MAXIMIZING THE VALUE OF RECYCLED ALUMINUM EXTRUSIONS IN AUTOMOTIVE ALLOYS

Authored By:
Aluminum Transportation Group

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Introduction

The use of aluminum extrusions in automobiles is on the rise, with future growth expected to outpace all other aluminum product forms [1]. As aluminum usage increases, so will the volume of aluminum entering the vehicle scrap stream. This shift is becoming more evident as the first generation of aluminum-intensive Ford F-150s, which hit showrooms in late 2014, reach their end-of-life (EOL) and begin entering the scrap stream. The number of these vehicles reaching EOL will continue to grow in the coming years, significantly impacting the aluminum scrap supply. Zhu et al. [2] explored this trend in their 2021 study, which analyzed the F-Series trucks, Ford Expedition, and Lincoln Navigator models. Figure 1 illustrates the projected volume of aluminum alloy sheet scrap from 2015 to 2050, highlighting its correlation with vehicle deregistration.

This paper will provide key insights into extrusion alloys, recyclability and the integration of recycled content into various aluminum alloys—essential factors for reducing carbon footprint and maximizing the value of scrap materials. The benefit of recycled content over primary metal is well documented by recent Aluminum Association reports, which show that a reduction of ~95% of the carbon footprint can be realized by using recycled aluminum versus North American industry average for primary metal of 8.5 tCO_2e / tAl [3,4].

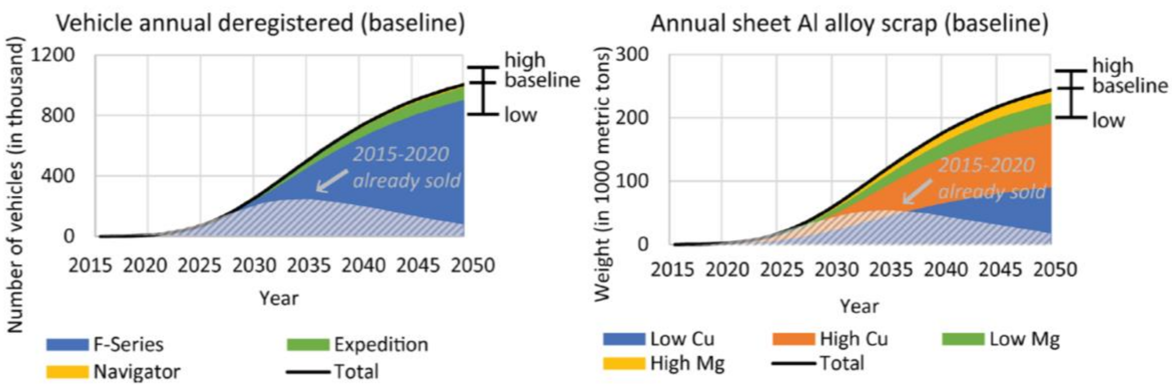


Figure 1: From Zhu et al [2], annual deregistered vehicle (left), and annual sheet aluminum alloy scrap (right) from the U.S. fleet for 2015 to 2050. The gray areas correspond to vehicles already sold in 2015 to 2020. The F-series is composed of F-150 and Super-Duty trucks.

6xxx Series Aluminum Alloy Extrusions

Most extrusions used in automotive applications are from the 6xxx family per the Aluminum Association, meaning silicon and magnesium are the primary strengthening elements. Typically, silicon is 0.3-1.5 weight percent, while magnesium is 0.4-1.0 weight percent, with 93-97 weight percent aluminum. Heat treatable alloys (like the 6xxx series) gain strength through the thermal processes of solution heat treatment and aging. Solution heat treatment can be done inline during extrusion (known as press quenching) or offline (separate or batch solution heat treatment). Press quenching combined with commercially available alloys makes extrusions a very cost-effective solution for the automotive industry.

Automotive extrusions are used in a variety of applications, from crash management systems to the body in white as shown in Figure 2. Different applications have different requirements, resulting in multiple alloys used across a vehicle, see Table 1 for the major alloying elements used in a range of 6xxx series automotive extrusion alloys (full composition information can be found in [5]). Alloys such as 6060 and 6063 have less alloying elements (often referred to as “low solute”) and lower strength, but higher ductility and are commonly used for applications dissipating crash energy, such as crush cans in bumper assemblies. Alloys like 6061 and 6082 have more alloying elements and are associated with higher strength, but less ductility. These higher strength alloys are often used for bumper beams, in electric vehicle battery housings and rocker panel applications, for example. The different alloys, while seemingly similar with relatively small changes in the levels of individual elements, have different properties and other attributes that lend themselves to the different application areas and associated property requirements.

