely marked by any indentations at the weld spots.

5.3 Resistance seam welding

Resistance seam welding is a variation of the spot welding process where a series of overlapping weld nuggets are produced that form a continuous, leak-tight joint. In resistance seam welding, the spot welding electrode tips are replaced by a pair of driven copper wheels (typically ~200 mm in diameter) or one wheel acting against a stationary backing piece. Although it would be theoretically possible that a seam welder actually runs with a continuous flow of current, a pulsed welding current is generally used to form the individual spots.

The electrode force and welding current are transferred to the work pieces (strips, sheets, wires, sections) by means of roller or disk type electrode which also ensure feed motion transmission. The overlap area of the work pieces with its comparatively high electrical resistance is intensively heated by the current and the semi-molten overlap surfaces are pressed together by the welding pressure causing them to bond together after cooling.



Resistance seam welding process

The size of the welding zone depends on the thickness of the individual parts and the electrode contact surface area. The pair of rollers makes contact with a small area of the work piece so that the current density required for the welding operation is achieved when the current passes through this zone. Because of the rotation of the roller electrodes, different points of the electrode are loaded with current. As a result, the thermal load and therefore wear of the electrode is smaller than with resistance spot welding. Most seam welding techniques use water cooling through the weld roller assemby due to the intense heat generated.



Resistance seam welding machine (Source: Sureweld)

The resistance seam welding process depends on three parameters:

- Power supply and the weld control unit
- Welding wheel configuration
- Sheet configuration.

The current and the heat generation are localized by the peripheral shapes of the electrode wheels. The electrodes are not opened between spots. The electrode wheels apply a constant force to the work pieces and rotate at a controlled speed. The welding current is normally pulsed to give a series of discrete spots, but may be continuous for certain high speed applications where gaps could otherwise occur between individual spots. Seam welding equipment is normally fixed and the components being welded are manipulated between the wheels. The process may be easily automated.

There are a number of process variants for specific applications, e.g. wide wheel seam welding with a flat wheel contact area or narrow wheel seam welding where a round wheel contact shape is used.



Wide (left) and narrow wheel seam (right)



Consumable wire (left) and mash seam welding (right)

Extensively used is also consumable wire seam welding where a properly shaped copper wire is fed between the wheels and materials to be joined in order to provide consistent clean contact. Another variant is mash seam welding where a narrow overlap of sheet edges is partly crushed together during welding.



Welding principle for pipes (left) and for flat products (right)

(Source: Soutec)

In consumable wire seam welding, the welding rolls assume the task of the electrode and the pressure tool. The copper wire is guided between the rolls and the work piece while simultaneously providing a constant high quality weld seam. The copper wire allows for minimal wear to the weld rolls. Welding spots are set closely by the rolls to allow for a continuous leak proof seam. The pulse frequency of the current determines the spot weld spacing. For tack or stitch welding, the spots are set further apart.

Roll seam welding enables high welding speeds compared with many other techniques, but can be limited by component shape and wheel access. The main issues concerning seam welding are in weld quality control and welding speeds. Factors such as material, control of pressing force and alignment of the electrodes are critical to achieve high speed, quality welding.

5.4 Projection welding

Another modification of the spot welding process is projection welding. In this process, the weld is localized by means of raised sections ("projections") on one or both of the work pieces to be joined. Current flow and thus heat generation is concentrated at the contact surfaces of the embossed, cold headed, or machined projections. They effectively localize the current, forcing the parts to heat predominately at the mating surfaces. This focuses heat at the mating surfaces of the pieces and minimizes bulk heating of the parts.

The concentration of the heat at the projections permits the welding of heavier sections or the closer spacing of welds. The projections can also serve as a means of positioning the work pieces. Projection welding is often used to weld studs, nuts and other screw machine parts to metal plate. It is also frequently used to join crossed wires and bars. Multiple projection welds can be arranged by suitable designing and jigging.

The welding sequence is similar to that for resistance spot welding. The welding electrodes are used to apply both force and current across the configuration. The point of contact constricts current flow and – since it is a point of high resistance in the welding circuit – heating occurs preferentially at this point. Thus the material softens and the projection collapses under the force applied by the welding electrodes.



Process sequence of resistance projection welding

Projection welding allows for precision joining of parts with complex shapes, joining of challenging material combinations and simultaneous formation of multiple welds. While the projections usually collapse early in the weld cycle, the localized heating raises the material resistance locally and promotes further heating and finally weld development at the initial contact point. The process can be developed to produce a fusion type weld or a solid state weld depending of the application.



a. Embossed b. Stud-to-Plate c. Annular

Weld configurations used in resistance projection welding

The most important process variable is the quality of the projections and the response of the cylinder as the projection collapses during welding. The welded metal must be strong enough to support the projection. Aluminium can be projection welded to a limited extent, but requires special projection geometries. Best results have been obtained for ring-shaped projections. However, the strength of most aluminium alloys is too low to allow the projections to survive under the forces applied by conventional projection welding equipment. Careful control of the applied welding forces is thus a necessity. Consequently, this technique is not much used for aluminium mainly because premature rapid collapse of the projections leads to unreliable joints.

5.5 Resistance butt welding (flash welding)

In the flash butt welding process, the ends of the piece to be welded are connected to the secondary circuit of a transformer. One piece is held firmly by a clamping device attached to a stationary platen; the other piece is clamped to a movable platen.

At the start of the process, the materials being joined are clamped rigidly in the dies and the parts are separated by a suitable air gap. Then the movable platen is advanced slowly. When the surfaces to be welded touch, the strong current passing through the local asperities starts to heat the edges ("flashing period"). The asperities start to melt, the molten bridges are broken and thrown off as flash particles. The objective of this step is to establish a suitable

temperature distribution in the work pieces to enable proper forging during the subsequent upset period of the cycle. When the metal behind the faying surfaces on either side is sufficiently heated to ensure adequate plasticity, the current is stopped immediately and the surfaces are rapidly squeezed together at a greater force ("upset period"). Oxides and other impurities are extruded out of the surfaces to be joined and satisfactory welding takes place.



TRIMMING

Flash butt welding process sequence

Resistance butt welding is used to produce joints in long rods and tubes with similar cross sections, but due to its high electrical conductivity not suitable for aluminium.

5.6 Resistance element welding

Resistance element welding is a further development of the conventional resistance spot welding process. It combines both thermal and mechanical joining principles by creating a metallic bond between an auxiliary joining element and the bottom plate, in combination with a force- and form-locking connection of the auxiliary joining element with the top plate.

In a first step, a hole is punched into the top (cover) sheet. Then the auxiliary element ("weld rivet") is inserted or positioned in the hole. One electrode is lowered onto the rivet and the other is positioned onto the bottom sheet. Pressure (F) and electric current (I) are applied simultaneously. The heat generated by the electrical resistance creates a weld nugget in the contact zone between the weld rivet and the base sheet and forms the connection.

In the final phase, an increase of the electrode force leads to a deformation of the weld rivet in the axial direction and therefore to a tight force connection (surface pressure) between the rivet head and the cover sheet. A frictional connection is obtained at the contact between the rivet shaft and the cover sheet and between the rivet head and the cover sheet (surface

pressure). The individual process stages can be controlled by a variation of the parameter settings (weld time, current, force) generally used in state-of-the-art mid-frequency, servo-controlled spot welding equipment.



Resistance element welding process (Source: LWF Paderborn)



Cross section of an aluminium (EN AW-6016, 1.5 mm) - steel (22MnB5, 2.0 mm) joint produced by resistance element welding

(Source: LWF Paderborn)

5.7 Resistance stud welding

Further stud welding technologies are covered in more detail under "3.3 Arc stud welding". In the present context, only the contact welding variant is relevant.

Studs are primarily used for fastening applications. They are rapidly applied with portable equipment. Studs designed for resistance stud welding have a small tip extending from the base of the stud. This special tip provides precise weld time control for consistent, automatic welding. The stud tip is placed in contact with the base metal. Upon triggering, peak currents vaporize the tip, drawing a precisely timed arc. The arc melts the full diameter of the stud and the same area of the work piece. The stud is then forced into the molten metal, completing the process in a few milliseconds, with little or no reverse-side marking. In general, the capacitor-discharge method is applied to supply the arc power.

A specific application of this technique is found in aluminium dent removal equipment, i.e. the use of weld-on studs for pulling dents out of aluminium panels. The capacitor discharge technology delivers very brief, but high current density to break through surface oxide layer

without damaging the sheet metal below. Up to 6 mm diameter aluminium or titanium stud bolts can be welded onto clean, bare aluminium surfaces.



Resistance stud welding system for dent pulling in aluminium panels

(Source: Elektron)

Conventional steel stud welders cannot be used for damaged aluminium body panels. The high heat dissipation of aluminium requires a power supply with a significantly higher current capacity.

5.8 High frequency welding

High frequency induction welding is primarily used to produce pipes or tubes from strip material. The rolled aluminium strip is fed into rolls which form the flat strip into a cylindrical shape. The faying edges are then brought together between squeeze (upsetting) rolls for welding. In addition, high frequency welding is nowadays increasingly integrated into roll forming lines to produce profiles with more complex, asymmetrical cross sections which may also include pre-punched holes, notches and other geometrical features.

There are two distinct types of high frequency welding:

- Induction welding, which uses an energized copper coil that is wrapped around the part without contacting it. As the material flows through the electromagnetic field created by the coil, current is induced into the material. The need to adjust, maintain, and replace contact electrodes is eliminated.
- **Contact welding,** which sends current flowing into the material through an electrode which touches the material.



High frequency welding techniques

(Source: EHE, Inc.)

High frequency welding is a form of electrical resistance welding. The high frequency current is concentrated on the edges of the strip and thus resistance heating will occur only in a

narrow zone at the edges of the material. A voltage is applied (HF contact) or induced (HF induction) across the edges of the open tube just prior to the point of closure. This voltage causes a current to flow along the edges to the point where they meet, leading to rapid heating of the metal edges up to the welding temperature. The pressure applied by the upsetting rolls forces the heated metal edges into contact and thus forms the bond. The applied pressure also forces molten metal and any impurities out of the weld zone, i.e. the resulting joint shows rather a forged microstructure with a narrow heat-affected zone and therefore possesses very good mechanical properties.

The only real difference between high frequency contact and induction welding is that with contact welding, the voltage is applied directly to the strip edges by means of sliding contacts, whereas in the case of induction welding, the voltage is induced by the magnetic flux surrounding the coil. Both methods have their advantages and drawbacks, but in general, induction welding will produce smoother, more consistent welds and is therefore mainly used for aluminium welding.

When compared with other processes, high-frequency welding produces a high-quality butt seam at relatively high speeds. Consequently, production volumes need to be relatively high to justify the capital equipment cost.



HF welded aluminium tubes (Source: Sapa)

EAA Aluminium Automotive Manual – Joining

6. Brazing

Content:

- 6. Brazing
- 6.0 Introduction

6.1 Brazing methods

- 6.1.1 Dip brazing
- 6.1.2 Flame brazing

6.1.3 Furnace brazing 6.1.3.1 Vacuum brazing 6.1.3.2 Controlled atmosphere brazing

6.1.4 Arc brazing

- 6.1.5 Laser beam brazing
- 6.1.6 Resistance brazing
- 6.1.7 Induction brazing

6.2 General principles of the aluminium brazing process

- 6.2.1 Aluminium alloys for brazing applications
- 6.2.2 Brazing filler metals
- 6.2.3 Joint design and assembly
- 6.2.4 Cleaning before brazing
- 6.2.5 Pre-assembly of the parts
- 6.2.6 Brazing fluxes
- 6.2.7 Flux application
- 6.2.8 Brazing cycle

6.3 Soldering

- 6.3.1 Soldering alloys
- 6.3.2 Solderable aluminium alloys
- 6.3.3 Soldering process

6.0 Introduction

Brazing is a metal-joining process where a filler metal is heated above its melting temperature but below the melting point of the metals being joined. The liquid filler metal is then drawn into the gap between the closely fitted surfaces of the joint by capillary action. Because of the importance of wetting and capillary effects, the quality of the surfaces to be joined is of utmost importance and the clearance between the parts must be small (generally less than 0.2 mm).

Soldering is a similar process to brazing, except that the process temperatures are lower. Traditionally, brazing and soldering of aluminium are distinguished from each other in the following manner:

- Soldering: T < 450 °C
- Brazing: T > 450 °C.

Brazing produces excellent joints, in particular when joining thin-walled, compact parts. It is especially useful for the realisation of complicated parts with many joining spots per area unit, large area joints or inaccessible joints. The waterproof joints produced by the brazing process are specifically advantageous for the fabrication of products containing liquids like oils, water and/or coolants, even at relatively high operative pressures.

Since brazing does not melt the base metal, it allows for precise control of geometrical tolerances and low distortions. In addition, it provides clean joints with no need for additional finishing. Brazed joints are strong and, because the meniscus formed by the filler metal in the brazed joint is ideally shaped for reducing stress concentrations, they offer better fatigue strength than most welds. In addition, dissimilar metal joints like aluminium-steel, aluminium-titanium, aluminium-magnesium, etc., are also easily joined by brazing.

However, brazing of aluminium and its alloys requires careful temperature control since the brazing temperatures are generally close to the melting temperatures of the applicable parent alloys. Aluminium alloys typically melt in the range 560-660°C, while the standard aluminium brazing alloys (based on the Al-Si and Al-Si-Mg systems) melt in the range 520-610°C. The aluminium brazing temperature range is normally 580-620°C. As a consequence, high strength aluminium alloys of the Al-Cu and the Al-Zn-Mg-Cu systems (which generally have lower liquidus temperatures) are generally not joined by brazing.

Furthermore, it must be taken into account that – in many cases – the high brazing temperature significantly lowers the strength of the base aluminium alloy, i.e. potential softening effects must be considered when alloy and temper are selected. The exceptions are low alloyed, heat-treatable Al-Mg-Si alloys which can be quenched from the brazing temperature and then naturally or artificially aged to a higher yield strength level.

For proper brazing, the braze filler metal must be placed between the two components to be joined. The filler metal can be added as a wire, a metal powder mixed with flux or a thin sheet. Molten filler metal is then distributed between the closely fitting joint surfaces by capillary forces. Because the liquid filler metal can flow along the solid contact surfaces between two closely spaced components, brazing of blind joints is possible.

In most cases, however, a multi-layer sheet material is used to produce brazed aluminium assemblies. Aluminium brazing sheets are sophisticated multi-layer compounds consisting of a core alloy which provides the strength and other life cycle requirements and the filler metal, sometimes separated from the core alloy by a further alloy layer which acts as a diffusion barrier. In some cases, the brazing filler on one side is also combined with a clad layer providing additional corrosion protection on the other side. The filler alloy is clad on one or both sides of an aluminium core (usually produced by roll cladding or using a multi-layer cast rolling ingot (e.g. Novelis Fusion[™] technology)).

During brazing, the liquid filler metal must be protected from the atmosphere by a suitable measure. A brazing flux, which cleans the brazing surfaces from any contamination and also removes the aluminium oxide surface layer when heated, is normally used for this purpose. In addition, the flux promotes base metal wetting and filler metal flow. Only if brazing is carried out within a furnace under vacuum, there is no need for flux addition.

Fluxes are chemical compounds applied to the joint surfaces before brazing. Traditionally, aluminium brazing has been based on chloride fluxes. More recently fluoride fluxes are commonly used. Fluxes can be added as powder or paste, alternatively the aluminium substrate or the filler material can be pre-coated with flux or a flux-containing composite filler rod can be used. In either case, the flux flows into the joint when heated and is subsequently displaced by the molten filler metal. Excess flux must be normally removed when the cycle is completed because many aluminium fluxes (particularly chlorides) can lead to corrosion. With non-corrosive fluxes, no post-braze cleaning step is required.

The most important automotive application of aluminium brazing is the fabrication of heat exchanger components. At the beginning of the 1970's, mechanically assembled aluminium heat exchangers started to replace the traditional copper and brass radiators. In the middle of this decade, the fluxless vacuum brazing process was introduced into large scale production. Finally the improved, flux-based controlled atmosphere brazing technique, developed in the early 1980s, enabled a breakthrough in the use of aluminium brazing material for heat exchangers. Today, controlled atmosphere brazing with non-corrosive fluxes (specifically the NOCOLOK[®] flux brazing technology) has evolved as the leading technology for manufacturing aluminium heat exchangers and aluminium has virtually replaced copper and brass.

A specific advantage is that the furnace brazing process can be easily automated. A major disadvantage of any brazing operation, however, is the difficulty of a non-destructive quality control of the resulting joints.



Brazed aluminium radiator with plastic tanks

(Source: Sapa)

6.1 Brazing methods

The most important brazing method for aluminium is furnace brazing (in particular for the production of heat exchangers). But the traditional aluminium brazing techniques like dip (flux) brazing and manual flame (torch) brazing still find their specific applications. In contrast to manual flame brazing, industrial brazing techniques such as dip and furnace brazing require fairly large capital investment and sophisticated production control systems.

In addition, also other heat input methods can be used. Industrially applied brazing methods include TIG (often referred to as GTA) and MIG (often referred to as GMA) brazing, plasma brazing, laser beam brazing or plasma brazing. These methods are selected in particular for small production volumes and when brazing aluminium to other metals. Furthermore, induction brazing or resistance brazing can be applied, specifically for brazing aluminium to steel.

6.1.1 Dip brazing

Dip brazing has been used widely and successfully for many years, in particular for complex assemblies. It enables rapid, uniform heating and can accommodate low dimensional tolerances. However, significant post-braze cleaning is required to remove flux residues and close attention must be paid to assembly design in order to avoid air traps.

Prior to the immersion into a molten flux bath, the assemblies are usually pre-heated to about 540°C. The flux is a molten mixture of chlorides of Na, K and Li with additions of fluorides of Na, Al and Mg and is periodically adjusted by further additions of molten chlorides and fluorides. The bath temperature should be controlled within ±3°C and may not drop more than 6°C when the aluminium parts are immersed. Immersion time may vary from 30 seconds to 30 minutes depending on the size and weight of the assembly being brazed. It is very important that the flux residues are removed after brazing to inhibit corrosive attack of the parent material.

Another disadvantage of the dip brazing process is that it has a large impact on the environment. It produces corrosive vapours as well as large amounts of wastewater. Therefore, dip brazing is used decreasingly today.



Dip brazing process

6.1.2 Flame brazing

Flame (torch) brazing of aluminium involves locally applied heat typically generated by a slightly reducing oxy-acetylene, oxy-hydrogen or oxy-natural gas flame. The latter is usually the preferred gas mixture for aluminium torch brazing as it is cheaper and generally more controllable. Care must be taken to ensure even heat distribution. As with other aluminium brazing processes, close temperature control is important. While this is relatively straightforward in automated torch brazing, it is more difficult in manual brazing as there is no colour change in the aluminium to indicate temperature. As an aid to temperature indication, some torch brazing fluxes are formulated to change colour (as well as liquefy) when the appropriate temperature is reached.



Flame brazing with a filler rod (left) and using clad material (right)

Apart from the selection of flux and filler material, important process parameters are the cleanliness and proper geometrical alignment of the individual components. Filler metal may be pre-placed or added during brazing using a brazing rod. Post-braze cleaning to remove chloride flux residues is required.

Flame brazing uses relatively simple equipment, but is limited to the production of simple parts. Manual flame brazing is mainly used as a joining method for repairs. Provided proper filler metals and fluxes are selected, flame brazing can also be used for brazing aluminium to copper.

6.1.3 Furnace brazing

Furnace brazing is a semi-automated process which allows joining of fairly complex multi-joint assemblies. Furnace brazing is accomplished using a variety of techniques including different furnace designs (batch as well as continuous furnaces). Furnace brazing offers the flexibility to join a wide range of metals. The materials being joined determine the type of atmosphere in which the assembly is heated to join its components. In addition to air, vacuum, protective (inert) or reactive atmospheres are used.

Aluminium may be furnace brazed in air using flux. The brazing process follows the standard brazing procedure outlined above. The material surfaces are cleaned and fluxed, the filler metal is positioned and the assembled parts are placed in the furnace. A disadvantage compared to dip brazing is, however, the lower heat transfer rate. Slow and prolonged heating may result in liquation of the parent metal or in significant diffusion effects; insufficient heating may cause lack of brazing. Thus aluminium furnace brazing in air finds little practical application.

The most important furnace brazing methods for aluminium are brazing in vacuum and under controlled atmosphere. There is also considerably less impact on the environmental compared to open furnace brazing and salt-bath brazing. The flux-less vacuum brazing process and the flux-based controlled atmosphere brazing (CAB) process solve the aluminium oxide layer penetration problem, a necessary precondition of any brazing process, by differing methods. Today, the CAB process is generally the preferred brazing process as it offers clear cost benefits (improved production yields, lower furnace maintenance requirements and greater process robustness). Newer developments also offer the possibility of flux-less CAB brazing.

6.1.3.1 Vacuum brazing

In vacuum brazing, the parts to be joined are cleaned, brazing filler metal is applied to the surfaces, and the parts are then placed into the furnace. No addition of flux is required. After the furnace has been evacuated of air, the entire assembly is brought to brazing temperature. The vacuum eliminates any risk of oxidation or contamination which could occur when the braze filler metal melts and flows into the joints.



Batch Vacuum Brazing Furnace

(Source: Ipsen)

Vacuum brazing is a high-end joining technology because it results in parts with extremely strong joints and the absence of any residual corrosive flux. Typical vacuum aluminium brazing furnaces are either single chamber (batch type) or multiple-chamber (semi-continuous). Batch type furnaces are usually loaded horizontally, but can be also designed for vertical loading. Semi-continuous furnaces are horizontally loaded and typically automated using load carriers and external conveyor systems. In this case, a pre-chamber is usually added for thermal degreasing. Successful vacuum aluminium brazing requires a short process cycle (i.e. fast pumping and heating characteristics of the furnace) and good temperature uniformity at soak temperatures.

The mechanism of the flux-free brazing process under high vacuum is as follows:

- When an aluminium alloy is heated, the oxide layer cracks due to differential expansion before the brazing alloy starts to flow (the coefficient of expansion of aluminium is about three times greater than that of aluminium oxide).
- The liquid brazing alloy can pass through these cracks down to the bare base material, but only if oxidation of the aluminium in the cracks can be prevented. Consequently, the atmosphere must be completely devoid of oxygen.

Thus, there is not only a minimum requirement put on the level of the vacuum (10⁻⁴ mbar or better), but in addition, a getter material must be used to scavenge all oxygen atoms from the atmosphere. In the late 1960's, it was discovered that the presence of Mg vapour serves this purpose. Thus a key element of vacuum aluminium brazing is the use of magnesium as an additive to the filler metal and/or the base metal of the parts to be brazed:

- When the magnesium starts to vaporise at about 570 °C, it acts as a "getter" for oxygen and water vapour, thus improving the purity of the brazing vacuum and preventing further oxidation.
- The vaporising magnesium may detach partially the oxide layer. Magnesium will also reduce the aluminium oxide on the aluminium surface, enhance filler metal flow and promote uniform, accelerated wetting of the joint surfaces.

In vacuum brazing, the parts to be brazed are provided with sufficient quantities of magnesium, normally present in the filler metal or in the aluminium alloy components. When brought to temperature in the brazing furnace, magnesium diffuses to the surface and then vaporizes at 570°C due to low pressure of 10⁻⁵ mbar. The magnesium vapour disrupts the oxide layer and thus enables the filler alloy to flow. But vacuum brazing can be even practiced using a Mg-free filler metal when magnesium powder is added separately to the brazing furnace.

The vaporization of the magnesium in a vacuum environment results in heavy outgassing during a short time period. Due to this gas load, the vacuum pumps must be adequately sized to maintain a good working vacuum.

In addition, precise temperature control and uniformity are important process parameters. The generally accepted temperature variation during a brazing cycle is +/- 3 to 5 °C. Thus it is

necessary to use a heat equalisation step at a temperature just below the solidus point of the braze filler metal to ensure that all parts of the component to be brazed reach the correct temperature at approximately the same time. When the further ramp-up to brazing temperature starts, the filler metal starts to melt, and the capillary wetting of the braze joints occurs. The length of time at brazing temperature must be kept to a minimum. After the brazing temperature soak is complete, it is followed by an immediate vacuum cooling cycle which solidifies the filler metal in the braze joints.

The precise temperature control and uniformity needed for vacuum aluminium brazing is achieved through the use of several separately controlled heating zones around the part. The surface temperature of the heating elements must be maintained as near to the part temperature as possible. A large temperature difference between the heating elements and the parts would result in an overheating of the part surface, possibly above the solidus temperature of the material.

Although capital costs of vacuum brazing equipment are relatively high and not all braze and parent alloys are suitable for vacuum brazing, vacuum brazing has been widely accepted by many volume producers. The process can be automated and, if properly controlled, allows the realisation of the cost and corrosion resistance advantages associated with flux-less brazing. A major disadvantage of vacuum furnace brazing is, however, the deposition of magnesium oxide inside the chamber and hot zone. Magnesium oxide deposits tend to retain water vapour which will slow down the vacuum pumping characteristics of the furnace and thus needs to be removed. Regular mechanical cleaning is the usual method for removing the magnesium oxide.

6.1.3.2 Controlled atmosphere brazing

In controlled atmosphere brazing (CAB), an inert gas is used to provide a non-oxidizing atmosphere in the furnace. The most commonly used inert gas is nitrogen, although nitrogen/hydrogen mixtures are also used in particular when aluminium is brazed to stainless steel.

There are various processes in use for the industrial scale manufacturing of heat exchangers. In the conventional CAB process, the ability to braze does not result from mechanical disruption of the oxide, but a non-corrosive, non-hygroscopic fluoride salt flux (typically potassium fluoraluminate) is employed to dissolve and break up the oxide layer before the filler alloy melts. But there are also CAB brazing processes without using a brazing flux which are in particular used to braze surfaces inside a heat exchanger with are very difficult to flux.

The controlled atmosphere brazing technique has a number of advantages:

- Compared to open furnace brazing considerably less or no flux is used.
- The furnace muffle can be made from standard steel and has a much longer lifetime.
- Only small amounts of salt residues remain on the component.
- Neither washing nor other post-treatments are required after brazing as only noncorrosive flux types are employed in modern controlled atmosphere brazing of aluminium components.

a) Conventional CAB brazing

Since the early 1980's, controlled atmosphere brazing (CAB) with non-corrosive fluxes has evolved as the leading technology for manufacturing aluminium heat exchangers in the automotive industry. It offers cost benefits and shows less environmental impact compared to open furnace brazing and salt-bath brazing. The dominating NOCOLOK[®] technology uses a non-hygroscopic and non-corrosive potassium fluoroaluminate flux that does not react with aluminium neither in the molten nor in the solid state and the post braze flux residues have a very low water solubility.

The major problems that have arisen from the NOCOLOK[®] process have been flux costs and the necessity for the integration of fluxing systems, many of which will suffer from variable flux loading., flux handling and the damage that flux causes to the furnaces. The flux can also be difficult to apply, especially on internal joints and can cause problems in terms of furnace

corrosion and cleanliness in the finished product. Moreover, it has been found that the flux can lose activity when exposed to magnesium. When the Mg content in the molten clad exceeds 0.3 %, the performance of the flux is reduced due to the formation of high melting K-Mg-F-compound. These compounds decrease the viscosity of the liquid filler and lead to poor brazing results. Thus, this process is not suitable for brazing magnesium-containing aluminum alloys.

The actual brazing process sequence depends on the specific component design, the cleaning method and the flux application technique. For automotive heat exchangers, the most common process sequence is:



This sequence minimizes handling of individual heat exchanger components, in particular handling of already fluxed components. Therefore, there is also minimum flux drop-off.

A fully configured controlled atmosphere brazing line includes an aqueous washer or thermal degreaser, a flux application unit, a dry off oven and the CAB furnace.



Continuously operating CAB furnace with five preheat and seven braze zones (Source: Seco-Warwick)

The loosely assembled and fixed heat exchangers are placed on an oven conveyor for processing.



Aluminium radiators ready for brazing (Source: Seco-Warwick)

A thermal degreaser oven then removes the lubricating oils present on the heat exchangers from prior fabrication stages. It typically operates at 250 to 300 °C. The vapours from light evaporative oils are oxidized in the combustion chambers. If heavier lubricating oils are used, an incinerator at the oven exhaust may be required. The products must then be cooled down to ambient temperature prior to the fluxing operation.



Thermal degreaser oven

(Source: Seco-Warwick)

After degreasing, the component is sprayed with a flux suspension. Excess suspension is blown off and the component is then dried in a continuous oven. Alternatively, other flux application techniques can be used.



Flux application station (left) and dry off oven (right)

(Source: Seco-Warwick)

The actual brazing process is carried out after applying the flux in an inert gas furnace. The brazing furnace is isolated from external air in such a way that the components can continuously travel in and out without undesired air entry into the furnace. The water vapour concentration must be low (dew point – 40 °C or lower) and the oxygen concentration in the inert gas must be < 100 ppm. Ideally, a uniform surface temperature of the work piece of 600 +/- 5 °C is aimed for brazing. A suitable treatment for the furnace exhaust (i.e. dry scrubber) is required. After leaving the brazing furnace, the components are finished and can be removed from the conveyor belt. No further treatments are required.



Controlled atmosphere brazing furnace (Source: Seco-Warwick)

b) Flux-less CAB brazing

In order to avoid the problems related to the use of flux in the CAB process, various attempt have been made to develop a multi-layer brazing sheet which enables brazing in inert atmosphere without using a flux. Developments are still ongoing, thus only two possible approaches are outlined below.

A solution is a brazing sheet comprising of an aluminium core alloy clad on one or both sides with an Al-Si alloy brazing alloy containing 0.1-5% Mg and 0.01-0.5% Bi as an intermediate layer and a thin Al-Si alloy outer cover. During brazing, the brazing material in the intermediate layer melts as the temperature is increasing, but no oxidation occurs because the surface is covered with the thin covering material which remains solid. When the temperature is further elevated, some portions of the thin covering material close to the molten brazing material are locally molten since segregation effects locally reduce the melting temperature. The brazing material then seeps and spreads over the surface of the thin covering material due to volumetric expansion. New intensive oxidation does not proceed due to the inert gas atmosphere.

An alternative method is to coat the part to be brazed with a braze-promoting metal such as cobalt, iron, or, preferably, nickel. If properly applied, the nickel reacts exothermically with the underlying aluminum-silicon alloy, thereby presumably disrupting the aluminium oxide layer, and permitting the underlying metal to flow together and join the parts.

6.1.4 Arc brazing

Arc brazing can be classified into gas metal arc and gas tungsten arc brazing processes. The principle is largely identical to the respective welding processes using the braze alloy as the filler wire.



MIG (also referred to as GMA) brazing was introduced in the 1990s. Very similar to MIG welding, the biggest difference is the use of a filler metal with a considerably lower melting point, since the base material must not melt during MIG brazing.

Since MIG brazing is done at low arc power, special precautions are required on the power source. Generally the pulsed arc process gives flatter seams than the short-arc process. Argon is often used as a shielding gas; also small amounts of other gases can be added to improve productivity and various properties.

The relatively low heat input makes MIG brazing particularly interesting for the welding of zinc-coated sheets in the automotive industry. Due to the low heat input, the zinc layer is left essentially undamaged and there is practically no thermal distortion. MIG brazing is also commonly used in automotive repair.



Schematic presentation of MIG brazing

(Source: MIG WELD GmbH)

For aluminium materials, no industrial application of MIG brazing is known today. However, good results have been achieved in laboratory tests using newly developed filler wires at BIAS (Bremer Institut für angewandte Strahltechnik). Suitable filler materials should have a low melting temperature, good wetting characteristics on aluminium surfaces, adequate mechanical properties as well as a good corrosion resistance. Suitable filler wires (AlZn13Si10Cu4 and AlSi10Cu8Mg2Sn1) were produced by spray forming and subsequent forming processes (extrusion moulding and rotary swaging). These filler wire qualities were also successfully used for aluminium laser brazing.

With proper adaptations of equipment and processing procedures, also TIG (often referred to as GTA) and plasma methods can be used for brazing. In particular the plasma brazing process offers some advantages over MIG brazing (less spatter, better seam appearance, and minimum zinc evaporation). But again, these techniques – although in industrial application for steel – have not (yet) been applied for aluminium in practice.

6.1.5 Laser beam brazing

The principle of laser brazing is based on melting a cold brazing wire with a laser beam. The brazing wire is introduced into the braze seam via a wire feeder unit. The molten wire material then flows into the seam and forms a brazing joint. As an alternative to the use of a brazing wire, an aluminium sheet with a suitable surface cladding can be used. Multi-layer aluminium sheets such as Anticorodal[®]-200RW (Novelis Fusion[™] alloy 8840) offer a cost-effective solution in this respect.



Shielding gas

Schematic presentation of laser brazing

The laser brazing process is used in the automobile industry, for example, for joining galvanised vehicle components and body parts. It is a relatively cold joining process where the base material is not melted and any zinc layers next to the joint remain largely intact. Suitable joint designs are flanged-butt and fillets. The process provides very high travel speeds of up to several meters per minute at a very low heat input. The resulting distortion is rather low. In general, laser brazing joints have very smooth weld surfaces that normally do not require any further finishing, even in visible areas of the car body ("class A joints"). As an example, laser brazing is used for the ditch joint attaching the roof and the side panel of the car. Compared to laser welding or spot welding, laser brazing improves the aesthetics of the joint so that the ditch molding can be omitted.

The use of Nd:YAG lasers for this application has already been established. Recently, however, diode lasers are being increasingly employed. Typical process demands on the laser beam source for brazing are: laser power from 2 to 4 kW and spot size of from 1.5 to 3 mm at a working distance of about 150 to 250 mm. Both the solid-state and diode laser types equally fulfil these demands.

Laser brazing offers higher process speeds than arc brazing and can be easily automated by attaching brazing optics to a robot. For a further increase of the process speed, it can be extended to laser hotwire brazing by an additional current on the filler wire. The closely localised heat application reduces heat input and thus part distortion. An interesting option is also the possibility to improve the absorption characteristics of aluminium by a proper modification of the composition of applied flux. The flux composition can be successfully tailored according to the technical requirement dictated by the specific joining problem.

In practice, laser brazing is mainly used for joining aluminium to other materials, in particular steel. Laser brazing of aluminium to zinc-coated steel proved to be a cost-effective, reliable joining method (see 11.2.2.1).

6.1.6 Resistance brazing

In resistance brazing, the joint to be brazed is made part of an electric circuit in which the local heat developed by the resistance to the passage of electric current melts the brazing filler metal and joins the elements. Resistance brazing is therefore suitable for applications where rapid and localized heating is required and where electrodes can apply the pressure required to establish electrical contact. The heat is generated in the workpieces, in the electrodes or in both, depending on the dimensions and on the resistivity of the respective materials.

There are two basic resistance heating techniques:

- For brazing high conductivity work pieces, the heat, generated in low conductivity (e.g. graphite) electrodes, will be transferred by thermal conduction to the joint through the base metal.
- For low conductivity base metals, high conductivity electrodes are used and the heat is developed electrode/work piece interface.

Two fundamental arrangements of electrodes and work piece are commonly used:



(Source: Johnson Matthey)

The direct heating approach can be used both with electrode heating and interface heating whereas indirect heating concept is only suitable for electrode heating.

Resistance brazing is ideal for joining small components, e.g. small temperature sensitive electronic or electro-mechanical metal components. In addition to working well with brazing alloys, this technique also works well with many lower temperature solder alloys. It can be performed in manual mode or in various degrees of automated modes, depending on configuration and production requirements.

6.1.7 Induction brazing

In induction brazing, two or more materials are joined together by a filler metal that has a lower melting point than the base materials using induction heating. Usually ferrous materials are heated rapidly in the electromagnetic field that is created by the alternating current from an induction coil.

With respect to aluminium, induction brazing is therefore only of interest when joining aluminium to other metals, in particular steels.

6.2 General principles of the aluminium brazing process

Because of its overriding industrial importance, in particular for the production of heat transfer equipment in cars, the following remarks concentrate on controlled atmosphere furnace brazing. However, information transfer to the other brazing processes (vacuum furnace brazing, dip and flame brazing, etc.) is easy and straightforward.

6.2.1 Aluminium alloys for brazing applications

a) Suitable alloy compositions

Most non-heat treatable aluminium alloys and many heat treatable aluminium alloys can be brazed. Taking into account the normal aluminium brazing temperature range of 580 - 620 °C, as a general rule, the maximum percentages of alloying elements which may be present for an alloy to be brazed are: Cu - 1.0%, Mg - 2.0%, Mn - 3.0%, Si - 2.0%, Zn - 6.0%. The most frequently brazed non-heat treatable alloys are found in the 1xxx, 3xxx and low magnesium (< 2.5% Mg) 5xxx alloy groups. The heat-treatable alloys most frequently brazed are EN AW-6061, 6063, 6101, 6151, 6951, 7004 and 7005.

Alloys with a low melting point, i.e. alloys which would require brazing temperatures below those of existing filler alloys, are not suitable for brazing. This applies for example to the high strength aluminium alloys of the Al-Cu and the Al-Zn-Mg-Cu systems (e.g. EN AW-2011, 2014, 2017 2024 and 7075).

A second group of aluminium alloys to be avoided in flux brazing processes are 5xxx series alloys with a magnesium content > 2.5% since the base metal is only poorly wet and yet excessive penetration and diffusion is experienced due to the low melting point. Similar effects can occur in higher strength EN AW-6xxx alloys. During the braze cycle, magnesium diffuses to the surface and reacts with the surface oxide. The resulting oxides (MgO and MgO:Al₂O₃ (spinel)) have a reduced solubility in the molten flux. Furthermore, Mg and/or MgO can react with the flux forming compounds, significantly reducing the flux effectiveness.

Aluminium casting alloys can be brazed too (if the solidus temperature of the alloy to be joined is sufficiently high), but brazing might be difficult when surface finish is poor or the metal is porous. Most critical are die castings because they do not wet easily with the filler metal. In addition, enclosed gases and other contaminants may cause blistering during brazing.

For controlled atmosphere brazing of heat exchangers, variants of the alloy EN AW-3003 are commonly used for the core. In special cases, also EN AW-1070 type materials are used. For vacuum brazing, EN AW-3005 is normally chosen due to its higher Mg content. In practice, however, aluminium brazing materials are specifically developed depending on the envisaged application and the applied brazing process. Thus there are numerous variants of core materials on the market.

The historically applied AI-Mn based alloys may be susceptible to inter-granular corrosion that is accelerated by the diffusion of silicon along grain boundaries from the cladding alloy during brazing. This encouraged the development of more corrosion resistant alloys ("Long Life Alloys"), i.e. modified EN AW-3xxx alloys showing a distinctive, elongated grain structure after brazing. In addition, during brazing, the silicon diffusion from the cladding leads to the precipitation of densely distributed AlMnSi particles at the interface between the cladding and the core alloy. The dense band of precipitates acts sacrificially to the core alloy, restricting corrosion to within this layer, and overcoming inter-granular attack. "Long life" brazing alloys are now widely used in many heat exchanger components.

If higher post-brazing strength levels are required, also heat treatable EN AW-6060, 6063 or 6951 alloys are applied as core material. During brazing, Mg₂Si particles are dissolved and the elements are kept in a solid solution by rapid cooling. The material strength is then enhanced by the precipitation of small particles which are subsequently formed at room or slightly elevated temperature. But the use of AIMgSi alloys in controlled atmosphere brazing is rather limited due to their Mg content.

Even higher strength is offered by an adapted EN AW-7020 heat exchanger core material (AMAG TopClad[®] UHS 7020) where solution annealing also occurs at brazing temperature. However, in this case, a further barrier layer has to be introduced in order to prevent diffusion phenomena.

b) Fabrication process

Aluminium brazing materials for serial production of brazed heat exchangers are sophisticated multi-layer compounds consisting of a core alloy which provides the strength and other life cycle requirements of the heat exchanger and the clad filler metal. Three- or five-layer compounds are commercially used; in the latter case, a diffusion barrier layer separates the core material from the filler. Furthermore, a protection layer can be clad on one side in order to prevent water-side corrosion. The applied core and cladding alloys depend on the chosen brazing process as well as the design and required performance of the heat exchanger.

Today, two basic cladding techniques – roll bonding and cast cladding – are industrially applied. Roll cladding is a solid-state welding process, used to join similar and dissimilar aluminium alloys. The cladding layers are locally welded to the core slab; planar metallurgical bonding is achieved when the composite rolling slab is hot rolled. The cast cladding technique is based on the use of a modified direct chill mould which allows casting a unitary multi-layer rolling ingot from multiple molten metal streams (e.g. Novelis Fusion[™] technology).

During brazing, only the clad brazing alloy melts while the core alloy remains solid. The design and the applied materials of the heat exchanger are adjusted to optimize the brazing result regarding the required post braze mechanical properties as well as the corrosion resistance. However, during the brazing cycle, elements of the core alloy and of the filler metal may diffuse from one to the other modifying the final properties of the assembly. As outlined above, such diffusion effects can enhance the corrosion resistance of the assembly by the formation of a sacrificial layer at the clad/core interface. However, there can be also adverse effects. Diffusion of silicon from the molten filler metal into the core alloy can take place, primarily along the grain boundaries. Consequently, the melting point of the affected area is lowered due the increasing silicon concentration and local melting of the core material can occur.

Dissolution of the core alloy must be minimised, because the reduction of the core thickness affects the strength and corrosion resistance of the product. It can even lead to a perforation of the core alloy. The extent of core dissolution is increased by:

- higher silicon levels in the clad,
- longer than recommended braze cycles,
- excessive peak brazing temperatures,
- excessive thickness of the clad alloy, and
- a design which allows pooling of the braze metal.

The most common factors leading to excessive core dissolution are linked to the processing conditions. Brazing beyond the recommended maximum peak temperature and/or extensive dwelling at brazing temperature are the primary causes.



Local dissolution of the core alloy caused by silicon diffusion from the molten filler alloy

6.2.2 Brazing filler metals

All of the commercially available filler metals suitable for aluminium brazing are based on the Al-Si eutectic system with the eutectic point at 12.6 wt% Si. Al-Si alloys are specifically used for brazing of aluminium components to minimise the risk of galvanic corrosion.

For all Al-Si brazing filler alloys, the solidus or the point at which melting begins is 577°C. However, for non-eutectic compositions, melting occurs over a temperature range. Between the solidus and liquidus temperature, the filler metal is partially molten, existing as both solid and liquid. Before the filler metal starts to flow, more than 60% of the material must melt, i.e. there is a minimum (threshold) temperature for each filler metal alloy in the brazing process.

Various brazing filler metals are used in industrial practice. Typical commercial filler metals contain from 6.8% to 13% Si:

• EN AW-4343 (6.8 to 8.2% Si)

This alloy (melting range: 577 to 605°C) has the lowest Si content and consequently the longest freezing range. It is the least fluid of the filler alloys and the least aggressive at dissolving the core alloy.

- EN AW-4045 (9.0 to 11.0% Si) This alloy (melting range: 577 to 590°C) is the most common of the filler alloys. Its properties are between EN AW-4343 and EN AW-4047.
- EN AW-4047 (11.0 to 13.0% Si)

This alloy (melting range: 577 to 580°C) has the highest fluidity because of its extremely narrow melting range (eutectic composition). EN AW-4047 flows rapidly on melting and is the most aggressive at dissolving the core alloy. Because of these properties, it is not used as a cladding alloy, but rather as filler wire in flame and induction brazing applications where these properties are in fact desirable.

Typical brazing filler alloys for CAB brazing are EN AW-4045 and EN AW-4343. For vacuum brazing, modified versions with up to 0.5% Mg (e.g. EN AW-4046 or EN AW-4747) are used.

The usual method of applying filler metal is to use a brazing sheet which consists of a core of aluminium clad with the lower melting filler metal. The cladding may be applied to one or both sides of the core sheet, usually making up 5% to 10% of the total thickness of the brazing sheet. The filler metal melts and flows during the brazing process, providing upon cooling a metallic bond between the components. However, filler metals can be supplied in the form of powder, paste, and wire or thin-gauge shim stock and are either face-fed or pre-placed in the joint area. For these product forms of the brazing filler metal, wetting and metal flow phenomena may be quite different in detail. The following discussion, however, refers generally to the application of clad brazing sheets.

Additions of Ti and Cu to braze filler alloys and alloy cladding can improve the overall joint properties without significantly altering the brazing characteristics. Ti increases the corrosion resistance of the brazing alloy on clad materials, while Cu (and Mn) can provide electrochemical corrosion protection and increase strength in critical areas. Furthermore, elements such as Zn, Sn and In may be added to specific areas of an assembly, designed to act as a local sacrificial anode.

Improvements in corrosion resistance centre around the use of Zn or Zn alloy coatings and their application routes. Alloys principally containing Cu and Ni additions (plus Zn) have also been developed for flux-less inert gas brazing down to 520°C.

Recent developments for filler metal alloys focus on the control of fluidity and flow pattern. By adding specific trace quantities of alloying elements (e.g. Na or Li), brazing characteristics may improve. These effects appear to be related to a reduced surface tension.

There are also several suggestions for brazing technologies where the filler metal is generated during the brazing cycle from a coating layer on an aluminium sheet or on extruded material ("clad-less brazing"). One method involves a flux mixture which also contains silicon powder, the NOCOLOK[®] Sil Flux process. At brazing temperature, the elemental silicon reacts with aluminum to melt in a eutectic reaction. Sil flux can be applied with a binder to specific component surfaces, e.g. extruded tubes. In this case, the filler metal would be supplied from the tube and a clad fin sheet is not necessary. In the Composite Deposition technology (CD process), the filler metal for joint formation is derived from a composite powder, a compound consisting of potassium fluoroaluminate flux and an Al-Si alloy. The CD

powder is selectively "deposited" on the heat exchanger components prior to assembly and brazing.

6.2.3 Joint design and assembly

In order to enable a most effective capillary action, a suitable clearance between the base metals is necessary. This means that in almost all cases, close geometrical tolerances have to be guaranteed for the single components as well as for the fixed mechanical pre-assembly.

There are basically two types of joint designs used in brazing: butt joints and lap joints. All other joint designs are modifications of these two. Lap joints increase the joint strength by providing additional brazed surface area and section thickness. They are easily fabricated and require minimal or no fixing before brazing. Butt joints are not as strong as lap joints, it should always be assumed that a brazed butt joint will be weaker than the base metal. A variation of the butt joint known as a "scarf" joint (where the two members have tapered ends which lap together) adds strength, but is more problematic to prepare and fixture. Another variation combines the advantages of both joints and is referred to as a "butt-lap" joint.

In butt joint design, the ends of the two metal pieces are butted-up against each other. Then, the brazing filler metal (BFM) is either pre-placed between the two parts prior to assembly, or applied along the top edge of the joint after the two parts are already butted together. When the assembly is brazed, the BFM will melt and flow into the braze-joint by capillary action.

Butt joints are usually used where strength requirements are not critical or where the use of a lap joint is not acceptable (e.g. thickness constraints). The main weakness of butt joints is the small braze area, which is limited to the cross-sectional area of the thinner of the two members being joined. Therefore, it is very important that joint edges are squared and parallel. Rounded edges can seriously reduce the effective braze area.



Brazed joint design

In lap joints, the two parts intended for brazing are simply laid on top of each, and the capillary spacing between the two pieces will comprise the braze joint. The joint strength of a brazed lap joint is a function of overlap distance and the thickness of the brazed joint itself. The reasonable amount of overlap is about three times the thickness of the thinner of the two members being joined. Any greater overlap does not contribute to joint strength, and a lower overlap might cause failure in the brazed joint rather than in the base metal. For good joint strength, the faying surfaces of the lap joint should be close and parallel to each other and not mismatched.

