Sorting of Automotive Manufacturing Wrought Aluminum Scrap

A Major Qualifying Project
Submitted to the Faculty of
Worcester Polytechnic Institute
in partial fulfillment of the requirements for the
Degree in Bachelor of Science in
Mechanical Engineering

By

Shady J. Zummar Ghazaleh

Date: 04/26/2018
Sponsoring Organization:
Metal Processing Institute

Approved by:

Professor Diran Apelian

Alcoa-Howmet Professor of Engineering, Advisor
Founding Director of Metal Processing Institute

Abstract

An increase of 250% in wrought aluminum usage in automotive manufacturing is expected by 2020. Consequently, the generation of new aluminum sheet scrap will also increase. Producing secondary aluminum only emits 5% of the CO_2 compared to primary aluminum – a significant 95% decrease. With the advent of opto-electronic sorting technologies, recovery and reuse of new aluminum scrap (generated during manufacturing) is at hand. A series of interviews with industrial experts and visits to automotive stamping plants were performed in order to identify: *(i)* the most common wrought aluminum alloys from which scrap is generated; *(ii)* the present scenario — how scrap is collected today; and *(iii)* the types of contamination that must be accounted for during and after sortation. Recommendations are made herein that will support the development of an optimized scrap management system including sorting criteria that will enable closed loop recycling.

Table of Contents

Acknowledgements

Above all, I would like to thank Professor Diran Apelian and Dr. Sean Kelly for the unconditional support especially during times of personal hardship. Their guidance and mentorship were not only helpful but also necessary for the completion of this project.

I would also like to thank the Metal Processing Institute at Worcester Polytechnic Institute for providing the necessary platform and resources and for immediately accepting me as part of their community.

I would like to show gratitude to the industry representatives in the focus group that offered counsel and guidance through their industry experience.

I also want to express my greatest appreciation to Ford and General Motors for allowing us to visit their stamping and assembling facilities.

Glossary

Alumina: Al_2O_3, also known as aluminum oxide, aloxide, aloxite and alundum.

Bauxite: Ore from which aluminum is refined. Consists mostly of hydrated alumina and a range of iron oxides.

Body-in-White (BIW): refers to the stage in automotive design or automobile manufacturing in which a car body's sheet metal components have been welded together — but before moving parts, the motor, chassis sub-assemblies, or trim have been added and before painting.

Charge: Process of filling a melting furnace with material.

Compositional Tolerance: The ability of a melt to accept scrap of a certain alloy or composition without it hindering (or without substantial required efforts to rebalance) its composition.

Dilution: Addition of the primary base material to reduce the concentration of alloying elements.

Downcycling: The reprocessing of a material into a new product of lesser quality or value.

Extrusion: A manufacturing process that consists of pushing a billet of material through a die orifice using a ram.

In-House Scrap: Material discarded during the manufacturing of semi-fabricated products (metal sheets, ingots, plates, etc.).

Laser Induced Breakdown Spectroscopy (**LIBS**): Consists of pointing a high-energy laser beam into a piece of metal, making it fluoresce. Optical emission spectroscopy is used to determine the metal's composition.

New Scrap: Material that is discarded when something is produced such as the punching scrap generated when producing an aluminum can.

Old Scrap: The material recovered after a consumer has discarded a used product such as an aluminum can after a consumer has drunk its contents.

Primary Aluminum: Metal produced from ore in deposits extracted from the earth's crust.

Secondary Aluminum: Metal that has been produced from recycling.

Sorting Criteria: The set of rules used to determine how mixed scrap is to be segregated.

Stamping: A process consisting of changing the shape of sheet metal into a desired form using a die and mechanical press.

Sweetening: The addition of primary alloying material to a melt in order to achieve a desired composition.

Upcycling: The processing of a material to create a product of higher quality or value.

Wrought alloys: Alloys that have been turned into consumer products by solid-state processing including rolling, extruding and forging.

X-Ray Fluorescence (**XRF**): Consists of shooting x-rays into a material, making it fluoresce. The spectral ratios are analyzed to determine the composition.

1 Introduction

1.1 Problem

Automotive manufacturers are pressured by regulatory bodies to limit weight to reduce emissions and by competitors and consumers to provide more fuel-efficient vehicles. Aluminum has now joined steel in the family of major materials used in car manufacturing due to its low density and high strength. Aluminum allows for weight reduction without sacrificing much of the structural strength required to ensure competitive performance and safety functionality [1]. This expected increase in aluminum usage has surfaced the need to predict scrap generation and management practice by the original equipment manufacturers (OEMs) that support the automotive sector.

Aluminum sheet usage is expected to increase to 61 pounds per vehicle in 2020 from 23 pounds per vehicle in 2015, a 250% increase. The majority of this growth is a direct result of the aforementioned advances in light-weighting efforts to maximize the incorporation of aluminum in auto-closure components. Aluminum hoods will increase to 71% from 50% and doors to over 25% from 5%. Aluminum Body in White (BIW) components are also expected to increase from 26 pounds per vehicle from 14 pounds per vehicle. Extrapolating this increase and assuming production stays at current levels, a total usage of 1.06 million tons of aluminum sheet can be expected by 2020 [2]. Up to 2/3 of the sheet consumed in stamping processes can become scrap meaning that up to 700 thousand tons of scrap could be generated by 2020 [8].

Downcycling is the reprocessing of a material into a new product of lesser quality or value [3]. The use of wrought scrap (*new and old*) to produce cast alloys can be considered a type of aluminum downcycling as the purity of wrought alloys is perceived as higher than that of cast alloys. This is due to the tighter compositional requirements in wrought alloys compared to their cast counterparts. The mixing of aluminum scrap of different alloys results in the downcycling of the aluminum due to a lack of compositional understanding of the resulting mixed stream.

1.2 Motives

Secondary aluminum production offers great energetic and environmental advantages over primary production. Secondary production requires ~2.8 kWh of energy and produces ~0.6 kg of CO_2 per kilogram of aluminum compared to primary production that requires ~45 kWh and emits ~12 kg of CO_2 per kilogram, around 5% of energy and emissions [4]. This energetic advantage makes aluminum recycling extremely desirable for both ecological and economic reasons.

Technologies are now available to sort or separate mixed alloy scrap. Most importantly, the advent of Laser Induced Breakdown Spectroscopy (LIBS) allows for high-volume industrial level scrap sortation required to prevent the downcycling of the increased scrap volumes. This technology combined with an automated sorting system and sound sorting criteria can optimize the recycling process by creating different scrap streams of known composition.

1.3 Need

Without proper management, the wrought scrap produced from the increase of aluminum usage in the automotive industry could be downcycled. To prevent this from happening a better understanding of the current state of scrap generation is required; specifically:

- Identification of scrap-generating alloys is required. These alloys determine the composition of the streams to be sorted and are a key factor when developing sorting criteria using compositional sorting technologies.
- Comprehension of the current handling processes is needed. This includes the nature of scrap generation, the regularity of scrap mixing of different alloys and the infrastructure associated with handling high scrap volumes.
- Determination of contaminants that pose issues when sorting and recycling is necessary. Their origins and the manner in which these can affect the aforementioned processes is to be understood.
- Development of sound sorting criteria compatible with compositional sorting systems is necessary. The criteria must be able to sort through the mixed streams to reduce the required scrap recycling processing and prevent downcycling.

2 Background

2.1 Aluminum in automobiles

Initially, aluminum was only used in high-performance luxury vehicles. The world of motorsport influenced this shift in material consumption by proving the performance benefits of light weighting. The first full aluminum body car released to the public was the Audi A8 in 1994 followed by other European luxury brands like BMW, Mercedes-Benz, Porsche, Land Rover, Jaguar, etc. The most recent and important milestone for aluminum in the automotive industry is the newest iteration of the iconic Ford F-150 truck, the bestselling pick-up for the last 38 years. A total reduction of 315 kg in weight was achieved, putting it above all its competitors in different categories including fuel efficiency, safety, carrying capacity, handling and emission reduction. Other companies have boasted their innovative usage of aluminum to increase safety and reduce weight. Tesla's Model 3 is an example; it features an aluminum body with strategic steel reinforcement and low weight distribution allowing it to absorb the energy from impacts and redirect it away from the passengers earning it the title of the safest SUV on the road. Another company that is embracing aluminum is Toyota that has unveiled plans to shift closure production to aluminum including those of the Camry, America's best-selling car in the last 12 years [5].