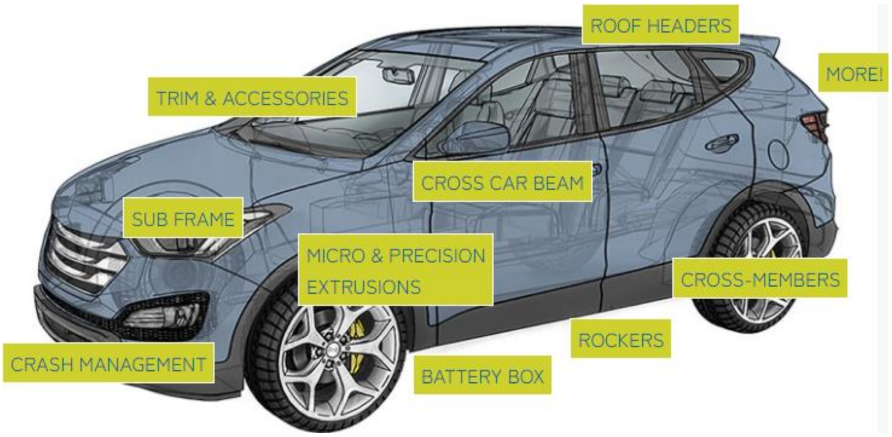


Figure 2: Overview of automotive Aluminum extrusion applications (Aluminum Extruders Council).

Alloy	Basis	Si	Fe	Cu	Mn	Mg	Cr	Notes
6060	min	0.3	0.1			0.35		
	max	0.6	0.3	0.1	0.1	0.6	0.05	
6063	min	0.2				0.45		
	max	0.6	0.35	0.1	0.1	0.9	0.1	
6005A	min	0.5				0.4	0	
	max	0.9	0.35	0.3	0.5	0.7	0.3	
6061	min	0.4		0.15		0.8	0.04	
	max	0.8	0.7	0.40	0.15	1.2	0.35	
6082	min	0.7			0.4	0.6		
	max	1.3	0.5	0.1	1.0	1.2	0.25	
6110	min	0.7		0.2	0.2	0.5	0.04	
	max	1.5	0.8	0.7	0.7	1.1	0.25	

Table 1: Typical Automotive 6xxx Alloy Compositions (major alloying elements, wt%).

Understanding the composition of an aluminum extrusion helps manufacturers maximize the value from scrap by segregating materials scrap with a known pedigree. A single alloy with known processing and contamination (oils, lubricants, etc.) offers the highest value, while mixed aluminum scrap (multiple alloys, clean and dirty scrap) has the lowest value. Yet both groups meet the requirements of recycled content per ISO-14021, which is the internation standard that specifies the requirements for self-declared environmental claims.

Recycled content can be further segmented into pre-consumer scrap and post-consumer scrap. This indicates if the scrap was generated during a manufacturing process, in the case of pre-consumer scrap, or after a product was put into use, as is the case for post-consumer scrap. Pre-consumer scrap is generally lower in cost to acquire as it is often generated internally. Whereas post-consumer scrap may require significant sorting so that different materials are separated into the appropriate groupings, potentially leading to increased cost to incorporate post-consumer scrap. It should also be noted that depending on the carbon accounting methodology used, scrap can be treated the same in terms of its carbon footprint; or alternatively provided a lower value for post-consumer scrap.

Composition and Properties

Compositions of commercially available extrusion alloys are registered with The Aluminum Association and are compiled in a publication that is commonly referred to as the “Teal Sheets” [5]. For automotive applications, the most common registered alloys (see Table 1) include 6060, 6063, 6005A, 6061, and 6082. Alloys for more specialized applications (see Table 2) include 6262 (a free machining alloy), 6008 (high ductility crash alloy), and 6110 (high strength alloy for extrusions and forgings). As shown in Tables 1 and 2, the total alloying element content ranges from 3-6 weight percent with the balance as aluminum (see also Figures 3a and 3b which show the maximum and average composition levels for the major alloying elements of these commonly used alloys).

