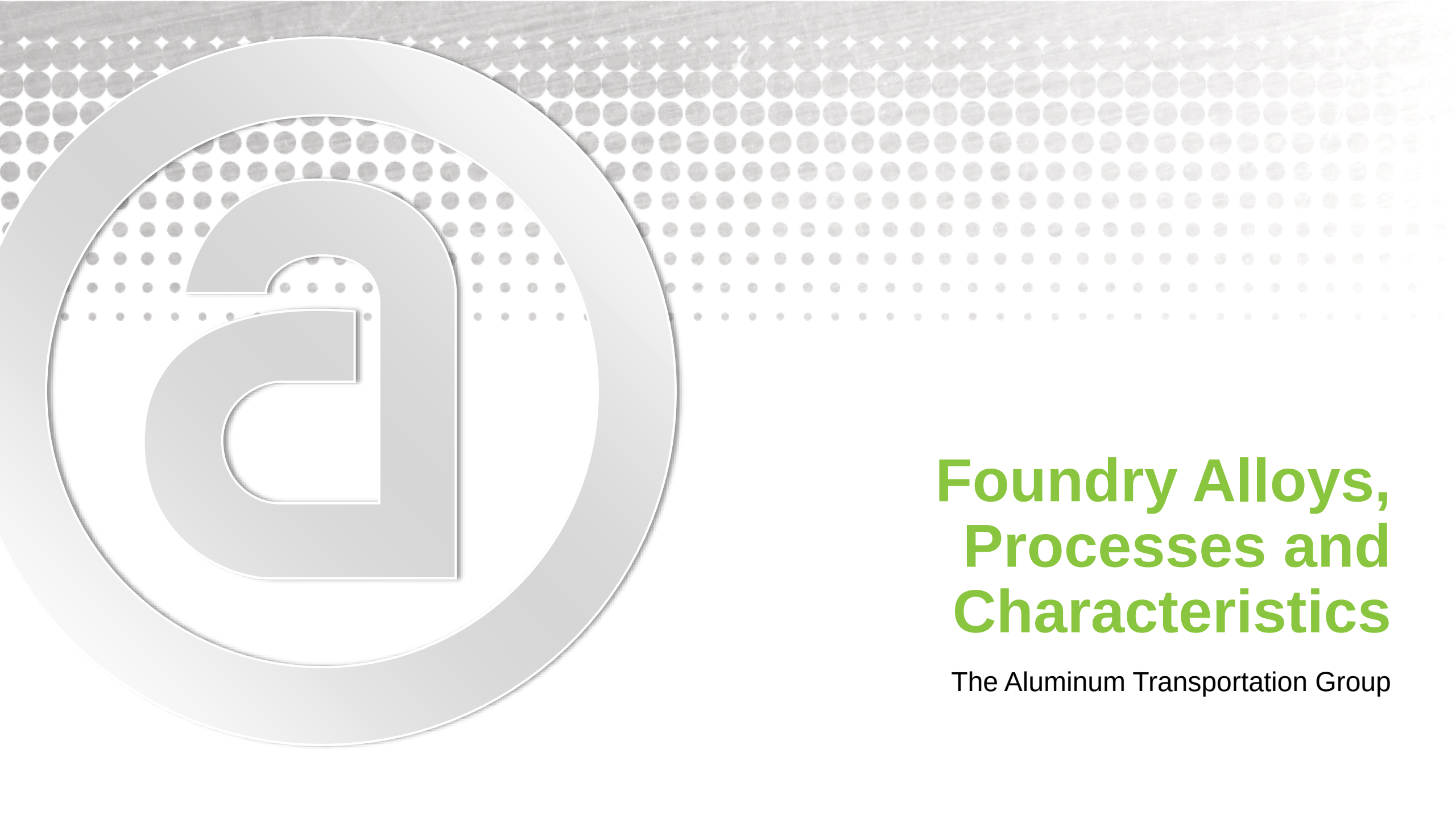




Foundry Alloys, Processes and Characteristics

The Aluminum Transportation Group

Presenters



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Rio Tinto

*Principal Advisor, Arvida Research
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Ray Peterson

Real Alloy

Director, Technology

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 - Joining
 - Modeling
 - Stress-engineering strain curves
- Casting alloys and designation system
- Permanent mold and die casting alloys

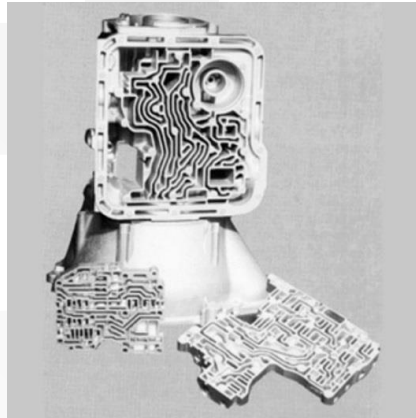
General Characteristics of Castings

Cast aluminum components are used in many different applications

- **From** highly engineered safety-critical and key powertrain components
 - body structure
 - chassis
 - suspension
 - cylinder heads and blocks
 - transmission cases
 - etc.
- **To** decorative interior parts



Source: Kolbenschmidt



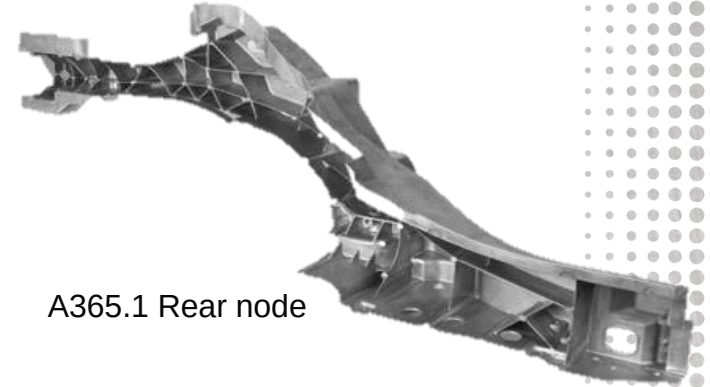
AlSi8Cu3 transmission case



Source: GF Automotive

Castings: An Engineering Solution

- Designed to be **cast to near-net shape**
- Alloy must be **castable**, i.e. show acceptable:
 - **Feeding** behavior
 - **Fluidity** (to fill the mold)
 - Resistance to **hot tearing** and/or **hot cracking**
 - Achieved by massive **alloying** – Al-Si
 - Achieved by “force” in **gate & riser** – non-Al-Si
- **Mechanical properties** are generated by:
 - **Alloy chemical composition**
 - Careful **part design** and rigging → solidification control
 - Local **solidification rate**: process dependent → microstructure
 - Control of **structure characteristics**
 - **Heat treatment**



A365.1 Rear node

Casting Processes

Automotive casting processes can be differentiated according to **(A) mold filling** and **(B) molding technologies**.

Methods ranked according to current usage:

1. Green sand casting
2. DISAmatic casting
3. Core package casting
4. Gravity die casting
5. Low pressure die casting
6. High pressure die casting
7. Vacuum die casting
8. Squeeze casting
9. Thixocasting & rheocasting
10. Vacuum riserless casting
11. Lost foam casting
12. Ablative casting

		Mold Filling Methodology		
Molding Technology	A	Gravity Casting	Low Pressure Casting	High Pressure Casting
	B			
	Permanent Mold	4	10 5	6 7 8 9
	Core Package	3		
	Green Sand Regular Sand	12 1	2	
	Lost-Foam	11		X Widely used in automotive casting Y Slightly used in automotive casting

Sand Casting (1 and 2)

- The process starts with a **pattern that is a replica** of the finished casting
- Molten aluminum **poured into the sand by gravity** (Shrinkage consideration)
- **Slow but flexible process**, can be combined with **high-speed molding lines**
- More economical for small quantities, intricate designs or very large castings



Green sand casting – horizontal molding

Intake manifolds
Oil pan housings
Structural parts
Chassis parts

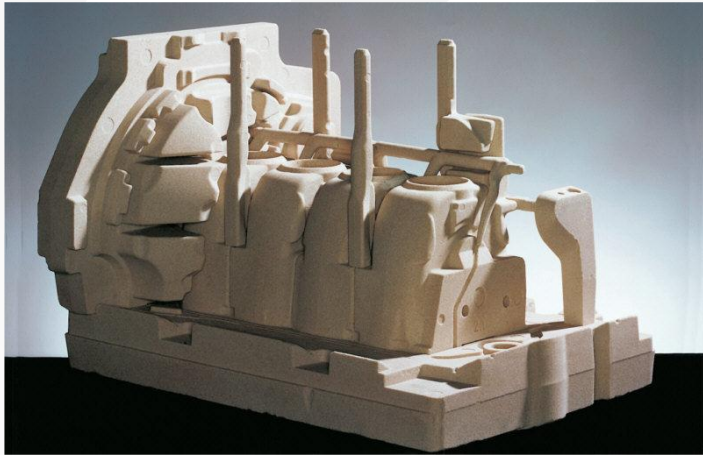


Modified DISAmatic casting

Source Alcoa

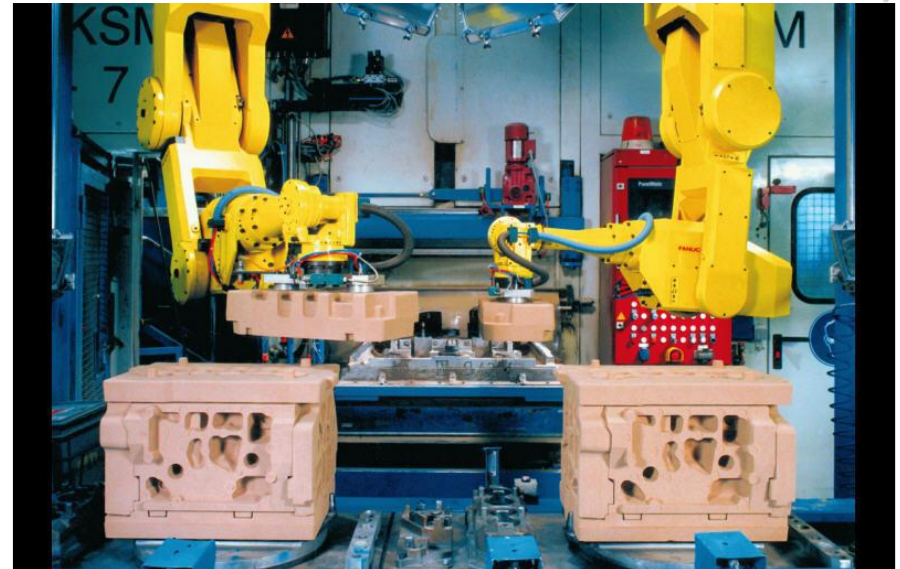
Core Package Casting (3)

- The **entire sand mold consists of single sand cores**
- Dimensional quality and complexity of the castings
- Core Package System (CPS®) process for volume production of engine blocks



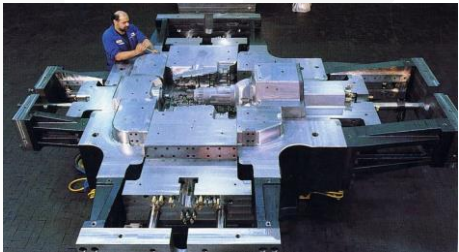
4-cylinder engine block

Source: VAW



Permanent Mold, Die Casting (4, 5, 6 and 7)

- HP, LP: molten **aluminum** forced into a **steel die** (mold) under pressure
- **High-volume** production
- **Precisely** formed castings requiring a **minimum of machining and finishing**



High pressure die casting
(+ vacuum)

Source IdraPrince



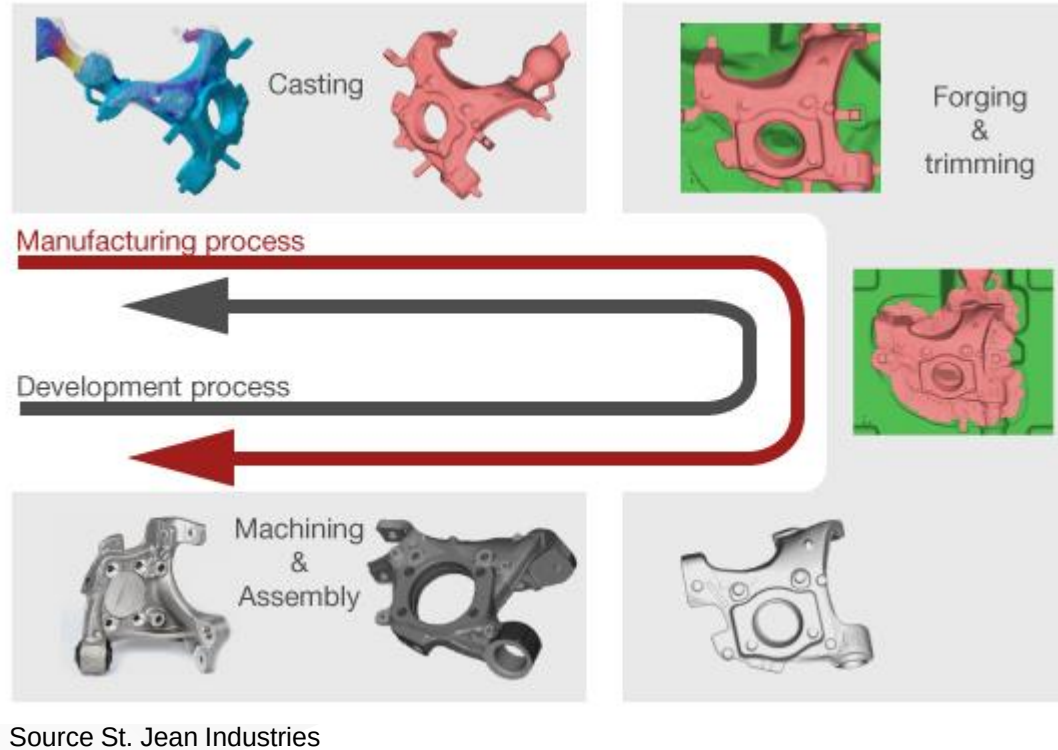
Gravity die casting: cylinder head, block (Rotocast®)



Low pressure die casting: wheel Source Kutz

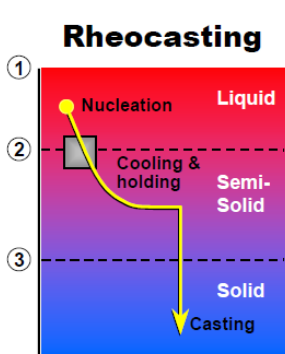
Squeeze Casting (8)

- Squeeze casting (i.e. COBAPRESS™)
- **High cooling speed + pressure = High mechanical**
- Suspension parts

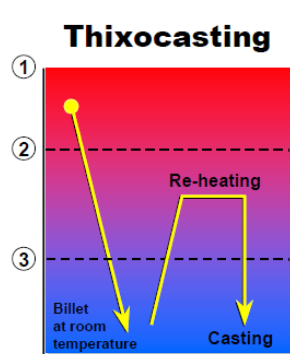
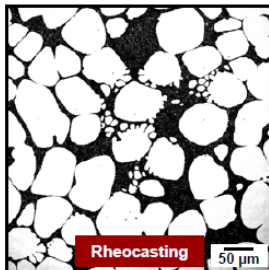


Thixocasting & Rheocasting (9)

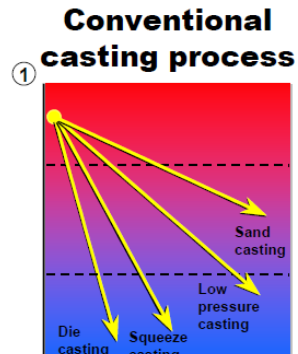
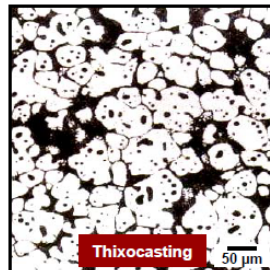
- Semi-solid forming by different processing paths
- Liquid metal is first **DC-cast to fine grained billets (Thixocasting)** which are then **reheated to the semi-solid state** and formed to the final product
- **Metal solidifies very rapidly during forming**; shrinkage porosity is reduced
- Net-shape parts can be produced



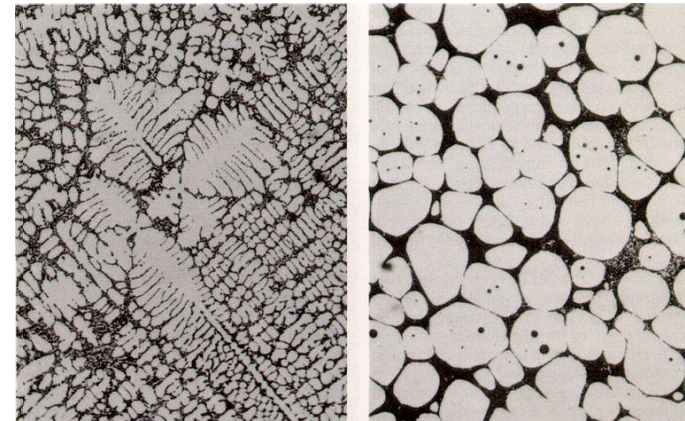
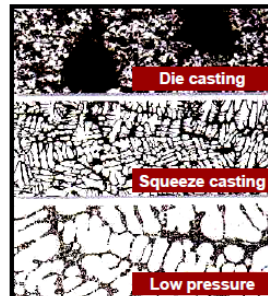
① Temperature
② Liquidus
③ Solidus



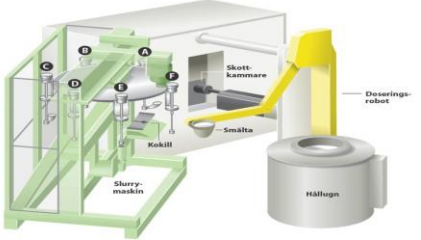
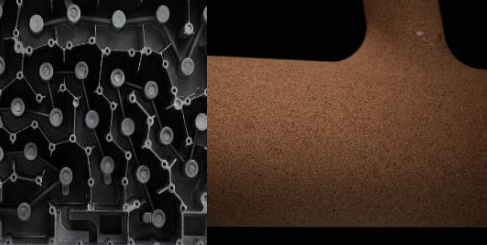
① Temperature
② Liquidus
③ Solidus



① Temperature
② Liquidus
③ Solidus



Thixocasting & Rheocasting (10)

Benefit	Example	Drivers	Applications
Alloy selection		W/mK, wear elongation, anodization strength	Oil pumps Compressors Heat sinks
Process cost, as HPDC		Tool life length Low cost equipment	5-25% of today's castings will benefit from Rheocasting
Porosity free		Pressure tight Weldable Heat treatment T6	Compressors Hybrid solutions
Geometry freedom		Sand cores Thin walls >0.4 mm	Telecom Hydraulics

Break through 2018/2019

Status:

- High volume production since 2018
- Massive interest, 15+ projects running
- Equipment sold

Show stoppers:

- Not industrialized 10 years back
- Many failed attempts 8-10 years back
- HPDC was "OK" 10 years back

The drivers of now:

- Telecom 5G
- Automotive (E cars, low emission)
- China

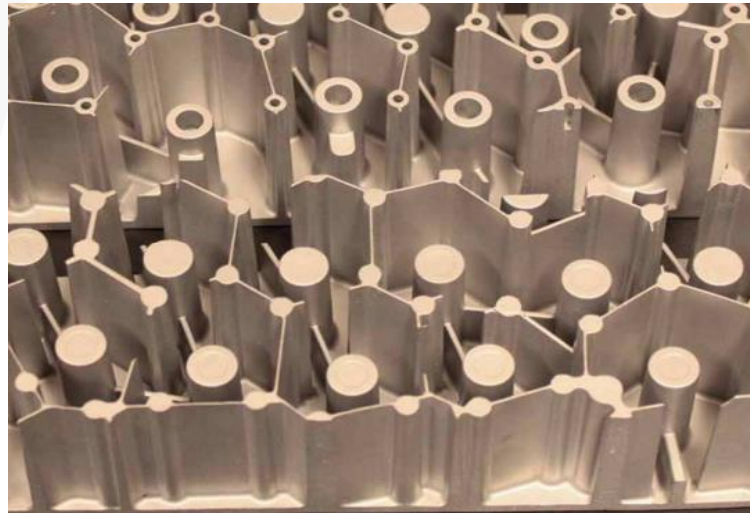
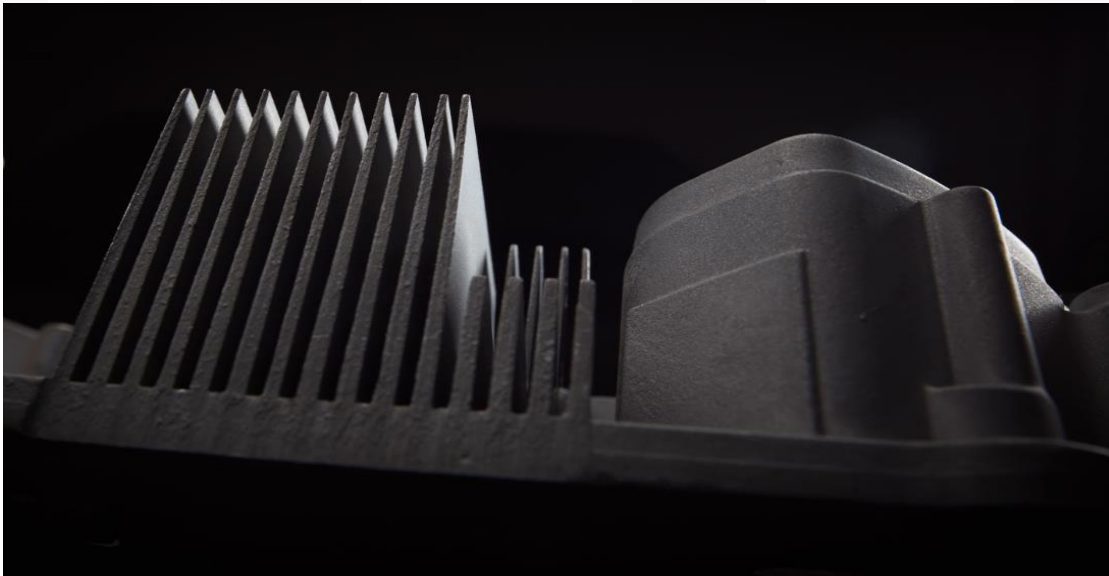
COMP
castings and
moulding innovation **tech**

Source:

Thixocastings & Rheocasting (9)



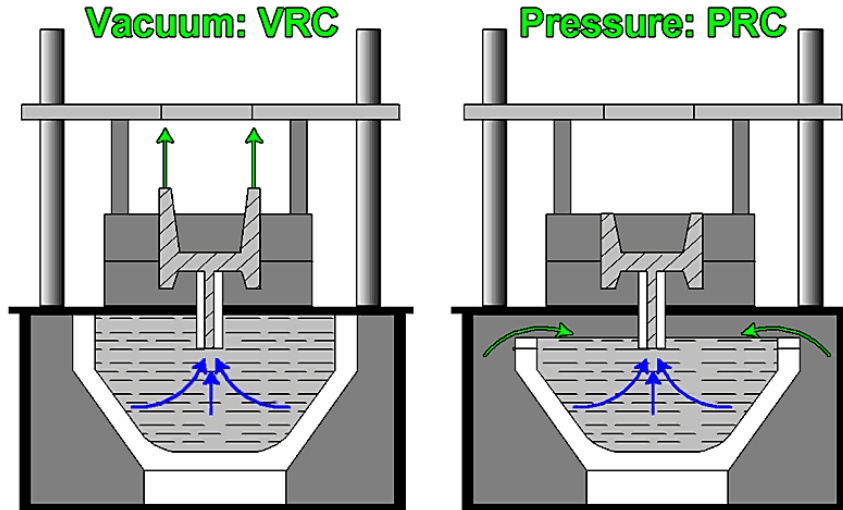
NADCA Casting of the year 2022
Hinge Pillar



Source: **COMP**
castings and *tech*
moulding innovation

Vacuum Riserless Castings (10)

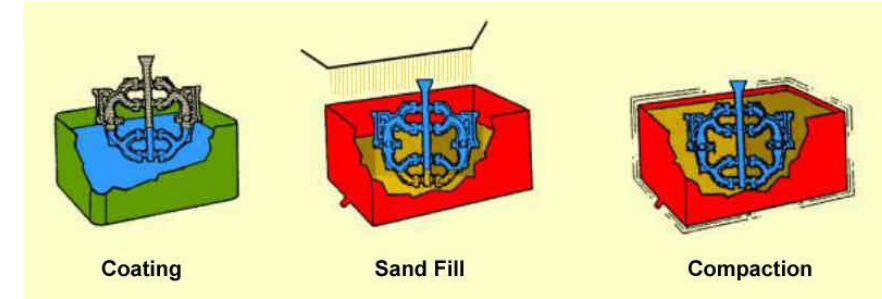
- PM - low pressure casting
- Combining vacuum riserless casting (VRC) with pressure riserless casting (PRC)
- Solidification direction controlled
- Automotive chassis parts high mechanical properties



Subframe, 1200mm wide

Lost Foam Casting (11)

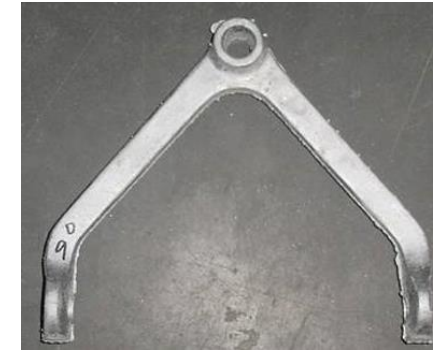
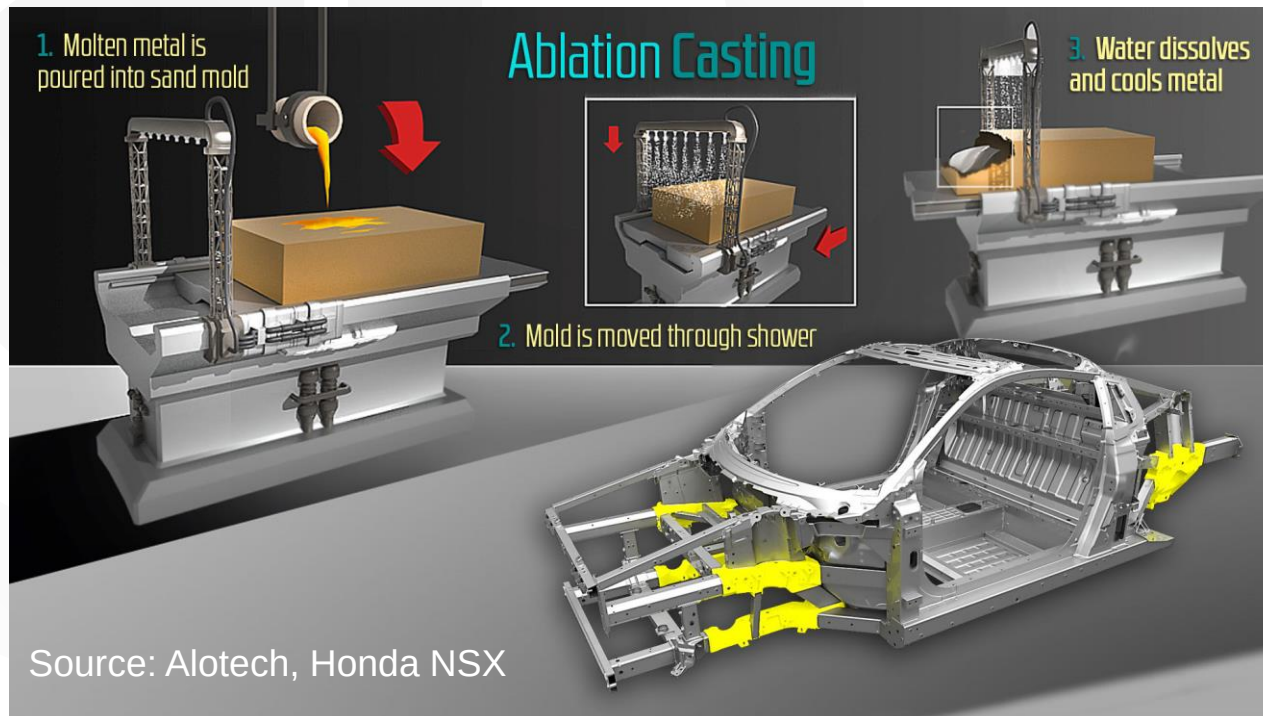
- Freedom of design, possibility to build-up complicated geometries by assemblies of several EPS parts
- Process parameters need to be controlled for optimum filling
- High productivity



Source: BMW AG Landshut

Ablative Casting (12)

- DC-casting of a near net shape casting
- Insulating Inorganically bonded sand mold
- Mold washed away by water jets
- Very sharp solidification temperature gradient
- Wide alloy flexibility, not limited to Al-Si



Upper Control Arm / Rio Tinto



(a) Ablation in progress



(b) Ablation complete

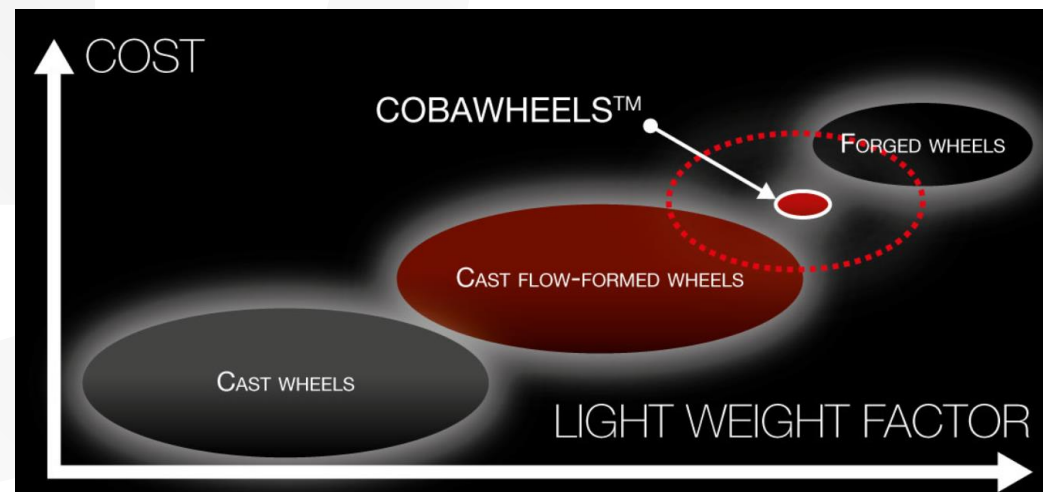
Wheel – 1985-1995



Source: Honda

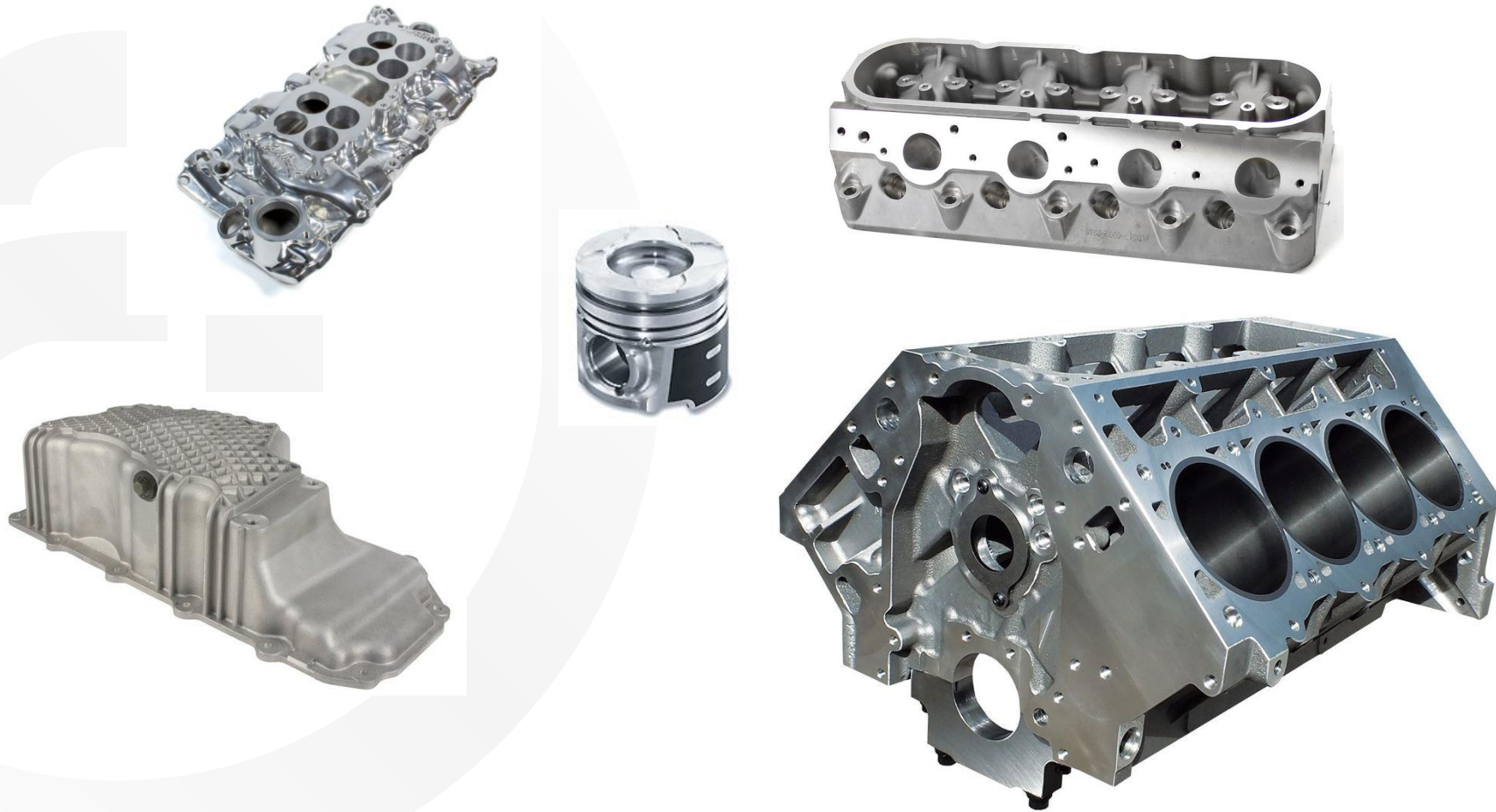


Source: Honda



Source: St. Jean Industries

Engine Components from 1980s



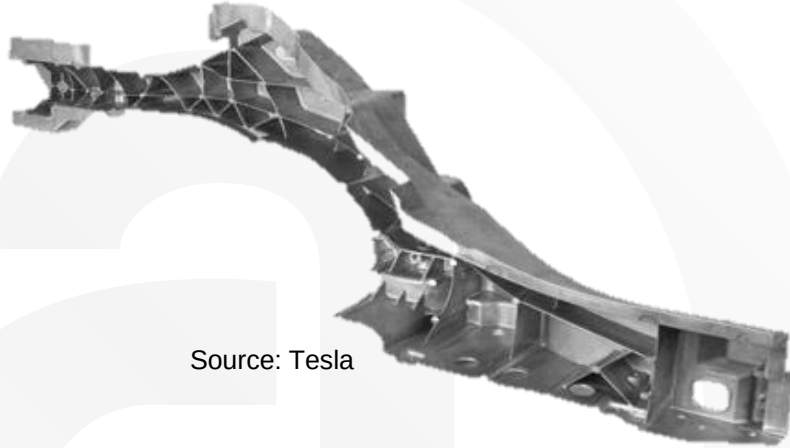
“Aluminum intensive” engine. Cast Al parts include: intake manifold, cylinder head, piston, engine block, skirt, oil pan, belt tensioners and pump cases.