When brazing aluminium alloys, the set-up of the individual components with respect to alignment and particularly joint gap is very important. A gap between the two components to be joined is necessary to allow the molten flux to be drawn into the gap and clean and dissolve the oxides and to allow the filler metal to be drawn in freely and evenly. The size of the gap determines the strength of the capillary pull. Larger gap clearances reduce capillary action while smaller gaps may restrict filler metal flow causing discontinuities in the joint. As a guide, when torch brazing fluxed lap joints with more than 6 mm overlap, a joint clearance in

the range 0.25 mm or more is recommended. For shorter overlaps, clearance should be in the range 0.05 - 0.2 mm. For dip and vacuum brazing, gap widths of 0.05 - 0.1 mm are common. In controlled atmosphere brazing, gap clearances of 0.10 mm to 0.15 mm are recommended for non-clad components. Friction fits must be avoided with non-clad components. For clad components, the clearance is provided by the thickness of the cladding layer and so intimate contact (gap width < 0.05 mm) is recommended.

6.2.4 Cleaning before brazing

For the majority of brazed products, assembly is followed by cleaning and subsequently by flux application. However, when internal surfaces need to be fluxed, the production sequence may follow a different order, determined by when and how the flux is applied.

Brazing uses the principle of capillary action to distribute the molten filler metal between the surfaces of the base metals. Capillary action will work properly only when the metal surfaces are clean. The purpose of cleaning is to remove fabricating oils and lubricants as well as other contaminants (dust and dirt, condensates, etc.). The cleaning procedure must allow for adequate flux retention and render the surfaces suitable for brazing. The effectiveness of the cleaning step has a great influence on the brazing quality, the post-braze product appearance and corrosion performance.

Two techniques are used to clean the components of residual oil and grease:

a) Aqueous cleaning

Aqueous or water based cleaning is an efficient and robust process, but generates some waste water. The cleaning solution usually contains a mixture of surfactants, detergents and alkaline ingredients such as carbonates that serves to elevate the pH. The cleaning solution works best at elevated temperatures, i.e. 50 °C to 80 °C. Cleaning takes place in a series of steps starting by dipping or spraying with the hot cleaning solution followed by a series of hot and cold water rinses.

The slightly alkaline cleaning solution has a mild etching action on the aluminium surfaces which causes the aluminium surface to be wettable. This means that the flux slurry will uniformly coat the work piece without the addition of a wetting agent.

b) Thermal Degreasing

Thermal degreasing works by elevating the temperature of the work piece so that lubricants present on the surfaces will be evaporated. This procedure only works with special types of lubricants known as evaporative or vanishing oils. These lubricants vaporise when heated to 150 - 250 °C. Lubricants not designed for thermal degreasing must not be used. They could leave behind thermal decomposition products and carbonaceous residues which – at higher level – prevent proper brazing and have the potential to degrade product appearance and accelerate corrosion.

However, thermal degreasing leaves the aluminium surface non-wettable, i.e. the flux slurry requires the addition of a surfactant (wetting agent) to lower the surface tension of the water, thus ensuring more uniform flux distribution.

6.2.5 Pre-assembly of the parts

Once the individual parts are cleaned and assembled, they are usually secured in brazing fixtures. Because the yield strength of aluminium alloys decreases rapidly at elevated temperatures, it is often necessary to provide support for components which otherwise could distort under their own weight at the high temperatures necessary for brazing. The brazing fixtures hold the parts together and keep them aligned during the brazing process in order to maintain joint gaps, joint alignment, flow passage alignment, and overall assembly tolerances. Fixtures may also be used to support attachments such as inlet or outlet tubes.

The materials used for the fixtures must be carefully chosen, keeping in mind the different coefficients of expansion of the involved materials. Low thermal mass fixtures reduce the brazing cycle time. Also heat transfer to the fixtures should be minimised to ensure uniform heating. Fixture design is very part dependent and an integral part of the manufacturing process.

6.2.6 Brazing fluxes

A most critical aspect is the penetration/removal of the oxide layer. All aluminium surfaces show a thin, but dense and stable oxide layer with a thickness of 2 to 10 nm. The surface oxide layer prevents the filler metal from wetting the aluminium parts to be brazed. Thus the oxide layer has to be removed or broken up prior to the actual brazing step. In the presence of oxygen, however, this oxide layer rebuilds immediately after having been removed, i.e. any rebuilding process must be prevented as far as possible.



In aluminium brazing, flux must be used for every process variant except flux-less inert gas or vacuum brazing. Molten fluxes partially dissolve and remove the oxide layer from the metal surface. The metal surface is cleaned, leaving the surface ideally prepared for the filler alloy to join the metal work pieces. Fluxes also prevent re-oxidation by coating the surfaces to be joined. In addition, by lowering the surface tension, they promote wetting of the base aluminium alloy by the molten brazing filler metal.

The composition of brazing fluxes is selected to fit the specific brazing method. The flux should have a melting point approximately 20 - 50 °C below that of the filler metal and remain stable at least to temperatures 20 - 50 °C above the maximum brazing temperature. It should exhibit minimal reaction or gas evolution at the aluminium surface and should either be non-corrosive or easily removable after brazing. The aluminium brazing fluxes, several different mixtures of alkali, alkaline earth chlorides and fluorides are generally used. Fluoride is the most reactive agent, but its presence increases the flux melting point and therefore other additions, such as Sb, Cd, Cr, Co, Cu, Pb, Mn, Sn and Zn chlorides are often made to control the desired melting temperatures and activity. However, chloride-containing fluxes leave a hygroscopic corrosive surface on the work piece which must be thoroughly cleaned after brazing. The first post-braze cleaning step is immersion of the part into boiling water. Since chloride fluxes are highly soluble in water, this will remove most of the residual flux. Subsequently, an appropriate chemical solution is used. The brazed assembly is then thoroughly rinsed in cold or hot water.

Consequently, fluoride-based fluxes primarily composed of K-AI-F without chlorides are today preferred. The best known chloride-free flux is Nocolok[®]. Provided that fluoride-based fluxes do not experience an ionising environment, the flux residues are not corrosive and do not need to be cleaned off after brazing. On the other hand, fluoride fluxes require protection by inert gas (generally nitrogen) during brazing.Chloride-free fluoride fluxes do not have to be removed after brazing. In fact, it is generally accepted that the presence of flux residues on a heat exchanger enhances its corrosion resistance.

6.2.7 Flux application

An essential requirement for reliable brazing results is a uniform flux coating on all surfaces involved in the joint formation. Flux can be applied in different forms including flux paste, liquid, powder or pre-made brazing pastes that combine flux with filler metal powder. Flux can also be applied using brazing rods with a coating of flux or a flux core.

Brushing is an effective method of applying a thin film of brazing paste to the joint and to surrounding component surfaces. Brazing flux may be also applied by dipping one or more components of an assembly into a container of flux. This is most effective when using a paste of a thin consistency.

Two application techniques are generally used for larger series production:

a) Wet flux application

Spraying an aqueous suspension is the most common flux application method for controlled atmosphere brazing. All aluminium surfaces are coated with the slurry, resulting in a uniform flux layer. Excess flux slurry is removed with a high-volume air blow; the excess is then collected, recycled and reused.



Wet flux application (schematic)

(Source: Solvay)

Constantly agitated flux slurries with concentrations of approximately 10 - 35 % solids are pumped from tanks to fluxing booths. The relatively plain header surfaces generally hold less flux slurry. Most fluxing stations are therefore designed with two flux slurry concentrations to ensure sufficient coverage in the header area by applying a 10 to 15% higher slurry concentration.

Capillary effects throughout the unit can result in a non-uniform flux distribution. Flux slurry tends to be held in fin/ tube joints, fin louvers, etc. Slurry also collects on the bottom surface in those areas that do not see direct air impingement. Excess flux slurry can be blown off from the bottom and side surfaces by installing a second overhead blow-off system or additional air knifes for cutting off droplets.

In practice, the recommended loading for fluxing is 5 g/m², uniformly distributed on all active brazing surfaces. Too little flux will result in poor filler metal flow, lower joint quality, higher reject rates and inconsistent brazing. Too much flux will not affect the brazing results. However, the excess flux is wasted and will increases process cost; it may also contaminate the system as well as the final product.

Work pieces entering the brazing furnace must be completely dry from water introduced via aqueous cleaning or flux slurry coating. Therefore, the pre-assembled components must be dried after wet fluxing prior to brazing in a separate oven. However, the surface temperature of the parts in the drier should not exceed 250 °C in order to avoid formation of high temperature oxides which will affect clad fluidity. At higher temperatures (about 300 °C), the oxide layer thickness increases drastically with temperature and time at temperature, particularly in the presence of moisture.

b) Electrostatic flux application

Electrostatic fluxing, also known as dry fluxing, is increasingly used as an alternative fluxing practice. In dry fluxing, the flux is electrostatically charged and applied to a grounded work piece. The electrostatic attraction results in the deposition of a layer of flux on the work piece. A typical flux application system consists of a powder feed system, the electrostatic spray gun, the gun control unit, the grounded work piece and finally the flux recovery system.

The advantages of such a system over conventional wet fluxing are obvious. There is no need to prepare flux slurries and no wastewater is generated. In addition, the dehydration

section of the furnace may be eliminated. However, flux adhesion is not as good compared to wet fluxing. The flux also tends to accumulate on the leading edges of the components and it is difficult to coat "hidden" areas (e.g. corners or tubes).

Dry fluxing is most interesting when used in combination with thermal degreasing. In this case, it is possible to completely eliminate or significantly reduce water consumption in the process.

There are also further possibilities for flux application techniques, e.g.:

Flux painting

The use of a flux paint (flux + carrier + binder) allows to pre-flux certain heat exchanger components and is helpful when fluxing of internal components is necessary. There are also different process variations possible depending on whether all heat exchanger components are pre-fluxed or whether only some components are pre-fluxed and conventional fluxing is used on the fin pack, etc.

Flux application with a binder system allows coating of specific surface areas with a precise flux amount. It also reduces flux drop-off during assembly. Binders used for pre-fluxing must evaporate during the process without interfering with the brazing performance or leaving any contamination on the surfaces.

Flux pre-coated brazing sheet

The concept of a brazing sheet which is supplied with a flux coating is very plausible. Such a material could significantly change the way heat exchangers are currently manufactured since the flux application step would be eliminated. The greatest challenge is the adherence of the flux to the metal surface throughout the forming process of the components. Uniform coverage and strong adhesion are equally important.

6.2.8 Brazing cycle

The main step in the brazing process is the brazing cycle itself. Because of its direct influence on the final product, the time-temperature cycle has to be carefully adjusted. Equally important are the furnace conditions, i.e. temperature profile, temperature uniformity, and atmospheric conditions.



Brazing time-temperature cycle (schematic)

Achieving an even brazing temperature distribution throughout the work pieces is a most important factor. Slow heating would ensure even temperature distribution. On the other hand, diffusion processes are facilitated and too slow heating can dry out the flux, reducing its effectiveness. There must be sufficient molten flux present when the filler metal reaches its melting point. As a rule, the heating cycle should be as fast as possible to achieve stable temperature distribution. In industry, heating rates up to 45 °C/min in the range of ambient to 500 °C are not uncommon.

During heat up, there may be quite a variation in temperature across the pre-assembled product. However, it is essential to aim for temperature uniformity when approaching the

maximum brazing temperature and this becomes increasingly more difficult with fast heating rates. At brazing temperature, it is recommended that the variation should not exceed \pm 5 °C. This can be difficult when larger units are processed which have differing mass areas within the product.

The brazed product should not remain at the maximum brazing temperature for any longer than 3 to 5 minutes. The reason is that filler metal erosion begins to take place as soon as the filler metal becomes molten. The longer the filler metal remains molten, the more severe the erosion is. Severe dissolution of the core metal is also caused by excessive brazing peak temperature. Consequently, the brazed products should also be cooled in a controlled manner.



Good and bad brazed joints in an aluminium radiator

6.3 Soldering

The term "soldering" actually describes a brazing operation using a molten filler metal with a melting temperature below 450 °C. On cooling, a metallurgical joint between the two parent metals is formed. The mechanical characteristics of the joint are reasonably good and thus soldering can be used for example for structural repairs.

Aluminium soldering is not difficult, but shows a number of critical areas that need tight process control. The tenacious aluminium oxide surface layer makes most attempts to solder using conventional means difficult. In addition, care must be taken regarding alloy choice due to possible galvanic corrosion effects as a result of the significant differences between the electrochemical potential of aluminium and that of many conventional solders. The varieties of aluminium alloys, gauges, and tempers often display widely varying soldering results, and the heating procedure during soldering must be carefully optimised for each individual job.



Repair soldering of a hole in an aluminium pipe

6.3.1 Soldering alloys

Soldering of aluminium components can be done with either soft solders (usually tin-based alloys with lower melting temperatures) or hard solders (zinc-based with higher melting temperatures) and with appropriate fluxes to fit processing temperature ranges. In the past, also lead- and cadmium-based soft solders have been used. However, with the anticipated worldwide ban on lead for environmental reasons, most industries have already or are switching to lead-free solders. Cadmium-bearing solders have been effectively banned due to worker health issues. This eliminated some of the more ductile and/or higher-temperature soft solders which were used in the past for aluminium soldering. Furthermore, any solder that contains tin may cause electrochemical corrosion problems due to its galvanic potential.

A eutectic formulation has advantages when applied to soldering: there is no plastic phase and it has the lowest possible melting point. Having the lowest possible melting point minimizes heat stress during soldering and having no plastic phase allows for quicker wetting as the solder heats up, and quicker setup as the solder cools. A non-eutectic solder formulation should remain immobile as the temperature drops through the liquidus and solidus temperatures. Any movement during the plastic phase may lead to the formation of cracks, resulting in an unreliable joint. Unfortunately, most lead-free solders are not eutectic formulations, making it more difficult to create reliable joints.

Specifically developed tin-zinc alloys for soldering aluminium to aluminium and /or copper parts with good strength and corrosion resistance include:

- 91 % Sn / 9 % Zn (KappAloy9[™]), eutectic alloy with a melting point at 199 °C
- 85 % Sn / 15 % Zn (KappAloy15[™]), melting range between 199 and 260 °C.

The eutectic solder is used extensively in furnace soldering and other automated soldering systems. It minimizes the heat applied to delicate parts by melting and solidifying quickly and evenly at 199 °C. In hand soldering, the KappAloy15[™] gives more flexibility. The slushy temperature range allows a manipulation of the parts before the solder solidifies completely during cooling. Also used are the solders:

- 80 % Sn / 20 % Zn with a melting range between 199 and 288 °C
- 70 % Sn / 30 % Zn with a melting range between 199 and 316 °C
- 60 % Sn / 40 % Zn with a melting range between 199 and 343 °C.

The higher Zn content improves in particular the wetting behaviour, but the liquidus temperature increases significantly with increasing Zn content.

The other important family of aluminium solder alloys ("hard solders") can be found in the zinc-rich corner. These solders offer excellent wettability of aluminium, good strength and corrosion resistance. Typical hard solder compositions are:

- 100 % Zn (pure Zn with a melting point of 419 °C)
- 95 % Zn / 5 % Sn (melting at about 382 °C)
- 70 % Zn / 30 % Sn (melting range 199 to 376 °C)
- 60 % Zn / 40 % Sn (melting range 199 to 341 °C).

Also used are zinc-rich Zn-Al solders, e.g. the alloy 95 % Zn - 5 % Al which melts at about 382 °C. Other alloys in the Zn/Al family include 98Zn/2Al, 90Zn/10Al, and 85Zn/15Al.

Recently, solder compositions in the Sn-Ag-Ti system have also been developed for low temperature (250-480 °C) flux-less soldering of aluminium and aluminium alloys.

6.3.2 Solderable aluminium alloys

Various aluminium alloys show different solderability: alloys from the systems EN AW-1xxx, 2xxx, 3xxx, 4xxx, and 7xxx are easier to solder than the 6xxx series alloys. Due to their magnesium content, EN AW-5xxx series alloys are most difficult to solder. The magnesium oxide rebuilds very quickly and does not allow solder wetting to take place.

In special cases, an aluminium alloy can be clad with a more solderable alloy, plated with nickel, or coated with zinc for improved soldering performance. Soldering aluminium to other metals (steel, galvanized steel, stainless steel, copper, brass, etc.) can also be done, but with some difficulty, since the joint design must allow for differential thermal expansion and many fluxes do not work for both metals. In addition, heating of the assembly at the joint area may become difficult since aluminium conducts heat away from the joint very rapidly compared to most other metals.

Soft solders do not pose much of a risk to the base materials, provided the parts are not held at soldering temperatures for an extended period of time. However, in some cases, exposure of aluminium to a molten zinc alloy (hard soldering), even for a short time period, may result in the diffusion of zinc atoms into the base metal. This may change the local material characteristics and cause for example heat cracks that emanate beyond the heat affected zone.

6.3.3 Soldering process

Soldering aluminium requires special solders and processing to achieve a solid bond. Breaking the oxide coating by agitation and fluxing is essential for successful soldering. It is important to follow these steps in a timely uninterrupted sequence. Otherwise, the strong oxide coating can rebuild and hinder the solder bond.

By definition, soldering is a low-temperature joining process. Typical soldering temperatures are between 225 and 450 °C. Therefore, less heat distortion of the aluminium component can be expected by soldering than by brazing, welding, or other fusion joining processes. Residual internal stresses in the aluminium work piece from preceding operations, however, can be changed by the heating encountered during soldering, and distortion may result. Therefore, preheating of the components, non-continuous joints, and careful selection of joint geometry may become critical success factors

Aluminium soldering methods generally involve mechanical rubbing with active solders, ultrasonic bath soldering, thermal spray soldering (no use of fluxes) and heating the assembly e.g. by a propane torch, infrared light, laser or within a furnace (all of which usually involve the use of fluxes). Furthermore, it requires an adequate volume of heat on the component and not on the solder. This allows the substrate to transfer heat to the solder and proper melting of the solder.

Temperature
too lowTemperature
correctTemperature
too highSolder does
not flowSolder flows
and bondsSolder becomes
brittle/burns

Temperature control, a most important quality criteria

Fluxes are used for removal of the oxide layer, to prevent re-oxidation and to facilitate wetting the aluminium. Removal of aluminium oxide requires strong fluxes such as organic aminebased fluxes (up to 285 °C) or inorganic fluxes (chloride or fluoride up to 450 °C). The residues of some soft soldering fluxes may be still active after soldering and must be removed.

The soldered joint is only as strong as the solder material. The surface of the solder seam is smooth and clean, forming a nicely curved transition to the work piece. In general, solder seams do not require finishing.

Soldering of aluminium has never been considered as a mainstream process for the automotive industry although it could be a very attractive joining method with little heat distortion due to the lower process temperature compared to brazing and fusion welding. Soldering requires adequate heat on the component. Because of the high thermal conductivity and reflectivity of aluminium, it has been found that neither soldering with an oxy-acetylene flame torch, plasma arc, laser, induction heater, nor thermal spray is capable of providing good results. Preliminary tests with a high density infrared source (300kW plasma lamp) have shown that proper joints can be produced for EN AW-6xxx alloys using an 80 % Zn - 20 % Al solder with flux at a soldering temperature of 490 °C. Mechanical tests showed that the joint area is stronger than the parent material with minimum softening. However, further optimization would be necessary before introduction into series production.

EAA Aluminium Automotive Manual – Joining

7. Solid state welding

Content:

7. Solid state welding

7.0 Introduction

7.1 Friction welding

7.1.1 Friction welding of components

7.1.1.1 Rotational friction welding

7.1.1.2 Linear friction welding 7.1.1.3 Orbital and multi-orbital friction welding

7.1.2 Linear friction stir welding

7.1.2.1 The linear friction stir welding process

- 7.1.2.2 Application of linear friction stir welding
- 7.1.2.3 Variants of the linear friction stir welding technique

7.1.3 Friction stir spot welding

7.1.3.1 The friction stir spot welding technique 7.1.3.2 Further developments of the friction stir spot welding technique

7.1.4 Friction stud welding

7.1.5 Friction element welding

7.2 Pressure welding processes

7.2.1 Contact and cold pressure welding

- 7.2.2 Diffusion and hot pressure welding
- 7.2.3 Explosion welding
- 7.2.4 Electromagnetic pulse welding
- 7.2.5 Roll bonding
- 7.2.6 Co-extrusion welding

7.3 Ultrasonic welding
7.0 Introduction

Solid-state welding describes a group of joining techniques which produces coalescence at temperatures below the melting point of the parent materials without the addition of third material. External pressure and relative movement may or may not be used to enhance the joining process. This group of joining techniques includes e.g. friction (stir) welding, cold pressure welding, diffusion welding, explosion welding, electromagnetic pulse welding, , and ultrasonic welding. In all of these joining methods, proper control of the process parameters (time, temperature, and pressure individually or in combination) results in the coalescence of the parent materials without melting or only negligible melting at the interface. Technically, solid-state welding methods are not welding processes in the traditional sense since the materials do not reach their melting point, but can be rather compared with the traditional forging techniques.

Solid-state welding offers specific advantages since the base metal does not (or only marginally) melt and re-solidify. The parent metals essentially retain their original properties; heat-affected zone problems - which generally develop when there is base metal melting - are significantly diminished. Also the formation of intermetallic phases at the interface which can be brittle and may yield corrosion concerns is largely eliminated or minimized. Furthermore, when dissimilar metals are joined, their thermal expansion and conductivity characteristics have much less influence on the resulting joint performance than with fusion welding processes.

7.1 Friction welding

The term "friction welding" covers solid-state welding processes which lead to the coalescence of materials under the influence of the heat generated by the mechanically-induced sliding motion between rubbing surfaces. The parts to be joined are held together under pressure. Mechanical friction may be produced between a moving work piece and a stationary component, two moving components or using a moving tool.

Friction welding techniques are generally melt-free; the base materials are kept below their melting or liquidus temperatures. The frictional heat creates a plastic zone ("softens the interface") between the parts to be joined. The applied external force presses the parts together and thus creates a joint. The combination of short processing times and the development of the heat directly at the interface results in fairly narrow heat-affected zones, also caused by upsetting a portion of the interface out of the weld joint during the process. The minimal width of the heat-affected zone means that, in general, there is no need for heat treating the parts before or after joining to relieve internal stresses. Also problems like local cracking or reduced corrosion resistance in the heat-affected zone can be avoided or reduced. No filler metal or flux is used.

Another benefit is that the motion tends to "clean" the surface between the parent materials. Full-strength welds require proper boundary-layer bonding, so there can be no contamination in the interface plane. Since friction welding works by displacing the original interface materials, the parts being joined only require minimum surface cleaning or pre-treatment.

Friction welding offers the possibility to produce high quality joints with short cycle times and no additional joining elements (i.e. no additional weight and cost). An important advantage of friction welding is that it allows joining of aluminium alloys that are considered to be not fusion weldable (i.e. various EN AW-2xxx and 7xxx alloys) and of dissimilar material combinations. The strength of a friction welded joint depends on the specific joining conditions, but typically approaches that of the weaker of the two parent materials (joint efficiency ranges between 70 and 90 %). Examples of friction welded joints between dissimilar materials include combinations of aluminium/steel, aluminium/copper or aluminium/ceramic, etc.

There are different variants of friction welding techniques, but all are based on the same basic principle.

7.1.1 Friction welding of components

Net-shaped or nearly net-shaped parts can be directly joined by friction welding. The methods used in practice mainly differ in the type of the reciprocal movement of the two work pieces.

Depending on the symmetry of the individual components and the envisaged joint quality, different movement patterns are used. Consequently, the complexity of the necessary machinery can vary significantly, a fact which influences both the quality of the resulting joint as well as the productivity and the cost of the joining process.

7.1.1.1 Rotational friction welding

The rotational (or spin) friction process involves rotating one part against a stationary component to generate frictional heat at the interface. When a sufficiently high temperature has been reached, the rotational motion ceases and additional pressure is applied ("forging phase") and coalescence occurs.











Rotational friction welding process

(Source: KUKA)

There are two variants of the rotational friction welding process. In the first ("direct-drive") variant, the rotating part is driven by a motor which maintains constant rotational speed. The two parts are brought in contact under a defined pressure for a specified period of time. The rotating power is then disengaged and the pressure is increased. When the rotating piece stops, the joining process is completed. This process can be accurately controlled when speed, pressure, and time are properly selected. The other variant (also called inertia welding) includes a flywheel which rotates one of the pieces to be welded. After the flywheel has reached a pre-set speed, the motor is disengaged and the parts are forced together under pressure. The force is kept on the pieces while the flywheel comes to a stop and additional pressure is provided to complete the weld. Both methods produce welds of similar guality, however, slightly better control is claimed with the direct-drive process.

Rotational friction welding is a short-cycle process which can be easily automated, but requires relatively expensive machines. There are three important factors involved in the production of a high quality friction weld:

- 1. The **rotational speed** which is related to the material to be welded and the diameter of the weld at the interface.
- 2. The **pressure** between the two parts to be welded: At the start, the pressure is generally low, but it is gradually increased to create the frictional heat. When the rotation is stopped, pressure is rapidly increased so that coalescence takes place immediately before or after rotation is stopped.
- 3. The **welding time**: Welding time (normally few seconds) which depends on the geometrical shape of the parts and the type of materials to be joined as well as the interface area.

For rotational friction welding, at least one of the parts to be welded should be rotationally symmetrical. But depending on the specific situation, exceptions are possible. The heat, along with the perpendicular force applied to the interface, leads to the deformation and

plasticisation of the material at the interface. Much of the plasticised material is removed from the joint interface into a welding bead, due to the combined action of the applied force and movement. Along with the plasticised material, surface oxides and other impurities are also removed; allowing metal-to-metal contact between parts and the formation of a solid joint. A visual inspection of weld quality can be done based on the shape of the bead formed around the outside perimeter of the weld. Optimally, the bead should extend beyond the outside diameter of the parts and slightly curl back toward the parts. As a final operation, the bead the bead may be removed by machining depending upon the service requirements of the joint.



Components produced by rotational friction welding: Aluminium shock absorber (left), aluminium/steel drive shaft (centre) and aluminium/copper cable end piece (right)

(Photos: KUKA)

Parts to be joined by rotational friction welding must have a sufficiently high strength to be able to transmit the axial pressure and frictional moment as well as a sufficient hot forming capacity. Normally, the material data alone are not sufficient to indicate whether friction welding can be successfully employed. In addition, there is no straightforward correlation between the strength of the base materials and the strength of friction welded joints. Thus in general, optimum joining procedures have to be determined experimentally. Under unfavourable conditions, frictional welded joints between dissimilar materials may exhibit brittle fracture with little plastic strain at the joining plane.

7.1.1.2 Linear friction welding

Linear friction welding is similar to rotational friction welding except that the moving part oscillates laterally instead of rotating. It is also a high-quality joining process that creates a solid phase bond with parent metal properties.



4.1 Operating principle of linear friction welding

(Source: GKN Aerospace)

One of the parts to be joined is firmly clamped in place while the other is linearly oscillated through a small amplitude. When the work pieces are pressed together by applying a pre-set force, the frictional heat produced at the interface heats both materials to hot forming temperatures. Then the moving part is brought into alignment with the stationary part and the axial load is maintained or increased to finalise the joining process. The weld bead formed in the joint region is subsequently removed by milling.

Linear friction welding is most suited to rectangular and irregular cross-sections and is used in complex parts with a number of weld sites and multiple parts. However, it requires even more complex machinery than rotational friction welding. Also rotary friction welding can weld much larger cross sections. The high equipment and tooling cost is a major disadvantage. Thus, in the automotive industry, no application of linear friction welding is currently known.

7.1.1.3 Orbital and multi-orbital friction welding

In orbital friction welding, parts do not have to be more or less rotationally symmetric. In this case, the friction heat is the result of a relative movement of the joining parts by means of a circular vibratory motion of one or both parts. However, the parts do not rotate towards each other, i.e. the orientation of the axes remains the same. In orbital friction welding, only one of the components vibrates, whereas both vibrate in the case of multi-orbital friction welding. When the material-specific plasticizing temperature is reached, the orbital motion is stopped while both ends are pressed together, creating a high strength joint.

In contrast to rotational friction welding where the relative speed of a point on the surface depends on the diameter of the component, the speed in orbital friction welding only depends on the diameter of the orbit. Each point on the contact area moves at the same speed, resulting in a more efficient and more consistent energy input. Therefore, the joining performance is significantly improved for materials prone to internal stresses and stress cracks (e.g. ceramics) or for materials that are sensitive to temperature differences in the joining area. But also in this case, the limitations mentioned under linear friction welding apply. No automotive applications are known.



Operating principle of orbital friction welding (Source: TWI)

7.1.2 Linear friction stir welding

Friction stir welding is a solid-state joining process that uses a third body ("tool") to produce the friction welded joint. Friction stir welding also employs frictional heat to plasticize the material, however, material consolidation significantly differs from the friction welding methods described above. It creates high-quality, high-strength joints with low distortion. Seam welds can be placed on either butt or overlapping joints, in a wide range of material types and thicknesses. Friction stir welding was invented by Wayne Thomas at TWI Ltd in 1991 and overcomes many of the problems associated with the traditional joining techniques.

It is a joining process which is particularly suited for aluminium alloys. Consequently, this joining method has gained significant interest within the automotive industry.

7.1.2.1 The linear friction stir welding process

In friction stir welding, a cylindrical shouldered tool with a profiled pin is rotated and plunged into the joint area between the two work pieces. The parts are securely clamped in a fixed position to prevent the joint faces from being forced apart. The heat generated by the constantly rotating, wear resistant tool "softens" the material near the friction stir welding tool, allowing the tool to traverse along the joint line. As the pin moves forward, a special profile on its leading face forces plasticized material to the trailing edge of the tool pin (or probe) and the two work pieces are essentially forged together by the clamping forces, assisted by the mechanical pressure applied by the tool shoulder and pin profile. The probe is slightly shorter than the required weld depth, with the tool shoulder riding atop the work surface. The surface of the finished weld is smooth and more or less flush with the surface of the parts. The top surface of the weld shows the characteristic wave-marks from the rotating friction stir welding tool.



Linear friction stir welding process

(Source: TWI / Sapa)



Cross section and top view of a friction stir welded joint

(Source: Sapa)

The relevant process parameters in friction stir welding are:

- Tool rotation speed and tool traverse speed

These two parameters govern the heat input during welding and must be carefully chosen to ensure a successful and efficient welding cycle. It is necessary that the material surrounding the rotating tool is hot enough to enable extensive plastic flow and minimize the forces acting on the tool. If the material around the tool is too cold, voids or other defects may develop in the stir zone and, in extreme cases, the tool may break.

On the other hand, excessive heat input may deteriorate the final properties of the joint and could result in defects due to the liquation of low-melting phases. The relationship between the tool rotation speed, the tool traverse speeds and the resulting heat input is complex, but generally said, a faster tool rotation speed or a slower traverse speed will lead to a higher weld temperature. Consequently, tool rotation and traverse speeds must be controlled within a properly defined processing window.

- Tool tilt and plunge depth

Tool tilt and plunge depth have found to be additional parameters for ensuring a good weld quality. Plunging the shoulder of the tool below the plate surface increases the pressure below the tool and helps to ensure adequate forging of the material at the rear of the tool. Depending on the tool type, slight tilting of the tool such that the rear of the tool is lower than the front proved to be also beneficial regarding the effectiveness of the forging process.

Tool design

The design of the tool is a critical factor as a good tool can improve both the quality of the weld and the maximum possible welding speed. Optimising tool geometry to produce more heat or achieve more efficient "stirring" offers two main benefits: improved breaking and mixing of the oxide layer and more efficient heat generation (i.e. higher welding speed and enhanced quality).



Some basic tool shapes for friction stir welding

(Source: TWI)

The tool material must be sufficiently strong, tough, and wear-resistant at the required processing temperature. It should also have a good oxidation resistance and a low thermal conductivity to minimise heat loss and thermal damage to the machinery further up the drive train. The combination of tool and base material is therefore crucial for the operational lifetime of the tool. Hot-worked tool steels are perfectly acceptable for joining aluminium alloys, but more advanced tool materials are necessary for more demanding applications. Advanced tool designs have enabled substantial improvements in productivity and quality. Specifically designed tools allowed to increase the penetration depth and thus the successful welding of parts with higher thickness.



Advanced friction stir welding tools developed by TWI

(Source: TWI)

During friction stir welding, different forces act on the tool:

- A downwards force maintains the position of the tool at or below the material surface. Some friction-stir welding machines are load-controlled, but the vertical position of the tool is generally preset and the load varies during welding.
- The traverse force acts parallel to the tool motion. This force is the result of the resistance of the material to the motion of the tool; it decreases when the material temperature around the tool increases.
- A lateral force may act perpendicular to the tool traverse direction.
- Torque is required to rotate the tool, the amount of which will depend on the down force and friction coefficient and/or the flow strength of the material in the surrounding region.

In order to prevent tool fracture and to minimise tool wear, the welding cycle must be properly controlled so that the forces acting on the tool are as low as possible and abrupt changes are avoided.

The acting forces during friction stir welding are significant, and proper fixture design is critical to the success of the joining process. The main purpose is to hold the work pieces in position and to avoid geometrical deformations of the structure during friction stir welding. Also important is a good stability during the process since any deflection or major vibration may affect the weld quality. The required fixture depends on the specific application, a sufficiently rigid construction requires only proper clamping whereas for sheet assemblies, the applied

fixtures may range from simple backing bars to specifically designed tools. The fixture design needs to take into account also potential temperature effects.

The heat generated in the joint area rises the local material temperature to about 80-90 % of its melting temperature. There are two main heat sources: the friction of the material(s) to be joined at the tool surface and the deformation of the material around the tool. Heat is predominantly produced under the tool shoulder. Heat flow and thermal profile differ during the welding cycle. In the beginning, the material is preheated by a stationary, rotating tool until the material temperature ahead of the tool allows the tool to move forward. This phase also includes the plunge of the tool into the work piece. When the tool begins to move, there is a transient period where the heat production and temperature around the tool will alter in a complex manner until essentially a steady-state situation is reached. Although fluctuations in heat generation may occur in the steady-state phase, the thermal field around the tool remains effectively constant, at least on the macroscopic scale. Only near the end of the weld, the resulting heat flow may "reflect" from the end of the plate and lead to additional heating around the tool.

The specific nature of the friction stir welding process produces in a highly characteristic microstructure:

- In the stir zone, the tool which traverses along the weld line in a plasticized tubular shaft leads to a severe deformation of the base material followed by dynamic recrystallization. The resulting grain structure is roughly equiaxed and the grain size is often an order of magnitude smaller than the grains in the parent material.
- The flow arm zone is on the upper surface of the weld and consists of material that is dragged by the tool shoulder from the retreating side of the weld, around the rear of the tool, and deposited on the advancing side.
- The thermo-mechanically affected zone is present on either side of the stir zone. In this region, the strain and temperature are lower and the effect on the microstructure is correspondingly smaller. Consequently, the microstructure of the parent material is still recognizable, but significantly deformed and rotated.
- The adjoining heat-affected zone is subjected to a thermal cycle, but is not deformed during welding. Nevertheless, the effect on the mechanical properties of aluminium alloys may be significantly.



Microstructure of a friction stir welded aluminium joint

(Source: Sapa)

7.1.2.2 Application of linear friction stir welding

In terms of materials, the focus of friction stir welding has traditionally been on non-ferrous alloys. It is almost an ideal technology to join aluminium components (sheets, extrusions and castings); without using filler wire or shielding gas. Material thicknesses ranging from 0.5 to 65 mm can be welded from one side at full penetration, without porosity or internal voids.

Recent advances have challenged this assumption, enabling friction stir welding to be applied to a broader range of materials. The technology has proven to be able to successfully join numerous metals and alloys, including high-strength steels, stainless steel and titanium. A

further expansion of the application range can be expected in the future based on improvements of the existing methods and tool materials as well as new technological developments.

To assure high repeatability and joint quality, proper friction stir welding equipment is necessary. Most simple welds can be performed with a conventional CNC machine, but for more demanding applications, purpose-built equipment becomes essential. The relevant process parameters are purely mechanical (force, friction, and rotation). The most important control feature is the down force which guarantees high quality even where dimensional tolerances of the work pieces are relatively large. It enables robust process control as the down force ensures the generation of sufficient frictional heat to soften the material. The other process parameters to be controlled are traverse speed, rotation speed of the welding tool and its tilting angle. With production machines, typical welding speeds for aluminium alloys are about 2000 mm/min (e.g. when joining extruded profiles with wall thicknesses of about 2 mm). With increasing material thickness, the maximum welding speed will decrease correspondingly.

The quality of a friction stir welded joint is generally superior to that of conventional fusionwelded joints:

- Higher strength (in particular also fatigue resistance)
- Homogeneous joint, entirely void-free and no disruptive oxide inclusions
- Joints are in principle flush with material surface
- Reduced thermal deformation, tight tolerances
- Improved repeatability (few process variables)
- Little (no) effect on corrosion resistance.

Mechanical (and corrosion) characteristics of the resulting joints depend on the specific material combination. As an example, when joining EN AW-6xxx alloys in the T6 temper, the tensile strength of the friction stir welded joint is >70 % of the base metal strength. Welding in the T4-temper condition followed by a post weld ageing could give >90 % of the base metal tensile strength in the weld. Due to the fine grained microstructure and smooth weld surface the fatigue properties are close to those of the base alloy.

The process can be applied to many joint designs. Butt and lap welds can be made even from materials with dissimilar thickness. Annular or circumferential joints can be produced by rotating the work piece underneath the friction stir welding machine, and CNC machines or robots are used for non-linear and three-dimensional joint lines.



Joint configuration for friction stir welding: (a) square butt, (b) edge butt, (c) T butt, (d) lap joint, (e) multiple lap joint, (f) T lap joint, (g) fillett joint

A limitation of the friction stir welding process is that the welding spindle must have access to all the joints to be welded. Other limitations include the effects observed at the start and end of the welds and the required fixtures and clamping.



Limitations of the linear friction stir welding process

The work pieces are usually clamped onto a backing bar and secured against the vertical, longitudinal and lateral forces, which will try to lift and push them apart. Normally a gap of up to 10 % of the sheet thickness can be tolerated before weld quality is impaired. In general, no specific surface preparation is necessary. However, depending on the actual surface condition, the application of a suitable part cleaning process may be considered (e.g. heavily lubricated components should be washed).

Most interesting possibilities are offered by the aluminium extrusion technology. Hollow profiles can be designed with internal backing by locating material or supporting legs in proper positions.



Joint design for friction stir welding of hollow profiles (top and right) and weld design of a plate cover to a cavity (left)

7.1.2.3 Variants of the linear friction stir welding technique

The systematic development of the friction stir welding technology has led to a number of process variants, covered by multiple patents. Development activities are on-going, thus further progress can be expected.

These process variants offer either improvements in quality, productivity or optimised performance for specific joining tasks. However, since the equipment cost for such single-purpose machines rises drastically, cost efficiency will have to be carefully examined in each application.

a) Twin-stir[™] welding techniques

The simultaneous use of two or more friction stir welding tools acting on a common work piece was evaluated using different configurations. An early concept involved a pair of contrarotating tools applied on opposite sides of the work piece. The simultaneous double-sided operation with combined weld passes reduces the reactive torque and results in a more symmetrical weld and heat input. The probes need not touch each other, but should be positioned sufficiently close that the softened material around the two probes overlaps to generate a full through-thickness weld. In order to avoid any problems associated with a zero velocity zone in mid-thickness, the probes can be displaced slightly along the direction of travel.



Simultaneous double-sided friction stir welding with contra-rotating tools (left) applied to a hollow extrusion (right)

(Source: TWI / Sapa)

Another approach used a preceding friction pre-heating tool which is followed in line by the actual friction stir welding tool. The "tandem" technique can be applied with both tools rotating in the same direction, but more interesting is the contra-rotating variant. The Twin-stirTM tandem contra-rotating variant can be applied to all conventional friction stir welded joints and will reduce reactive torque. This has benefits in terms of simplification of clamping and jigging for holding parts to be welded. More importantly, the tandem technique will improve the integrity of the weld by disruption and fragmentation of any residual oxide layer remaining within the first weld region by the following tool.



In-line contra-rotating tandem concept with the welding direction

(Source: TWI)

The Twin-stir[™] parallel contra-rotating variant enables the positioning of defects associated with lap welding between the two welds. Owing to the additional heat available, increased travel speed or lower rotation process parameters will be possible in parallel overlap welding.



Parallel side-by-side configuration transverse to the welding direction

(Source: TWI)

A further development of this method is the staggered tool arrangement. In this case, the tools are positioned with one in front and slightly to the side of the other so that the second probe partially overlaps the previous weld region. This means that an exceptionally wide weld region can be created. Residual oxides within the overlapping region of the two welds are fragmented and dispersed.

b) Bobbin stir welding

A disadvantage of the friction stir welding process is the need for a backing bar or advanced fixtures. The bobbin tool which enables double-sided welding eliminates this problem ("self-reacting friction stir welding") and avoids the risk of root defects. It consists of two shoulders, one on each side of the work piece to be joined. The two elements of the tool are connected with the pin, which runs through the material.



Bobbin friction stir welding

(Source: ESAB)

The bobbin technique provides a fixed gap between two shoulders, while the adaptive technique enables adjustment of the gap between the shoulders during the welding operation. The first variant offers a simple mechanical solution for the welding head since the fixed bobbin tool does not differ from a conventional tool at the tool interface. In contrast, the adaptive tool allows an independent control of the contact conditions for the two shoulders to compensate for variations in material thickness. Initiating a bobbin weld either involves first drilling a hole in the material in which the tool is inserted, or by employing a run-on preparation of the material. The end of the weld is normally welded through, leaving the exit un-bounded, for removal at a later stage.

The self-reacting principle of the bobbin technique means that the normal down force required by conventional friction stir welding is reduced; the reactive forces within the weld are contained between the bobbin shoulders. For certain applications, also bobbin tools that are driven from both ends are envisaged. The concept of a double driven bobbin also includes a double adaptive technique where both shoulders can be adjusted independently and a load can be applied from both ends.

c) Corner welding and dual-rotation friction stir welding technique

TWI also developed a technique called stationary shoulder friction stir welding mainly for welding low heat conductivity materials where a more uniform heat input into the weld is beneficial. It consists of a rotating pin located in a non-rotating shoulder component which slides over the surface of the material during welding.



Schematic of the corner welding technique applied to a T joint configuration

(Source: TWI)

This concept offers the potential to join plates which are positioned in different angular planes (e.g. T joints) by using a stationary shoulder shaped according to the internal corners of the specific weld configuration. The shaped shoulder contains the stirred material and slides over the surface of the material during welding.



Dual-rotation friction stir welding with rotation of the probe and shoulder in the same direction

(Source: TWI)

A further development of the stationary shoulder concept is the dual-rotation friction stir welding technology. The dual-rotation technique allows for a differential in speed and/or direction between the independently rotating probe and the rotating surrounding shoulder. It can be used, for example, to reduce the shoulder rotational speed as appropriate in order to reduce any tendency towards over-heating or melting, while maintaining a higher rotational speed for the probe. Thus it is possible to lower the welding temperature and minimise the thermal softening of the weld region of certain heat-treatable aluminium alloys.

d) Retractable pin friction stir welding

Friction stir welding has two major drawbacks. At the end of the weld, the single-piece pin tool is retracted and leaves a "keyhole" which is unacceptable when welding cylindrical objects such as drums, pipes and storage tanks. Another drawback is the requirement for different-length pin tools when welding materials of varying thickness.

At NASA's Marshall Space Flight Center, an automatic retractable pin tool was designed that uses a computer-controlled motor to automatically retract the pin into the shoulder of the tool at the end of the weld, preventing keyholes. This design allows the pin angle and length to be adjusted for changes in material thickness and results in a smooth hole closure at the end of the weld.



Retractable pin friction stir welding tools (Source: NASA Marshall Space Flight Center)

7.1.3 Friction stir spot welding

Recently, friction stir spot welding, a variant of linear friction stir welding technique (invented by Mazda Motor Corporation in 1993) has received considerable attention from the automotive industry. It shows great potential to be a replacement of single-point joining processes like resistance spot welding and riveting and further developments are ongoing.

7.1.3.1 The friction stir spot welding technique

Friction spot joining is similar to friction stir welding, although generally applied as an overlap sheet joining technology. Both techniques use a rotating tool with a specially designed pin and shoulder. However, whereas in linear friction stir welding, the tool traverses along a seam between two metal plates, the tool keeps to one spot in friction spot joining. The configuration and dimensions of the tool, especially the pin, vary depending on the material, the thickness of the sheets, and the strength requirements of the joint.



Friction stir spot welding process

(Source: Kawasaki Heavy Industries Ltd.)

The friction spot joining process consists of four steps. First, the tool is positioned perpendicular to the work surface and starts to rotate at a high angular speed. Then the tool is plunged into the work piece materials to be joined until the tool shoulder touches the surface of the top sheet. Friction heats the materials, and the pin enters the softened metal. After the pin has plunged completely into the work piece, the tool continues to spin and apply pressure for a set length of time. More heat is generated by friction and plastic deformation between the tool and materials as the locally softened material moves along the pin and the shoulder under the applied stress. This causes the formation of a strong

metallic bond between the sheets at temperatures below the melting point of the work piece materials. After a sufficiently long dwell time, the joining process is complete and the tool is retracted from the work piece materials. The entire process takes approximately two seconds. A backing bar prevents denting and ensures that the tool does not simply plunge straight through the sheets. The top side of the joint has a circular indentation (keyhole or exit hole) in the centre and a small ring-shaped projection along its outer edge. The surface that was pushed against the backing bar is unblemished. Because the process does not apply excessive heat, warpage of the sheets is minimal.

The key parameters of the process are the rotational speed of the tool, the axial force, and the duration of the force. The speed of the tool is usually kept constant. Once the pin contacts the work piece, the axial force rapidly increases. When it reaches a set point, the force is held constant. The speed at which the tool enters the sheets is fairly constant until the shoulder contacts the work surface. At that point, the plunging speed decreases and stops. All three variables can be monitored for quality control.

The depth to which the tool penetrates depends on the length of the pin, i.e. the sheet thickness cannot be changed without changing the tool. Thicker sheets require a longer pin. The pin is generally made of tool steel with tapered threads like a screw. When joining sheets of different thicknesses, the thicker sheet should be placed on the bottom.

Friction spot joining has been used on aluminium sheets ranging from 1 - 3 mm thickness. It is possible to weld thicker sheets, but the longer plunge time may become an issue. Although the technique was originally developed for aluminium, it can also be applied to other lightweight metals such as magnesium and for aluminium/steel joints. The possibility of using the friction stir spot welding technology to join high strength steels has also been demonstrated, but this application is more problematic due to the higher forces and processing temperatures.

A friction spot joining system includes two servomotors; one spins the joining tool and the other pushes the tool against the work piece. The joining tool is positioned opposite the backing bar, which is fixed to the end of a C-shaped frame. The joining system can be operated as a stand-alone pedestal machine or integrated with a six-axis robot.

Joint strength with friction spot joining is comparable to resistance welding (better than clinching, but less than self-piercing rivets). A disadvantage of this technique is the characteristic keyhole in the spot centre, which significantly decreases the mechanical properties of the joints.



Application of the friction stir spot welding technique (Source: Mazda)

7.1.3.2 Further developments of the friction stir spot welding technique

Several process variants have been proposed in order to eliminate the keyhole or increase the strength of friction stir spot welded joints.

The **refill friction stir spot welding process** developed by Helmholtz-Zentrum Geesthacht, Germany is used to join two or more sheets in the overlap configuration. The key element is a three-component tool comprising a pin, a sleeve and a clamping ring. The clamp holds the sheets firmly against a backing plate and also constrains the material flow during the process. In a first phase, the pin and sleeve begin to rotate in the same direction and simultaneously press onto the upper surface ("friction"). The pin and the sleeve then move in the opposite direction (i.e. one is plunged into the material while the other moves upwards), creating a cavity where the plasticised material is accommodated ("first extrusion"). After reaching the pre-set plunge depth, the pin and sleeve return to their initial position forcing the displaced material to completely refill the keyhole ("second extrusion"). Finally, the tool rotation is stopped and the tool is withdrawn from the joint leaving a flat surface with minimum material loss ("pull-out").