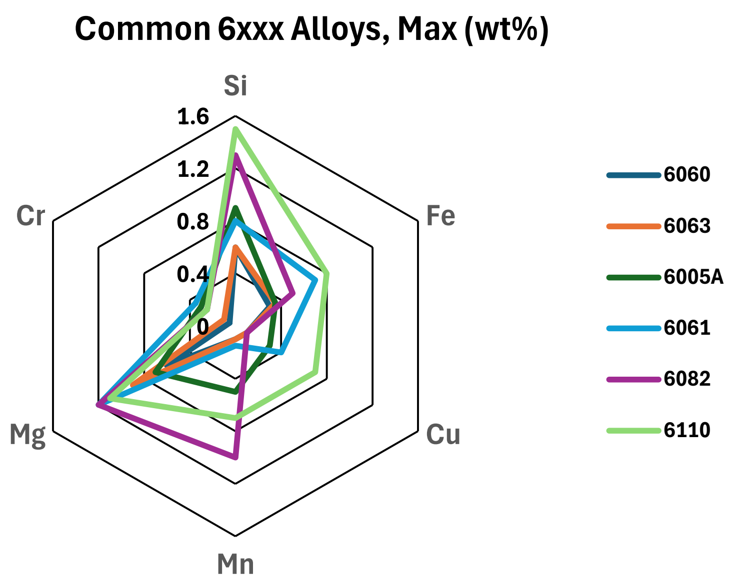


Figure 3a: Typical 6xxx automotive alloys (maximum).

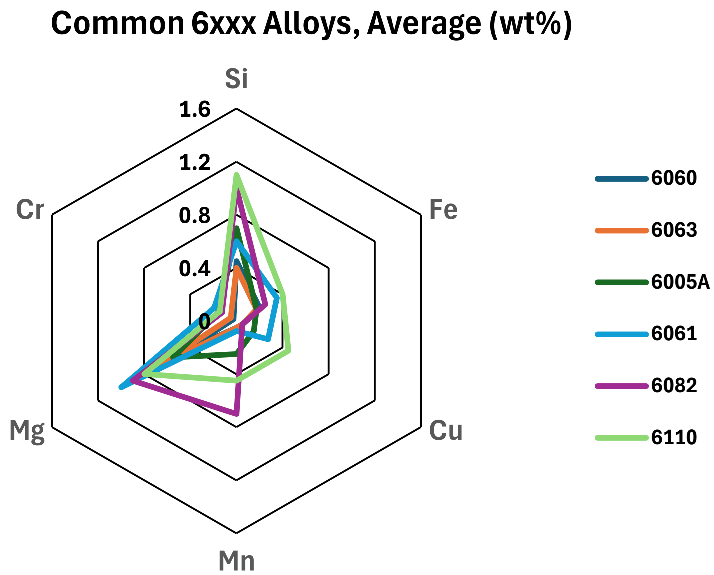


Figure 3b: Typical 6xxx automotive alloys (average).

When specifying an alloy, it is important to understand the impact of the major and minor alloy elements. For the common alloys, major elements primarily control strength (silicon, magnesium, copper) and grain structure (manganese, chromium). Minor elements include elements not deliberately added, or those added in small amounts, like titanium for cast grain size control.

The most common way to evaluate composition is with optical emission spectroscopy, per ASTM E1251 "*Standard Test Method for Analysis of Aluminum and Aluminum Alloys by Spark Atomic Emission Spectrometry*." It is important to understand that composition evaluated in this manner is not absolute; it can be impacted by the calibration method and the set-up of the certified reference material (CRM) used to conduct the spectrometer analysis. ASTM E1251 includes repeatability data from an interlaboratory study for multiple elements. The Aluminum Association recognized this problem and published a paper on the value of using "guard bands" to ensure composition requirements are met, regardless of any measurement uncertainty [6].

While an alloy's registered limits are the industry standard, reducing product and process variation often requires billet producers and/or extruders to hold tighter internal composition limits. These tighter limits may be needed due to strength ranges (instead of a one-sided limit), process conditions (consistent productivity / lower cost), or product requirements (ductility testing). It's important to note the registered limits may allow an unacceptable level of variation, especially for automotive applications. The previously mentioned guard bands can be applied to internal limits as well.