Suspension Parts – > 1995



Include lower suspension control arms, upper control arms, knuckles (+ cross members). Source: St. Jean Industries

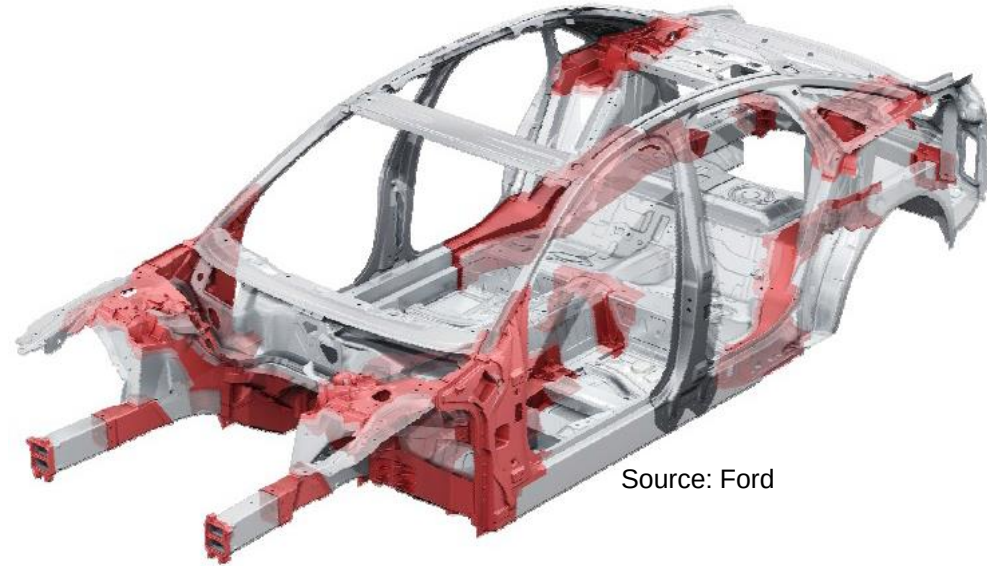
Structural Casting > 1994



Source: Tesla



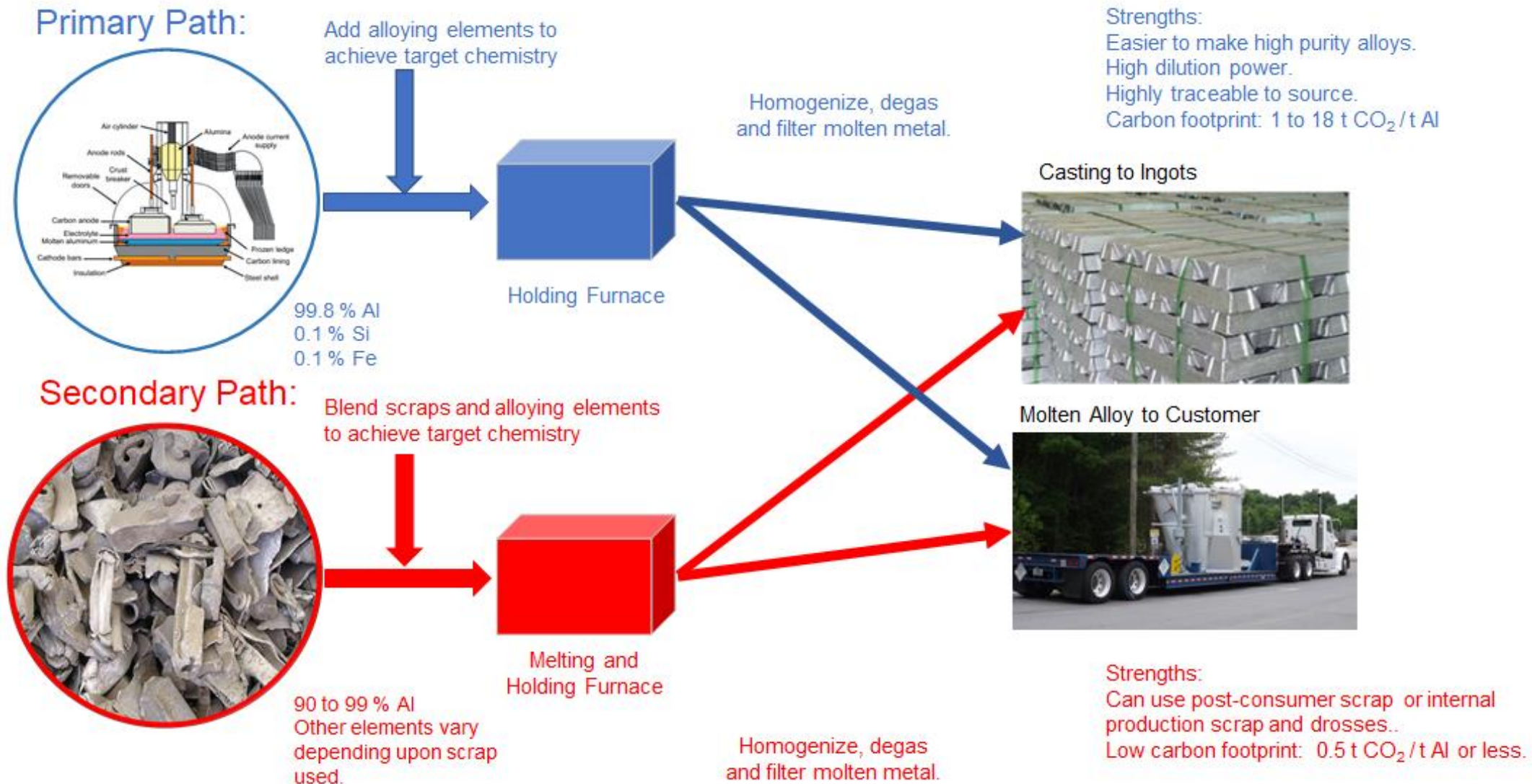
Source: BMW



Source: Ford

Shock tower
Node
Torque box
C Pillar, B Pillar
Instrument panel
Engine mount
Vibration damper, housing

Primary & Secondary Production Paths



Foundry Alloys – Form of Delivery



T-bar ingot 500 to 850kg

Source: Rio Tinto



Small form cast
ingot 6 to 23kg
(15kg typical)

Source: Rio Tinto

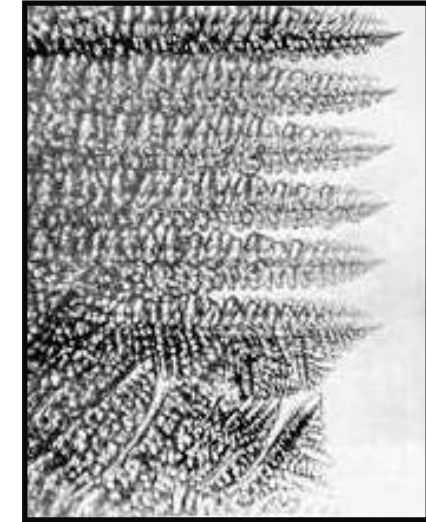
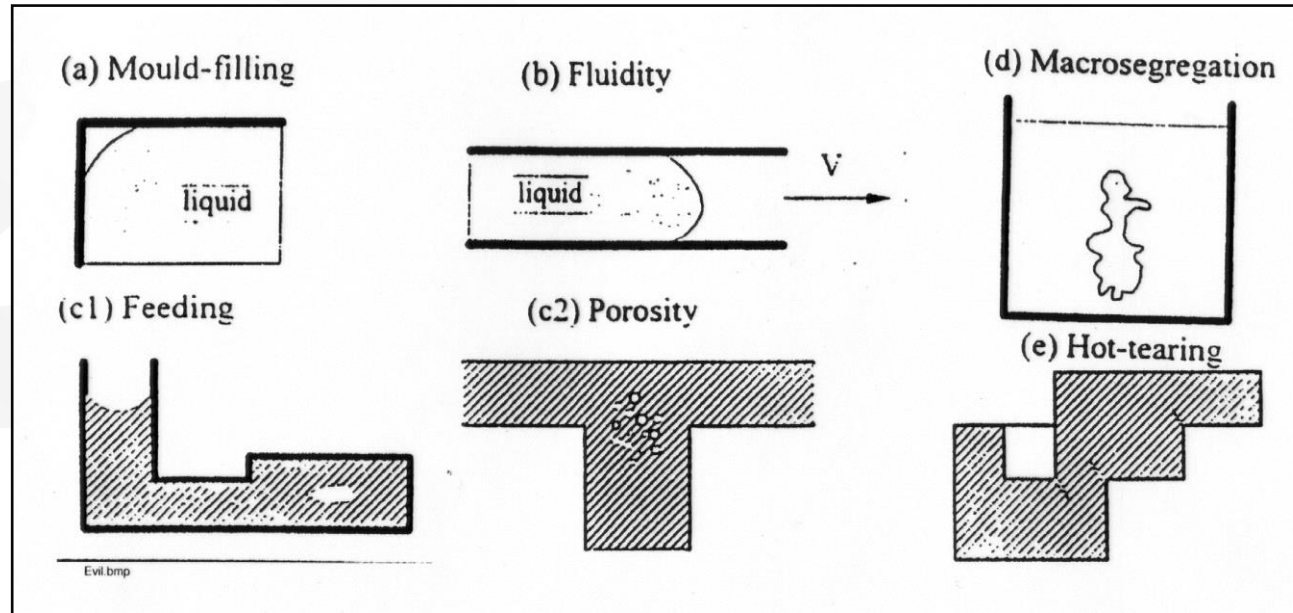




Metallurgy Essentials 101



Alloys Ratings — Classification



Dendrite columnar growth

Typical casting, fabrication and application characteristics											
Foundry alloys	Casting method	General castability	Fluidity	Hot shortness	Shrinkage tendency	Elevated temperature strength	Corrosion resistance	Pressure tightness	Machinability	Weldability	Anodizing appearance
206.2	Sand & PM	4	4	4	2	1	4	4	2	4	3
A206.2	Sand & PM	4	4	4	2	1	4	4	2	4	3

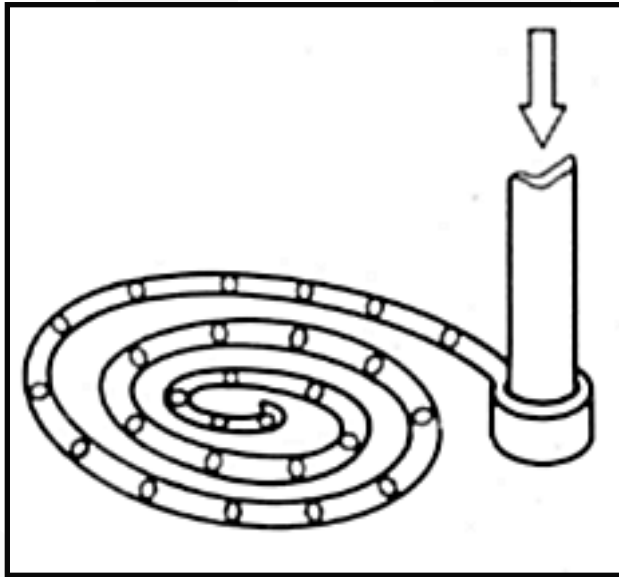
Ratings: 1 = excellent 2 = very good 3 = good 4 = fair 5 = poor X = not recommended
 Sand = sand casting PM = permanent mold Die = die casting

Similar tables in Aluminum Alloys - ASM Handbook.

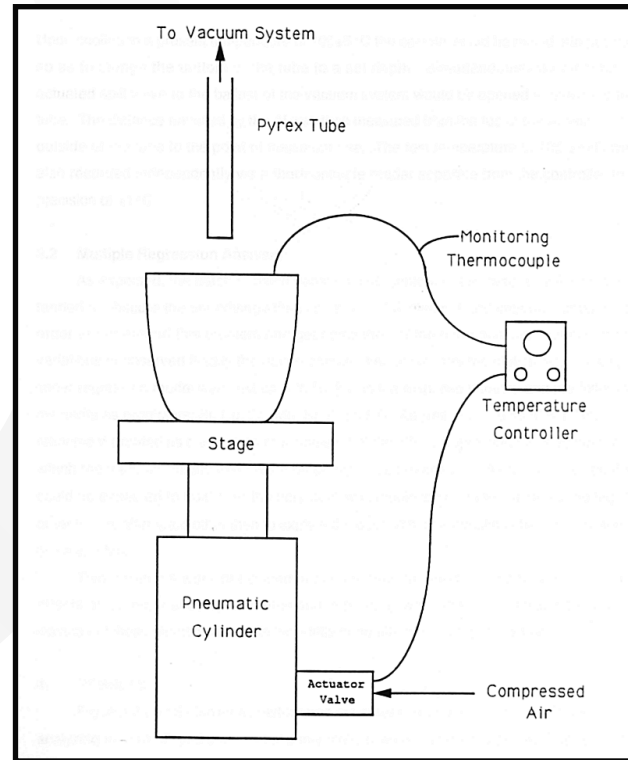
Source: Rio Tinto

Fluidity — Metallurgy Essentials (101)

- Spiral or vacuum fluidity test measure the length the metal flow
- Metal at a carefully controlled temperature is presented to the Pyrex tube connected to a vacuum system



Spiral fluidity test



Vacuum fluidity test

- Rapid and easy
- Highly reproducible
- No sand molding

Source: Rio Tinto

Fluidity — Metallurgy Essentials (101)

Fluidity is a complex technological property of the molten metal, which depends on many factors

- **Casting temperature**

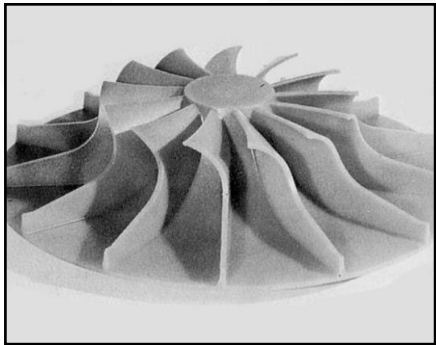
Fluidity increases linearly with increasing melt superheat for a given alloy composition

- **Mold properties**

The channel diameter, heat extracting power, die coatings

- **Kinetic energy of the metal** (metallostatic head)

Gravity die casting, sand casting, etc. rely on the metal flowing downhill under its own. In LP or HP die casting the metal flows under pressure



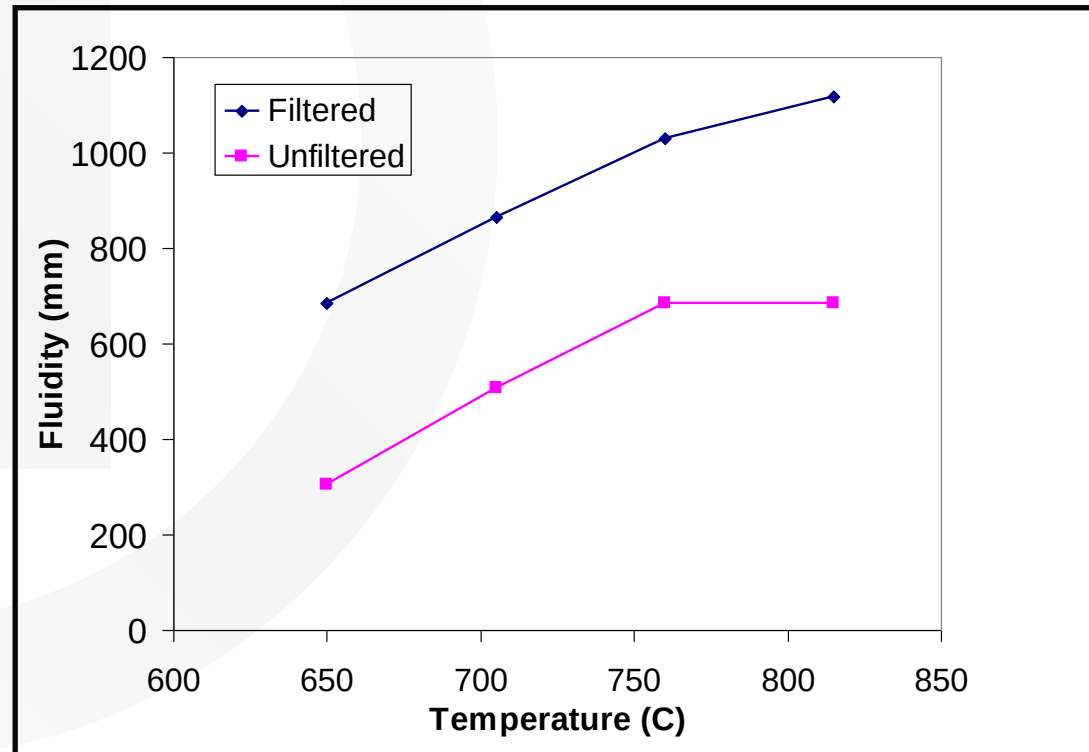
Turbo propeller wheel



Source: Buhler – for Ericson 5G
High pressure vacuum die casting

Fluidity — Metallurgy Essentials (101)

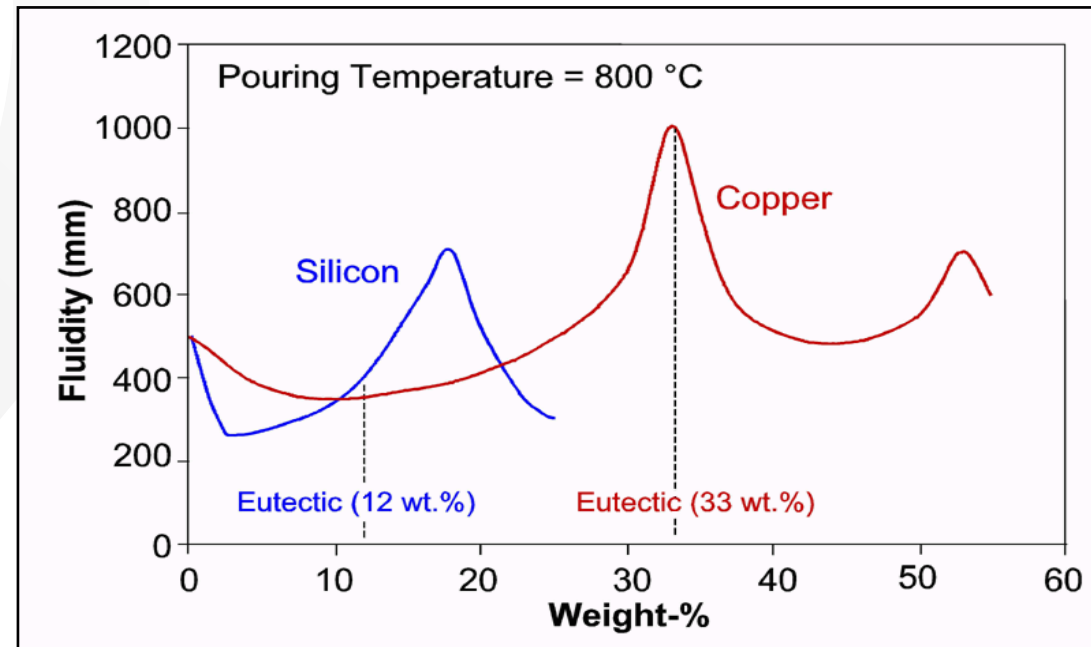
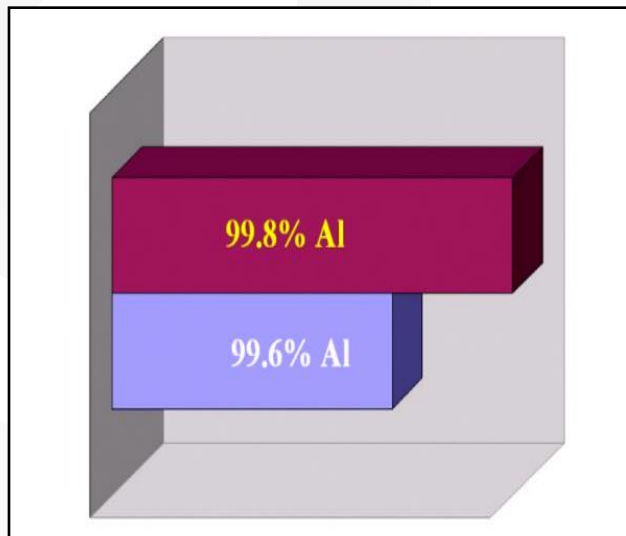
- **Metal cleanliness**
 - Oxides, particle and hydrogen content have a large impact; oxide inclusions decrease the fluidity especially at a low pouring temperature
 - Final opportunity for metal cleanliness occurs at the casting facility so proper precautions and practices are required.



Source: Rio Tinto

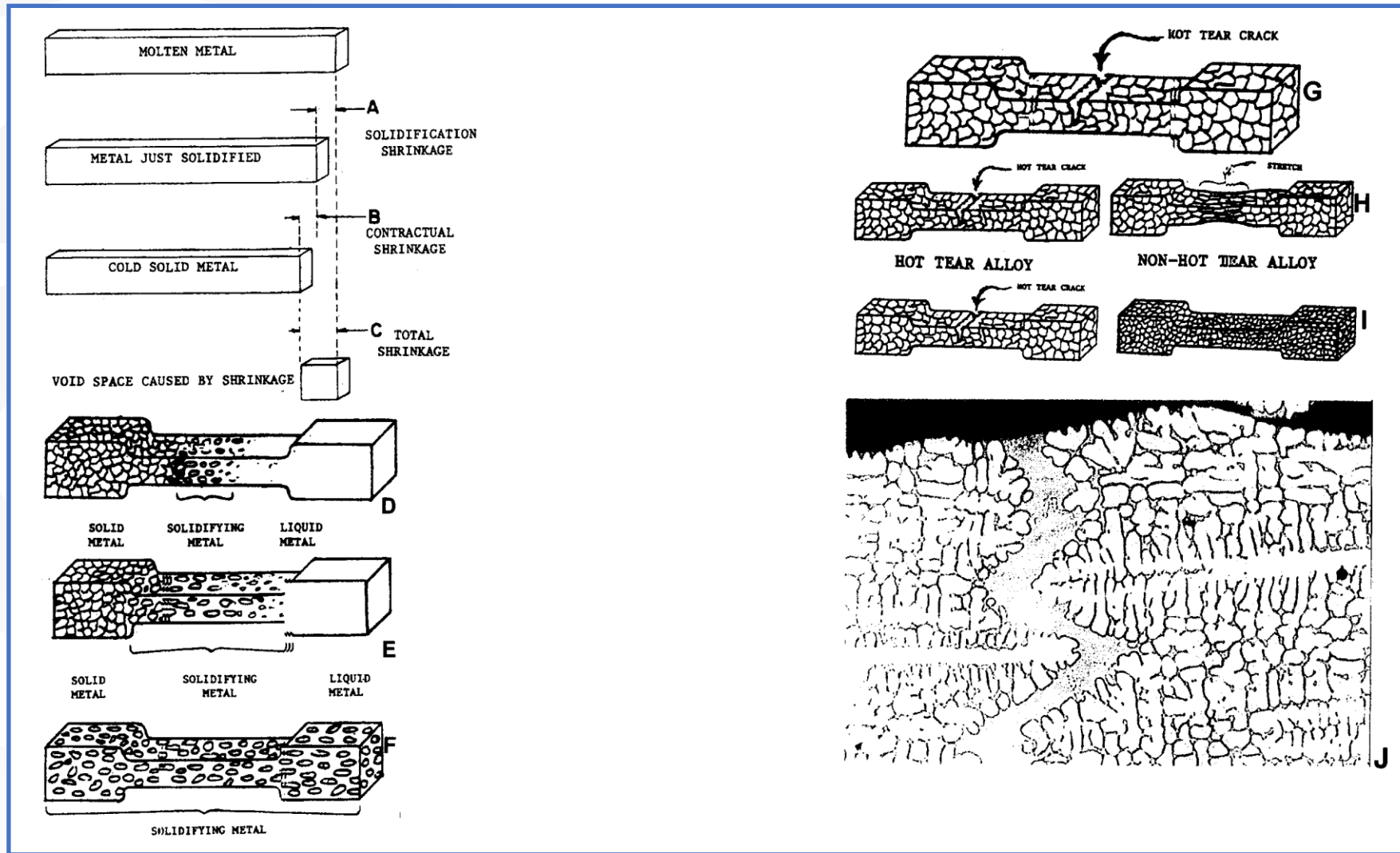
Fluidity — Metallurgy Essentials (101)

- Alloy composition
 - **Composition is one of the main factors influencing fluidity**
 - Fluidity of pure metal and eutectics is higher than for alloys. Even **small impurity levels strongly reduce the fluidity** of pure aluminium
 - Alloying elements such as **Cu or Si significantly influence the fluidity** of aluminium foundry alloy melts



Source: Rio Tinto

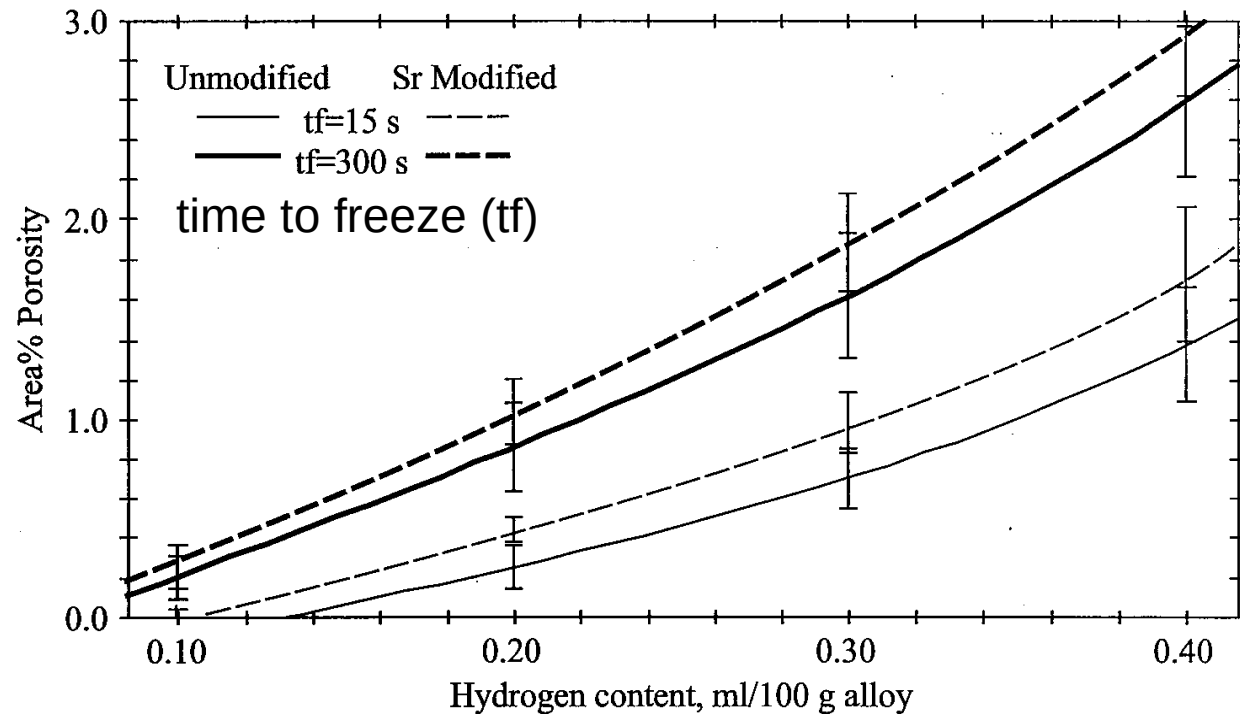
What is Hot Tearing?



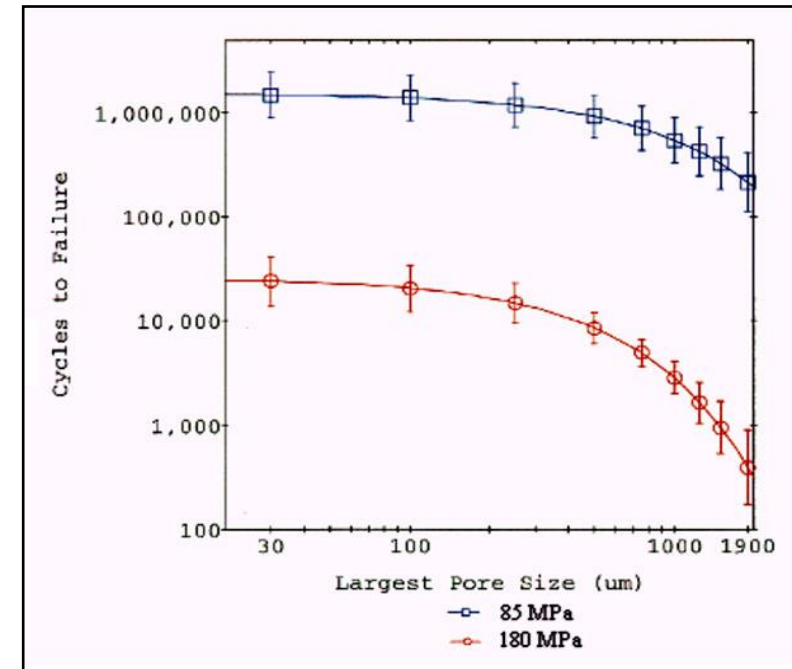
Schematic Drawings of the Origins of Hot Tearing and the Need to Feed Solidification Shrinkage (Source: A. Kearney, AFS)

Porosity — Metallurgy Essentials (101)

Porosity impacts the fatigue life, so it is a very important consideration
Factors influencing porosity: **gas, freezing time (tf), gradient, modification**



Plot of the predicted area % porosity according to a statistically derived parametric model for the A356 alloy

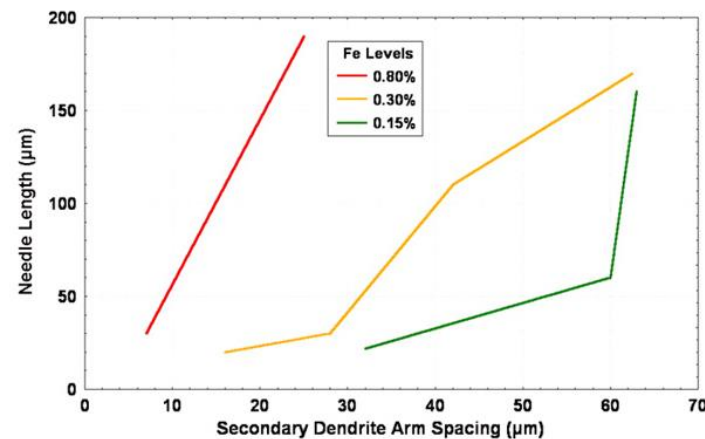


Metallurgy Essentials (101)

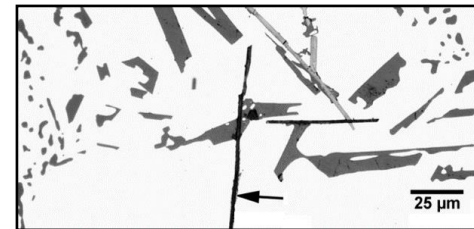
Intermetallic phases: size, shape and distribution

- Formation determined by the concentration of the **alloying** and **impurity** elements (Fe)
- The size, morphology and type depends mainly on the **solidification rate**

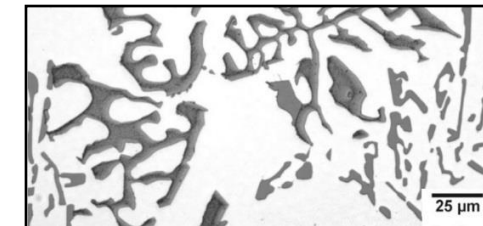
Slow solidification rates = coarser intermetallic particles and second-phase concentrations at grain boundaries = low mechanicals, brittleness



β -AlFeSi needle length as function of secondary dendrite arm spacing
Source: Biswal et al.



β -AlFeSi needles (left) and the **Chinese script** α -Al₁₅(Fe,Mn)₃Si₂ phase (right) in an A356 casting



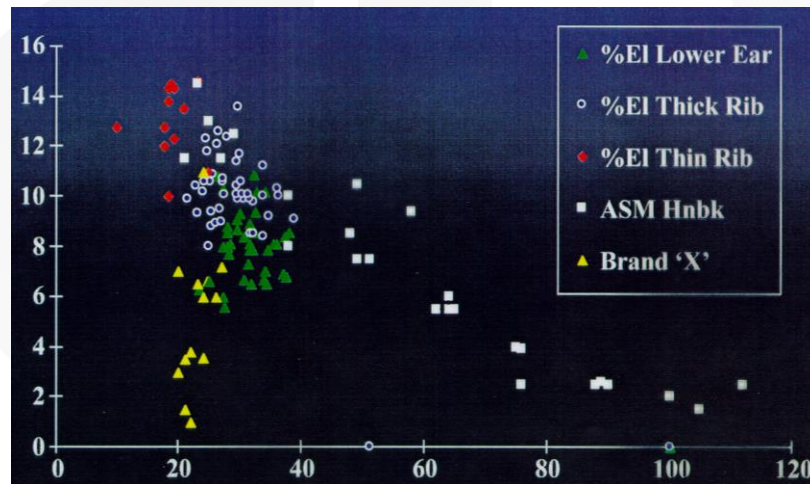
Source: Rio Tinto

Metallurgy Essentials (101)

Dendrite arm spacing (DAS): solidification occur through the formation of dendrite

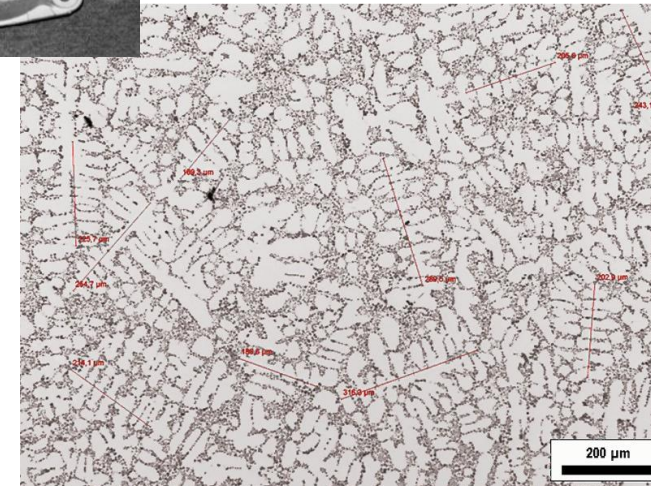
- DAS defined as the distance between developed secondary dendrite arms
- Controlled by the cooling rate

A larger DAS = coarser intermetallic particles = negative effect on properties



The tensile strength, ductility and elongation increase with decreasing dendrite arm spacing (or increasing solidification rate). A smaller dendrite arm spacing also reduces the time required for a homogenisation heat treatment since the diffusion distances are shorter.

Casting is Lincoln Mark VII A356-T61, lower suspension Control Arm



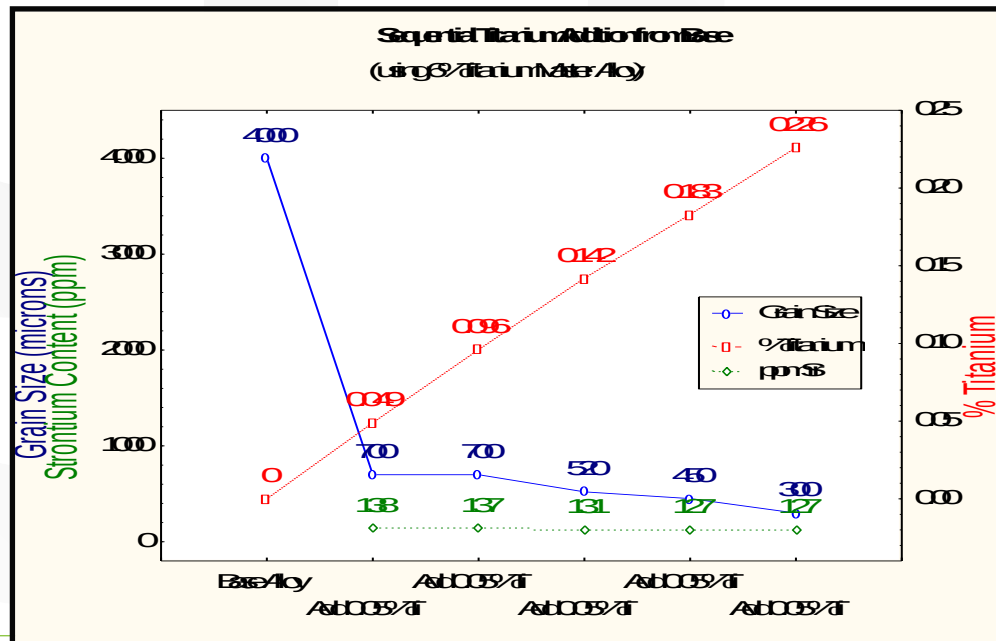
Measurement of dendrite arm spacing Source: Rio Tinto

Metallurgy Essentials (101)

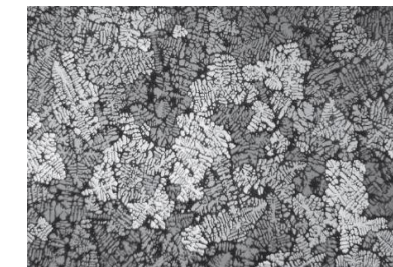
Grain refinement: solidification occur through the formation of dendrite

- Grains are formed during solidification
- Type and size are function of composition, solidification rate and concentration of nucleation sites
- Addition of grain refiners increases nucleation sites and finer dendrites and grains

Fine grains = improved casting performance (↑internal feed, ↑ flow and mold filling, ↓porosity, ↓ hot cracking) and better material properties



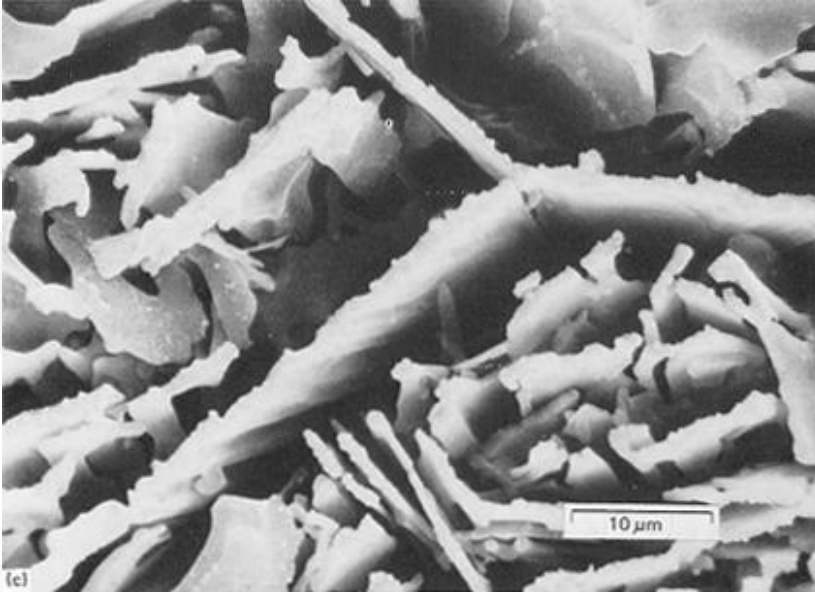
Measurement
before (top)
and after grain
refinement
(bottom) A356



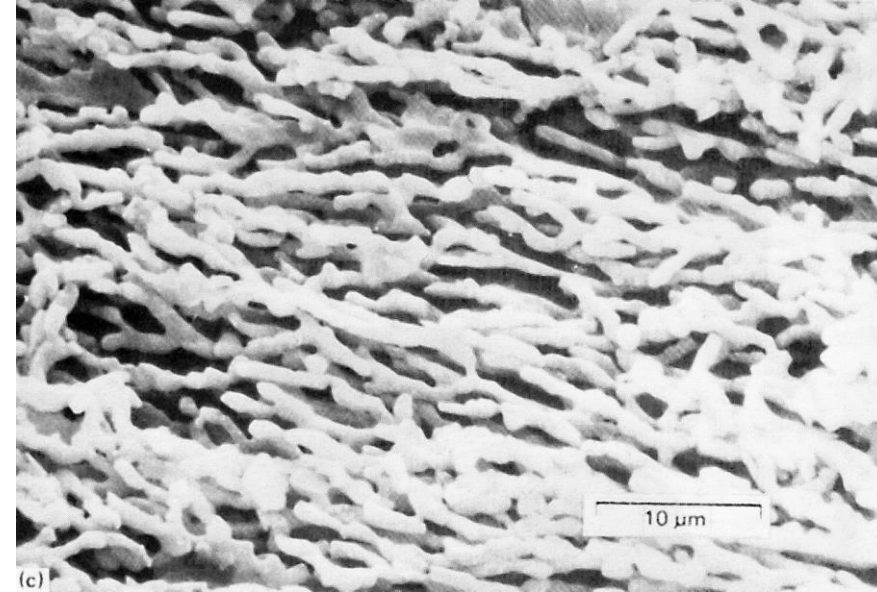
Source: Rio Tinto

Metallurgy Essentials (101)

Why Sr as a Modifier?