(Source: GKSS Forschungszentrum)



Refill friction stir spot welding machine

(Source: Harms+Wende)

The disadvantages of this process are the more complicated procedure, a relatively long dwell time and higher cost. However, the keyhole can be eliminated, and the weld strength and appearance is significantly improved.



Joint produced by the refill friction spot welding technique

(Source: Riftec Gmbh)

The **pin-less friction stir spot welding process** was invented by Tazokai et al. in 2009. It is a variant of the friction stir spot welding process where the tool has no pin, but includes a scroll groove on its shoulder surface. In thin aluminium sheets (~1 mm) where the deformation zone from the shoulder penetrates sufficiently into the bottom sheet, a pin-less tool provides excellent results because it contacts more uniformly across the tool surface. If either a steel or ceramic anvil is used (to reduce heat loss at the bottom face), welds can be produced which are as strong as those produced with an optimum pin length. Preliminary data have shown that this approach can be used to produce high-strength welds with a short dwell time.



Pin-less friction stir spot welding process

The **swing friction stir spot welding process** was developed by TWI. In this process, the tool moves along pre-set path after plunging. This process increases the actual area of weld and the strength of joints, while it cannot eliminate the keyhole.



Principle of swing friction stir spot welding

(Source: TWI)

A further variant of the friction stir spot welding process was proposed by Sun et al. in 2011. In the first step, a specially designed backplate containing a round dent is used for conventional friction stir spot welding. A keyhole is formed in the joint, along with a protuberance on the lower sheet due to the flow of materials into the dent. In the second step, a pinless tool and a flat backplate are employed to successfully remove both the keyhole and the protuberance.



Friction stir spot welding process

(Source: Science and Technology of Welding and Joining, vol. 16, no. 7, pp. 605–612, 2011)

7.1.4 Friction stud welding

In its simplest form, friction stud welding involves rotating a stud in the form of a solid rod and forcing it onto the surface of a work piece. Rotation and downward force create frictional heat which causes the materials to plasticise in the region of contact. Rotation of the stud is then stopped and the axial force either maintained or increased to consolidate the joint.

The weld time is very short, around four seconds for a 10 mm diameter stud. The weld quality is consistently high, and when tested to destruction, failure invariably occurs in the weaker parent material and well away from the weld. A number of material combinations can be joined using friction stud welding, in particular dissimilar metals. An important limitation of the friction stud welding process is that it can only be applied when the work pieces have different forging temperatures. In general, the optimum processing conditions have to be determined experimentally depending on the application. Practical tests may be also necessary to evaluate whether applying a high rotation speed can reduce the forging force.



Friction stud welding

(Source: TWI / IEV Group)

For welding small diameter studs to thin sheets, small portable friction stud welding machines are available, which can be operated either attached to a robot or hand held.

In some cases, a mechanical interlock between the stud and the work piece may be required. When dissimilar materials are joined, the friction plunge welding process can fulfil this requirement. A pin with a recessed area and a containment shoulder has to be machined from the harder material. This pin is then rotated until the plasticised material of the softer work piece is forged into this recess by the forces generated by the shoulder. The process offers significant technological benefits for safety-relevant parts.

In cases of similar hardness, the use of an interlayer with a relatively low melting point can be considered. The interlayer is softened and extruded during processing. The presence of reentrant features promotes a good mechanical lock, even when a true metallurgical bond is not achieved. This process is known as third body friction joining.



Friction plunge welding (left) and third body friction joining (right) (Source: TWI)

7.1.5 Friction element welding

EJOWELD® friction element welding offers the possibility to join different materials (lightweight materials and high strength steels) without any pre-treatment (cleaning, decoating, pre-drilling). The friction element welding technology combines thermal and mechanical welding principles by the use of an auxiliary joining element.



EJOWELD® friction welding process

(Source: Ejot)

The two work pieces to be joined are placed in an overlap configuration with the softer material on top of the harder material. The joining process starts with the acceleration of a rotationally symmetrical joining part ("friction element") to a high rotation speed (10'000 – 20'000 rpm). The rotating friction element is then pressed against the surface of the upper joining partner. The resulting frictional heat causes a plasticisation of the cover sheet and allows to penetrate the upper joining partner without any pre-hole operation or melting. When the friction element contacts the surface of the harder underlying base sheet, the friction and therefore the temperature of the friction element increases significantly. Thus also the joining element plasticises and forms the characteristic "upset". The sliding surface of the upset cleans and activates the surface of the lower sheet. After a pre-set reduction of the length of the friction element, the rotation is stopped and the axial force is increased for a specified holding time. As a result of this "forging" process, the cleaned surfaces of the friction element and the bottom sheet form a rigid metallic bond.



(Source: LWF Paderborn)

The decreasing temperature after the completion of the friction element/base metal joint causes axial shrinking of the friction element, creating a force-lock between the friction

element and the cover sheet. In addition, the radially displaced material from the plasticised cover sheet fills the under hand groove of the friction element causing a solid positive lock. The main process parameters are the tip geometry of the friction element, its penetration depth, the force, the rotation speed and friction time.



Aluminium/steel joints produced by friction element welding

(Source: LWF Paderborn)

Compared to the existing mechanical and thermal joining processes, new fields of application arise for friction element welding with the use of highest-strength sheet metals with a tensile strength of around 1500 MPa. But also other multi-material connections will be possible using this technology.

7.2 Pressure welding processes

Different pressure welding processes are possible and have been tested. The applied pressures vary within a very wide range. In addition, also heat can be used. But except for special applications, pressure welding has found little use in industrial practice.

Forge welding is the oldest solid-state welding process. Two pieces of metal are heated to a high temperature and then joined by hammering them together. It is one of the simplest methods of joining metals, but also very versatile as it is able to join a host of similar and dissimilar metals. However, in industrial practice, forge welding has been largely replaced today by other joining technologies.

Forge welding between similar materials is caused by solid-state diffusion. This results in a weld that consists of only the welded materials without any fillers or bridging materials. Forge welding between dissimilar materials is caused by the formation of a lower melting temperature eutectic between the materials. The temperature required to forge weld is typically 50 to 90 % of the melting temperature.

7.2.1 Contact and cold pressure welding

Cold or contact welding is a solid-state welding process in which joining takes place without any fusion or heating at the interface of the two parts. In the 1940s, it was discovered that two clean, flat surfaces of similar metal would strongly adhere if brought into contact under vacuum. In practice, however, bonding is virtually impossible under most conditions, because of surface irregularities, organic surface contamination and chemical films such as oxide films.

In order to obtain proper weld efficiency, any form of contamination must be reduced to a minimum, while the contact area must be made as large as possible.

In contrast, cold pressure welding uses very high pressure at room temperature to produce coalescence of metals with substantial deformation at the joint interface. Welding is accomplished by using very high pressures on extremely clean interfacing materials. The process is readily adaptable to join ductile metals like aluminium or copper. Both butt and lap joints can be realized. But in practice, this joining method is usually limited to the realization of electrical contacts. Other applications include aluminium clad cookware although in this case, some heat (but relatively low) is applied.

Significantly improved butt welds are possible using the "multi upset principle" developed by GEC. The materials to be joined are inserted in a die and each time the machine is activated, the material is gripped by the die and fed forward. Thus, the two opposing surfaces are stretched and enlarged as they are pushed against each other. Oxides and other surface impurities are forced outward from the core of the material and a proper bond is achieved. A minimum of four upsets is generally recommended to ensure that all impurities are squeezed out of the interface.



Cold pressure welded copper/aluminium rods

Cold pressure welding is restricted to nonferrous materials. It offers a most satisfactory way of joining copper to aluminium without the formation of brittle inter-metallic phases. The joint quality is excellent because it produces a worked structure as opposed to the cast structure obtained in fusion welding. Also, there is no heat-affected zone.

7.2.2 Diffusion and hot pressure welding

Diffusion welding is a solid state welding process by which two metals (which are usually dissimilar) can be bonded together. The necessary diffusion processes involve the migration of atoms across the interface due to the existing concentration gradients. The two materials - whose surfaces must be machined as smooth as possible and kept free from contaminants - are pressed together at an elevated temperature; usually between 50 and 70 % of the melting point. The pressure is used to relieve the void that may occur due to the different surface topographies. The process does not involve plastic deformation, melting or relative motion of the parts. A filler metal may or may not be used (e.g. in form of electroplated surfaces). Once clamped, pressure and heat are applied to the components, usually for many hours; preferably under vacuum or inert atmosphere. When a layer of filler material is placed between the faying surfaces of the parts being joined, the term "diffusion brazing" is generally used.

Hot pressure welding, on the other hand, is a solid state welding process where coalescence occurs due to the application of heat and sufficient pressure to produce substantial plastic deformation at the interface. The deformation of the faying surfaces induces cracks in the surface oxide films and increasing areas of "clean" metal are developed. Welding is accomplished by diffusion across the clean regions of the faying surfaces. This type of operation is normally carried out in closed chambers where vacuum or an inert atmosphere can be used. The parts are brought to contact and upset together under pressure, usually by hydraulic equipment.

A variation is the hot isostatic pressure welding method. In this case, the pressure is applied by means of a hot inert gas in a pressure vessel.

7.2.3 Explosion welding

Explosion welding is a solid state welding process where coalescence is accomplished by the high-velocity impact of one of the components onto the other part. The moving part is accelerated by the controlled detonation of chemical explosives. Due to the nature of this process, the producible joint geometries must be simple (typically plates or tubes).

The impact energy plasticises the materials, forming a weld. Although the explosion generates intense heat, there isn't enough time for the heat to transfer to the metals, i.e. there is no significant increase in the metal temperature and, thus, no significant change in the material characteristics.

The generated heat originates from several sources. One source is the energy expended in the collision. Another source are the shock waves associated with the impact which produce extremely high pressures. The shock waves spread out and create a "material wave" at the joining plane. Heat is also released by the plastic deformation associated with jetting and ripple formation at the interface between the parts being welded. At the collision point, a thin jet of material is heated to a high temperature, causing melting and mechanical mixing at the interface. Surface jetting leads to pronounced plastic interaction between the two metals, a necessary condition for a high quality weld.



Explosion welding process

(Source: Dynamic Materials Corporation)

Explosion welding creates a strong weld between almost all metals. The surfaces have to be simply ground to achieve a smooth finish, oxides and other impurities are expelled, leaving the surfaces metallurgically pure and creating the metallurgical bond. Aluminium can be effectively joined with itself and also with other metals, e.g. steel and copper. The strength of dissimilar weld joints is equal to or greater than the strength of the weaker of the two metals.

Explosion welding is only used in a few applications. Most important is the cladding of a thick base metal plate with another metal. Also bimetallic inserts between dissimilar metals are often produced by explosion welding.

7.2.4 Electromagnetic pulse welding

Electromagnetic pulse welding uses electromagnetic forces to deform and join the work pieces. It is an automatic welding process which can be used for tubular and sheet metals placed in the overlap configuration. It is a process similar to explosion welding, both techniques rely on a high impact rate to create the bond and the joint boundary display a ripple effect.

A typical magnetic pulse welding system includes a power supply, which contains a bank of capacitors, a high-speed switching system and a coil. The power supply is used to charge the

capacitor bank. When the required amount of energy is stored in the capacitors, it is released into a coil during a very short period of time (typically 10 - 15 μ s). The discharge current induces a strong transient magnetic field in the coil, generating a short, but high magnetic pressure which causes one work piece to impact onto the other work piece. Extremely high velocities (600 – 1000 m/sec) can be produced over a distance of a few millimetres.



Electromagnetic pulse welding of tubular work pieces

(Source: PST)

The process parameters of the magnetic pulse welding process are the geometrical parameters (air gap between both parts, axial position of the work pieces in the coil or overlap distance of the work pieces) and electrical parameters (charging voltage and discharge frequency). Magnetic pulse welding needs on average a 1 mm gap between the tube surfaces to achieve a successful weld. The reason is that the metal needs time to build up to its terminal speed at impact. If the metals are too close, a good crimp can be achieved, but not a weld. Also a minimum of two to three times the thickness of the outer material is needed to achieve a weld. Standard cleaning is generally sufficient for magnetic pulse welding as the speed of the created wave breaks down light oxide layers and ejects any dirt from the weld area.

Magnetic pulse welding is a "cold" joining process. The temperature increase is very local (in the order of 50 μ m), i.e. the temperature of the outer surface of the work pieces reach no more than 30 - 50 °C. There is no heat affected zone is created, and the metal is not degraded. The weld becomes the strongest part of the assembly. Another advantage of magnetic pulse welding is the contact-free operation: there are no marks of the forming tools.





(Source: PST)

The process is commercially used for joining cylindrical work pieces in the overlap configuration, but it can also be used for sheet overlap welding. Tubular joints are the easiest task, from both the energy consumption and coil design viewpoints. The joint area needs sufficient clearance for the coil to surround the joints. Most commonly are closed coils where the part is inserted, i.e. at least one end should not have a diameter much larger than the joint diameter. But also swivelling coils have been developed which can clamp over parts that cannot be inserted into a closed coil. A critical aspect is always the lifetime of the relatively expensive coils, i.e. there are today few practical applications.



Electromagnetic pulse sheet welding

(Source: PST)

The magnetic pulse welding technique is adaptable to a wide variety of electrical conductive metals, however, for joining materials with a lower electrical conductivity, a higher energy is required. Similar and dissimilar metals have been successfully welded. The cross section of a weld shows many resemblances with this of an explosion weld.



Aluminium/copper (left) and aluminium/steel joints (right) produced by magnetic pulse welding

(Source: PST)

The magnetic pulse technology also can be used for joining or crimping parts that do not necessarily need a metallurgical bond, such as a metal to a non-metallic part. It can create a mechanical lock on ceramics, polymers, rubber, and composites, so adhesives, sealants, and mechanical crimps are not necessary. With the process, metal is basically shrink-wrapped over the components.

7.2.5 Roll bonding

Roll bonding (or roll welding) is a solid state welding process which joins two or more metals by rolling. The starting materials are generally pre-heated and sufficient pressure must applied by the rolls to cause deformation at the faying surfaces. Coalescence occurs at the interface between the two parts by means of diffusion at the faying surfaces. Thus a subsequent diffusion anneal is often added. Surface cleanliness of the starting materials is most important, i.e. the individual strips are usually chemically or mechanically cleaned to provide contaminant-free surfaces. The plates or strips then pass through either a hot mill (e.g. for the production of aluminium brazing sheets) or a highly customized cold rolling mill designed specifically for cladding.

In practice, roll bonding is exclusively used in the fabrication of semi-finished products. Apart from roll bonded aluminium brazing sheets, there are also roll-clad plates and sheets combining aluminium with with other metals, in particular copper and steel.



Production of clad metals by roll bonding (Source: Wickeder Westfalenstahl)

7.2.6 Co-extrusion welding

Co-extrusion welding is a solid-state process that produces a weld by forcing both materials together through an extrusion die. The process is typically carried out at elevated temperatures to improve welding, but mainly to lower the necessary extrusion pressure.

The extrusion technology is widely used to produce aluminium profiles with different cross sections. Extruded profiles consisting of aluminium and another metal (e.g. steel or copper) can be produced by the introduction of a designed metal strip or wire into the extrusion chamber. Proper control of the extrusion conditions leads to the formation of a metallic bond when the plasticised aluminium and the solid additional material are simultaneously pressed through the extrusion die. Also in this case, coalescence occurs at the interface between the two materials by diffusion at the faying surfaces.

7.3 Ultrasonic welding

Ultrasonic welding differs from the pressure welding technique described above in that the applied pressure is relatively small, i.e. the contact pressure between the parts being joined is significantly lower than either in friction welding or pressure welding processes. Ultrasonic welding creates a solid state weld by the local application of high-frequency vibrations as the work pieces are held together under pressure. It is a cold welding process, since the heat generated by the ultrasonic energy is not essential to the formation of the joint. Welding occurs when the ultrasonic tip that is clamped against the work pieces oscillates in a plane parallel to the weld interface.

Ultrasonic welding has been used to join metals since the 1950s. It is a flexible and fast joining process, characterised by low energy consumption and capital cost. Typical weld times range from 0.25 - 2.0 seconds, while the cycle time (including tool actuation) ranges from 1 - 3 seconds. Whereas the lap shear strength values are slightly below that achieved in conventional resistance spot welding, the cross tension strength values are significantly lower. A longer welding time results in a more even welded connection, a higher yield limit and a higher fracture strength.

Soft, low-yield strength materials work best with ultrasonic welding. It is particularly suited for joining aluminium and its alloys with each other as well as for joints with other metals, in particular copper. The process is restricted to relatively thin materials (wires and thin foils). However, it has been shown that ultrasonic welding performs well on aluminium materials with thicknesses up to 1.0 mm. The process would be also capable of joining thicker materials; but due to power limitations of the commercially available systems, consistent high quality welding of thicker aluminium sheets (1 mm or higher) is today not yet possible.

Prior to welding, the welding system clamps the work pieces between weld tip and anvil. The static pressure force is then superimposed by a high frequency oscillating shearing force. However, as long as the forces within the work pieces are below the limit of linear elasticity, the pieces do not deform. The shearing forces break and disperse contaminants and oxide layers at the weld interface. Thus, mechanical and chemical surface cleaning is not necessary (except removal of excessive oil or other lubricants). Surface coatings (e.g. coated wire) and impurities behave in a similar manner. At the same time, local asperities are deformed and sheared due to the friction-like motion; clean metal surfaces are exposed and a solid-state bond forms as a result of atomic diffusion. The further oscillation leads to the growth of the deformed zone at the interface until a large welding area has been produced.

The minute deformations lead to a moderate temperature increase at the interface. But there is no fusion as long as the pressure force, the amplitude and the welding time are properly adjusted. It is estimated that local peak temperatures of 35 - 50 % of the melting point of the parent metal are reached.

The vibratory energy that produces the minute deformation comes from a transducer which converts high-frequency alternating electrical energy into mechanical energy. A number of methods, such as spot, torsion, seam, and micro welding, exist to deliver ultrasonic energy to a weld joint.



Lateral drive and wedge-reed ultrasonic welding systems

(Source: EWI)

The most relevant method is spot welding using either the lateral-drive or the wedge-reed system. The sonotrode couples with the work pieces in a manner sufficient to transmit vibratory energy. In the lateral drive system, this task is accomplished using a knurled surface which is machined into the tip of the sonotrode that presses into the work piece when a force is applied. The anvil which has a knurled surface similar to the sonotrode is commonly used to hold the other work piece stationary. The anvil and its support structure must be strong enough to resist both the static clamping force and the shear forces generated at the weld interface during a weld cycle.

In the wedge-reed system, the transducer and the wedge vibrate in a longitudinal mode, but drive the reed into a bending vibration mode. The tip is replaceable and contains a knurl pattern used to grip one work piece. The design of the anvil is usually rigid, but the anvil can also vibrate in a bending mode out of phase with the reed to increase the net relative motion between the work pieces. Wedge-reed systems have been adapted to C frames to improve access and automation integration for automotive applications.



WELDMASTER[™] C frame ultrasonic spot welder

(Source: Sonobond Ultrasonics)

The parameters commonly used for ultrasonic welding are:

- Vibration frequency

The frequencies used in ultrasonic welding typically range from 15–60 kHz, but can be several hundred kHz for micro-welding applications. However, frequencies above 20 kHz may not provide the power required for joining aluminium sheets of 0.8 mm or greater.

- Vibration amplitude

The vibration amplitude is the linear motion of the weld tip, parallel with the faying surfaces. Typical peak-to-peak displacements are of the order of 20 - 100 μ m. As the

amplitude increases, so does the power requirements to drive the system. In most systems, amplitude is a controlled variable, able to be set on the power supply. In some systems, input power is the controlled variable, with the resulting amplitude dependent on part and material conditions.

- Static weld force

Typically, the static force which clamps the faying surfaces together ranges from 500 - 5000 N. It is generally delivered by a pneumatic cylinder.

- Welding power, energy and time

Power, energy and time during a welding cycle are interdependent. Typically, one of these three variables is chosen as the process control variable, while the other two variables are monitored for weld quality control.

- Tooling

Ultrasonic welding schedules are generally developed on a case-by-case basis. Weld tip designs vary widely in terms of the design of the knurl features, so that a change in process parameters is typically required if tip designs change. Generally speaking, as the footprint of the knurl area increases, so do the power requirements of the weld system for achieving an acceptable weld.

Ultrasonic welding requires the use of a lap joint. The overlap can be minimized because only a few millimetres of material around the weld tip are required for a suitable weld. A disadvantage is that the welded parts have markings on both sides of the joint due to the weld tip and the anvil knurl indentations. The spot welds can be overlapped or spaced at virtually any interval.

When considering joint design, the thickness of the thinner work piece is most critical. Dissimilar thickness joints can be achieved if the thinner work piece does not exceed the force and power capabilities of the welding system. As a work piece thickness increases, more static clamping force and higher peak powers are required to produce an acceptable weld. If possible, the thinner work piece should be next to the weld tip. Transferring vibration energy into the work pieces is inherent to the ultrasonic process and work piece resonance must therefore be considered. If resonant vibrations exist, they can be minimized by different measures.

The most important practical application of ultrasonic welding in the automotive industry is making electrical connections between aluminium or copper wires /cables and end pieces, e.g. to be used in battery cables and wire harnesses.



Aluminium cable (cross section 120 mm²) ultrasonically welded to a Ni-plated copper end piece

(Source: Telsonic)

A new development for such applications is the PowerWheel[®] technology where the sonotrode is excited by a torsional oscillator. The welding action is carried out in a rocking movement directly at the weld. This means that the maximum amplitude is always at the centre of the weld area and the power output can be precisely focused. Due to the new construction of the sonotrode and its movement, it is possible to transfer significantly more energy into the weld than by using the conventional linear movement.



High frequency longitudinal movement in the linear axis (left) and oscillating movement around a central axis (right) in the μ m range

(Source: Telsonic)

EAA Aluminium Automotive Manual – Joining

8. Mechanical joining

Content:

8. Mechanical joining

8.0 Introduction

8.1 Mechanical joining without additional fastener

8.1.1 Hemming 8.1.1.1 Hemming process 8.1.1.2 Hemming systems

8.1.2 Clinching 8.1.2.1 Clinching with local incision 8.1.2.2 Clinching without local incision 8.1.2.3 Design criteria for clinched joints 8.1.2.4 Quality criteria for clinched joints

8.1.3 Mechanical interlocking

8.2 Mechanical joining with an additional fastener

8.2.1 Screws and bolts

8.2.1.1 Threaded fasteners
8.2.1.2 Self-tapping screws
8.2.1.3 Hole and thread forming screws
8.2.1.4 Functional components for screw joints
8.2.1.5 Blind rivet nuts and bolts
9.2.2 Division

8.2.2 Riveting

8.2.2.1 Solid rivets 8.2.2.2 Blind rivets 8.2.2.3 Lockbolts 8.2.2.4 Self-piercing rivets 8.2.2.5 Clinch riveting 8.2.2.6 Tack high-speed joining

8.0 Introduction

Two groups of mechanical joining techniques can be differentiated:

- Mechanical joining methods without additional fastener
- Mechanical joining methods with an additional fastener.

In the first group, the joint is realised without the need of additional joining elements, only using the work pieces to be joined. In the second group, an additional fastener is applied which, in general, remains within the joint.



Compared to fusion welding techniques, the advantages of mechanical joining methods include:

- Applicable for materials difficult to weld and dissimilar material combinations
- Little or no damage to pre-coated materials
- No fume or heat generation, low noise emission, low energy consumption
- Minimum geometrical distortion (no heat input).

Because of the sensitivity of work-hardened and age-hardened aluminium alloys for the heat input from fusion and resistance spot welding and due to the effects of oxide films on electrode life in resistance spot welding, the use of "non-thermal" joining techniques has gained particular importance in automotive applications. Mechanical joining techniques like bolting, self-piercing riveting, blind riveting, clinching and the combination of these techniques with adhesive bonding have, therefore, been developed to substitute the traditional resistance spot welding.

8.1 Mechanical joining without additional fastener

8.1.1 Hemming

In automobile assembly, hemming is used as a secondary operation after the deep drawing, trimming and flanging operation to join two sheet metal parts (generally outer and inner closure panels) together. Typical parts for this type of assembly are hoods, doors, trunk lids and fenders. This technique is also used for the reliable joining of sunroofs.

8.1.1.1 Hemming process

Hemming is a metalworking process in which a sheet metal is folded over onto itself. Normally hemming operations are used to connect parts together, to improve the appearance of a part and to reinforce part edges.



Various hem designs: Flat hem (left), wedge-shaped hem (centre) and droplet-shaped hem (right)

The accuracy of the hemming operation is very important since it affects the appearance of the surface and surface quality. Compared to the standard flat hem, a wedge-shaped hem (which can be further developed to a 180° bend of the outer panel) allows the creation of a sharper edge, improving the visual appearance of the gap between two adjoining panels. A droplet-shaped hem ("rope hem") is only used when insufficient ductility of the outer panel prevents the realization of a flat hem. A "rope hem" can also alleviate the potential for the formation of unfavourable "streamers" across the visible surfaces of the outer panel.

Hemming belongs to the cold forming processes. Basically, it consists of three steps:



Step 1: bending 90°, Step 2: hemming 45°, Step 3: folding 180°

The quality of the hem strongly depends on the formability of the applied sheet material characterized by its minimum bend radius. Important influencing factors are:

- the applied aluminium alloy (composition and heat treatment),
- the thickness of the aluminium sheet,
- the forming history of the sheet / part, and
- the hemming process parameters.

Today, the droplet-shaped hem – formerly common for aluminium alloy sheets – is applied only in exceptional cases where formability is strongly reduced, for example by preceding age hardening effects or strong cold deformation. Normally the flat hem can be realised without any difficulty. High requirements on the visual appearance of the gap may lead to special demands with regard to gap clearance. Specifically developed aluminium alloys for outer body applications fulfill the requirements for flat folds (bending factor <0.5) and enable the realisation of flanges with inner bending radii of almost 0 mm.

The material deformation during the hemming process, can lead to dimensional variations and other defects. Typical hemming defects are splits or wrinkles in the flange, material overlaps in the corner areas or material roll-in. In practice, numerical simulation tools are used in order to better understand the hemming process and to reduce the number of loops during try-out and production. The standard software packages used for the simulation of stamping processes also properly represent the hemming process.

Closure panels are usually made by hemming the outer panel over the inner panel which also conceals the sharp metal edges. Generally, the hem flanges are protected by a sealant to prevent crevice corrosion of the sandwiched metal. In principle, the hemming technique produces sufficiently strong mechanical joints around the periphery of closure panels. Nevertheless, hemming adhesives are widely used in these flanges to give improved strength, part stiffness, crash performance and corrosion protection (see also 10.1.1). Applied adhesives used include epoxies, PVC or acrylic plastisols, rubber based materials and PVC-epoxy hybrids.



Set-up of the hem flange of a typical closure panel

A more sophisticated hem seam design has been introduced by Honda to join dissimilar metals (steel and aluminium). In the patented "3D Lock Seam" structure, the steel and aluminium panel are layered and hemmed together twice.



(Source: Honda)

8.1.1.2 Hemming systems

Different hemming systems are available. In addition to optimised solutions for volume production with extremely short cycle times, there is also equipment for niche vehicle production. Special emphasis is always placed on the requirements for increasing fitting accuracy and minimum gap dimensions at reduced costs and with maximum process reliability.

The hemming process involves bending an outer metal sheet around an inner metal sheet. In automotive applications, two methods are used:

- Conventional die hemming
- Roll hemming.

In conventional die hemming, the flange is folded over the entire length with a hemming tool. In roll hemming, the hemming roller is guided by an industrial robot to form the flange.



Conventional die hemming (left) and roll hemming (right)

Conventional die hemming is suitable for mass production. The flange is folded over the entire length with a hemming tool. Normally, the actual hemming operation is the result of a forming step where the flange is formed with a hemming tool after completion of the drawing and trimming operations. The formed flange is then hemmed in several steps. These steps include, for example, the pre-hemming and final hemming depending on the respective opening angle of the flange. Production plants for conventional die hemming are very expensive, but the cycle times are very short.

Roll hemming is carried out incrementally. A robot guides the hemming roller and forms the flange. Roll hemming operation can also be divided into several pre-hemming and final hemming steps. It is a very flexible process and tool costs are significantly lower compared to those of conventional die hemming. However, the cycle times are much longer since the hemming is the hemming roller follows a defined path.

a) Press hemming

Hemming presses are widely used in automotive manufacturing. The process uses traditional hydraulically operated stamping presses to hem closure parts as the last forming step in the stamping line. Press hemming is a fully automated, high cost process suitable for large parts, but due to the complex force geometries restricted to relatively flat, uncomplicated panels.

b) Tabletop hemming

Today, table top hemming is the dominate die hemming technology. Instead of a large hydraulic press, tabletop hemming uses a series of electrically actuated heads. Tabletop hemming devices are used for medium to high production volumes, achieving cycle times down to 15 seconds.



Tabletop hemming equipment (Source: DV Automation)

Tabletop hemming is a highly adaptable process. It can be used in a variety of cases where conventional die hemming equipment is less suitable, such as for high-mix, low-volume production and most complex panel geometries. Optimum panel surface quality is guaranteed through the hemming principle of the closed ring (corresponds to hemming in the stamping tool).

c) Roll hemming

A particularly flexible solution in closure manufacture, primarily developed for low to medium volumes, is robotic or roller hemming. With roller hemming, the plates are clamped in a tool bed. The roller hemming head is attached to an industrial robot. Rollers which are necessary for various hemming work steps are attached to the roller hemming head. As a result of reduced process forces, the surface quality of complex sheet metal geometries is improved. Dimensional accuracy and tolerances are controlled by selectively influencing the robot program.


Robotic roll hemming

(Source: Kuka)

Automation of the hemming operation can be implemented flexibly. For example, changeable roller hemming tools for different work pieces and manufacturing processes can be provided in an automated cell. Minor changes and modifications to panel hemming conditions can also be accommodated allowing a quick and cost-effective reaction.

8.1.2 Clinching

Clinching is a high speed, mechanical fastening method to join two or more sheet metals by local plastic deformation without an additional fastener or heat impact. It is an inexpensive and easily automated process which only requires a punch and a die. The punch pushes the sheet metal into the die, forming an interlocking friction joint with good static and dynamic strength.

In technical terms, clinching is defined as a single or multi-step fabricating process with a common displacement of the materials to be joined combined with local incision or plastic deformation and followed by cold compression, so that a quasi-form locking joint is produced by flattening or flow pressing (impact extrusion)



Clinch point geometries with and without local incision

The most significant feature of the clinching technique, which is established in the DIN 8593 standard, is that the joint is formed from the material of the metal parts to be joined. The parts to be clinched can be of the same or differing sheet thickness. In industrial applications, clinching is applied from a single

sheet thickness of 0.1 mm up to a total layer thickness of 12 mm and materials up to a tensile strength of 800 N/mm². In laboratory tests, materials with significantly higher strength values have been successfully clinched.

The clinching process is applicable for aluminium alloy combinations as well for multi-material combinations (e.g. aluminium and steel) and also with pre-coated, painted or galvanized materials. Furthermore, clinching can be combined with an adhesive, a sealant or an intermediate layer (e.g. a sound dampener).

Special tools are used to plastically form the mechanical interlock between the sheets. Tool systems with and without moving die parts have been designed. During clinching with movable die parts, the flow of the displaced metal is determined by the yielding characteristic of the dies. On the other hand, during clinching without movable die parts, the displaced metal flow into a grooved ring in the die. A further differentiation can be made according to the process kinetics. The two main principles are single stroke and double stroke. Single-stroke clinching requires special tool sets for each set of parameters, especially different sheet thicknesses. While double-stroke clinching can adapt to a range of thicknesses, it requires a larger capital investment and is difficult to integrate into the stamping press line.

The wide range of clinching geometries and tool concepts allows the selection of the appropriate type of joint for the each application.



Different types of clinched joints

(Source: Eckold)

Most widely used in automotive applications is the round clinching element where neither sheet is cut ("closed joint"). Clinching joints where either both sheets or only one sheet are cut have generally a rectangular shape. In the latter case, the element is closed on the punch side. In special cases, also a sheet with a pre-punched hole can be placed on the die side.

Clinching often replaces spot welding. The static and dynamic strength of clinched joints are higher than with common spot welded connections. Clinched joints are lower strength than comparable self-piercing rivet connections. The reason is the absence of the auxiliary joining fastener that affects the cross tension strengths in particular. Clinching is thus used primarily in non-crash-relevant areas.

It is a cold forming process, offering up to 60% cost savings over spot welding. Life expectancy for clinching tools is in the hundreds of thousands of cycles. There is no need for pre-cleaning or a process-specific surface pre-treatment and subsequent finishing. Also clinching provides a quieter and cleaner working environment (no sparks and fumes, little noise). An additional benefit of clinching is the avoidance of damage to the integrity of the coatings eliminating such problems as corrosion and degradation.



Joining of an aluminium heat shield with a hand held clinching tool (Source: Attexor)

Clinching systems come in all sizes and types of operations and speeds. Options range from handheld units to multi-head systems with double-acting punch and dies, and self-centring heads. Clinch machines can be used to simultaneously set one or several points and can be easily integrated within robotic cells or other manufacturing systems.

8.1.2.1 Clinching with local incision



Process steps in single-step clinching with local incision

Clinching with local incision creates a permanent joint under the combined action of shear and penetration processes, in which the penetration and incision limit the joint region, and a cold compression process, in which the sheet material pushed out of the sheet plane is compressed and flattened. In the single-step clinching process, the joint is created during an uninterrupted stroke of a single tool component. In the multi-step process, the clinch joint is created under the action of successive motions of the tool components.

Based on this principle, joints with different geometries have been developed over the years. The joint strength increases with an increase of the sheared area as well as with a reduction of the locally incised part (which is replaced by a corresponding increase in the plastically formed part). For this reason, clinching joints without local incision are generally preferred.



In automotive application, clinching with local incision has found limited application. Clinching systems with local incision are primarily suited for multi-layer joints (up to 5 layers or more), certain dissimilar material combinations and high strength, low ductility materials (ultra high strength steels, stainless steels, etc.). Two or more layers of metal typically ranging in thickness from 0.2 mm to 4.0 mm per sheet can be reliably joined in most cases.

As an example, in the Lance-N-Loc[®] system, a joint is formed by lancing the two long sides of the joint and gradually drawing the ends. The material on the sides of the joint is compressed, expanding the width to form a lock on two sides, all in a single press stroke. The resulting joints are characterized by a "button" formed on the die side layer of metal and a recess formed in the punch side layer. The button is a good indicator of joint quality and simplifies quality control.



Lance-N-Loc[™] button side (left) and cross section (right) (Source: BTM)

8.1.2.2 Clinching without local incision

The clinching process without incision is a method of joining two or more material layers by localized cold forming using a special punch and die. The punch forces the material layers into the die cavity ("local penetration") where the pressure exerted by the punch forces the metal to flow laterally ("cold compression"). The result of the process is a button shaped extrusion on the die side of the assembly (which acts as an interlocking joint) and a small, cylindrical cavity on the punch side. No finishing is required. The produced clinch joints are visually appealing, gas tight, protect existing surface coatings better and offer high corrosion and fatigue resistance. In general, round points are utilised. However, with special die designs, also rectangular joints can be created.

a) Solid dies (without moving parts)

The clinch joint is carried out by plastic deformation of the materials to be joined inside a rigid die. In the simplest form ("single-stroke process"), a round punch presses the overlapping materials into the die cavity. As the force continues to increase, the punch side material is forced to spread outwards, but is contained by the solid die walls. Consequently, the die side material is squeezed into a ring-shaped channel in the mechanically locked anvil until a preset clinching force is reached. The result is an aesthetically pleasing round button, which joins clearly without any burrs or sharp edges. The material strain hardening in the neck area and the lack of any notch effect result in a high retaining forces.



TOX[®] round clinch joint, a one-step process with a solid die

(Source: TOX Pressotechnik)

The advantage of the die without moving parts lies in the absence of wear of the components. The disadvantage is that oiled aluminium sheets can lead to the formation of a "hydrostatic cushion" in the closed die, leading eventually to the destruction of the die. Similar problems arise in hybrid joining "adhesive bonding plus clinching" or in connection with other intermediate layers.

More sophisticated methods include a blank holder and a moving die ("multi-stroke process"). In a first step, the punch and blank holder move downward, the work pieces are clamped and fixed by spring force of the blank holder. By action of the punch, the material flows into the bottom die cavity forming a cup (step 2). The process parameters and dimensions of the punch and die are tuned to the sheet thicknesses of the work pieces to ensure that no material is laterally drawn into the joint from surrounding area. Finally, the thickness of the cup's bottom is reduced by upsetting and the material forced into the die groove and in lateral direction, forming the necessary undercut (step 3). After reaching a pre-set maximum force (force controlled) or a pre-set displacement (stroke controlled), the punch is retracted and the clamping force relieved (step 4).



Single-step clinching without cutting using solid dies

b) Dies with moveable parts

In clinching systems using dies with moveable parts, the materials to be joined are generally clamped by a punch side stripper. Then the punch draws a material section into the die. The die wall, which is split in two or more segments, remains closed. As soon as the material touches the die anvil (i.e. the bottom of the die cavity), the material starts to flow laterally under the pressure exerted by the punch. The movable die sections are pushed outwards, sliding on a base, until the punch-to-anvil distance reaches a pre-set value. Thus, the material forms the button-like mechanical interlock. Finally, the punch is returned to its starting position by the operator or by a pneumatic timer which removes the force. The joined component can now be removed and the die walls close again.



Single-step clinching using a die with moveable segments (Source: Attexor)

Various die designs are used by the different system suppliers. Dies may include two or more moveable segments which are pulled back together by a spring or a similar mechanism. More versatile die designs include fixed as well as flexible segments. The materials and the punch are centred by the solid segments, thereby guaranteeing that the joint formation is perfectly concentric. The mobile parts allow an interlocking of the material in the joint.



Examples of clinching dies with moveable segments: Eckold R-DF (left), Böllhoff RIVCLINCH[®] (centre) and TOX[®] SKB (right) system

(Sources: Eckold / Böllhoff / TOX Pressotechnik)

The advantages of clinching with moveable dies over methods with non-segmented dies are seen in a more flat protrusion of the joint and a higher flexibility when sheet metals of different thickness have to be joined. Very high pull-out tension values can be achieved due to improved flow behind the material because the die opens during clinching and the material can flow to the side. Moveable die systems are also beneficial when joining oily sheets and for applications where an adhesive is applied between the metal layers.



Clinch joints produced with moveable dies, at right, a cross section of an adhesively bonded material combination

(Source: Böllhoff/Eckold)

c) Clinching methods for special applications

The applications for clinching are so diverse that special methods have been developed to take into account the individual requirements.

Clinching creates a protrusion on the die side, which might be considered as an obstruction. In this case, the standard clinch joint created in a first step can be flattened (\pm 0.1 mm) in a secondary operation using a flat die. The high shear and pull strengths of the clinch point are left virtually intact.



Special clinching methods: Flat joint (left) and twin joint (right) (Source: TOX Pressotechnik)

The twin clinch point shown above provides protection against rotation. Also it almost doubles the joint strength in comparison to the single joint. Whereas this solution was developed for a solid die clinching technique, anti-rotation benefits can also be achieved when using moveable dies.



Oval-shaped clinch joint: Button side view and cross section

(Source: BTM)

Originally developed to respond to a request for a visually improved clinch joint button, the V-Loc[™] joint also results in an improved material flow within the clinch joint. A thicker side wall and improved interlock increase shear and peel strength by approximately 25% over the standard Tog-L-Loc[®] joint when joining some aluminium alloys. The V-Loc[™] joint features a raised spherical inner diameter with a concentric outer ring, intended to give the appearance of a more traditional fastener.



V-Loc[™] button side view and cross section

(Source: BTM)

Special clinching methods are also available for difficult cases, e.g. joining of sheet metal with large differences in thickness, joining of high strength or non-ductile materials with ductile materials or joining of non-metallic materials. One layer is pre-punched; the ductile material is then pushed through the hole. The resulting connection has radial and axial strength. Multiple joints can be applied in a single press stroke. However, this process requires precise alignment of the parts.



Two process variants for clinching difficult material combinations (Source: TOX Pressotechnik)

8.1.2.3 Design criteria for clinched joints

Clinching requires open flanges with good access to both sides for punch and die tooling. Proper accessibility is needed for clamping and pressing the material between the punch and the anvil. The flange width must be sufficient to accommodate the interlocking button produced during clinching spot as well as the surrounding deformed material. Otherwise, the button may burst out of the edge of the flange or cause a local distortion of the part. As a general rule, the clearance between the centre of the joint and the flange outer edge should be 1.5 times the punch diameter. Also, the clearance between the joint.

Clinch spots should be spaced to avoid previously formed joints or the strained area immediately around them. Clinching in or near prior joints may result in unsatisfactory joint appearance, excessive thinning of the bottom sheet and accelerated tool wear. Placing several clinch spots too near to each other may also cause distortion or bending of the joint. However, there must be enough joints to guarantee the overall design strength of the assembled component. A minimum joint spacing of two to three times the button diameter is recommended.

Proper planning of the clinching sequence and suitable clamping of the work pieces will avoid such problems. Good process control ensures that the material layers to be joined are properly drawn

together as the clinch spots are driven and set. In addition, no joining process forces will be diverted into component. Accurate overlap of the layers to be joined and a correct flange width facilitate proper alignment between the work pieces, punch and die. A pre-clamping step may be helpful if joining a flange width close to the minimum width is to be undertaken. Joints should be fully closed after the clamping stage. Poor fit-up and alignment are major contributors to inconsistent clinch quality.

The strength of a clinched joint depends basically on four main factors:

- The type of aluminium alloy of the work pieces,
- The sheet thicknesses,
- The clinch button size (the diameter should be as large as possible),
- The surface condition of the material.

A completely dry, grease-free surface will give a stronger joint than if the surface is oily or wet On the other hand, a minimum lubrication avoids adhesion of the aluminium to the tool and significantly improves the tool life. Thus a suitable compromise must be found.

Cinching is a cold forming process. Therefore, the formability of the involved materials must be sufficiently high. As a rough estimate, good clinch joints can be achieved if:

Elongation to fracture	A ₈₀ ≥ 12 %
Yield ratio	$R_{p0.2}/R_m \le 0.7$.

A limited ability to apply clinch joints is given when:

Elongation to fracture	12 % ≥ A ₈₀ ≥ 8 %
Yield ratio	R _{p0.2} /R _m ≥ 0.7.

In this case, it is important to qualify the clinching performance in laboratory tests before practical application.

When dissimilar materials are being joined, best results are achieved if the following rules regarding the joining direction are observed:

"Thick sheet into thin sheet" and "High strength into low strength".

The localisation of the thicker material on the top ensures that enough material can flow into the die cavity. Otherwise, the neck area will be very fragile. The thicker material should not be more than twice the thickness of the thinner material. The combined thickness of the two plies should not exceed the combined maximum thickness recommended for the die. Also, if one material is considerably harder than the other, the harder material should be on the punch side. If the softer material is on the punch side, the punch may go right through the softer material, instead of deforming. However, for special applications, various suppliers also offer tool designs which can be optimised to adapt different combinations.

8.1.2.4 Quality criteria for clinched joints

The quality of a clinched joint is determined by many different factors. It depends on the joining method/equipment, the applied tools and specific joining parameters and in particular on the parts to be joined (number of parts, material quality and thickness, surface conditions, joint geometry and accessibility, joining direction, etc.). Therefore, prior laboratory tests of the specific joint arrangement are recommended to determine the relevant design parameter like static and dynamic strength, crash resistance, etc.

For clinching, there is a causal relationship between joint quality and the geometry of the clinch joint. It is therefore possible to estimate the quality of the joint from a visual evaluation of the clinch joint and

by measuring geometric parameters. As an example, for non-cutting, round button clinching techniques, the strength of the connection is determined by the magnitude of the undercut and the neck thickness. These values are influenced by the tool dimensions, such as the punch diameter and the depth and diameter of the die cavity, as well as by the setting of the displacement limits for the upper-die. A larger undercut can be achieved by reducing the residual bottom thickness. However, to avoid overloading the tools and work piece due to excessive joining forces, a compromise between maximum joint strength and tool life is required.



Quality criteria for a clinched connection

a) Quality control

Clinched joints result from the interaction between clinching equipment, material, and punch and die. As a consequence, the material has been geometrically changed in comparison to the original flat sheet metal. Therefore, the joint quality can be monitored by measuring the bottom thickness of the joint and/or the button width.

The residual bottom thickness correlates well with the joint strength and is generally used as a nondestructive quality control measurement.



Practical quality control normally includes measuring the residual base thickness (St) and the joint diameter (D) on the die side of the joint. The optimum values are predetermined in laboratory tests for each application. Comparison of these reference data with the parameters measured during production guarantees a reliable quality control of the clinch joints.

b) Process monitoring

An electronic, process controller can be used to check the joining process for automated or mass production. Process monitoring consists of measuring force and displacement of the punch, as joints are being made, and checking that the values of these parameters are being correctly maintained by the clinching equipment.

A force sensor is installed on a C-frame. Another sensor measures the tooling position. Thus, a forcedisplacement curve is generated in real time for every clinch joint. The software allows checking process "windows" which must be previously programmed along the curve. The last one is the final value of the completed joint. The width of this acceptance range can be altered to suit the requirements of specific applications. Results outside the acceptance range normally indicate faults or variations in process operation or materials, which could lead to unacceptable joint quality.

8.1.3 Mechanical interlocking

Due to its elasticity, aluminium is highly suited to realise snap-fit joints, allowing far quicker assembly than, for example, screw or welded joints. Snap-fit joints are a most interesting joining technique for extruded aluminium profiles and widely used in a range of industries. In automotive design, relevant application areas can be found primarily in the floor structure and in the interior, in particular when joining extruded aluminium and plastic sections.



Design of snap-fit joints

(Source: Sapa)

In detachable snap-fit joints, the hook angle is $\alpha = 45^{\circ}$. In permanent snap-fit joints, the hook angle is $\alpha = 0^{\circ}$ (or negative). The length of the snap-fit joint has an effect on design; it should not be below 15 mm. If a design cannot accommodate hooking arms of sufficient length, however, the sprung part of the profile should be replaced by plastic clips. The same applies if the joint is to be repeatedly opened as the fatigue properties of aluminium do not permit frequent changes in loading.

As an example, larger cross-sectional areas can be economically created by joining together a number of extruded aluminium profiles together. This solution is often chosen because it is easier to machine smaller profiles individually rather than a single construction as a whole.



Large cross-sectional areas realised with snap-fit joints

(Source: Sapa)

For latitudinal joining, mechanical (snap-fit) connections can be used as a cost-efficient alternative to other joining methods like adhesive bonding, fusion welding or friction stir welding. The use of a flat bar or a similar measure ensures proper flatness. The assembled structure can be additionally fixed with screws, the introduction of a tubular spring or properly designed clamps.



Latitudinal joining using with a snap-fit (left or centre) or screw ports (right) (Source: Sapa)



Snap-fit joints allow various design solutions (from left to right):

- Longitudinal joint using spring and friction mechanisms
- Snap-fit joint with a formed sheet panel
- Snap-fit joint between aluminium and plastic profiles
- To deal with high local surface loads and reduce wear (e.g. from a rolling steel wheel), a steel strip can be inserted into the aluminium profile.

(Source: Sapa)

8.2 Mechanical joining with an additional fastener

Mechanical assembly methods using an additional fastener can be classified according to the necessary preparation of the parts to be joined and the accessibility.