The biggest driving factor in the increase of aluminum usage are the 2025 fuel economy goals of 50+ mpg. Many technologies are being explored but no technology can single-handedly reach these targets [6]. Light weighting is among the main approaches taken by the automotive manufacturers to increase fuel efficiency using lighter materials. Aluminum is a good replacement for steel in bodies and closures. Aluminum has around one third the density of steel but also one third the elastic modulus. This weight advantage and strength disadvantage results in the need to redesign the structures previously made from steel. For example, the inner geometry of a hood has to be redesigned into a more complicated folded geometric pattern to improve component stiffness [1]. Aluminum also offers other advantages such as corrosion resistance (advantageous over steel), superb energy abortion properties (twice as much energy as steel and folding predictability) [7], great formability and cost effectiveness.

The most common aluminum alloys are those of 2xxx, 5xxx, 6xxx and 7xxx series. 2xxx, especially 2008, 2010 and 2036, experience bake-strengthening adding final panel strength. 5xxx, especially 5182, 5454 and 5754, do not have any bake hardening properties but have high formability, ideal for exterior panels. 6xxx, especially 6022, 6111 and 6009, do experience bake hardening and have high strength and great formability, which makes them great for exteriors. 7xxx are mainly used for extrusions [8].

Ducker Worldwide confirmed the increase in aluminum usage in their *Aluminum Content in North America Light Vehicles 2016 to 2028* report released in July of 2017. Ducker expects an increase to 466 from 397 pounds of aluminum per vehicle by 2020 since 2015. Aluminum content will range from 262 pounds in the A/B segment passenger cars to over 550 in average pick-up trucks, with the average at 362 pounds in cars and 532 pounds in light trucks. Most of the content growth in the next five years will be for closures, crash management, steering knuckles and structural vacuum die casting parts. Beyond 2020, the most likely scenario for weight reduction is that of 7% by 2028 and not the proposed 7% by 2025.

Aluminum sheet usage is expected to increase to 61 pounds per vehicle in 2020 from 23 pounds per vehicle in 2015, a 250% increase. Almost all of this growth is focused on closures. Aluminum hoods will increase to 71% from 50% and doors to over 25% from 5%. Aluminum Body-in-White (BIW) components are also expected to increase from 26 pounds per vehicle from 14 pounds per vehicle. Extrapolating this increase and assuming production stays at current levels, a total usage of 1.06 million tons of aluminum sheet can be expected by 2020 [2].

2.2 Recycling

Primary metal production is referred to metal produced from ore in deposits extracted from the earth's crust while secondary metal production refers to material that has been produced from recycling. Aluminum recycling is also referred to as secondary aluminum production [9].

It is important to note that secondary production offers great energetic and environmental advantages over primary production. Secondary production requires ~2.8 kWh of energy and produces ~0.6 kg of CO_2 per kilogram of aluminum compared to primary production that requires ~45 kWh and emits ~12 kg of CO_2 per kilogram, around 5% of energy and emissions [4].

The material used to produce secondary metal can usually be divided into two general categories: new scrap and old scrap. New scrap refers to material that is discarded when something is produced such as the punching scrap generated when producing an aluminum can. Old scrap is defined as the material recovered after a consumer has discarded a used product such as an aluminum can after a consumer has drunk its contents. It is important to note that the main distinguishing factor between new and old scrap is the consumer's involvement. New scrap can be considered pre-consumer scrap and old scrap can be considered post-consumer scrap. Another scrap category is that of material discarded during the manufacturing of semi-fabricated products (metal sheets, ingots, plates, etc.) this category is often known as the in-house recycling loop or pre-manufacturing scrap.

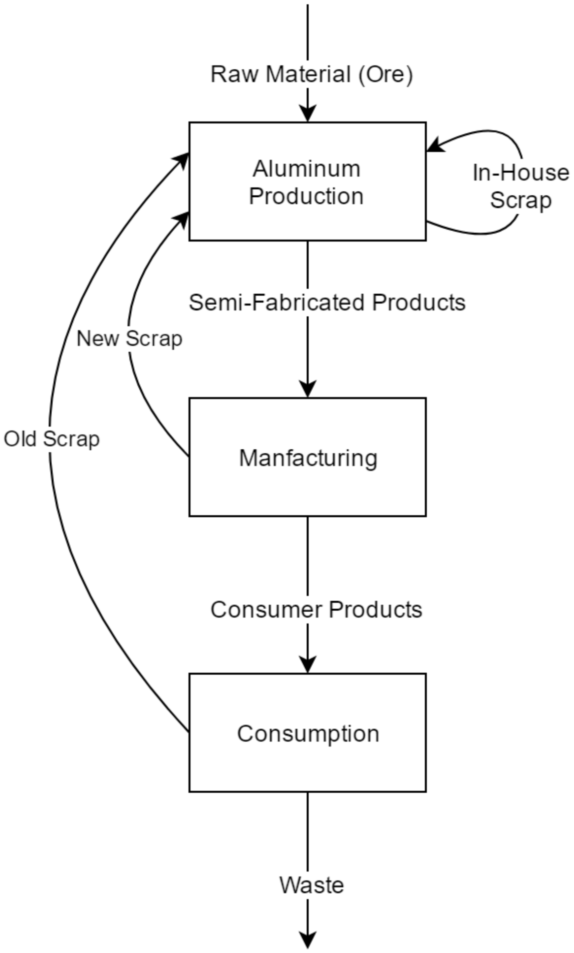


Fig. 1: Different Types of Scrap Flows.

2.3 Alloy Sortation

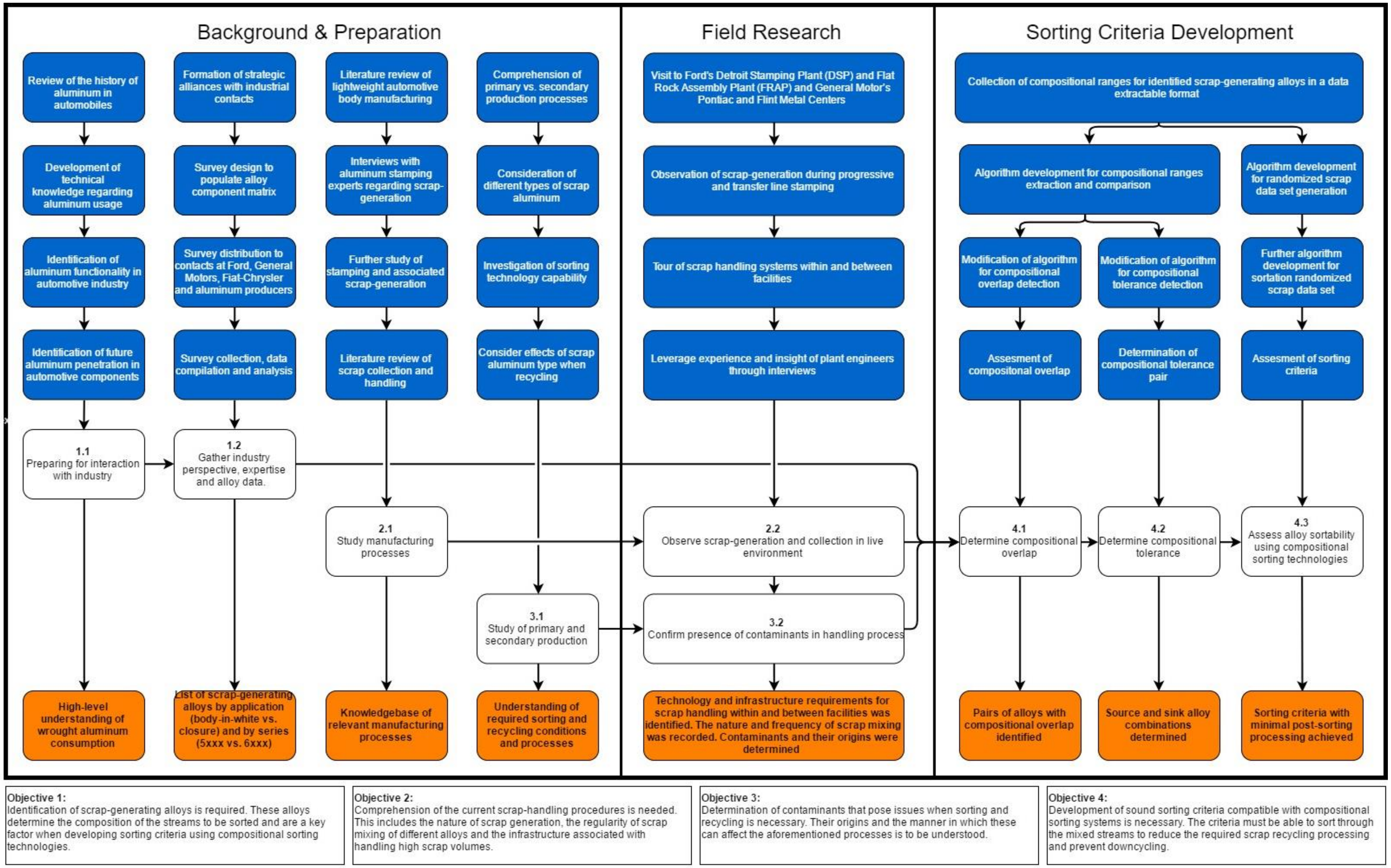
Alloy sortation has improved dramatically in the last two decades. Initial efforts were focused in differentiating between cast and wrought alloys. Methods such as the hot crush were developed in which cast alloys' lower initial melting (solidus) temperature was used to differentiate them from wrought alloys. The main issue with hot crush is that it requires relatively large sized scrap, making it difficult for shredded scrap to be sorted. The cast scrap would more easily deform into smaller pieces when crushed, making them differentiable by size. The use of acids and bases to etch aluminum alloys surfaces is also another approach. Treating cast alloys with sodium hydroxide turns them black and wrought alloys grey. Issues with surface finishing of the scrap pieces can affect the resulting color hindering the classification process. Environmental issues also arise from high volume chemical use. X-Ray fluorescence (XRF) is another approach in which X-rays are used to trigger fluorescence characteristic to different alloying elements. The spectral ratios are analyzed to determine the alloying composition [10]. XRF is used in laboratory settings and handheld units. Even though the handheld XRF scanner is extremely useful, some limitations have hindered it from becoming an ultimate sortation tool including high unit costs, long exposure time requirements, surface cleanliness requirements, alloy identification accuracy issues and the impracticability of utilizing handheld units in high volume applications. Recent improvements have made this technology even more promising with reductions in required exposure time and higher accuracy when distinguishing between individual alloys [11].