Unmodified Si looks like large 2-D platelets if you **chemically etch** away the Al phase in a **356** type alloy



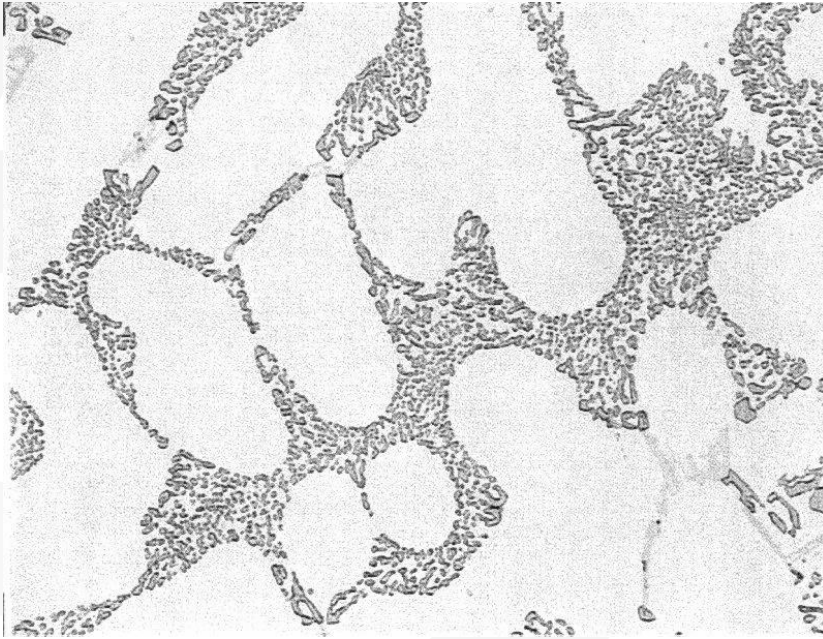
The microstructure of the **Si changes** to a **fine fibrous structure** which looks like this if you **add Na or Sr**

Metallurgy Essentials (101)

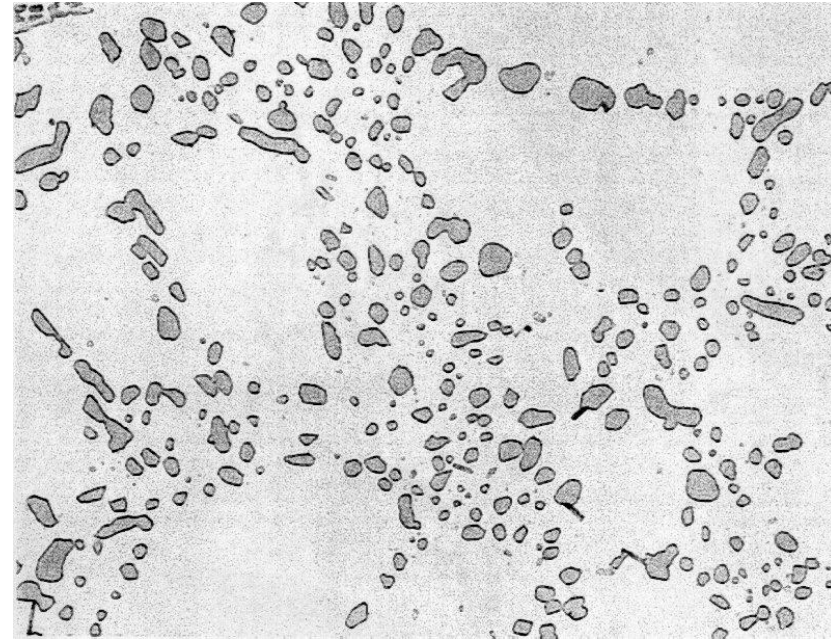
Why Sr as a Modifier?

AFS Modification Rating = 5

DAS=24 μ m



F –Temper **As-cast** look like this

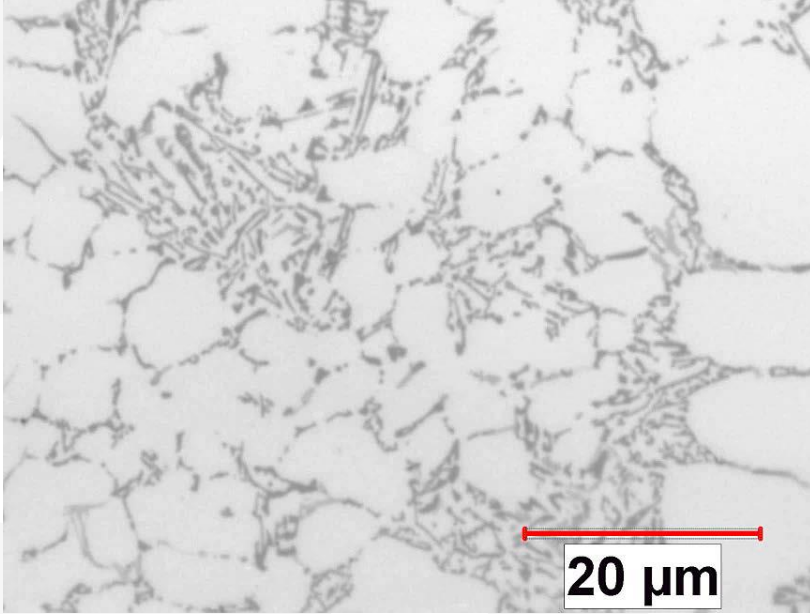


Once the alloy is subjected to a **T6 heat treatment** the fibers spheroidized and break up into isolated **globules of Si** which look like this.

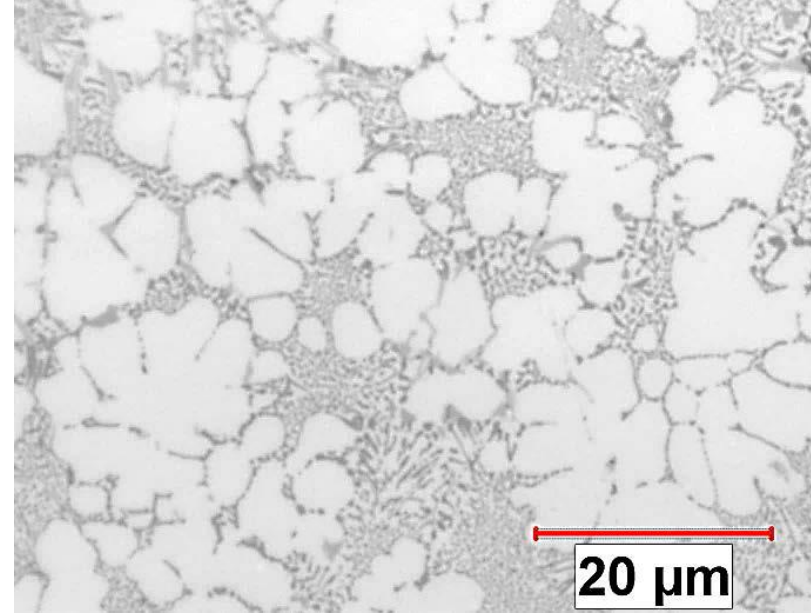
Source: Rio Tinto

Metallurgy Essentials (101)

Why Sr as a Modifier?



A365.1 F
(without eutectic modification)

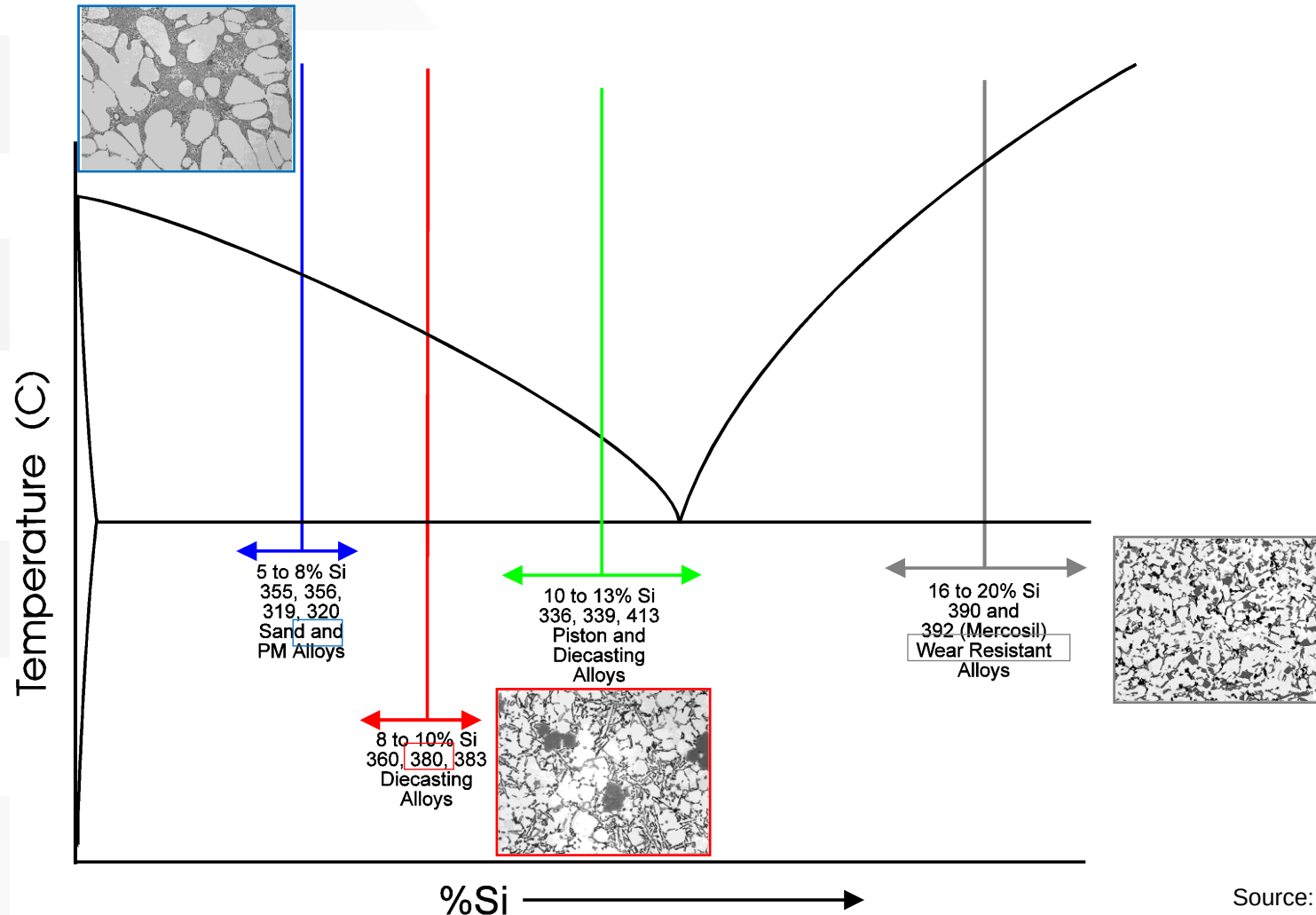


A365.1 F + Sr
(eutectic modification)

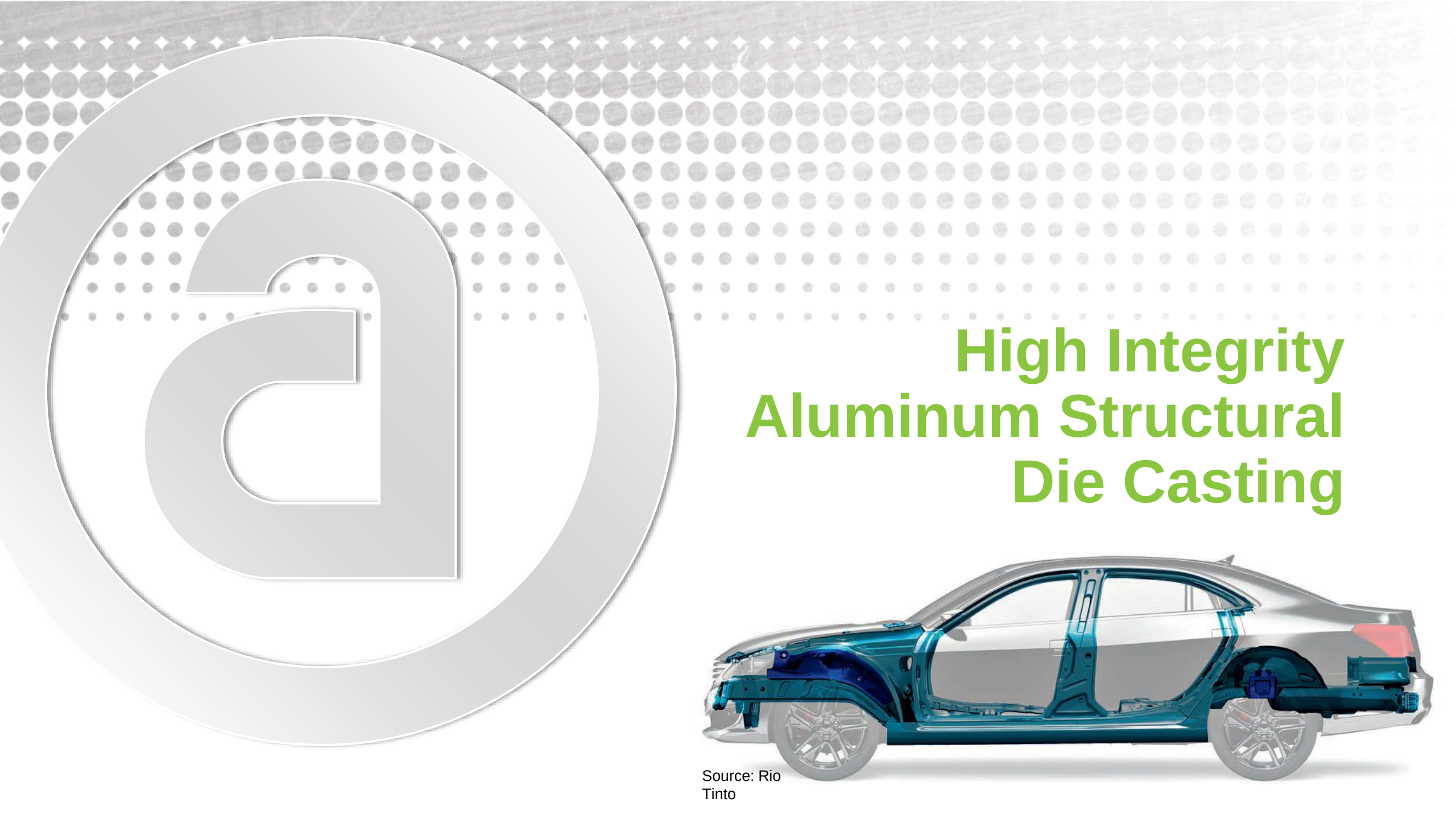
Source: Rio Tinto

Metallurgy Essentials (101)

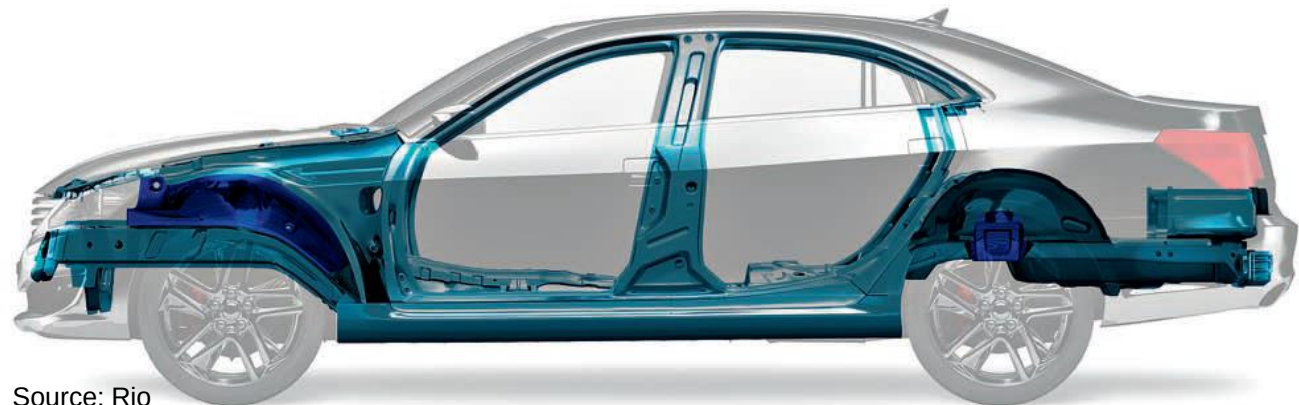
Micrographs from the
Four Regions of the
Al-Si Diagram



Source: Rio Tinto



High Integrity Aluminum Structural Die Casting

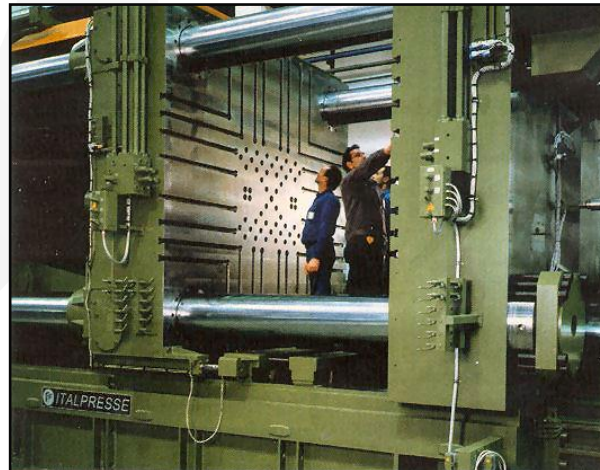


Source: Rio
Tinto

Conventional High Pressure vs. Vacuum Die Casting (HPVDC)

Conventional high pressure die casting (HPDC) has many advantages

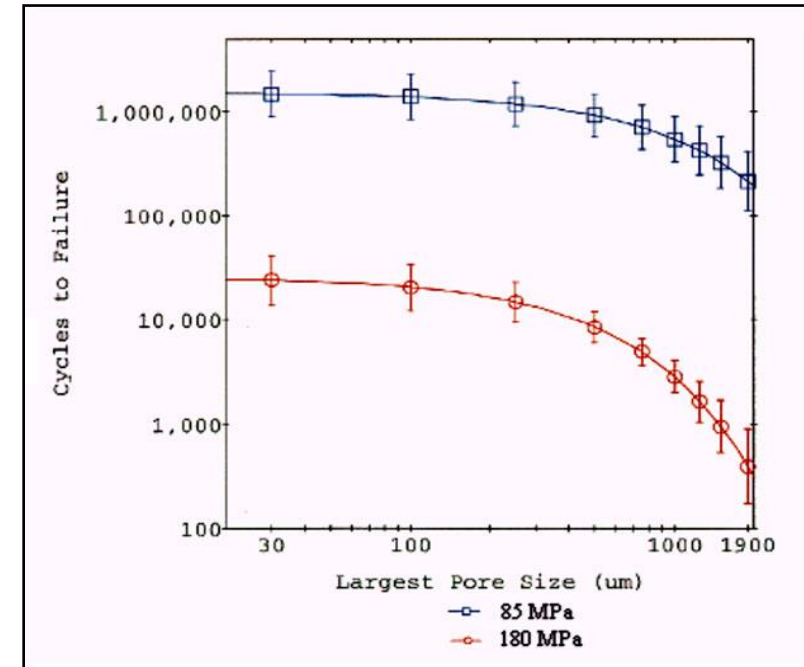
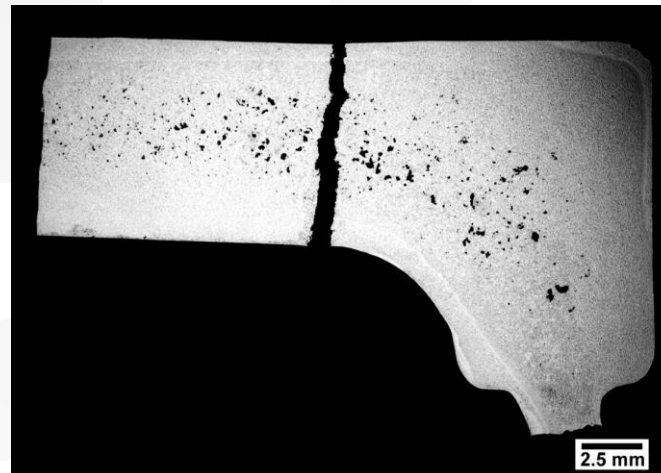
- Low cost production process for **high volume** applications
- **Near net complex shape** capability
- Compatible with lower cost **secondary alloys**
- Very tight **dimensional tolerances** and **thin wall** (1.8-3mm)
- Excellent **surface finish**
- Very easy to automate casting/extraction/cropping



Conventional High Pressure vs. Vacuum Die Casting (HPVDC)

Conventional HPDC are **not** typically used in **structural applications** due to the **inability** to meet strength and ductility requirements

- Gas and shrink **porosity**
- Inability to **heat treat**
- Inability to **weld**
- Low **ductility**
- Large **variation** in mechanical properties

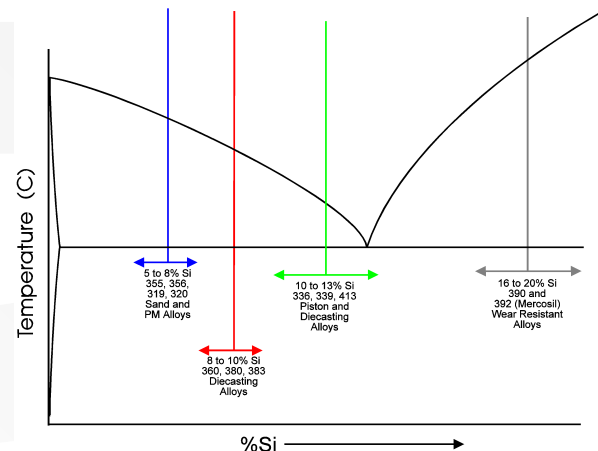


Source: Rio Tinto

Conventional High Pressure vs. **Vacuum** Die Casting (HP**V**DC)

Over the years high pressure **vacuum** die casting (HP**V**DC) has been developed, capable of producing **high integrity, thin-wall components** that can be used in **structural applications**

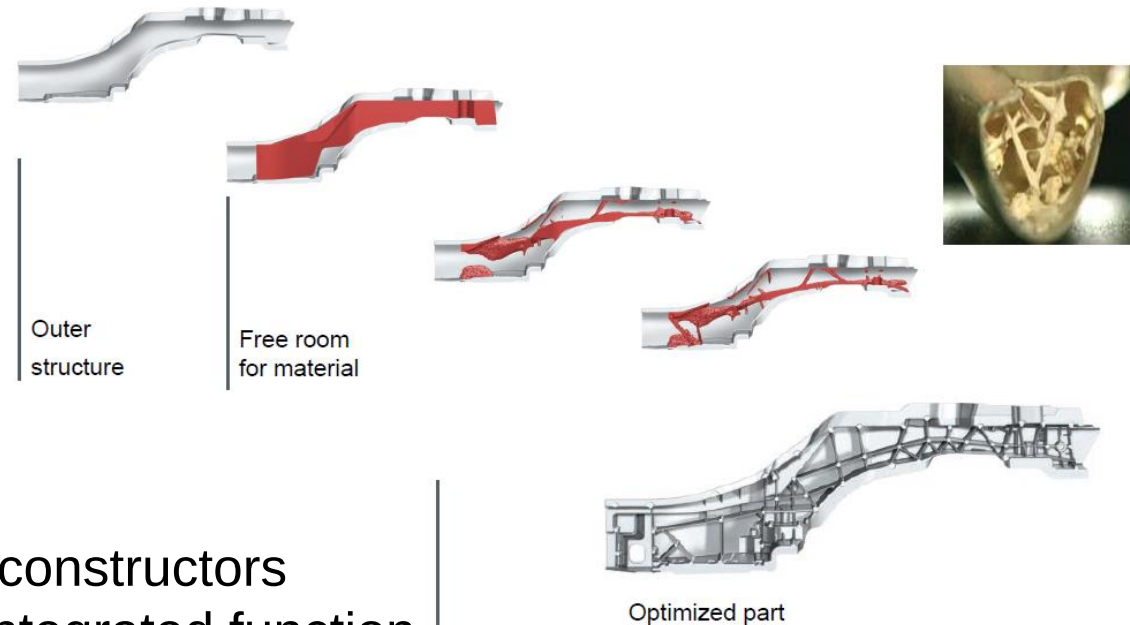
- **Minimal gas** and shrink porosity
- Uniform **mechanical properties**
- Ability to **heat treat and/or weld**
- **High strength and ductility**



Source: Rio Tinto

Conventional High Pressure vs. Vacuum Die Casting (HPVDC)

- **Weight reduction** by specific strength
- **Low corrosion** without coating



- **Wide design flexibility** for constructors
 - **Complex structures** with integrated function
 - **More dimensional exactness** in comparison to welding
- >> Thin wall HPVDC offer possibilities for local optimization**

Conventional High Pressure vs. Vacuum Die Casting (HPVDC)

... are being used for

- **Saving weight & assembly costs** by replacing
 - Heavier materials
 - Thicker walled parts
 - Steel assemblies and stampings
 - Higher cost materials and processes
- For performance increases
- For pressure tight parts



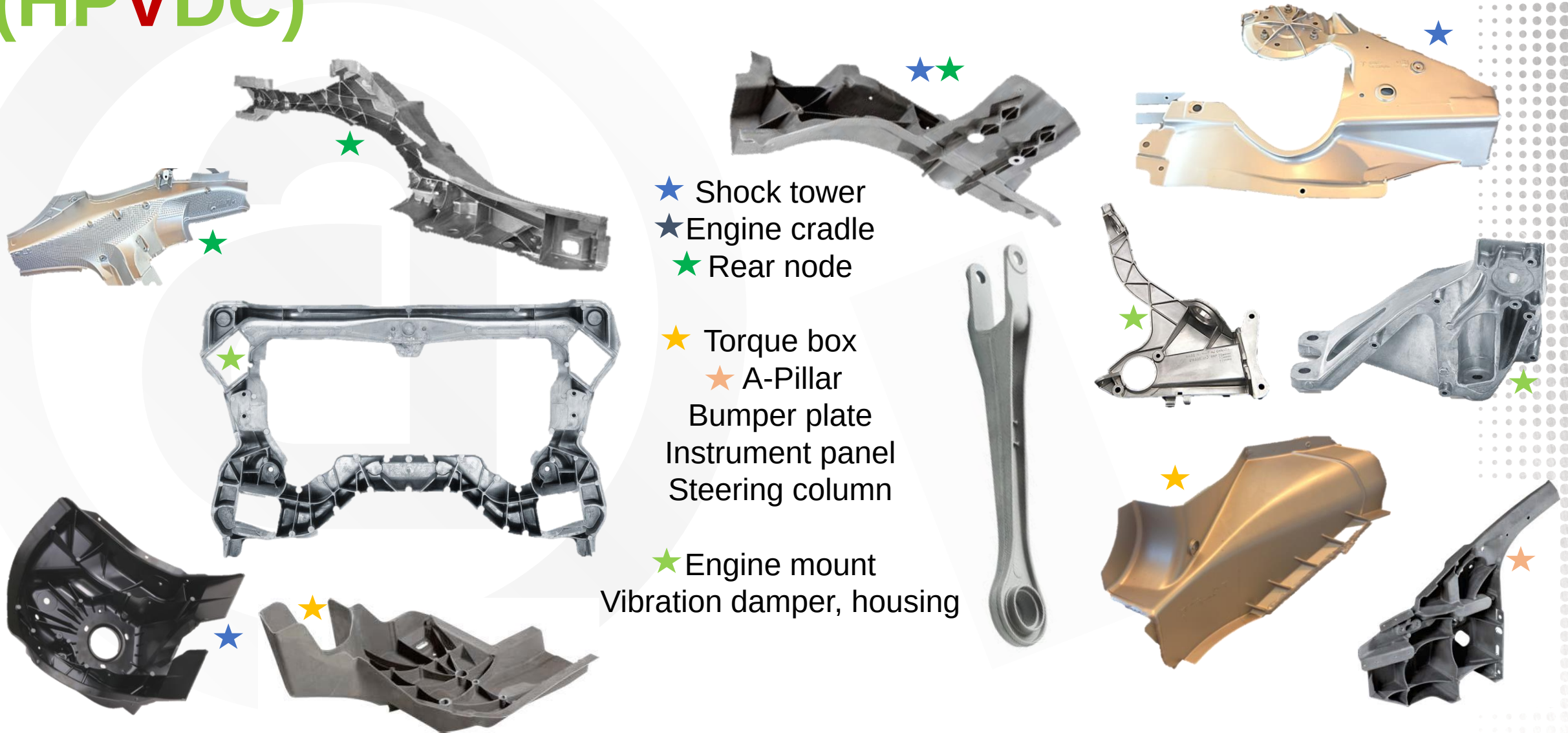
7.2 lbs.



5 welded steel
stampings: 18 lbs.