In this section, functional components are also covered. In particular when joining thin sheets, it is often difficult to introduce a load-bearing screw thread. Therefore, functional components which fulfil the function of either a nut or a bolt or screw are often attached, depending on the specific joining task. The functional component which is later used in the actual joining process stays within the assembled structure.

8.2.1 Screws and bolts

With the help of screw-and-nut fasteners, it is possible to create large clamping forces. Bolted or threaded connections for the attachment of equipment to aluminium components and structures may be produced by simply bolting through the aluminium part. In some cases, it may be necessary to provide internal support if bolting through a closed section, e.g. when attaching the engine or

suspension to the body front rails. This support can be with tubes or extrusions fixed inside the hollow section to prevent the section from collapse under high installation loads.

Bolted connections can also be achieved with threaded studs and nuts which are fixed to the aluminium part. The selection of insert type depends upon the strength (torque) required and whether access is only possible from one side (blind) or both sides of the aluminium part. Aluminium welded studs and nuts are available that may be welded directly to the aluminium parts, e.g. by an electric arc welding process (see 3.3). Aluminium threads are, however, not recommended for situations where frequent removal for service is required. Steel threaded studs and nuts are preferred for applications where higher strength or frequent dismantling may be necessary.

Care must be taken if bolting material combinations are used, which are critical with respect to galvanic corrosion. Except for stainless steel, all steel inserts assembled into aluminium parts must be coated to prevent galvanic corrosion. Insert manufacturers can supply a range of suitable coatings. Sealants, gaskets or protective coatings may be required in severe corrosive environments, whereas simple surface treatment of the steel and/or the aluminium may be adequate in a dry internal environment.

8.2.1.1 Threaded fasteners

Threaded fasteners are one of the most universal and widely used types of fasteners and are manufactured in a wide variety of shapes and sizes. Threaded (or screw) joints belong to the group of detachable joints. They can be designed as pierced, pierced and protruding or blind-hole joints. Threaded fasteners require either a mating thread (which must be manufactured separately) or the use of an extra, internally threaded component (nut).

A distinction can be made between connections formed using a clearance hole (bolts) and internally threaded holes (screws). If appropriate measures are taken against corrosion, screw joints are suitable for formed aluminium sheet components, profiles and castings with other aluminium alloys or dissimilar materials.



Bolted (left) and screwed joint (right)

Threaded fasteners for aluminium are usually made of stainless steel or properly surface-coated steel, but also other materials (including high strength aluminium alloys) can be used. Since aluminium alloys have a relatively low compressive strength, the contact surfaces must be generally protected by the use of washers under the screw and the nut.

The classic threaded connection is formed by joining two or more components by means of form-fit or friction-fit fasteners. Threaded connections should be designed in such a way that the permissible stresses in the mating components are never exceeded by the forces acting on the connection as a whole. The tightening torque should be selected such that the preload force produced creates a purely frictional connection between the components and thus prevents them from sliding against each other or having to be supported by the shaft of the fastener (as compared to a rivet connection).



Clamped components



(Source: Böllhoff)

The selection of the required fastener relies upon a precise knowledge of all loads that might occur, and is thus dependent on the specific application. The most important factor is that sufficient load-bearing turns of the thread are engaged to be able to withstand the prevailing forces.



Threaded screws with driving features particularly suited to automatic assembly

(Source: Böllhoff)

In order to meet the increasing demands for automation in manufacture, special fasteners have been developed to satisfy the dual requirements of suitability for automatic feeding and optimisation of force transmission geometry. Angle controlled tightening methods are generally used for fully automated assembly processes.

A special benefit of the aluminium extrusion technology is the integration of continuous tracks for nuts or bolt heads into the cross section of the extruded profile. Continuous tracks enable step-less fastening with no need to machine the profile. Using special nuts/bolts, fastening can even take place without having to slide the nut/bolt in from the end of the track. Various solutions are available from screw and fastener manufacturers.



Continuous tracks for step-less fastening in extruded profiles (Source: Sapa)

8.2.1.2 Self-tapping screws

Self-tapping screws are thread forming fasteners, which form their own threads when screwed into core holes. Self-tapping (thread rolling) screws are designed to be driven into pre-drilled core holes in solid metal parts. They roll their mating thread without any cutting action. The thread end is tapered to make it easier to start the thread forming process. The rolled thread is compatible with metric external threads, i.e. a standard metric screw can be used in case a repair is required.



Self-tapping screw (Source: Böllhoff / EJOT)

The component should be prepared either as a blind hole in full material or as a stamped (or laser cut) hole in sheet metal. For thin sheet applications, prior formation of a rim may be considered. After positioning the screw, the thread is formed and the screw is tightened. The required tapping torque is relatively low whereas the tightening torque is high. The positive fit in the self-formed thread prevents spontaneous loosening of the joint.



Joining with thread forming screws

(Source: Betzer)

The female thread is formed by the screw thread. The prerequisite is that the screw thread is harder than the work piece and that the mating material is sufficiently ductile to allow the thread to be formed. The basic rule is: "Coarse pitch threads for soft materials – fine pitch threads for hard materials".

Self-tapping fasteners are highly suited for joining aluminium alloys, in particular when larger aluminium parts like extrusions and castings are involved. Using self-tapping fasteners increases productivity during assembly and reduces the joining cost. The production sequence is economised, there is no need for prior thread cutting and the number of assembly components is reduced. Furthermore, the overall component weight is lowered.

Extruded aluminium profiles offer most interesting solutions in this respect. Screw ports for transverse connections can be directly integrated into the cross section. As shown below, the screw ports will generally have projections to centre the self-tapping screws. Where the design requires a more robust screw, also closed screw port can be used. Similar approaches can be used for longitudinal connections.



Integration of screw ports into extruded aluminium profiles

(Source: Sapa)

The reliable assembly of thin sheets with pre-punched holes with self-tapping screws presents more problems. New developments, however, offer a secure solution for the reliable assembly of pre-punched metal sheets with less 1.5 mm thickness.



Joining thin sheets with pre-punched holes (EJOT SHEETtracs® system)

(Source: EJOT)

The EJOT SHEETtracs[®] screw features a 45° (30° / 15°) asymmetric flank angle and creates a stronger female thread in the sheet with less material displacement. This increases the stripping torque level of the joint and enables multiple repeat assemblies. In the lower, tapered area of the screw, the flank angle is reversed, and the resulting through draught is formed mainly into fastening direction. The non-circular thread forming zone ensures easy, centred application and the raised thread areas ensure a secure penetration of the sheet material. The circular cross section in the upper, load bearing thread results in higher thread engagement in the sheet metal compared to non-circular thread geometries.

8.2.1.3 Hole and thread forming screws

The use of hole and thread forming screws for direct mounting of thin sheet metal parts allows substantial cost savings and significant quality improvements. Hole and thread forming screws eliminate the drilling operation in the assembly of thin sheets and enable the realisation of high strength screw joints due to increased thread engagement in the formed draught. The economical and qualitative advantages are essentially the same as for self-tapping screws. However, special measures must be taken as the rim necessary for the female thread is formed directly in the joining process without producing chips. Thin materials can be also joined without pilot hole; for specific material combination, a pilot hole may be recommendable. Joining of steel sheets with thicknesses up to 2 mm and of aluminium sheets with up to 5 mm thickness is generally possible.

Since there is no need for preparations like pre-punching or pre-drilling, the usual tolerance problems for screw joints such as overlapping of draught and insertion hole do not apply. The one-sided accessibility of the part provides for an assembly into hollow profiles (e.g. hydroformed or extruded aluminium profiles) without any counter support. Joining with hole and thread forming screws is highly suited for automated assembly; the screws can be also removed and the female thread can be used in case of future maintenance and repair. There are essentially two different methods.

a) Cold hole and thread forming screws

The basis for joining with cold hole and thread screws is a more sophisticated screw design. The special geometry of the screw point produces a high contact pressure per unit area which then leads to the necessary plastic deformation of the material.



Hole and thread forming screws for thin sheet metal

(Source: Betzer)

The hard point of the screw ensures that only little manual contact pressure is required. The hole begins to form after just a few turns of the screw. The specially designed cone shape and thread flanks enable proper forming of hole and rim. Then the thread is formed, the screw is fully screwed in and tightened. The resulting short cycle times allow cost-efficient assembly. Apart from the conical point, also screws with a truncated cone point are available. The conical shank end facilitates finding and positioning in particular in case of stamped thin sheets.



Process sequence for hole and thread forming screws

(Source: Betzer)

b) Flow forming screws

In the flow forming (drilling) process, a tapered, but unthreaded punch rotating at high speed is forced down to pierce through the metal. The sheet metal heats up and is momentarily softened. Thus, a collared hole is formed by plastic deformation. A thread can then be tapped into the cylindrical hole. Stainless steel sheet metal screws are most often used for joining aluminium alloys.



After a short warming up period, the material is penetrated. Then, the draught and the thread are formed. After full thread engagement, the screw joint is tightened.



Process steps of flow drilling screws

(Source: EJOT)

Due to the increased thread engagement in the formed draught, a high-strength screw joint is created – without any undesired metal chipping. The screw joint is able to transfer high pull-out as well as shearing forces. The positive fit of the screw in the self-formed thread prevents spontaneous loosening, i.e. ideally suited for the safe assembly of dynamically loaded screw joints.

Since a small amount of the material flows against the fastening direction, the geometry below the screw head was optimised. While in the past the clearance hole was used for taking up the displaced material, it is now absorbed by the increased space below the screw head.

8.2.1.4 Functional components for screw joints

Another possibility to form a solid direct connection when the part to be screwed is thinner than the thread pitch of the tapping screw is the use of functional joining components. The applied functional components are generally threaded elements which take on the role of either the nut or the bolt and enable the attachment of additional parts by screws in a second step. Threaded studs and nuts fixed to the aluminium part may, however, also be used for other purposes. Steel threaded studs and nuts are usually installed for applications where higher strength or frequent dismantling is necessary. Aluminium studs and nuts are applied for lightly loaded connections for internal trim, electrical harnesses, equipment attachment, etc.

Different types of steel inserts for studs and nuts are available that can be installed in pre-pierced holes in the aluminium part. Other type of studs and nuts are self-piercing and do not require prepared holes. Sometimes, installation of the inserts can be incorporated into the part forming operation, e.g. in the press line after the forming, trimming and piercing or into a hydroforming tool. They can be also installed separately at any stage in the assembly sequence including in-process and in-service repair.

After installing, some types of stud and nut inserts leave a raised element on the opposite side that must be allowed for in the design of subsequent assembly of the part. For specific applications, there are also nut inserts that are sealed to prevent any leakage through the fixed joint. Due to the large variety of possible solutions, only a limited selection can be presented here.

Three types of functional components can be differentiated:

- Press-in elements using pre-punched holes
- Elements using pre-punched holes, attached by riveting
- Self-piercing elements.

Characteristic for the application of these types of functional components is, however, the necessity of double-sided access. On the other hand, a big advantage is the possibility to insert functional fasteners directly in a stamping operation. With each stroke of the press, any number or combination of fasteners may be positioned together for multiple installation. Compared to welded nuts and studs, significant cost savings can thus be achieved.

a) Press-in nuts and bolts

Press-in (or self-clinching) fasteners are threaded inserts that are pressed into a pre-punched hole in a sheet metal by applying a steady squeezing force. Self-clinching nuts and studs are available in various shapes and different materials (e.g. steel, stainless steel and aluminium).



Different types of self-clinching fasteners

(Source: Emhart Teknologies)

Depending on the material combination, suitable measures have to be taken to avoid galvanic corrosion.

Characteristic for press-in fasteners is that the functional component is not deformed during installation. The deformation of the work piece leads to a displacement of the material out of the area of the wall of the hole into the gear ring / annular grooves of the insert. The clinch ring then locks the fastener into place. Once fully embedded (i.e. when the shoulder of the fastener is seated flush with the sheet surface), the knurled area underneath the shoulder of the fastener prevents torque out during the tightening of the mating part; a permanent connection is formed.



Screw joints realised with press-in nuts (left) and studs (right) (Source: Kerb-Konus)

The receiving hole is punched, laser cut or drilled, but not deburred or countersunk. With punched holes, the insert is preferably pressed in from the punching burr side. The press-in process takes place on a plane parallel basis using a customary press with adjustable pressure level. Self-clinching or press-in fasteners are used to create wear-free screw connections capable of withstanding high loads in thin walled components from metallic materials.



Press-in nuts and studs (Clifa[®] system) (Source: Kerb-Konus)



Installed press-in nuts and studs (Clifa[®] system)

(Source: Kerb-Konus)

Press-in nuts and studs are torque-proof, wear-resistant and capable of withstanding high loads. Press-in nuts are typically used in thin-walled work pieces with thicknesses above 0.8 mm up to 6 - 8 mm. The use of press-in studs is generally limited to metal thicknesses of 0.7 to 2.5 mm.

When installing a clinch stud, the stud is fed threaded side forward into the pre-punched hole. Initially the hole in the panel is widened by the calibrating collar, which also centres the stud. The material is deformed and pressed into the ribs under the head. Proper clinching is achieved by the displacement lobes underneath the stud head which squeeze the metal into the locking groove. An optimized tool design and the special displacement lobes guarantee a high torsion resistance and ensure that the bolt has a high load capacity. The force is applied until the shoulder of the fastener is seated flush with the sheet.



Installation of a press-in bolt (RIVTEX[®] system)

(Source: Arnold & Shinjo)

The installation of a clinch nut occurs in a similar way. The most important factor ensuring proper service performance is that the surface of the shoulder in the nut comes to rest flat against the surface of the sheet metal.

b) Elements using pre-punched holes, attached by riveting

In comparison to the self-clinching functional components, positive locking is ensured in this case by cold deformation of the functional component alone or together with the work piece.



Bolt and nut, attached by riveting

In practice, this approach is mainly chosen for the insertion of nuts. The introduction of bolts (or studs) into pre-pierced holes by riveting is only used for thicker materials.



Screw connection with a rivet bushing (Source: Kern-Konus)

The result is a rivet bushing for captive, torque-resistant screw connections capable of withstanding loads from both sides in thin-walled work pieces (0.5 to 5 mm thickness).



Rivet bushing (Anchor[®] system) (Source: Kerb-Konus)



(Source: Arnold & Shinjo)

At the start of the installation, the rivet nut is mounted in the clamps on the ram. The pre-punched sheet lies on the die. During the down stroke of the press, the rivet collar is introduced into the prepared hole. The nut shoulder comes up against the sheet. The nut is moved together with the sheet to the die and riveting begins. In the final stage, the rivet collar has been completely reshaped and an optimal connection has been achieved. Depending on the design type of the nut elements, the sheet blank is to be prepared with or without a bead.



Installation of a stud by riveting (Source: FabriSteel)

The rivet bushing is a threaded insert with a counter bored and serrated shank. It is riveted into thinwalled work pieces with pre-punched or pre-drilled receiving holes using a simple riveting tool. During this process, the riveted serrations of the shank cut into the side wall, creating an absolutely secure fastening. The special shape of the shank and the countersinking at the bottom protect the thread from damage during installation. In order to avoid deformation of thin sheet metal components, the use of a double-acting riveting tool is recommended.

c) Self-piercing functional elements

Self-piercing nuts and bolts pierce their own hole through the part. The hole is punched and the fastener is permanently fixed to the plate in one operation. Self-piercing fasteners can be installed in pre-embossed areas, but also in flat areas. Compared to the systems using pre-punched holes, additional cost savings are possible.



Self-piercing nut after installation (Source: Arnold & Shinjo)



(Source: aluMATTER)

Installation of the self-piercing nut starts with the nut clamped in the punch; the sheet metal is placed on the die. When the punch moves down, the spigot of the nut punches a hole into the sheet component. The stamping waste drops through the die (or is pressed out by an ejector) and the sheet is pressed into the nut. When the punch is in its lower position and the sheet metal is completely forced into the undercut of the nut, the connection is completed. A positive locking connection is achieved as the metal is squeezed through the special shape of the die into the circumferential locking groove of the nut. The sectional view shows how the sheet metal has flown into the special clinching feature. As a rule, the geometry of the nut does not undergo any alteration. The joint is flush on one side.



Various designs of self-piercing nuts are used in practice. The standard form of the self-piercing nut has a rectangular geometry, which ensures higher torque performance via a positive connection. Depending on the sheet thickness and the design of the nut, the sheet blank is to be prepared with or without a bead. Positive and non-positive connections, which can be loaded from both directions, are achieved via beading.

Rotational symmetrical self-piercing nuts require a special knurl on the punch collar to offer a torsionally strong seat in the sheet blank. Round shoulder nuts are used to attach dynamically highly-loaded components. Self-piercing nuts are typically applied for sheets with 0.6 to 2.5 mm thickness; special nut designs are applicable for sheet thicknesses up to 5 mm.



Self-piercing nuts for different applications:

- PIAS[®]HN piercing nuts for thicker sheets offering high mechanical strength and vibration resistance (upper left)

- Round RIVTEX[®] RX piercing nuts for automatic installation providing high resistance against push out and torque (upper right)

- PNC piercing nuts, a cost-effective solution for medium-strength applications (bottom)

(Source: Arnold & Shinjo)

Self-piercing bolts are installed in a single step in a manner such that a plane bolting surface results. Acting forces from operating loads can be equally well accepted in both traction and compression directions. After positioning the self-piercing bolt, the sheet is pre-formed, partially cut and subsequently completely cut. As the self-piercing/rivet segment of the bolt is pressed against the cutting/curling surface of the die, it is partially rolled while being widened. The joint is completely when the partially rolled end of the self-piercing and rivet section surrounds the rim of the hole completely and generates a closed, continuous, u-shaped interlock. The slug produced during the punching process is pushed against the bottom surface of the self-piercing bolt and permanently fixed to it by the locally acting high pressure.



(Source: aluMATTER)



Installation of a self-piercing bolt

(Source: aluMATTER)

In contrast to self-piercing nuts, self-piercing bolts (or studs) are, however, seldom used in practice.

8.2.1.5 Blind rivet nuts and bolts

Blind rivet nuts and bolts are thread-bearing insert fasteners. They are a most versatile solution for fastening high-strength nut or bolt threads to components when tapped threads are not possible due to small wall thicknesses. They are also used when the material is too soft to support tapped threads or where disassembly is required.



Blind riveting nut and bolt, installed by upsetting

(Source: Böllhoff)

Blind riveting elements are inserted into a pre-punched, pre-lasered or pre-drilled hole from one side and efficiently and rapidly set with a processing tool. They are mounted without counter pressure ("blindly") and can therefore be set also at hollow sections. No additional finishing is required.

Blind riveting nuts and bolts are available in many variations and sizes offering numerous fastening solutions with additional functions. Most important are blind rivet inserts which are installed by upsetting. These types of fasteners generally protrude through the backside of the application material. During the installation process, the insert collapses into a buckled fold on the backside of the application material, trapping the material between its flange and the backside fold. The result is a high resistance to pull-out loads. The folded part also serves as a load bearing surface, which absorbs the force of setting the insert. Otherwise the setting force could spread into the application material and might damage the material.



Different types of blind rivet nuts (RIVKLE[®] system):

- Blind rivet nut with hexagonal body (left)
- Blind rivet nut with splined round body (centre)
- Closed blind rivet nut (right)

(Source: Böllhoff)

Blind rivet nuts with a hexagonal or even square body (or shank) improve the torque-to-turn in metallic materials up to 200 % or more compared to plain round body inserts. They are primarily used when high resistance to turning under vibrating loads is required (e.g. in chassis components). An improved torsionally stiff joint can be also achieved by the selection of a round insert with a splined body (up to 50 % compared to a plain body insert). The closed end prevents the ingress of dirt and fluids into the thread. Blind rivets fasteners are generally supplied in steel, aluminium and stainless steel. The choice of material depends on the required strength of the blind rivet nut or stud and corrosion resistance of the final product.



Blind rivet bolt (RIVKLE[®] system) (Source: Böllhoff)

Setting of blind riveting bolts and nuts requires a rotary action to release the inserted fastener from the chuck (in case of a blind rivet bolt) or mandrel (for a blind rivet nut). Special tools for manual and automated installation are available. The spin-pull-spin setting technique is usually used. With this technique, the blind nut or stud is threaded (spun) onto the mandrel, inserted into the hole and then pulled back (without rotation) to upset the rivet nut body. Finally the mandrel is spun out.



Installation of a blind riveting nut (top) and bolt (bottom) (Source: Böllhoff)

For special applications, further blind rivet nut designs have been developed. Specifically for applications in thin-walled sheet metal, hollow sections or plastic parts, a nut with a slit shaft is offered. Thus, the shaft is splayed out on the blind side of the carrier material and forms four" petals". With the resulting large bearing surface, it is possible to achieve maximum pull-out forces.



Blind rivet nut offering maximum pull-out resistance (RIVKLE[®] PN system) (Source: Böllhoff)

Also available are blind rivet fastener with noise and vibration damping characteristics. The elastic blind rivet nut consists of a threaded metal insert captured in an elastomer or thermoplastic elastomer body. It is used for load-bearing threaded inserts in thin-walled components where noise and vibration dampening is also required.

Another type of blind rivet design relies on four flared legs expanding outwards, with a threaded inner ring for threading a bolt into, to attach the other work piece. The "tri-fold" rivet is used where a distributed load is required – spreading it across the wide area formed by the compressed legs.



"Trifold" blind rivet nut (Source: Emhart)

A different mounting method is used for the expanding inserts. An expanding insert is a single piece which breaks into two pieces during installation. The lower, threaded section of the insert is drawn up inside the upper sleeve section, causing the sleeve to expand over its entire circumference, thus swaging the insert into the hole. Expanding inserts show a reduced rear-sheet protrusion. However, because the insert does not form a buckled fold on the backside, an expanding insert has less resistance to push out forces (i.e. mainly suited for low load bearing applications).



Expanding blind rivet nut (Nutsert[®] system)

(Source: Avdel)

8.2.2 Riveting

Rivets are permanent (non-detachable) mechanical fasteners. For a long time, riveting was considered to be outdated and uneconomical. Recently, however, riveting has been rediscovered as a cost-efficient high quality joining technology for automotive applications.

In the riveting process, the parts to be joined are clamped together using an auxiliary joining element. In principle, one of the components to be joined could be designed that part of it could act as the auxiliary joining component so that no separate riveting element is necessary (e.g. a protruding flange of an aluminium casting could serve as a solid rivet). However, such connections are mainly applicable as secondary, low performance joints, suitable only in specific situations and will not be covered in more detail.

Rivet technologies can be subdivided into two groups:

- Rivet systems requiring pre-punched holes
- Self-piercing systems which do not require pre-punched holes.

The first category includes standard (upsetting) riveting systems (solid riveting and blind riveting). In particular, the blind riveting process – which can be applied from one side only – is of great importance in automotive applications.

Assembly systems used for riveting range from hand tools and simple work stations to fully automated systems. Pneumatic, hydraulic, manual or electromagnetic processes are all highly effective in driving the rivets.

8.2.2.1 Solid rivets

Solid rivets are the oldest and most reliable type of mechanical fasteners. Solid riveting requires prepunched or pre-drilled holes as well as two-sided access. Before being installed, a solid rivet consists of a cylindrical shaft (or shank) with a head on one end. Once the rivet has been inserted, the closing head is formed from the rivet shank by plastic deformation. Because there is effectively a head on each end of an installed rivet, it can support tension loads (loads parallel to the axis of the shaft); however, it is much more capable of supporting shear loads (loads perpendicular to the axis of the shaft). Bolts and screws are better suited for tension applications.



Different head shapes and shank forms of solid rivets

Rivets are classified according to the shape of the rivet head and the form of the shank. The most common types of solid rivets show a round or flat, sometimes also countersunk heads. Apart from solid shanks, also semi-tubular or tubular shanks are used in order to reduce the closing forces. Joint characteristics can vary greatly depending on the rivet type, material and geometry.

The rivet forming process and the resulting joint characteristics depend on the type of rivet shank. The shank on a solid rivet expands in the hole during the riveting process, typically forming an interference fit. On a semi-tubular rivet, where the part of the shank which protrudes beyond the back of the second work piece is hollowed out, the hollow tenon curls over on impact, drawing the parts together with minimal shank swell. Semi-tubular or tubular rivets are thus ideal to use as pivot points since the rivet only swells at the tail.

With all-aluminium constructions, cold-formed aluminium rivets are used almost exclusively. Hotformed steel rivets are only used for joining aluminium and steel, however, care must be taken to avoid negative effects of the rivet heat on the properties of the aluminium component.



Joining by solid riveting

Solid rivets are pressed through the two materials and into a solid die. When they hit the die, the penetrating end deforms and spreads out. This creates a permanent hold since the head and the

deformed tail of the rivet are both larger than the hole in the material. Once in place, the only way to remove a rivet is to cut it from the work piece.



Installation of a solid rivet

Solid rivets are used in applications where reliability and safety are top priorities (e.g. in structural parts of aircrafts), but also in critical automotive components.

8.2.2.2 Blind rivets

A characteristic feature of blind riveting is the fact that the joining element is only inserted and closed from one side using pre-punched, pre-drilled or -laser cut holes. However, blind fasteners can be also used in joints with both-sided accessibility in order to simplify complicated assembly processes or to improve the visual appearance.

The application of blind rivets offers benefits in many joining applications. Fast and easy-to use blind rivets enable speed of assembly, consistent mechanical performance and excellent installed appearance, making blind riveting a reliable and economical assembly method. Blind rivets are available in different designs both for non-structural and structural applications. The selection depends on the respective requirements, e.g. component material and envisaged strength. Typical examples are shown below:



Different types of blind rivets

Structural blind rivets should be considered where:

- Access is not available to both sides of the assembly
- Speed of installation is required
- Skilled labour is not available
- Uniform clamping is desirable and consistency of appearance is desirable
- Fastener removal is not necessary for maintenance.
- Repair fasteners for field use by untrained personnel are needed.

a) Standard (break stem) blind rivets

Blind rivets (also called break stem rivets) proved to be an ideal joining process to support the increasing application of aluminium and the emergence of new materials as plastics in automotive design. Break stem blind rivets allowed the design and assembly of large, complex structures including tubular shapes and other closed systems.

The standard blind break-mandrel rivet consists of two components, a smooth, cylindrical rivet body (shell or sleeve) and a solid rod mandrel with a head (headed stem or tool pin) which runs through the hollow rivet shaft. Mandrels have weakened grooves where this separation occurs, and some have a mechanical lock that snaps into place. While the shaft of the mandrel is discarded after setting, the mandrel head generally remains permanently attached.



Illustration of a standard blind rivet

(Source: BRALO)

Today, many types of standard break stem rivets are offered by various suppliers. Depending on the design of the rivet body, different functions can be fulfilled.



Three basic types of rivet heads: Dome head (left), Countersunk head (centre) and Large head (right)

(Source: BRALO)

With respect to the rivet head, there are three basic types:

- The dome head is the most versatile type of head. It provides enough bearing surface to retain all kinds of materials, except those extremely smooth and brittle.
- The countersunk head allows the riveting of a bigger thickness and it is designed to obtain a flat surface, free of projections.
- The large head provides a larger bearing area compared to the dome head and offers a great resistance. It is designed for applications where a soft or brittle material must be assembled to a rigid support material.

b) Blind rivets for non-structural applications

Most types of blind rivets are of the mechanical lock type. In specific cases, however, also friction lock blind fasteners can be used. In this case, the tail end of the rivet body is not deformed. The mandrel portion of the solid stem leads to an expansion of the rivet shank when the stem is pulled into the rivet. When the friction force is sufficiently high, the stem will snap at the break-off groove. The plug portion (bottom end of the stem) is retained in the shank of the rivet giving the rivet much greater shear strength than could be obtained from a hollow rivet.



Self-plugging friction lock blind rivet: Protruding head (left) and countersunk head (right)

The main problem is that under vibrations, friction lock rivets tend to loosen and possibly fall out. In case of mechanical lock blind rivets, the stem is retained in the rivet sleeve by a positive mechanical locking collar at the tail end.


Standard break stem blind rivets for non-structural or lightly loaded applications: Standard blind rivet, Peel type rivet, Slotted rivet, Sealed rivet and Multi-grip rivet (from left to right)

(Source: Böllhoff)

A special type of blind rivet is the drive rivet. Drive-in blind rivets have a short mandrel protruding from the head that is driven in with a hammer. This causes the end of the rivet to split open. Components with through hole or blind hole can be riveted. All kinds of different material combinations are possible. However, drive-in rivets have less clamping force than most other rivets. It is an extremely effective method of joining sheets and profiles to soft and fibrous materials.



Blind drive pin rivets

(Source: VVG Befestigungstechnik)

Peel (split) rivets are break-mandrel blind rivets designed for the fastening of rigid materials to soft materials. They provide additional grip support and pull-out resistance by splaying out into three or four segments when inserted. Edges pressed onto the mandrel head that longitudinally cut the rivet body on the blind side. The rivet body is divided into four petals that bend outwards and come into contact with the material to be fastened, creating a locking head with a big diameter. The large expansion on the blind side distributes the load and the clamping force, reducing the risk of crushing and breaking of materials. Once the riveting process is finished, the head of the mandrel head falls out of the rivet body.



Split blind rivet (ARCO[®] split ends) (Source: VVG Befestigungstechnik)

Analogous to the split rivet, a blind rivet with slotted shanks form a large bearing area in the shape of a clover. The large expansion on the blind side uniformly distributes the load and the clamping force, reducing the risk of crushing and material breaking. It is ideal for applications with soft materials or materials with a low resistance to pressure. The connection is splash-proof due to the locking of the remaining section of the mandrel.



Slotted break-mandrel blind rivet

(Source: BRALO / VVG Befestigungstechnik)

The large load bearing surfaces on the blind side of the work piece also allow break stem fastening in thin gauge metals that require added fastener support. Together with large rivet heads, the joined materials are tightly clamped; an ideal joint for thin sheets or low strength material offering high resistance to pull-out loads.

Standard rivets are blind rivets with a breaking mandrel are designed for the fastening of all kind of materials when there is no need for an especially high torque force or vibration resistance. When a blind rivet is installed, the rivet is first placed into an installation tool and then inserted into the application. Activating the tool pulls the mandrel into the rivet body and through drilled or punched holes in the material layer.

When the mandrel head is drawn into the blind end of the rivet body, the rivet walls are expanded, compressing them firmly in the hole while forming a tightly clinched load bearing area on the reverse side of the material. The upset head on the rivet body securely clamps the application materials together. Finally, the mandrel reaches its predetermined break-load, with the spent portion of the mandrel breaking away and being removed from the set rivet. The remaining portion of the mandrel is captured inside the sleeve and plugs the opening in the rivet shell. The entire installation cycle takes about one second.



Installation of a blind rivet (Avex[®] multi-grip break stem blind rivet)

(Source: Stanley Engineered Fastening)

These types of break stem fasteners (open end blind rivets) are primarily found in non-structural and lightly loaded structural applications. The mandrel breaks off near the blind side head.



Standard blind rivets of the multi-grip design accommodate variations in material thicknesses

(Source: BRALO)

Standard blind rivets of the multi-grip design offer significant advantages. Unlike threaded assemblies, there are no concerns over tool clearance and secondary parts such as bolts and washers. Good bearing pressure characteristics are ensured by the expansion of the rivet walls in the hole. In addition, the edges of the machined hole are covered on both sides. Blind rivets also compensate for hole irregularities (e.g. misalignment or oversized holes). Even with hole diameters that vary within 1 mm, the fluently adjusting closing head ensures a tight fit of the rivet.

A special design of the rivet body even ensures the alternative forming of a simple or double closing head depending on the clamp area, thus allowing the bridging of a wide thickness range. For structurally loaded applications, the double closing head configuration should be chosen.



A further variant are closed end blind rivets which seal the holes by closing off the tail end of the rivet body, preventing passage of vapour or liquid around or through the set rivet and safely capturing the mandrel inside the rivet bore. Closed end break stem rivets are not used as extensively as before. Today, they are largely replaced by improved open end designs which are optimised for high strength and seal the rivet body bore with equal effectiveness.



Installation of a closed end blind rivet (POP blind rivet)

(Source: Stanley Engineered Fastening)

c) Blind rivets for structural applications

Selecting and installing the right blind rivet in the right hole is a systematic process that requires careful evaluation of the different factors affecting quality and durability of the joint. Among these are rivet diameters, grip ranges, hole preparation, head styles and corrosion resistance.

In order to prevent corrosion effects, rivet bodies and mandrels are generally made from identical materials. In all-aluminium designs, aluminium rivets are often used. However, often steel mandrels are chosen for strength reasons. Stainless steel is the preferred option, but also steel mandrels with protective coatings can be used.

For structural applications, the breaking point of the mandrel is generally shifted to the rivet head. Most important for structural applications is also the controlled expansion of the break stem rivet body. This is achieved through an appropriate design of the mandrel and selection of the rivet material. Uniform compression ensures proper locking of the stem and hole filling. The goal must be to consistently ensure that the rivet bodies deform precisely as specified and the mandrels break precisely at the planned forces.

The most reliable blind fastening solutions are offered by structural blind fasteners where – during installation – an internal lock between pin and sleeve is created also at the rivet head. The shear strength of structural blind fasteners is generated by the combined resistance against failure of pin and sleeve. This takes place along the joint's shear line between the fastened plates. Since the blind fasters form a blind side positive lock either by bulbing or expanding of the sleeve, the sleeve, assisted by the permanently secured pin, resists failure under tensile loads along its centre line. Different options for mechanically locking the pin to the sleeve have been developed.



Working method of structural blind fasteners (Source: AFS Huck)

One possibility to ensure maximum strength and resistance to vibration is the introduction of a solid circle lock under the rivet head. As the tool pulls on the pintail, the pin (mandrel) expands the sleeve and begins drawing the work pieces together. Continued pulling on the pintail draws the hollow pin head inside sleeve. The pin extrudes itself inside the sleeve and the work pieces completely expand the sleeve to match the hole of the work pieces. A solid circle lock between the pin and sleeve is formed just prior to the pin breaking flush with the sleeve head, completing the installation.



Installation of a blind fastener with a solid circle lock (Huck Magna-Lok®)

(Source: AFS Huck)

Another option is a double locking system which locks the assembly from both sides. The "breakaway" ring design lets the shear ring settle into an appropriate catch groove, ensuring a consistent clamp throughout the whole grip range. As the tool pulls on the pintail, the shear ring pushes the rivet sleeve outward, forming a bulb that compresses against and tightens the application. During bulb formation, the shear ring forms a support ring from the rivet sleeve by creating a build-up of material above the ring. The shear ring breaks free and is pressed onto the catch grooves. The pulling action continues until the internal rivet shoulder engages the lock groove on the pin and forms an internal lock. The pintail then breaks off, completing the installation. The solid pin provides an exceptionally high strength in the shear plane.



Installation of a "breakaway" ring design blind fastener (HuckLok®)

(Source: AFS Huck)

Most demanding high-tensile application (e.g. in auto suspensions) can be fulfilled with optimized mechanically locked blind fastening systems. Blind fasteners for high tensile and shear strength applications are installed using a push-and-pull design. The rivet body shows a collar which – in a second step – is locked to the pin through a "swaging" process, creating a high vibration resistant connection. Large bearing areas on both sides of the work piece ensure a permanent tamper-resistant joint.



Installation of a high tensile strength blind fastener (BOM®)

(Source: AFS Huck)

When the tool pulls on the pintail, the unique collar design delays the swaging action until the maximum allowable bulb is formed. Continued pulling on the pintail then draws the work pieces together and the swaging anvil overcomes the standoff. As it moves down the length of the collar, the collar is securely locking to the pin. Once the collar is swaged, the pin breaks.

A selection of other high strength blind rivets for various applications is shown below.

- Bulb-forming blind rivets for thin sheet applications and the joining of softer materials

The formation of a bulb in the rivet tail during installation spreads the load over a wide surface area. The increased bearing area makes bulb-forming blind rivets ideal for pull-out resistance in thin materials, and oversized or misaligned holes. The positive, mechanical pin-retention ensures structural integrity, supplying a strong, long-lasting connection. Also available are variants providing a fully sealed, visually attractive connection.



High strength break stem blind rivet for thin sheet applications (Magna-Bulb®)

(Source: AFS Huck)

The shear ring design promotes bulb formation and grip adjustment for flush break throughout the grip range. As the tool pulls on the pintail, the shear ring feature on the bolt acts to initiate bulb formation and draws the work pieces together. Continued pulling on the pintail expands the bulb to the maximum allowable diameter. The shear ring then breaks and catches on the annular grooves as the pin continues to draw down inside the sleeve. A solid circle lock between the bolt and sleeve is formed just prior to the pin breaking flush with the sleeve head, completing the installation. Breaking flush throughout the entire grip range, the Magna-Bulb fastener eliminates costly cosmetic finish work and ensures "visually" that the fastener has been installed correctly.

- Hole-filling blind rivet

Hole-filling blind fasteners are moisture-resistant. They offer a unique circle-lock feature, which means a simple visual inspection ensures it is installed properly.



Structural break stem blind rivet providing a fully sealed joint (Monobolt[®])

(Source: Stanley Engineered Fastening)

Pulling on the pintail draws the hollow pin head inside the sleeve. The pin expands the sleeve and begins drawing the work pieces together. Then the pin extrudes itself inside the sleeve and the work pieces and completely expands the sleeve to match the hole of the work pieces. A solid circle lock between the pin and sleeve is formed just prior to the pin breaking flush with the sleeve head, completing the installation.

- Structural blind rivet with interference lock

Exceptional shear and tensile strength can be achieved with an interference lock formed by a splined feature on the pin ensuring a strong vibration resistant joint whilst the large blind side bearing area spreads the load and prevents creep.

Continued pulling on the pintail after complete expansion the bulb brings a spline feature on the pin into contact with a step on the sleeve, creating an interference lock between the pin and sleeve. The pin will break close to flush in minimum grip and below flush as the grip increases.



Structural blind rivet with interference lock (Huck Auto-Bulb™) (Source: AFS Huck)

- Three-piece blind fastener

The same service performance can be realized with a three-piece blind fastener, i.e. using a separate collar similar to the lockbolt principle. In a first step, the installation tool pulls the pintail to form the bulb. Once the bulb has formed, the clamp up force is applied to the joint pulling the work pieces together. The collar material is then swaged into the pin lock grooves, trapping the clamp up load and

forming a tamper proof lock. At a pre-determined load, the pin breaker groove fractures; the pintail is detached and the joint is complete.



Installation of a three-piece Avbolt[®] structural blind fastener (Source: Stanley Engineered Fastening)

d) Pull-through blind rivets

"Pull-through" or "hollow" type rivets are used where the high shear strength of the self-plugging type of rivet is not required. This design provides excellent clamp up characteristics, but possesses inferior mechanical characteristics.

An example is the Pull-Thru (PT) rivet, a steel countersunk blind fastener designed to set surface flush on both sides of an application. It is best used in the assembly of any product where clearance is extremely limited and protrusion of the rivet body from the application surface must be either minimized or eliminated. When the PT rivet sets, the mandrel head remains integral with the mandrel, i.e. there is no danger of loose mandrel heads.



Installation of a "pull through" rivet (Pull-Tru (PT) rivet)

(Source: Stanley Engineered Fastening)

Based on this principle, the Speed Fastening[®] system for different types of blind rivets was developed. Speed fasteners are placed using a unique repetition mandrel system. The rivets are loaded into a special tool which also pulls the mandrel through the fastener body. The mandrel expands the rivet in the radial direction, ensuring clamp-up and hole fill. At the end of each cycle, the next rivet is automatically delivered to the nose piece ready for placement providing continuous feed with cycle times as low as 1.5 seconds.

The following figure shows the installation of a Chobert[®] rivet. The Chobert[®] rivet is the original speed fastener which was developed in the 1930's. It is primarily a hole filling rivet, i.e. it expands radially into the application hole. The rivet does not collapse or shorten during installation. Maximum performance is realized by interaction of the tapered inner diameter of the rivet body and the flared shape of the mandrel head. The flared mandrel head passes through the tapered bore expanding the rivet fully against the application hole and surrounding material. This ensures consistent controlled light clamp and maximum hole fill without damaging soft or brittle materials.



(Source: Avdel)

Also available are blind rivet variants that have a bulbed tail providing consistent high clamp and shear which are specifically useful for assembling softer materials. Most interesting is also the Grovit[®] rivet which was developed for blind hole applications in plastics, composites and aluminium (to be used specifically in cast components). The grooves on the Grovit rivet expand radially during installation to provide a vibration resistant joint and increased pull-out resistance.



Installation of the Avdel Grovit[®] speed fastener

(Source: Avdel)

The Rivscrew Speed Fastening[®] system has been developed for similar application areas. It is a threaded, removable speed fastener that combines the speed of rivet placement with the benefits of being able to remove and re-fasten. During installation, it expands radially to form a thread in host material.



8.2.2.3 Lock bolts

Lock bolts allow the realisation of high strength joints with a high, controlled clamp. They are specified whenever robust and reliable fastening is desired. Lock bolts consist of two parts: a pin made of high strength materials and a closing collet (collar) which is fixed onto the rivet. The pin is inserted into one side of the joint material and the collar is placed over the bolt from the other side of the joint material.

Application asks for two-sided accessibility and pre-punched or pre-drilled holes. An installation tool is used to swage the collar materials into the grooves of the bolt providing a permanent and vibration resistant fastening.



Working method of a lock bolt (Source: AFS Huck)

The shear strength of lock bolts varies according to the material strength and minimal diameter of the fastener. By increasing the diameter or selecting a higher strength material, the shear strength of the fastener can be increased. The tensile strength of lock bolts is dependent on the shear resistance of the collar material and the number of grooves it fills.

In a first step, the pin is placed into the prepared hole and the collar is placed over the pin. In the initial stage of the installation process, the tool engages and pulls on the pintail. The joint is pulled together. At the same time, the conical shaped anvil is forced down the collar, pushing the collar against the joint and generating the initial clamp. In a second step, the tool swages the collar into the grooves of the harder pin. The squeezing action reduces the diameter of the collar, increasing its length. This in turn stretches the pin, increasing the clamp force over the joint. When the collar is fully swaged, the pin breaks and the installation is complete.



(Source: AFS Huck)

There are different designs of lock bolts, depending on the specific application. The original Huck design is shown below.



Original lock bolt design (Huck C6L[®]) (left) and the BobTail[®] lock bolt (right) (Source: AFS-Huck)

The BobTail[®] system is a new style lock bolt with lower installation loads than previous style lock bolts, allowing for lighter and smaller installation tools and shorter cycle times. The standard lock bolt features such as vibration resistance, high and consistent clamp load, and high fatigue strength are still provided. Lock bolts can be also installed in tight access areas since the pintail, the part of the bolt that the tool holds onto, is so small that it now remains on the pin after swaging the collar. This eliminates bare surfaces that can corrode, tail break off noise, and picking up discarded pintails.



Installation of the BobTail[®] lock bolt

(Source: AFS Huck)

In case of the BobTail[®] system, the installation tool is applied to annular pull grooves. When the tool is activated, a puller in the nose assembly draws the pin into the tool, tension loading the joint and drawing up any sheet gap. At a predetermined force, the anvil begins to swage the collar into the pin's lock grooves. Continued swaging elongates the collar and pin, developing precise clamp. When swaging of the collar into the pin lock grooves is complete, the tool ejects the fastener and releases the puller to complete the sequence.

8.2.2.4 Self-piercing rivets

Self-piercing riveting can be classified as a single-step joining process where the prior formation of holes, necessary for conventional riveting processes, is unnecessary and replaced by a combined cutting-riveting process. It is a high-speed mechanical fastening method for point joining of two or more material layers. Two-sided access to the work piece is necessary. Depending on the type of

rivet, two technologies can be differentiated. Mainly semi-tubular (half-hollow) rivets are applied, but there are also solid self-piercing rivets.

Self-piercing rivets pierce and fasten the components to be joined in one operation, eliminating the need for insertion holes and alignment and minimizing distortion and other material changes. The process can be used on a wide variety of materials including steel, aluminium and other metals, plastic and composites, and rubber. Also dissimilar materials and pre-coated, pre-painted or pre-plated materials can be joined. Furthermore, also joining of material layers with intermediate compounds (e.g. adhesives) or materials covered with oil or other surface contaminants is possible.

With solid rivets, the punch drives the rivet which pierces the sheet plies completely. Using semitubular rivets, the punch drives the rivet which pierces the top sheet and is set into the work-piece by partially piercing the bottom layer. The lower sheet layer is not penetrated in the process. A shaped die on the underside reacts to the setting force and causes the rivet tail to flare within the bottom sheet. This produces a mechanical interlock which includes the added rivet joining fastener and creates a button in the bottom sheet.



Self-piercing riveting with half-hollow (left) and solid rivets (right)

(Source: Novelis)

Although aluminium self-piercing rivets are available, steel elements are generally used which are covered with a special protective layer to prevent galvanic corrosion.

Assembly equipment can be stationary, robotic or integrated into an assembly cell, depending on production rates and complexity of parts joined. Typically, equipment is comprised of a support structure engineered to endure setting forces up to 50 kN, ensuring rivet alignment with the die. The force used to install the rivet is generated by a hydraulic cylinder that drives a plunger against the rivet head. Approximately 70 % of self-piercing rivet applications use robot-mounted equipment. Typically, the rivet setter and die are mounted in a C-frame, which must be large enough to allow access into the areas to be riveted. In automated application, the punch rivet is separated out from a bin and conveyed to the setting tool through a feed tube. A magazine can also be used for the feeding process.

a) Semi-tubular self-piercing rivets

Self-pierce riveting is done by driving a semi-tubular rivet through the top material layers and upsetting the rivet in the lower layer – without piercing this layer – to form a durable joint. The entire process takes less than 1.5 seconds, depending on cylinder stroke and feed tube length.



Process sequence for self-piercing riveting with a semi-tubular rivet

(Source: Böllhoff)

The process starts by clamping the sheets between the die and the blank holder. The semi-tubular rivet is driven into the materials to be joined between a punch and die in a press tool either at a controlled force or speed. The rivet is forced to pierce through the punch-side sheet and while driven into the die-side sheet, it is plastically formed and forced to penetrate laterally into this sheet by the special shape of the die. The resulting rivet collar in the plastically formed lower layer acts as a mechanical interlock. The rivet may be set flush with the top sheet when using a countersunk rivet head.

The length of the rivet, the diameter of the inner die contour, the ratio of the depth of the inner die contour to the diameter of the rivet shank, and the design of the tooling mainly determine the final result of the joint and the button on the underside of the joint. Self-piercing rivets and process equipment are offered by various system suppliers. Although the operation principles are basically the same, there are variations from one system to another in, for example, rivet and die shape. Since the joints are generated by local plastic deformation the fastener and the work-piece, the joint properties may depend strongly on the chosen tooling and fastener parameters.

The combination of rivet, die and material must lead to a virtually form-fit joint. To ensure optimum conditions, an analysis of the riveting conditions and material properties is necessary, i.e. tests have to be carried out to determine:

- Appropriate rivet length
- Suitable die contour for optimum joint conditions
- Required setting force.





A most important part is the determination of the proper die design. Apart from destructive tests to determine the mechanical properties of the joint, relevant quality features such as undercut (S_H) and remaining base thickness (t_{min}) are determined in a cross section.

Semi-tubular rivets can fasten stacks of two or more layers. Current applications include up to 12 mm total thickness in aluminium (6 mm in steel). A joint made with self-piercing rivets is both leak proof and has a very high degree of joint integrity. It will not damage coated or painted surfaces; also it is compatible with adhesives or sealants. Furthermore, the joint has a higher dynamic strength in comparison to a spot welded joint. For these reasons, self-piercing riveting is more and more used in automotive applications.



Three layer Al/steel/Al joint produced by self-piercing riveting (Source: Böllhoff)

b) Solid self-piercing rivets

During self-piercing riveting with solid rivets, the rivet sits flush with the sheet and almost fully retains its original geometrical form. In contrast to punch riveting with semi-tubular rivets, the rivet is punched through both sheets to be joined. The parts of the sheet punched out during the punch process do not remain in the hollow shaft and has to be removed. Thus, the tools used must have an arrangement for allowing the removal of the punched out parts.