The most promising technology in alloy identification is laser-induced breakdown spectroscopy (LIBS). It consists of pointing a high-energy laser beam into a piece of scrap making it fluoresce. Optical emission spectroscopy (OES) is used to determine the scrap’s composition. LIBS has multiple advantages over XRF including higher accuracy and shorter required exposure times, making the alloy identification of moving pieces possible. Limitations do exist such as minimum scrap size requirements, laser reflection issues and the surface cleanliness requirements (some coatings contain alloying elements). In practice, the scrap moves at high speed and is shot with two lasers. The first laser is used to vaporize any coatings and paint, leaving the surface exposed for a second clean shot to induce fluorescence. The analyzed scrap can later be separated by using mechanisms that push it into the appropriate bin [9].

It is important to note that identification through spectroscopy (XRF or LIBS) is executed by a computational system that processes the signal from the sensors and determines the alloying composition and where to eject the scrap piece. The computer ultimately compares the scraps’ specific composition with programmed criteria for each bin corresponding to different alloys [10].

3 Approach

The following chart demonstrates the approach followed. Steps taken were framed by four objectives.



Objective 1:
Identification of scrap-generating alloys is required. These alloys determine the composition of the streams to be sorted and are a key factor when developing sorting criteria using compositional sorting technologies.

Objective 2:
Comprehension of the current scrap-handling procedures is needed. This includes the nature of scrap generation, the regularity of scrap mixing of different alloys and the infrastructure associated with handling high scrap volumes.

Objective 3:
Determination of contaminants that pose issues when sorting and recycling is necessary. Their origins and the manner in which these can affect the aforementioned processes is to be understood.

Objective 4:
Development of sound sorting criteria compatible with compositional sorting systems is necessary. The criteria must be able to sort through the mixed streams to reduce the required scrap recycling processing and prevent downcycling.

4 Results / Discussion

4.1 Alloys Identified

The following list of alloys was identified through a survey distributed to representatives of the "Big Three" of the United States automotive manufacturing industry (Ford, General Motors & Fiat Chrysler) and of aluminum producers. **Table I** shows the alloys organized by family, **Table II** by their use, and **Table III** shows their corresponding compositional limits.

Table I: Identified Alloys by Family.

5xxx-alloy	6xxx-alloy
5182 5454 5754 5005A	6005 6016 6022 6061 6063 6111 6182

Table II: Identified Alloys by Use.

Bodies	Closures
5182 5454 5754 6022 6061 6063 6111 6182	5182 5754 6005 6016 6022 6111

Table III: Compositional Limits of Identified Alloys [12].

Alloy	Si	Fe	Cu	Mg	Mn
6005	0.6 - 0.9	0.35	0.1	0.4 - 0.6	0.1
6016	1.0 - 1.5	0.5	0.2	0.6	0.2
6022	0.8 - 1.5	0.05 - 0.2	0.01 - 0.11	0.45 - 0.7	0.02 - 0.1
6061	0.4 - 0.8	0.7	0.15 - 0.4	0.8 - 1.2	0.15
6063	0.2 - 0.6	0.35	0.1	0.6 - 0.9	0.1
6111	0.6 - 1.1	0.4	0.5 - 0.9	0.5 - 1	0.1 - 0.45
6182	0.9 - 1.3	0.5	0.1	0.7 - 1.2	0.5 - 1
5182	0.2	0.35	0.15	4 - 5	0.2 - 0.5
5454	0.25	0.4	0.1	2.4 - 3	0.5 - 1
5754	0.4	0.4	0.1	2.6 - 3.6	0.5
5005A	0.3	0.45	0.5	0.7 - 1.1	0.15

It is important to note that manufacturers tend to have special alloying compositions developed for their specific purposes. The alloys identified represent the broader compositional designation where the specialty alloying compositions would fall. For example, a company might utilize a specialty alloy where the compositional ranges fall within 6111 but actually requires much tighter and precise compositions than the official designated compositional ranges reported for 6111. Regardless, 6111 would have been reported by the company representative for this specialty alloy as it falls within 6111's compositional ranges.

4.2 Handling

Visits to Ford's Detroit Stamping Plant (DSP) and Flat Rock Assembly Plant (FRAP) and General Motor's Pontiac and Flint Metal Centers were performed to identify current scrap collection practice, including the technology utilized to manage and sort scrap. The identification of contaminants and their origin was also achieved during these visits. An understanding of what scrap treatments may be required must be accounted for and documented to optimize sortation and ultimately recycling

1.1.1 Transport

<u>Inside the Facility</u>

Conveyers

Conveyer belt systems transport material within the facilities. It is important to note that the conveyer systems may also be used for steel, depending on the parts being stamped. The conveyers never transport steel and aluminum at the same time as the stamping of these materials is not done simultaneously on the same press line. Due to oil used in both aluminum and steel stamping, small particles can get stuck at junctions, even surviving a purging process when the conveyer's material is switched from aluminum to steel or vice versa.

The size of the scrap transported through these systems can vary significantly. The size of the particles observed ranged from the small buttons about 1 cm in diameter to blanking scrap of around 45 cm of length. Some conveyers are connected to shredding systems. The shredders are an additional opportunity for ferrous cross-contamination as small material could be stuck between the moving parts.

Fig. 2: Conveyer Transporting Aluminum Stamping Scrap.

Vacuum and Cyclone Systems

Vacuum and cyclone systems have been used effectively to transport aluminum stamping scrap within facilities to trucks waiting to be loaded. The system is normally composed of three steps: shredding, vacuum transport and then truck loading using a cyclone.

Aluminum scrap is initially transported in conveyers like other traditional operations. Sometimes these conveyers are used with steel but ideally, their use is reserved for aluminum as cross-contamination may occur (See Conveyers). The scrap is then fed into a shredder, **Fig. 4**, where its size is reduced to a size adequate for high-speed transport through large vacuum tubes. The tubes are connected to large cyclones that reduce the scrap's speed for safe loading. These systems, although highly effective, are sometimes problematic. Reports of scrap cold-welding onto system parts exist. These have been addressed by water treatment that unnecessarily exposes scrap to contamination and is a step that might cause issues in further processing (See Hydrogen). Another issue can be metal dust (particles extremely small and inadequate for sortation) which can accumulate in the cyclone system; briquetting can be used to salvage this form of scrap. Compass Systems and Sales, LLC is an example of a firm that offers these systems in its line of services and products.

Fig. 3: Shredder Fed by a Conveyer and Connected to a Vacuum Tube [13].