High integrity Structural Castings (HPVDC)



Shock Towers Processed in HPVDC



Case Study – B Pillar Evolution

Audi ~2000'

B pillar 1st Audi A8

parts: 8
weight: 4180 g

diecast part

extrusion

sheet

1150

B pillar Audi A2

parts: 1
weight: 2300 g

1220



Case Study - Multi Material Lightweight Vehicles (MMLV) - 2013 Ford Fusion

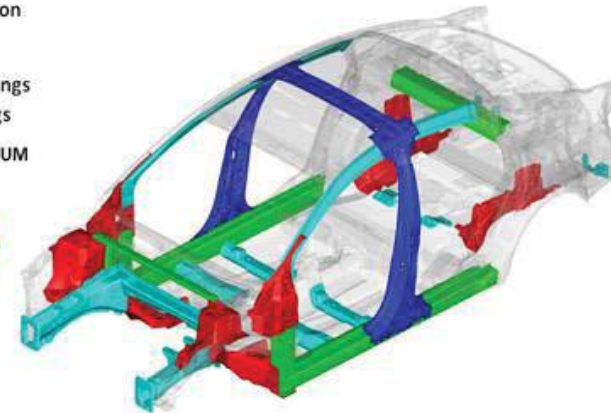
**23.5% mass reduction
1,170kg vs. 1,559kg**



Vehma/Cosma Engineering, a division
of Magna International
The U.S. Department of Energy
Ford Motor Company



Aluminum Extrusion
Hot Form Usibor
HSLA Stampings
Aluminum Stampings
Aluminum Castings
36% STEEL – 64% ALUMINUM



Source: TMS - 2015

Case Study - Multi Material Lightweight Vehicles (MMLV) - 2013 Ford Fusion

Front shock tower

From steel-constructed parts into a single, lightweight component,
40% lighter (from 7.5lbs to 4.6lbs)



Torque box (Kick down rail)

From steel stampings parts into a single, lightweight component,
35% lighter (from 13lbs to 10lbs)



Source: TMS - 2015

Case Study - Multi Material Lightweight Vehicles (MMLV) - 2013 Ford Fusion

Hinge pillar

From steel stampings parts into a single, lightweight component,
35% lighter (from 9.4lbs to 7.4lbs)

Mid Rail

Combiner rear shock tower and rear rail, from 12 piece to 1 single lightweight component, **35%** lighter (from 12.5lbs to 9.2lbs)



Source: TMS - 2015

Case Study – Battery Enclosure

Full EV

Strong enclosure frame with sophisticated crash structures

- 47% **extruded** sections
- 36% **sheet** (3.5mm)
- 17% **die cast** parts (node)

Bolted to the body structure in 35 points

- Increased torsional rigidity by 27%
- High level of the safety

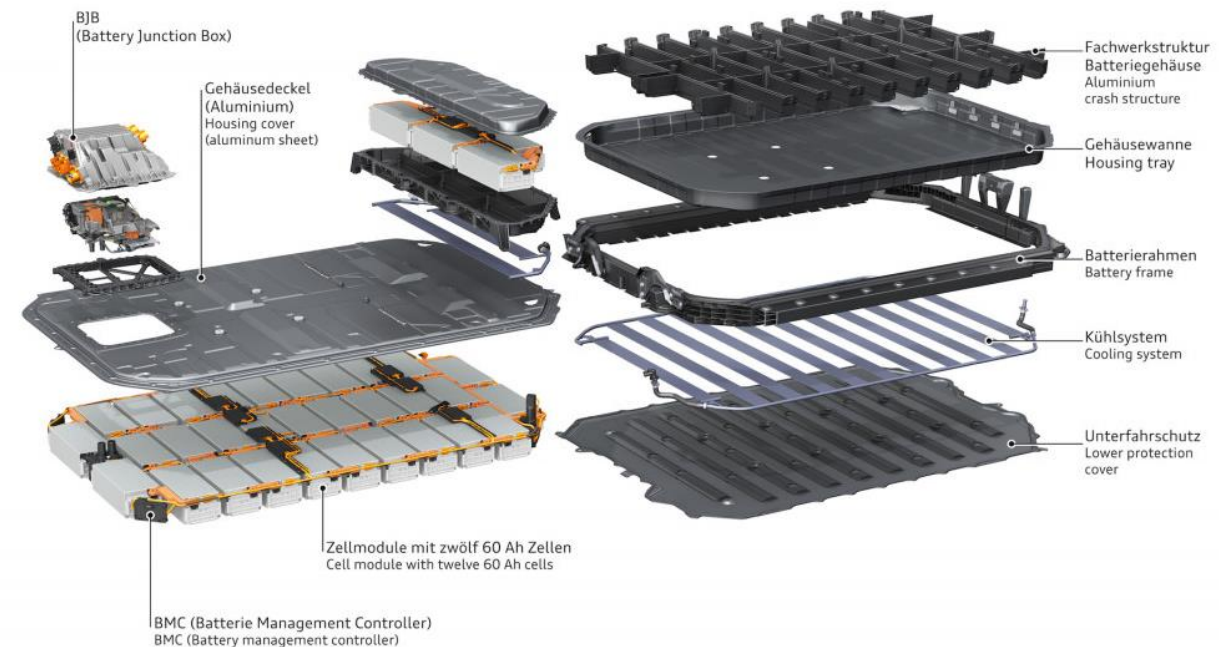


Large high-voltage battery (95 kWh of energy), around 700 kilograms (1,543.2lb)



Audi e-tron

Audi e-tron Prototype
Flüssigkeitsgekühlte Lithium-Ionen-Batterie
Liquid cooled lithium-ion battery
04/18



Source: Audi
Enclosures by Constellium's 3xxx,5xxx and 6xxx alloy sheet, hollow extrusion

Case Study – Battery Enclosure Hybrid Vehicle



Source: Buhler – produced for BMW by Magna BDW
High pressure vacuum die casting

Shot weight: 27.8kg and 19.2kg

Part weight: 14.1kg and 7.3kg

Case Study – Battery / Thermal Management Radiator

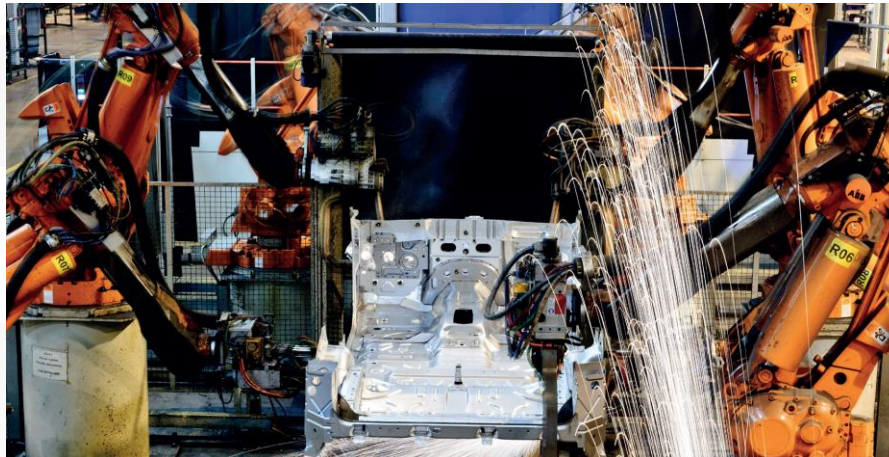


Part weight: 8.2kg

Source: Buhler – for Ericson 5G
High pressure vacuum die casting

Requirements for Thin Wall Structural Casting

- Weight reduction
- Crash performance
- Elevated mechanical properties
- Corrosion resistance
- Very low level of air entrapment for heat treatment

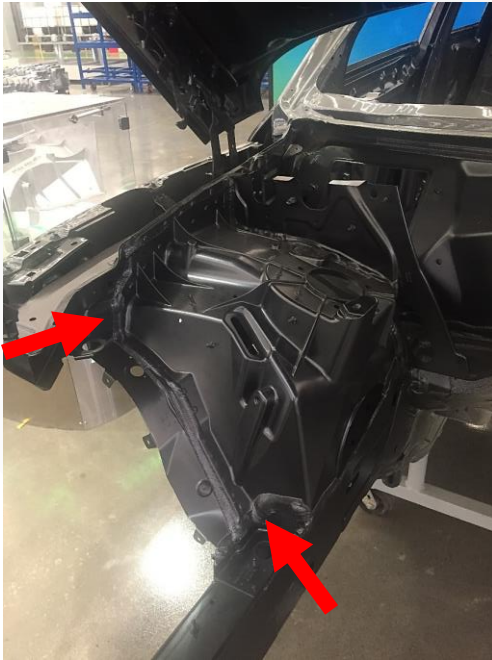


Source: Rio Tinto

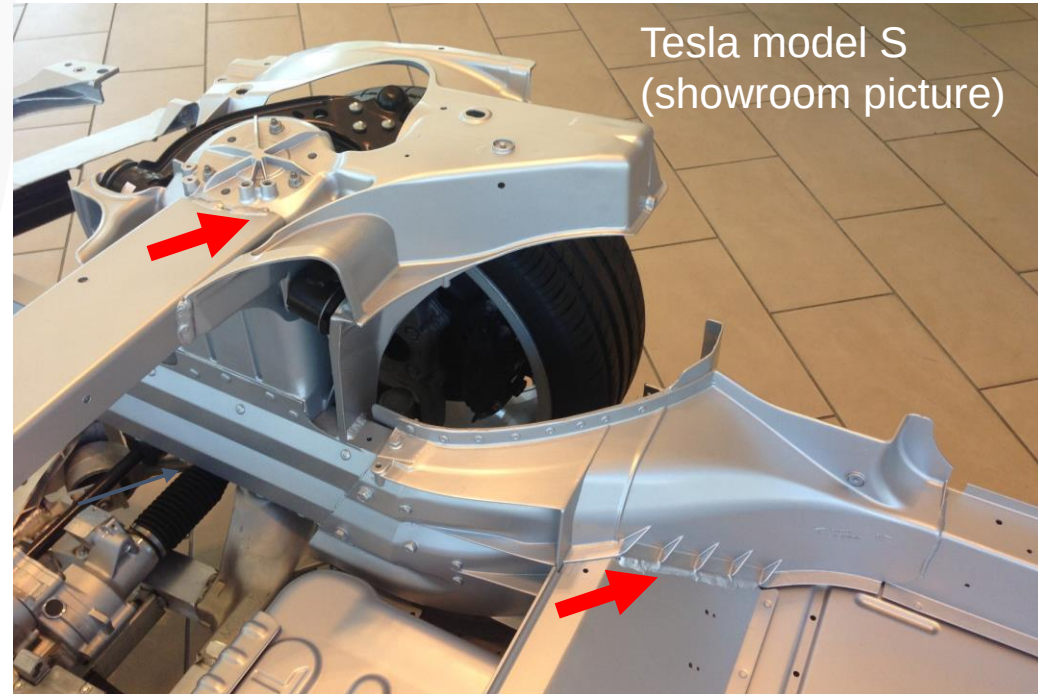
Requirements for Thin Wall Structural Casting

Joining

- Weldable castings (MIG, FSW, laser)
- Distortion free and good dimensions (rivets, adhesive...)

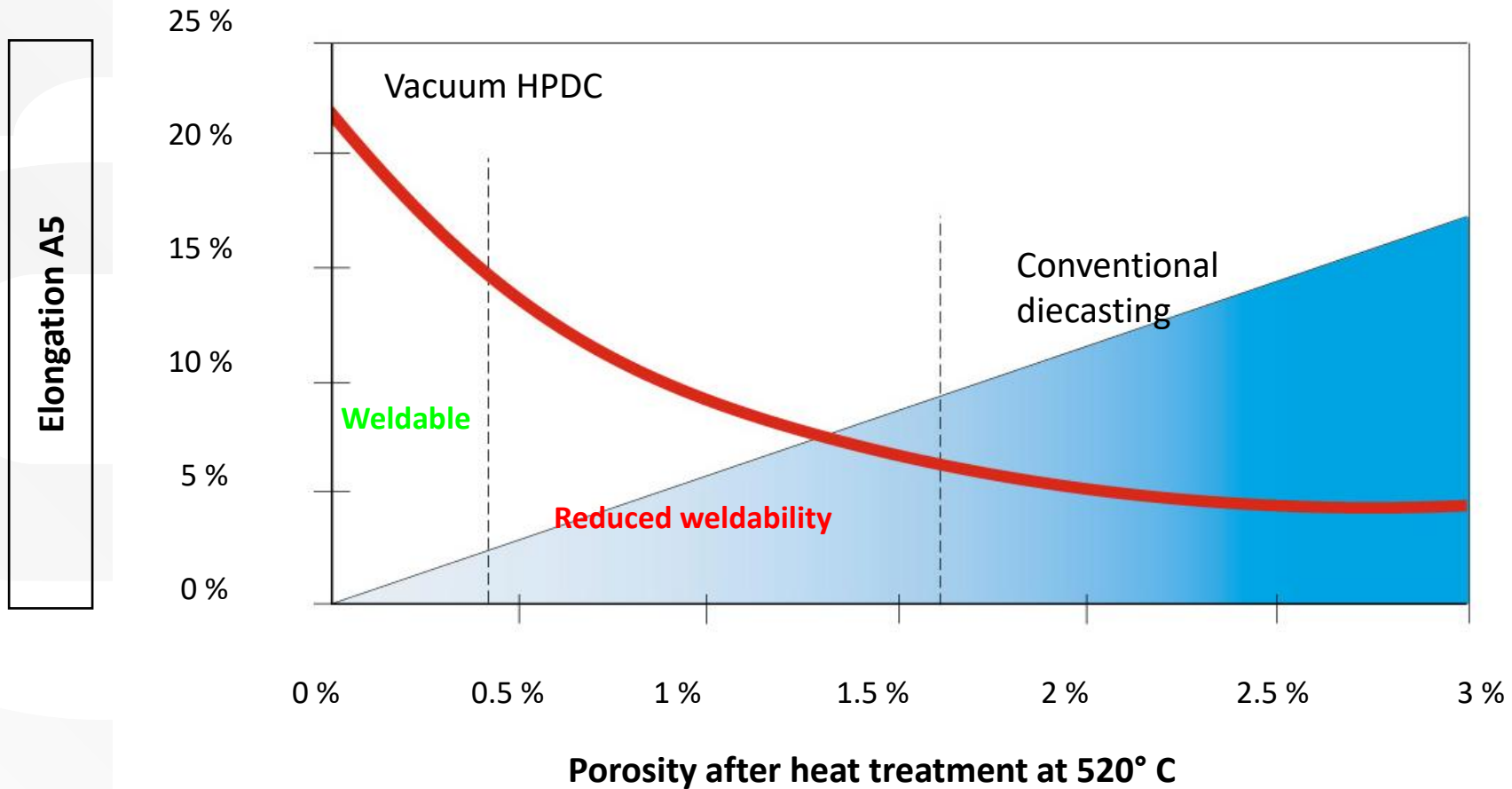


Casting & extrusion assembly



Source: Rio Tinto

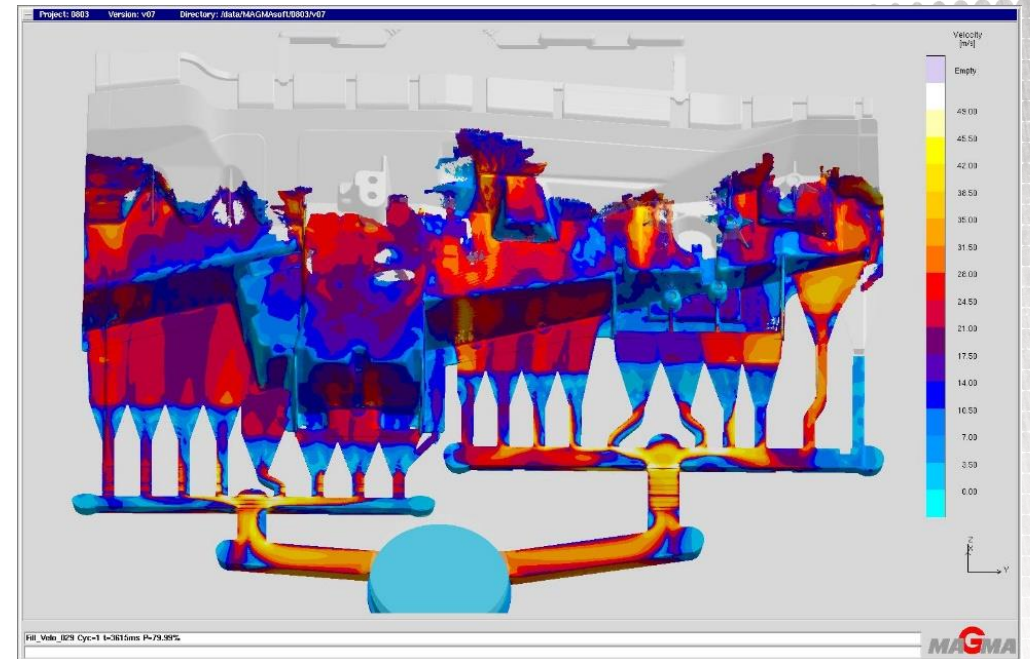
Weldability and Porosities by Process



Source: Rio Tinto

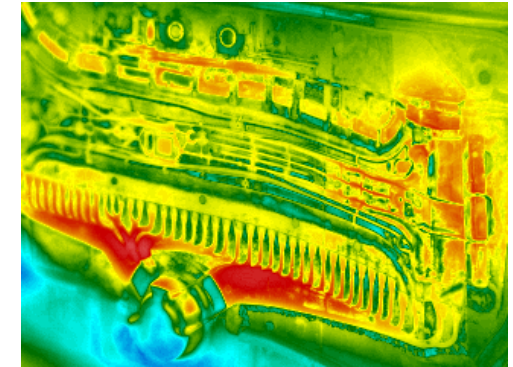
Factors Affecting Thin Wall Structural Casting

- Alloy composition and impurities
- Metal quality (oxides, hydrogen content, sludge, dross, other inclusions)
- Metal temperature, treatment, transfer, delivery to shot sleeve
- Die-casting machine (size, type, equipment)
 - clamp/platen: clamp pressure/platen programmable
 - shot end: shot speeds/profile, pressure, closed loop control
- Monitoring/control system
 - for all critical process parameters/full machine diagnostics
 - graphical user interface (HMI) provide SPC



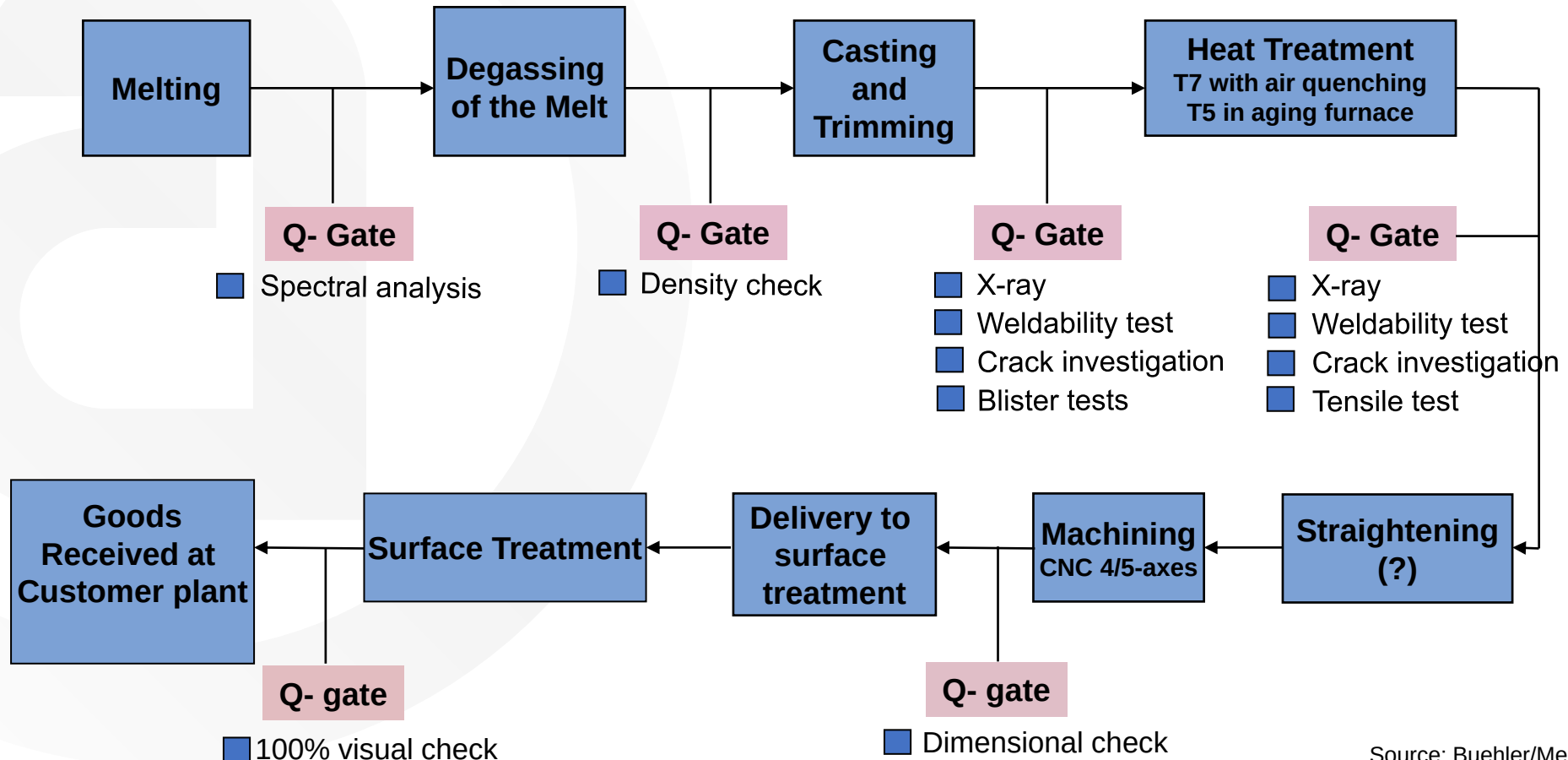
Factors Affecting Thin Wall Structural Casting

- Shot tooling:
 - Cold chamber (proper size, temperature control, etc.)
 - Shot tip (with ring to create seal and internal cooling)
 - Plunger lube (type and application)
- Die-casting dies/gating design/overflow design
- Part design (wall thickness, changes, etc.)
- Die temperature
- Lubricant type, application and efficiency
- Vacuum system: level & type/cavity pressure / control
- Part extraction, quench system, trimming
- Heat treatment and other process steps



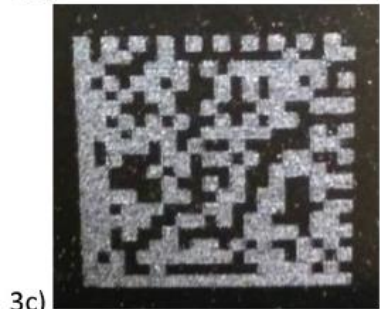
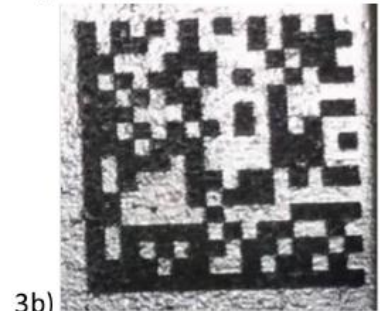
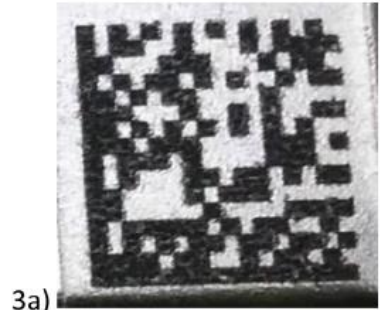
Process Control for HPVDC

Process flow and quality assurance



Source: Buehler/Mercedes

Process Control – Part traceability



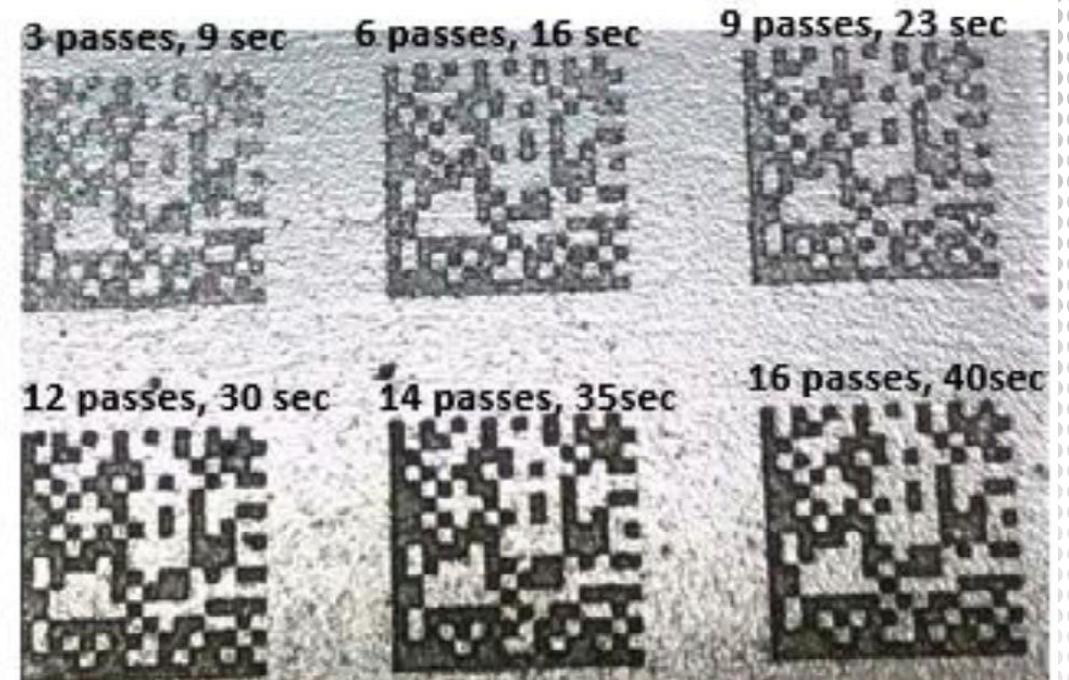
Pictures of data matrices **after E-coating** with a white background (a) and without a white background (b and c), with cell size of 1 mm



Engraving on die casting right off the press

	Material temperature			
	25 °C	100 °C	300 °C	400 °C
Marking speed	300 mm/s	300 mm/s	400 mm/s	500 mm/s
Line spacing	0.125 mm	0.15 mm	0.125 mm	0.125 mm
Time per unit area	2.9 s/cm ²	2.4 s/cm ²	2.2 s/cm ²	1.7 s/cm ²
Contrast	110.3	105.2	111.0	107.7

IATF 16949



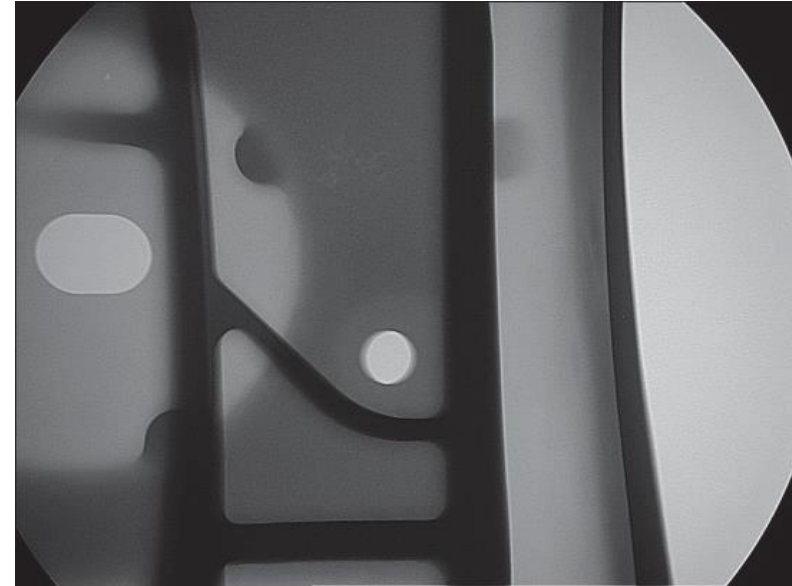
Influence of marking depth on contrast, **after shot blasting and painting**

Process Analysis – X-Ray Analysis

- Castings are subjected to **100% x-ray** (radiographic) inspection
- Critical areas in the castings must satisfy ASTM E155 (HPVDC)
- Castings must also pass **100% dimensional inspection** using a typical tolerance of +/- 0.7 mm and cast surfaces and +/- 0.25 mm for machined surfaces



Source: Rio Tinto



Aluminum shock tower casting x-ray

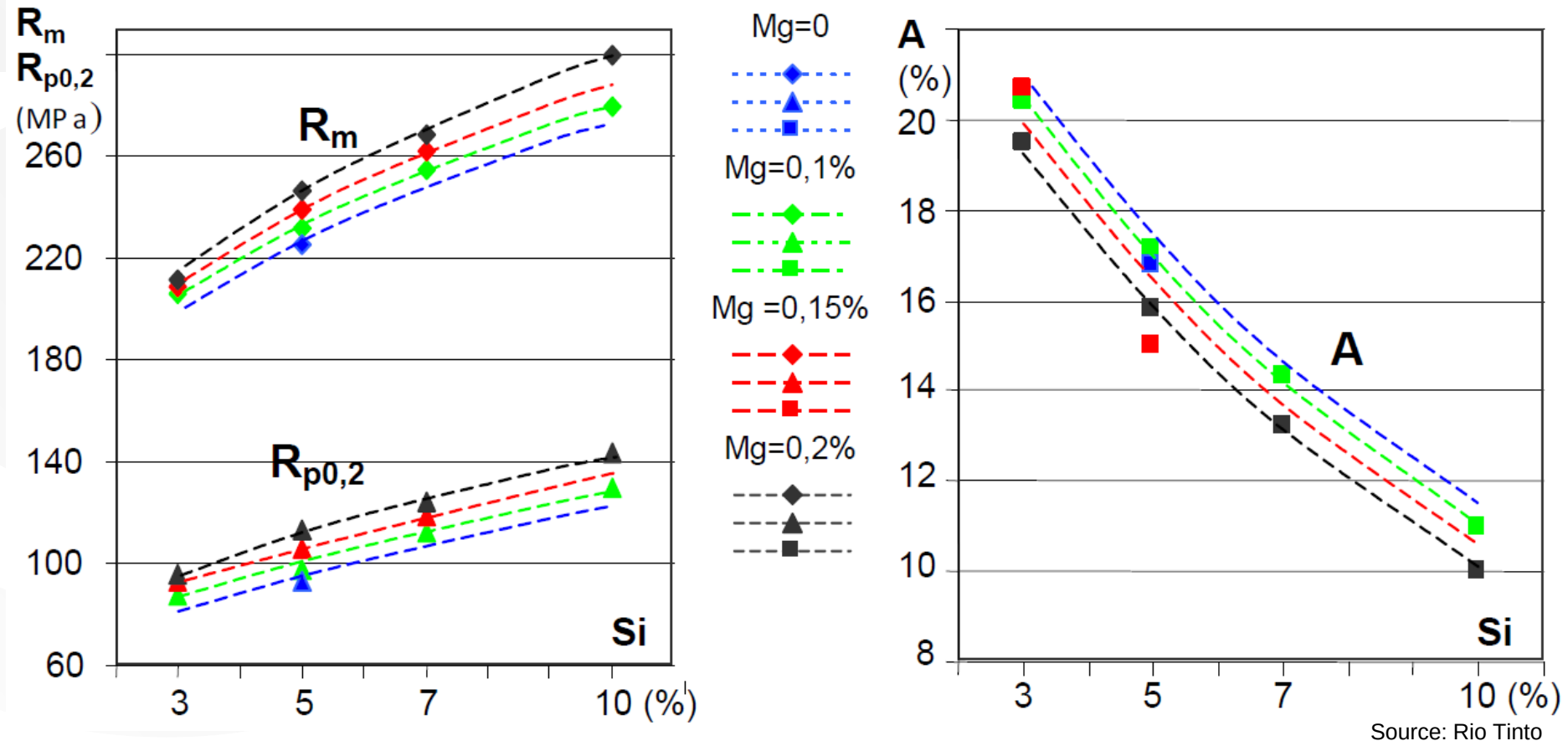
Alloy Characteristic for Structural HPVDC



Element	A365.1		
	Min	Max	
Si	9.5%	11.5%	Good feeding characteristic (fluidity), good hot tear resistance
Fe	0.15%	0.20%	Good hot tear resistance, low die soldering , no coarse intermetallics phases , high dynamic strength
Cu		0.02%	High resistance to corrosion , high strength and hardness
Mn	0.30%	0.6%	Correct Fe phase from β -needle to α -script, low die soldering
Mg	0.15%	0.6%	Strength and hardness development in heat treat. High corrosion resistance
Zn		0.03%	Increase resistance to corrosion
Ti		0.10%	Grain structure refinement, reduce cracking tendencies
P		0.001%	Low trace element
Sr		0.03%	Modify the eutectic silicon, thereby improving ductility of the alloy – reduce die soldering
Others (each)		0.05%	Low level and well controlled due to primary metal

Composition Variation on Properties

Si and Mg influence on mechanical properties in high pressure die casting (F Temper)



Actual Compositions A365.1, 374.1, 375.1

Low Mg

A365.1	Si	Fe	Cu	Mn	Mg	Zn	Ti	Sr
Min	9.5	0.16		0.45	0.25			
Max	11.5	0.20	0.02	0.55	0.35	0.03	0.10	0.03

High Mg

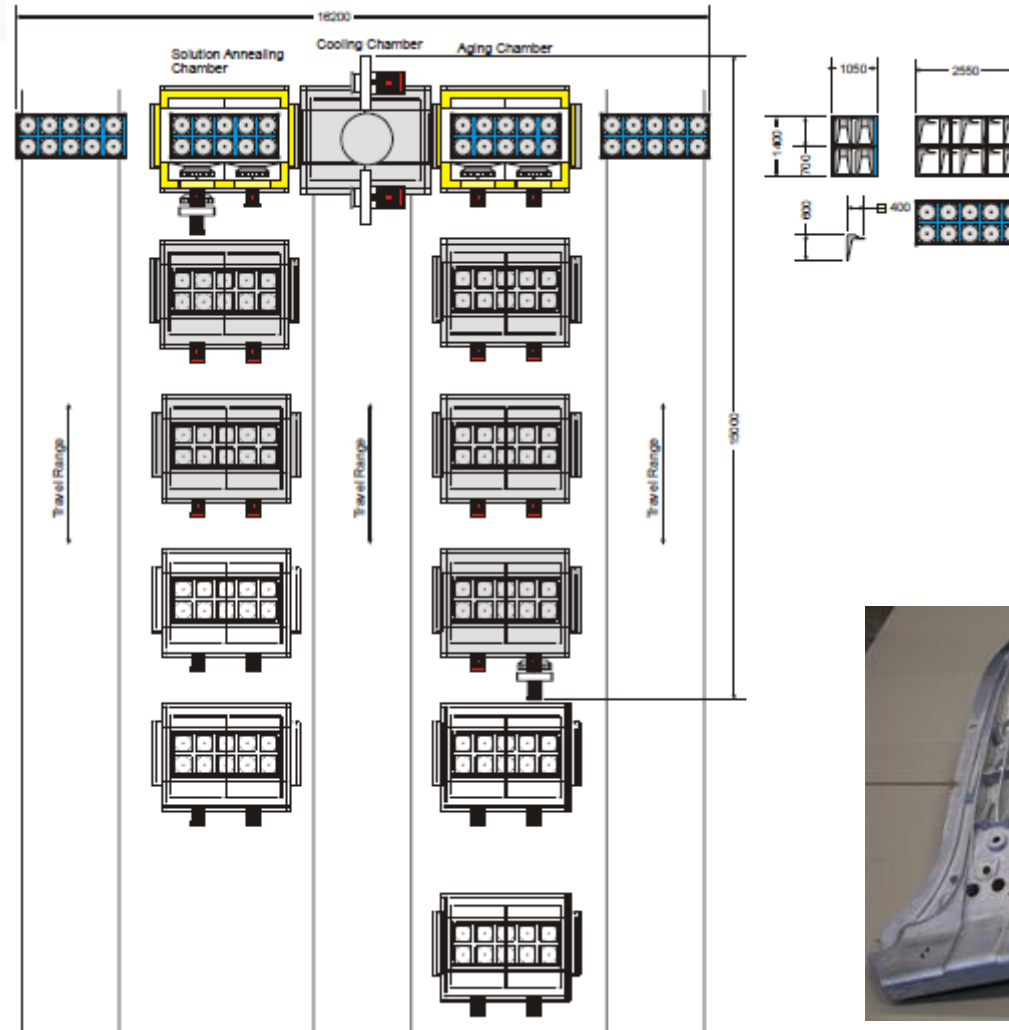
A365.1	Si	Fe	Cu	Mn	Mg	Zn	Ti	Sr
Min	9.5	0.16		0.45	0.45			
Max	11.5	0.20	0.02	0.55	0.55	0.03	0.10	0.03

374.1	Si	Fe	Cu	Mn	Mg	Zn	Ti	Sr
Min	7	0.16		0.45	0.15			
Max	8	0.20	0.02	0.55	0.25	0.03	0.10	0.03

375.1	Si	Fe	Cu	Mn	Mg	Zn	Ti	Sr
Min	9.5	0.11		0.54				
Max	11.5	0.18	0.02	0.64	0.10	0.03	0.10	0.03

Source: Rio Tinto

Heat Treatment Layout from T4, T6 and T7



F = as-cast
T4 = solutionized + **water quench**
T5 = as-cast + artificially aged
T6 = solutionized + **water quench** + artificially aged
T7 = solutionized + **air quench** + artificially aged



Typical Properties at Various Tempers

Low Mg

High Mg

Alloy/Temper	R _{P0,2} YS [MPa]	R _m UTS [MPa]	A ₅ [%]
A365.1 / F	130 - 160	280 - 320	5 - 11
A365.1 / T4	100 - 150	200 - 270	15 - 22
A365.1 / T5	165 - 220	270 - 320	4 - 8
A365.1 / T6	100 - 160	210 - 250	8 - 14
A365.1 / T7 with Sr	120 - 150	190 - 220	12 - 18
A365.1 / F	160 - 180	300 - 340	6 - 10
A365.1 / T4	100 - 140	200 - 240	12 - 17
A365.1 / T5	190 - 240	300 - 340	4 - 6.5
A365.1 / T6	130 - 215	235 - 275	9.5 – 13.5
A365.1 / T7 with Sr	170 - 190	225 - 245	8 – 11
374.1 / F	110 - 130	240 - 270	8 – 12
374.1 / T4	60 - 100	160 - 200	17 - 22
374.1 / T5	120 - 160	200 - 260	7 - 11
375.1 / F	100 - 120	250 - 280	10 – 14

F = as-cast

T4 = solutionized,
water quench

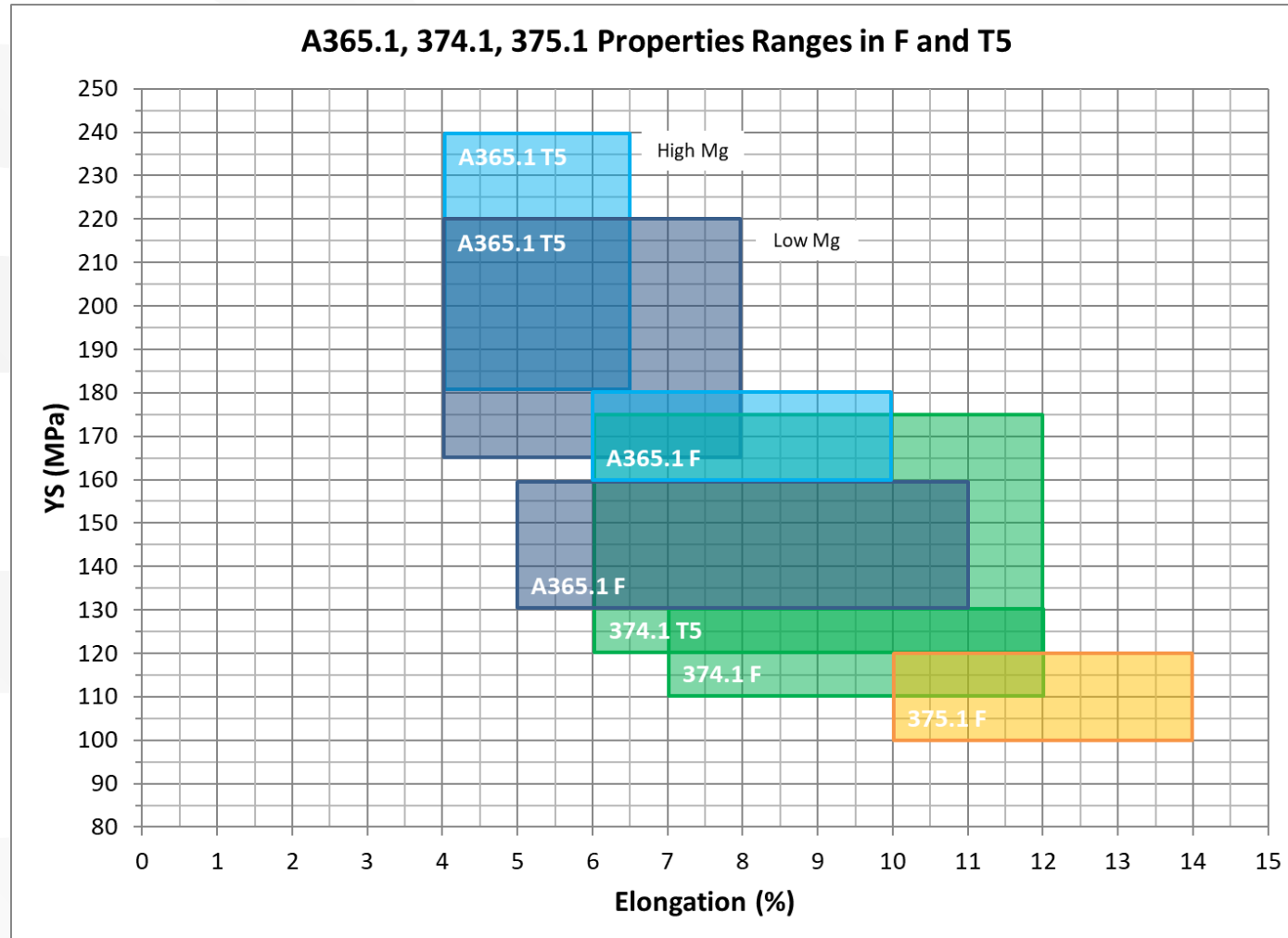
T6 = solutionized,
water quench,
artificially aged