Two variants of self-piercing riveting with solid rivets are used industrially. One possibility is that the material in the region of the cut joint is forced to flow around the concave rivet due to the compressive action of the shoulders both on the punch and the die. In the other case, the applied rivet offers one or more grooves in the rivet shaft. The punch-side rivet is flat while the die plate has a ring-shaped contour that presses into the bottom sheet layer in order to create the undercut necessary for the connection strength.



Different form-locking methods when self-piercing riveting with solid rivets

In addition to the geometrical parameters, the selection of the rivet material is most relevant for a highquality riveted joint; the material used for the rivet depends on the parts being joined and determines the strength and corrosion behaviour as well as the punching performance and formability during processing. Solid punch riveting involves the use of aluminium, coated steel or stainless steel rivets.



Cross sections of punch rivet joints:

EN AW-6181A (1.5 mm) in EN AW-5754 (2.5 mm) (left) and St1203 (2.0 mm) in EN AW-5754 (2.0 mm) (right)

(Source: Kerb-Konus)

The solid punch rivet can be placed by C-bow or column presses, hand held or robot tongs as well as by custom made devices. Two or more material layers of the same or different materials up to a combined sheet thickness of approximately 9 mm can be automatically joined. Solid punch rivets offer large tolerance allowances regarding sheet metal thickness and strength variations, i.e. high strength steel grades (R_m up to approximately 1700 MPa) as well as less ductile materials (e.g. aluminium castings or fibre reinforced composites) can be also riveted if they are placed on the punch side. However, the strength of solid punch riveted joints is inferior to that of semi-tubular riveted joints.

On the other hand, solid punch riveting is suitable for visible applications; there is minimum piece part distortion and a flush surface on punch and die side is possible. When aluminium solid punch rivets are used, they can be even reworked mechanically.

In punch riveting, the work pieces are clamped to the bottom die by the hold-down device. They are then punched by the solid rivet that acts at the same time as the blanking die. The punching waste that is created with the through punch is removed automatically. When the stop-point is reached, both the hold-down device and rivet punch are flush with the work piece surface. In the last phase, the contour of the bottom die and the compressive force applied by the rivet punch and hold-down device cause the material to flow in the opposite direction of the punch movement, pressing the material into the peripheral shank groove(s) in the rivet.



Process sequence for self-piercing riveting using solid rivets (Source: Kerb-Konus)

The rivet is not deformed in this process. Rivet shaft diameters between 3 and 5 mm are generally used, the standard rivet length varies between 3.5 and 9 mm.



Typical shapes of Tuk-Rivet[®] solid punch rivets (left) and an aluminium heat shield assembly consisting of a sheet and a die casting (right)

(Source: Kerb-Konus)

The obvious difference between semi-tubular and solid punch rivets is that the semi-hollow rivet creates an elevation ("button") on the die side, whereas the solid punch rivet shows a level surface. Moreover, almost no distortion of the work piece takes place with the solid punch rivet. Solid punch rivets are, in addition, better suited for joining high-strength and ultra-high-strength materials (tensile strengths higher than $R_m = 1600$ MPa) and aluminium castings with lower ductility. With regard to joining directions, the only restriction with solid rivets refers to ultra-high-strength materials saying that the brittle/hard material must be put on the punch side.

The self-piercing rivet technologies outlined above involve using special patented rivets. In specific applications, the auto-piercing technology offered by Capmac Industry which is based on the use of standard solid rivets could be also used.



Auto-piercing riveting process (above) and finished joint (bottom) (Source: Capmac)

c) Practical application

Self-piercing rivets can be used to fasten not only similar and dissimilar metals, but also different type of materials, as long as the bottom material layer is a ductile material. Actual ranges are dependent on application requirements and material types. Two conditions are required for the successful use of self-piercing rivet systems:

- Access for tooling on both sides
- Material thickness, strength and ductility need to fall within the practical range for self-piercing technology.

Generally, the range for sheet metal applications is a total joint stack thickness of up to 6 mm for steels, and 12 mm for aluminium. However, there are many exceptions in production, such as for high-strength steels, aluminium castings, and multi-layer joints with metallic and non-metallic layers. Furthermore, new requirements are constantly expanding fastening capability ranges.

The minimum thickness for steel and aluminium is 1.6 mm. For best results – when dissimilar materials are being joined – the rivet is generally applied from the direction of the **thin sheet into the thick sheet**, or from the **low strength material into the high strength** material. If this is not possible, it is recommended that the bottom layer thickness is not less than one-third the joint stack thickness.

Self-piercing rivet joints have virtually the same static strength (in tensile and peel loading) as resistance spot welded joints. However, self-pierce rivet joints generally show higher strength and stability under dynamic load. The joints need to be of a lap-type configuration. In terms of part size or configuration, the only condition is that the rivet actuation cylinder and C-frame can access the joint. It is important to allow for die clearance, to specify adequate flange dimensions and to avoid closed box sections.



Car body assembly by self-piercing riveting

(Source: Audi)

Just as in the case of conventional riveting, different head forms are used for simple and complex components and for varying loads. The rivet elements can be stored in magazines or supplied directly. The rivets can be protected against corrosion by surface coating. Today, chromate and galvanised steel rivets are generally used for self-piercing riveting aluminium. If necessary, also aluminium self-piercing rivets made from special high-strength aluminium alloys can be applied.

The cycle time for a self-pierce riveting system is generally the same as for spot welding. The process can be easily automated; it offers high productivity and consistent joint quality. Self-piercing rivets are generally installed with a servo-driven or hydraulic tool allowing proper control of the rivet-setting process.

A process load monitoring incorporated into the installation tooling system allows tracking and notifying the operator of any variance in joint quality.

d) Joint design

In principle, joint configurations suitable for resistance spot welding can be also used for self-piercing riveting.



Possible joint configurations

(Source: Avdel)

The following recommendations for joint design should be observed:

- Flange width should be sufficient to contain the deformation zone
- Adequate spacing between rivets must be maintained
- Ensure good fit up of components.

In case of semi-tubular rivets, the flange width (D), i.e. the distance from the edge to where the rivet is placed, must be sufficient to ensure that there is enough material to contain the deformed rivet as well as the surrounding deformed material.



Otherwise, the button may break out of the edge of the flange or cause distortion of the component. Proper overlap of the material layers to be joined and a correct flange width also help to ensure proper alignment between the work-piece, punch and die. A pre-clamping step may be helpful if joining a flange width close to the minimum width. Similar considerations are also applicable to solid punch rivets. As an example, for a rivet with a diameter of 4 mm, the minimum flange width should be about 12 mm.

The length of a solid punch rivet should correspond to the thickness of the material ply. In case of semitubular rivets, the rivet length L can be estimated as follows:

- 3 mm rivet diameter: L₃ = thickness of sheet plies + 2.5mm
- 5 mm rivet diameter: L_5 = thickness of sheet plies + 3.5mm.

Rivets should be spaced to avoid contact with neighbouring rivets or the strained area immediately around them. Since the rivets are made of harder material than the work pieces, riveting over an existing joint may result in serious damage to the tooling. Placing several rivets too near to each other may cause distortion of the joint. A pre-clamping step can help to minimise this. Poor fit-up and alignment may reduce joint performance and accelerate tool wear.

A precise relationship between part fit-up, alignment and joint quality is not easy to quantify. However, good control of these two variables will help ensure that the layers of material to be joined are drawn together properly as the rivets are driven and set.

e) Quality criteria

In self-piercing riveting with semi-tubular rivets as well as solid rivets, the strength of the joint is determined by the amount of undercutting.

Since the tool and rivet dimensions are carefully tuned to each other and to the joint thickness, the amount of interlock is determined by the "compression measure", which can also serve as a non-destructive quality criterion when compensated for the position of the rivet head within the joint.



Quality criteria for semi-tubular (left) and solid rivets (right)

8.2.2.5 Clinch riveting

With the introduction of the solid punch or clinch riveting technology, the clinching technology was further developed. The materials to be joined are complemented with an additional retaining member. Clinch riveting has its preferred application in the field of automotive lightweight constructions, respectively for the joining of hybrid components.



Clinch riveting, a spin-off development of clinching

(Source: TOX Pressotechnik)

The actual rivet connection is made using a simple cylindrical rivet in a joining process including a combined deep drawing/pressing operation. A simple, cylindrical rivet is pressed-in and formed during the clinching process. Just like with the clinch joint, the materials to be joined are not cut, but only deformed inside a die cavity. The result is a very strong joint, even when used with thin materials.



Installation of the TOX®-ClinchRivet

(Source: TOX Pressotechnik)

The special advantage of the clinch riveting technology is the simple, symmetrical and inexpensive rivet. This provides for a trouble-free feeding and pressing operation.

The high strength values of the TOX[®]-ClinchRivet joint result from the formed full rivet firmly positioned in the joint and the work hardening of the sheet metals in the neck zone created during the deep-drawing process. The die with solid and flexible elements enables a closely controlled guidance of the rivet, ensuring higher process reliability even with unfavourable production conditions (e.g. when applied with gaps and adhesives between the metal layers). An additional benefit of the closed rivet shape compared to the "open" forms of semi-tubular self-piercing rivets lies in the absence of any adhesive or air pockets, and their potentially higher risk of corrosion in the riveted joint. Furthermore, the essentially smaller die diameter permits the utilization of significantly smaller flanges when clinch riveting is used instead of self-piercing riveting.



Quality control of TOX®-ClinchRivet joints

(Source: TOX Pressotechnik)

The quality control dimension "Remaining rivet height + remaining bottom width" can be easily and nondestructively determined and provides an excellent quality measure. It is proportional to the shear and tensile strength of the joint, provided that the joining parameters have been appropriately observed.

8.2.2.6 Tack high-speed joining

The name "tack joining" describes a simple and fast joining process. It requires only one-sided access; however, there is a need for a relatively stiff counterpart. Therefore a preferred application is a sheet/profile joint. No pre-punching of holes is required. Especially advantageous are the very short joining and cycle times of less than 1 second.



Classification of RIVTAC® high-speed joining within the mechanical joining processes

(Source: Böllhoff)

In the tack joining process, a nail-like fastener is accelerated to high speed and driven into the parts to be joined. In a single step, the tack penetrates both components and joins them efficiently without prepunching. The ogival tip of the tack displaces the material without forming a slug. The component material

flowing in joining direction forms the draught. Material flowing contrary to the joining direction is taken in by the ring groove or lower head ring groove of the tack.

The speed, which can be controlled via the adjustable pressure, is optimised to suit the material type and the wall thickness. An important prerequisite is a sufficient stiffness of the joining parts, ensuring that the joining parts can sustain the penetration impulse of the tack without major deformation.

Joint stability in the lower joint section is achieved by a combination force fit (resulting from the restoring force of the displaced material) and of form fit. During penetration, the material experiences a momentary temperature rise in the joining zone and the locally heated material flows into the knurled shaft of the tack leading to a high form fit.



Tack joining element (RIVTAC®)

(Source: Böllhoff)

In the tack setting process, the joining energy is transferred onto the tack via a punch piston which accelerates the tack is to high speed. Only a single process step, concluded in a split second (approx. 6 ms), is required, which has a positive effect on the processing time. A wide range of different applications can be joined with only one tack geometry. A disadvantages is the inevitable impulse noise during joining, in particular when the components favour a large-scale sound radiation. Also required is a sufficient support which can be achieved by a sufficient inherent stiffness of the components or by a temporary rear support.





A tack joint is characterised by the tack head which is directly placed on the cover sheet and a draught on the back which tightly encloses the tack shaft. For this joining process a preferably consistent and complete contact of tack head and cover sheet is desired, which can especially be attributed to optical and corrosive aspects. The following illustration also indicates test criteria for joint quality, which can be examined by visual inspection or in a cross-section. Another quality control measure is on-line process monitoring the joining process.



Joining zone formation and test criteria for joint quality

(Source: Böllhoff)

The material combinations which can be joined with a single tack geometry reach from aluminium materials to a wide range of plastics (including fibre-reinforced plastics) to ultra-high strength and press hardened steel. Multiple-layer joints can also be realized. In combination with adhesive, joints can be achieved for which a constant thickness of the adhesive layer in the joint flange is specified. Due to the high tack setting speed, the adhesive layer acts as a third rigid layer, preventing the adhesive from spreading uncontrollably.



Three-layer aluminium profile joint with adhesive produced by RIVTAC[®] high-speed joining (left) and sheet-profile joint (right)

(Source: Böllhoff)

EAA Aluminium Automotive Manual – Joining

9. Adhesive bonding

Content:

- 9. Adhesive bonding
- 9.0 Introduction
- 9.0.1 Adhesive joints
- 9.0.2 Benefits of adhesive bonding
- 9.0.3 Adhesive bonding in the automotive industry
- 9.0.3.1 Sealants
- 9.0.3.2 Anti-flutter adhesives 9.0.3.3 Hem flange bonding
- 9.0.3.3 Hem flange bonding 9.0.3.4 Structural bonding
- 9.0.3.5 Interior bonding
- 9.0.3.6 Glass bonding
- 9.0.3.7 Repair bonding

9.1 Design aspects

- 9.1.1 Design for adhesive bonding
- 9.1.2 Types of Adhesive Bonds
- 9.1.3 Design for adhesive bonding
- 9.1.4 Structural analysis and modelling
- 9.2 Adhesive selection
- 9.2.1 Selection criteria
- 9.2.2 Type of adhesives
- 9.2.2.1 Two-step acrylic adhesives
- 9.2.2.2 Cyanoacrylates
- 9.2.2.3 Epoxy adhesives 9.2.2.4 Hot melt adhesives
- 9.2.2.4 Hot melt adhesives 9.2.2.5 Polyurethane adhesives
- 9.2.2.6 Elastomeric adhesives
- 9.2.2.7 Anaerobic adhesives
- 9.2.2.8 Plastisols
- 9.2.2.9 Rubber adhesives 9.2.2.10 Modified phenolics
- 9.2.2.11 Pressure-sensitive adhesives
- 9.3 Adhesive application
- 9.3.1 Application techniques
- 9.3.2 Adhesive curing
- 9.4 Surface pre-treatment for adhesive bonding
- 9.4.1 Aims of a surface pre-treatment
- 9.4.2 Surface pre-treatment of aluminium alloys
- 9.4.2.1 Surface cleaning
- 9.4.2.2 Conversion-Coating Systems 9.4.2.3 Thin anodised films
- 9.4.2.3Thin anodised films9.4.2.4Primer coating
- 9.4.2.5 The total system approach

9.5 Properties of adhesively bonded aluminium alloys

- 9.5.1 Mechanical and thermal properties of adhesives
- 9.5.2 Performance of adhesively bonded joints
- 9.5.3
- 9.5.3.1 9.5.3.2
- Long-term durability Effect of moisture on a bonded joint Test methods for evaluating adhesive bond durability

9.0 Introduction



Robotic application of structural adhesive to aluminium sheet

Adhesive bonding is a reliable, proven and widely established technique for joining metals, plastics, composites and other materials. In recent years, adhesive bonding has been used more and more in automotive joining for a variety of components including closures and structural modules. The application of adhesive bonding instead of or in combination with conventional joining technologies enables a significant weight reduction of the vehicle, an increase of the body stiffness, improved crash performance/safety and enhanced NVH characteristics. In addition, adhesive bonding allows the realisation of new, innovative designs, in particular mixed material designs including high strength steels, non-ferrous metals, plastic and composites offering further lightweighting potentials. Also possible are the introduction of new, efficient assembly opportunities.

In fact, the introduction of adhesive bonding into car manufacturing can be viewed as one of the key enabling technologies for the production of aluminium closures and all-aluminium car body structures. In general, exclusively bonded joints are today not applied for structural purposes. However, several automakers have demonstrated that aluminium bodies assembled using adhesives in combination with self-piercing rivets, spot welds or other joining techniques equal or exceed conventional stiffness requirements (see 10.1.2). Purely adhesively bonded joints show limited strength in peel and cleavage and thus punctiform joints provide peel-stopping points in the case of overload (e.g. crash). The combination of the assembly methods ensures a high fatigue strength and offers economic benefits because there is no need for fixtures during the polymerisation of the adhesive (and – compared to purely adhesive bonding – assembly times can be shortened).

Adhesive joining is defined as the process of joining parts using a non-metallic substance (adhesive) which undergoes a physical or chemical hardening reaction causing the parts to join together through surface adherence (adhesion) and internal strength (cohesion). Ideally, the joining surfaces should be clean (although adhesives are also often applied over stamping lubricants) and generally require proper preparation of the aluminium surface. Furthermore adhesives require time and/or temperature to cure (harden). However, the cure can also be achieved in inevitable post-processing steps, such as during the paint cycle.

Today, many different types of adhesives, pre-treatment methods and processing techniques are available and on-going developments are looking for further improvements. The selection of the optimum solution involves a close consideration of multiple criteria, close contact with the respective suppliers is recommended. In some cases, extensive experimental testing may be required.

9.0.1 Adhesive joints

Adhesive joints are multi-layer organo-metallic materials whose strength depends on both the geometrical design and loading type as well as the material properties of the joined components, the adhesives and/or the characteristics of the bonded surfaces. A direct combination of these factors in order to determine the characteristics of the bond is, however, generally not possible.

The characteristics of an adhesively bonded joint are basically determined by three components:

- The wetting behaviour of the surfaces to be joined
- The bonding (adhesion) of the adhesive to the joined component
- The inner strength (cohesion) of the adhesive.

Adhesion is the result of mechanical interlocking between the adhesive polymer and the rough material surface (mechanical adhesion) and the physical and/or chemical interaction between the adhesive and the material (material-specific adhesion). Mechanical adhesion is determined by the (micro-) morphology of the joining surfaces, i.e. the anchoring of the hardened adhesive in the material surface.

Material-specific adhesion summarises the attractive forces between the molecules of the adhesive and the surface(s) to be bonded. These forces have a maximum range of about 0.5 nm. Thus, a necessary condition for attaining high adhesion forces is that the adhesive is able to wet the material surfaces spontaneously and uniformly. This can be achieved by the selection of an adhesive with an appropriate viscosity and a lower surface tension than the material(s) being bonded. In general, polymers and other organic materials have low surface energy while metals and ceramics have high surface energy. Therefore, careful consideration should be taken when bonding plastics and composites to aluminium. Either the adhesive needs to have a low enough surface energy or the surface of the plastic needs to be modified such that it can accept the adhesive.

An important factor to keep in mind is that the incoming aluminium surface typically shows multiple surface chemistries due previous processing. This can include both inorganic and organic contaminants including, but not limited to, lubricants, oxides, dust, and dirt. These contaminants will prevent the adhesive from bonding to the base material and must be removed to prepare the surface for bonding. If the adhesive would be simply applied to the typical aluminium surface, the adhesive would not form a long-term bond to the base material, but to impurities and reaction products present on its surface. The surface contamination will reduce bond strength by interfering with the ability of the adhesive to form a proper bond (resulting in a weaker bond or a reduced bond area).

For this reason, aluminium-based materials are normally subjected to a suitable cleaning and surface treatment before bonding. It is absolutely necessary to first remove impurities in a surface layer of undefined thickness (i.e., dust, dirt, oil, grease, fat, water). Also the subjacent inactive adsorption layer created by foreign molecules (i.e., water, gases) must be removed. Furthermore, the native (heat-generated) oxide layer ("reaction layer") which is both inert and inhomogeneous must be generally replaced as well.



Typical aluminium sheet surface layers

Adhesive bonding in the automotive industry presents an interesting challenge. General instructions for adhesive bonding usually include measures such as "clean the mating surfaces thoroughly", "use an adhesion promoter" and/or "use a primer". Priming can be an appropriate surface coating that provides a more consistent, bondable surface. An adhesion promoter may activate the surface, providing chemical groups ready to latch onto the adhesive when applied. However, both the use of adhesion promoters and primered parts is usually limited to adhesive bonding processes in final assembly operations (e.g. the attachment of interior and exterior components to an already lacquered car body). Such measures are not used in the body shop.

The surfaces of all the aluminium parts (sheets, extrusions and components ready-to-assemble) which will be adhesively bonded in the body shop are generally cleaned and properly pre-treated by the material or part supplier. But in manufacturing of the body-in-white, there is no specific surface cleaning of the components before assembly (i.e. before hem flange bonding and structural bonding). Proper cleaning of the body-in-white is only carried out prior to painting.

In the stamping plant, only a light cleaning of the pressed panels may take place occasionally. Consequently, it is most important that the adhesives applied in body-in-white manufacturing are compatible with the protective coatings and/or processing lubricants applied in any subsequent operations at the material manufacturer or in the press shop (e.g. during finishing, transport and stamping). The adhesive must be able to displace, absorb or otherwise tolerate any specifically applied coating. Proper care must be taken to avoid any additional contamination of the material surface.

9.0.2 Benefits of adhesive bonding

The application of structural adhesives, alone or in combination with other joining methods, enables significant improvements of the overall efficiency and effectiveness of a car body structure and is therefore a key element of aluminium-based lightweight design solutions. The use of adhesives in automotive manufacturing processes offers the designer additional possibilities to exploit new, innovative design and manufacturing concepts. Adhesives are particularly popular for light-weight constructions, where thin-walled parts (wall thickness < 1 mm) must be joined. Adhesive bonding also allows combining different types of materials (e.g. aluminium with other metals, plastics and composites) which otherwise could not be reliably joined or would require additional measures (e.g. to avoid galvanic corrosion effects). Adhesives generally feature excellent adhesion to properly surface pretreated aluminium and a wide range of other substrates including steel, magnesium, plastics and composites. For mixed material structures, most interest is in joining aluminium to thermoset composites, such as carbon fibre reinforced epoxy composite. However, aluminium can be bonded to thermoplastic composites as well.

In adhesive bonding, unlike most other joining methods, the bulk of the material is not involved in the joining process. Adhesive bonding is an attachment to a surface and does not interfere with the aluminium metallurgy or results in thermally or mechanically weakened metal zones. Compared to a conventionally joined structure, the entire interfacial surface in the joint can be bonded. The uniform stress distribution over the entire bond face has a very positive effect on the static and dynamic

strength of the joint, i.e. the static and dynamic stiffness of the vehicle structure is significantly increased. More rigid body structures have higher resonance frequency modes and faster structural damping, providing improved vehicle handling and NVH characteristics (reduced vibrations and noise). In particular in combination with other joining methods, also crash performance and fatigue strength are improved by adhesive bonding, allowing an additional weight reduction of the body structure (e.g. by the application of lower material gauges).

Apart from pure strength transfer, adhesively bonded interfaces can fulfil additional functions, including damping or insulation. Adhesives can also act as sealants, preventing loss of pressure or liquids and blocking the penetration of condensation water. Proper gap filling eliminates crevice corrosion and galvanic corrosion of dissimilar joints is hindered by the presence of an insulating layer. Properly selected adhesives can join materials with different coefficients of thermal expansion (as long as the coefficients of thermal expansion are not radically different). The adhesive may also acts as an electrical and thermal insulator.

Another advantage of the adhesive bonding technology compared to conventional joining techniques is the improved aesthetics of the final assembly (although there may be a need for fillet control in order to obtain a completely "clean" aesthetic which can be accomplished by precise metering during application). There are no visible weld seams, rivet heads or discolorations and pre-treated and/or lacquered surfaces are not damaged. Thus, adhesive bonding may minimizes or eliminates secondary operations like grinding and polishing. Most beneficial is also its gap filling potential. Adhesives can bridge large gaps between panels and improve the overall appearance compared to other joining methods. Therefore, in many cases, joining and sealing operations can be combined.

Properly designed adhesively bonded joints have distinct advantages over those made by mechanical or thermal joining methods. Whereas spot welding and riveting result in localized stress peaks, adhesive bonding achieves uniform distribution and absorption of stress loads. Adhesive bonding eliminates holes or other local disruptions as observed in connection with mechanical joining techniques. The cured adhesive ensures a uniform stress distribution which leads to strong and stiff joints with improved fatigue performances. A riveted joint, for example, is highly stressed in the vicinity of the rivets and failure tends to initiate in these areas of peak stress. Similar, inhomogeneous stress distributions are observed with other punctiform joining methods. A continuous welded joint is, like a bonded joint, uniformly stressed, but the metal in the heat affected zone will have undergone a change in performance. In addition, adhesive bonding enables the design of smooth external surfaces and integrally sealed joints with minimum sensitivity to crack propagation.



mechanical joint



bonded joint

Adhesive bonding offers also additional design possibilities over conventional joining methods. As an example, large panels of thin gauge material can be more effectively stiffened by bonded stiffeners. Towards the edge of the sheet, the top hat stiffener may be cut away in order to reduce stress concentrations even further.



Stiffening of large panels

In automotive assembly, the rapid and easily automated application of adhesives proved to be a clear benefit. For example, whereas thermal joining methods can cause distortion of the individual components which may affect the overall assembly performance, adhesive bonding does not distort sufficiently inflexible parts.

However, there are also some limitations. A basic limitation compared to some mechanical joining methods is that adhesively bonded structures (similar to welded structures) cannot be easily dismantled for in-service repairs. Care must be given to use of adhesive joining on thin metal automotive panels where localised modulus (strength) variations may increase the potential for appearance concerns known as "read-through". The biggest problem is that assembled joints must be supported until the adhesive has sufficiently cured. This can significantly slow down the assembly process as it is necessary to allow for the relative slow strength build-up during assembly and processing of adhesive bonds. An alternative is to use temporary fixtures that ride along with the assembly processing. The generally applied solution is to combine adhesive bonding with (resistance or laser) spot welding or with mechanical joining techniques such as, for example, self-piercing riveting or clinching as part of the overall assembly process. Combining welding or riveting with adhesive bonding is known as weld-bonding or rivet-bonding, respectively. These methods are most commonly used today and will be covered in more details under "10. Hybrid joining techniques".

9.0.3 Adhesive bonding in the automotive industry

Adhesive bonding has been applied in automotive manufacturing for a long time. However, adhesive bonding for structural application is relatively new. Today, the variety of adhesives on the market is enormous. The biggest problem is the selection of the optimum adhesive for a specific application, depending on its processing behaviour (application and curing characteristics) and the final service performance (in particular long-term stability).

Moreover, development activities are going on and improved adhesives, surface preparation methods and application systems are continuously introduced giving body designers yet even more cost-effective and/or higher-performing assembly tools. Considering the amount of sealants and caulks used in modern car body construction, a most promising development route is the combination of the role of sealants with the function of adhesives in the joints and thus gain improved structural performance at little additional cost.



Adhesive application to light metal intake manifold (Source: Henkel)

9.0.3.1 Sealants

Before paint is applied to the car body, joints and crevices must be sealed to prevent possible damage of joined substrates by protecting against unfavourable environmental influences, penetration of air, moisture or dust, leakage of hazardous materials and gasses, corrosion, etc. They also allow simplified designs and, in many cases, seam sealers are also used to provide a superior painted finish.

Seam-sealing materials must show very good corrosion resistance and gap filling properties. Additional requirements include the ability for smooth manual and automatic application, stability and wash out resistance during cleaning, electro-coating and lacquering, and durability in service.



Manual and automatic application of sealants (Source: Sika / Henkel)

Sealants form a "bridge" between different part surfaces. The strength of the bond depends upon adhesion of the sealant to the surface of the substrate and cohesion (strength within the sealant itself). The physical and chemical properties of sealants depend to a large extent on the selected raw material basis.



(Source: Henkel)

The basic difference between adhesives and sealants is that sealants typically have lower strength and higher elongation than adhesives. Since the primary objective of a sealant is to seal assemblies and joints, sealants need to have sufficient adhesion to the substrates and resistance to environmental conditions to remain bonded over the required life of the assembly. When sealants are used between substrates having different thermal coefficients of expansion or differing elongation under stress, they need to have adequate flexibility and elongation. Low shrinkage after application is often required too.

Sealants generally contain inert filler materials and are usually formulated with an elastomer to give the required flexibility and elongation. Normally, they have a paste consistency to allow the filling of gaps between substrates. Conventional sealants are one-component adhesives which generally rely on the moisture in the air to cure.

Many newly developed sealants are designed to also perform structural functions. They are partially cured in the assembly process with full curing during the paint processing. Urethanes, epoxies and vinyl-plastisols are widely used as adhesives/sealants. Also solid hot melts are growing in popularity.

9.0.3.2 Anti-flutter adhesives

The function of an anti-flutter adhesive is to reduce or eliminate any "fluttering" or vibration of the outer and inner panels relative to each other. Anti-flutter adhesives are commonly used on horizontal closure panels such as bonnets, trunk lids or roofs with less application on vertical panels like doors.

A characteristic of anti-flutter applications is the relatively large thickness of the bond line (up to several millimetres). In addition, the anti-flutter adhesives are generally not applied as a bead; but as local "drops" strategically spaced across the inside surface of the outer panel, aligning with the shape of the inner panel. The applied anti-flutter adhesives have a low modulus and a lower strength than for example hem flange adhesives. The very low modulus enables anti-flutter adhesives to function as a stress-relief interlayer, improving the read through performance on thin panels.



Application of anti-flutter adhesive/sealants

(Source: Sika)

The materials used in this application include vinyl plastisols, elastomeric or rubber-based, and warm-applied adhesives. New elastomeric rubber based technologies exist, known as high damping foams, which provide additional acoustic (NVH) performance, by converting the kinetic energy of vibration into thermal energy. A specific surface preparation is generally not necessary.

9.0.3.3 Hem flange bonding

The closure panels, i.e. doors, bonnets, trunk lids, tailgates, etc., of cars are usually made from an outer panel which is hemmed (or clinched) over an inner panel around its periphery. Whilst hemming alone would produce sufficiently strong mechanical joints, adhesives are widely used in these flanges to provide improved strength, stiffness, crash performance and corrosion protection.

Hem flange bonding takes place in the body shop, i.e. before painting. At this moment, the stamped panels are usually covered with processing lubricants (rolling oil, drawing oils or dry lubricants, etc.). Residues of these processing lubricants will be present when the adhesive is applied since before hemming, the pressed panels will be subjected only to a light cleaning step, if at all. Therefore hem flange adhesives have to be compatible with the lubricants applied in earlier processing steps as well as other potential contaminations.



Adhesive application for hem flange bonding (Source: Sika)

After the adhesive is applied to the outer panel either as an extruded bead or a sprayed film, the inner panel is positioned and the hem flange is formed. Hem flange adhesives are applied using swirl, bead or fine jet nozzles. In order to avoid "zero gap" in the hem flange, hem flange adhesives often contain glass beads to ensure constant distance between outside and inside panels. A hem flange includes a very thin adhesive film (around 0.1 mm). Bead size is carefully controlled in order to completely fill the bond line, but to avoid that excessive adhesive is squeezed out as it would contaminate the equipment.

A cure step may be introduced at this stage, such as induction curing. This can be a full cure or just enough to prevent any movement of inner to outer panel during subsequent processing. The induction process is a rapid cure technique that begins the chemical cross-linking process within the adhesive so it is "set". The cure is usually not complete, but will be finished in the paint ovens. However, the resulting pre-gelling holds the adhesive in place and improves resistance to wash-out of the adhesive.

The most widely used hem flange adhesives are one-part epoxies. They are sufficiently thixotropic that they stay within the bond line through application, mating of the inner and outer panels, attachment of the closure parts to the body-in-white, and movement through the paint line until final cure in the paint ovens.

In some applications, an elastomeric adhesive/sealer that functions both as a hem flange adhesive and an anti-flutter adhesive is used. Also two-part epoxies are used as hem flange adhesives. In this case, cure starts under ambient conditions and is completed in the paint ovens. Specific formulations of two-part epoxies improve wetting through lubricant films allowing hem flange bonding without any lubricant removal. Furthermore, improved adhesives have been produced with higher modulus (to increase body stiffness), instant grab (to eliminate the need for extra fixings and alignment aids) and more rapid development of green strength.

9.0.3.4 Structural bonding

Structural adhesives must be able to form and sustain a strong bond between the adherents in various environmental conditions over a long period of time. The majority of current automotive bonding applications are based on epoxy adhesives. This is due to the combination of various advantageous characteristics such as oil absorption capacity, good wash-out resistance, durability, and outstanding mechanical characteristics across a wide temperature range. An important requirement is also good processing performance (automated applicability, compatibility with mechanical joining techniques, resistance spot welding, etc.). While for pure stiffening applications the modulus of the adhesive is most important mechanical parameter, a combination of high modulus and high flexibility is essential for adhesives applied to improve vehicle component behaviour under high strain rates. Both parameters are important for optimum distribution of stress, optimum energy transfer between outer panel and carrier and broadening of the deformation area.



Structural bonding in the body shop (Source: Sika)

Special impact resistance-modified epoxy structural adhesives allow additional load pathoptimization, thus further improving crash performance. They are mainly used for structural bonds in the car body, but also in hem flange bonding for closures. Compared to previous generation structural adhesives, new generation adhesives show greater elongation at fracture, reduced bonding strength loss after corrosion, and reduced loss of dynamic peel strengths at low test temperatures.

In special applications, two-component polyurethane adhesives are used. Polyurethane adhesives are characterized by high strength and stiffness values at high elongation levels, resulting in improved impact and fatigue properties of bonded joints. Choices in adhesive chemistry may be influenced by surface conditions (absence of soils and oxide layers) and application process conditions.

In addition to the established epoxy systems, innovative rubber-based structural adhesives with glass transition temperatures of over 90° C are becoming increasingly popular due to an attractive cost-benefit ratio. Many closures are bonded with low modulus rubber-based adhesives. These adhesives, however, show some disadvantages over epoxy adhesive systems. The static and dynamic strengths are significantly lower than epoxy adhesives and they are generally less corrosion resistant. Also their temperature resistance is limited as their glass transition temperature is at the upper limit of the operating temperature range of the vehicle.

The relatively high elastic modulus of epoxy resin-based structural adhesives can result in read through effects when bonding exterior panels. Since sheet thicknesses have continuously decreased over recent years, read through becomes an increasingly relevant issue. A low-modulus adhesive can prevent such problems. Consequently, very flexible epoxy resin adhesives with low modulus have been developed which possess significantly higher static and dynamic characteristics than rubber-based adhesives. The new adhesive technology unites sealing and reinforcing characteristics in a single product. This is an especially significant improvement in the application of multi-material joining where both adhesive and sealing (insulating) characteristics are required to prevent the development of corrosion in the joint.

9.0.3.5 Interior bonding

Bonding applications for the interior of cars include a wide variety of substrates, adhesives, sealers, and requirements. Although most applications can be considered as trim bonding, there are also some with structural character. For example, the headliner may be designed in such a way that it contributes to the structural integrity of the roof.

Bonding applications for the interior of cars occur in the final assembly stage of the vehicle assembly plant. The bonding process needs to be as clean, quick, and as easy as possible. Therefore, cyanoacrylates adhesives, pressure sensitive adhesives, tapes, and hot melts are most popular. Two-part epoxies that cure at ambient temperatures have limited application. New technologies
receiving customer acceptance include hybrid cyanoacrylate-epoxy based adhesives which produce rapid fixture capability with more robust and longer term joint performance.

9.0.3.6 Glass bonding

There are several areas of glass bonding, such as windshield, rear window, side windows, or headlamps. In earlier applications, the primary function was to keep the glass in place and to act as a sealant.

New structural requirements take advantage of the large bond area and the strength of the glass to make the joint load-bearing and thus part of the load bearing structure. Therefore stronger adhesives/sealants are needed, and urethanes are usually chosen for these applications. They offer the required strength as well as the flexibility to bond two materials with very different expansion coefficients and can seal against moisture.

The adhesive can be one- or two-part polyurethane, with the second part more of an accelerator since the adhesive will eventually cure on its own in the presence of moisture. Other adhesives are also being investigated. Innovative direct glazing technologies are now available that eliminate the need for application of surface primers over painted surfaces



Windshield application (Source: Sika)

9.0.3.7 Repair bonding

In many repair situations, a replacement part will need to be attached to the vehicle. Adhesives may be involved in the manufacture of a new part, which is then employed as a replacement unit in the repair shop. For these applications, the same or similar adhesives as used in the original joint will be used, as the part is prepared before shipping to the repair shop. Examples include replacement hoods, rear deck lids or roof panels where adhesively bonded flanges or hems may be present.

For the repair of structural members, there is generally a lack of high temperature curing facilities in the repair shop. The selection of adhesives for structural repair is likely to be limited to two-part epoxy formulations, but with significantly reduced joint strength and performance compared with the adhesive used in original manufacture. Consequently, this will lead to relatively low strength repair bonds compared to welded alternatives. Hence, structural bonding repairs should always be supplemented by mechanical reinforcements such as rivets, screws, clinches, etc.

Since the staff of repair shops will likely have limited experience in the use of adhesives and metal preparation techniques, bonding practices must be simple, safe and quick. In addition, the aluminium surface pre-treatment techniques originally used in automotive manufacturing are generally not applicable. Therefore special methods for local surface pre-treatment will have to be applied (e.g. flame spraying (Pyrosil[®] technology), modified grit blasting techniques or manually applied pre-treatments (Bonderite[®] /Prep-n-Cote)). It has been demonstrated that certain two-part epoxy

adhesives, used in conjunction with suitable in-situ cleaning/pre-treatment practices can provide a total system with very good bond durability performance. Such systems form the basis of a mechanically reinforced bonded joining technology for structural repairs.

9.1 Design aspects

When designing adhesive bonding applications, optimizing joint design is an important consideration. An adhesive joint requires sufficient surface contact between mating work pieces to allow for a squeeze-out effect, a tiny bead that squeezes out from between the clamped, mated surfaces. An understanding of the various possible joint designs for application is an essential step to finding the optimum bonding solution. During the design phase, particular attention must be paid to the potential mechanical loads (static and dynamic). Furthermore, assembly, manufacturing methodology, and cost factors must all be taken into account when proposing a joint design.

In some cases, suitable measures can be already taken in the design of the individual components, e.g. by proper adaption of the cross section of an extruded aluminium profile. Where tongue and groove type bonded joints are possible, properly designed aluminium extrusions may be often the best solution.



Aluminium extrusions designed for adhesively bonded joints

(Source: Lotus)

9.1.1 Design for adhesive bonding

Adhesive bonding involves the formation of a load-carrying element connecting the joined components. The material in the cured adhesive bond (plastic or rubber) is not as strong as aluminium. In practice, however, this can be easily compensated by providing a larger contact surface. An optimal joint design for adhesion is therefore an overlap configuration of sufficient width.



Types of adhesive joint design:

- a) Lap (overlap) joint, formed by partially placing one substrate over another
- b) Offset lap joint, similar to the lap joint
- c) Strap joint (single or double), a combination of an overlap and a butt joint
- d) Butt joint, formed by bonding two objects end to end
- e) Scarf joint (angular butt joint), cutting the joint at an angle increases the surface area
- f) Cylindrical joint, a butt joint between two cylindrical objects

(Source: Henkel)

Butt joints are generally not applicable for adhesive bonding; certainly not for components with small wall thicknesses. Scarf joints would be highly suitable for tensile-shear loading since the load distribution is in this case most favourable, however, they can be used only for parts with larger material thicknesses and are complicated to manufacture. In general, the practical alternative is a (single or double) strap joint which is a combination of an overlap joint with a butt joint.

Bonded joints may be subjected to a range of stresses including tensile, compressive, shear or peel and often a combination of these. Adhesives perform best in shear, compression and tension. They behave relatively poorly under peel and cleavage loading.



Loading types relevant for adhesive joints

A bonded joint needs to be designed so that that the adhesive is used to its fullest mechanical advantage. The main advantage of adhesive joining over welding, riveting and screw fastening is that the load is distributed more evenly at right angles to the loading direction. In the loading direction, however, this is valid only for scarfed joints. Within a given structure, the bond should be aligned so that it is stressed in its strongest direction. The design should reinforce the tensile,

compressive and shear stresses. For maximum strength, cleavage and peel stresses should be designed out of the joints as far as possible.

When an adhesive bond experiences a tensile or compression stress, the joint stress distribution is represented as a straight line. The stress is evenly distributed across the entire bond.



Joint stress distribution in tension (left) and compression (right)

(Source: Henkel)

A shear stress results in two surfaces sliding over one another. On loading a simple lap joint, the main force resolves into a shear component along the plane of the interface with a peel component at right-angles. The stresses are highest at the edges of the bond causing strain and twisting. Adhesives accommodate high loads in shear because there is a large active joint area.



Shear stress distribution

(Source: Henkel)

A cleavage stress occurs when two rigid substrates are opened at one end. When a flexible substrate is lifted (peeled) from the other substrate, a peel stress develops. Cleavage and peel loading concentrate the applied force at one end into a single line of high stress.



Cleavage (left) and peel stress (right)

(Source: Henkel)

Furthermore tensile loading resulting in peel or cleavage peel is not desirable for adhesive bonding. On the other hand, many joints designed for spot welding or riveting emphasize peel mode loading because welds and rivets perform relatively well in peel. As an example, the standard T (or coach) joint is not a suitable design for adhesive bonding. Therefore, the direct conversion of an existing joining system to adhesive bonding is not a good approach.



T-peel joint under tension

In most cases, the stress distribution throughout a T joint can be improved by leaving intact the small amount of resin squeeze-out and tapering the overlap to remove the sharp, right-angle ends. Appropriate design concepts which have proved most successful also exist for corner joints, closed-sectioned profile joints and tube joints.

In the manufacture of automotive structures, however, a large percentage of adhesively bonded joints will be peel-type joints in order to enable the application of an additional joining method (e.g. clinching, self-piercing riveting, friction stir spot welding, laser stitch welding or resistance spot welding). The use of adhesive bonding in combination with spot-type joining techniques significantly increases the joint stiffness and will result in a positive contribution to the overall stiffness of the vehicle structure.

For this reason, the strength of bonded T-peel joints in peel must still be considered. The amount of adhesive in the fillet region has a considerable effect on the stiffness of the T-peel joint. As the fillet size increases, the strength of the T-peel joint also increases. During manufacturing, however, the fillet size will not be controlled and will be influenced by panel fit-up and alignment. It is therefore important to develop experimental test data based on a conservative fillet size.



Definition of fillet size in T-peel joint

Joints that favour shear loading are the best types for adhesive bonding. Some examples of shear joints that can be used in automotive construction are shown below. Aluminium, other metals, or composites can be successfully combined using any of these approaches.



Shear joints suitable for automotive design (from left to right): Double lap, Step (offset) lap, and Hem joint

The following design guidelines which should be considered when designing an adhesive joint:

• Maximise shear/minimise peel and cleavage

Justification follows from the stress distribution curve. Whereas in the case of shear, both ends of the bond resist the stress, stress is located at one end of the bond line for cleavage and peel.

• Maximise shear/minimise tensile

For compression and tension, stress is uniformly distributed across the bond. In most adhesive films, the compressive strength is greater than the tensile strength. Thus an adhesive joint is less likely to fail under compression than under tension.

Joint width more important than overlap

The ends of the bond show a higher stress level than the centre of the bond. If the bond width is increased, stress will be reduced at each end and the overall result is a stronger joint. If the overlapping length is greatly increased, however, there is little, if any, change in the bond strength ("increase the joint width rather than the overlap area").

Another aspect that must be considered when designing adhesively bonded joints is the fact that bond strength decreases with increasing temperature. Proper selection of the applied adhesive helps, but compared to conventional joining methods like welding or mechanical joining, the thermal degradation of adhesively bonded joints is nevertheless significant. It is also important to note that an adhesive can behave like rubber at room temperature, but can become like glass at subzero conditions.

Bonded joints distribute stress relatively well. However, stress is rarely evenly distributed across the entire surface area of a bonded joint. Generally, stress is greatest at the edges of the joint. The local concentration of any subsequent loading stress is the higher, the stiffer the chosen adhesive. In order to avoid unnecessarily high stress on the adhesive and the surface that has been bonded, the chosen adhesive should not be stiffer than necessary. Also thicker bonded joints reduce the concentration of stress at the edges of the joint. Thus, especially when using a stiff adhesive, it is important that the design spreads any load evenly throughout the bonded joint in order to reduce edge effects.



Lap joints modified to reduce stress at a joint's edges (Source: Sapa)

9.1.2 Structural analysis and modelling

Finite element analysis (FEA) and fracture mechanics methodologies are routinely used for designing bonded joints. Bulk mechanical properties and single lap shear data taken off an adhesive technical data sheet are not valid for design purposes. The reported adhesive bulk properties do not reflect the true adhesive bond strength. Single lap shear data, while representative of relative performance, do not provide pure shear mode values. It is necessary to obtain genuine engineering design data from actual peel and shear tests. These measurements provide actual engineering data that reflect the surface condition expected to be used in practice.

For modelling, the interfacial regions between the adhesive and the bonded surface are often represented as viscoelastic elements rather than rigid elements. To model the bond, spring elements are placed at the interface. Spring elements are necessary because the load is applied through one side of the joint, into and out of the adhesive, and through to the other side of the joint through a viscoelastic fluid (adhesive), as opposed to a fairly rigid, homogeneous material (welds or rivets). Welds and rivets can be inserted into the model and defined as rigid elements, or another protocol commonly used by the analyst can be modelled. This is particularly important in modelling crash behaviour.

Modelling the adhesive joints as springs is, however, an inconvenient modelling procedure as spring properties are not intrinsic in nature and are not mesh-size independent. Modelling of adhesives with solid elements can provide good prediction of the mechanical behaviour of adhesively bonded joints, but is time-intensive and impractical for large vehicle models. Various attempts have been made to develop simplified finite element models; however, all these approaches have limitations and drawbacks. There is still a need for further developments before an efficient, numerical method for the simulation of the crashworthiness of an adhesively bonded car structure is available.

9.2 Adhesive selection

Identifying a suitable adhesive is a complex task due to the range of available adhesives and the specific application requirements. Such requirements can include specific structural and environmental performance, such as load transmission, media exposure, leak tightness, electrical conductivity, heat conductivity, and damping. This necessitates a holistic consideration of the entire process – from the design and surface pre-treatment to integration into the relevant production process.

9.2.1 Selection criteria

When an adhesive is selected for a specific application, it is important to ensure that the chosen adhesive fulfils all the engineering and service requirements (good adhesion to the applied materials), static and dynamic strength (with defined levels of strength retention after environmental exposure), impact peel strength (especially at low temperatures), creep (ability to carry load at temperature), etc. Equally important, however, is to consider whether the processing characteristics of the adhesive are compatible with the planned assembly process. The adhesive must have sufficient fluidity and the necessary time to mould itself to the surface topography of the substrate. Fast setting, high-viscosity adhesives rarely permit this. In this case, it might be advisable to first apply a low-viscosity primer. Other relevant processing characteristics are related to the application and curing properties of the adhesive:

- What type of dispensing equipment is required; is the adhesive easily dispensed using automated and/or manual methods?
- Is special curing equipment (e.g. ovens or UV light sources) required?
- What is the influence of environmental factors (i.e. temperature and relative humidity) on the curing rate of the adhesive?
- How much time needs the adhesive to develop sufficient strength to proceed to the next step in the assembly process?

In addition to the correct chemical and mechanical properties of the adhesives applied in automobile fabrication, their robustness in the manufacturing system must be considered as well. The adhesive must be easy to handle, it must offer suitable rheological properties for automated application (pumpability, dispensability, etc.). Most important is also material consistency from batch to batch and storage stability. Furthermore, two-part adhesives must have a tolerance of off-ratio mixing.

Another aspect is sag and slump resistance during application. During assembly, there is always the possibility of larger gaps present between the flanges due to poor panel fit-up or misalignment. The adhesive should have sufficient gap bridging capability and the cured joint must offer consistent properties over a certain range of bond line thicknesses. Experience showed that for both single-lap and T-peel structural joints, there is very little joint property change over a bond line thickness range of 0.2 to 0.5 mm. Additional requirements exist if the adhesive should act simultaneously as a sealant.