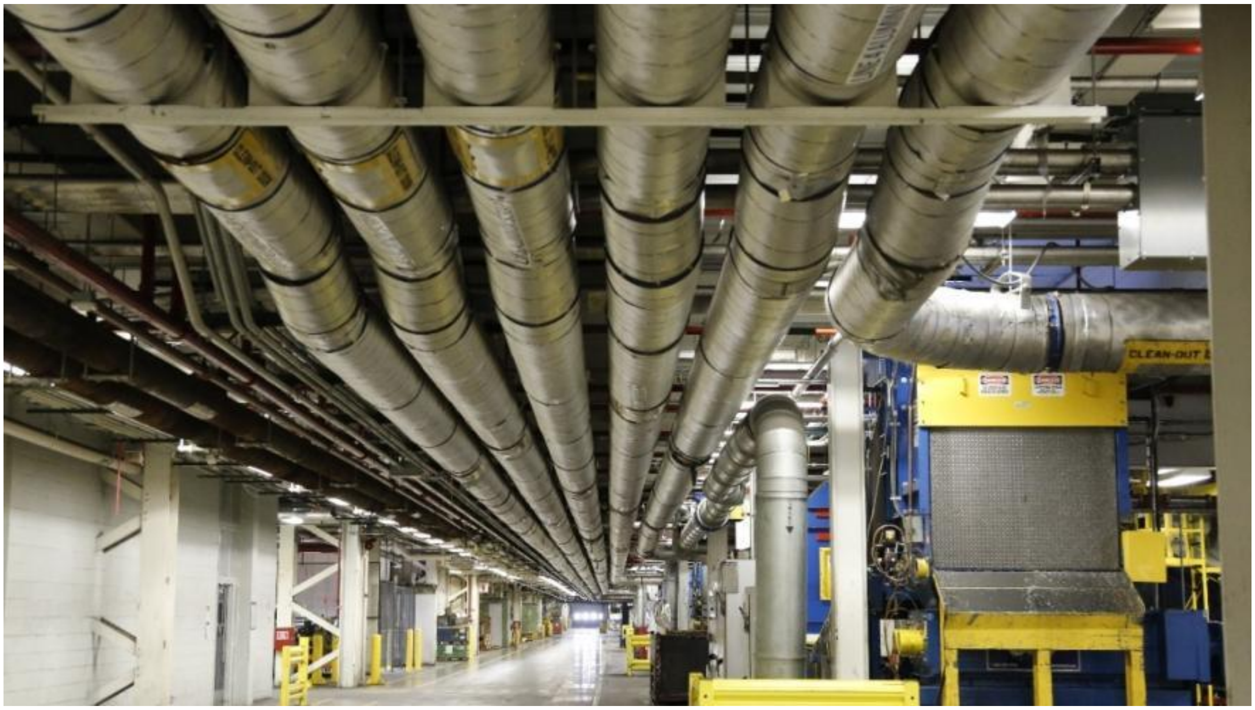


Fig. 4: Vacuum Tubes for Different Scrap Streams at Ford's Dearborn Stamping Plant [14].

Fig. 5: A Cyclone Fed by a Vacuum Tube [13].

Truck Loading

Truck loading depends on each individual plant's scrap handling practices. Truck loading can be a large contaminant source as it is mostly done in outside. The largest hazard is moisture that can result from rain or snow. Ford has taken steps to reduce its scrap exposure to moisture by having a sealed loading process.

Fig. 6: Universal Trailers. Utilized by Ford to both deliver aluminum coil and take scrap. The trailers are loaded by the cyclone systems procedures that reduce expose to the environment [15].

Another consideration is the scrap density, which depends on the scrap size. Large pieces of scrap result in low scrap density. Once piled onto a truck, the irregular and large shapes create large gaps between the materials. The truck's maximum weight capacity may not be taken advantage of due to wasted volume and result in an increase of trips and higher transport costs. Smaller scrap results in better scrap density and more effective transport but minimum scrap size for adequate sortation must also be taken in consideration (See Alloy Sortation).

1.1.2 Collection Streams

For the purposes of this study, all materials streams are composed of aluminum alloys. The discrimination of different alloys is what distinguished a stream type from another.

Mixed Streams

In these streams, alloys are mixed and no criteria for discrimination is observed. Ideally, no cross contamination with steel occurs, but due to reasons discussed in Transport and Summary of Contaminants, cross contamination might still be present.

Ford's 4-Streams

The 4-Stream method is observed at Ford's closed loop recycling program. Ford separates into four streams using compositional criteria.

- **High Copper**: Characterized by copper contents ranging from 0.5% to 0.8%. These fall under the alloy designation of 6111.
- **Low Copper**: Characterized by copper content up to 0.2%.
- **High Magnesium**: Characterized by high levels of magnesium. These would fall under the alloy designation of 5182.
- **Low Magnesium**: Characterized by low levels of magnesium. These would fall under the alloy designation of 5754.

The streams are kept separate since scrap generation. There is no mixing and sortation. Ford uses vacuum tubes to lead the scrap into different cyclones designated for each of the four streams. The vacuum and cyclone systems are controlled dynamically through digital recognition of the loaded stamping die to divert the generated scrap into the cyclone corresponding to each stream [15]. For more on cyclone systems see Vacuum and Cyclone Systems.

Uni-Alloy Streams

In cases where the stamping presses are not connected to dynamic handling systems such as Ford's 4-Streams, a uni-alloy approach can be taken. In these cases, stamping presses are connected to handling systems designated for only a single alloy avoiding any mixing or need for sortation. This can present an issue since automobiles require a high variety of components manufactured from a diverse array of alloys, so limiting stamping and collection systems to single alloys increases the amount of these systems needed or the reduction of parts produced per system. This normally results in parts for multiple vehicles made from the same alloy being produced in single stamping plant to then being transported to their corresponding assembly locations decentralizing the manufacturing process and in turn increasing operational costs. The benefit to the uni-alloy approach is the reduction of contamination from steel and other aluminum alloys to practically non-existent and a high understanding of the scrap's compositional characteristics as the stamping, collection and transport systems are exclusively used for a single alloy.

4.3 Summary of Contaminants

The following is a list of major possible contaminants identified and that could present an issue when sorting or recycling:

- **Oil**: Stamping operations require oil lubrication. Oil content is difficult to measure as it results from accumulation in transport systems such as conveyers that collect oil continuously through their operation and rarely are purged or cleansed. The accumulated oil comes into contact when the scrap moves through the conveyer.

- **Steel (ferrous metals)**: Ferrous contamination arises from the shared use of scrap transport systems. Even if steel and aluminum are not handled simultaneously, small steel pieces can linger in systems, such as conveyers, and then be mixed in once the system has been switched to handle aluminum. A risk exists of the ferrous material reaching the scrap's ultimate destination and increasing the iron content of the secondary melts to unexpected levels as the exact degree of ferrous contamination from these small particles can be difficult to determine.

- **Moisture**: Water arises from the scrap being exposed to the environment and could be especially problematic if no measures are taken to prevent exposure to weather especially rain and snow. Water presents issues during processing reacts with aluminum to produce aluminum oxide and hydrogen (See Hydrogen).

- **Plastics, fibers and boxes**: Plastic, fabrics and other may result from negligence or malpractice of the operating stamping staff that might view the scrap stream and collection system as trash and might dispose of trash through the system. Possible contaminants include but are not limited to plastics (PETE bottles, polystyrene boxes, HDPE jugs, LDPE bags, etc.), fabric (oil rags, clothing, etc.) and cardboard boxes from packaging. These contaminants are more likely to arise if hoppers are used as part of the scrap collection system as these tend to be more accessible to the operating staff and more easily perceived as trash.

4.4 Sortation of mixed streams

Sortation is a necessary step in closed loop recycling. The following section identifies the sorting criteria for effective recycling of mixed scrap. The criteria were designed and tested using multiple python scripts generating randomized data sets representative of a mixed alloy stream and sorting through it. See **Appendix B**.

Mixed streams of aluminum tend to have countless of alloys and many times the alloys forming the stream are not known. It is important to highlight the difference between the stream-forming alloys and the compositional characteristics of such alloys. The former would be a list of the alloys in the stream (*i.e., the alloys identified in previous sections*) and later the chemical composition of such alloys.

When the stream-forming alloys are known, then the sorting criteria can be set to sort for these specific alloys as these could just be re-melted and reprocessed to form new material with minimum needs for compositional rebalancing, as these would already be within the targeted compositional ranges of the alloy being produced.