For automotive applications, strength, ductility and cosmetic appearance are the most important attributes of extrusions. Depending on the application, one, two or all three may be relevant or not. Variation in alloying elements will influence these properties differently. For example, silicon, magnesium, and copper generally require a variation of only ~0.1 wt% to significantly impact strength (note that the main strengthening elements in 6xxx series alloys are Si and Mg, with Cu providing additional alloy strengthening when added). Chromium (through its impact on grain structure), however, can affect ductility at an additional level of 0.05 weight percent or less. Significant differences in grain structure, and hence properties, can be obtained between alloys with 0.05 versus 0.1 wt% additions. Copper and zinc can also change the surface appearance (anodized quality) at levels as low as of 0.02 weight percent, with changes of 0.01 wt% of each being significant in affecting cosmetic appearance. These examples emphasize the importance of tightly controlling and accurately measuring the composition.

Recyclability and Ease of Incorporating Recycled Content

In general, alloys such as 6060 and 6063 with lower solute content (i.e., “lean”) are easier to recycle into other alloys. Figure 4 shows a plot of the major alloy elements for both alloys (maximum values); this plot shows the relatively low maximum levels of Cu, Mn and Cr which can limit their ability to accept recycled content.

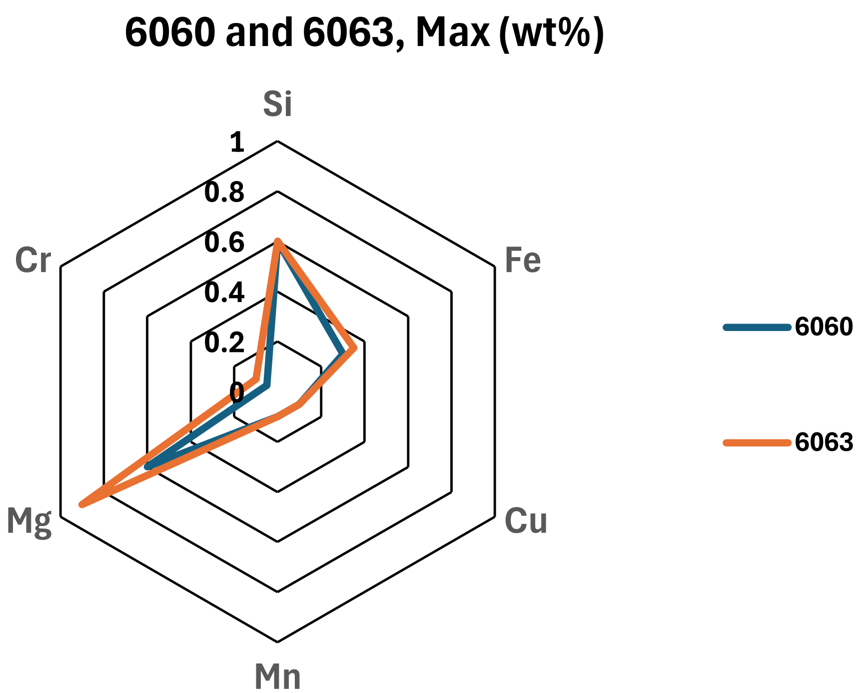


Figure 4: low strength (solute) automotive alloys 6060 and 6063 (maximum).

However, these lean alloys can be recycled into both low and, much more easily, higher solute alloys as illustrated by Figure 5 which compares the maximum composition limits for 6063 versus 6082. The composition limits of 6063 typically fit (with the exception of Cu) well within those of 6082.

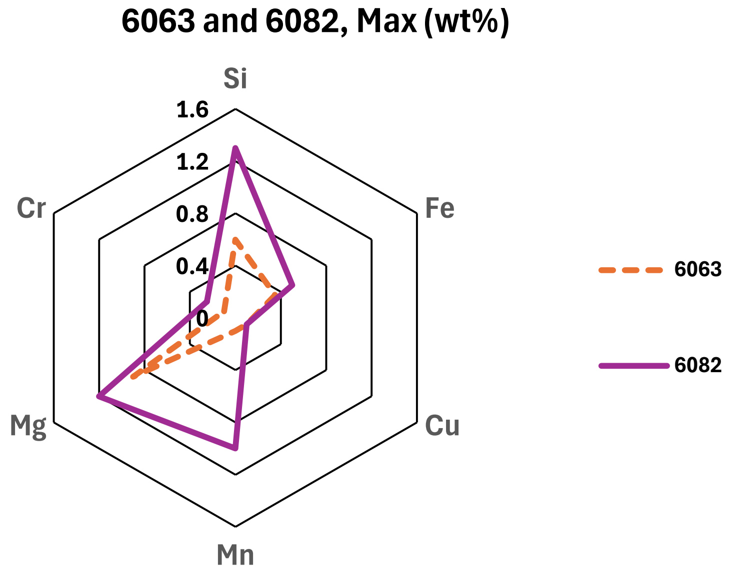


Figure 5: Maximum composition (wt%) of 6063 and 6082 showing the ability to accept 6063 alloy scrap into the higher solute 6082 composition.