T5 = as-cast,
artificially aged

T7 = solutionized,
air quench,
artificially aged

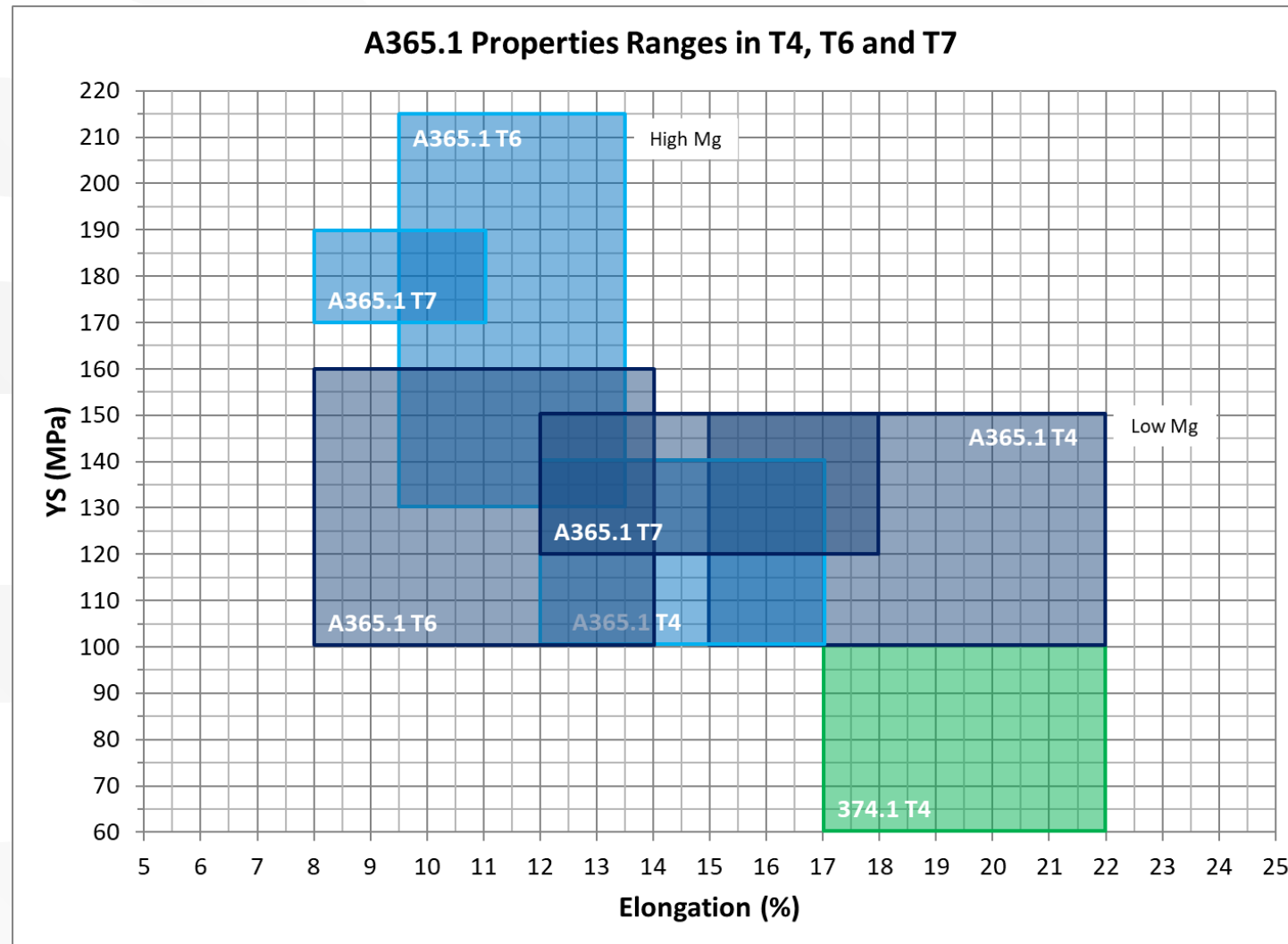
Source: Rio Tinto

Typical Properties A365.1, 374.1, 375.1 in F and T5



Source: Rio Tinto

Typical Properties A365.1 in T4, T6, T7

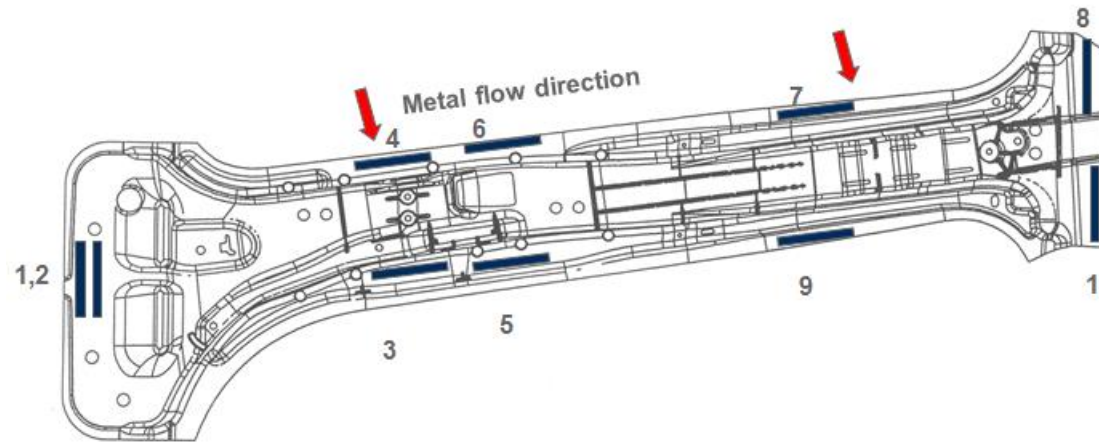


Source: Rio Tinto

Actual Properties A365.1 T7 (Low Mg)

Alloy / Temper	$R_{P0,2}$ YS [MPa]	R_m UTS [MPa]	A_5 [%]
A365.1 (low Mg) / T7 with Sr	120 - 150	190 - 220	12 - 18

Sample	Y.S. (MPa)	T.S. (MPa)	A5 (%)
1	130.5	202.0	18.8
2	133.1	203.8	17.7
3	134.5	203.9	18.4
4	132.9	203.2	17.7
5	137.3	205.6	14.4
6	134.7	204.5	18.8
7	133.8	203.6	17.2
8	132.4	203.6	19.3
9	134.0	203.9	20.9
10	134.9	204.7	13.4
11	135.4	205.0	14.0
12	136.3	205.4	16.5



Actual Properties A365.1 T7 (High Mg)

Alloy / Temper	$R_{p0,2}$ YS [MPa]	R_m UTS [MPa]	A_5 [%]
A365.1 (high Mg) / T7 with Sr	170 - 190	225 - 245	8 – 11



Side beam requirements

$R_{p0,2}$ (YS) $\geq$ 180 MPa

R_m (UTS) $\geq$ 230 MPa

$A_5 \geq 6\%$

HB $\geq$ 80

Source: Rio Tinto

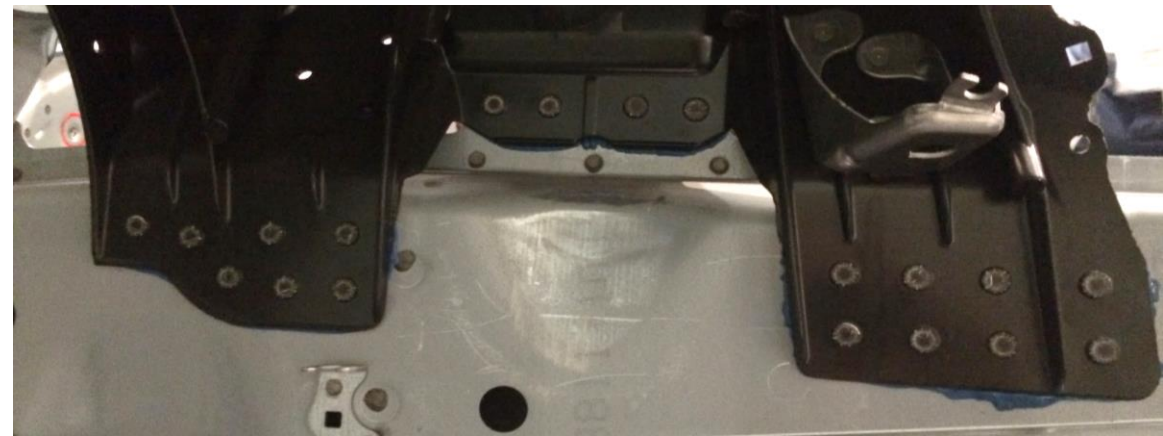
A large, light gray stylized letter 'a' logo is positioned on the left side of the slide. It consists of a thick circular stroke with a smaller circle inside, creating a stylized 'a' shape.

Questions?

Break time!

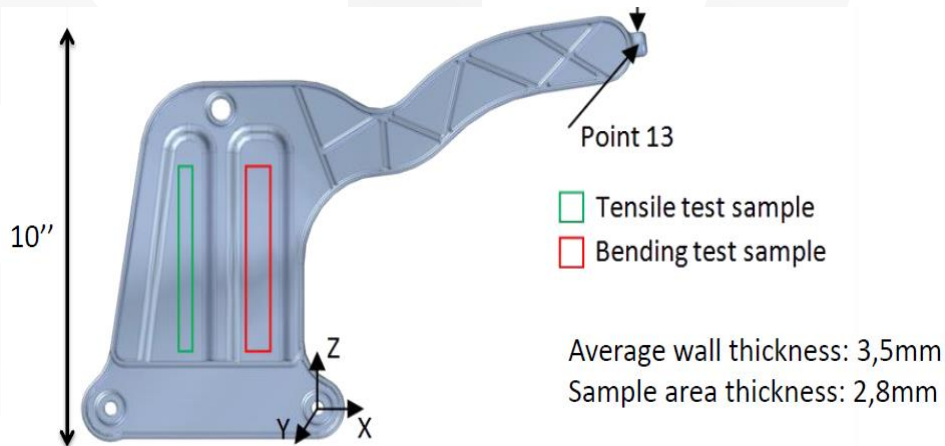


F, T4 and T5 Tempers with Structural Die Casting Alloys

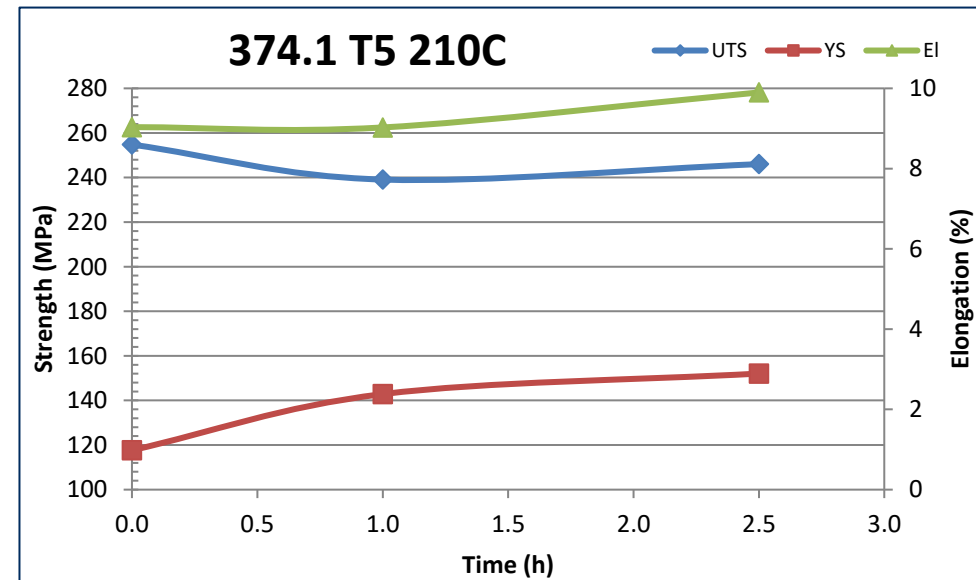


Typical Properties A365.1 and 374.1-T5 Tempers

Alloy/Temper	$R_{p0,2}$ YS [MPa]	R_m UTS [MPa]	A_5 [%]
A365.1 (low Mg) / T5	165 - 220	270 - 320	4 - 8
A365.1 (high Mg) / T5	190 - 240	300 - 340	4 - 6.5
→ 374.1 / T5	120 - 160	200 - 260	7 - 11



ASTM B557 flat subsize specimens



Source: Rio Tinto

Process

AMT A+ High-Vacuum
High Pressure Die
Casting

Information

- Application : **Snowmobile Chassis**
- Alloy : **A365.1 low Mg**
- Heat-treatment : **T5**
- Straightening : **None**
- Weldable : **Yes**

Mechanical Properties

ELONGATION

Min : 5%

YIELD STRENGTH

Min : 215MPa

TENSILE STRENGTH

Min : 290MPa



www.amtdiecasting.com

Example: Snowmobile Chassis

Process

- AMT A + High-Vacuum
- High Pressure Die
- Casting

Information

- **Application:** Snowmobile Chassis
- **Alloy:** A356.1 low Mg
- **Heat-treatment:** T5
- **Straightening:** None
- **Weldable:** Yes

Mechanical Properties

- **Elongation** — Minimum: 5%
- **Yield Strength** — Minimum: 215 Mpa
- **Tensile Strength** — Minimum: 290 MPa



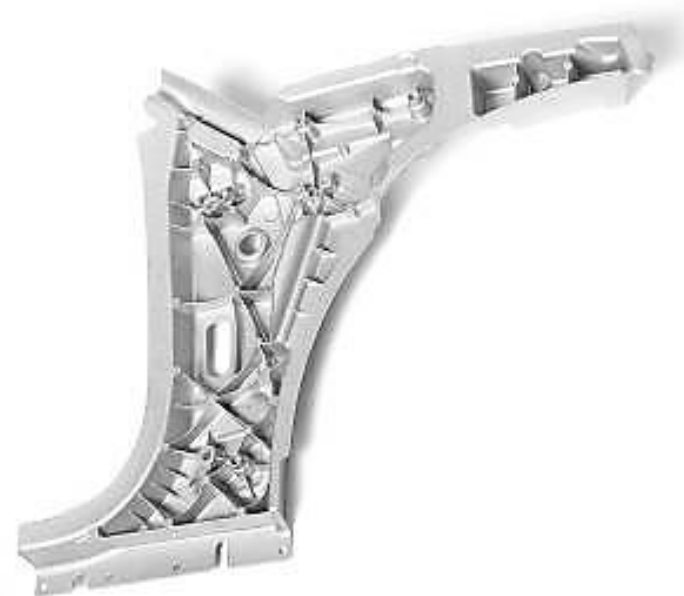
www.amtdiecasting.com

Actual Properties Example: 374.1-T5

Part	Sample	Rp0.2 [N/mm2]	Rm [N/mm ²]	A5 [%]
Part 1	1	122.93	244.1	11.7
	2	123.91	233.96	10.37
	3	138.43	260.23	9.9
	4	145.52	261.97	11.57
	5	129.68	256.87	10.78
		132.09	251.43	10.86
Part 2	1	122.17	237.58	10.12
	2	132.36	251.24	11.64
	3	134.11	260.69	10.99
	4	136.89	260.38	11.95
	5	126.46	255.43	10.45
		130.4	253.06	11.03
Part 3	1	129.12	249.14	10.66
	2	130.47	251.69	10
	3	140.67	265.54	10.21
	4	139.22	260.06	8.12
	5	128.64	259.66	10.11
		133.62	257.22	9.82

Mechanical properties as cast (F) artificial aging 40 min/210°C

374.1-T5
A-pillar



Source: Rio Tinto

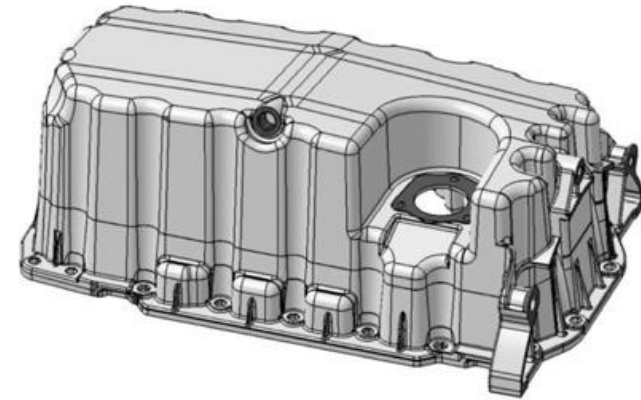
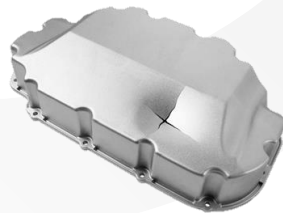
Actual Properties Example: 374.1-T5

Requirements (without heat treatment)

- Flange hardness: 70 HB
- Elongation (bottom): 8%
- Stone-chipping resistance: 65 lbf/ft²
- Leak tightness: 5 ml/min

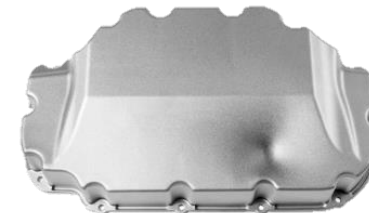
A380

- Flange hardness: 95 HB
- Elongation (bottom): 2 %
- Stone-chipping resistance: 35 lbf/ft²
- Leak tightness: 2 ml/min



374.1 (as cast)

- Flange hardness: 88 HB
- Elongation (bottom): 10 %
- Stone-chipping resistance: 96 lbf/ft²
- Leak tightness: 2 ml/min

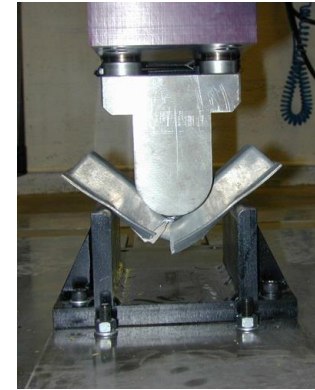
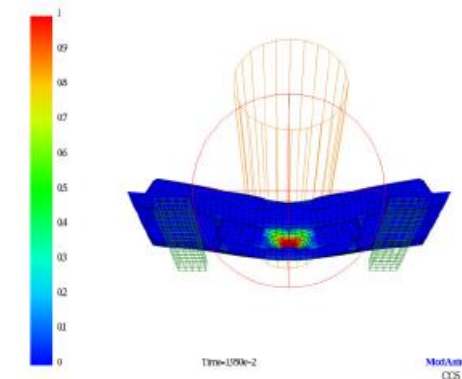
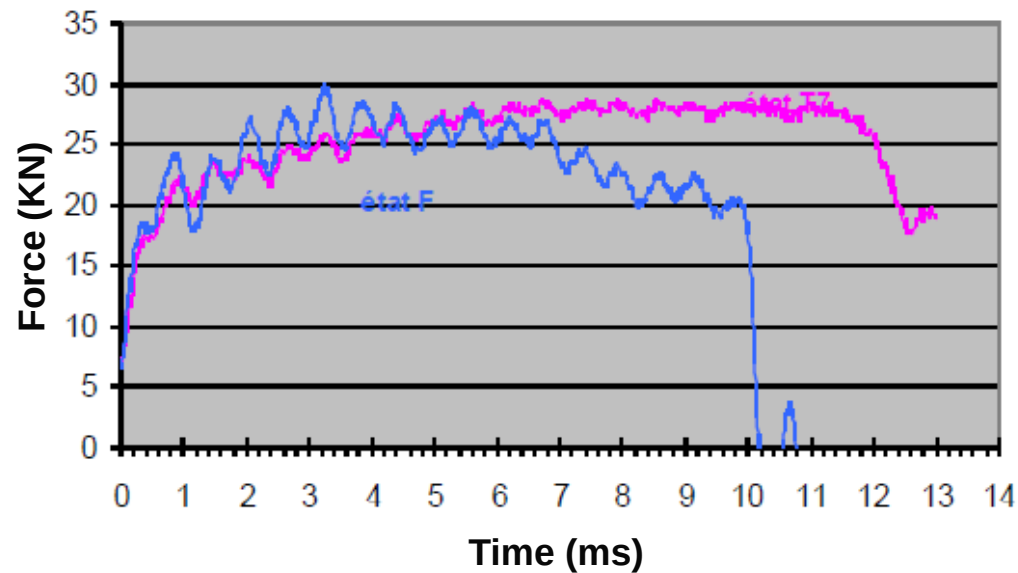


Source: Rio Tinto

A365.1 (Low Mg) - Crash Behavior Difference F vs. T7

Alloy/Temper	$R_{p0.2}$ YS [MPa]	R_m UTS [MPa]	A_5 [%]
A365.1 (low Mg) / F	130 - 160	280 - 320	5 - 11
A365.1 (high Mg) / T7 with Sr	120 - 150	190 - 220	12 - 18

Force vs time curves, T7 and F conditions



T 7 – 2.5mm



F – 2.5mm

Source: Rio Tinto

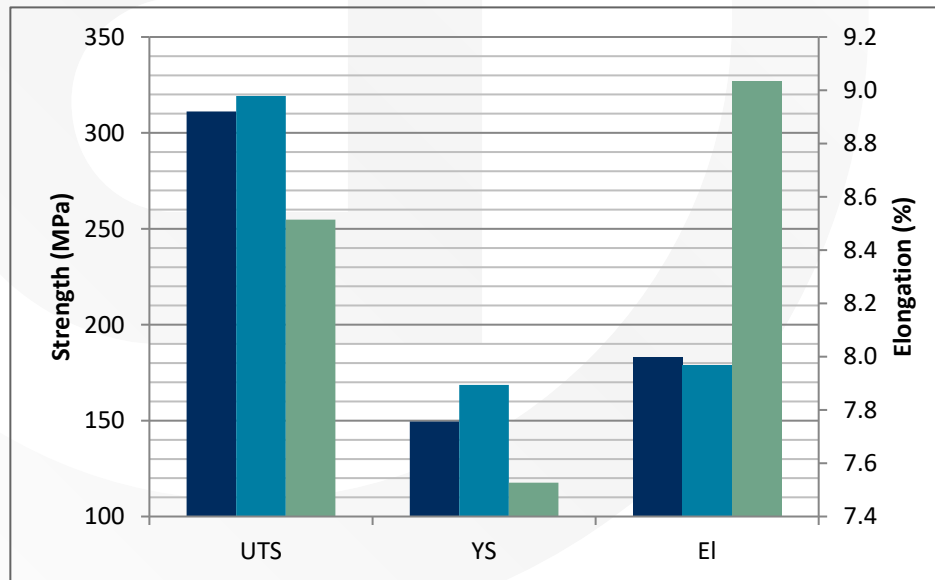
Comparison of As-Cast F and T5 Properties

Alloy/Temper	YS [MPa]	UTS [MPa]	A ₅ [%]
A365.1 (low) / F	130 - 160	280 - 320	5 - 11
A365.1 (low) / T5	165 - 220	270 - 320	4 - 8

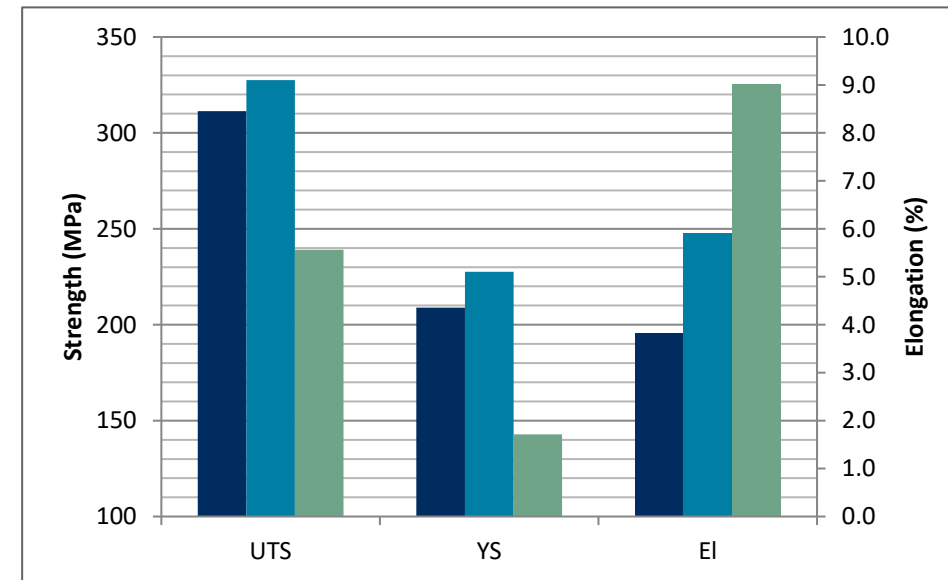
Alloy/Temper	YS [MPa]	UTS [MPa]	A ₅ [%]
374.1 / F	110 - 130	240 - 270	8 - 12
374.1 / T5	120 - 160	200 - 260	7 - 11

Alloy/Temper	YS [MPa]	UTS [MPa]	A ₅ [%]
A365.1 (high) / F	160 - 180	300 - 340	6 - 10
A365.1 (high) / T5	190 - 240	300 - 340	4 - 6.5

F = as cast T5 = as cast, artificially aged



F temper of A365.1 (low, high) and 374.1

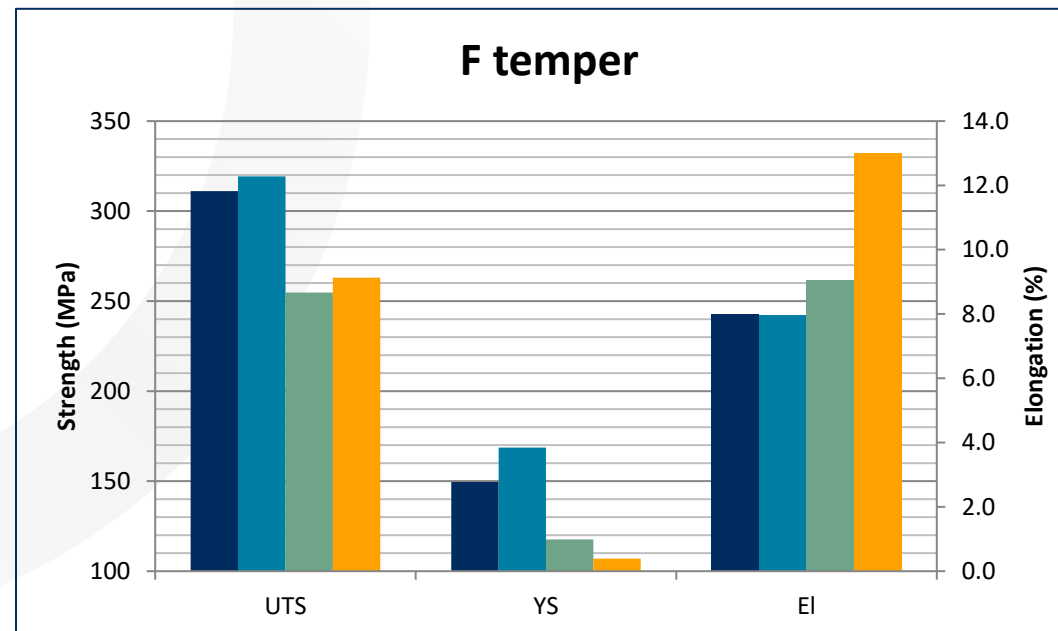


T5 temper of A365.1 (low, high) and 374.1

Source: Rio Tinto

Typical Properties Including 375.1 in F Temper

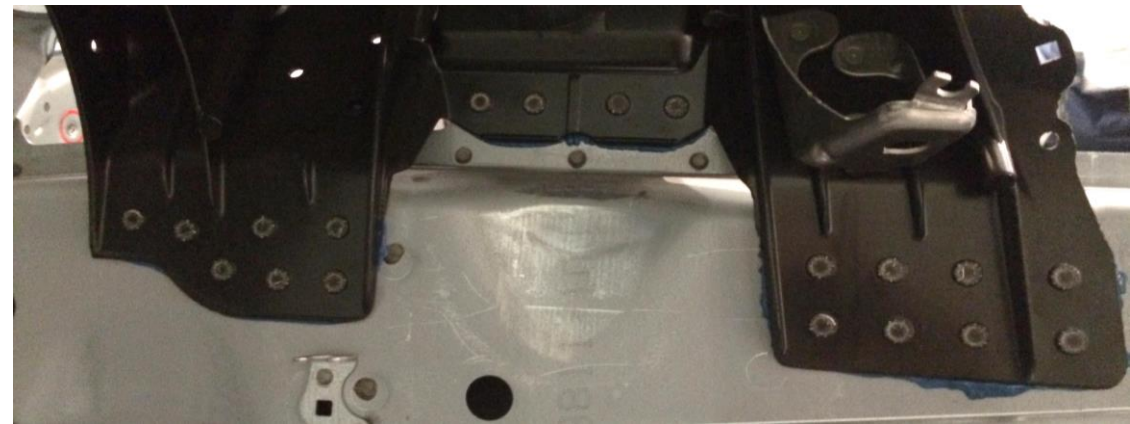
Alloy/Temper	$R_{P0.2}$ YS [MPa]	R_m UTS [MPa]	A_5 [%]
A365.1 (low Mg) / F	130 - 160	280 - 320	5 - 11
A365.1 (high Mg) / F	160 - 180	300 - 340	6 - 10
374.1 / F	110 - 130	240 - 270	8 - 12
375.1 / F	100 - 120	250 - 280	10 - 14



Source: Rio Tinto

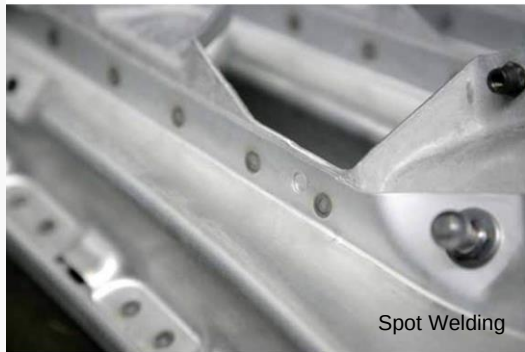


Joining of Structural High Pressure **Vacuum** Die Castings (HP**V**DC)



Joining Solutions

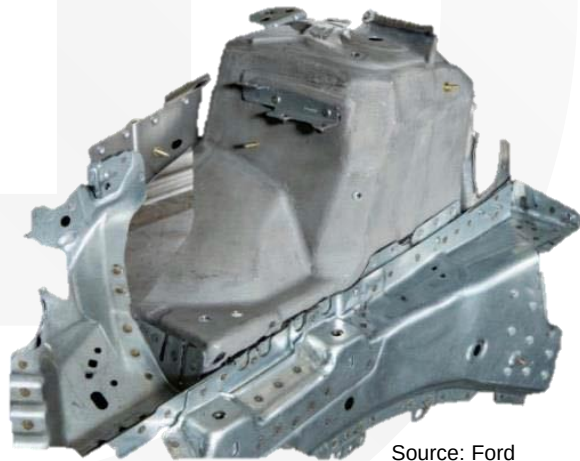
- HPVDC are specifically suited for joining
 - Welded (MIG, laser, arc, CMT, FSW, FSSW, RSW)
 - Brazed
 - SPR
 - Adhesive bonding
 - Screw



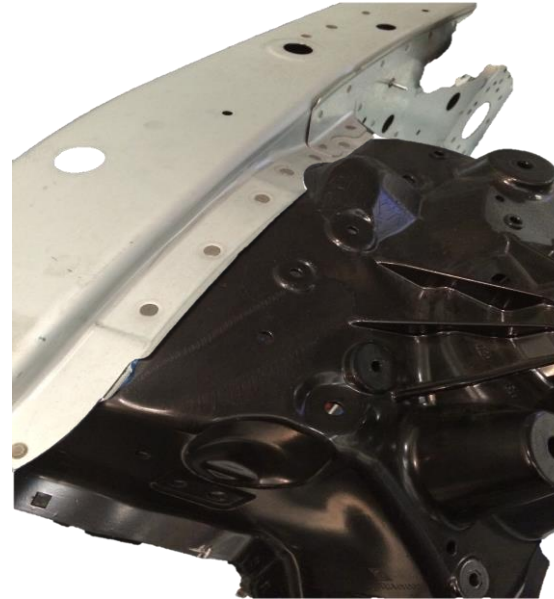
Spot Welding



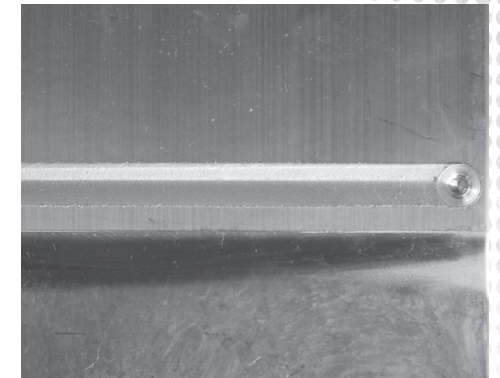
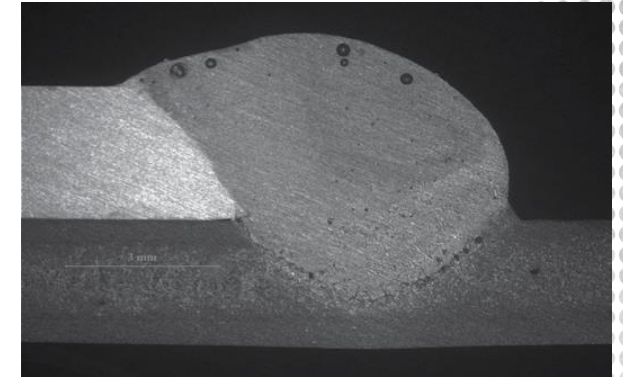
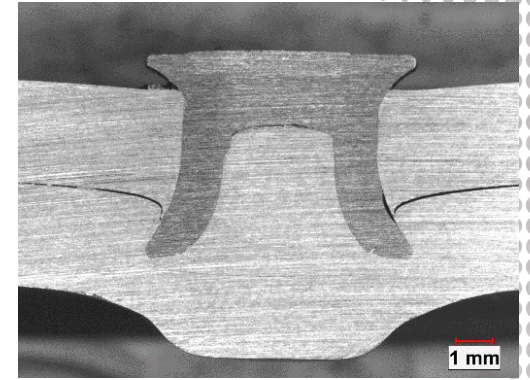
Friction Stir Spot Welding



Source: Ford



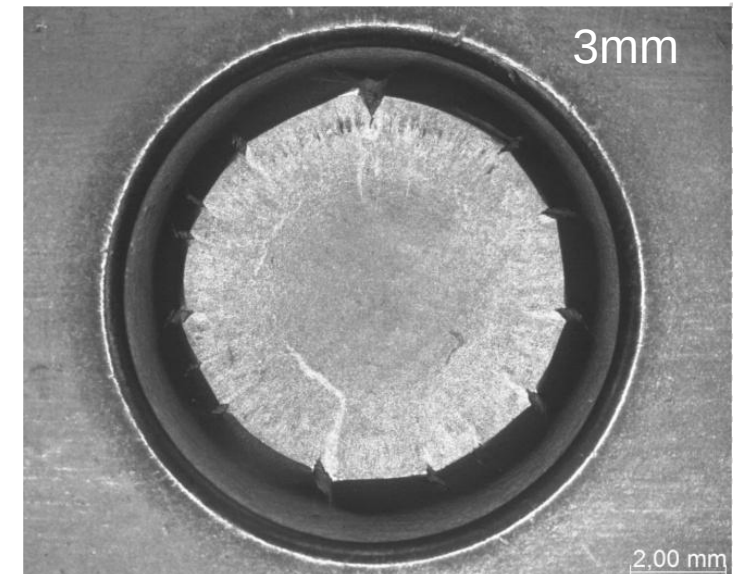
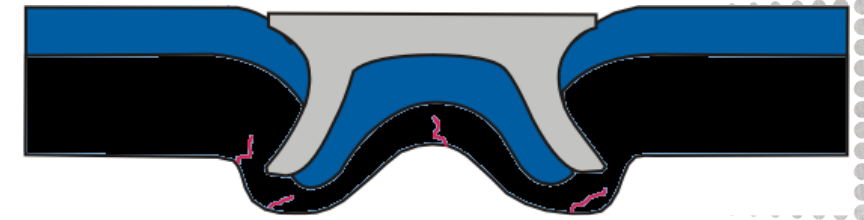
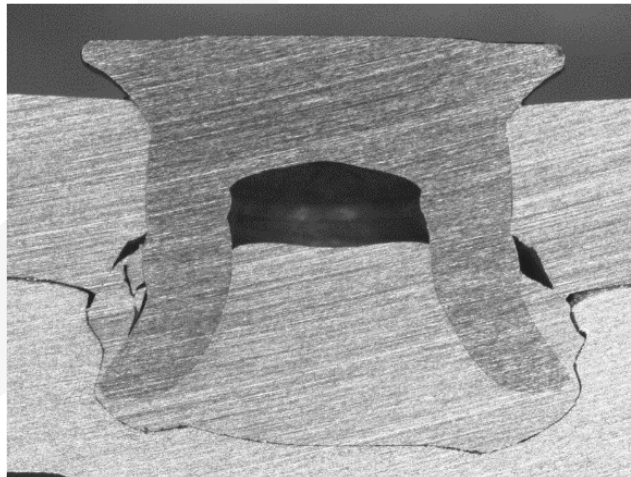
Source: BMW