Further complicating the adhesive application process are the unique needs of an automotive production line. Adhesives are applied to separately assembled parts (e.g. closure panels like bonnets or doors). These parts are then attached to the car body structure which may also include adhesively bonded joints. After completion of the body-in-white, the assembled structure will go through a cleaning and painting process before additional components are attached by adhesive bonding in the final assembly. The applied adhesives need to have the ability to stay in place during subsequent assembly processes as well during all the different surface treatment steps (i.e. washout resistance and electro-coat compatibility are generally necessary). Also required is proper planning and control of the curing conditions (e.g. time, temperature and/or humidity) at all steps.

An important aspect is the fact that adhesive bonding in structural joints is usually combined with a secondary joining technique (hybrid joining). As an example, when combined with mechanical joining methods, it must be ensured that the displacement of the adhesive does not lead to disturbances within the adhesive film. It is most important that the adhesive still completely protects the flange because any open gap may increase the corrosion risk. When combined with resistance spot welding, it must be ensured that the adhesive will not interfere with the formation of the weld nugget. The adhesive must be fluid enough to flow out of the weld area without leaving significant residue that would weaken the weld, but not so fluid that it escapes the joint area or contaminates the weld equipment. In this context, it must be kept in mind that the heat introduced during spot welding will also affect viscosity of the adhesive. Furthermore, the adhesive must not catch fire, smoke excessively, or produce any toxic gases.

9.2.2 Type of adhesives

Adhesives are generally classified by either the way they are used (specifically by the way they are setting) or by their chemical type. There are only three ways of setting (although combinations of these may occur):

- Setting through drying (i.e. the solvent or water evaporates). Since most of the drying must take place through the material, this adhesive type is not suitable for bonding aluminium to aluminium or other metals. However, it could be used for example for bonding porous materials to aluminium.
- Setting through cooling. Some of the drying adhesives can be heat activated. They are applied to one or both surfaces and dried. When joining, the adhesive is activated (melted) on one of the parts and quickly joined with the other. This type of adhesive (not to be confused with hot melts which are applied hot) enables rapid assembly, but is only suitable if one of the materials is readily deformable.
- Setting through curing (chemical reaction): The two most common types of forced cure adhesive are one and two component systems. One component system adhesives are supplied in a ready to use form, which cures when exposed some external energy (heat, radiation or moisture). Two component system adhesives utilize the mixing of two different materials which creates a chemical reaction that causes the polymerization (curing or setting) of the materials.



Illustration of adhesive curing methods

(Source: Henkel)

The strongest adhesives solidify by chemical reaction, with the less strong types hardening by a physical change. In the following, the most important types of adhesives are shortly described, for more detail please contact the adhesive suppliers.



(Source: Henkel)

9.2.2.1 Two-step acrylic adhesives

Two-step acrylic adhesives consist of a resin and an activator ("hardener"). The resin component is a solvent-free, high-viscosity liquid, the activator is typically a low viscosity liquid. When the resin and activator contact each other, the resin begins to cure very rapidly at room temperature (typical fixture times are 15 seconds to several minutes), depending on the gap width. The resin can be fully cured with light or heat (typical heat curing time 10 - 20 min at 150 °C). Heat curing normally offers higher bond strengths, improved thermal resistance and better chemical resistance.

Two-step acrylic adhesives require no mixing and bond to lightly contaminated (oily) surfaces. The hardener is generally spread on one surface and the adhesive on the other. These types of adhesives show high peel strength and toughness as well as good environmental resistance. They bond well to a range of materials, but are not particularly suitable where gap filling is required. They are best suited for small to moderately large surfaces.

9.2.2.2 Two-part acrylic adhesives

Two-part acrylic adhesives consist of a resin and an activator, both of which are normally highviscosity liquids. The activator is chemically similar to that of a two-step acrylic, but it is delivered as a high viscosity liquid. The two components are mixed just prior to dispensing, i.e. a homogenous one-part material is dispensed. The curing times are somewhat longer than those which can be achieved with two-step acrylics. These adhesives can therefore also be used for thicker joints. For high volume applications, meter mix dispense equipment is used. Two-part acrylics cure at room temperature (5 – 30 min), but cure can be accelerated with heat. Contactless handling and good ventilation is required as the components have a strong smell.

Two-part acrylic adhesives offer high peel and impact strength as well as good environmental resistance and bond to moderately contaminated surfaces. As a consequence, acrylic adhesives are now becoming more and more common.



Extrusion pumps for low to high viscosity adhesives (Source: WIWA)

9.2.2.3 Cyanoacrylates

Cyanoacrylates are one-part, room-temperature curing adhesives that harden very quickly in contact with moisture. They are available in viscosities ranging from water-thin liquids to thixotropic gels. When pressed into a thin film between two surfaces, the moisture present on the bonding causes the adhesive to form a rigid thermoplastic with excellent adhesion to most substrates. Typical fixture times are 5 to 30 seconds.

Cyanoacrylates are particularly suited for bonding aluminium to plastic parts and rubber. A bond between two aluminium surfaces takes longer to harden than a bond between aluminium and plastic or rubber materials. However, the peel and impact strength of cyanoacrylates is pretty poor, also their solvent resistance is relatively low. Thus, cyanoacrylates are not appropriate for the bonding of the metal parts in an automobile. The automobile-specific environmental conditions (exposure to moisture, temperature variations, solvents like gasoline or oil, salt spray, ultraviolet light, etc.) will lead to severe degradation of the bonded joint.

In addition to standard cyanoacrylates, there are many specialty formulations with somewhat enhanced performance properties. New two-part cyanoacrylates adhesives can provide larger gap filling capabilities, faster curing, and open/closed cavity cure potential.

9.2.2.4 Epoxy adhesives

Epoxy adhesives consist of an epoxy resin plus a hardener. They are supplied as one and two-part systems with viscosities ranging from thin liquids that can be sprayed to thixotropic pastes which must be pumped. They have very good gap filling properties. Upon cure, epoxies typically form tough, rigid thermoset polymers with high adhesion to a wide variety of substrates and good environmental resistance. When exposed to elevated temperatures, epoxy adhesives may become rubbery, but cannot melt as a thermoplastic material would.

A big advantage of epoxy adhesives is that there are a wide variety of commercially available resins, hardeners and fillers. Thus the performance characteristics of epoxy adhesives can be tailored to the specific requirements of almost any application. Basically, there are two types of epoxy adhesives: Toughened (flexible) epoxies and glassy matrix (stiff) epoxies. Glassy matrix epoxies are extremely strong and rigid, and they resist shearing at very high force levels. Toughened epoxies are more flexible, but break under lower shearing forces and the bond is fairly heat-sensitive. Toughened epoxies contain a dispersed, physically separated, but chemically attached rubber phase which improves fracture and impact resistance. They are successfully used in many structural applications since they offer a suitable balance of toughness and durability. There are both stiff and elastic, two-component epoxy based adhesives.

When using a one-part heat-cure system, the resin and a latent hardener are supplied already in a mixed state and can have extended shelf life (storage) when refrigerated. By heating the system, the latent hardener is activated causing cure to initiate. The epoxy will normally start to cure rapidly in the temperature range 125 - 150 °C; curing temperatures of 150 °C and times of 30 to 60 minutes are typical. Heat curing also generally improves bond strengths, thermal resistance and chemical resistance.

When using a two-part system, the resin and hardener are packaged separately and are mixed just prior to use. This allows the use of more active hardeners, i.e. two-part epoxies will rapidly cure at ambient conditions. Two-part systems are normally mixed by passing them through a mix tip and dispensed as a single, homogenous liquid. However, two-component epoxy adhesives that cure at room temperature can rarely be loaded at temperatures above 80 °C. Epoxy adhesives with considerably higher heat resistance require heat curing, but also offer higher strength and improved durability.

Epoxy resins can accommodate significant addition of fillers, etc., without adversely affecting desired adhesion properties. Any single property (peel strength, shear strength, durability) can be improved by selecting an alternative chemistry, but usually to the detriment of the overall balance of properties. Formulating to meet specific application requirements provides epoxy adhesives with a wide range of properties that includes good chemical resistance, excellent adhesion, good mechanical properties, and little shrinkage, but also optimum cure and other processing conditions. In addition, epoxy adhesives can be formulated to be either conductive or insulating.



Multi-material application rendering of epoxy adhesive on aluminium shock tower to steel rail (Source: Henkel)

9.2.2.5 Hot melt adhesives

Hot melt adhesives ("hot melts") are mostly one-part, solvent-free mixtures of thermoplastics that are solid at room temperature. At dispensing temperatures (typically higher than 175 °C), they show low to medium viscosity and can be easily processed. After dispensing, hot melt adhesives cool and rapidly build up their internal strength allowing efficient assembly and further processing. But the high curing speed also has a drawback. When the hot adhesive meets a cold surface, setting is often so rapid that the adhesive does not properly wet the surface. The non-wetting effect is more distinct with increasing temperature difference between surface and adhesive as well as with increasing thermal conductivity of the substrate. Therefore, metals are sometimes heated before bonding with hot melts.

In the cured state, hot melt adhesives can vary in physical properties from soft, rubbery and very tacky to hard and rigid. Hot melts have excellent long term durability and resistance to moisture, chemicals, oils, and temperature variations. They are usually designed for light loads, only polyamides and polyesters can withstand limited loads at elevated temperatures without creep. Adhesion to plastics is good, but rather poor to metals since the thermoplastic hot-melt adhesives usually set too quickly.

The performance of the hot melt varies widely based on their chemistry:

Ethylene vinyl acetate (EVA) hot melts are the "original" hot melt. They have good adhesive to many substrates, lowest cost, but typically have the poorest temperature resistance (upper service limit is about 50 °C).

Polyamide or polyester hot melts are higher cost, higher performing adhesives with good temperature resistance (up to 150° C), but long term strength at 70 – 80 °C is already quite low. The application temperature for this adhesives type is approx. 250 °C, i.e. a shielding gas must be generally used since at this temperature, the adhesive breaks down if it comes into contact with oxygen.

Polyolefin hot melts are specially formulated for high adhesion to plastics.

Because hot melts are based on thermoplastic polymers, they can be repeatedly heated to melt and cooled to solidify. Thus, they can be used to create bonded joints that are thermally detachable and can be re-attached later. However, this unique characteristic limits the temperature resistance of hot melt bonds and explains their tendency to creep when subjected to continuous stress or elevated temperatures. Many thermoplastic hot-melt adhesives also become brittle in cold environments.

Today, curing hot-melt adhesives are available too. These adhesives are based on polyurethanes that cure on contact with moisture. They are solid before the curing process actually starts. The application temperature of the polyurethane-based hot melts is considerably lower than for the thermoplastic hot-melt adhesives.



Application of hot melt adhesives

(Source: Nordson)

9.2.2.6 Polyurethane adhesives

Polyurethane adhesives are supplied as one and two-part systems which range in viscosity from self-levelling liquids to non-slumping pastes. They are made of urethane polymers with chemical based of isocyanate group. There are three different types of polyurethane adhesives:

- Two-component polyurethane adhesives
- One-component polyurethane adhesives curing by heat (rigid)
- One-component polyurethane adhesives curing by moisture (elastic).

Polyurethane adhesives are extremely versatile and can range in the cured form from highly elastic elastomers to rigid thermosets. The elastic polyurethane adhesives are cured by moisture whereas the rigid polyurethane adhesives are cured by heat input.

Single component systems typically consist of non-volatile urethane pre-polymers. The elastic variants are cured by polyaddition; moisture acts as the hardener. Since the cure is dependent on moisture diffusing through the polymer, curing is comparatively slow (hours) and the maximum depth of cure that can be achieved in a reasonable time is limited at approximately 10 mm. However, because the curing time mainly depends on the moisture concentration, curing can be accelerated through the addition of a product containing mostly water in a mixing nozzle, resulting in a homogeneous and fast cure. The curing temperature has only a small effect on the curing times and 70 °C is a practical upper limit. Moisture-curing polyurethane adhesives show an elongation to fracture of up to 600 %, but their strength level reaches only about 8 MPa.

In rigid one-component systems, temperatures in the range 100 $^{\circ}$ C – 200 $^{\circ}$ C are required to unlock the isocyanate groups necessary to produce the polyurethane. Heat curing results in a lower curing rate compared to that of polyurethane adhesives cured by moisture, but produces a highly cross-linked thermoset polymer with a strength of about 15 MPa, a maximum elongation to fracture over 20 % and high fatigue resistance. Innovative snap-cure one component hybrid polyurethane technologies are being introduced to facilitate shorter cycle times in assembly operations.

Two-component polyurethane adhesives can be elastic or rigid, depending on the structure the adhesive acquires once it has fully cured. For the resin, polyols with low molecular weight are used; for the hardener low molecular weight pre-polymers with isocyanate ends. After mixing the two components in the right proportions, the curing process of the adhesive starts immediately. The fast

cure usually means that the adhesive must be applied by machine. In case of the elastic variant (elastomer structure), the main advantage of the two-component system compared to the one-component variant is a very good creep resistance. The rigid two-component polyurethane adhesive (thermoset structure) offer an interesting combination of cohesive strength (about 25 MPa) and flexibility (maximum elongation to fracture over 50 %) that results in a good fracture toughness. A specific advantage is the minimal dependence of the adhesive properties over a service temperature range between approx. – 30 °C to + 80 °C. Some types of two component ambient cured polyurethane adhesive can be applied over some surface soils without need for pre-cleaning or oxide removal.

A preferred application of two-component polyurethane adhesives is structural bonding in the assembly area, i.e. after electro-coating and/or painting, in particular for the combination of dissimilar materials (e.g. metals to plastics and fibre reinforced composites) or pre-painted metal assemblies. This is due to the fact that there is no need for surface pre-treatment or external heating for curing. It is also possible to fill joints that have large gaps.

Initially, polyurethane adhesives were considered as possible replacements for epoxy adhesives for health and safety reasons. However, the risks of isocyanates means that they cannot be seen as a safer option than epoxies. When using epoxy, skin allergies are the greatest risk, for polyurethane adhesives, breathing difficulties dominate.

9.2.2.7 Elastomeric adhesives

Elastomeric adhesives, specifically silane modified polymers and silicones, are available in one-part moisture curing systems as well as two-part static mix systems that range in viscosity from self-levelling liquids to non-slumping pastes. On curing, they form soft thermoset elastomers with excellent thermal resistance. Silane modified polymers and silicones offer good adhesion to many substrates, but their applicability as structural adhesives is limited by the low cohesive strength. Elastomeric adhesives are typically cured via reaction with ambient humidity at room temperature, although formulations are also available which can be cured by heat, mixing of two components, or exposure to ultraviolet light.

Since the cure of moisture-curing elastomers is dependent on moisture diffusing through the elastomeric matrix, the cure rate is strongly affected by the ambient relative humidity and the maximum depth of cure is limited to about 10 mm. Complete curing depends on the film thickness and can take several days. This occurs because the reaction between the reactive groups on the polymer and the reactive groups on the substrate surface is slower than the crosslinking reaction of the products groups with themselves.

Silicones remain highly elastic at low temperatures (-75 °C), and also have very good temperature stability; up to 200 °C continuous exposure and up to 300 °C for short periods. The properties of silicones remain virtually unchanged over this temperature range. Silicones are nearly inert to chemicals and have excellent resistance to moisture and weathering. Bonds made with silicones can, however, only be subjected to relatively small mechanical loads. That is why they are chiefly used as sealants. They are used for bonding metal when the low bond strength is offset by the higher flexibility and resistance to low temperatures. Several types of moisture curing silicones are available depending on the bonding conditions and substrates.



Liquid gasket sealant adhesive robotically dispensed onto an aluminium cover

(Source: Henkel)

Two component silicone adhesives are available with a range of properties and cure rates. The initial strength and rate of strength build-up is typically higher than that of moisture cured silicones. The curing reaction can take up to 24 hours. Meter mix equipment is used to pump the two components through a mixing element. The mixed adhesive is then dispensed in bead form.

9.2.2.8 Anaerobic adhesives

Anaerobic adhesives are based on synthetic acrylic resins and only harden when in the presence of a metal and absence of oxygen. Anaerobic adhesives work by completely filling gaps between metal components. They are often termed locking compounds as they are used to secure, seal and retain close-fitting parts. Using an anaerobic adhesive augments the holding force of a mechanically joined assembly and prevents loosening under vibration and protects the joint from corrosion. They are typically used as thread lockers, thread sealants, flange sealants, etc.

Anaerobic adhesive are thermosets and provide high shear strength. They maintain their integrity at temperatures up to 200 °C. The bonded joints are, however, very brittle and are not suitable for flexible substrates. Curing occurs exclusively in the joined area and only relatively small gap widths can be bridged (maximum gap about 0.1 mm). Special formulations have been developed which provide improved overall performance under thermal and mechanical stress and are less surface-sensitive, i.e. which can be applied also on oily and contaminated surfaces. Besides their bonding function, anaerobically curing adhesives are often simultaneously used for their sealing properties because they are very resistant to oils, solvents and moisture. However, they cannot be used for bonding to plastics.

9.2.2.9 Plastisols

Plastisols are single-component adhesives that are applied as a paste consisting of solid polyvinylchloride (PVC) particles dispersed in a liquid plasticizer. In order to form a bond, the applied adhesive is heated so that the thermoplastic PVC swells and can take up the plasticizer. The two-phase system converts to a single-phase system by incorporating the plasticizer in the swollen polymer. This process occurs at a temperature between 150 and 180° C and results in an adhesive film consisting of a plasticized polymer. The cured product may be a soft, rubber-like material or a tough, hard solid.

Plastisols have high flexibility and good peel resistance. However, they are sensitive to shear stress and also tend to undergo creep when subjected to loads. For most applications, as an adhesive sealant this has no adverse effects. Being thermoplastics, they only have limited resistance to heat.

If overheated, for example during spot welding, there is also the risk of liberating hydrochloric acid. A typical area of application for plastisols is in vehicle body construction. Besides their bonding function, they also serve to seal joints against moisture, to dampen vibrations and to increase the rigidity of the body. Plastisols can also be used to bond non-pretreated metal sheets as they have the ability to take up oil. On the down side, PVC plastisols give rise to environmental problems when recycling the bonded components, and consequently have become increasingly replaced by alternative adhesives, such as epoxy resins.

9.2.2.10 Rubber adhesives

Based on solutions or latexes, rubber adhesives solidify through loss of solvent or water. Rubber is particularly suited as a bonding element because of its flexibility. In many situations, sealants must be able to expand and contract because they are sometimes used on parts that experience temperature variations. Styrene is one type of rubber adhesive commonly used in automobile manufacturing because it adapts well to temperature and pressure changes. However, they are not suitable for sustained load.

9.2.2.11 Modified phenolics

Phenol-formaldehyde adhesives cure at temperatures between 100 and 140° C depending on the composition of the adhesive. During the cure, water is liberated from the adhesive. As the curing process requires temperatures above 100° C, the liberated water is present in gaseous form. In order to avoid foaming, phenolic resins are cured under pressure. Pure phenolic resins are very brittle and sensitive to peel stress, thus modified phenolic resin adhesives which contain additives in order to increase the elasticity are generally used. They offer good mechanical properties and temperature stability. In the automobile, they are used for bonding brake and clutch lining materials.



Brake linings are bonded using modified phenolics (Source: www.adhesives.org)

9.2.2.12 Pressure-sensitive adhesives

The special feature of pressure sensitive adhesives is that they do not solidify to form a solid material, but remain viscous. As a result, they remain permanently tacky and have the ability to wet surfaces on contact. Bonds are made by bringing the adhesive film in contact with the substrate and applying pressure. If inadequate pressure is applied or the processing temperature is too low, bonding faults such as bubbles or detachment can occur. Since these adhesives are not true solids, the strength of pressure sensitive adhesives decreases when the temperature is increased. Pressure sensitive adhesives also exhibit a tendency to undergo creep when subjected to loads. They are typically formulated from natural rubber, certain synthetic rubbers, and polyacrylates. Pressure sensitive adhesives are often used to temporarily hold components in position during assembly.



Attachment of decorative trims with adhesive tapes

(Source: Lohmann)

Roof and decorative trims are often bonded to the vehicle using adhesive strips. On the one hand, the trim has to bond reliably at all temperatures and under all weather conditions. On the other hand, the adhesive tape must remain invisible for cosmetic reasons. The tape has to be adapted perfectly to the thermal expansion characteristics of the trim and the bodywork. As the trim usually expands more in heat and contracts more in cold weather than the metal or the plastic to which it is bonded, the tape must be able to compensate for these differences.

9.3 Adhesive application

Developments in robotics, control systems and metering, dispensing and monitoring equipment have made adhesive application a highly automated, controlled and repeatable process. However, various measures have to be taken in order to guarantee consistent, reliable high quality bonds.

Adhesives must be stored under correct conditions (one-part adhesives usually refrigerated) and should not be used after their expiration date. Also adhesive containers must be kept covered and free of contaminants. Temperature must be carefully controlled. Some warming can be useful to lower the viscosity during compounding, but care must be taken not to start a chemical reaction that might prematurely cure the adhesive. Mixing is generally achieved under vacuum to minimize air and moisture entrapment, neither of which would benefit an adhesive bond.

9.3.1 Application techniques

The possible application processes, depending on the consistency (solid or fluid) of the adhesive and on the application method used (manual or mechanised). Viscosity of the applied adhesive must be tailored to the application. Depending on the situation, the adhesive can for example maintain the bead shape until the force is applied to fill the bond line or it can flow into the bond line and fill any unevenness in the surface of the substrate.

In automotive manufacturing, automated application of adhesives is generally used. A wide range of equipment is available to apply virtually any adhesive or sealant during the manufacturing process. The optimum adhesive application method depends on the specific production requirements and the type of adhesive being used. Manual application is limited to repair bonding and the production of niche vehicles. Typical handgun systems can be cartridge-based or hose fed. Cartridge-based systems are portable, but require frequent refilling and costly cartridges. In addition, product quality strongly depends on operator skill. With selected nozzles for producing bead or spiral spray patterns, hose fed systems offer more consistent output than cartridge-based systems and optimize productivity.

Extremely short possessing times are attained through robot based adhesive bonding and seam sealing with appropriate adhesive application systems. The simplest method of robotic dispensing is extrusion. However, the extrusion method has now been largely replaced by the streaming and spraying technique which offers a significantly higher production rate. Automated guns offer a variety of options for achieving precise, consistent dot and bead patterns. Air-driven guns provide accurate timing and are insensitive to material viscosity and system pressure. Today's automatic pneumatic

guns deliver reliable, long-life operation and can run at speeds that exceed 3500 cycles per minute. Also automatic electric guns can accommodate very fast cycle times. Typically incorporating an allelectric driver to optimize performance, these guns can achieve greater pattern control and consistency. In addition, by eliminating the used of compressed air and dynamic seals, automatic electric guns lower operating costs and minimize module maintenance.



Different dot and bead patterns (Source: www.adhesives.org)

The small beam method is utilised to apply minute adhesive beads to the component, ensuring the same seam height and width. It is used for example in hem flange bonding. A constant width of the sealed seam can be consistently attained at high advance speeds by precisely controlled feeding of the adhesive. Depending on the specific requirements of the component, the quantity of the applied adhesive can be closely controlled. Adhesive bead diameters of less than 2 mm are possible. Finally, the quality of an adhesive bead determines the quality of the adhesive bond. Optical quality assurance devices can be integrated, because apart from the dosing system also the type of the feeding unit and the programmed robot track can have an influence on the produced adhesive bead.



Various application methods in the adhesive technology

(Source: Eisenmann)

The wide slot application method enables dispensing of support adhesives or filler adhesives as well as silencing materials on large surfaces. The wide slot nozzles equipped with automatic low-wear high-pressure ball valves are available in dispensing widths up to 200 mm. This method is used in the automotive industry to apply dampening materials to components where no offset is allowed between the applied lengths. For this reason precision in series production is also indispensable in connection with the wide slot application method.

Further possibilities are the multipoint adhesive application method where the adhesive is applied at multiple points and the airless flat stream method. In the flat stream method, different dispensing patterns can be individually implemented using customized, single or multiple nozzles. Consequently, the flat stream method offers highest degree of flexibility.



Wide slot application method (Source: intec Bielenberg)

In spiral spraying, large surfaces can be coated with adhesive in a single step and at high advance speeds. Reproducible spray patterns are created under full temperature control. The constant material flow enables rapid production processes. An interesting option is also the short bead technology which works with an electric servo drive allowing a much faster and more precise opening and closing of the applicator head than conventional needle valves and pneumatically operated pistols. The adhesive bead can be interrupted at precisely defined intervals for example when using a combination of spot welding and adhesive bonding. Adhesive-free sections can be attached with spot welds and without "burning" the glue. Thus the short bead technology improves the efficiency of the joining process both by saving adhesive material and reducing the cycle time in the body shop.



Spiral spraying (left) and short bead application technology (right) (Source: intec Bielenberg/Dürr)

Bond line thickness is generally maintained through the tolerances of the manufacturing equipment, such as folding the sheet metal over to make a hem flange bond or moulding features into the bond area of a plastic panel. When manually preparing test samples, glass beads or wire of the appropriate diameter can be used to control the bond line thickness.

An important aspect is also proper environmental control of the area where adhesive bonding is performed (temperature, humidity, airborne contaminants, cleanliness, etc.). Also important is the correct handling of the parts to be joined, in particular any contamination of previously pre-treated surfaces must be prevented. In addition, it is necessary to anticipate any stresses (particularly peel

or cleavage) which may be encountered during assembly or handling. In specific cases, fixture or racks may be required to hold the assembly while the adhesive is curing.

9.3.2 Adhesive curing

Structural adhesives cure, generally with negligible contraction, in different ways. The applicable curing methods for the various types of adhesives have been outlined above. Generally, structural adhesive bonds in automotive manufacturing are cured by heating (although in some cases, precuring at ambient temperature takes place e.g. as a result of the mixing of two components or by contact with moisture). Cure is most often achieved with an oven cure, usually concurrent with the paint bake cycles in automotive applications. Curing by contact between hardener and adhesive and curing with UV light are relatively seldom used.



Curing temperatures for structural adhesives

As a rule, a higher cure temperature means more cross-linking and higher environmental resistance, but less toughness. Single part epoxies generally represent a good compromise with a wide range of properties, but they require curing at well over 100 °C. In case of two-component epoxy adhesives (where curing occurs already at room temperature), joints of a higher strength and improved durability can be achieved by curing at elevated temperatures. The curing times can be also considerably reduced as the curing time roughly halves for each 10 °C rise in temperature. Ultimate adhesion and mechanical properties are accomplished by extending the polymer chain and cross-linking between chains, with the cross-linking making the resultant polymer a thermoset. The reaction is often exothermic, releasing heat and furthering the cure. There are no by-products, i.e. potential outgassing issues are avoided.

9.4 Surface pre-treatment for adhesive bonding

Because adhesives bond to surfaces, the actual surface condition is most important. As a rule, the surfaces to be joined should be as clean and dry as practically possible. Surface pre-treatment will, therefore, normally be necessary if optimum performance of the adhesively bonded joint is aspired. Proper surface preparation generally improves both adhesive bonding and paint adhesion. On the other hand, alloy differences or even different materials are of less concern as long as the appropriate surface treatment methods are used and the applied adhesive bonds to both sides of the joint.

Surfaces are likely to be contaminated with materials that could adversely affect joint performance. Therefore, impurities (i.e. dust, dirt, oil, grease, fat or water) and the inactive adsorption layer created by foreign molecules (i.e. water and gases) are generally first removed. Care must be taken to avoid contaminating the surfaces during or after pre-treatment. Contamination may be caused for example by part handling ("finger marking") or by other working processes taking place in the bonding area, e.g. oil vapours from machinery, metal dust from abrasive processes or vapours from spraying operations (paint, mould release agents, etc.).



Light truck entering multi-metal pre-treatment immersion stage (Source: Henkel)

9.4.1 Aims of a surface pre-treatment

The main aims of a surface pre-treatment for adhesive bonding are:

- Removal of oil, greases and other contaminants as well as other surface layers, including weak oxide layers formed by heat treatment or exposure to humid atmosphere.
- Protect the substrate surface prior to bonding and maximise the degree of intimate molecular contact between the adhesive and the substrate surface.
- Generation of a stable surface topography for optimum mechanical interlocking.
- Improve durability and corrosion resistance of the adhesively bonded joint; promote formation of intrinsic adhesion forces that exhibit both resistance to environmental attack by moisture and chemical stability over a wide pH range.

The type and intensity of the surface treatment necessary for successful adhesive bonding depends on the materials to be bonded and the performance requirements of the bonded joint. It may include a simple surface cleaning step, a chemical conversion of the substrate surface, and/or the application of a suitable inorganic or organic coating.

In automotive manufacturing, however, a pressing lubricant is often present on the material surface when adhesive bonding takes place. Thus the adhesive must be able to absorb and displace this layer before wetting the metal surface. Due to the complex interactions of the adhesive and the adherent surface, and possible lubricant interactions, the adhesive cannot be selected in isolation. The adhesive, pre-treatment and lubricant must be chosen as a fully compatible system. In addition, pre-treatments employed in the automotive industry generally need to be simple and rapid in order to comply with the low cost and high manufacturing speeds required for automotive production. High performance aerospace pre-treatment techniques are clearly not appropriate for volume car production.

9.4.2 Surface pre-treatment of aluminium alloys

The surface treatment methods applicable for aluminium alloys are covered in detail in another section of the EAA Aluminium Automotive Manual (see **Manufacturing – 4 Surface Finishing**). In the following, only some aspects relevant to the adhesive bonding process will be reviewed shortly.

The aluminium surface is a complex transition zone between the bulk of the alloy and the environment (see 9.0.1). A thin ("natural") aluminium oxide layer lies on top of a subsurface layer

with different chemical and microstructural properties than the bulk material. In rolled aluminium products, the disturbed ("deformed") surface layer generally has a thickness of a few 100 nm. It contains rolled-in oxide particles from the high forces used during hot and cold rolling; it has elongated and smaller grains than the bulk and it can contain various intermetallic particles different in chemistry and concentration to the bulk.

The natural aluminium oxide film has a thickness of a 5 - 20 nm and follows exactly the material surface topography. In principle, this oxide film would present an ideal basis for adhesive bonding. In fact, a high initial joint strength can be often obtained without any pre-treatment or by a simple degreasing of the aluminium surface before adhesive bonding. But in order to maintain the integrity of bonded joints, in particular in humid environments, some form of surface pre-treatment is always necessary, specifically if the joints are subjected to tensile stresses.

The underlying reason is that the natural oxide film is not perfect. It may show thickness variations and exhibit defects such as pores and fine cracks; the aluminium oxide can be disturbed locally (e.g. where intermetallic particles are present in the adjacent aluminium metal) and it can contain surface contaminants (e.g. residues of rolling oils). Furthermore, depending on the thermal history (temperature and time), solute alloying and impurity elements can diffuse from the matrix into the surface oxide layer, modifying the structure and composition of the surface oxide film. Surface enrichment and the formation of a heterogeneous surface oxide layer is particularly pronounced for element like Mg, Li, Na, Be, and Ca. These effects degrade the characteristics of the surface oxide layer, i.e. make it more hygroscopic and less corrosion resistant. Therefore, the natural, inhomogeneous aluminium oxide surface film is often removed and replaced by a properly controlled, new, homogeneous surface film.

Depending of the specific aluminium product (sheet, extrusion, casting, etc.), the applied surface pretreatments in preparation for adhesive bonding may be somewhat different; however, the individual steps are essentially the same. Rolled aluminium products are often already surface pre-treated in the mill in order to avoid chemical processes within the press shop or assembly plant. Other product forms are generally surface treated by the supplier and delivered ready-for-assembly.

9.4.2.1 Surface cleaning

Simple cleaning ("degreasing") removes surface oils and contaminants. Cleaning approaches differ in aggressiveness depending on need. In some cases, detergent solutions may suffice. More aggressive cleaning ("deoxidizing") requires an alkaline rinse, an acid rinse, or polyphenols followed by water rinsing. Deoxidizing only involves minimal metal removal. These cleaning methods are minimum practice in automobile applications. Proper degreasing provides a clean bonding surface which can be sufficient for moderately stressed joints in a dry environment. In general, however, degreasing is followed by additional surface treatment steps.

Mechanical cleaning approaches include surfacing techniques such as brushing, grinding, polishing, and sand or dry ice blasting. For many substrates, light abrasion of the surfaces to be bonded may allow a better interlock of the adhesive. However for aluminium, the application of abrasive methods is generally not recommended. If mechanical surfacing methods are applied, special care must be taken since the resulting deformed surface layer may severely impair corrosion resistance.

Although mechanical cleaning is not a commonly used process step in automotive manufacturing, mechanical surfacing methods are often used in rework and repair. If necessary, aluminium surfaces should be cleaned with a suitable abrasive cloth or water-proof abrasive paper. When using such techniques, operating under wet conditions can assist in the removal of contaminants and keeps dust generation to a minimum. If wet techniques are used, then the substrate must be thoroughly dried immediately after mechanical surfacing.

Fine grinding/blast cleaning removes weak surface layers and is therefore slightly safer than simple degreasing, but should be only used for stressed joints in dry environments. In specific cases, in particular for local adhesive bonding on painted surfaces, also laser cleaning may be applied. A further option is a surface activation step (such as plasma treatment).

The preferred surface cleaning option for aluminium is generally the alkaline or acidic cleaning/etching process which involves overt metal removal, in particular in preparation for subsequent surface pre-treatments that provide a properly controlled, stable surface oxide. Cleaning and etching may be two distinct steps, or may be combined into a single step. In case of rolled

aluminium products, the cleaning/etching step removes rolling oil residues, aluminium debris generated during rolling as well as the natural inhomogeneous oxide layer. After an alkaline cleaning step, an acidic cleaning step must be always carried out to remove any smut layer (brittle aluminum hydroxide). For the acidic cleaning step, sulphuric acid or a mixture of sulphuric and hydrofluoric acid is often used. Additionally, nitric, nitric/hydrofluoric and phosphoric acids can be used. Also, there are continuous treatment lines which use electrolytic cleaning in a phosphoric acid electrolyte.

For high quality adhesive bonding, the alkaline or acidic cleaning/etching step is followed by the controlled build-up of a new oxide layer (i.e. conversion coating or thin anodised film). The exposure of the freshly acidic etched (pickled) surface to boiling water produces a corrosion resistant, but only moderately strong oxide layer. Thus this surface treatment method should only be used for lightly stressed joints using flexible adhesives.

9.4.2.2 Conversion coating systems

Chemical conversion coating includes the dissolution of the natural oxide film and the controlled formation of a new, stable aluminium surface layer which reduces the risk of corrosion and improves the bonding of adhesives and/or organic coatings. The natural oxide film is removed by alkaline or acidic cleaning.

Traditionally, chromate films were formed on the aluminium surface. Conversion processes containing hexavalent Cr⁶⁺ ions perform exceptionally well for corrosion protection purposes because of their self-healing ability: when scratched or damaged, Cr(VI) reduces to Cr(III) and locally restores the film by forming chromium(III) oxide, thus healing possible weak spots. Cr(VI) is, however, a highly toxic and carcinogenic substance; its use is now being restricted for many applications by strict legislation. In response to the ban of Cr(VI), Cr(III) processes were developed for some applications. Chromate layers offer good corrosion resistance, but their load bearing properties are relatively poor (i.e. for adhesive bonding, the chromate layer must be thin). This method works best for moderate loads and elastic adhesives. But for environmental reasons, Cr(III)-based conversion treatments are also not applied in the automotive industry.

Widely used in automotive applications are chromium-free conversion treatments based on either titanium fluoride or a mixture of titanium and zirconium fluoride (commercially offered for example by Henkel[®] or Chemetall[®]). The processing baths often contain organic acids or phosphate compounds to further improve adhesion. The surface pre-treatment is carried out either by conventional immersion, spray or no-rinse processes. During these types of chemical treatment, modified mixed oxide surface films containing titanium and zirconium ions are formed which are homogeneous, stable and offer good adhesion to organic compounds. Fluoride is necessary for the activation of the aluminium surface. The very thin conversion layers (10 - 30 nm) have no negative effects on the formability of the material; also material performance during welding or during the zinc-phosphating process (which normally precedes the final lacquering operation) is not influenced. Although the fluoride level in these conversion solutions is kept very low for health and safety reasons, its presence presents nevertheless a potential issue.

For this reason, other non-toxic alternatives have been developed. An early solution was PT2 (developed by Novelis). PT2 is a chrome- and fluor-free pre-treatment for structural adhesive bonding of aluminium sheet. It is applied on the strip surface as an aqueous suspension of colloidal silicate, with some additions required for film formation and wettability. The generated surface film follows exactly the strip surface topography and has a thickness of about 50 to 100 nm. Providing excellent long term stability of adhesive bonds, PT2 also offers good welding performance. The PT2 pre-treatment has been primarily developed for inner and structural sheet, it is not recommended for outer panel applications.



Ti/Zr-fluoride based conversion treatment (TEM micrograph of cross section through pretreatment layer)

(Source: Novelis)

In addition, the use of silanes as adhesion promoters and for corrosion protection is widely investigated. Silanes are hybrid organic-inorganic molecules containing Si-O-C_nH_{2n+} groups which can interact with the metallic substrate to form a complex interface region containing -Si-O-M bonds (M=metal). After application, curing of the silane film is required to obtain a dense film network, which provides good corrosion barrier properties.

The newest development is the Alcoa 951 technology, an aluminium pre-treatment process that results in enhanced adhesive bonding durability compared with the conversion coating systems described above. The technology is applicable for aluminium sheets, extrusions and castings. It employs an organic, environmentally friendly system tailored for both the aluminium substrate and the structural adhesives used for joining. The surface treatment is applied through an immersion or spray application. The molecular structure chemically binds aluminium oxide with one end, and adhesive with the other. This creates a strong link at the molecular level resulting in lasting, durable joints for automotive structures. The minimal level of treatment on the surface offers full compatibility with downstream steps in the automotive manufacturing process such as forming, resistance spot welding and painting. In tandem with a suitably selected adhesive, the Alcoa 951 treatment is amenable to a variety of wet and dry film stamping lubricants.

9.4.2.3 Thin anodised films

In this case, a controlled film of active aluminium oxide, highly suited for structural bonding, is grown on the properly pre-treated aluminium (generally after electrolytic cleaning in an acidic bath); its thickness being dependent on the chemical process and the alloy used. Thin anodised films are generated using an AC or DC powered electrolytic process and have several advantages over conventional chemical cleaning and pre-treatment methods. They consist entirely of aluminium oxide and thus offer an environmental-friendly alternative to chromium or other transition metal based pretreatments. In addition, the thickness and morphology of thin anodised films can be closely controlled by varying cell voltage and applied current. The formed oxide film consists of an amorphous barrier layer, which improves the corrosion resistance of the material, and a porous filament layer which provides excellent adhesion to adhesives, primers and lacquers. Thin anodized films can be tailored to ensure excellent long term stability of adhesive bonds. For structural bonding, a film thickness in the range of 80 to 120 nm is recommended with a barrier layer of 30 to 40 nm and a filament layer of 50 to 80 nm. Thin anodised films do not affect sheet formability, joining characteristics, surface appearance or corrosion resistance after painting. The films are compatible with wet and dry press lubricants. During a typical layer forming zinc phosphating treatment of the body-in-white, the thin anodised films are removed and a homogeneous zinc phosphate layer is formed.



Thin anodised film produced by anodising in phosphoric acid (cross section and surface view)

(Source: Novelis)

Suitable aluminium oxide films with an open structure are produced by anodising in phosphoric acid; the anodic oxide contains "bound" phosphate which will provide some degree of durability to the final adhesive joint. The resulting, very stable oxide film exhibits the optimum pre-treatment for highly stressed adhesively bonded joints in corrosive environments. The porous surface is ideal when used with low-viscosity adhesives and primers. Sulphuric acid anodising techniques can also be used to pre-treat aluminium alloy surfaces, but the resulting thicker oxide film leads to a lower adhesive strength and durability. Anodising with sulphuric acid is best used with elastic adhesives for lightly stressed joints in corrosive environments. Some improvement is possible by dipping the anodised components in a solution of phosphoric acid to dissolve part of the anodic oxide layer in order to reveal a more open structure more amenable to adhesive bonding.

For other performance criteria, e.g. for a spot-weldable substrate, much thinner < 30 nm barrier nonporous films have been shown to be more suitable. This is readily achievable as the anodising process is highly controllable, i.e. for any given electrolyte, the process relies solely on the selection of the correct electrical parameters.

9.4.2.4 Primer coating

Modern coil treatment lines allow the application of an organic coating, subsequent to a suitable chemical pre-treatment step which is required to ensure adequate primer adhesion and corrosion resistance. Both conductive and non-conductive primers are available. The use of non-conductive primers offers the possibility to save surface finishing process steps at the car producer. Conductive primers are of particular benefit for protection against galvanic corrosion in mixed metal constructions, i.e. aluminium and steel and/or galvanized steel. Other advantages of coated material include for example surface protection during transport and handling, improved formability as well as good adhesive bonding characteristics. However, there are also some disadvantages, e.g. welding of primer-coated aluminium sheet is not possible.

The main purpose of priming prior to the bonding of aluminium is to fill (seal) the surface when highviscosity and/or fast setting adhesives are to be used. Priming becomes more important where the aluminium is to be used in a corrosive environment and no surface treatment that improves corrosion resistance (e.g. anodising) is considered.

9.4.2.5 The total system approach

As outlined above, care must be taken that the chosen adhesive is compatible with subsequent processing steps in car body manufacturing, in particular all the various operations in the lacquering line. However, the selected adhesive must be also able to comply with preceding processing steps. This aspect is most important for rolled aluminium products where various surface pre-treatment steps are often already carried out in the rolling mill. As a consequence, a holistic approach is necessary.

The Aluminium Vehicle Technology (AVT) concept for the production of aluminium car bodies developed by Novelis covers the selection of the appropriate sheet alloys, the surface cleaning and chemical surface treatment method, the application of a suitable lubricant and finally the choice of the proper structural adhesive. Depending on the customer requirements, either complete coils or cut blanks (rectangular or specific shapes) are supplied. The supply of aluminium blanks in any arbitrary geometry ("ready for stamping") produced on highly automated laser cutting lines in the rolling mill offers substantial cost reduction potential in particular for smaller production volumes (elimination of the blanking step, more effective process scrap handling and recycling, etc.).

In the AVT system, the aluminium sheet material is supplied by the aluminium manufacturer as a pre-treated and lubricated sheet. The car body panel is then stamped in the conventional way, without further application of lubricant. Only in specific cases, minimum additional local lubrication is required. The parts are joined by adhesive bonding (generally using a single part toughened structural epoxy adhesive) and locally supported by self-piercing riveting (or another secondary joining technique). The adhesive in the complete body structure is then cured during paint baking of the electro-coat layer. No cleaning or surface preparation is needed in the press shop and assembly plant.

A key element of this approach is the lubricant on the sheet surface. Different kinds of lubricants can be applied. Normally, only a thin lubricant film is applied to protect the material surface against corrosion and friction effects. In the press shop, this film is then replaced by a proper press forming lubricant. In principle, it would be possible to directly apply a lubricating oil that can be used for forming, eliminating the need to apply additional lubrication at the press shop. However, the oil can redistribute during transport and storage resulting in an inhomogeneous distribution.

The preferred approach is therefore the application of a dry lubricant film suitable for press forming in the rolling mill. Depending on the complexity of the panel to be formed, typical coating weights are in the range of 0.5 to 1.2 g/m². The trend is to use mineral oil based dry lubricants that are applicable for both aluminium and steel sheet. The lubricants are applied at temperatures of about 60 to 70 °C, and solidify at about 50 °C. In general, the dry lubricants are not removed from the stamped panels. Consequently, the applied dry lubricants must be compatible with any adhesives applied during assembly as well as with all the agents used in the sprays and immersion tanks during zinc phosphating and electro-coating. In practice, the lubricant is removed from the assembled body-in-white only in the alkaline degreasing step immediately before zinc phosphating. But even if the body-in-white is thoroughly degreased, traces of lubricant might still be present (e.g. in crevices) and could be transferred into the electro-coat bath. If the applied lubricant is not fully compatible with the electro-coat process, craters or pimples could develop on the lacquered surface which would lead to costly rework.

A disadvantage is that up to now, no dry lubricants are available which allow high quality fusion welding of the lubricated material. Without a pre-cleaning step, weld porosity will generally be observed when dry lubricated sheets are fusion welded.

9.5 Properties of adhesively bonded aluminium alloys

Joint design incorporating adhesives requires specific attention because of the large property differences between the adhesive and the materials being bonded. In order to correctly understand the effect of different adhesives on a bonded joint, the bonded joint must be considered as an independent structural element in a composite structure. It has different mechanical properties which can be influenced in a different manner by temperature and other environmental conditions. Since the durability of the various adhesives in different environments is generally known, the selection of an appropriate adhesive presents normally little problems.

Low-strength bonded aluminium joints are often a boundary layer problem, i.e. the result of undesired effects between adhesive and aluminium oxide. Water, either in its liquid or vapour phase, is the most common and generally most severe environmental stress factor. Different adhesives can differently interact with the aluminium surface in the boundary layer as a result of the electrolytes that can form in the presence of water. The effect on the boundary layer is even more negative if the water contains salts.

The long-term strength of a bonded aluminium joint exposed to moisture depends on the quality of the connection between the adhesive and the aluminium surface (e.g. water can penetrate into incompletely filled surface roughness's) and the stability and durability of the existing surface oxides

in the presence of the water (or a salt-containing electrolyte). Bonding to a naturally formed aluminium oxide surface layer does not provide the required long-term strength. If there is water or high air humidity in the service environment, the natural surface oxide must be replaced by a stable oxide layer formed under carefully controlled conditions to increase the durability of the bonded joint.

In addition, during any assembly operation, there is always the possibility that no adhesive is dispensed over a certain flange length/area (e.g. due to problems with the adhesive dispensing equipment). This will result in local loss of joint strength. Experimental work showed that the reduction in strength is directly proportional to the length of the adhesive skip. A small skip will generally only result in a small reduction in joint strength (assuming joints are loaded uniformly). In real structures, however, joints are often non-uniformly loaded and the position of the skip will be as important as its size.

9.5.1 Mechanical and thermal properties of adhesives

Detailed information about the inherent bulk mechanical and thermal properties of the adhesives is generally available from the respective suppliers. But the bulk mechanical properties of adhesives do not quite represent the strength performance of a bonded joint. Nevertheless, the bulk properties are still important parameters. Structural adhesives suitable for aluminium have an inherent bulk tensile strength of 10 to 60 MPa and an elastic modulus of 1 to 5 GPa.

The shear strength of a good adhesive bond on aluminium reaches approximately 30 MPa, even if the bulk tensile strength of the adhesive material reported in the technical data sheet may be 40–50 MPa. High-strength aluminium alloys for automotive applications have yield strength level approaching 300 MPa and an elastic modulus of approximately 70 GPa. The elastic modulus for steels and fibre reinforced composites is significantly higher. Consequently, the adhesive mechanical properties will always be lower than those of the materials being bonded together. Thus, it is reasonable to assume that an adhesive bond on aluminium can (and should) fail internally in the adhesive itself ("cohesive failure").



Lap shear strength of bonded aluminium joints

(Source: Dow)

The coefficient of thermal expansion for most adhesives is slightly higher (30 - 40 ppm/°C) than that of aluminium alloys (approx. 20 - 25 ppm/°C). Because the adhesive has a lower elastic modulus, this mismatch is generally manageable. However, the mismatch is about triple that for steel (12 ppm/°C) and double that for carbon fibre reinforced composites (10 - 20 ppm/°C). Thus, in mixed material joint design, it is important to allow for thermal strain effects. The joint will fail if thermal strain exceeds the bond shear strength. Similarly, residual strain or any other added strain in combination with the operating load must be compensated in joint design.