When the stream-forming alloys are not known then a different sorting criteria must be used. Criteria that create value for the new sorted scrap over the mixed scrap. To do this the sorted scrap must serve a purpose to the aluminum producer that will re-melt it and produce a new alloy, either wrought or cast. For the aluminum producer to use scrap effectively the composition of the scrap must be known. It is important to distinguish between the necessities of determining the composition versus matching such composition to an alloy designation. Overlapping Compositional Ranges

Sorting aluminum scrap by specific alloy is extremely challenging, and in some cases impossible due to overlap in compositional ranges. A piece of scrap generated from some alloy through the stamping process might be difficult to categorize after it has been mixed into a scrap stream even if the alloys of such stream are known. For example, alloys 5005A and 6063 have overlapping compositional ranges for the major elements (silicon, iron, copper, magnesium and manganese). If a scrap piece is found to have a chemical composition that lies within the specifications of both alloys, then achieving an accurate distinction between the two is difficult. The sorting decision is made by comparing the compositional reading to a preset sorting criterion. This sorting algorithm encounters errors or difficulty in determining the corresponding alloy bin when there is significant compositional overlap. **Table V** shows an example of a scrap piece that could problematic when sorting between 5005A and 6063. From the alloys identified in the previous section, the pairs presented in **Table VI** expose issues due to compositional overlap during compositional sorting.

Table V: Compositional Limits for 5005A, 6063 and Scrap Example.

Alloy	**Si [%]**	**Fe [%]**	**Cu [%]**	**Mg [%]**	**Mn [%]**
5005A	0.3	0.45	0.5	0.7 – 1.1	0.15
6063	0.2 – 0.6	0.35	0.1	0.6 – 0.9	0.1
Scrap Example	0.25	0.2	0.08	0.75	0.075

Table VI: Alloys with Compositional Overlap.

6005 & 6063
6022 & 6005
6022 & 6016
6063 & 5005A
5454 & 5754
5005A & 6063

It is important to note that for most of pairs to present an issue when sorting the aluminum scrap's composition would have to be on the compositional limit to create overlap. In the 5005A & 6063 example, the piece of scrap would have to have a composition of ~0.25% silicon. Even though this is unlikely, due to errors in composition reading by sorting systems, a value close to this one might result in erroneous sortation. Another consideration would be the criteria in which the sorting systems are programmed to operate. Limitations on compositional readings of some elements could result in insufficient data to sort adequately. In the 5005A & 6063 example, a criterion for alloyed silicon is required to sort most accurately as silicon is the alloying element with the least overlap.

1.1.3 Compositional Tolerance

Optimized sorting criteria must be developed to recycle aluminum alloy scrap effectively and should keep compositional tolerance in mind. Compositional tolerance refers the ability of a melt to accept scrap of a certain alloy or composition without it hindering (*i.e.*, *without substantial effort required to rebalance*) its composition. The desired melt composition can be of a specific value or range depending on the material. Scrap with lower contents of alloying elements than the desired composition can be used as the charge for a melt and then using basic stoichiometric principals it can be sweetened by adding primary or new material to achieve the desired composition.

This approach is compatible with all the major alloying elements. It is important to note that the composition of the resulting melts will always fall between the scrap of the highest and lowest compositions by the nature of averaging. The exact composition of the melt be can only be known through testing the melt once the scrap has been combined or stoichiometric analysis of each piece of scrap's mass and composition to calculate the resulting average prior to melting. The latter remains impractical if not impossible at high volumes as each scrap piece has different amounts of alloying elements even if these are from a single alloy.

The following stoichiometric formula determines the amount sweetening material to be added:

$$\text{Material to be Added} = \mathrm{M_i}\left(\frac{\mathrm{n_{b_i}}}{\mathrm{n_{b_f}}}\mathrm{n_{e_f}} - \mathrm{n_{e_i}}\right)$$

$$\mathrm{M_i} = \text{Mass of melt prior to material addition}$$

$$\mathrm{n_{b_i}} = \text{initial alloying element composition}$$

$$\mathrm{n_{e_f}} = \text{final alloying element composition}$$

$$\mathrm{n_{b_f}} = \text{final alloying base metal composition}$$

$$\mathrm{n_{e_o}} = \text{initial alloying element composition}$$

For example, if there is a melt of 34 kg with an initial composition of 97% aluminum and 0.5% magnesium with a desired composition of 96% aluminum and 0.6% magnesium then around 0.36 kg of magnesium should be added. An analysis was carried out to identify which alloys are tolerant to each other using an algorithm that compares their nominal compositional ranges. Full tolerance to an alloy implies that the upper limits for each major element are equal to or below those of the desired melt. Full tolerance results in every piece of this alloy scrap not exceeding the sink upper compositional limits. The following table shows alloys, the scrap of which, are fully tolerant to produce melts of the desired alloys.

Table VII: Fully Compatible Sink and Source Alloys.

Source: Fully Tolerated Alloys	Sink: Desired Melt Designation
6005	6016
6063	6061
6005, 6063	6111
6005, 6063	6182

Partial tolerance to an alloy implies that the lower limits for each alloying element are below the upper limits of the desired melt. This indicates that a portion of the source alloy scrap will be under the sink upper compositional limits. The following table shows alloys, the scrap of which, are partially tolerant to produce melts of the desired alloys.

Table VIII: Partially Compatible Sink and Source Alloys.

Source: Partial Tolerated Alloys	Sink: Desired Melt Designation
6063	5005A
5754, 5005A	5182
6063, 5754, 5005A	5454
6063, 5005A	5457
6022,	6005
6022	6016
6005, 6016, 6063	6022
6005, 5005A	6061
5005A	6063
6016, 6022, 5005A	6111
6016, 6022, 5005A	6182

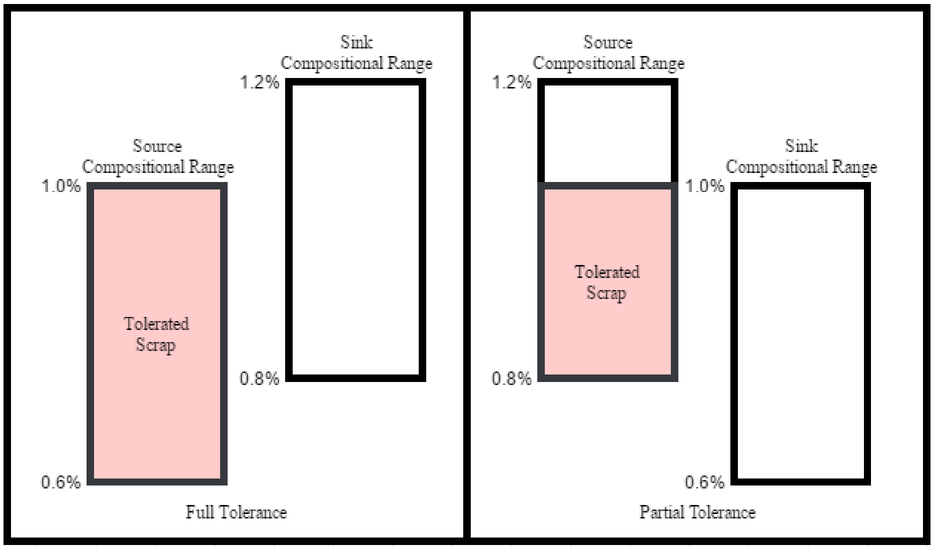
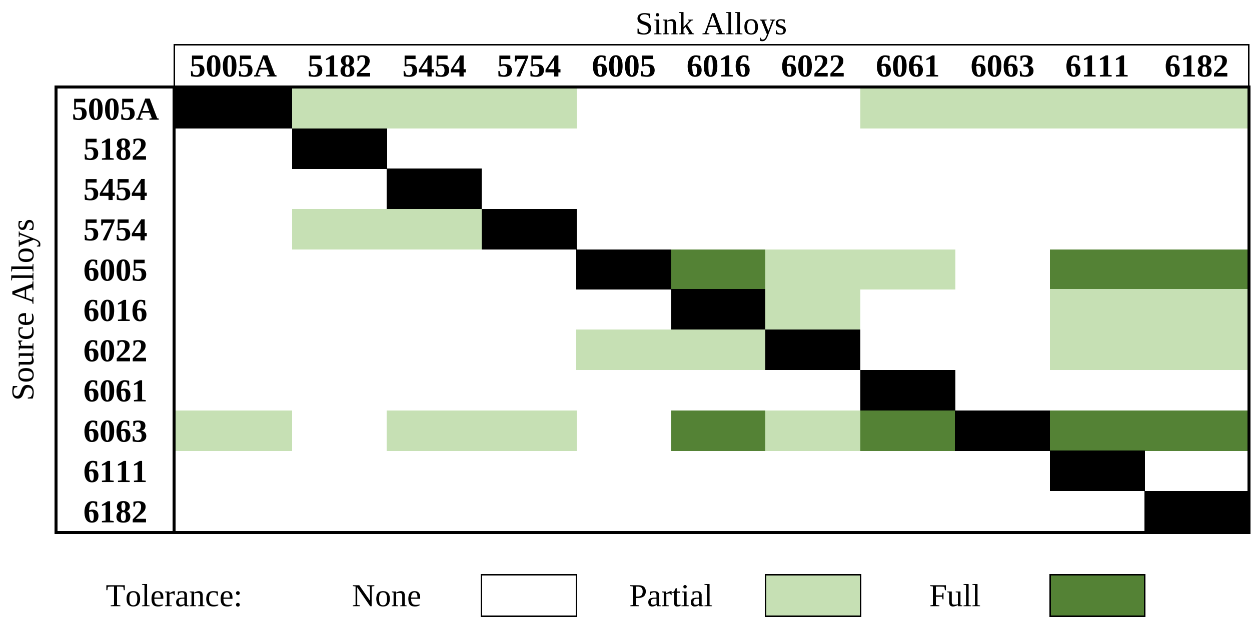


Fig. 7: Full vs. Partial Tolerance.