Prerequisites for Joining Cast Material

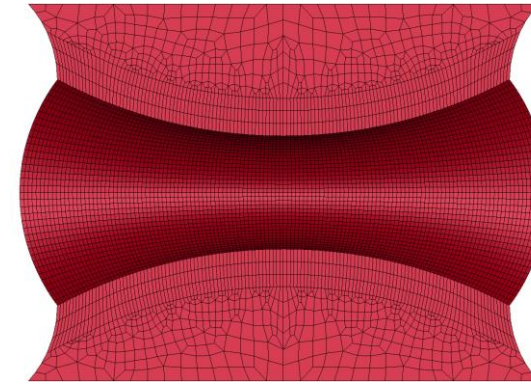
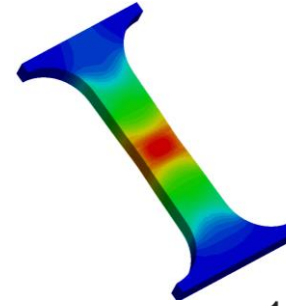
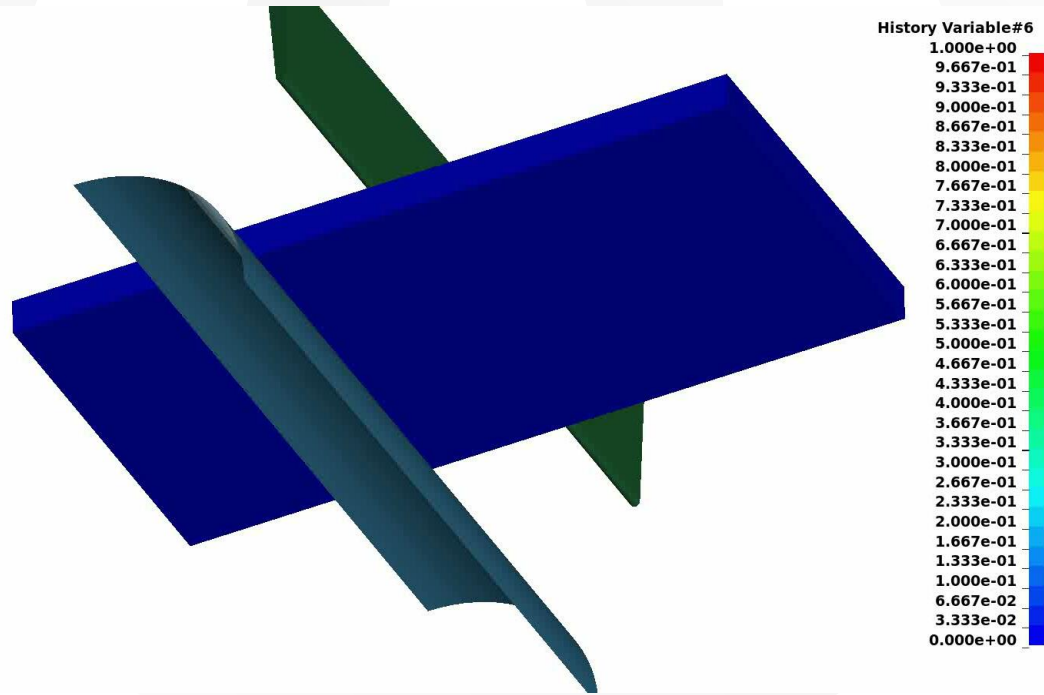
Lower layer key aspect to consider

- Low breaking elongation ability
- Thickness variation
- Inhomogeneous mechanical characteristics
- Gets easy cracks in the locking head
- Asymmetric spread and rivet shaft buckling

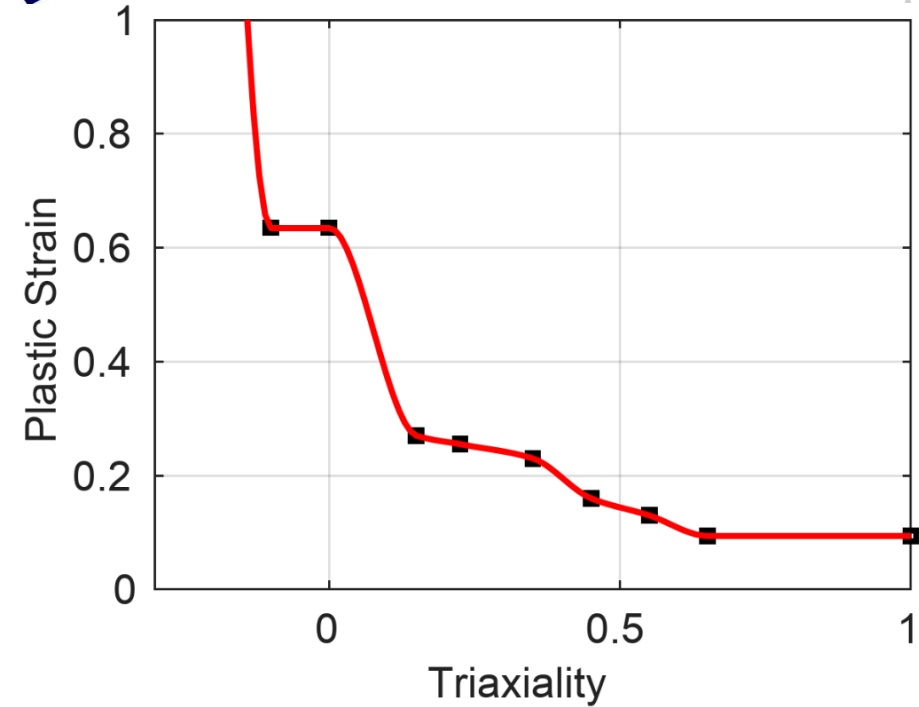


Joining Solutions

Modeling parameters calculated for OEMs - LS-Dyna



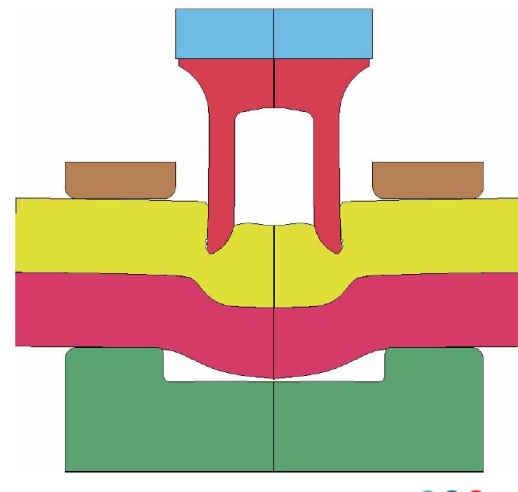
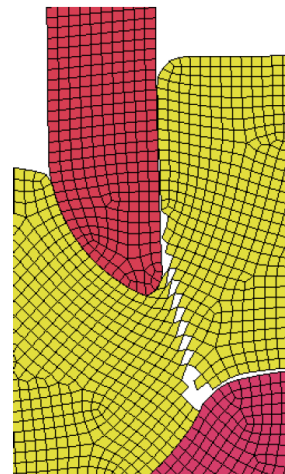
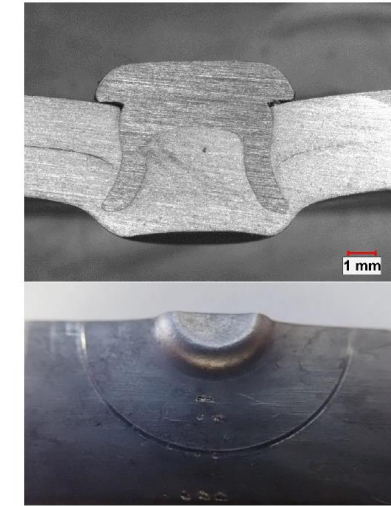
Equivalent plastic strain at failure evaluated with a mesh of 0.1mm



Source: Rio Tinto/NRC-CNRC

Joining Solutions

New SPR technique development

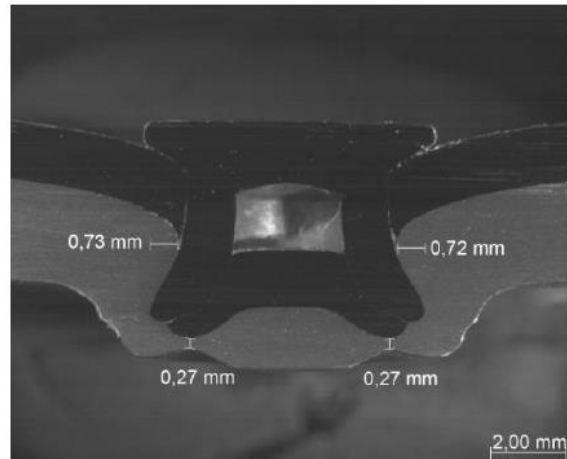


Source: Rio Tinto/NRC-CNRC

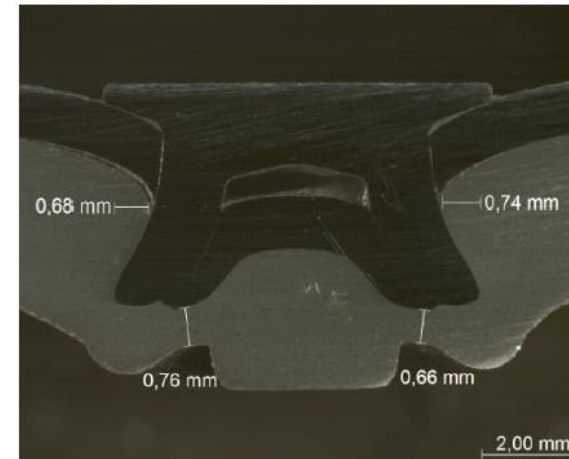
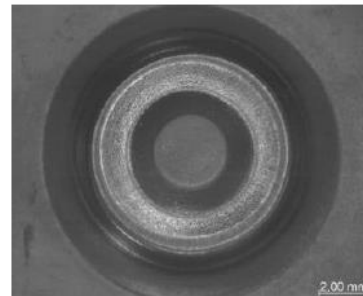
Joining Solutions

SPR development steel with cast HPVDC material

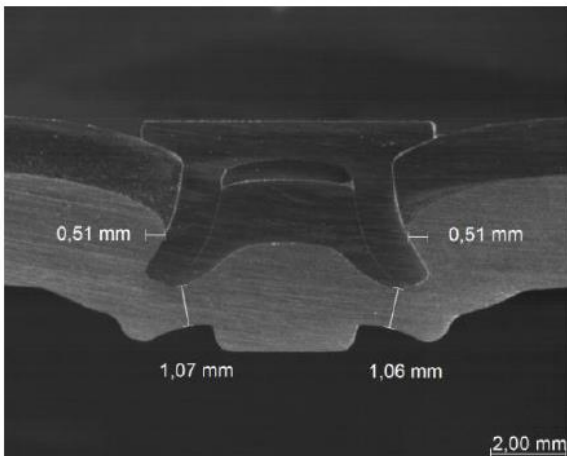
Source: Bollhoff



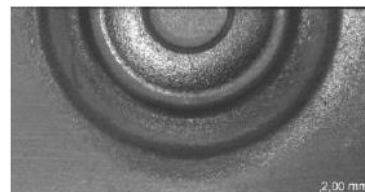
DP 800 1,5 mm
A365.1-T7 (low) 2,5 mm
P 5x6 H4
SM 120 0254



HC450X 1,0 mm
A365.1-T7 (low) 3,0 mm
HD3 5x5,5 H4
SM 120 0235 / 5°

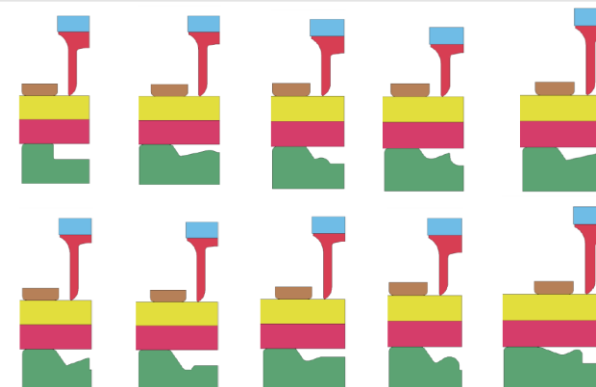


HC340 LA 1,50 mm
A375.1-F 3,00 mm
HD2 5x5,5 H4
SM 120 0223 / 5°



Process Optimization

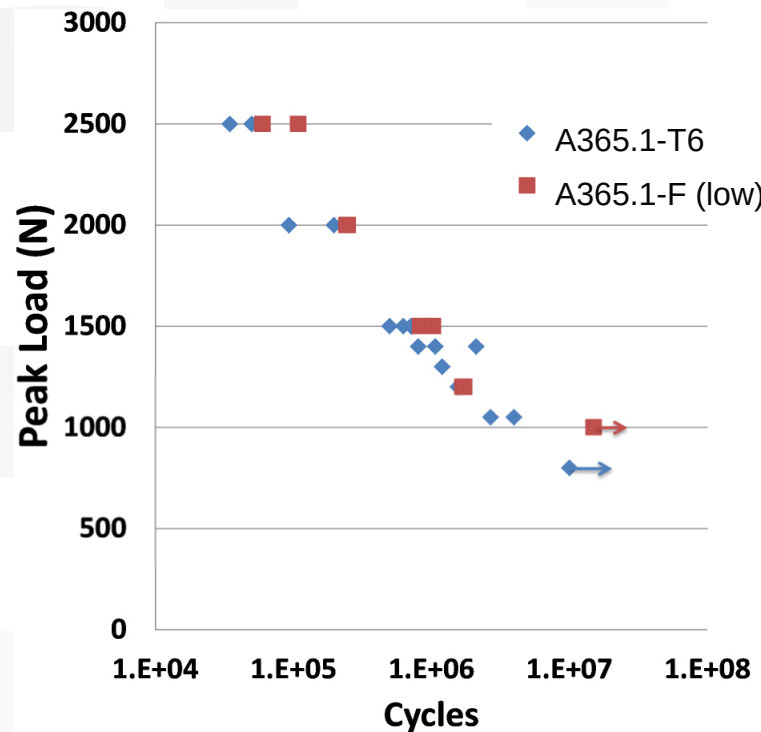
Examples of dies and rivets shapes



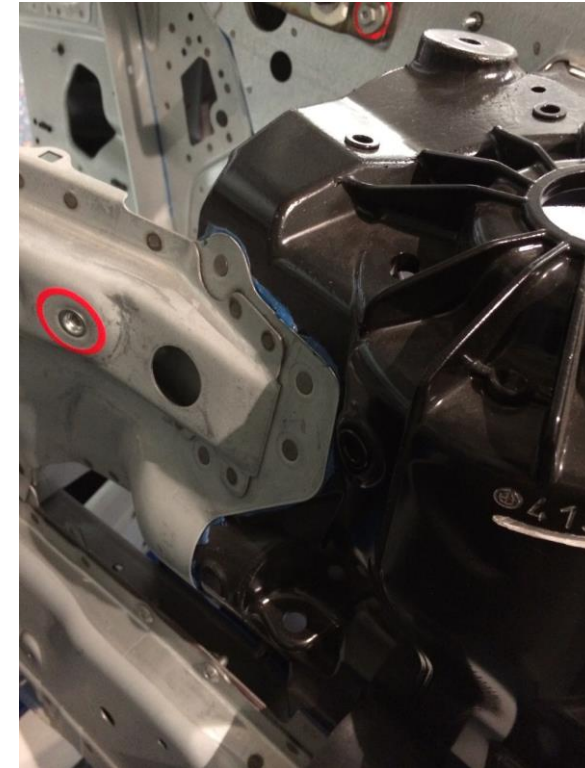
Source: NRC-CNRC
● ● ●

A365.1 (Low Mg) FSSW Joining

- A365.1 (low) can be FSSW in F temper
- Peak Load vs number of cycles to failure for lap shear samples tested at 40 Hz and R=0.1

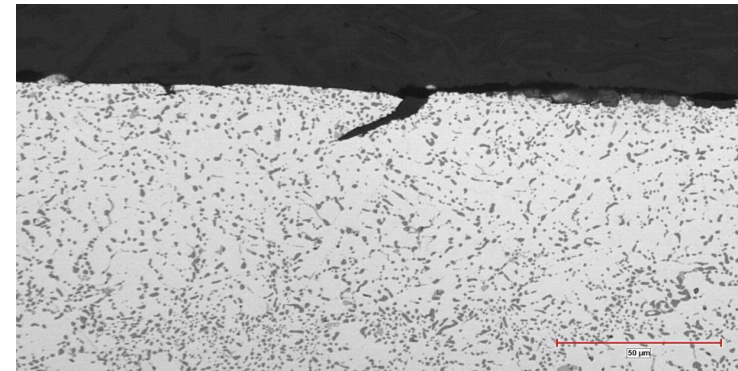
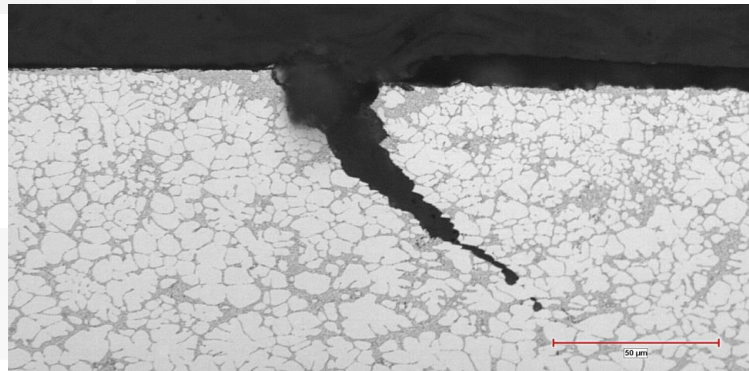


Source SAE 2014 – Ford study



VDA Bending Tests: A365.1 (Low) and 374.1

Alloy	Avg. Max Force (N)	Avg. Angle	UTS (MPa)	YS (MPa)	El. (%)
374.1- F	5998 $\pm$ 105	32.4 $\pm$ 1.9	250	115	11.5
374.1- T5	6036 $\pm$ 142	16.8 $\pm$ 1.8	260	160	9.0
A365.1- T7	5788 $\pm$ 277	48.2 $\pm$ 6.2	212	150	10.0



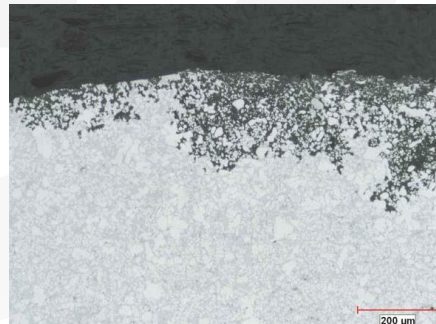
- Good VDA bend angles can be achieved but are affected by:
 - Silicon morphology
 - Strength
- Elongation does not provide an adequate assessment of bendability

Source: Rio Tinto

Accelerated Corrosion Test: ASTM G85-A3 (SWAAT); 20-Day Exposure

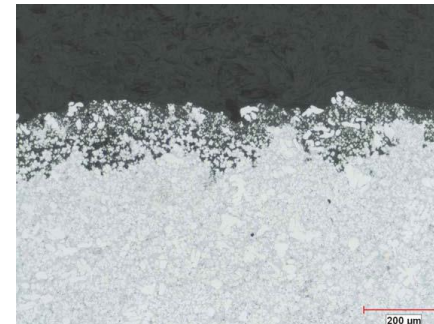
A365.1 (low Mg)-T7

Few shallow pits (2/6)
Deepest attack = 500 μm
Corroded surface = 30%



A365.1 (high Mg)-T7

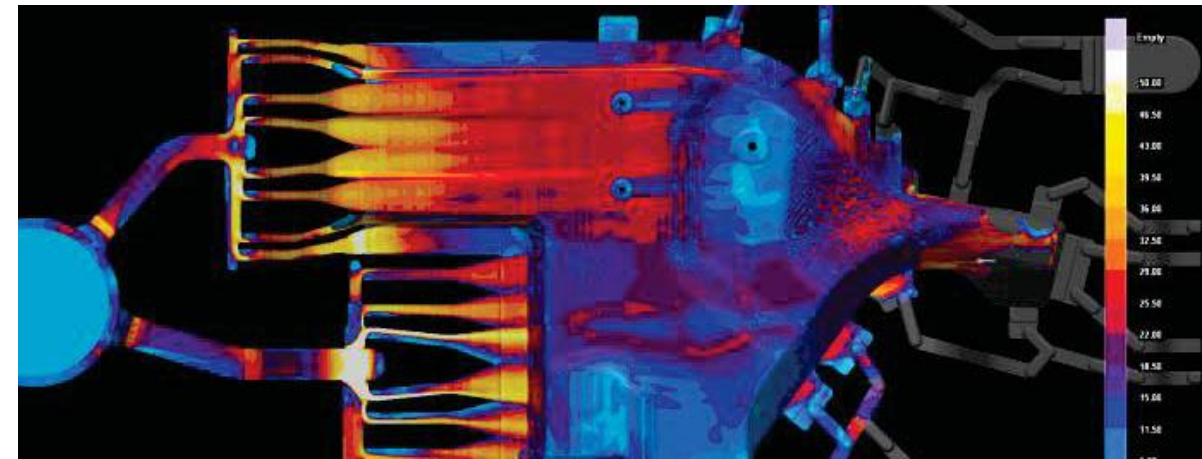
Average shallow pits (3/6)
Deepest attack = 400 μm
Corroded surface = 60%



Source: Rio Tinto



Modeling of Structural Die Casting Alloys



Modeling

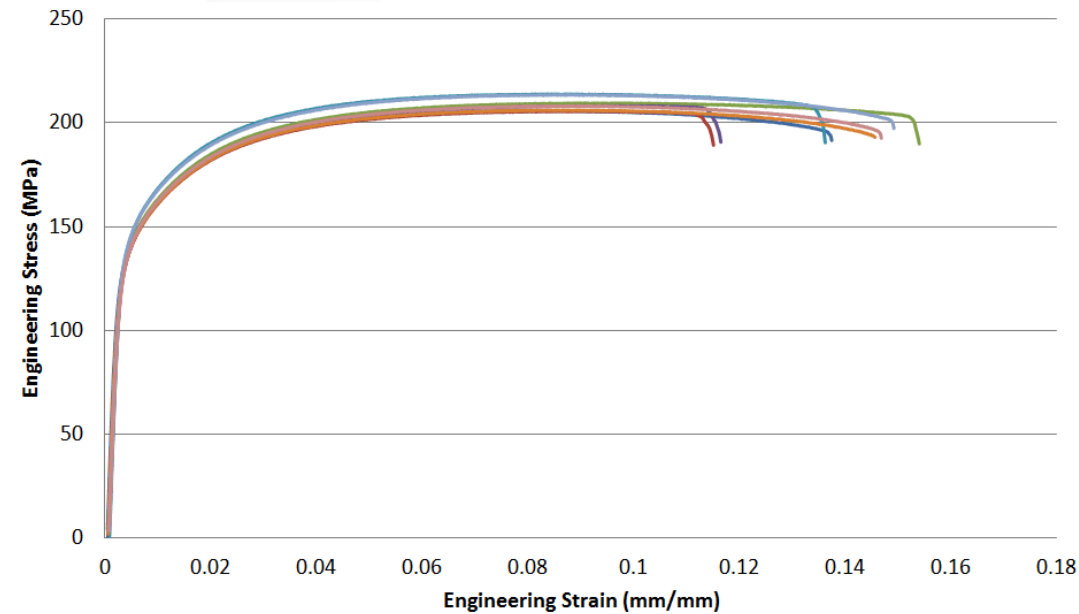
- Liquidus
- Solidus
- Latent heat of fusion vs temperature
- Specific heat vs temperature
- Density vs temperature
- Solid fraction vs temperature
- Molar volume vs temperature
- Enthalpy vs temperature
- Volume change vs temperature
- Average expansion coefficient vs temperature
- Liquid diffusivity vs temperature
- Total diffusivity vs temperature
- Bulk modulus vs temperature
- Shear modulus vs temperature
- Elastic (young) modulus vs temperature
- Poisson ratio vs temperature
- Liquid viscosity vs temperature
- Total viscosity vs temperature
- Surface tension vs temperature
- Thermal conductivity vs temper
- Electrical resistivity vs temper
- Electrical conductivity vs temper



Stress-Engineering Strain Curves



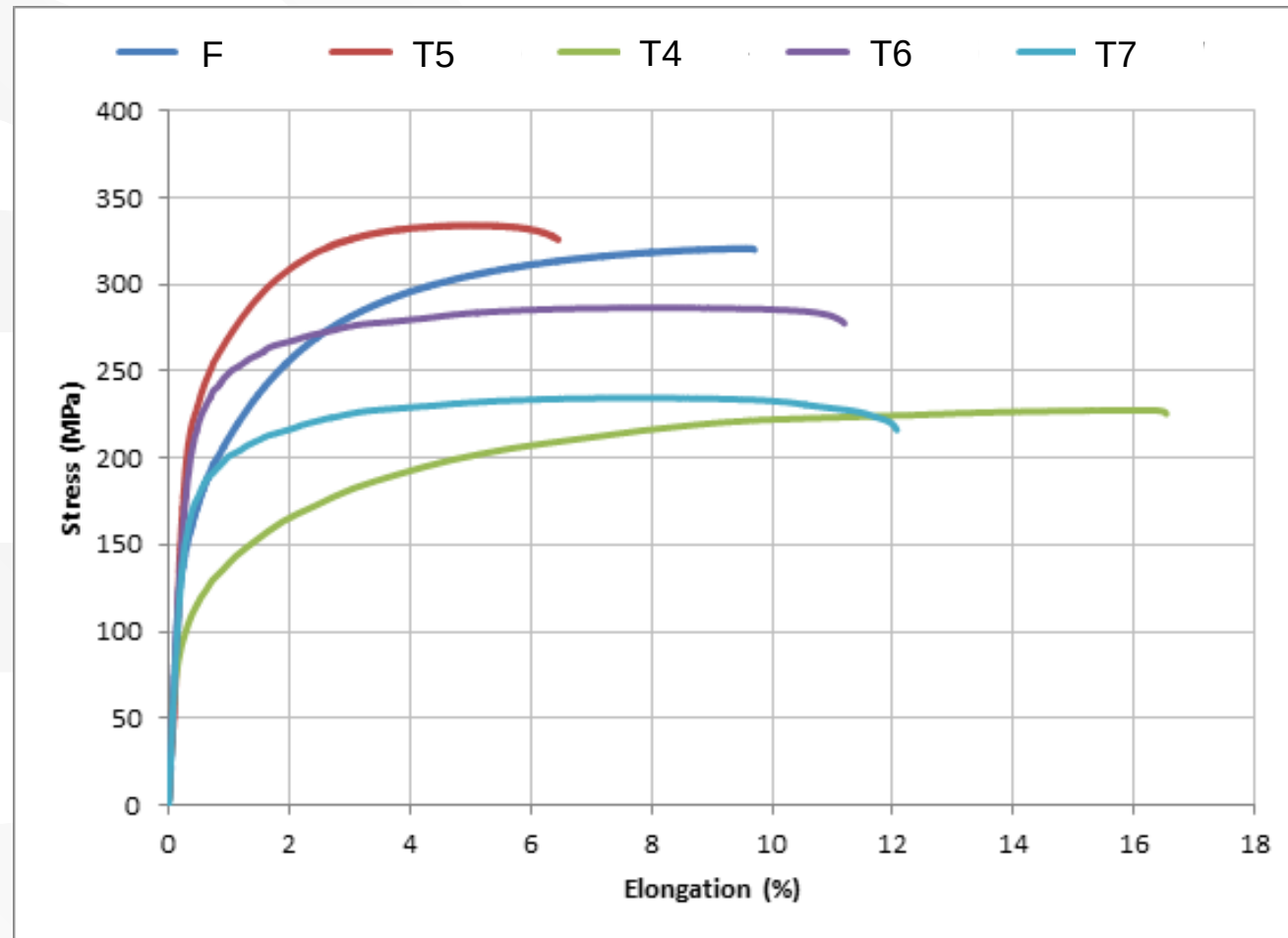
Stress-Engineering Strain Curves: A365.1-T7 (Low Mg)



Specimen	C1	C2	C3	C4	C5	C6	C7	C8	Average
UTS (Mpa)	205.9	205.1	209.6	208.3	213.9	206.2	213.7	208.2	208.9
YS (Mpa)	145.9	143.7	147.3	144.8	151.6	144.5	151.7	146.4	147.0
Total Elongation (%)	13.7	11.4	15.3	11.6	13.5	14.5	14.8	14.6	13.7

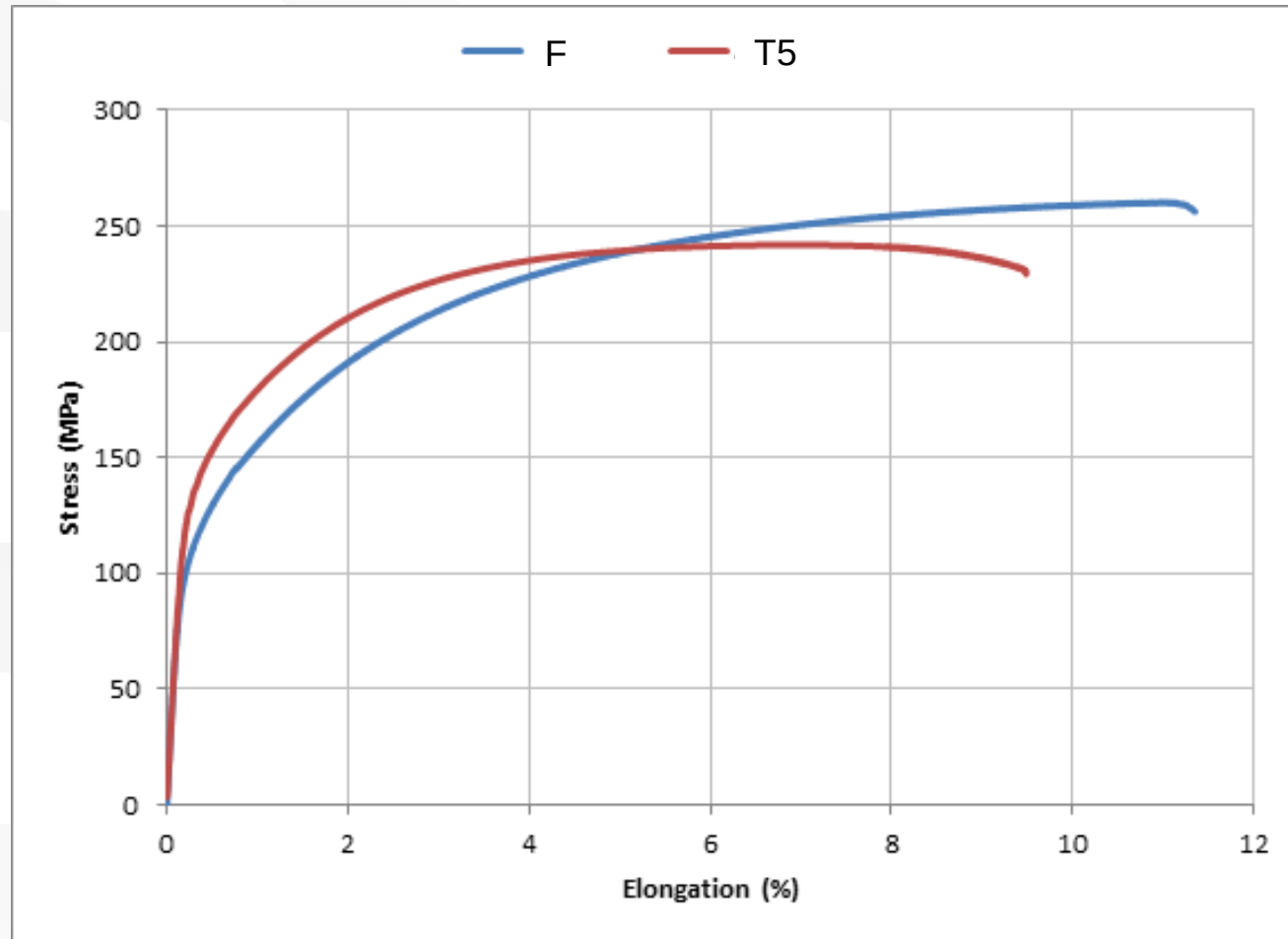
Source: Rio Tinto

Stress-Engineering Strain Curves: A365.1 (High Mg)



Source: Rio Tinto

Stress-Engineering Strain Curves: 374.1





Casting Alloys and Designation System



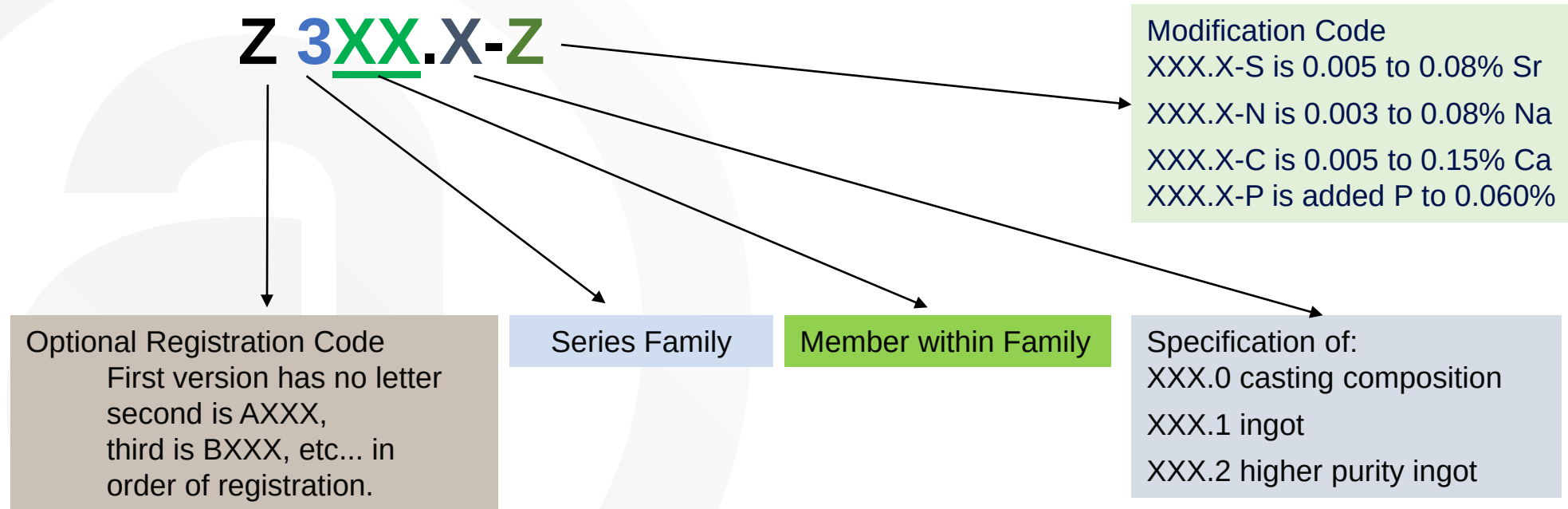
Casting Alloys

- Alloys are **tailored** to cover a wide range of **performance characteristics**
- Exceptional mechanical properties are obtained with
 - accurate control of **chemistry**
 - casting and **heat treatment** conditions
- The **four main families** of aluminium casting alloys
 - Al-Cu
 - Al-Si: vast **majority** because of its excellent **castability**
 - Al-Mg
 - Al-Zn
- Other than Al-Si alloys, casting properties are generally poor and high tendency to **hot tearing**

Casting Alloys Designation System (AA)