The properties of an adhesive are strongly temperature dependent. The elastic modulus of an adhesive decreases with increasing temperature. At some point, the adhesive ceases to be visco-elastic and deforms plastically. Therefore, when stressed by further heating or mechanical loads, the resulting strain leads to permanent deformation. The temperature at which permanent deformation occurs is called the glass transition temperature. For a structural joint to be thermally stable, it is best to select an adhesive with a glass transition temperature that is 10 °C – 15 °C higher than the highest expected operating temperature.

For many adhesives, the maximum temperature at which stressed bonded joints can be used in practice is between 60 and 80 °C. The highest heat resistance (approx. 150 – 250 °C) is achieved with heat-curing adhesives. Silicon adhesives can also provide a heat resistance of about 250 °C without heat curing.

Most critical are the reduced creep resistance of adhesives at high temperatures and an increased sensitivity to stress concentrations and shock loads at low temperatures. Different adhesives, even within the same group, can be affected to a different degree by temperature. When bonded joints are to be exposed to long-term tensile loads at elevated temperatures, application-specific tests will be often necessary to ensure that the creep strength of the applied adhesive meets the requirements.

9.5.2 Performance of adhesively bonded joints

In order to design a component or structure with adhesives, it is essential to have confidence that an adequate joint strength and performance will survive throughout the lifetime of the vehicle. The mechanical performance of adhesively bonded joints differs widely. It depends on the actual bond strength, the joint design, and the environmental exposure conditions. There are many different standardized test methods, e.g. to determine the lap shear strength of boded joints or the peel resistance of adhesives. Apart from a suitably durable adhesive, it is essential that the substrate and interface do not fail during the vehicle life.

Specific shear strength data for adhesively bonded joints are available from the adhesive suppliers. Typically, bond strengths are evaluated at ambient conditions and after exposure to high temperatures as well as high humidity and corrosive environments. Sometimes, also the effect of the surface roughness of the substrate has been evaluated.

On the other hand, there are no completely non-destructive methods for testing adhesively bonded joints. Non-destructive tests allow the measurement of pores, non-uniform adhesive layer thickness and absolute joining defects; however, the quality of adhesion cannot be determined. Normally, specially prepared test samples which run through the standard manufacturing process are used to control the adhesive joining process.

Bonded joints are normally regarded as rather insensitive to vibration and fatigue at high frequencies. They are often used as vibration dampers. Nonetheless, mechanical loads and specific environmental conditions can exacerbate boundary layer problems. The simultaneous effects of temperature, environment and mechanical load may result in a significantly faster strength reduction than would occur if these three stresses operated individually and had their outcomes added together. The stress concentrations that can arise when an adhesively bonded structure is loaded manifest themselves at the edges of the joints (especially if the joint has not been designed to minimize such concentrations), where environmental impact is also greatest. This can result in more rapid aging of the bonded joint than would otherwise have been the case.

9.5.3 Long-term durability

The most important environmental factors determining the durability of adhesive bonded aluminium joints are humidity, temperature and mechanical stress. Normally, moderately increased temperatures or mechanical stresses have no adverse effect on a structural joint. However, in the presence of water, increased temperatures may lead to accelerated degradation. Apparently, increased diffusion of water into the adhesive is an important factor. The rate of joint degradation by water is further increased if the joint is subjected to stress. Cyclic loading seems to be more detrimental than a constant load.

Under standard environmental conditions, there is normally no problem with respect to degradation of the adhesive or failure of adhesion. However, adhesively bonded joints are often located in

confined zones where water and salt can accumulate for longer times. Thus the micro-environment in these confined zones is usually much different from the open (outdoor) atmospheric conditions.

9.5.3.1 Effect of moisture on a bonded joint

Water (often in the form of salt water) is the predominant factor in bond degradation. Water can enter the bonded system by bulk diffusion through the adhesive, interfacial diffusion along the interface between the adhesive and substrate, and by capillary action through cracks or defects in the adhesive or conversion layer. Absorption of water may slowly plasticize and weaken the adhesive, i.e. lower the glass transition temperature of the adhesive and decrease the load bearing capacity of the joint. Water may also displace the adhesive at the interface and cause true interfacial failure. Furthermore, the presence of water may cause chemical degradation of the adherent interface by corrosion of the metal (in particular in the presence of salt). Hydrolysis can also lead to weakening of the oxide layer covering the aluminium substrate. The aluminium oxides produced by the applied surface pre-treatments are often not thermodynamically stable in a humid environment and may react with water to form hydrated oxides. All these effects will intensify with increasing temperature and humidity.

But there are also additional factors. Since the aluminium surface is never completely flat, highly viscous (slow flowing) and fast setting adhesives will most probably only come into limited contact with the surface. This results in a bond with in-built weak points (air pockets). In humid environments, the air will eventually be replaced by (salty) water.

Furthermore, the type of the applied adhesive may influence the stability of the interfacial region as a result of chemical reactions between water and specific components of the adhesive, thus forming products that leach out and can react with aluminium oxide. Specifically, it is assumed that an alkaline environment is formed in epoxies by reactions between water and curing agents such as dicyandiamide, causing attack of the aluminium oxide. In contrast, residues leaching from phenolic based adhesives are slightly acidic, which possibly contributes to the superior joint durability often shown by phenolic based adhesives.

9.5.3.2 Test methods for evaluating adhesive bond durability

For a structural joint, load and ability to withstand creep under extreme conditions are most important. In practice, long term performance of bonded joints cannot be reliably predicted from the properties of the adhesive and the adherent surfaces. Bond lifetime depends on the synergistic effects of stress, temperature and environment. The complexity of the interfacial chemistry generally requires experimental testing of the bonded structures. Hence, structural joints are usually exposed to severe testing conditions including variations of temperature and moisture, often with addition of salt for corrosion and some form of load.

Weathering tests of adhesively bonded aluminium generally include outdoor exposure (in case of automotive applications usually field tests under extreme climatic conditions) or accelerated testing under aggressive laboratory conditions. Although the conditions encountered in actual driving tests are close to service conditions, this type of testing is time consuming and requires several years before an evaluation of the bond durability can be made. The main difficulty is that in field tests – even at locations with extreme climatic conditions – rather static environmental conditions are encountered (e.g. relative humidity and temperature change slowly and within a rather limited range).

Therefore many efforts have been made to develop short-term laboratory test procedures which allow to draw safe conclusions concerning the long-term stability of adhesively bonded joints. Vehicle testing showed that environmental parameters such as dirt and mud have a significant influence. Fairly good correlation was obtained when using accelerated laboratory tests including cyclic temperature and humidity conditions and salt additions. Although it is difficult to use results from these tests to predict real life durability, a pre-treatment / adhesive system that performs well in accelerated tests provides a good starting point for the design and manufacture of bonded joints.

There is no harmonised specimen geometry and test procedure to evaluate adhesive bond durability in accelerated tests. Different conditions are used by the different car manufacturers and also by the suppliers. The test conditions used by car manufacturers often result from their experience with steel sheet. In addition, quite aggressive test conditions are applied during corrosive exposure in order to enhance the testing process and to allow a clear discrimination of different bonding systems.

Usually tensile lap shear tests are used for screening. Sometimes also wedge tests are carried out, although in this case, the preparation of the test samples is more complicated. Following the screening trials in the laboratory, actual driving tests are carried out at the car companies to evaluate the performance of the joined components under severe service conditions.

In laboratory testing, the geometry of the test specimen plays an important role. The use of a small sample width (or the introduction of drilled holes in the joint area) results in a stronger edge effect, i.e. it leads to a higher sensitivity regarding corrosive undermining effects compared to samples with higher width. Also pre-straining of bonded samples before corrosive exposure (e.g. 10 sec at 50 % of initial lap shear strength) should be considered. Pre-straining is used to simulate loading during service and may introduce micro cracks at the bond interface which are expected to increase corrosive exposure. The use of plain test specimens results in most severe conditions as corrosive undermining can easily propagate from the plain edges. More realistic testing conditions are seen for samples with a zinc phosphate and electro-coat layer or even for samples with a zinc phosphate layer and a full lacquer system.

In general, the adhesively bonded samples for accelerated corrosion testing are aged in a cyclic environment including temperature and humidity; also important is the chloride concentration. In addition, a load is sometimes also applied. The samples are then evaluated based on both strength retention and failure mode. Typical tests applied in practice are the VDA Cycle Test (VDA 621-415 standard) or the Salt Spray Test (DIN 50021, ASTM B117). But there are also additional OEM-specific test procedures, e.g. the SCAB test defined by General Motors, the Climate Cycle Corrosion test (used by Audi/VW), the APGE test of Ford or the KWT test used by Daimler. More often a combination of different accelerated laboratory test methods is used in practice.

EAA Aluminium Automotive Manual - Joining

10. Hybrid joining techniques

Content:

10. Hybrid joining techniques

10.0 Introduction

10.1 Combination of adhesive bonding with mechanical joining

10.1.1 Hem flange bonding

10.1.2 Adhesive bonding in conjunction with mechanical point joints

10.1.2.1 Adhesive bonding and clinching

10.1.2.2 Adhesive bonding and self-piercing riveting

10.1.2.3 Adhesive bonding and blind riveting

10.1.2.4 Adhesive bonding combined with other mechanical fasteners 10.1.2.5 Adhesive bonding combined with solid state joining techniques

10.1.3 Adhesive injection fasteners

10.2 Combination of adhesive bonding with fusion welding

10.2.1 Adhesive bonding combined with resistance spot welding

10.2.2 Adhesive bonding combined with other fusion welding processes

10.3 Combinations of fusion welding techniques

10.3.1 Laser – arc welding processes 10.3.1.1 Laser - MIG welding

- 10.3.1.2 Laser TIG welding
- 10.3.1.3 Laser plasma arc welding

10.3.1.4 Laser – MIG tandem welding process

10.3.2 MIG plasma welding

10.4 Friction self-piercing riveting – a combination of two mechanical joining techniques

10.0 Introduction

In hybrid joining, two or more joining operations are carried out either simultaneously or sequentially, leading to enhanced properties of the joint due to a synergistic load bearing interaction under service conditions.

The most common type of a hybrid joint includes an adhesive in conjunction with a point joint such as for example a mechanical fastener (e.g. rivet or threaded device) or a spot weld. It is mainly used for joining sheet materials, but there are also applications involving extrusions and thin castings. The main advantages of combining a point joining method with an adhesive are:

- production of continuous, leak-tight joints
- in general improved strength (static and dynamic)
- increased joint stiffness
- improved peel and impact resistance (the point joint arrests crack growth in the adhesive bond).

An important advantage is also that the immediately effective spot-joint fixes the position of the components until adhesive curing takes place, i.e. the assembly process is significantly shortened and facilitated.

The adhesive is normally applied to the surfaces to be joined prior to assembly and fixing with point joints. The most widely used hybrid sheet joining methods are:

- adhesive bonding / hemming
- adhesive bonding / resistance spot welding ("WeldBonding")
- adhesive bonding / self-piercing rivets ("RivBonding")
- adhesive bonding / clinching
- adhesive bonding plus other mechanical fasteners (screws, tacks, ...).

The second important group of hybrid joining techniques involves the combination of two different fusion welding methods. This combination is mostly used in structural applications in order to join thicker sheet materials, extrusions and castings. The combination of two different welding processes allows to achieve an optimum in weld quality and welding speed by exploiting the advantages of individual processes. Although the term "hybrid welding" includes in principle any other combination of welding techniques (e.g. also plasma arc / MIG welding or plasma arc / laser welding), in practice, it is used to specifically describe the MIG augmented laser welding process.

Other possible combinations of joining methods are:

- mechanical joining / fusion welding
- mechanical joining / mechanical joining
- adhesive bonding / adhesive bonding

however, these combinations are much less important.

The combination of a mechanical and a fusion joining method in the form of a hybrid technology has little practical relevance, although the combination of some mechanical fixation techniques and the subsequent fusion welding process could well be considered as a sequential "hybrid joint".

The sequential use of two different mechanical joining methods can be observed in practice quite often. But only one example for the simultaneous use of two different mechanical joining methods has been found.

Also the combination of two different types of adhesive joining methods can be considered as a hybrid joining technique. As an example, combining pressure sensitive adhesive bonding with structural adhesives can offer advantages in terms of processing and load bearing capacity when high levels of both static and dynamic mechanical resistance are required.

Additionally, pressure sensitive adhesives can be combined with structural thermosetting adhesives (e.g. as a formulated blend), creating a thermo-curable, pressure sensitive bonding technology. The so-called structural bonding tapes exhibit pressure sensitive properties at ambient temperature, but can be cured to develop structural adhesive-like properties at temperatures above 140 °C. This material represents an adhesive hybrid system combining pressure sensitive and structural adhesives.

10.1 Combination of adhesive bonding with mechanical joining

The various aspects related to adhesive bonding are described in detail in the previous section (9. Adhesive bonding). Therefore only those aspects relevant for the specific hybrid joining technology are mentioned.

10.1.1 Hem flange bonding

Closure panels like doors, hoods, trunk lids or tailgates are usually made from an outer panel which is hemmed (or clinched) over an inner panel around its periphery. Whilst the hemming technique (described in section 8.1.1) produces a sufficiently strong mechanical bond, adhesives are today widely used in the flange to give improved strength, stiffness, crash performance and corrosion protection.

Hem flange bonding happens in the body shop of an assembly plant, i.e. before painting. The body panels are stamped and formed starting from rolled sheets, thus they may be covered with residues of various lubricants (rolling oils, pre-lubricants and/or drawing compounds). Aluminium surfaces are typically provided properly surface pre-treated for bonding (cleaned and pre-oiled or covered with a dry lubricant). However, in general, there is no cleaning step used in the stamping plant which removes the applied stamping lubricants.

The adhesive is applied using swirl, bead or fine jet nozzles. In order to avoid "zero gap" in the hem flange, most hem flange adhesives contain glass beads to ensure constant distance between the outer and inner panels. Then the inner panel is positioned and the outer panel is bent around the inner panel, forming the hem flange. The bead size is carefully controlled to fill the bond line, but not to squeeze out. Adhesives that escape the bond line would contaminate the equipment and cause cleanliness and maintenance issues in the assembly plant. Ideally, the excess adhesive would help seal the cut edge (where the bare metal is exposed), but equipment contamination issues are usually considered to be more critical.

A curing step may be introduced at this stage, such as induction curing. This can be a full cure or just enough to prevent any movement of inner to outer panel during subsequent processing. Depending on the applied adhesive, pre-gelling by induction heating holds the adhesive in place while improving resistance to wash-out of the adhesive.

However, in most cases, hem-flange bonded closure panels are not pre-cured. They are attached to the rest of the body-in-white and sent to the paint shop where the body-in-white is cleaned, primed (electro-deposition of a zinc phosphate film, complete with oven cure), and painted. Cure of the adhesive is completed in the paint ovens.

One of the reasons for using an adhesive in the hem flange is to reduce or eliminate the use of spot welds or mechanical point joints to hold the inner and outer panels together. Such point joints are sometimes noticeable on the outer panel, necessitating a finishing or polishing step prior to painting. Nevertheless, there are usually a few remaining spot joints which hold the panels together until the adhesive is cured, reducing the susceptibility of the adhesive to any peel loads.



Hem flange bonding (Source: Fluidmetering)

Hem flange adhesives have to fulfill a wide range of requirements. They must not interfere with the integrity of the spot welds or mechanical point joints and may not escape during the joining process and get on the joining equipment. They must show improved wetting through lubricant films to ensure proper hem flange bonding on oily or draw-lubricated metals. Panel distortion during curing must be minimal, the adhesives should be tolerant to over-curing during lacquer baking and, last not least, must show good structural bond strength, excellent long-term durability and corrosion resistance. In practice, different types of one- or two-component adhesives are used.

10.1.2 Adhesive bonding in conjunction with mechanical point joints

Hybrid joints combining adhesive bonding with spot-joints with can generally be created in one of three ways:

- The "**fixing**" method, in which the adhesive is first applied to the parts being joined. Once the components have been joined together, a spot-joint is made to complete the process. This is followed by the hardening of the adhesive layer.
- The **injection** method where the parts are joined with a spot-joint before injecting the adhesive into the gap between the components. Capillary action causes the adhesive to spread throughout the joint. The adhesive layer then hardens.
- In the **sequential** method, the parts are joined after the adhesive has been applied. But the parts are spot-joined only when the adhesive has hardened.

Most industrial applications make use of the "fixing" method; the injection and the sequential variant are seldom chosen.

These types of hybrid joints are generally used for joining sheet materials and involve an adhesive in conjunction with a point joint such as a mechanical fastener, a clinched joint or a friction stir welded joint. The adhesive is applied to the surfaces to be joined prior to assembly and fixing with point joints. Similar results are achieved by combining resistance spot welding with adhesive bonding (see section 10.2.2).

The adhesives used in these hybrid bonds are predominantly liquid adhesives like single component hot curing or two-component room temperature curing toughened epoxy adhesives. However, combining pressure sensitive adhesive bonding with mechanical joining may also offer advantages in specific cases. The apparent advantages of pressure sensitive adhesives include quick-fix properties due to tack, easy roll-on dispensing and viscoelastic properties creating a high level of impact resistance and vibration dampening properties for pressure sensitive adhesive joints.

Hybrid joints using pressure sensitive adhesive tapes or structural bonding tapes with pressure sensitive properties in combination with mechanical joining exhibit superior

properties in terms of incipient tear and peel resistance. A negative interference can only be observed in case of clinching. A proper interlocking of the clinch punch is not achieved in the presence of the pressure sensitive adhesive tape.

The self-fix properties of the acrylic adhesive tapes greatly facilitate the overall hybrid joining process. As an example, the combination of acrylic pressure sensitive tape with self-piercing rivets leads to hybrid joints with an excellent peel resistance without the need of a thermal curing process. This practice is preferentially applied for mounting parts in final assembly (i.e. on the painted body).

10.1.2.1 Adhesive bonding and clinching

In this variant, the point joints are produced using the clinching technology (see section 8.1.2). Clinch-bonding has the advantage of being a cold joining process but, compared to other mechanical joining techniques, the only consumable is the adhesive. The adhesive is applied to one of the components being joined, and the two items are placed together. The components being joined are then subjected immediately to the clinching process, which causes some adhesive to ooze out of the joint. Once clinching has taken place, the joint is left to harden.



Clinch-bonding process

(Source: aluMATTER)

Proper control of the clinching operation is necessary. There is a risk that "pockets" are formed when the still liquid adhesive is squeezed out of the clinch point and the required clamping force cannot be achieved.



Formation of adhesive pockets in clinch-bonding

(Source: FhG Chemnitz)

Clinch joints are not as strong as riveted or spot welded joints. Therefore clinch-bonding is used mainly for less demanding applications in the automotive industry, e.g. for joining steel to aluminium in areas where the structural loads are relatively small.

10.1.2.2 Adhesive bonding and self-piercing riveting

This combination developed to the predominant joining technology in the production of aluminium car body structures, in particular when using aluminium sheets. For details on the self-piercing riveting process, see section 8.2.2.3.

The adhesive is pre-applied to the faying surfaces, the joint is formed and the rivets are inserted. The adhesive is displaced by the self-piercing rivet and surrounds the resulting mechanical linkage. In an adhesive-intensive joint, the rivets serve as peel stops and thus compensate for the adhesive's inherent shortcoming in peel performance. In contrast, the adhesive excels in shear performance. The net result is a joint that shows significantly improved shear strength and peel performance and a much better fatigue life.

The result is a considerable potential to reduce the sheet thickness (and to save weight). Rivets produce point loads and stress concentrations. The material between the junction points transfers the load from one point to another, but does not participate in "joining" even though it is part of the "joint". With the addition of the adhesive, the material between junction points contributes to stress management all along the joint. Therefore, in structural applications, also less punctiform mechanical joints are require to transfer relatively high point-to-point loads. In addition, the reduced metal gauge may allow for higher fatigue life overall.



Formation of a self-piercing rivet / adhesively bonded joint

(Source: FhG Chemnitz / Boellhoff)

Proper control of the subsequent mechanical joining operation is required in order to ensure that the squezzing out of the adhesive does not lead to local imperfections. Of specific importance is the avoidance of open channels to the seam edges since these could to serious corrosion problems.

10.1.2.3 Adhesive bonding and blind riveting

In specific cases, also the combination of adhesive bonding with blind riveting (see section 8.2.2.2) may be useful. In this case, the adhesive is applied to one of the previously-drilled components. Then the items are joined, the joint is blind-riveted and the adhesive is left to harden. If a two-component adhesive system is used, it is important that the joint is finalised within the shelf-life of the product. Also this joining process causes some adhesive to ooze out of the joint.


Adhesive bonding and blind riveting

(Source: aluMATTER)

10.1.2.4 Adhesive bonding combined with other mechanical fasteners

In principle, all types of mechanical fasteners can be combined with adhesive bonding. Threaded fasteners (see section 8.2.1.2) were for example used in combination with structural adhesive bonding in the construction of the Lotus Elise. The screws hold the assembly together during cure of the adhesive, they clamp the parts together to give metal-tometal contact and help to resist peel forces during impact.



Self-threaded drive screws hold the assembly together during adhesive cure

Another possibility for a preliminary fixation of the assembled structure is for example the tack high-speed joining technology (see section 8.2.2.6).



Aluminium-hybrid joint produced in RIVTAC® high-speed joining (Source: Boellhoff)

10.1.2.5 Adhesive bonding combined with solid state joining techniques

The combination of friction stir spot welding (see section 7.1.3) with adhesive bonding has been evaluated on an experimental basis. The adhesive does not only serve for bonding, but also seals the gap between the metal sheets to be joined. Positive effects of this hybrid joining method were observed in dissimilar Al/Mg welds. It seems that the adhesive suppressed the formation of large brittle intermetallic compounds during the welding process. However, no further applications are known.

Experimental tests have also been carried out combining adhesive bonding and ultrasonic welding (see section 7.3) using lap joints of EN AW-6022-T4 sheets. However no further developments were made in this case either.

10.1.3 Adhesive injection fasteners

Invented by TWI, AdhFAST[®] is a hybrid joining technology which differs from the methods described above in that the adhesive is introduced into the joint after the structure has been assembled using fasteners. The adhesive is injected into the joint through specially designed fasteners which incorporate a means of controlling the spacing between the top and bottom substrates. This gives greater control of bond-line thickness and, therefore, improved process reliability and joint quality, maximising the benefits of hybrid joint technology.



Computer simulated graphics showing cross sections of AdhFAST[®] in-situ and exploded views

(Source: TWI)

The fastener design is very flexible and must only enable the three functions of retention, spacing and injection. Injection of the adhesive can be carried out manually or by an automated process. Again no automotive applications are known.

10.2 Combination of adhesive bonding with fusion welding

Only a few hybrid joining methods combine adhesive bonding with fusion welding. In principle, there are two possibilities to additionally join adhesively bonded sheets by a fusion welding process:

- a weld nugget can be placed between the two sheets
- a weld spot or bead can be made joining the upper to the lower sheet.



A necessary requirement is that the heat input by the applied fusion welding method is limited. Otherwise, the efficiency of the adhesive bond would be deteriorated too much. Consequently, only two fusion welding techniques are of specific interest: resistance spot welding (see section 5.1) and laser (spot or seam) welding (see section 4.1).

10.2.1 Adhesive bonding combined with resistance spot welding

The combination of adhesive bonding and resistance spot welding ("WeldBonding") allows designers to maximise the vehicle performance (e.g. body-in-white torsional rigidity, fatigue, weight reduction, etc.) while still maintaining the relative ease and speed of assembly.

It is one of the most common hybrid joining technologies used in the high volume automobile production (specifically for steel-intensive cars). The dominating joint configuration, which consists normally of overlapping sheets, is highly suited for both processes either singly or when combined. The weld-bonding process is generally fully automated and utilises robotic dispensing systems. Today, structural adhesives are used rather than low strength adhesives or sealants.

The adhesive is normally applied to one sheet in the area to be joined. After assembling the two elements, resistance spot welds are performed through the adhesive. Before the actual welding starts, the electrode force displaces the adhesive to obtain electrical contact between the sheets and the weld can be made in the normal way. The local heating generated during spot welding causes only a limited damage around the weld. The adhesive is finally cured to complete the assembly.

Heat curing paste type adhesives are normally used as these are stable and have a consistent viscosity at room temperature. Typically, such adhesives are cured in the lacquer baking ovens at up to 180°C for 30 minutes. Some adhesives are also available in tape form and incorporate a metal particle filler which allows initial electrical contact to be made for spot welding.

In automotive applications, adhesives and sealants are welded through in order to improve joint strength, load distribution, fatigue performance and joint sealing. Whereas for steel materials, no special difficulties are encountered, some development work was required for aluminium alloys. The surface condition (or prior surface treatment) of the aluminium sheets must be properly selected to ensure the long-time durability of the adhesive especially in difficult service conditions, but not to interfere with the spot welding process. It was found that a special, tightly controlled aluminium surface treatment step is necessary to achieve the required consistent surface quality which ensures long-term durability of adhesive bonds in hostile environments (e.g. in the presence of moisture, especially when under load), but nevertheless offers the required spot welding performance (where normally a low surface resistance is needed).



Examples of peeled weld-bonded aluminium joints: Peeled prior (left) and after (right) adhesive cure (note the clearance zone around the weld)

Good process control is required to ensure correct joint filling for the adhesive and to avoid weld quality problems. In the weld-bonding process, the work piece and tooling may be more susceptible to contamination as a result of adhesive being squeezed out of the joint. Also, health and safety issues linked to the use of adhesives need to be considered. Welding

through adhesives may create hazardous fume, thus suitable ventilation/fume extraction systems should be used.

The success of the resistance spot welding step relies primarily on the force applied by electrodes to displace the adhesive before welding starts (during the "squeeze-time"). Thus, some specific recommendations be made:

- Spherical shaped electrodes will assist adhesive to flow from the weld site.
- Squeeze time must be long enough to allow adhesive to flow (typically ~1 sec).
- Temperature strongly affects adhesive viscosity. Too low temperatures (ambient or water-cooling temperatures) will make the adhesive hard to displace.
- A weld current profile that uses a pre-heat to warm the adhesive prior to welding can be an advantage.

10.2.2 Adhesive bonding combined with other fusion welding processes

Arc or beam welding can be used to produce welds spot or beads which join the upper to the lower sheet. Different weld-bonding hybrid processes have been evaluated with limited success.

As an example, the combination of a modified metal inert gas (MIG) spot welding process (see section 3.1.3.5) with adhesive bonding was examined. In another experiment, the "Plasma arc weld bonding" process, a combination of plasma arc welding (see 3.2.2) and adhesive bonding, was used to weld magnesium. It was found that the presence of the intermediate adhesive layer played an important role. However, the existence of the adhesive layer had not only advantages, but also some disadvantages. During fusion welding, the adhesive decomposes and produces a mass of decomposition products. The result is significant weld porosity and thus a decrease of the properties of the welded joint.



Plasma arc weld bonding process

(Source: L. Liu et al., Dalian University)

A further hybrid joining concept, called laser continuous weld bonding, was tested by joining the magnesium alloy AZ31B (upper sheet) to the aluminium alloy EN AW-6061 (lower sheet). The formation of brittle intermetallic phases in the fusion zone could be effectively reduced. It seems that the rising adhesive vapour hinders the downward movement of liquid magnesium. Hence, the weld is composed of a two-phase mixture with less intermetallic compounds and more solid solution.

The process consists of four stages: (1) spreading of the adhesive on the lower sheet surface; (2) applying pressure and assembling; (3) laser (spot or seam) welding and (4) adhesive curing.



Laser weld bonding process

(Source: Liu et al., Dalian University)

A hybrid assembly process which combines laser welding and adhesive bonding ("Laser weld bond") to generate higher joint shear and peel strengths over conventional welding or adhesive bonding alone has also been evaluated in aircraft production. It has the ability to demonstrate significant manufacturing process simplification to produce very cost effective airframe structures and control surfaces. A variety of lasers, adhesives and substrates were tested. It was shown that the laser weld bond process is a viable joining alternative capable of producing joint strengths which exceed target rivet joint strength requirements.

However, the concepts combining adhesive bonding and arc or beam fusion processes described above are today not yet ready for practical application in the automotive industry. Further developments are necessary.

10.3 Combinations of fusion welding techniques

The term "Hybrid welding" is often used to describe the Laser-MIG welding process, but there are other combinations of fusion welding techniques used in practice (e.g. plasma arc and MIG welding).

The combination of two welding techniques allows the exploitation of the advantages and reduce as much as possible the negative factors of the individual techniques. It is, however, important to recognise that hybrid joining techniques need to be adapted to each specific application if maximum reliability is to be achieved. A good example is the influence on the weld profile.



Characteristic profiles of hybrid welds

10.3.1 Laser – arc welding processes

The combination of laser light and an electrical arc into a hybrid welding process has existed since the 1970s, but introduction into industrial applications took some time. Hybrid laser-arc welding is a joining process whereby arc welding and laser welding are carried out simultaneously, in the same weld pool and in the same welding operation.

Laser beam welding is described in detail in section 4.1. Since the laser is primarily used to ensure the deep penetration capability, power-intensive laser sources (CO₂, Nd:YAG, diode, fibre, etc.) are preferentially combined with any arc welding process (MIG welding, TIG welding, plasma welding). However, hybrid laser-MIG (often also referred to as GMA) welding

and laser-TIG (often referred to as GTA) welding are perhaps the most common combinations.

The hybrid process exhibits the individual advantages of both – laser beam and arc – welding processes when carried out separately. Deep penetration welds comparable with laser welds can be made, but at the same time, the tolerance to joint fit-up and the resulting weld profile are more comparable with arc welds. Furthermore, arc welding consumables (and gas mixtures) can be used, leading to a higher degree of control over weld quality and properties than with laser welding.

In hybrid welding, the laser beam is feeding heat to the weld metal in the top part of the seam, in addition to the heat from the arc, i.e. both welding processes act simultaneously in the same process zone. Depending on which arc or laser process is used, and depending on the process parameters, the processes will influence one another to a different extent and in different ways. Also the character of the overall process may be determined to a greater or lesser degree either by the laser or by the arc.



Laser and arc process operating in a single process zone (left) or in tandem (right)

There is also the possibility a sequential configuration where two separate welding processes act in succession, but still in a joint weld pool. In this case, the greatest effect is achieved if the laser beam is used to produce the root pass, and MIG or TIG arc welding is used for filling the pass.

Where there are two separate weld pools, the subsequent thermal input from the arc means that the laser-beam welded area is given a post-weld heat treatment.

The biggest potential of laser-arc hybrid welding is seen in the addition of filler material. Thus the laser - MIG hybrid welding process is currently the most preferred laser-arc hybrid welding method. Using the MIG process (continuous or pulsed arc) as the arc process in laser hybrid welding, the gap bridging ability can be increased as the addition of filler metal is better controlled and filler metal volume can be higher than by using cold wire feeding together with the plasma or the TIG arc.

10.3.1.1 Laser - MIG welding

The laser and the MIG arc have a common process zone and weld pool. The process can be controlled in such a way that the MIG welding technique (see section 3.1.3) provides the appropriate amount of molten filler material to bridge the gap and to close the joint, while the laser delivers the high power densities needed to ensure the desired penetration depth and to enable higher welding speeds. Thus, the hybrid technique is faster than MIG welding alone, and the joined components are subject to less distortion.



Principle of the Laser - MIG welding process

As soon as the laser beam impinges on the material surface, it vaporises a spot on the surface. A vapour cavity is formed in the weld metal due to the escaping metal vapour, creating a deep and narrow heat-affected zone. The use of expensive laser energy is restricted almost exclusively to the deep-welding effect, which also permits thicker sheets to be joined. The remaining energy requirement is met by the cheaper MIG process, whose melting electrodes at the same time provide better gap-bridging capabilities. Since both processes focus their energy on the same processing zone, weld depth and speed and significantly improved compared to the individual processes. Depending on what ratio of the two power inputs is chosen, the character of the overall process.

In hybrid welding, the arc torch has to be oriented with a flatter angle than in conventional arc welding because the laser beam may impinge the gas nozzle if the arc torch is too close to the laser beam.

Laser – MIG hybrid welding is particularly suitable for applications that use industrial robots, as the potential offered by this high-performance process can only be exploited by automated applications. The heart of the hybrid welding system is a compact welding torch with an integral MIG system and laser optics. A robot holder gives the welding head the flexibility to access difficult-to-reach areas of the work piece. The filler wire can be placed in any position with respect to the laser beam, thus enabling the joining process to be adapted precisely to the wide variety of seam preparations, outputs, wire types, wire grades and joining tasks. A coated protective glass is required to protect the laser optics from welding spatter damage. In order to prevent weld-spatter from soiling the protective glass, a cross-jet is used to divert the spatter so that it can be vacuumed off through an exhaust-air duct. The work area remains free of contaminants and welding fumes.



Laser – MIG welding head

(Source: Fronius)

Both the weld penetration depth and the welding speed are greater in the combined process than when either of the processes is used on its own. The Laser – MIG hybrid welding process is suitable for a wide range of materials and thicknesses. It is specifically suitable to weld components where tolerances and preparation times make them unsuitable for laser welding. Another positive aspect is the relatively low heat input and the reduced amount of shielding gas required. On the one hand, high-strength materials exhibit hardly any loss of strength, while on the other hand, the low levels of thermal delay mean improved component precision.



Laser – MIG hybrid welding of two vacuum high pressure die-cast aluminium half shells

Laser – MIG hybrid welding asks for lower tolerance requirements for edge preparation (low sensitivity for gap width variation) than laser welding, leads to an improved weld seam quality (less blowholes, porosity, undercuts, solidification cracks, better seam surface quality) than either laser or MIG welding and produces smoother thickness transitions and bead surfaces than by laser alone.

10.3.1.2 Laser - TIG welding

When the TIG arc technique (see section 3.2.1) is operated simultaneously with a laser beam, the absorption of the laser energy into the base material is enhanced in the heated region. Laser-TIG hybrid welding has proven to be a promising technique to weld thin steel sheets in a butt joint configuration. However there are no known practical application of this hybrid welding method with aluminium.



Principle of hybrid laser – TIG welding process

10.3.1.3 Laser - plasma arc welding

For laser - plasma hybrid welding, the laser beam and the plasma jet (see section 3.2.2) are brought together in the process region close to the work piece. The plasma torch is generally positioned at an angle of about 45° to the laser beam.

Plasma arc welding can be also used together with the laser beam process in such a way that the laser beam is surrounded by a concentric plasma arc. The heat of the plasma arc reduces the cooling rate of the weld zone and decreases the development of residual stresses. It is therefore possible to tailor the microstructure of the weld and the heat affected zone to a specific application.



Plasma arc augmented laser welding system

10.3.1.4 Laser - MIG tandem welding process

The combination of laser and MIG tandem welding (see section 2.1.3.4) is a logical development of hybrid laser – MIG welding. The laser beam is set at approx. 90° to the work piece and is used for welding the root. Both of the trailing arcs have a pushing tilt angle and are used to increase the ability to bridge root openings and increase weld throat thickness.



Laser - MIG tandem arc welding

The process uses three different power outputs, thus the weld joint geometry, the preferred joint overfill and the welding speed can be selected by means of a suitable power output. The key advantage of combining the processes in this manner is the fact that as the filler metal melts off, it generates an arc pressure which does not act on the work piece, but is distributed across separate arc roots.



Laser - MIG tandem arc welding unit

(Source: Fronius)

An automated high-performance welding process is the combination of laser – MIG hybrid welding with MIG tandem welding. The combination of a laser beam with three arcs offers new possibilities to join heavy gauge metallic sheet materials: high welding speeds with good gap bridging and metallurgical characteristics.

The preceding laser - MIG hybrid process with one arc creates a very narrow heated zone with a great weld-depth to seam-width ratio. The following tandem welding process has considerably less concentrated energy and is characterised by a very high deposition rate.



Torch for laser – MIG hybrid plus MIG tandem welding (Source: Fronius)

10.3.2 MIG plasma welding

MIG plasma welding is a high-performance welding process that was specifically developed for aluminium welding. The combination of MIG and plasma arc welding achieves an increase of the filler wire melting rate by adding the plasma arc and enables improved pre-heating of the work piece and filler wire, thereby avoiding cold shut defects at the weld start. However, it is unsuitable for manual welding due to the required large sized welding torches.

The process is a variation of MIG welding method in which the MIG arc is constricted with the help of a plasma gas. Unlike conventional MIG torches, a MIG plasma torch has a second, inner, water-cooled nozzle through which the plasma gas flows. The MIG electrode is placed in the centre and the ring electrode in which plasma arc is generated is placed in the circumference. The plasma gas, usually argon, is ionised by high-frequency pulses between the wire and the plasma arc and ignites the pilot arc, which then ionises the whole column of gas between the plasma arc and the work piece. As with MIG welding, the outer gas layer acts as a shield for the plasma arc to prevent the molten metal from reacting with ambient air.

The melting power of the MIG welding arc is increased by the addition of the plasma arc. Furthermore the plasma arc preheats the work piece and the wire, thus avoiding cold-shut (lack of fusion) defects at the start of the weld. The "hot" wire can be fed at a higher rate resulting in a higher melting performance. The higher heat input improves gap bridging, but may also lead to thermal distortion of the work piece. Thus the MIG plasma welding process is applied only in special cases (e.g. when welding aluminium components with large wall thicknesses).



MIG plasma torch (Source: aluMatter)

A slightly different arc configuration is used in the Super-MIG[®] technology. This hybrid welding technology combines the plasma arc and the gas metal arc technique into one operational welding system. It provides welding capabilities not available by each of the two welding technologies alone.

The equipment combines a plasma torch and a MIG torch in one processing torch. The axes of the non-consumable electrode (plasma arc) and the consumable electrode (MIG arc) are positioned in an acute angle facing the work piece. Thus the plasma arc at the leading position creates a keyhole and the following MIG arc operates typically in the conduction welding mode to fill the void created by the plasma arc. The net result is that the hybrid process relies on the plasma arc for deep penetration and high arc efficiency and metal deposition rate of the MIG process to finish the weld.



Super-MIG[®] processing torch (Source: Plasma Laser Technologies)

The interaction between the plasma arc flow and the MIG arc promotes wire heating and current transfer at the anode spot (at the end of the MIG filler wire), where the molten weld metal droplets form and subsequently detach. The hybrid process uses a negative plasma arc electrode and a positive MIG electrode to achieve maximum processing speed and to operate in the spray transfer mode. The magnetic force causes deflection of the plasma arc toward the front of the weld pool, compensating for the plasma arc's natural tendency to trail behind the torch axis during high-speed welding. The resultant effect is an increase in plasma arc rigidity and stability, leading to increased penetration depth and welding speed when compared with conventional MIG technology.



(Source: Plasma Laser Technologies)

10.4 Friction self-piercing riveting – a combination of two mechanical joining techniques

Self-piercing riveting is currently the most popular mechanical joining technique for dissimilar materials and is widely used in joining all-aluminium and multi-material vehicle bodies. However, when riveting magnesium alloys, cracks always occur for its low ductility. A hybrid joining process named friction self-piercing riveting, which combines the mechanical joining mechanism of self-piercing riveting with the solid-state joining mechanism of friction stir spot welding was developed aiming at joining the low-ductility materials. In this process, the rivet rotates at high speed during the actual riveting process.

The effectiveness of the friction self-piercing riveting process was validated by riveting 1 mm thick EN AW-6061-T6 aluminium and 2 mm thick AZ31B magnesium sheet. The results showed that the riveting performance of magnesium alloys could be significantly improved and the joint strength could be greatly increased.



Friction self-piercing riveting process (Source: YongBing Li et al.,J. Manuf. Sci. Eng. 2013; 135(6))

EAA Aluminium Automotive Manual – Joining

11. Joining dissimilar materials

Content:

11. Joining dissimilar materials

11.0 Introduction

11.1 General issues and limitations

- **11.1.1 Metallurgical limitations**
- 11.1.2 Galvanic corrosion
- 11.1.3 Thermal expansion

11.2 Joining aluminium to other metals

11.2.1 Fusion arc welding processes

- 11.2.1.1 Fusion welding with transition inserts
- 11.2.1.2 Coating dissimilar material prior to welding 11.2.1.3 Fusion-brazing arc welding processes

11.2.2 Other fusion welding processes (beam welding, resistance welding) 11.2.2.1 Joining of aluminium to steel with lasers

11.2.2.2 Resistance spot welding trials for joining steel to aluminium

11.2.3 Solid-state joining processes

- 11.2.3.1 Friction stir welding
- 11.2.3.2 Friction stir spot welding
- 11.2.3.3 Laser assisted friction stir welding
- 11.2.4 Brazing and soldering
- 11.2.4.1 Brazing 11.2.4.2 Soldering

11.2.5 Mechanical joining processes

- 11.2.6 Adhesive bonding 11.2.6.1 Hem flange bonding
- 11.2.7 Joining aluminium to magnesium

11.3 Joining aluminium to plastics and composites

11.3.1 Joining aluminium to plastics

- 11.3.1.1 Joining with mechanical fasteners 11.3.1.2 Laser-assisted metal and plastic joining
- 11.5.1.2 Laser-assisted metal and plastic joining

11.3.2 Joining aluminium to composites

- 11.3.2.1 Transition joints
- 11.3.2.2 Adhesive bonding
- 11.3.2.3 Mechanical fasteners 11.3.2.4 Friction spot welding
- 11.3.2.5 Injection clinching joining

11.0 Introduction

As aluminium alloys are more frequently applied in the automotive industry, the joining of aluminium to itself, but in particular also to other materials becomes increasingly important. When joining aluminium to other materials, three different tasks can be differentiated:

- Joining aluminium to compatible metals (with some degree of solubility in each other)
- Joining aluminium to incompatible metals (little or no solubility in each other)
- Joining aluminium to different types of material (e.g. plastics and composites, ceramics).

Joining dissimilar materials is generally more difficult than joining the same material (or alloys with minor differences in composition) and the number of applicable joining techniques decreases. However, in most cases, dissimilar materials can be successfully joined using an appropriate joining method and properly adapted processing conditions.

Applicable joining processes for aluminium to other metals may be:

- Fusion arc welding processes
- Other fusion welding processes (beam welding, resistance welding)
- Solid-state joining processes
- Brazing and soldering
- Mechanical joining processes
- Adhesive bonding.

However, when aluminium must be joined to other types of materials, e.g. plastics and composites as well as ceramics, fusion welding methods cannot be applied.

Some of the processes described in the previous sections can be applied to join dissimilar materials with little adaptations. They will not be covered in detail in this section. The main focus will be on processes which have been specifically developed or modified to fulfil the additional requirements.

A basic rule is that there is not a single process or a set of processing parameters which is best for all material combinations or fits all performance requirements. Each process has its advantages and limitations. Thus each dissimilar material joint is best viewed as a special application with unique requirements. Furthermore, many of the new developments are still in the laboratory or pilot-plant stage and not yet approved for large series application. Often extensive qualification tests may be necessary and time will show which joining techniques will be most successful for joining specific material combinations.

11.1 General issues and limitations

A number of factors must be taken into consideration when designing a dissimilar material joint, including:

- Material combination and performance requirements
- Joint design and material thicknesses
- Thermal expansion-contraction mismatch during joining and in service
- Potential for galvanic corrosion problems in service
- Fixturing requirements and constraints regarding joining stresses.

Depending on the specific joining process, additional factors have to be considered as well, e.g. in case of fusion welding:

- Differences in melting temperature
- Formation of brittle intermetallic compounds during joining which may lead to brittle joints
- Heating and cooling rate effects on the microstructure of the joint
- Need for pre- and post-heating to minimize stresses during welding and cooling
- Need for composite transition materials or special filler materials during joining.

With respect to the automotive market, the most important task is joining aluminium to steel. Consequently, this problem is also the main driving force to develop new, improved joining methods for dissimilar materials. Most examples will therefore cover the aluminium-steel system. But the wish to produce innovative lightweight products has also raised significant interest in the production of structural joints between aluminium and plastics as well as carbon fibre reinforced composites. On the other hand, joining aluminium to ceramics is rather used in niche applications.

11.1.1 Metallurgical limitations

The following table shows the ease of joining aluminium to other metals by fusion welding processes. It indicates that aluminium is, in general, difficult to weld to other materials. For this reason, joining of aluminium to other metals has been mainly done using other joining methods than fusion welding in the past (in particular mechanical joining and adhesive bonding). However, new developments have led to a renewed interest in fusion welding processes.



Fusion welding performance of aluminium to other metals

When joining aluminium to other metals, the major difficulty is that at high temperatures, and in particular in the presence of a liquid phase, brittle intermetallic compounds are formed at the interface which result in poor joint characteristics. As an example, fusion welding of aluminium to steel leads to the formation of particles of intermetallic phases such as FeAl₂ and Fe₂Al₅. Brittle intermetallic phases are also formed when "fair weldable" metals such as copper, magnesium or titanium are directly fusion welded to aluminium.

11.1.2 Galvanic corrosion

Galvanic corrosion is an electrochemical process in which one metal corrodes preferentially to the other. Both metals must be in electrical contact in the presence of an electrolyte. Dissimilar electrically conductive materials have different electrode potential and when two or more come into contact in an electrolyte, one material can act as anode and the other as cathode. The difference in electrode potential between the dissimilar metals is the driving force for an accelerated corrosion attack on the anode member of the galvanic couple. The anode metal dissolves into the electrolyte, and the corrosion products deposit on the cathode.

There are several possibilities to reduce or even prevent this type of corrosion:

- The easiest option is the electrical insulation of the two materials from each other. If they are not in electrical contact, no galvanic couple will develop. This can be achieved by using non-conductive materials between metals of different electropotential.
- The prevention of contact with an electrolyte can be done by using water-repellent compounds (such as greases) or by coating the metals with an impermeable protective layer (e.g. a suitable paint, varnish or plastic). If it is not possible to coat both materials, the coating should be applied to the material with the higher electrode potential. If the coating would be applied only on the more active material, there will be a large cathodic area if the coating is damaged and for the exposed, very small anodic area, the corrosion rate will be correspondingly high.
- Electroplating or other metallic coatings can also help. More noble metals are generally used since they resist corrosion better. Galvanizing with zinc protects the steel base metal by sacrificial anodic action.

- Cathodic protection uses one or more sacrificial anodes made of a more active metal than the protected metal. Alloys of metals commonly used for sacrificial anodes include zinc, magnesium and specific aluminium alloys.
- Cathodic protection can also be achieved by connecting a direct current (DC) electrical power supply to oppose the corrosive galvanic current.

11.1.3 Thermal expansion

Thermal expansion is the tendency of matter to a volume change in response to a temperature change. For solids, the main concern is the change along a length or over some area. The coefficient of thermal expansion is a material-specific parameter and generally varies with temperature. However, common engineering solids usually have coefficients of thermal expansion that do not vary significantly over the range of temperatures where they are designed to be used, thus practical calculations can be based on an average value of the coefficient of expansion.

When the applied joining technique involves significant temperature changes, thermal expansion effects must be considered already during the joining operation of dissimilar materials. In addition, also the impact of temperature changes in the service phase must be taken into account. For body-in-white applications, however, the most important post-joining effect is the lacquer bake hardening process which takes place at temperatures up to about 180°C.

11.2 Joining aluminium to other metals

Most of the technologies that have been used to join dissimilar metals in the past (e.g. mechanical joining processes, solid state joining techniques, adhesive bonding) are only able to deal with certain geometries or require extensive control inputs. Thus there is a big interest in the introduction of more flexible joining techniques in industrial practice.

The most critical factor when joining aluminium to other metals (including steel) are the metallurgical issues. Under the influence of heat, intermetallic phases are formed at the interface between the two materials either during solidification of the molten mixture or by diffusion processes at the interface. The more heat is applied, the larger the zone containing the intermetallic phases and the poorer the mechanical properties of the joint.

However, the different chemical and physical properties also require appropriate measures to be taken. Differences in the thermal expansion coefficients of the two materials may create a stress field around the joint. There may be also a marked tendency for corrosion as a result of the difference in electrochemical potential.