Sink Alloys

Source Alloys	5005A	5182	5454	5754	6005	6016	6022	6061	6063	6111	6182
5005A	■	▨	▨	▨				▨	▨	▨	▨
5182		■									
5454			■								
5754		▨	▨	■							
6005					■	🟩	▨	▨		🟩	🟩
6016						■	▨			▨	▨
6022					▨	▨	■			▨	▨
6061								■			
6063	▨		▨	▨		🟩	▨	🟩	■	🟩	🟩
6111										■	
6182											■

Tolerance: None ☐ Partial ▨ Full 🟩

Fig. 8: Summary of Alloy Tolerance.

Fig. 8 shows what alloys can be fed into another's melt. It shows that if the upper compositional limit is used as the sorting criteria, some alloys remain unusable as a source material such as 5182, 5454, 6061, 6111 and 6182 due to its higher element ranges. However, it can be seen that these alloys can act as sinks to other alloys suggesting that scrap generated from another alloy can be useful for the fabrication of alloys other than that being recycled.

1.1.4 Sorting for Alloy Identification

If distinguishing between alloys is the objective, an understanding of the stream-forming alloys is necessary, as the criteria for sortation would be based on the ability of sorting systems to discern between alloys depending on their compositional ranges. The issue of overlapping compositions may arise depending on the set of alloys being sorted, as there might be scrap pieces that have compositions satisfying two alloying compositions (See Overlapping Compositional Ranges). The following alloys can successfully sort from the identified alloys of the previous section of this study as these present no compositional overlaps in at least one of the major alloying elements.

Table IX: Sorting Bins Using Two-Elements.

Alloy Bins	Si [%]	Fe [%]	Cu [%]	Mg [%]	Mn [%]
5182	0.2	0.35	0.15	4 – 5	0.2 – 0.5
5754	0.4	0.4	0.1	2.6 – 3.6	0.5
5454	0.25	0.4	0.1	2.4 – 3	0.5 – 1
6111	0.6 – 1.1	0.4	0.5 – 0.9	0.5 – 1	0.1 – 0.45
6182	0.9 – 1.3	0.5	0.1	0.7 – 1.2	0.5 – 1
Other	1.5	0.7	0.5	0.25 – 1.2	0.2

To successfully sort between the alloys there has to be at least one alloying element whose compositional range does not overlap with any other alloy. **Fig. 9** shows a graph of the copper and magnesium compositional ranges of the alloys. It can be observed that alloy 6111 can be discerned from the rest due to its distinct alloyed-Cu content. In addition, 5182 can be discerned through its magnesium content.

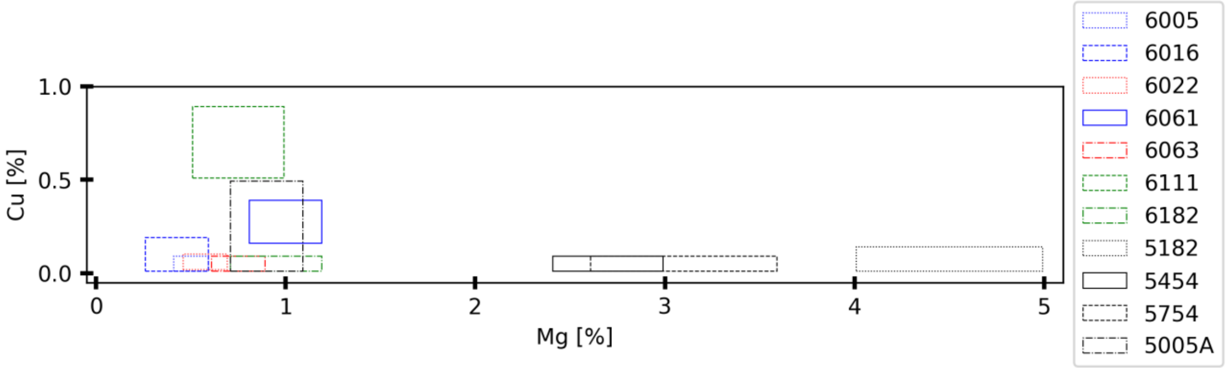


Fig. 9: Copper and Magnesium Compositional Ranges for Identified Alloys.

From **Fig. 9** it can be observed that distinguishing between 5454 and 5754 is difficult as these have overlapping magnesium ranges. Another element can be used to differentiate between the two alloys.

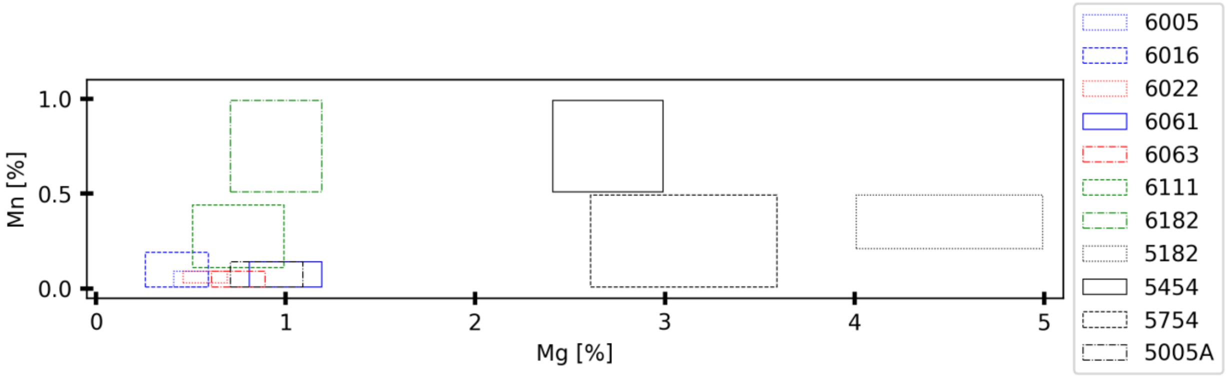


Fig. 10: Manganese and Magnesium Compositional Ranges for Identified Alloys.

Fig. 10 shows that discerning between 5454 and 5754 can be done through their Mn compositional ranges. It is also observed that 6182 can be differentiated from the rest of the alloys using manganese content. In this set of alloys, analyzing other major alloying elements does not yield any possible bin using this method. The rest of the alloys that are unable to be sorted are grouped in a category named "other." The result is six sortable alloys for this set of alloys.

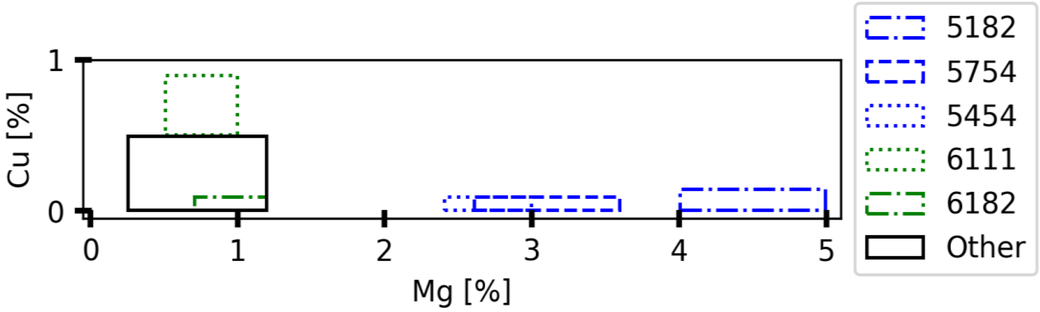


Fig. 11: Copper and Magnesium Compositional Ranges for Sortable Alloys.