For some specific applications, however, tight controls may make this difficult unless the scrap has a known pedigree. Bright dip anodize applications is one such use. Incorporating recycled content into these alloys can be a challenge. If the scrap is mixed, has an unknown pedigree, or is unsorted post-consumer scrap it can have large variation in composition on the end properties of the extruded product. For applications like crash cans with a tight range on yield strength, this may be a concern. Variation in multiple elements (for example silicon, magnesium, copper, and manganese) can change the alloy's strength and ductility to an unacceptable degree.

Medium solute alloys, like 6005A (see Figure 6a), are somewhat more challenging to recycle into lean alloys, but are relatively easy to recycle into medium and high solute alloys. This is shown in Figure 6b, which compares the maximum composition limits for 6005A versus both low solute (6063) and high solute (6082) alloys. In this example, the composition limits of 6005A are either equal to or lower than those of 6082 except for copper. In general, it is difficult to reduce the amount of an alloying element without increasing the carbon footprint. The most common method is to dilute the melt with higher purity primary metal, which often has a higher carbon footprint (note that there are multiple grades of prime metal such as P1020 or P0406 that refer to the level of Si and Fe present). Incorporating recycled content into medium solute alloys is also relatively easy. These alloys are less sensitive to strength variation and are not typically used for cosmetic applications. One area of concern with the medium strength alloys is grain structure. Controlled mainly by the presence of manganese and chromium, these alloys can be used with either an unrecrystallized (sometimes referred to as "fibrous") or recrystallized microstructure (or grain structure).

Figure 7 shows examples of the two microstructures. There can be significant processing and performance differences between them, with unrecrystallized alloys having higher strength and ductility, but lower productivity. Segregation of scrap and having a known pedigree (i.e., composition) is key to understanding how scrap will impact the medium solute alloys.

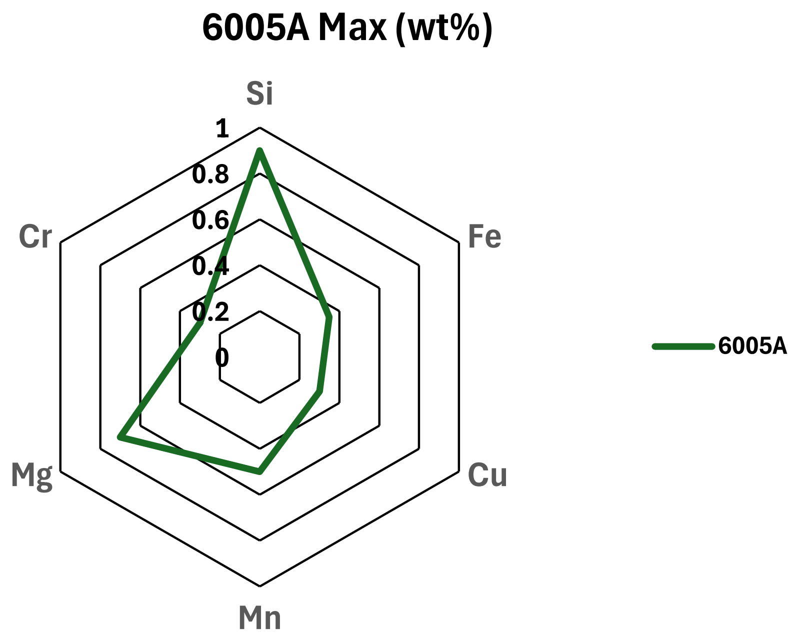


Figure 6a: Medium strength (solute) automotive alloys 6005A (maximum).