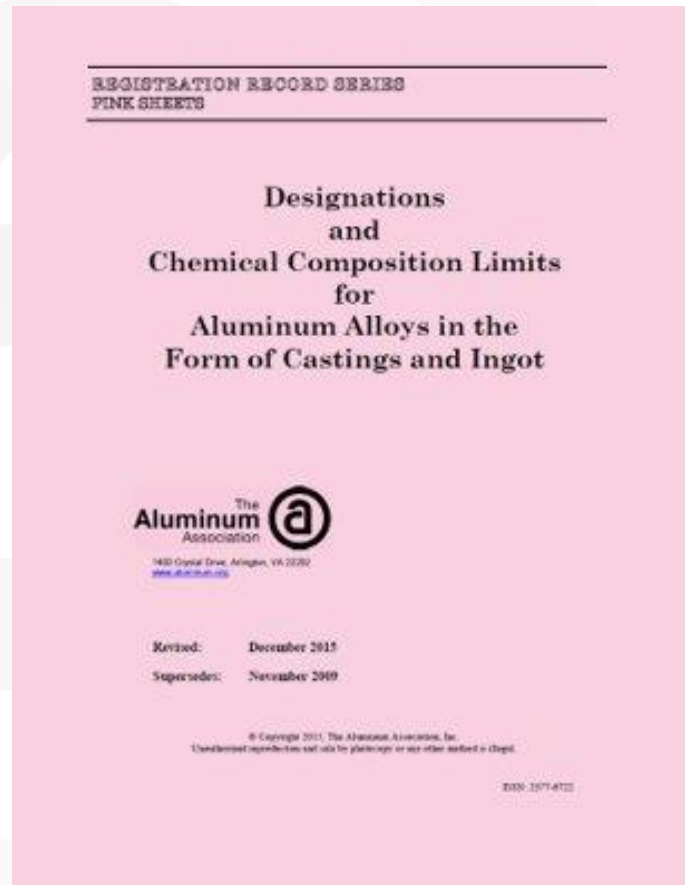
Series	Chemistry	End Uses
1XX.X	99% <u>Minimum</u> Aluminum	Low strength, high conductivity, e.g. rotor cages for electric motors, busbars, etc.
2XX.X	Al + Cu	Very high strength cast parts
3XX.X	Al + (Si + Mg, Si + Cu, Si + Mg +Cu)	Engine components, wheels, aerospace structural castings, almost anything
4XX.X	Al + Si	Intricate castings and non-heat treated parts, wheels (European)
5XX.X	Al + Mg	Castings required excellent surface finish and/or corrosion resistance. Marine applications, food preparation
7XX.X	Al + Zn +Mg	Naturally ageing alloys with excellent surface finish and high dimensional stability e.g. molds for blow-molding plastic bottles. Brazable
8XX.X	Al + Sn + Cu (+Si)	Bearings and bushings

Casting Alloys Designation System (AA)



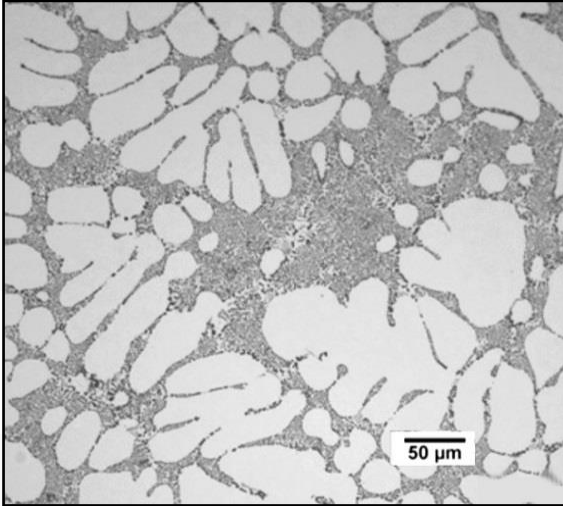
e.g.	Alloys	%Si	%Cu	%Mg	%Fe	
Secondary	356.0	6.5-7.5	<0.25	0.2-0.45	<0.60	Casting Ingot Higher Purity Ingot
	356.1	6.5-7.5	<0.25	0.25-0.45	<0.50	
	356.2	6.5-7.5	<0.10	0.3-0.45	0.13-0.25	

Casting Alloys Designation System (AA)

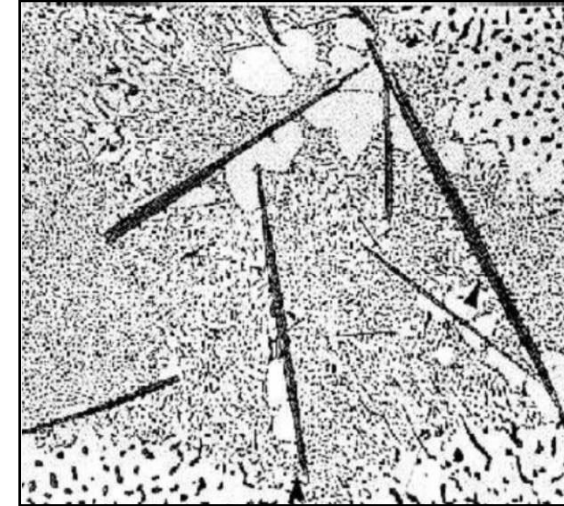


Primary and Secondary Alloys

- **Primary:** virgin Al + alloying elements added
- **Secondary:** recycled Al + alloying elements adjusted
- **Differentiation:** levels of impurities, especially Fe, and sometimes Ca
- Fe - forms FeSiAl5 needles - lowers ductility severely (Mn addition?, stay <0.20%)
 - + increases fluidity
 - + counteracts soldering (stickiness) in die casting
 - - decreases ductility in structural casting
- Ca - reduces surface tension of hydrogen bubbles, metal appears “gassier”, stay <20ppm



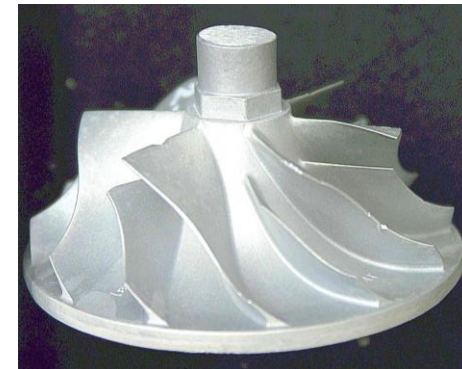
Typical hypoeutectic AlSi7Mg (A356) Microstructure
Al dendrites surrounded by Al and Si eutectic



FeSiAl5 needles in a 1% Fe-containing permanent
mold cast Al Si12

Al-Cu Casting Alloys

- Outstanding mechanical properties
- Strength and toughness at room and elevated temperatures
- Aerospace, some applications in automotive for highly loaded parts where the limited corrosion resistance is no obstacle (heavy-duty pistons, high-end turbocharger impellers, etc.)
- Suitable for sand and gravity die casting
- Good fluidity, but only fair resistance to hot cracking and solidification shrinkage. Can be difficult to cast in complex shapes



Al-Si Casting Alloys

- Most of the **commercial foundry alloys**
- Excellent castability, resist hot tearing, good machinability
- Mg addition results in good mechanical properties after heat treatment
- Cu addition enhances machinability and increases strength at temperature
- **Al-Si wheels, structural castings, suspension parts:** high strength and ductility
- **Al-Si-Cu(-Mg)** for **power train components** where strength at temperature and/or wear resistance is more important than ductility

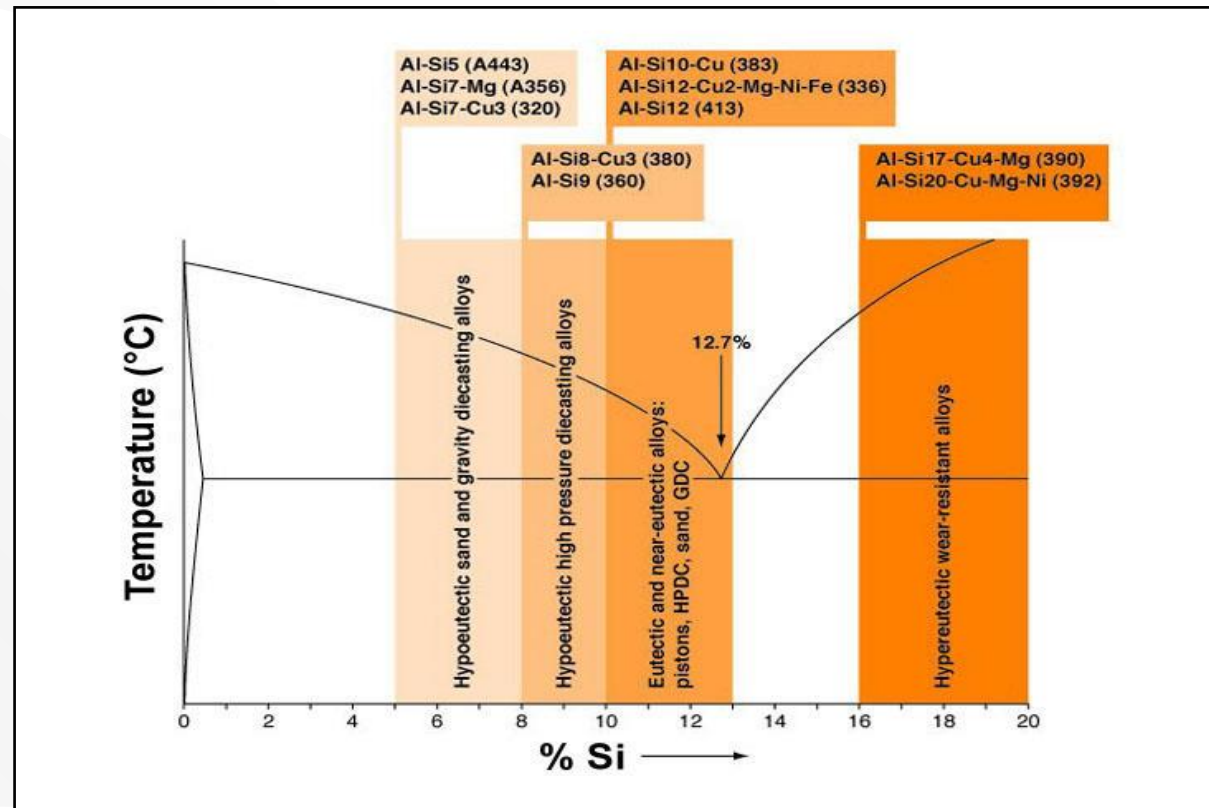


Source Honda



Source GMC

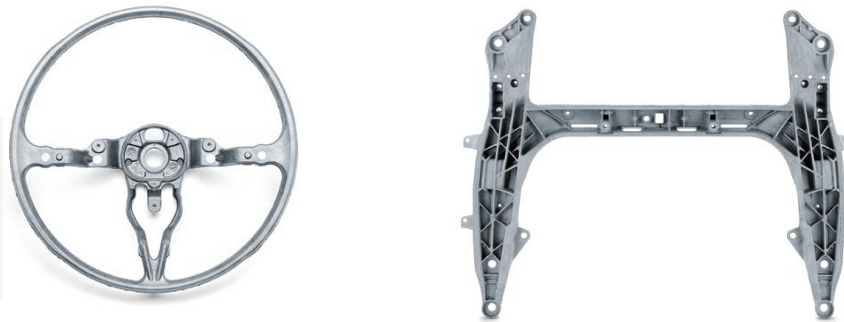
Al-Si Casting Alloys



- Hypoeutectic alloys (<10% Si) are composed of a forest of aluminium dendrites surrounded by an interdendritic Al-Si eutectic (1:1 ratio depending on alloy)
- Eutectic or near eutectic alloys (10% <Si <13%) may consist almost entirely of eutectic
- Hypereutectic alloys (>13% Si) consist of a eutectic matrix together with wear resistant primary silicon particles

Al-Mg Casting Alloys

- **High corrosion resistance**, can be polished to a **high gloss anodised**
- **Good strength/ductility** compromise, impact toughness **without heat treatment**
- Suited for HPDC of **structural automotive components**
- Require a **high-quality casting technique**
- Al-Mg(-Si) family are more **aggressive to the die and more difficult to cast** than the alloys of the Al-Si(-Mg) family
- **Mg fading** must be managed (beryllium typical but HSE issue)

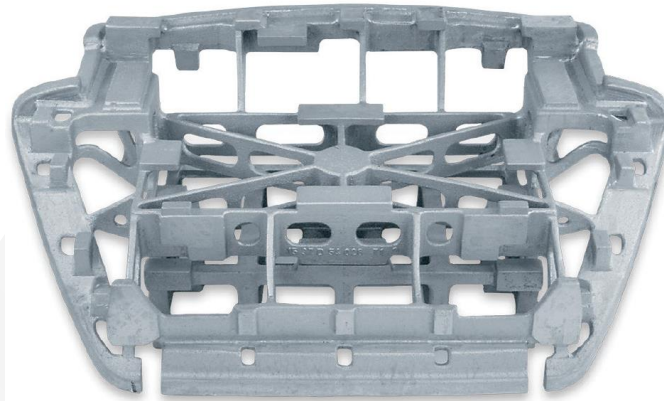


Steering wheel (left), cross member (right)

Source: Aluminium Rheinfelden

Al-Zn Casting Alloys

- Al-Zn (+Mg) alloys offer **good castability** (fluidity, solidification, shrinkage)
- Limited shaping properties (limited resistance to hot cracking)
- **Sand castings for large parts** requiring high strength **without heat treatment**
- **Good strength and ductility**, especially in **LP gravity die casting**
- **Good machinability and weldability**



Door sheet metal template (sand casting as finished component)

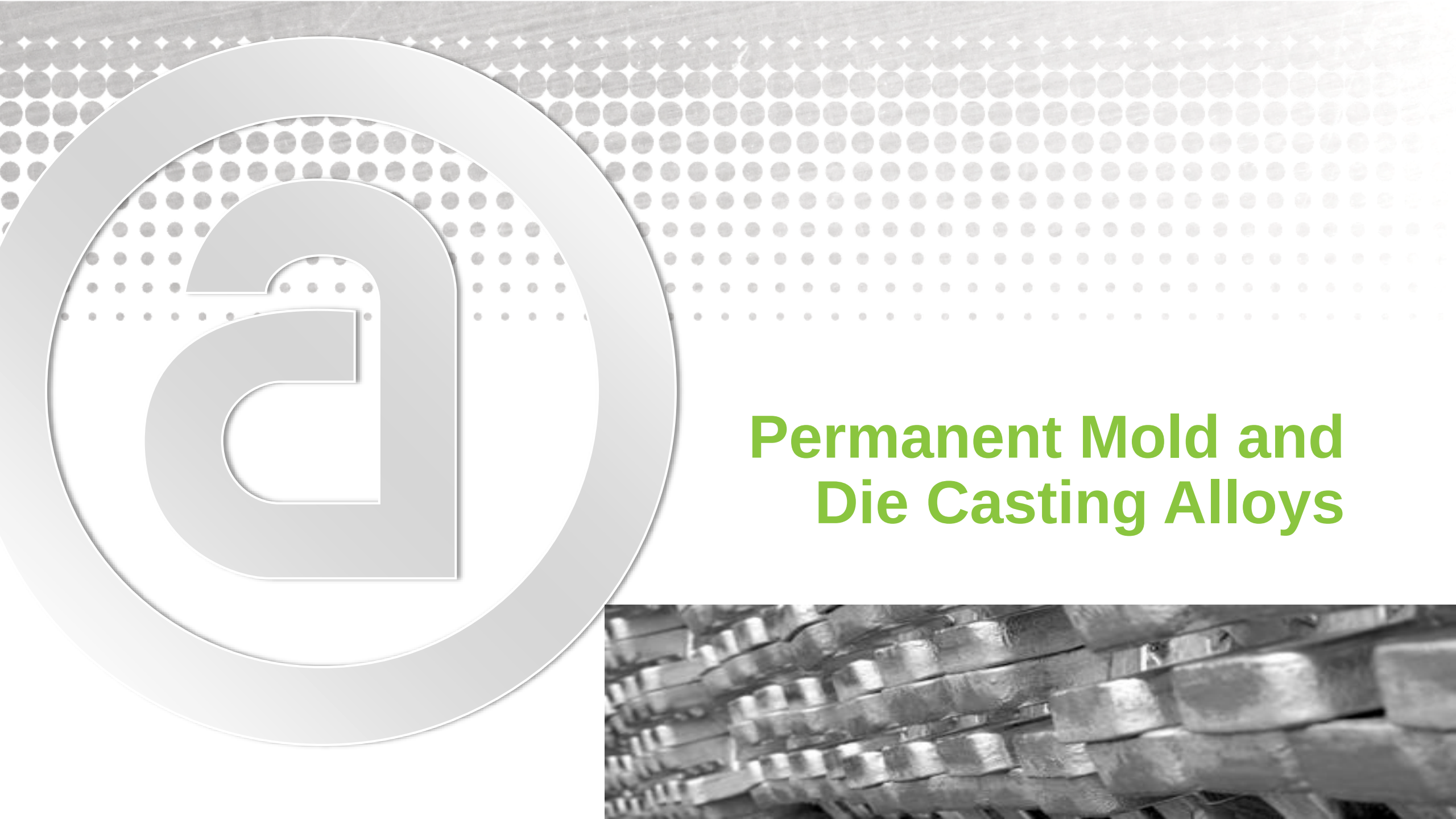
Source: Aluminium Rheinfelden

Al-Metal Matrix Composites Casting Alloys

- Al-MMC consist of non-metallic reinforcements uniformly distributed in an aluminium matrix
- Reinforcements can be **ceramic particles** (mainly SiC)
- **High stiffness and wear resistance** than the base aluminium alloys
- Suitable for **sand, permanent mold casting and die casting**
- ANSI specifies that Al-MMCs are identified as: matrix/reinforcement/volume%/form, i.e. an AA 356 aluminium alloy reinforced with 20% SiC particulate is designated as 356/SiC/20p



Cast brake drum and rotor using AA 359/SiC/20p
Source: Rio Tinto

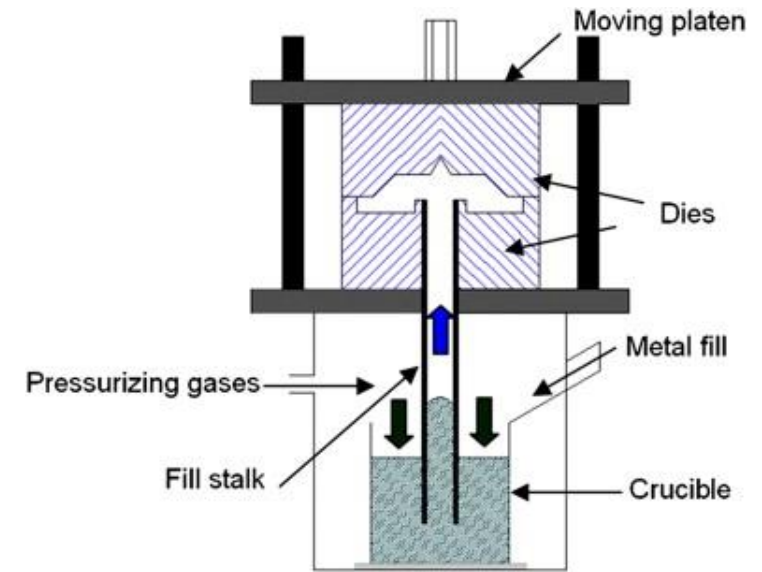


Permanent Mold and Die Casting Alloys

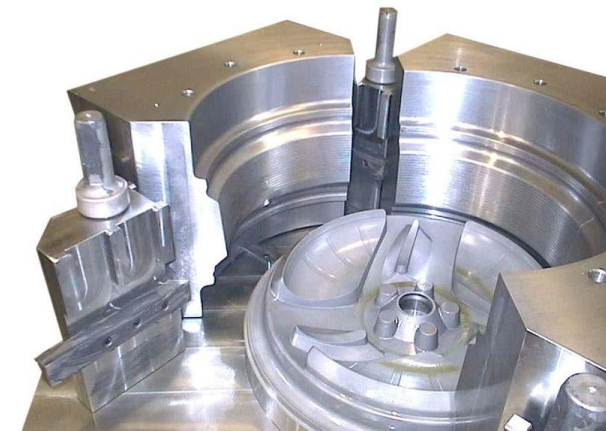


Permanent Mold and Die Casting Alloys

A \ B	Gravity Casting	Low Pressure Casting	High Pressure Casting
Permanent Mold	4	10 5	6 7 8 9
Core Package	3		
Green Sand Regular Sand	12 1	2	
Lost-Foam	11		X Widely used in automotive casting Y Slightly used in automotive casting



Gravity casting (tilt pour)



Low pressure (wheel)

Some AA 3XX Primary Foundry Alloys

	Alloy	Si	Fe	Cu	Mn	Mg	Ti	Zn	Others	
									Each	Total
	A356.0	6.5-7.5	0.20	0.20	0.10	0.25-0.45	0.20	0.10	0.05	0.15
	A356.1	6.5-7.5	0.15	0.20	0.10	0.30-0.45	0.20	0.10	0.05	0.15
→	A356.2	6.5-7.5	0.12	0.10	0.05	0.30-0.45	0.20	0.05	0.05	0.15
	B356.0	6.5-7.5	0.09	0.05	0.05	0.25-0.45	0.04-0.20	0.05	0.05	0.15
→	B356.2	6.5-7.5	0.06	0.03	0.03	0.30-0.45	0.04-0.20	0.03	0.03	0.10
	C356.0	6.5-7.5	0.07	0.05	0.05	0.25-0.45	0.04-0.20	0.05	0.05	0.15
→	C356.2	6.5-7.5	0.04	0.03	0.03	0.30-0.45	0.04-0.20	0.03	0.03	0.10
	F356.0	6.5-7.5	0.20	0.20	0.20	0.17-0.25	0.04-0.20	0.10	0.05	0.15
→	F356.2	6.5-7.5	0.12	0.10	0.10	0.17-0.25	0.04-0.20	0.05	0.05	0.10
	354.0	8.6-9.4	0.20	1.6-2.0	0.10	0.40-0.6	0.20	0.10	0.05	0.15
	354.1	8.6-9.4	0.15	1.6-2.0	0.10	0.45-0.6	0.20	0.10	0.05	0.15
	354.2	8.6-9.4	0.06	1.6-2.0	0.10	0.45-0.6	0.20	0.10	0.05	0.15
	A355.0	4.5-5.5	0.09	1.0-1.5	0.05	0.45-0.6	0.04-0.20	0.05	0.05	0.15
	A355.2	4.5-5.5	0.06	1.0-1.5	0.03	0.50-0.6	0.04-0.20	0.03	0.03	0.10
	C355.0	4.5-5.5	0.20	1.0-1.5	0.10	0.40-0.6	0.20	0.10	0.05	0.15
	C355.1	4.5-5.5	0.15	1.0-1.5	0.10	0.45-0.6	0.20	0.10	0.05	0.15
	C355.2	4.5-5.5	0.13	1.0-1.5	0.05	0.50-0.6	0.20	0.05	0.05	0.15

Al-Si-Mg Family (356 Type)

- The **356 alloy family** covers a wide range of compositions
- **A356** is the workhorse for structural applications. Used where moderate to high strength and ductility are required
- **356**, a low-cost, frequently recycled alloy for non-critical applications
- **B356 and C356**, high purity alloys (0.06%, 0.04% Fe), maximum ductility
- **F356**, reduced Mg level, for energy absorbing or crashworthy applications where the highest ductility is required allowing the part to bend, deform, and absorb energy with less regard for strength

	Si	Mg	Fe	Cu	Ti
→ A356.2	6.5-7.5	0.30-0.45	<0.12	<0.10	<0.20
A356.1	6.5-7.5	0.30-0.45	<0.15	<0.20	<0.20
A356.0	6.5-7.5	0.25-0.45	<0.20	<0.20	<0.20
→ 356.2	6.5-7.5	0.30-0.45	0.13-0.25	<0.10	0.20
356.1	6.5-7.5	0.25-0.45	<0.5	<0.25	0.25
356.0	6.5-7.5	0.20-0.45	<0.6	<0.25	0.25

Source: Rio Tinto

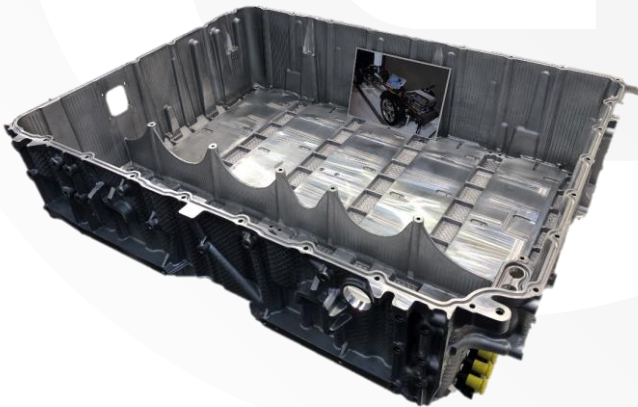
Al-Si-Mg Family (A356.2 & 357 Type)

Advantages:

- High strength and ductility - structural components
- Largely immune to hot tearing/cracking
- Large database on mechanical performance
- Good corrosion resistance
- Good fatigue properties

Considerations:

- Must be heat-treated to achieve strength and hardness - \$
- Cost is higher - primary A356



Source: Kurtz – Produced for VW, Samsung SDI – EV
Low pressure die casting, A356.2



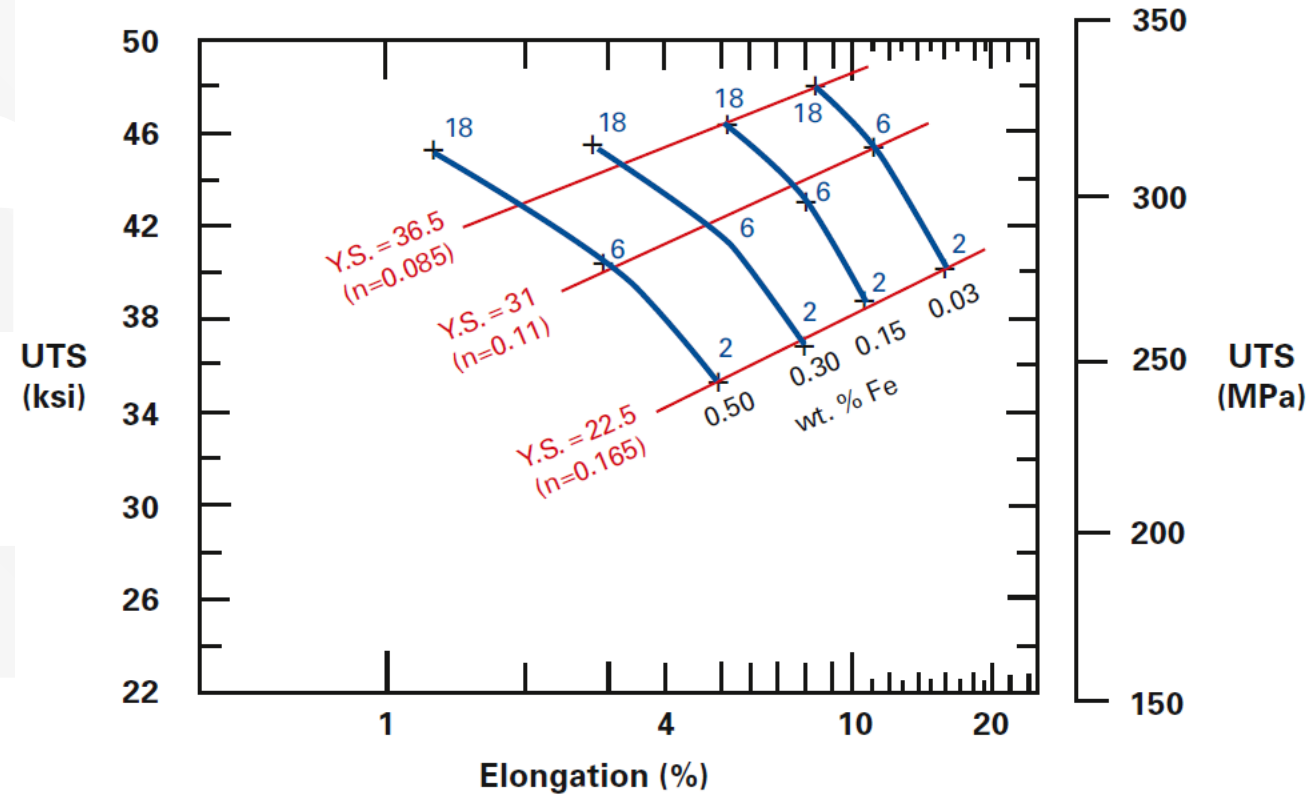
Knuckle
Source: StJean Industries

Foundry alloys	Corrosion resistance
206.2	4
A206.2	4
B206.2	4
242.2	4
A242.2	4
319.2	3
354.2	3
355.2	3
C355.2	3
356.2	2
A356.2	2
357.1	2
F357.1	2
F357.2	2

Ratings:
2 = very good
3 = good
4 = fair

Source: Rio Tinto

Effect of Fe on Mechanical Properties for A356.2



- Three YS refers to three aging: 2, 6 and 18 hours at 310 F (155 C)
- In each case the E% is reduced as the Fe level raised, tensile also suffers

[From Geoff Sigworth, "Quality Issues in Aluminum Net-Shape Castings", AFS Paper No. 04-075(2), Unpublished Work by Ken Whaler, Stahl Specialty]

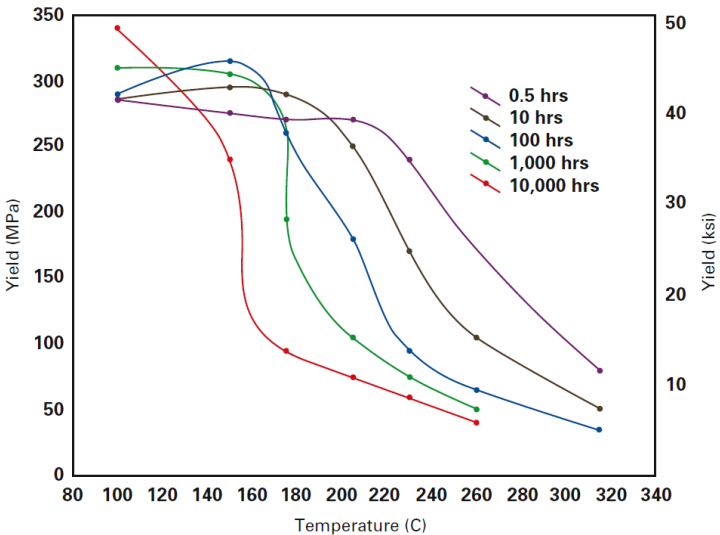
High Strength 354 Alloy

→

Alloy	Si	Fe	Cu	Mn	Mg	Ti	Zn	Others	
								Each	Total
354.0	8.6-9.4	0.20	1.6-2.0	0.10	0.40-0.6	0.20	0.10	0.05	0.15
354.1	8.6-9.4	0.15	1.6-2.0	0.10	0.45-0.6	0.20	0.10	0.05	0.15
354.2	8.6-9.4	0.06	1.6-2.0	0.10	0.45-0.6	0.20	0.10	0.05	0.15

- 354 is a **high strength, heat treatable alloy trade off ductility for strength**
- Shows higher elevated temperature strength than 356/357 due to Cu
- Cu somewhat reduces the **corrosion** resistance

Typical mechanical properties								
Temper	Casting method	Tension			Compressive yield strength ¹ MPa (ksi)	Shear strength MPa (ksi)	Hardness ² Brinell No.	Fatigue strength ³ MPa (ksi)
		Ultimate strength MPa (ksi)	Yield strength 0.20% offset MPa (ksi)	Elongation at break % in 2 in. (50mm)				
T61 (at room temperature)	PM	380 (55)	285 (41)	6.0	227 (33)	-	-	145 (21)



Source: Rio Tinto

Medium Strength 355 Alloy

	Alloy	Si	Fe	Cu	Mn	Mg	Ti	Zn	Others	
									Each	Total
→	A355.0	4.5-5.5	0.09	1.0-1.5	0.05	0.45-0.6	0.04-0.20	0.05	0.05	0.15
	A355.2	4.5-5.5	0.06	1.0-1.5	0.03	0.50-0.6	0.04-0.20	0.03	0.03	0.10
	C355.0	4.5-5.5	0.20	1.0-1.5	0.10	0.40-0.6	0.20	0.10	0.05	0.15
	C355.1	4.5-5.5	0.15	1.0-1.5	0.10	0.45-0.6	0.20	0.10	0.05	0.15
→	C355.2	4.5-5.5	0.13	1.0-1.5	0.05	0.50-0.6	0.20	0.05	0.05	0.15

Used in large variety of products in **PM** and **sand castings structural components** and other highly stressed castings

C355.2 is a modification of 355.2 for **higher elongation and tensile strengths** than 355.0

Typical mechanical properties				
Temper	Casting method	Tension		
		Ultimate strength MPa (ksi)	Yield strength 0.20% offset MPa (ksi)	Elongation at break % in 2 in. (50mm)
T51	Sand	195 (28)	160 (23)	1.5
	PM	205 (30)	165 (24)	2.0
T6	Sand	240 (35)	170 (25)	3.0
	PM	290 (42)	185 (27)	4.0
T61	Sand	270 (39)	240 (35)	1.0
T62	PM	310 (45)	275 (40)	1.5
T7	Sand	260 (38)	250 (36)	0.5
	PM	275 (40)	205 (30)	2.0
T71	Sand	240 (35)	200 (29)	1.5
	PM	250 (36)	215 (31)	3.0

¹Test results from specimens with an L/r ratio of 12.

²Tensile properties and hardness values determined by tests on standard 0.50 in. (12.5mm) diameter test specimens without surface finishing; each cast in permanent or green sand molds.

³Endurance limit is based on 500 million cycles of completely reversed stresses using a rotating beam-type machine and specimen, unless otherwise specified.