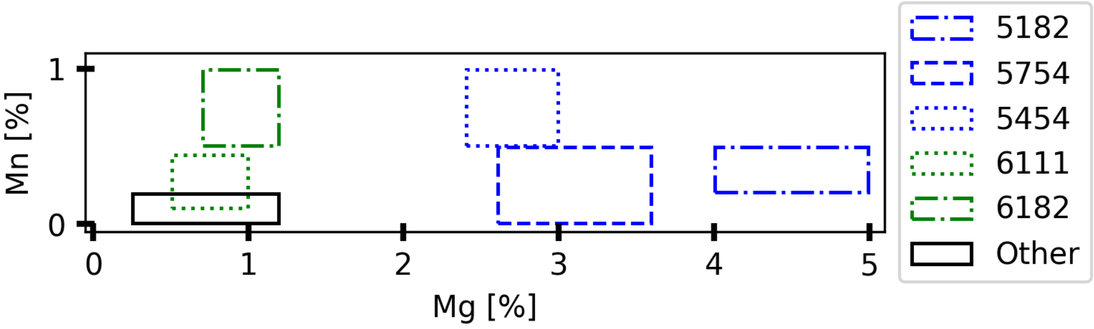


Fig. 12: Manganese and Magnesium Compositional Ranges for Sortable Alloys.

In **Fig. 11** and **Fig. 12**, progression towards optimized sorting criteria is clear as compositional overlap is decreasing. It is important to note that not all producers would be satisfied in simply recreating alloys that have compositions that fall within the acceptable ranges, as producers tend to hold themselves to stricter quality standard and ranges. The resulting melts produced from the bin approach should result in compositions close to those desired by the producers. The producers can then take steps to rebalance the composition by either "sweetening" the material to increase the alloying element concentrations or by increasing the base metal, aluminum, to dilute the alloying concentrations. This can prove to be rather labor intensive as the rebalancing melts requires stoichiometric work that varies from melt to melt.

The "other" category proves to be quite problematic. Sorting for alloy identification is ultimately an issue of multiple dimensions. In the previous plots, only two dimensions or elements where considered at a time which resulted in the ability to discern only five alloys from the mixed stream. To be able to discern all alloys, a higher dimensional approach must be taken, or one that takes into account more alloying elements (dimensions). In this case, five elements are being considered so for full alloy identification all these have to be taken into account.

When running a randomly generated digital mixed sample of 50 scrap pieces of each alloy through a sorting algorithm that takes into account all of the five elements, it results in a higher ability to discern between alloys. Alloys such as 6061 are now fully discernable from the other bin. A massive improvement over a 2D approach but it still has its limitation.

Compositional overlap remains an issue even when sorting using five elements. The sorting algorithm was not capable distinguishing scrap pieces of overlapping alloys from each other. For example, 23 scrap pieces of alloy 6022 where categorized under 6016. That is 46% of 6022 scrap overlapped in composition with the designation of 6016. This pair was not the only to present issues but also all the other pairs identified in **Table VI**. See **Appendix C** for sorting results.

1.1.5 Sorting for Charge Melts

Since compositional overlap presents an issue, even when sorting using all elements, a better approach might be to sort with the intention of creating charge melts. The scrap that is sorted into the inappropriate bin due to compositional overlap is also fully tolerated by the melt to be formed from the bin, as its composition must be within the desired alloy's composition. The scrap composition is within that of the desired range. Even though this approach is similar to that of alloy identification, it differs in its intention. This approach is concerned in creating melts to produce a certain alloy instead of identifying the scrap's original alloying designation.

The sorting algorithm sorted 23 pieces of 6022 into the 6016 bin but every single one of these 6022 scrap pieces' composition was within that of the 6016 range. This resulted in 73 total pieces with the following average composition.

Table X: Average Composition for 6016 Sorting Bin.

Scrap Count	Cu [%]	Fe [%]	Mg [%]	Mn [%]	Si [%]
73	0.09	0.21	0.45	0.09	1.23

This average composition is in fact within the desired compositional range of 6016 so if re-melted and used to produce an ingot, the ingot would fall under 6016 designation. This shows that sortation for alloy identification should not necessarily be the goal but sortation for alloy charge for melts. Every other bin that experiences identification issues also behaves this way. Even though not all scrap pieces are of the desired alloy designation, every piece's composition falls under the desired range making the average composition also fall within the desired range.

It is important to note that post-sortation processing will most likely always be necessary. Producers hold themselves to stricter compositional ranges than those used to define alloy designations so "sweetening" or dilution of the melts will most likely always occur to rebalance the melt to the desired composition. This is done through the process described in the compositional tolerance section.

Since sorting technologies might have limitations for elements analyzed, and since sorting and rebalancing will most likely always occur, sorting using two elements can still be useful. For example, the sorting algorithm when set to sort for scrap of alloy 5005A using all elements resulted in a total of 59 pieces of which 50 were 5005A and 9 were 6063. The average composition was the following:

Table XI: Average Composition of 5005A Sorting Bin Using All Elements for Sortation.

Scrap Count	Cu [%]	Fe [%]	Mg [%]	Mn [%]	Si [%]
59	0.23	0.19	0.89	0.076	0.17

As expected, the compositions are all within the desired range even through there are 9 pieces of 6063 scrap. When the sorting algorithm was utilized only using magnesium and copper ranges as sorting criteria, it resulted in 114 scrap pieces of which 50 were 5005A, 25 were 6063 and 39 were 6061. Using such criteria, 6061 is expected to be part of the mix as there is compositional overlap for magnesium and copper between 5005A and 6061. The average composition is the following:

Table XII: Average Composition of 5005A Sorting Bin using Cu and Mg for Sortation.

Scrap Count	Cu [%]	Fe [%]	Mg [%]	Mn [%]	Si [%]
114	0.23	0.25	0.91	0.064	**0.35**

Only silicon is out of range when sorting using copper and magnesium. It is at ~0.35% when it should not exceed 0.3%. The easiest way to rebalance this melt would be through dilution with more aluminum. If the two-element sortation is used, then magnesium and copper should be used, as these are the elements with least compositional overlap. Most of the rest of the elemental compositional ranges tend to be defined by an upper limit only, making them difficult to use to discern among alloys. See **Appendix C** for the sorting results using magnesium and copper as criteria.

4.5 Further Remarks

Ultimately, scrap management has to be analyzed on a case-by-case basis. A developed analysis of costs has to be developed to decide what approach is best. Multiple variables go into determining which scrap management strategy is best for a stamping operation.

Initial intuition seems to point at avoiding the mixing of scrap of different alloys. Even though this is effective, there are some requirements associated to this approach. To be able to control different streams of segregated scrap is not an easy task. Stamping operations are frequently performed using the same stamping press with interchangeable tooling (dies). Even though the tooling is changed, often the stamping presses are connected to single scrap collection system that leads to the same place. This can become even more problematic if the equipment is used to stamp aluminum and steel for aforementioned reasons. Some engineers have tried taking a scheduling approach to evade the need to change any of the physical capital. Even though it is a clever proposition, manufacturing schedules are extremely volatile and are always changing due to varying demand. Assuming that all production can be scheduled without unforeseen circumstances is idealistic. Proper scrap management is often not the upmost priority when production goals are not met.

The uni-alloy approach discussed in this study is a solution when it comes to always making sure that scrap remains unmixed but presents logistical issues. Limiting the use of a stamping press configuration to single alloy implies that the equipment will be underutilized or used to produce parts for multiple vehicles that will have to be shipped to assembly plants increasing associated transport costs.

The acquisition of proper scrap management infrastructure is a significant investment that has to be justified. Vacuum and cyclone systems are extremely useful when managing different scrap streams and alloys for operations making Ford’s 4 streams possible. Ford’s streams manage an extremely high volume of scrap making the investment highly justifiable. Their centralization of the stamping operation also helps to reduce the investment, as a single plant is able to carry out most of the aluminum operations. In the case where the stamping operations are spread out between multiple plants, the required investment would increase, as each plant would require its own management system. The layout and size of each plant is relevant as it is often what determines the required investment or feasibility of infrastructure integration. Large plants with long distances between stamping operations and loading areas require longer vacuum tubes or conveyers that increases the infrastructure’s cost. In other cases where space is limited by the proximity of equipment, the addition of scrap management infrastructure might simply not possible.

Many of the aforementioned situations can lead to a mixed alloy streams. The mixed alloys stream are most likely to come out of many low volume operations and not out a large volume operations since the latter are more likely to justify efforts to maintain alloy streams separate. It is also important to note that acquiring alloy sorting technology is also a considerable investment and a case has to be made to justify such acquisition. Understandably, the best places where to allocate such technology would be in the hands of aluminum recyclers that can serve areas with high scrap output. Areas, such as the United States Midwest, seem to be promising due to a high stamping operations density that could see recycling centers serving multiple stamping plants to satisfy volume requirements (See Appendix D for map of stamping operations). Not only the availability of the scrap is beneficial but also the lower the distance the scrap has to travel. There are multiple considerations involved when transporting scrap including associated costs of scrap density and liability issues regarding ownership of the scrap in the case of an accident.