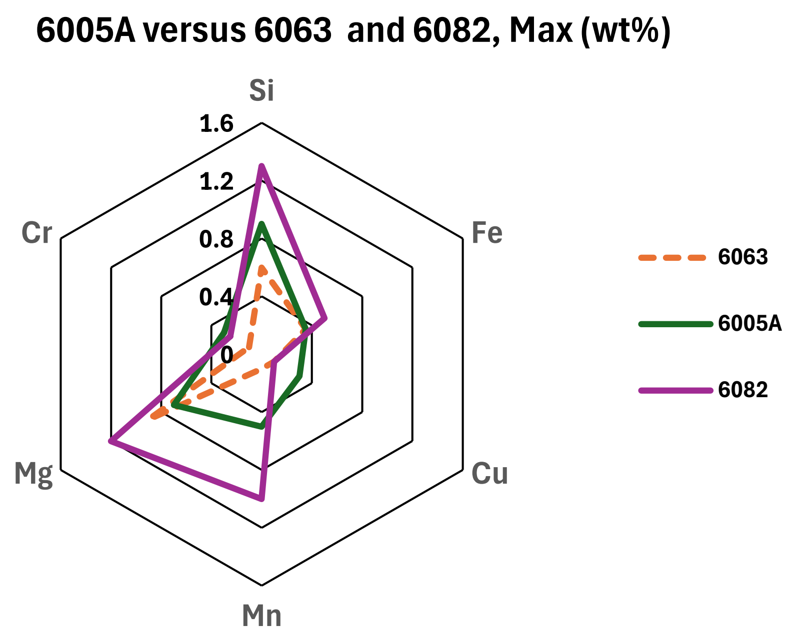
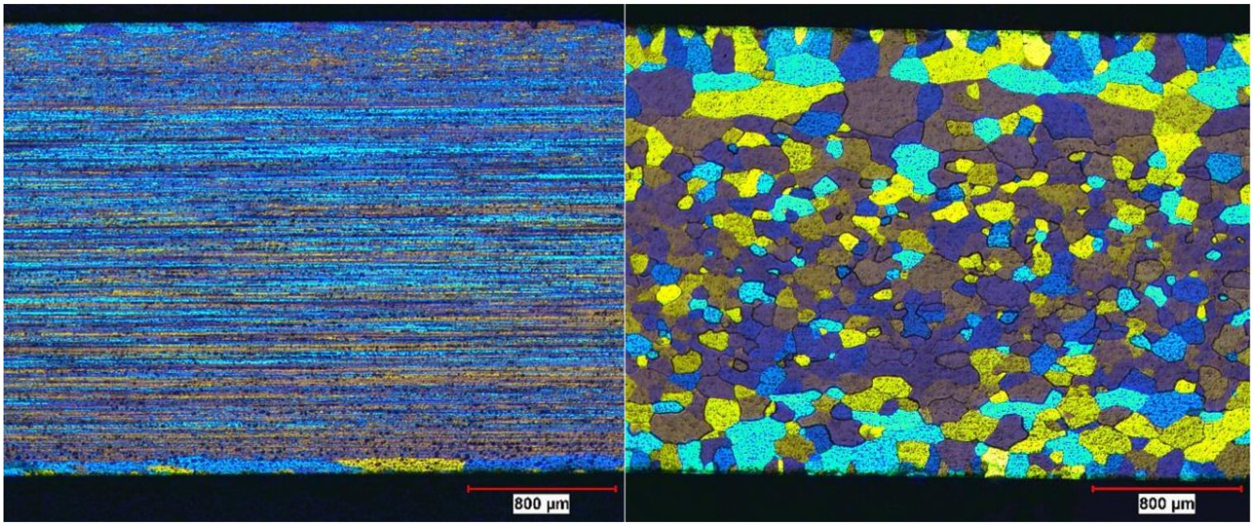


Figure 6b: Medium strength (solute) automotive alloys 6005A versus 6063 and 6082 (maximum).



Unrecrystallized structure Recrystallized structure

Figure 7: Examples of an unrecrystallized (fibrous) microstructure (left image) and recrystallized microstructure (right image). Images courtesy of Rio Tinto.

It is generally easiest to incorporate scrap into high solute alloys like 6061, 6082, 6110 (see Figure 8 for the maximum composition limits for these three alloys compared with the limits of low solute 6063). These alloys have wide ranges and are even more tolerant of trace elements than the medium solute alloys. The converse of this, is that they are also difficult to recycle into lower solute alloys. When recycled back into lower solute alloys the relatively high levels of multiple alloying elements can easily cause these "leaner" alloys to be outside of their specification limits for composition (this is often described as an alloy being "off-analysis"). There are also significant differences between the alloys which can make it difficult to recycle these alloys into anything other than themselves. For example, 6082 has a maximum copper level of 0.1 wt% and so the incorporation of a significant amount of 6061 scrap, which already has a minimum copper level of 0.15 wt%, will likely lead to an out-of-specification copper level.