Most examples described below include aluminium/steel joints. However, the basic process principles can be also applied to joints of aluminium with most other non-ferrous metals. Because of its importance in lightweight design, a specific chapter is only added for aluminium/magnesium joints.

11.2.1 Fusion arc welding processes

The two most common methods which enable the application of arc welding processes for joining aluminium to steel are the use of bimetallic transition inserts and the application of a suitable coating to one of the metals prior to welding. More promising, however, are recent efforts to limit the heat input in fusion welding to the absolutely necessary minimum in order to closely control the formation of intermetallic phases. Today, the Cold Metal Transfer (CMT[®]) welding technology is industrially applied to join aluminium and steel sheets in automotive applications.

11.2.1.1 Fusion welding with transition inserts

The use of bimetallic transition inserts is today widely employed in the shipbuilding industry. The application of bimetallic transition inserts means that similar material joints can be made

on either side of the insert (i.e. one side of the insert is a steel-to-steel and the other an aluminium-to-aluminium joint). Thus standard arc welding methods can be used. However, care must be taken to avoid overheating the inserts during welding since this may cause growth of brittle intermetallic compounds at the interface of the transition inserts.

Aluminium/steel transition joints are applied only for special cases in the automotive sector. The primary requirement is to keep the heat input sufficiently low to restrict the time above temperatures of about 300 °C and thus minimise the formation of brittle intermetallic phases. It is good practice to perform the aluminium-to-aluminium weld first. This way, a larger heat sink can be provided when the steel-to-steel weld is performed.

Bimetallic transition materials combining aluminium with different other materials as steel, stainless steel and copper are commercially available. The methods used for joining the dissimilar materials - and thus producing the bimetallic transition inserts - are usually solid state joining processes (e.g. roll bonding, explosion welding, friction welding or hot pressure welding).



Welding of dissimilar metals with transition joints

(Source: Shockwave Metalworking Technologies)

As an example, a transition insert for aluminium/steel (Triplate[®]) welding produced by explosion welding is shown above. It consists of a sandwich of three metals (steel, EN AW-1050A and EN AW-5083).

Another type of transition joints has been developed at TWI. The Stir-lock[™] technique is a forge/forming seam joining technique. One side of the Stir-lock [™] joint can be compared with riveting. A rivet head is formed into a countersunk hole, to provide a mechanical interlock between two or more plates. The countersunk holes are made in the harder sheet material. The material that forms the interlock (or "rivet head") remains an integral part of the softer, more easily formable sheet.



Possible application of the Stir-lock[™] technique for joining dissimilar metals (Source: TWI)



Single sided, Stir-lock[™] aluminium-to-steel transition joint: Friction treated side (left) with a continuous weld track and opposite side showing aluminium extruded into the pre-machined holes (right)

(Source: TWI)

11.2.1.2 Fusion welding of coated materials prior to welding

Another option is the application of fairly thick aluminium coatings to the other material. Different methods can be used to coat steel with aluminium, e.g. roll bonding, dip coating (hot dip aluminizing) or brazing an aluminium sheet to the steel surface. Once coated, the steel member can be arc welded to the aluminium component. Care must be taken to prevent the arc from impinging onto the steel. Proper processing includes directing the arc onto the aluminium member and to allow the molten aluminium from the weld pool to flow onto the aluminium coated steel.

Another method of joining aluminium to steel involves coating the steel surface with silver solder. The joint is then welded using an aluminium filler alloy, taking care not to burn through the barrier layer of silver solder.

Neither of these coating methods can ensure full mechanical strength of the joint; they are usually used for sealing purposes only.

11.2.1.3 Fusion-brazing arc welding processes

In the fusion-brazing welding process, the aluminium base metal and the filler metal melt and form a fusion weld, whereas the molten aluminium alloy spreads on the top surface of the steel plate and forms the brazed joint with steel. As the steel does not melt, the excessive formation of the intermetallic compounds can be effectively prevented. The heat source used in brazing-fusion welding of aluminium to steel can be a MIG arc or a TIG arc. But also electron beams or laser beams can be used for this purpose (see 11.2.2.1).

In fusion-brazing welding, a properly controlled, stable energy input is necessary to make sure that the steel does not melt. Arc welding has the advantage of low cost, but its power output is normally not sufficiently stable and the welding efficiency is not satisfactory keeping in mind the increasing application requirements. Some progress could be achieved using the pulsed MIG welding technique (see 3.1.3.2). Better results were achieved by the application of the Laser MIG hybrid technique (see 10.3.1.4). However, up to now, only aluminium/steel joints produced by the cold metal transfer (CMT[®]) welding process have found practical application in the automotive industry.

a) Arc brazing-welding

As an example, butt brazing-welding was carried out between an aluminium alloy and stainless steel with the help of a TIG arc using an AI - 6 % Cu filler alloy and a non-corrosive flux. On the aluminium side, the interface shows the characteristics of a welded joint whereas on the steel side, the interface characteristics are that of a brazed joint.



Electromagnetic hybrid TIG welding-brazing

(Source: J.Luo et al.)

A thin intermetallic compound layer formed at the interface between the weld seam and the steel with an average thickness of $3 - 5 \mu m$ (which is less than the generally accepted limiting value of 10 μm). The dominating factor determining the joint quality is the wetting action on the steel side (i.e. the spreading performance of the liquid filler wire). Further improvements could be achieved using a longitudinal electromagnetic hybrid TIG welding-brazing method on an aluminium alloy/low carbon steel joint. The distribution of the second phase particles in the welding seam was more uniform and the grain size is much smaller than in a normal TIG brazing weld seam.

b) Laser MIG (or TIG) hybrid joining

In a first attempt, a large spot laser was used to stabilize the MIG welding process and maintain a constant MIG arc energy output. In addition, the leading large spot laser preheats (but does not melt) the galvanized steel and thus improves the spreading of the liquid aluminium alloy on the steel top surface in case of overlap joints. The MIG arc energy (which is the main heat input) is used to melt the filler metal and the aluminium base metal; the laser energy plays a secondary role in brazing-fusion welding. Similarly, laser TIG hybrid welding (see 10.3.1.2) can also be used. Whereas dissimilar metal joints could not be produced in laser or arc welding only, acceptable joints without obvious defects were obtained using the laser-assisted hybrid processes with a relatively wide processing window.





(Source: C. Thomy and F. Vollertsen, BIAS)

Using laser MIG hybrid welding, aluminium/steel joints for both structural as well as tailored blank applications have been produced successfully in the laboratory. The aluminium and the steel sheet were arranged in a butt joint configuration. In this case, the laser beam was positioned on the aluminium side. During joining, the edge of the aluminium sheet is molten -

and together with the molten filler wire - the gap between the aluminium and the steel is bridged and the steel is wetted by the aluminium melt. The main task of the MIG arc is to create a large molten melt pool and to supply filler material to the melt pool. The laser beam, which is operated in the keyhole mode, allows to increase the welding speed by stabilising the MIG arc. Thus, heat input is reduced and the negative effects of a too large heat input such as excessive phase layer formation and distortion are avoided.



Laser MIG hybrid welded joint between EN AW-6016 to zinc coated DC05 steel sheet

(Source: C. Thomy and F. Vollertsen, BIAS)

c) Cold metal transfer (CMT®) welding

The principle of the cold metal transfer process is described in detail in section 3.1.3.6. This process is commercially used both in car body assembly as well as for the production of aluminium/steel tailored blanks.

The CMT[®] process evolved from the continuous adaptation of the MIG process to resolve the problems posed by the joining of steel and aluminium. It allows the material transfer to take place with barely any flow of current. The aluminium base material melts together with the aluminium filler, with the melt wetting the galvanised steel. Although the steel base material is only wetted during this brazing process and does not melt, fracture always occurred in the aluminium base material, not in the weld seam.



Cold metal transfer (CMT®) welding of aluminium to galvanised steel

(Source: Fronius)

The special gas-shielded cold metal transfer process fulfils the crucial requirements of a joining process for dissimilar metals: low thermal input and good controllability. When steel is joined to aluminium, the filler metal and the aluminium wet the galvanised steel sheet and the filler metal fuses with the aluminium. On the steel side, a brazed joint is obtained, which the aluminium is then welded against. A special aluminium filler metal (Al - 3 % Si - 1 % Mn) has been developed for braze-welding.



Steel-aluminium hybrid blank (Source: voestalpine Europlatinen)

11.2.2 Other fusion welding processes (beam welding, resistance welding)

A more detailed evaluation of resistance spot welding (see 5.1) to join aluminium to steel was an obvious step keeping in mind the widespread use of this joining process in the automotive industry. However, as shown below, little success was achieved in laboratory tests.

Laser (and electron) beam welding offer the possibility of a closely controlled, localized heat input and thus may allow better control of the formation of brittle intermetallic phases at the interface. Practical tests were successful, but no series application are known today. Electron beam welding techniques have been applied with some success in industrial tests, however, the following considerations will be limited to laser beam welding.

11.2.2.1 Joining of aluminium to steel with lasers

Experimental tests using keyhole laser welding (see 4.1.2.2) in order to join aluminium to steel have been carried out, but with limited success. Some approaches to decrease the thickness of the layer of intermetallic phases which are formed during laser welding at the aluminium/steel interface are described in the scientific literature. The results achieved up to now using different laser welding configurations and a wide range of processing conditions are not convincing. The tests in the keyhole welding mode using a steel-on-aluminium overlap configuration showed that changes of the processing parameters which decrease the percentage of intermetallic components also cause unfavourable effects such as inadequate penetration depth, spattering and cavity formation.

On the other hand, laboratory tests using conduction laser welding (see 4.1.2.1) have shown very promising results. The advantage of using the conduction laser welding method to join dissimilar materials is based on the high process stability which allows a better control of the temperature in the interaction area between aluminium and steel.

a) Laser conduction welding

A possible approach based on the conduction welding principle is the use of a defocused laser beam which is directed onto the steel sheet; causing local heating, but no melting. Heat is conducted through the steel and causes local melting of the adjacent aluminium. The molten aluminium wets the steel and then solidifies, resulting in a metallic bond. The process can be applied to both lap joints and butt joints, although it is most suited to lap joints. In practice, the difficulty is to control heat input so that melting of steel is more or less prevented. However, even when a small amount of local melting of the steel sheet does take place, a relatively strong bond is formed when the intermetallic transition zone is sufficiently small.

The technique was used to join Zn-coated steel sheets typically used in automotive body-inwhite fabrication to aluminium sheets. Some intermetallic phases were formed at the interface, but the use of adequate process control measures ensures that the intermetallic particles do not significantly influence joint strength.



Schematic of the laser joining process for both lap and butt joints

(Source: TWI)

Overlap welds can be made best using steel on top and aluminium at the bottom. This configuration results in a better joint quality mainly due to the thermal characteristics of both materials. When aluminium is used on top, the higher thermal conductivity of aluminium results in a much larger affected interfacial area since the heat tends to flow along the interface in the aluminium part rather than heating the steel. When steel is used on top, the conduction of heat from steel to aluminium can be much better controlled.

b) Laser roll welding process

The laser roll welding process was developed in 2002. The basic idea was to exploit the high local heat input and short process time of laser welding to shorten the thermal cycle in order to control the formation and growth of the brittle intermetallic phases. Furthermore, good thermal contact and rapid heat transfer from the steel sheet to the aluminium alloy sheet should be ensured by a pressure roller.

Tests have been carried out using zinc coated steel and an aluminium alloy sheet. A layer of intermetallic compounds was observed in all welded joints. However, when the thickness of the intermetallic particles was less than 10 μ m, tensile test specimens failed in the base metal (i.e. the damaging effect of the brittle intermetallic compounds can be tolerated). The welding speed influences the joint performance (intermetallic phase layer thickness and tensile shear strength) to a greater degree than the roll pressure.



Schematic diagram of the Laser Roll Welding process

(Source: M. Kutsuna et al.)

This method was further developed to produce cold-formable aluminium-steel hybrid blanks. The aluminium and the steel sheets converge with an overlap of 5-10 mm and are guided between the rolls of a modified cold mill. One of the joining rolls is grooved, so that the roll forces mainly act on the overlapping area. The joining zone is activated and heated by means of a laser, immediately before undergoing the cold-rolling pass.

c) Laser welding-brazing process

Preliminary tests using a high-power semiconductor laser showed that welding-brazing of aluminium to steel is possible. As an example, an aluminium/steel butt joint is shown below. Aluminium/steel joints can be made with both CO₂ and solid state lasers using an AlSi12 filler wire and directing the laser spot primarily onto the aluminium alloy sheet. However, relatively large and brittle intermetallic phases are formed in the transition zone.



Laser welded aluminium/steel butt joint

(Source: BIAS)

The use of a brazing flux (Nocolok[®] brazing flux) led to some improvement. The specimens were overlapped and while the brazing filler (EN AW-4043) was supplied to the lapped corner. The flux improved the wettability of the brazing filler metal and increased the brazing width. It also restrained the formation of a layer of Fe-Al intermetallic phases at the joint interface. However, the use of flux involves the application of a flux coating before brazing and the removal of residual flux after brazing, which tends to reduce work efficiency and productivity.

Even better results were achieved when a Zn-based brazing wire was used in combination with a Zn-coated steel.



Laser brazed aluminium/steel joint using Zn-based brazing wire and non-corrosive flux (Source: Novelis)

Further developments led to the realisation of flux-less laser welding-brazing joints. Using an AlSi12 filler wire, a normal weld is produced between the filler wire and the aluminium substrate. Subsequently, the molten filler metal wets the steel and creates a brazed joint on the steel side. The preferred joint configuration for "Fluxless Laser Brazing" is a T joint, but also overlap joints can be realized. Both hot dip and electro galvanised steel sheets can be joined with this brazing method. Favourable results are achieved up to a brazing speed of 4 m/min.



Principle of the "Fluxless Laser Brazing" (Source: Aleris)

For flux-less laser welding-brazing of an aluminium alloy sheet to a galvanized (zinc coated) steel sheet steel, the application of a zinc-based filler alloy (Zn - 2 wt. % Al) produced better results than an Al-based wire. The reason is the use of similar materials for the zinc coating and the filler wire as well as the high miscibility of aluminium in zinc.



Laser welding-brazing process

(Source: H.Laukant et al., Science & Technology of Welding and Joining, 10 (2005) 219)

For the filled overlap weld geometry, the laser beam was directed at the aluminium sheet. Hence the composition of the formed weld seam is aluminium-rich. In case of the filled flange geometry, the laser is positioned between the two flanges and a smaller amount of the aluminium sheet is melted. In both geometries, the intermetallic layers are limited to a small area where the laser transfers the highest energy into the steel. The intermetallic layers exhibit a maximum thickness of 5 μ m, i.e. the mechanical characteristics of the joints exhibit tensile strength values of up to 80 % and an elongation of 40 % in relation to the used aluminium base material (EN AW-6016, T6).



Laser welding-brazing joints: filled overlap (left) and filled flange geometry (right)

(Source: H.Laukant et al., Science & Technology of Welding and Joining, 10 (2005) 219)

The key advantage of this process is the freedom to select laser power, brazing speed and filler wire speed independently from one another. In analogy to the use of a laser beam, such a brazing process could also be made using an electron beam.

11.2.2.2 Resistance spot welding for joining steel to aluminium

When the standard resistance spot welding technique is used to join steel and aluminium alloy sheets, the very brittle intermetallic phases which are produced at the interface significantly decrease joint strength.

A possible solution offers a hot dip aluminized steel sheet which was developed by Kobe Steel and Nissan Steel specifically for joining to aluminium using conventional welding equipment. It has a nitrogen-rich layer at the interface of the base steel to the aluminium coating layer which effectively prevents the inter-diffusion of iron and aluminium atoms, i.e. the formation of brittle intermetallic phases at the interface is prevented. The resultant joint strength is almost equivalent to that of a resistance spot welded aluminium/aluminium joint.

In another approach to overcome the brittle intermetallic phase problem by technological means, aluminium (and magnesium) were resistance spot welded to steel in a triple layer lap joint configuration with steel sheets on both sides. During welding, the current and electrode force in the spot welding operation were controlled so that the heat (generated mostly within the steel) was sufficient to melt the aluminium (or magnesium) sheet. It was expected that the molten metal, contained by the electrode force, would wet the steel surface, forming a bond at the interface between the two materials.



Joining aluminium (or magnesium) to steel by resistance heating

(Source: TWI)

Experimental tests with different electrode forces and welding currents indicated that it was possible to produce some bonding in the interface between the steel and magnesium alloy. However, bonding could only be achieved when the welding current was adjusted to melt only the central magnesium sheet at a pre-set electrode force. Furthermore, severe porosity and solidification cracking occurred in the centre of the nugget and the welds exhibited weak, brittle interface failures in peel testing. When the same approach was used to join aluminium to steel, a continuous layer of intermetallic phases was formed at the interface since a steel

surface layer also melted. The weld failed in a weak, brittle manner at the interface on peel testing.

In a second set of experiments, aluminium was joined to steel using an aluminium/steel transition piece. In this case, a weld nugget formed on the steel side as in conventional resistance spot welding. The generated heat also melts the aluminium at the interface of the transition piece to the outer aluminium sheet.



Resistance spot welding of aluminium to steel using a transition material

(Source: TWI)

The heat sink effect of the aluminium within the joint prevents the steel from melting completely through to the contact with the aluminium. However, shrinkage defects were observed at the steel interface since that part of the nugget solidifies last. In addition, intermetallic phases are formed at the interface within the transition piece. Consequently, the resulting joints failed on peel testing in a brittle manner by pulling a plug out of the thin aluminium layer of the transition material. Nevertheless, some joint strength could be achieved.

11.2.3 Solid-state joining processes

Solid-state joining processes are generally well suited to join dissimilar metals. Friction welding processes such as rotational friction welding (see 7.1.1.1), friction stud welding (see 7.1.4), etc., ultrasonic welding (see 7.3) and electromagnetic pulse welding (see 7.2.4) are routinely used to manufacture specific automotive components.

Therefore in the following, only some new developments in connection with the friction stir welding technology will be covered in more detail.

11.2.3.1 Friction stir welding

Linear friction stir welding (see section 7.1. 2.1) can be used to join aluminium to steel. The rotating pin is plunged into the aluminium. Then, the rotating pin is pushed toward the faying steel surface and the oxide film is mechanically removed from the faying surface by the rubbing motion of the rotating pin. Aluminium, which is in a plasticized state due to the heat generated by the friction of the rotating tool shoulder, consequently adheres to the activated faying steel surface, i.e. a joint between steel and aluminium is achieved.

Since the rotating pin is plunged into the softer aluminium and does not come in contact with the steel, the rotating pin shows minimal wear. When the rotating pin was inserted in the standard position (around the centre of the interface), no joint could be produced due to excessive wear of the rotating pin.



Schematic of the rotating pin position

(Source: K. Kimapong and T. Watanabe)

No intermetallic compounds were observed at the interface between the steel and the aluminium alloy. However, some intermetallic compounds were observed in the upper region of the friction stir weld where the temperature is higher due to the additional heat generated by the rotating tool shoulder.

11.2.3.2 Friction stir welding

Variants of the friction stir spot welding technology (see section 7.1.3.1) are well suited to join aluminium and steel. It was first used in closure applications in 2005 to join the trunk lid and bolt retainer for the Mazda MX-5 sports car.



Friction stir spot welding of steel to aluminium (MX-5 trunk lid and bolt retainer)

(Source: Mazda)

Galvanized steel helps to prevent galvanic corrosion that results from the contact of two types of metal. The joining tool pushes aside the zinc coating. Then the heat bonds the two metals together. A residual layer of zinc remains on the metal surrounding the area where the two metals are joined, preventing local corrosion of the metals.

A variant of the linear friction stir welding process (see 7.1.2) can be also used to form continuous structural aluminium/steel joints. A stable metallic bonding between steel and aluminium is achieved by moving a rotating tool on the top of the aluminium which is lapped over the steel with high pressure. The technology is used in practice to manufacture aluminium/steel subframes.



Friction stir welding of aluminium to steel (Source: Honda)

11.2.3.3 Laser assisted friction stir welding

In an effort to produce hybrid tailor welded aluminium-steel blanks by friction stir welding, the steel blank was preheated with a laser beam in order to diminish the flow strength of the material. The diode laser spot was positioned directly in front of the welding direction of the tool. The results show the high potential of laser assisted friction stir welded steel/aluminium tailored hybrid blanks in a sheet thickness of about 1 mm. Simultaneously, the welding speed could be significantly increased up to 2000 mm/min.



Appearance of the weld seam in a cross section (I-III) and a top view (Source: M. Merklein et al., University of Erlangen)

11.2.4 Brazing and soldering

Brazing (see 6.1) and soldering (see 6.4) have a significant advantage over other molten metal joining techniques. The formation of brittle intermetallic compounds can be significantly inhibited through the use of brazing alloys and solders with low melting points. Dissimilar metals and even non-metals (i.e. metallized ceramics) can thus be joined to aluminium. For joining ceramics to metals, thin metal layers are usually deposited onto the ceramic part prior to brazing in order to facilitate the bonding process.

11.2.4.1 Brazing

Furnace brazing, however, encounters some difficulties to ensure the required short process cycles (fast heating/cooling). Specific problems associated with torch brazing include the need for high levels of technical skill. Arc and, in particular, laser brazing offer the prospect of solving these problems.

Aluminium can be brazed readily to other metals such as nickel, titanium and – with some limitations – steel. Only a thin layer of intermetallic phases is formed. However, when brazing aluminium to magnesium and copper, i.e. metals where the phase diagram shows a low melting eutectic, much larger particles of brittle intermetallic phases develop. Thus, brazing aluminium to Mg or Cu is practically not possible.

Brazing processes require the use of a filler alloy and an adequate fluxing agents. As an example, suitable options when brazing aluminium to stainless steel are:

- NOCOLOK® flux and AI-Si filler alloys or

- CsAIF complex flux (melting range between 420 and 480 $^\circ\text{C})$ and a 85 % Zn – 15 % Al filler alloy.

Joining of aluminium to stainless steel using the NOCOLOK[®] flux is carried out for different applications on large a scale for non-structural joints outside of the automotive industry. It works both with NOCOLOK[®] flux + AI-Si brazing alloy and with NOCOLOK[®] Sil flux. After the flux melts and the oxides are removed, a thin layer of intermetallic phases is formed which serves as a metallurgical bond between steel and aluminium. The thickness of the brittle intermetallic layer is a function of the brazing time and temperature; consequently the need for a short brazing cycle with fast heat-up and very short holding time at maximum temperature.

11.2.4.2 Soldering

Soldering is highly suited to join a wide variety of materials, including aluminium to other metals as well as ceramic materials. Conventional soldering uses lead and tin based solders or silver, copper, nickel or other precious metals and/or alloys that melt at a lower temperature than either of the materials being joined. The soldering alloy fuses into the surfaces of the materials being joined, forming a metallurgical bond without significantly melting either of the two materials. When soldering in air, fluxes are used to react with oxide surface layers and to shield the joint area.

When soldering dissimilar materials, the following aspects have to be considered when selecting the appropriate soldering system:

- The compositional compatibility of the solder with both interfaces.
- The differences in the coefficient of thermal expansion between the two materials.
- The differences in melting points.

Since aluminium has a high coefficient of thermal expansion, soldering – which is carried out at significantly lower temperatures than brazing – may be the preferred solution in many applications.

An advanced soldering technology for dissimilar materials was developed by EWI. The EWI SonicSolder[™] works in conjunction with the ultrasonic soldering process. Ultrasonic soldering offers the advantages of flux-less, lead-free soldering with the ability to join difficult-to-wet materials. The binary Sn-Al lead-free solder alloy allows for successful joining of aluminium, copper, titanium, glass, ceramics, and other difficult-to-bond materials.

11.2.5 Mechanical joining processes

Until recently, mechanical joining was the main technology used to join aluminium and steel components. In general, all the different mechanical joining methods used within the automotive industry (see section 8) are also suitable to join dissimilar metals. However, depending on the material combination (strength and ductility of both partners), some limitations may exist in particular for mechanical joining techniques which are based on forming and cutting processes (e.g. clinching, self-piercing riveting, flow drilling screws, etc.).



Aluminium 2.45 mm Steel 1.4 mm



Aluminium 1.2 mm Steel 1.0 mm Aluminium 1.2 mm

Clinching (left) and self-piercing riveting (right) of aluminium to steel (Source: Böllhoff)

Furthermore, thermal expansion effects must be considered both during design and in the assembly process. Subsequent thermal influences (e.g. during bake hardening of the lacquered body-in-white) may result in severe distortions of an aluminium body panel mechanically joined to a stiff steel structure. Proper measures have to be taken for compensating the differences in the thermal expansion coefficient.



Aluminium to steel joining technologies in the Audi TT

(Source: Audi)

In most cases, mechanical joining techniques are combined with adhesive bonding to increase the static and fatigue strength of joints and prevent any deterioration of corrosion resistance of joints caused by the contact between the dissimilar metals.

11.2.6 Adhesive bonding

Adhesive bonding (see section 9) is a standard joining technology for dissimilar materials. As mentioned above, adhesive bonding is also often used to mitigate galvanic corrosion when joining dissimilar metals. The adhesive must be compatible with both metals, and both metals may require some form of surface treatment, in special cases even including the application of an appropriate electro-coat primer. In addition, when bonding aluminum to another metal, for example, steel or magnesium, the difference between their respective thermal expansion coefficients is a major concern.

Adhesive bonding is key technology to join steel to aluminium in the automotive industry. But as a consequence of the different thermal expansion coefficients, rigid bonds that have worked in homogeneous designs, may now require some flexibility. Elastic bonding techniques provide the required amount of flexibility of an adhesively bonded joint without cohesive or adhesive failure. The characteristics of elastic adhesives enable successful bonding of materials with dissimilar coefficients of thermal expansion and maintaining bond strength and integrity in service. In addition, these types of adhesives help to minimize readthrough of the bond, i.e. they prevent a visually noticeable appearance of the bond line on the surface.

Elastic bonding is not a new concept to vehicle design. Different types of adhesives are available for elastic bonding, e.g. polyurethanes and silane modified polymer formulations with a proven track record in truck and bus applications.

11.2.6.1 Hem flange bonding

Hem flange bonding is the standard solution when aluminium and steel closure panels are joined. In order to prevent any problems related to galvanic corrosion and thermal deformation between an aluminium outer panel and a steel inner panel, Honda recently presented three newly developed technologies:

- Adoption of "3D Lock Seam" structure, where the steel panel and aluminium panel are layered and hemmed together twice.
- Adoption of a highly corrosion-resistant steel for the inner panel and a new flange form that assures the complete filling of the gap with adhesive agent to prevent galvanic corrosion.
- Adoption of an adhesive agent with a low elastic modulus and optimised seam position to control thermal deformation.



Optimised hem flange bonding technique to join an aluminium outer and a steel inner panel

(Source: Honda)

11.2.7 Joining aluminium to magnesium

The combination of aluminium and magnesium components offers interesting new lightweight solutions. Whereas in case of dissimilar joints such as steel/aluminium alloys, it is possible to realize a solid/liquid state reaction at the joining interface between the two metals where only the metal with lower melting temperature melts, it is difficult to apply this method to magnesium/aluminium alloys joint due to the small difference between their melting points. Numerous attempts have been made to join magnesium to aluminium using arc and resistance spot welding, but they have invariably led to failure. The two metals react to form brittle intermetallic compounds in the melted zone and the weld literally falls apart. However, laboratory laser welding proved the possibility of a controlled molten metal penetration depth in the lap joint configuration.



Laser welding of lap joint

(Source: R. Borrisutthekul et al., Science & Technology of Advanced Materials 6 (2005) 199)

It was found that an edge-line welding lap joint could be realized with the required shallow penetration depth of molten metal into lower plate, effectively reducing the reaction between the two metals and, thus, the formation of larger intermetallic compounds.

Some work has also been done to demonstrate the basic feasibility of the friction stir welding process to join magnesium and aluminium alloys. Initial results were encouraging. The two materials are plasticised, but do not melt. The joint is a complex mechanical interlock and there is no evidence for the formation of intermetallic compounds.



FSW of magnesium alloy (AZ91) to aluminium alloy (EN AW-2219)

(Source: TWI)

The most important methods for joining magnesium to other materials are mechanical fastening systems, often combined with adhesive bonding (in general with pre-fabricated holes in the magnesium part). However, in recent years, the self-piercing riveting and clinching techniques were also used with considerable success. The principal difficulty is the poor ambient temperature ductility of magnesium, which requires heating of at least the magnesium component prior to making the joint. Successful industrialisation of this process requires the development of machine tools capable of providing the right temperature conditions in an acceptably short time.



Self-piercing riveting (left) and clinching (right) of aluminium (1mm thick) and magnesium (3mm thick) alloys

(Source: TWI)

11.3 Joining aluminium to plastics and composites

The following consideration focus on processes suitable to join aluminium and fibre reinforced composites. Aluminium-plastic joints are usually not structural joints. In practice, adhesive bonding and specifically developed mechanical joining methods are mostly used.

Another most interesting possibility – which will not be covered here – is to join properly shaped aluminium components directly in the injection moulding process.



The injection moulding process combines metal stamping with plastic structures (Source: Lanxess)

11.3.1 Joining aluminium to plastics

Adhesive bonding is probably the least expensive joining methods for permanent bonds. Adhesive bonding uses commercially available materials that are specifically formulated to bond plastic parts to the other material.

11.3.1.1 Joining with mechanical fasteners

Specifically for assemblies that must be taken apart a limited number of times, mechanical fasteners (i.e. screws, bolts and rivets) are the least expensive, most reliable and commonly used joining methods. If the part is going to be disassembled regularly, metal inserts in the plastics should be considered. Rivets offer a simple, easily automated installation process that can be used in particular for plastic-to-sheet metal joints.



Inserts for thermoplastic parts: screwed-in (left) or joined by ultrasonic welding (right)

(Source: Tappex Ltd.)

In a typical large plastic and metal assembly where movement is restricted, high compressive or tensile stresses can develop since the expansion coefficient of plastics is four to six times higher. To avoid such problems, slotted screw holes in the plastic part should be used for temperature-sensitive designs.

Designed into the geometry of mating parts, snap fits offer a very inexpensive, quick and efficient joining method. Press fits must be designed with great care to avoid excessive stress in the assembly. A special mechanical method has been developed to create hybrid automotive front-end assemblies. The approach is to form projecting annular collars in a metal sheet and then to cold-press those collars into plastic parts. Undercuts in the metal collars act as claws to firmly lock together the sheet metal and moulded plastic. The collar-joining approach well with a number of reinforced and unreinforced materials, including nylons, PBT, and polypropylene, although most work to date has been with 30 % glass-filled nylon 6 and 66. No significant crazing or fracturing occurs when the metal collars are pressed into the plastic.



Collars punched out of sheet metal are cold-pressed into plastic parts

(Source: BASF)

Also clinching seems to be a promising technology to join metals with short fiber reinforced polymers since there is to no thermal influence on the materials and the process requirements to surface finishing are low. One of the main challenges in designing a suitable clinching process is to consider the quite different stiffness, plastic behavior and forming limits of these two materials.

11.3.1.2 Laser-assisted metal and plastic joining

Laser-assisted metal and plastic joining is applicable to many combinations of metals (e.g. steels, titanium, and aluminium alloys) and plastics (e.g. PET, polyamide (PA), and polycarbonate (PC)). The laser beam heats the metal either from the plastic or the metal side of a lap joint and melts the plastic near the joint interface. The key point is the formation of small bubbles (diameter 0.5 mm or less) which induce a high pressure in the molten plastic. Thus the molten plastic is forced to the metal surface. Anchoring effects in concavities of the surface topography, physical Van der Waals forces and chemical bonding through the oxide film produce a strong joint.



Mechanism of laser-assisted metal and plastic joining (Source: S. Katayama, Osaka University)

The surfaces of plastic sheets and metal plates are cleaned with alcohol; no other surface treatment is required. If the plastic sheet has more than 60% transparency, it may be placed at the upper side. The transmitted laser beam is absorbed to heat the metal surface, and the plastic near the joint can be melted to form bubbles by the heat conducted from the metal. A shielding gas should be used to keep the top plastic sheet surface clean and cool.

For non-transparent plastics (e.g. GFRP and CFRP with high laser absorption), the metal sheet is placed on top. If the metal is thick, a partially penetrating weld should be produced to heat the plastic near the joint interface. The metal interface near the lap joint is not melted, but the plastic on the metal plate is melted and the required small bubbles are formed.



Laser-assisted metal and plastic joining (Source: S. Katayama, Osaka University)

11.3.2 Joining aluminium to composites

Composite materials consist of a polymeric matrix resin which is used to bind fibrous reinforcements into the combined material. The type, volume fraction, length and layup of the fibres determine its mechanical properties. Composites can have complex directional mechanical properties, differing by in-plane and out-of-plane orientations. In the fibre direction, properties such as tensile strength, modulus, and yield strength are considerably

higher and depend on the adhesion between the resin matrix and the fibre. Perpendicular to the fibre, the properties approach those for the matrix resin alone.

Composites can be divided into two major classes based on the matrix resin: thermoset composites and thermoplastic composites. A thermoset polymer matrix composite cures and crosslinks when heated; it cannot be re-formed by heating. Examples are epoxy, acrylic, or urethane reinforced with either glass or carbon fibres. A thermoplastic matrix composite softens with heating and continues to soften every time it is heated. Examples are polypropylene or nylon, also reinforced with glass or carbon fibres. These can be molded into shapes or welded by using some form of heat and pressure.

Both thermoset and thermoplastic composites may be laminated, impregnated fabric structures. A typical laminar carbon-fabric composite might contain 50 - 60 vol. % reinforcement. Thermoplastic composites, especially, may take the form of short- or long-fibre random reinforcement mixed into the bulk and then molded into shapes. These may contain as much as 50 vol. % reinforcement, which gives rise to quasi-isotropic behavior, except at the surface, which will be high in resin.

Joints between aluminium and either a thermoset or thermoplastic composite are generally achieved by adhesive bonding or a combination of adhesive bonding and mechanical fasteners. However, joining a composite panel to aluminium presents some problems. The mechanical anisotropy of the composite in the joint region must be accounted for in the design. In a shear-loaded joint, the fibers nearest the faying surface should be oriented along the joint in the direction of the maximum expected shear. Therefore, the fibre direction might be parallel to the long axis or the short axis of the joint, depending on the expected loading. Often, the layer nearest the joint is oriented to give maximum strength performance in the direction of maximum stress. To deal with complex loading at the faying surfaces, biased fibre layers can be oriented nearest to give an average directional stress distribution.

It is also necessary to allow for thermal mismatch. The coefficient of thermal expansion for epoxy-based parts matches that of aluminium fairly well. In comparison, the coefficient of thermal expansion for a thermoplastic composite, such as glass fibre-polypropylene, is higher, and so has the potential for thermal strains at the bond line.

Furthermore, when carbon fibre composites are in contact with aluminium, galvanic corrosion is a concern. An adhesive can provide a galvanic corrosion barrier. An electro-coat layer could provide additional protection. However, any through-holes (e.g. for riveting) require specific attention.

11.3.2.1 Transition joints

Transition joints are important auxiliary means to join metals and composite materials. They are normally metallic elements which are integrated into the composite during part manufacturing. Attachment to the metal part is then possible using conventional joining methods.

Different concepts are evaluated to realize transition structures between aluminium and carbon fibre reinforced composites. As an example, using the Stir-lock[™] technique (see 11.2.1.1), reinforced transition joints can be produced. A stainless steel mesh, which provides a skeleton for the application of the composite material, is joined to an aluminium element by friction welding.


Stainless steel mesh reinforcement joined to aluminium by the Stir-lock[™] technique

(Source: TWI)

Another possibility is a "wire" concept characterised by a parallel arrangement of miniaturised loop connections. It consists of a carbon fibre-titanium wire-textile which is joined to an aluminium sheet. A carbon fibre loop is threaded through a titanium wire loop on one side. On the side opposite, the titanium wire loops are joined to the aluminium component.

The "foil" concept can be characterised as a hybrid laminate. It consists of carbon fibre reinforced plastic layers which alternate with titanium foils. The area of the laminate which only consists of titanium foils is then welded to aluminium.



Titanium wire (left) and foil concept (right) to join CFRP-aluminium structure (Source: Fraunhofer IFAM)

Both joint configurations, are in principle suitable to produce load-bearing carbon fibre reinforced plastic-aluminium structures, when using a laser beam welding process to join aluminium to titanium.

11.3.2.2 Adhesive bonding

Thermoset composites are easier to adhesively bond than thermoplastic composites because they have higher surface wettability. Epoxy, urethane, or acrylic adhesives can all be used for adhesive bonding with aluminium. Epoxies are especially reliable when used with epoxybased composites because they have similar flow characteristics.

Careful preparation of both material surfaces is essential to achieve a high quality adhesive bond. The required surface treatment for the composite component varies depending on the type of composite and the adhesive used. The recommended preparation of many composite materials includes a solvent wipe (to remove loose surface dirt and oil) and an abrading operation. Abrasion should be done carefully to avoid damaging composite surface fibers. In some cases, a primer must be used to coat the composite before applying the adhesive.

Thermoplastic composites do not wet well with adhesive and usually require a form of surface activation. This can be a flame, corona, or a plasma treatment that oxidizes the surface to increase wetting. A primer can also improve wetting. Once the polymer surface is acceptable for bonding, the system can be adhesively bonded or rivet-bonded. Efforts have been made

to weld-bond thermoplastics to metals. So far, these are mostly heat seal joints and may involve adhesives as well. But this is clearly an area which must be watch in future.

Another possibility to adhesively bond composites to aluminium is the use of a primered aluminium component (preferably an electro-coat primer). The bond would then be between the primer and the composite. Normally the joint can then be designed with the assumption that the weak link is the primer/aluminium interface.

A successfully bonded joint with a composite member will be one in which the composite fails rather than the adhesive joint. Typically, a laminated composite structure will fail between the first and second plies under the phenomenon of interlaminar shear failure. In this situation, the layers of fabric are held together only with resin (unless the material is braided), and the fault begins in the resin between two layers and propagates along the fabric interface.

Joints with enhanced mechanical performance can be produced by the combination of adhesive bonding and mechanical interlocking between composite materials and metals. There are different possibilities to produce a metal surface topography which is optimized for mechanical interlocking. As an example, the Surfi-Sculpt surface topography is the basis for the proprietary Comeld [™] method developed by TWI.



Surfi-Sculpt[™] surface treatment (top) and double step Comeld[™] joint (bottom)

(Source: TWI)

Comeld[™] joints can be produced from a wide variety of metals and composite materials using a variety of processing techniques. In the joints shown above, the matrix of the composite was used as the adhesive; however, an additional adhesive layer may be used at the interface between the composite material and metal.

11.3.2.3 Mechanical fasteners

Mechanical fasteners are often used to join aluminium with plastics and composites, in many cases combined with adhesives.

Different standard mechanical joining methods (e.g. rivets, two-piece bolts or blind fasteners made of stainless steel or aluminium) use pre-drilled holes, both in the aluminium and the composite part. When specifying the applicable mechanical fasteners, several factors must be considered:

- Thermal expansion of the fastener in the joined materials (differential of the thermal expansion coefficients of the fastener with respect to aluminium and the composite).
- The effect of drilling on the structural integrity of the component as well as the possible fibre delamination caused by the fastener under load.
- The possibility of water (humidity) intrusion between the fastener and the aluminium/composite material.
- Possible galvanic corrosion effects at the aluminium/composite joint.

Fasteners for composites should have large heads to distribute the load over a larger surface area in order to reduce crushing of the composite material. Fasteners should fit as close as possible to reduce fretting effects in the clearance hole. Interference fits may cause

delamination of the composite and should be avoided. If an interference fit is necessary, special sleeved fasteners can limit the chances of damage in the clearance hole. Fasteners can also be bonded in place with adhesives to reduce fretting. Furthermore, in carbon-fibre reinforced composites, contraction and expansion of the fasteners can cause changes in clamping load.

Drilling and machining damage composite materials. The number and size of defects (e.g. delamination, resin erosion or fibre breakout) allowed in a structure depend on the application. For instance, delamination is a much more serious defect than fibre breakout in a carbon-fibre composite application. Applicable drilling techniques and tools are determined by the resin, the fibre (or fibre combination) in the resin as well as the way the fibres are configured.

When carbon-fibre composites are cut, fibres are exposed and can absorb water and thus weaken the material. Local application of sealants can prevent moisture absorption, but this both complicates the process and prevents to maintain electrical continuity between the composite fibres and the fasteners. Moreover, carbon-fibre composites may corrode galvanically if aluminium fasteners are used. A solution is to apply a suitable coating to the fasteners. Another possibility is to replace the aluminium fasteners by titanium and stainless steel fasteners.

Similar problems as with pre-drilled holes in the composite material have to be considered for joining elements which form their own hole (e.g. flow drilling screws, self-clinching functional elements, self-piercing rivets, etc.). The cut through fibres reduce the load carrying capacity. Friction effects between the self-cutting joining elements and the fibre reinforced composite as well as the introduced axial forces lead to delamination and other damaging effects. In addition, the composite material is being crushed. The respective damaging mechanism – and the appropriate countermeasures – are still under investigation. Nevertheless these types of mechanical joining processes are of high interest for the design of future lightweight vehicles.



Self-piercing rivets used to join an aluminium alloy sheet (EN AW-6181A) to glass fibre reinforced composites (a,c,e,f) and to ABS plastic (b,d)



(Source: University of Paderborn)

Hole and thread forming screw joining a fibre reinforced thermoplastic (2 mm) and a 3 mm aluminium alloy sheet (EN AW-6181A)

(Source: University of Paderborn)

Joining is generally easier when the ductile aluminium part is used as the bottom layer, i.e. if the joining elements first cuts through the carbon fibre composite. Therefore, an interesting

approach is also to use an aluminium counter piece for a joint where the aluminium sheet is positioned on top of the carbon reinforced composite.



Hybrid CFRP/aluminium profile joint adhesively bonded and fixed by RIVTAC® tacksetting (left) and a joint using a flow forming screw (right) with an aluminium counter piece

(Source: Böllhoff/Volkswagen)

A further development of the counter piece concept is a proposal made by the University of Paderborn. In this case, a solid self-piercing rivet is used with a suitable closing element on the composite side.



Joining principle using a solid self-piercing rivet with a closing element

(Source: University of Paderborn)

11.3.2.4 Friction spot welding

Friction spot joining (see 7.1.3) is a possible technique to produce hybrid structures by joining aluminium alloys with high performance thermoplastic composites. A non-consumable three-part tool is used to generate frictional heat. The tool comprises of a stationary clamping ring, as well as a pin and a sleeve which can rotate and move independently.



Friction spot joining tool

(Source: Helmholtz Research Center, Geesthacht)

The joining partners are clamped together in an overlap configuration with the metal piece on top of the polymer or composite against a backing plate. The sleeve and pin start to rotate in the same direction. Then, the sleeve plunges into the metallic sheet to a pre-defined depth while the pin retracts upwards. Due to the friction between the sleeve and the metal, the

temperature rises locally and the plasticized metal is squeezed into the reservoir left behind by the retraction of the pin. In the second step, the pin is forced against the soften metal to refill the key-hole. In this step, sleeve and pin return to their original position. Finally, the tool is retracted and the joint consolidates under pressure.



Friction spot joining technique for polymer-metal joining (Source: Helmholtz Research Center, Geesthacht)

During the joining process, heat flows by conduction from the metallic part to the composite and melts a thin layer of the polymer matrix at the interface. The thermo-mechanical phenomena involved in the process result in two bonding mechanisms: Mechanical interlocking due to the metallic nub created at the metal-composite interface and adhesion bonding since the thin layer of the molten polymer produced in the spot region spreads throughout the entire lap area due to the low viscosity of the molten polymer.

Friction riveting (FricRiveting) is another innovative joining concept for polymer-metal hybrid structures, developed and patented by the Helmholtz Research Center Geesthacht in Germany. The basic configuration includes a rotating cylindrical metallic rivet which is inserted into a polymeric base plate. Heat is generated by the high rotational speed and the axial pressure. Due to the local increase of temperature, a molten polymeric layer is formed around the tip of the rotating rivet. As a result of the low thermal conductivity of the polymer, the further local temperature increase leads to the plasticizing of the metallic rivet tip. While the rotation is being decelerated, the axial pressure is increased and the plasticized rivet tip is deformed and anchored in the polymeric plate. After the consolidation under pressure, the joint is held by the anchoring forces related to the deformed tip of the rivet, as well as by adhesive forces in the polymer/metal interface.



(Source: Helmholtz Research Center, Geesthacht)



FricRiveting of aluminum EN AW-2024 and polycarbonate (Source: Helmholtz Research Center, Geesthacht)

The technology is adequate to produce overlap riveted joints between metal-polymer, metalcomposite and composite-composite connections. Thermoplastic polymers or even fiber reinforced composites can be joined. The main process parameters are:

- Rotational Speed (angular velocity of the rotating rivet): It is important in the heat generation and associated phenomena.
- Joining Time: It controls the joining speed as well as the amount of heat energy supplied to the molten polymeric film, influencing the level of volumetric defects related to thermo-mechanical processing.
- Joining Pressure: The main role of this process parameter is to control the rivet forging and consolidation phases, but it is also related to the normal pressure distribution and heating of the rubbing surfaces.

11.3.2.5 Injection clinching joining

Injection clinching joining is a new joining process (patented by Helmholtz-Research Center, Geesthacht) for hybrid structures composed of a thermoplastic-based partner and a metallic or thermoset partner. The working principle is to produce joints through heating and deformation of a thermoplastic element, such as a cylindrical stud integrated in the polymeric partner, which is previously inserted in a drilled hole of the metallic / thermoset component, therefore creating a rivet from the structure itself.

Injection clinching joining joints make use of specially designed cavity profiles in the throughholes of the joining partner. The molten/softened polymer fills the cavity and remains anchored after the joint cools down and consolidates; the mechanical performance is improved by the additional anchoring performance. By the end of the process, a tight joint is obtained in which there are no additional parts other than the joining partners. Possible cavity profiles include chamfers and profiles such as threaded and dove-tail.

The electrical-heating injection clinching joining process is shown in the figure below. A polymer-based part with a protruding stud is pre-assembled with a joining partner containing a drilled hole so that the stud fits into the hole. The tool system consisting of a hot case and a punch-piston approaches the pre-assembled parts (step a). The stud is heated to the pre-determined processing temperature (step b), after which the punch-piston pushes the molten/softened polymer into the cavity (step c). The system is then cooled under pressure to reduce polymer thermal relaxation and the joint is consolidated (step d). The use of a hot case has the advantage of good heat distribution through the volume of the rivet, facilitating cavity filling. The main parameters of this process are the heating time and heating temperature. Joints can be produced in times from a few seconds to a few minutes.



Joining Time

Steps of the electrical heating injection clinching joining process

(Source: Helmholtz Research Center, Geesthacht)

A variant is the friction-based injection clinching joining which uses a simple cylindrical tool. In its simplest configuration, a rotating tool approaches the polymeric stud (see figure below, step a), melting layers of the polymer through friction and pressure (step b). After the required amount of frictional heat is achieved, axial pressure is increased while tool rotation decelerate (step c); finally, the tool retracts and the joint is consolidated (step d). The design of the final rivet geometry can be tailored by defining the height of the original stud. A short stud will yield a shallow, more aesthetic rivet head, while a tall stud will deform into a large, more resistant rivet head. The main parameters of this process are rotational speed, joining pressure and joining time. This technique is fast (cycle times of a few seconds) and energy efficient.





Injection clinching joining is a potential candidate to substitute metallic rivets on secondary structures, especially when joining plastic partners with dissimilar materials.



Injection clinching joining: Multiple spot hybrid structure (left) and cross-section of an EN AW-2024/PA66-GF joint (right)

(Source: Helmholtz Research Center, Geesthacht)