Typical mechanical properties				
Temper	Casting method	Tension		
		Ultimate strength MPa (ksi)	Yield strength 0.20% offset MPa (ksi)	Elongation at break % in 2 in. (50mm)
T6	Sand	270 (39)	200 (29)	5.0
	PM	330 (48)	195 (28)	8.0
T61	PM	315 (46)	235 (34)	6.0
T62	PM	330 (48)	255 (37)	5.0

Source: Rio Tinto

High Strength-Fracture Toughness 357 Alloy

	Alloy	Si	Fe	Cu	Mn	Mg	Ti	Be	Others	
									Each	Total
→	357.0	6.5-7.5	.15	.05	0.03	0.45-0.6	0.20	-	0.05	0.15
	357.1	6.5-7.5	.12	.05	0.03	0.45-0.6	0.20	-	0.05	0.15
	A357.0	6.5-7.5	.20	.20	0.10	0.40-0.7	0.04-0.20	0.04 - 0.07	0.05	0.15
	A357.1	6.5-7.5	.12	.10	0.05	0.45-0.7	0.04-0.20	0.04 - 0.07	0.03	0.10
→	B357.0	6.5-7.5	.09	.05	0.05	0.40-0.6	0.04-0.20	-	0.05	0.15
	B357.2	6.5-7.5	.06	.03	0.03	0.45-0.6	0.04-0.20	-	0.03	0.10
	C357.0	6.5-7.5	.09	0.05	0.05	0.45-0.7	0.04-0.20	0.04 - 0.07	0.05	0.15
	C357.2	6.5-7.5	.06	0.03	0.03	0.50-0.7	0.04-0.20	0.04 - 0.07	0.03	0.10
	D357.0	6.5-7.5	0.20	-	0.10	0.55-0.6	0.10-0.20	0.04 - 0.07	0.05	0.15
	E357.0	6.5-7.5	0.10	-	0.10	0.55-0.6	0.10-0.20	0.002	0.05	0.15
	E357.1	6.5-7.5	0.07	-	0.10	0.6-0.7	0.10-0.20	0.002	0.05	0.15
	E357.2	6.5-7.5	0.07	-	0.10	0.6-0.7	0.10-0.20	0.0003	0.05	0.15
	F357.0	6.5-7.5	0.10	.20	0.10	0.40-0.7	0.04-0.20	0.002	0.05	0.15
	F357.1	6.5-7.5	0.07	.20	0.10	0.45-0.7	0.04-0.20	0.002	0.05	0.15
→	F357.2	6.5-7.5	0.07	.20	0.10	0.45-0.7	0.04-0.20	0.0003	0.05	0.15

- **Heat treatable and weldable**
- **6 variants:** i.e. **B357.2** is a low Fe: when higher ductility fracture toughness is critical
- **Non-Beryllium** containing variants to this family

Source: Rio Tinto

357 Fe Impact on Mechanical Properties

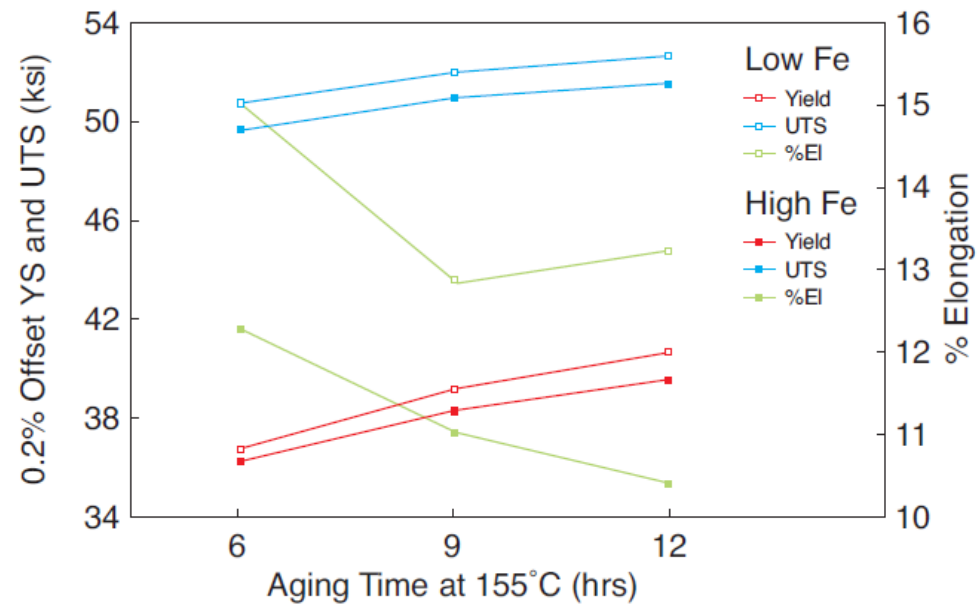
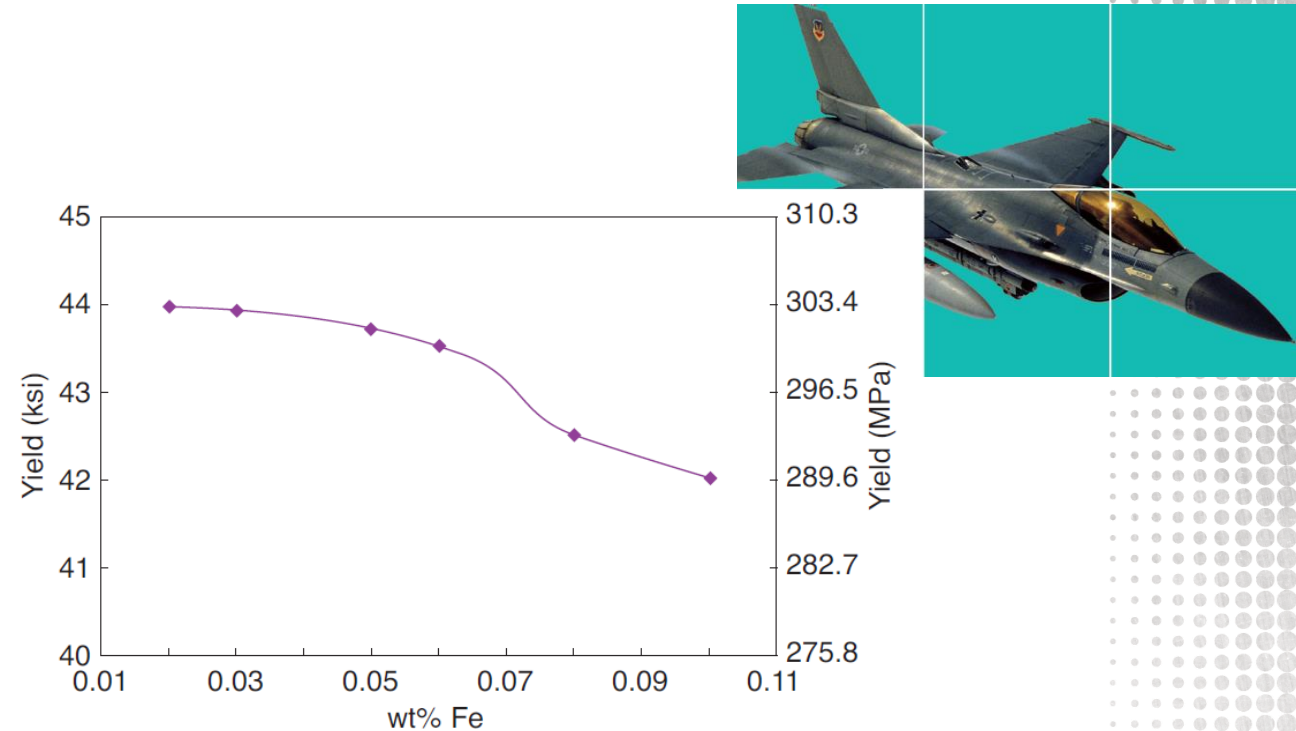


Figure 1. The above plot shows the difference in mechanical performance that one sees as a function of Fe level in a B356.0-T61 alloy compared to 357.0-T61. The lower Fe level gives markedly higher ductility. In this case the Fe levels were 0.055 and 0.093% respectively. Note that the T61 temper gives more ductility for applications in which fracture toughness is considered more important than just the strength.



Source: Rio Tinto

Some AA 3XX Secondary Foundry Alloys

Alloy	Si	Fe	Cu	Mn	Mg	Ti	Zn	Others	
								Each	Total
A319.0	5.5 - 6.5	1.0	3.0 - 4.0	0.50	0.10	0.25	3.0	---	0.50
A319.1	5.5 - 6.5	0.8	3.0 - 4.0	0.50	0.10	0.25	3.0	---	0.50
B319.0	5.5 - 6.5	1.2	3.0 - 4.0	0.80	0.10 - 0.50	0.25	1.0	---	0.50
B319.1	5.5 - 6.5	0.9	3.0 - 4.0	0.80	0.15 - 0.50	0.25	1.0	---	0.50
A380.0	7.5 - 9.5	1.3	3.0 - 4.0	0.50	0.10	---	3.0	---	0.50
A380.1	7.5 - 9.5	1.0	3.0 - 4.0	0.50	0.10	---	2.9	---	0.50
→ A380.2	7.5 - 9.5	0.6	3.0 - 4.0	0.10	0.10	---	0.10	0.05	0.15
383.0	9.5 - 11.5	1.3	2.0 - 3.0	0.50	0.10	---	3.0	---	0.50
383.1	9.5 - 11.5	1.0	2.0 - 3.0	0.50	0.10	---	2.9	---	0.50
→ 383.2	9.5 - 11.5	0.6 - 1.0	2.0 - 3.0	0.10	0.10	---	0.10	---	0.20
A390.0	16.0 - 18.0	0.50	4.0 - 5.0	0.10	0.45 - 0.65	0.20	0.10	0.10	0.20
→ A390.1	16.0 - 18.0	0.40	4.0 - 5.0	0.10	0.50 - 0.65	0.20	0.10	0.10	0.20

All three ranges of the Al-Si Phase diagram are covered by these alloys.
 Just like the Primary Alloys there are more restrictive alloys within a family.
 Fe and “Others” limits are higher than Primary Alloys.

- This allows the alloys to be more “Recycle Friendly.”

Source: Real Alloy

Al-Si-Cu Family (319 Type)

The **319 alloy family** is a hypoeutectic composition.

- 319 is used in many automotive applications where good casting characteristics, pressure tightness, and moderate strength are required.
- 319 can be heat treated to increase strength.
- The higher Fe and other alloying elements limit elongation.
- Typically used in sand castings and permanent mold castings.

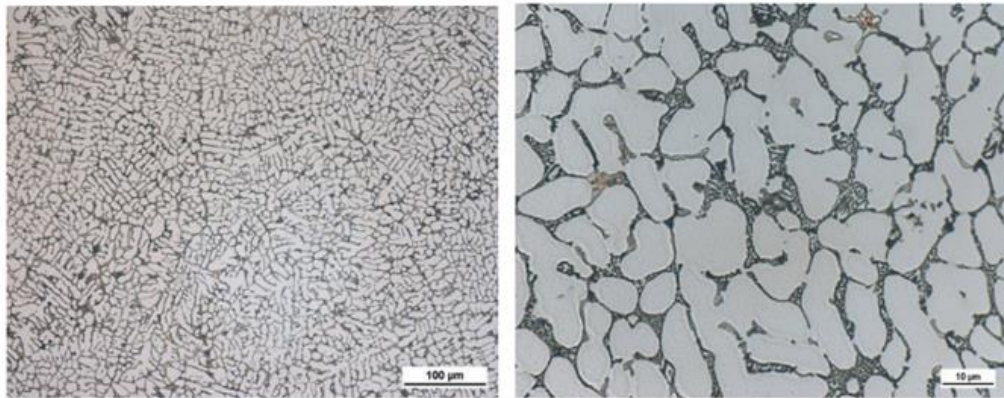
	Tensile (Mpa)	Elongation (%)	Hardness (HB)	Fatigue (Mpa)
Sand Cast				
As-Cast	185	2.0	70	70
T6	250	2.0	80	75
Permanent Mold				
As-Cast	235	2.5	85	70
T6	280	3.0	95	---

Source: Real Alloy

Al-Si-Cu Family (319 Type)

319 alloy is Recycle Friendly alloy that can be used in many permanent mold and sand-casting applications.

- Classic hypoeutectic dendritic structure.



a) mag. 250× etch. 0.5 % HF b) mag. 1600× etch. 0.5 % HF

Fig. 3. Micrographs showing the microstructure of as-cast 319 alloy (0.0038 wt. % Sb)

Source: D. Medlen and D. Bolibruchova, Arch. Metall. Mater., Vol 61 (2016), No. 2, p,553-558.



Source: Leitel Brothers Foundry

Source: Real Alloy

Al-Si-Cu-Zn Family (380 and 383 Type)

The **380 alloy family** is a near-eutectic composition while the **383 alloy family** is a eutectic composition.

- 380 is the most commonly used alloy in High Pressure Die Casting.
- Both alloys have high fluidity which allows formation of complex shapes.
- Neither alloy is heat treatable.
- 380 and 383 die castings are used in many general-purpose automotive applications: housings, covers, and cylinder heads.
- Both alloys are usually cost-efficient options.
- Alloys will have limited elongation due to high alloying.
- Increasing Fe will lower ductility.

Alloy	Tensile (Mpa)	Elongation (%)
A380.0	325	4.0
383.0	310	3.5



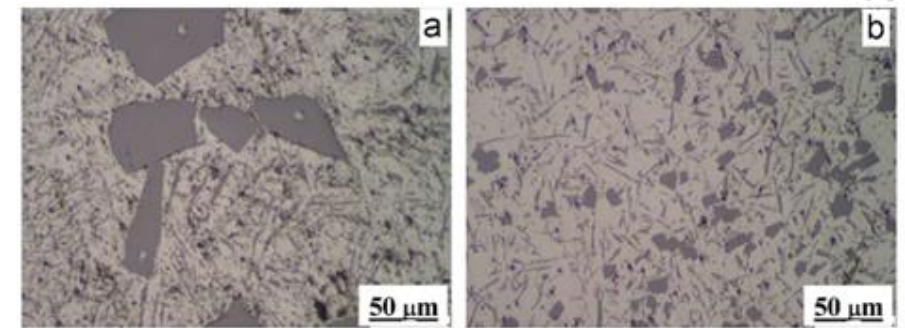
Source: Real Alloy

Al-Si-Cu-Mg Family (390 Type)

The **390 alloy family** is a hypereutectic composition.

- The high Si content leads to the formation of Si platelet like particles.
 - Typically, the alloy is modified with P to reduce Si particle size.
- 319 is used in automotive applications where good wear resistance characteristics are required.
 - Compressors, pumps, and pistons
- Can be heat treated.
- Can be used in sand castings, permanent mold castings, and die castings.

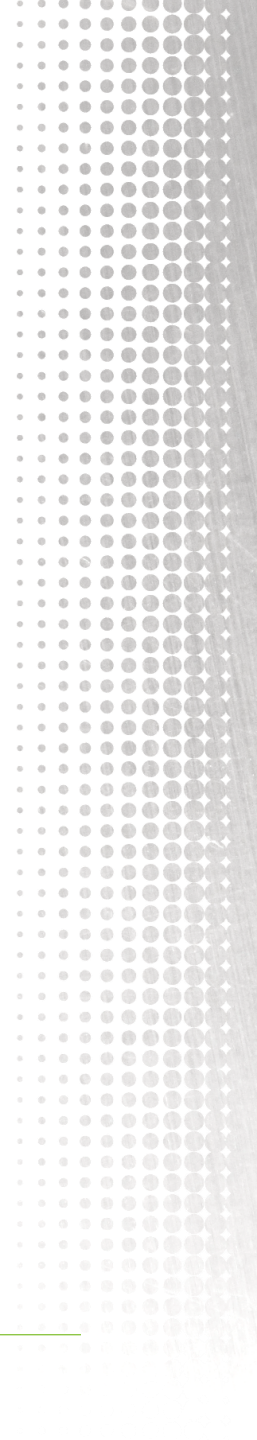
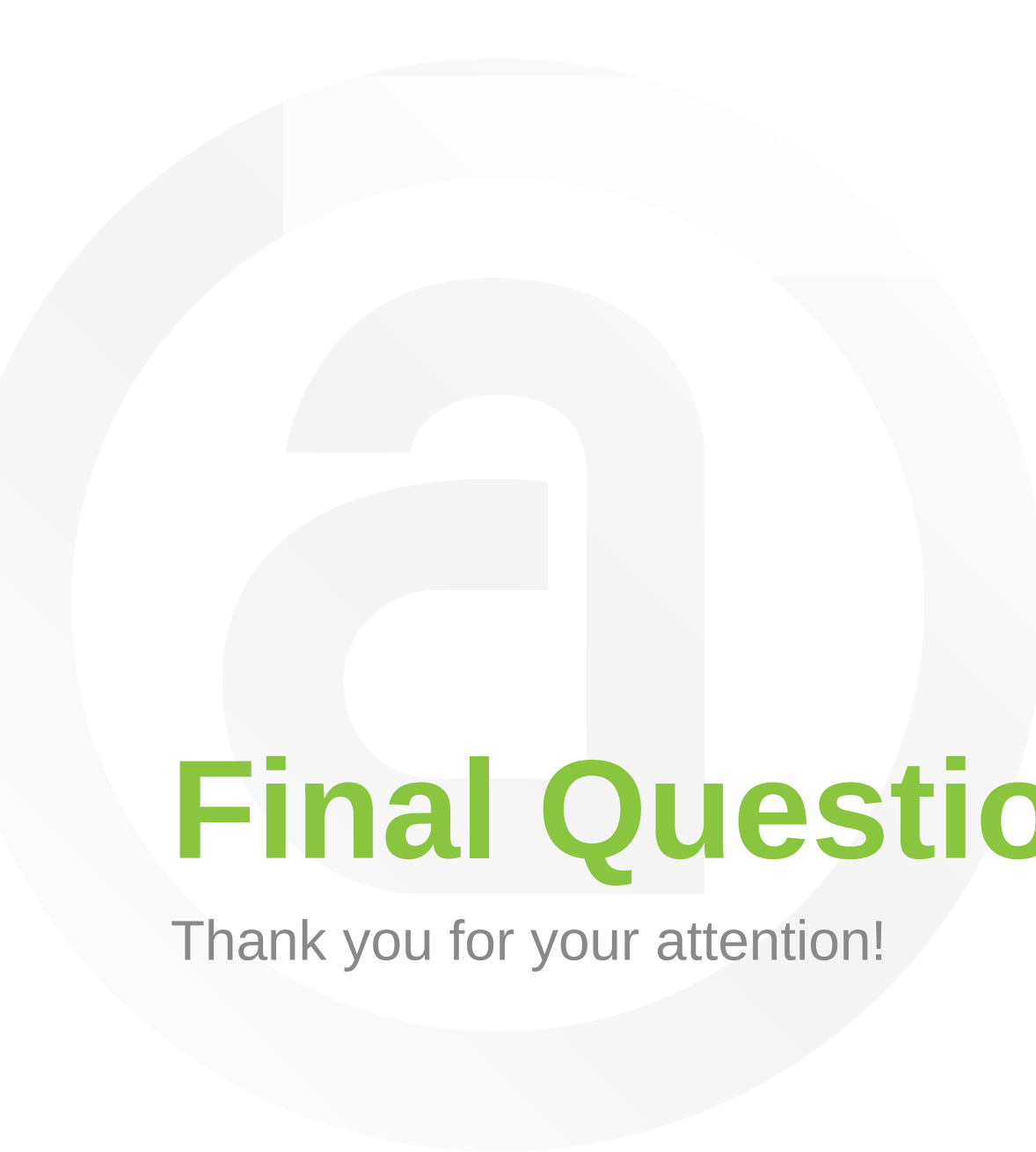
Alloy & Temper	Tensile (Mpa)	Yield (Mpa)	Hardness (HB)
A390.0 Sand Cast			
F, T5	180	180	100
T6	275	275	140
T7	250	250	115



Unmodified Al-Si18

Al-Si18 modified w/P

Source: Real Alloy



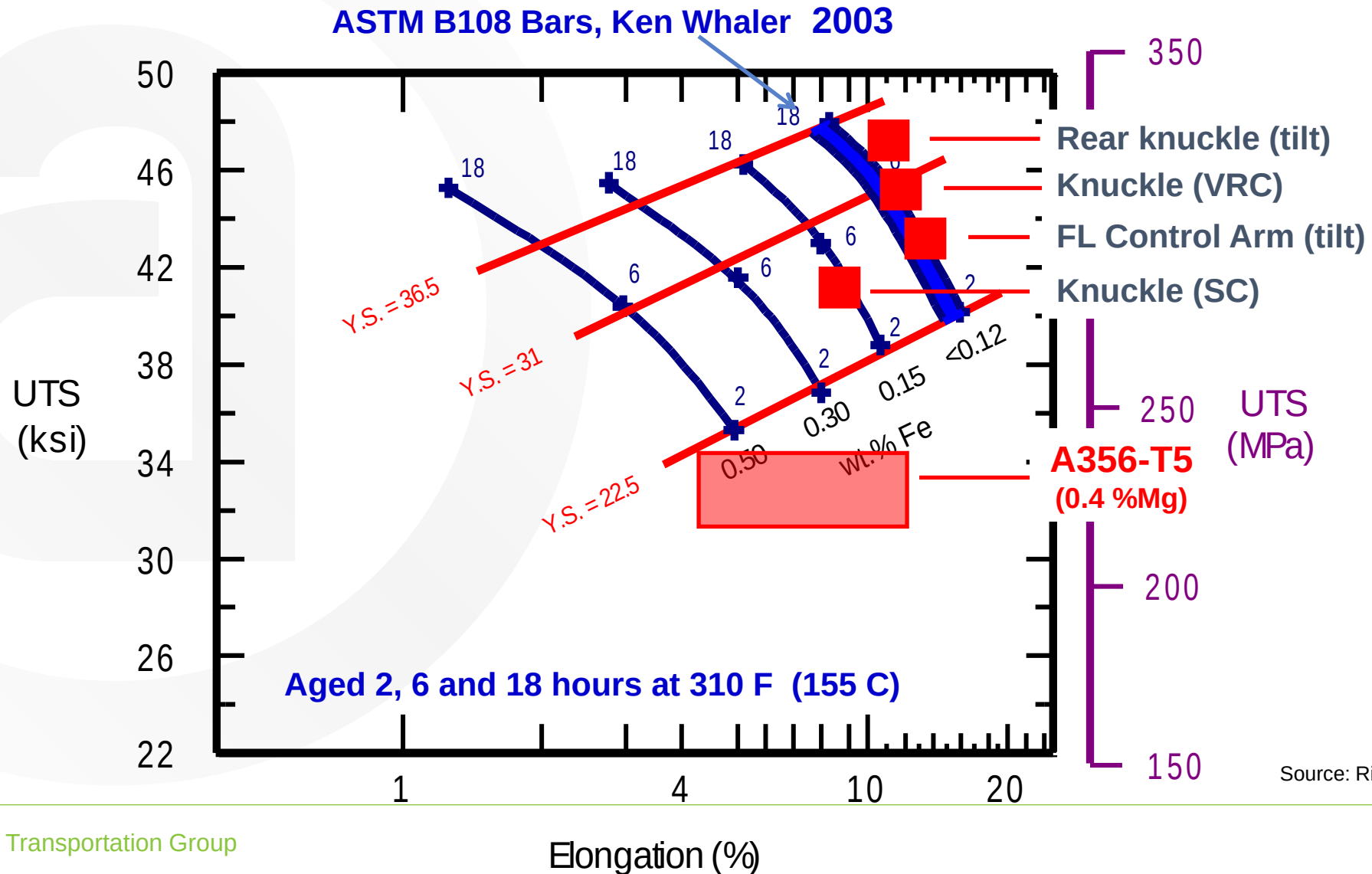
Final Questions?

Thank you for your attention!



Appendix

Effect of Fe on Mechanical Properties for A356.2



Source: Rio Tinto

High Purity B356.2 Compared to A356 and 356

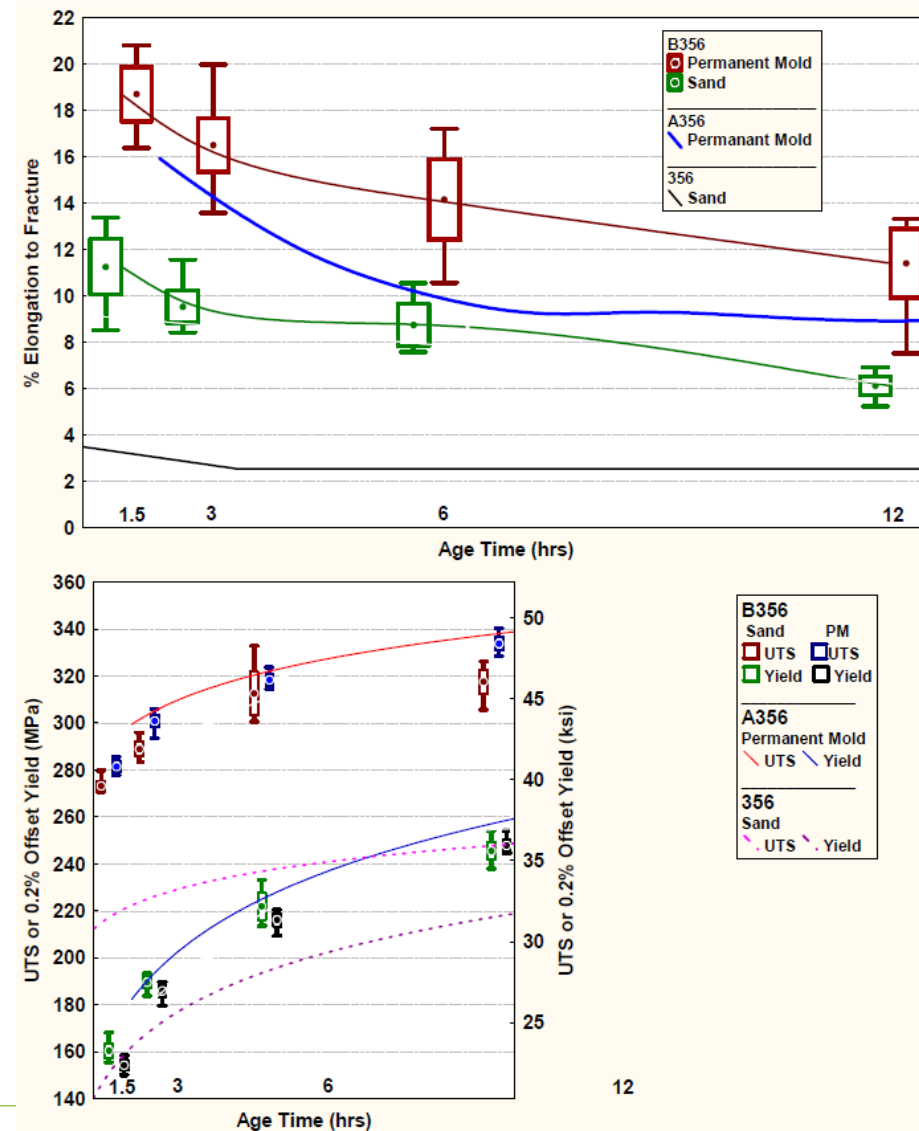
High-purity B356.2 (0.06% Fe max) frequently the alloy of choice in **demanding applications** (high ductility for a given level of strength required)

Premium quality sand casting techniques, B356.2 has one of the **lowest sensitivities to low cooling rates** of any member of the 356 family.

Use in applications where the **volumes** involved may not justify the higher tooling costs associated with PM casting

Properties at 6 Hours Ageing Time
Ranked by Ductility

Alloy	Process	Yield (MPa/ksi)	UTS (MPa/ksi)	% Elongation
B356-T6	PM	216 / 31.3	318 / 46.2	14.2
A356-T6	PM	227 / 32.9	324 / 47.0	9.7
B356-T6	Sand	222 / 32.2	312 / 45.3	8.7
356-T6	Sand	203 / 29.5	241 / 35.0	2.5



359 Alloy – PM Application

Ingot composition limits*										
Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Other	
									Each	Total
8.5–9.5	0.12	0.10	0.10	0.55–0.7	-	-	0.10	0.20	0.05	0.15

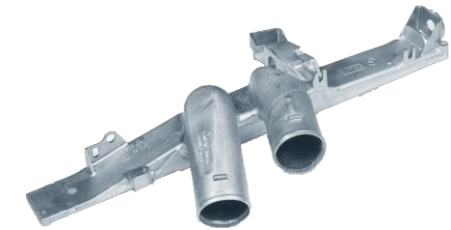
Typical mechanical properties								
Temper	Casting method	Tension			Compressive yield strength ¹ MPa (ksi)	Shear strength MPa (ksi)	Hardness ² Brinell No.	Fatigue strength ³ MPa (ksi)
		Ultimate strength MPa (ksi)	Yield strength 0.20% offset MPa (ksi)	Elongation at break % in 2 in. (50mm)				
T62	Sand & PM	360 (52)	290 (42)	8.0	-	-	-	115 (17)

Alloy A359.2 is a **moderately high strength permanent mold** casting alloy frequently used when **higher fluidity than 356/357** is required for use in a **structural part**

Source: Rio Tinto

413 Eutectic Alloys – B413.1 for Thin Wall Casting

	Alloy	Si	Fe	Cu	Mn	Mg	Ti	Zn	Sn	Others	
										Each	Total
→	A413.0	11.0-13.0	1.3	10	0.35	0.10	-	0.50	0.15	-	0.15
	A413.1	11.0-13.0	1.0	10	0.35	0.10	-	0.40	0.15	-	0.15
	A413.2	11.0-13.0	.6	0.10	0.05	0.05	-	0.05	0.05	-	0.15
→	B413.0 (G6290)	11.0-13.0	.50 (†)	0.10	0.35	0.05	0.25	0.10	-	0.05	0.15
	B413.1 (G6290)	11.0-13.0	.40 (†)	0.10	0.35	0.05	0.25	0.10	-	0.05	0.15



Intercooler Manifolds

Permanent mold or sand castings for thin and intricate parts

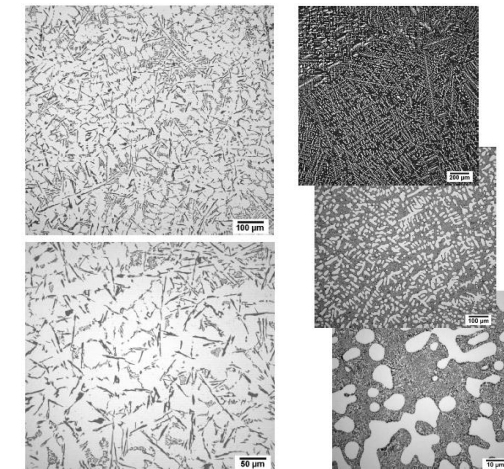
Low **Cu** improves the **corrosive resistance**, trading some strength
B413.1 (†) is batched to purity levels as appropriate to the part

B413.0 F Temper	Tensile Strength		0.2% Yield		%EI	BH N
	MPa	ksi	MPa	ksi		
Sand	175	25.5	65	9.5	7.5	50
PM	210	30.5	75	11.0	11.0	55

Typical B413.0-F properties for
sand or permanent mold cast

Property ²	ksi	MPa
0.2% Offset Yield	14.2 ± 0.2	97.8 ± 1.3
Tensile Strength	32.1 ± 0.6	221.4 ± 4
%EI	10 ± 0.4	

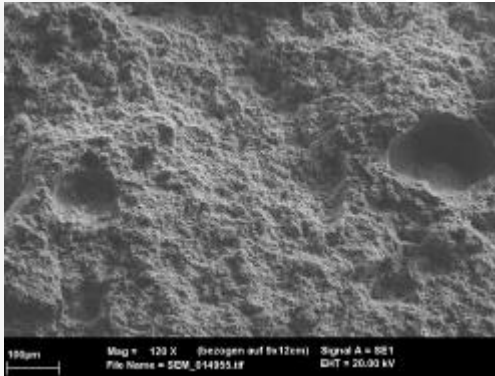
Sr-modified B413.1-F
properties for PM fine
microstructure at high cooling
rates (0.26% Fe)



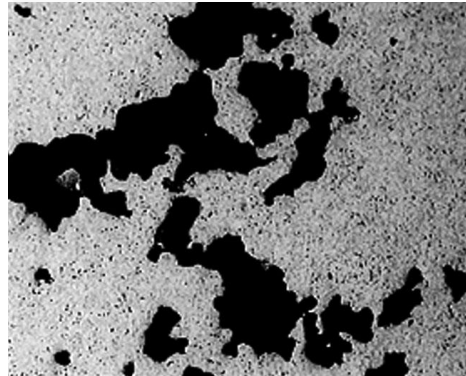
(left) typical PM microstructure
(right) B413.1 Desirable microstructure. Sr
modified and high purity enhance properties Source: Rio Tinto

Typical Die Casting Attributes

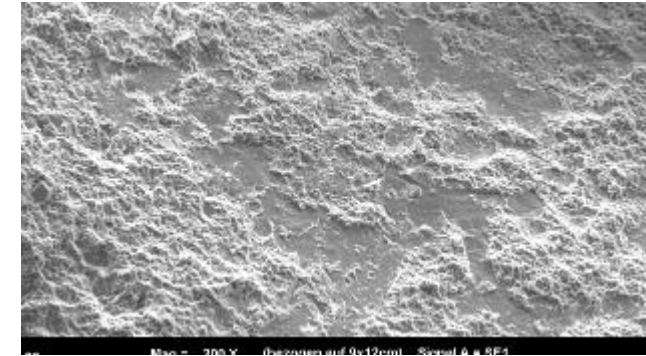
Gas porosity



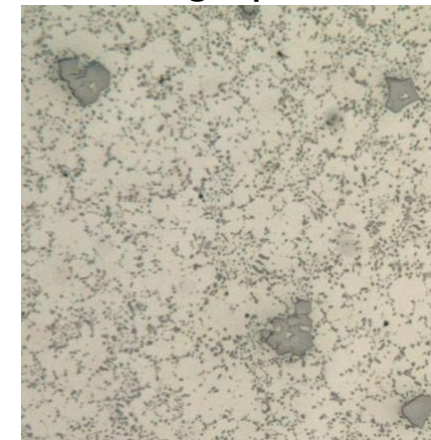
Shrinkage porosity



Oxide inclusions



Sludge particles



Source: Rio Tinto

Typical Application Areas

Automotive Alloys by Family and Application	Most Commonly Used Alloys	Common and Alternative Processes	Typical Composition	Application Notes
Al-Si-Cu Alloys for Power train Applications - The primary requirements include elevated temperature strength and hardness. - Ductility is generally low.	EN AC-Al Si5Cu3(Mg)(Mn) EN AC-Al Si7Cu3Mg EN AC-Al Si8Cu3 (AA 319 / AA320) EN AC-Al Si9Cu3Fe (AA 380) EN AC-Al Si11Cu2 (AA 383)	- Gravity diecasting (with sand cores) - Lost foam - Cosworth - Low pressure - Conventional or vacuum high pressure diecasting	4.5 - 8.5% Si 3 - 4% Cu 0 - 0.5% Mg < 0,5 (0.8)% Fe Na, Sr, or Sb refinement 8-11% Si 2-4% Cu 0,05 - 0.55% Mg < 1.3% Fe	- Hydraulically cooled engine blocks and cylinderheads. - Closed deck cylinderhead design - Large inline 4 or 5 cylinder blocks - V6 and V8 cylinderblocks - Small to medium 4 cylinder engine blocks with open deck design. - Transmission cases

Automotive Alloys by Family and Application	Most Commonly Used Alloys	Common and Alternative Processes	Typical Composition	Application Notes
Al-Si-Mg Alloys for Powertrain Applications Thermal fatigue resistance, and/or strength and ductility.	EN AC-Al Si7Mg EN AC-Al Si7Mg0,3 (AA 356 / AA A356) EN AC-Al Si9Mg EN AC-Al Si10Mg (AA 359 / AA 360)	- Gravity diecasting (with sand cores) - Low pressure diecasting	7-10 % Si 0,25-0,5% Mg < 0,2% Fe (1) < 0,1% Cu (1) < 0,6% Fe (2) < 0,3% Cu (1) Na, Sr, or Sb ref.	- Heavily stressed diesel engine cylinderheads - Differential carriers (1) = primary alloys (2) = secondary alloys
Al-Si-Mg Alloys for Suspension Components - Ductility, fracture toughness - Safety critical components	EN AC-Al Si7Mg0,3 EN AC-AlSi7Mg0,5 (AA A356 / AA A357)	- Gravity diecasting - Low pressure diecasting - Squeeze casting - Semi-solid forming	6,5-7,5% Si 0,2 – 0,6% Mg < 0,2% Fe < 0,1% Cu Na, Sr, or Sb refinement	- Upper and lower suspension control arms. - Rear knuckles - Front steering knuckles - Cross-members

Typical Application Areas

Automotive Alloys by Family and Application	Most Commonly Used Alloys	Common and Alternative Processes	Typical Composition	Application Notes
Al-Cu Alloys for Automotive Suspension Parts	EN AC-AI Cu4MgTi (AA A206 / AA 206)	- Premium quality sand casting - Gravity diecasting	4.2-5.0% Cu 0.15-0.35% Mg < 0.35% Fe 0.15-0.30% Ti	Simply shaped knuckles or control arms for speciality automotive applications: sports cars and other limited volume high price cars.
Al-Si-Mg and Al-Si Alloys for Wheels	EN AC-AI Si7Mg0.3 (AA A356) EN AC-AI Si11	- Gravity diecasting - Low pressure diecasting	6.5-7.5% Si < 0.05% Cu 0.25 – 0.45% Mg < 0.20% Fe Sr or Sb refinement 10.5-12.5% Si < 0.05% Cu < 0.45% Mg < 0.20 % Fe Sr modification	- General purpose fully heat treated automotive wheels. - Lightly loaded non-heat-treated automotive wheels.
Automotive Alloys by Family and Application	Most Commonly Used Alloys	Common and Alternative Processes	Typical Composition	Application Notes
Al-Si and Al-Mg Alloys for Steering Wheel Cores - Impact energy absorption - High ductility requirement - Safety critical part	AA B443 (Al Si5Fe) (no EN equivalent) EN AC-AI Mg3 (AA 511)	- High pressure diecasting - High pressure diecasting	4.5– 6.0% Si < 0.15% Cu < 0.05% Mg < 0.35% Mn < 0.8% Fe 2.5–3.5 % Mg < 0.55% Si < 0.55% Fe < 0.45% Mn	- High pressure diecast steering wheel cores where high ductility at moderate strength is required. - High pressure diecast steering wheel cores where very high ductility at low strength is required.

Typical Application Areas

Automotive Alloys by Family and Application	Most Commonly Used Alloys	Common Processes	Typical Composition	Application Notes
Al-Si-Cu-Mg Alloys for Automotive Pistons - Hypoeutectic, eutectic, and hypereutectic compositions are all commonly used. - Hot Hardness and Wear Resistance are the primary requirements. - Thermal Fatigue is also critical.	AA 332 (Al Si10Cu3Mg) ^{*)} - Commonly used alloy for light duty pistons EN AC-Al Si12CuNiMg (AA 336) - Increased elevated temperature strength. AA A390 (Al Si17Cu4Mg) ^{*)} - Highest wear resistance	Gravity Diecasting <u>Notes:</u> ^{*)} no EN equivalent ^{**)} when fine scattered Si primary particles are needed	8.5 – 10.5% Si 2.0 – 4.0% Cu 0.5 – 1.5% Mg < 1.2% Fe; < 0.5% Mn 10.5 – 13.5% Si 0.8 – 1.5% Cu 0.8 – 1.5% Mg 0.7 – 1.3% Ni < 0.7% Fe; < 0.35% Mn Na modif., or P ref. ^{**))} 16.0 – 18.0% Si 4.0 – 5.0% Cu 0.45 – 0.65% Mg < 0.50% Fe; P refinement	- The complexity of these alloys varies with the piston type. The more heavily loaded the piston is, mechanically or thermally, the more highly alloyed it must be to survive the service environment. - Both gasoline and diesel engine pistons are commonly cast. - Many proprietary compositions exist. - The more highly alloyed compositions have a high intermetallic compound content, which gives the wear, and scuff resistance in a very demanding environment. - The intermetallic content also helps to give the alloys hot hardness and strength at elevated temperatures. - When requested, the presence of Si primary particles gives the alloy the wear behaviour of a natural composite.