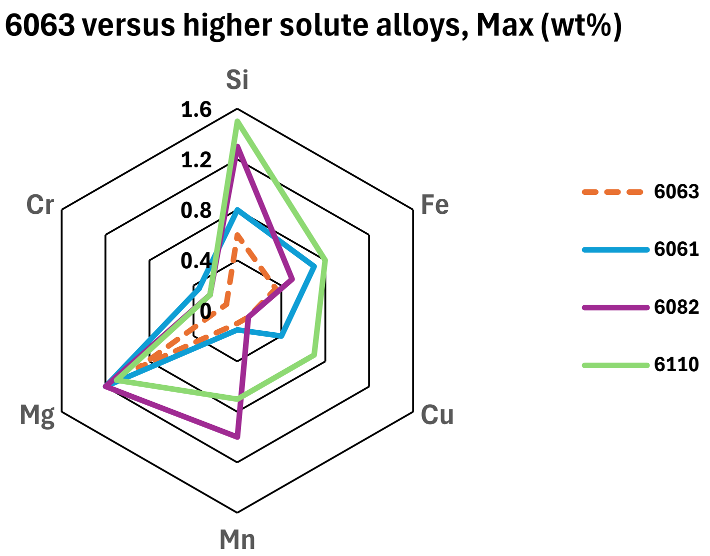


Figure 8: High strength (solute) automotive alloys versus 6063 (maximum).

A fourth group of alloys are identified by unusual or special alloying additions which are added for specific purposes (see Notes in Table 2 below). These include 6262 and other free-machining alloys such as 6042 and 6026 (with lead, bismuth, and/or tin additions), 6008 (which has vanadium), and 6110A (where zirconium is added). These alloys can often incorporate recycled content of other alloys based on their solute levels (e.g., of Si, Mg, Cu) but they are not easily recycled back into the more common 6xxx alloys such as 6063, 6061, 6082. This is because the more widely used alloys have limits of "impurity" elements that are often set at 0.05 wt% for a given element and a total of 0.15 wt% which control how much of the special alloying elements could be present (the Teal Sheets [5] provide details of these Other – Each/Total limits for all alloys.). It should also be noted that these special alloying elements can also have a relatively high value (e.g., V, Sn) and so it is preferable that the scrap of these alloys is carefully segregated and recycled back into comparable alloys to maintain that high value and not contaminate the more common alloy scrap sources.

Alloy	Basis	Si	Fe	Cu	Mn	Mg	Cr	Notes
6008	min	0.50				0.40		0.05-0.20 V
	max	0.9	0.35	0.3	0.3	0.7	0.3	
6110A	min	0.7		0.3	0.30	0.7	0.05	0.20 Ti+Zr
	max	1.1	0.5	0.8	0.9	1.1	0.25	
6026	min	0.6		0.20	0.20	0.6		0.50-1.5 Bi; 0.40 Pb; 0.05 Sn
	max	1.4	0.7	0.50	1.0	0.2	0.3	
6042	min	0.50		0.20		0.7	0.04	0.20-0.8 Bi; 0.15-0.40 Sn
	max	1.2	0.7	0.6	0.4	1.2	0.35	
6262	min	0.40		0.15		0.8	0.04	0.40-0.7 Bi; 0.40-0.7 Pb
	max	0.8	0.7	0.40	0.15	1.2	0.14	

Table 2: Selected specialized automotive 6xxx alloy compositions (major alloying elements).

Recycling efficiency and the ability to incorporate recycled content depend on the alloy composition. Alloys with lower solute content are easier to recycle since their scrap can be repurposed across multiple alloy types. However, without proper segregation of scrap by known alloy pedigree, integrating high scrap levels into low-solute alloys becomes challenging. Application matters too—some uses are more sensitive to trace elements than others. While higher-solute alloys can accommodate a wider range of scrap, careful management is essential to ensure quality and performance. Mastering these factors is key to maximizing both sustainability and material value.

Conclusion

The use of aluminum extrusions in high-volume trucks and large vehicle platforms has surged over the past decade, and now, as these vehicles reach end-of-life, they are entering the recycling stream. This presents opportunities to reduce new metal production and decrease the overall carbon footprint in vehicle manufacturing. By understanding how automotive alloys can be efficiently recycled and reintegrated, automakers can unlock the full potential of sustainable manufacturing with aluminum.

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