Two different approaches on the development of sorting criteria are discussed in this study but by no means are representative of all that can be done to improve the creation of multiple segregated streams or bins from mixed alloy streams. The analysis was made using an artificially created randomized data set of 50 pieces of scrap of alloy type. The data is not an accurate representation of real scrap. Compared to real scrap, the randomized data set displays high compositional dispersity. Since producers hold themselves to tighter ranges, then real scrap would not display this dispersity. Another consideration is that the randomized set displays no compositional errors. All the scrap produced by the algorithm is in fact within the desired ranges. In reality, production mistakes do occur making some pieces of metal have compositions outside the intended ranges that could be problematic when sorting for identification or charge material. The accuracy and reliability of the sorting equipment is not taken into account in this situation. There are limitations posed by the sensors that affect the accuracy of the compositional reading. These misreading are not taken into account by the sorting algorithm used in this study and in reality could pose issues when trying to sort using all elements as an inaccurate reading in one element could result in a sorting mistake.

Scrap characterization would be greatly beneficial to improve mixed stream sorting. To understand the stream beyond which alloys form it but also to also gather data on the average compositions of such alloys would greatly improve the quality of sorting criteria. This would allow for sorting algorithms testing with real data over the artificially generated scrap sample.

5 Conclusions / Implications

Aluminum sheet automotive usage is expected to increase to 61 pounds per vehicle in 2020 from 23 pounds per vehicle in 2015, a 250% increase. Almost all on closures and Body-In-White. Assuming production stays at current levels; a total usage of 1.06 million tons of aluminum sheet can be expected by 2020. This increase requires appropriate scrap management practices to prevent mismanagement and downcycling of the material.

Eleven alloys were identified from which scrap can be generated. Three different possible scrap streams were identified, one in which the scrap is all mixed, one in which the scrap is separated by general composition (high and low magnesium and high and low copper), and one in which only one alloys is present (uni-alloy). The most important contaminates were identified as lubricant oil, steel, moisture and packaging materials.

The exposure to contaminants can be reduced by using the appropriate transport and collection technologies. The use of minimal lubrication of conveyer belts can help reduce the accumulation of oil on scrap in contact with the handling equipment. Alternatives, such the vacuum and cyclone systems, can improve the scrap handling rate and reduce its exposure to oil and water. Water can exposure can be limited to by having sealed truck loading operations. Limited contaminant exposure can reduce the amount and intensity of recycling steps required.

Sorting criteria must be developed in a case-by-case basis taking into account what is known of the alloy composition of the mixed stream, the limitations of the sorting equipment and alloy compositional overlap. This study looks at the unrealistic possibility of sorting a mixed stream composed of the 11 alloys. Stamping operations do not necessarily use all alloys, so the generated mixed streams could be reassessed to produce more effective sorting criteria. When full sortation is not possible due to compositional overlap issues, the goal of sorting should not be alloy identification but the segregation of material that can potentially be used to charge wrought melts with minimal rebalancing.

Operations that output mixed streams can gain from the advent of sorting technology adequately allocated to serve high production zones such as the United States Midwest. The density of stamping operations would allow for the justification of the required investment when acquiring compositional sorting systems. Low volume stamping operations can also benefit from evading the large investments required to acquire handling systems to maintain segregated scrap streams upon generation.

Large volume operations have the most to gain from investing in scrap handling systems for segregated scrap streams to facilitate closed loop recycling and reduce required sorting. The penetration of sorting systems in the United States cannot handle the increasing scrap generation. Large operations allow for the justification of scrap handling systems, as these would be serving a higher volume of scrap.

6 Recommendations for Future Work

Compositional characterization of a representative sample of real wrought scrap using LIBS would be extremely beneficial in advancing this research. This would improve on multiple aspects limiting this study.

This study used a randomized set of data with 50 pieces of each of the identified alloys. First, the scrap composition could confirm the identified alloys. Second, the sample would also prove insightful in understanding the relative volumes of each alloy scrap. Compositional sorting equipment do not perform sortation based on mass but composition and the volume of each alloy consumed by the automotive industry is not necessarily related to the volume and pieces of scrap being produced. Taking this in consideration, scrap characterization of a representative sample is the best method to increase the comprehension of the relative volumes of the alloys forming the scrap instead of just assuming an equal amount of scrap pieces for each alloy. Another advantage of the characterization would be an understanding of the dispersity of the alloying compositions. This study assumed a randomized composition for each piece of scrap within the alloying limits. This is not realistic, as the physical properties desired by most automotive manufacturers tend to result from the same specific combination of alloying compositions. An understating of this dispersity can result in the development of better of randomized data sets that would lead to the development of better sorting criteria.

This study does not take in consideration compositional reading errors produced by sorting system that can cause the sorting criteria to inaccurately sort scrap pieces. The use of sorting systems, such as LIBS, would be ideal to calculate the rate of missorts and integrate the error rate into the sorting models and sorting criteria development.

Machine learning tools can be used to analyze the characterized data to determine better sorting criteria that might not be achievable through traditional analysis. Machine learning can allow for the continuous improvement of sorting criteria but would require the development of a large and representative sample of characterized scrap as a training data set to prepare the sorting systems for real tests using industrial scrap.

7 Works Cited

[1] A. Graf and Constellium, "The Case for Aluminum Body-in-White Design," *Light Metal Age,* pp. 38-39, 2015.

[2] Ducker Worldwide, "Aluminum Content in North American Light Vehicles 2016 to 2028," Ducker Worldwide, Troy, MI, 2017.

[3] W. McDonough and M. Braungrt, Cradle to Cradle, New York: North Point Press, 2002.

[4] J. A. Green, Aluminum Recycling and Processing for Energy Conservation and Sustainabilty, ASM International, 2007.

[5] "Aluminum in Transport," Aluminum Leader, [Online]. Available: http://www.aluminiumleader.com/application/transport/. [Accessed 01 October 2017].

[6] EDAG ENGINEERING GmbH, "VENZA Aluminum BIW Concept Study," 2013.

[7] Aluminum Transport Group, "Aluminum Advantages: Safety," Drive Aluminum, [Online]. Available: http://www.drivealuminum.org/aluminum-advantages/safety/. [Accessed 15 April 2018].

[8] M. A. Omar, The Automotive Body Manufacturing Systems and Process, West Sussex: John Wiley & Sons Ltd., 2011.

[9] M. E. Schlesinger, "Aluminum Recycling," Tylor & Francis Group, Boca Raton, FL, 207.

[10] G. Gaustad, E. Olivetti and R. Kirchain, "Improving aluminum recycling: A survey of sorting and impurity removal," *Resources, Conservation and Recycling,* no. 58, pp. 79-87, 2012.

[11] L. Brooks, T. Mortvedt, G. Gaustad and A. J. Gesing, "Potential for Handheld Analyzers to Address Emerging Positive Material Identification (PMI) Challenges," *Light Metals 2018,* pp. 1131-1135, 2018.

[12] The Aluminum Association, "International Alloy Designations and Chemical Compositional Limits for Wrought Aluminum and Wrought Aluminum Alloys," Arlington, VA, 2005.

[13] Compass Systems, "Case Study - Automotive Industry Handling Metal Scrap," [Online]. Available: http://compasssystems.com/automotive-case-study/.

[14] Ford, "One Chip at a Time: How One Engineer's Innovation has Ford now recycling 20 million pounds of aluminum a month," 21 April 2017. [Online]. Available: https://media.ford.com/content/fordmedia/fna/us/en/news/2017/04/21/ford-recycling-20-million-pounds-of-aluminum-monthly.html.

[15] L. B. Chappuis, *Materials Specifications & Recycling. An Industrial Perspective,* Vancouver, BC: University of British Columbia, 2017.

[16] P. Mallick, "Materials, design and manufacturing for lightweight vehicles," CRC Press LLC, Boca Raton, FL, 2010.

[17] Edimet Spa, aluminum&cars, Brescia, Italy: Tipografia Camuna, 2004.

[18] S. Surak, "Downcycling," in *Encyclopedia of Consumption and Waste: The Social Science of Garbage*, Thousand Oaks, CA, SAGE Publications, Inc., 2012, pp. 193-194.

[19] O. Bloor, E. Scott-Clarke and K. Scott, "The brewery that turns bread into beer," CNN, 17 December 2017. [Online]. Available: https://www.cnn.com/2017/11/14/world/toast-ale/index.html. [Accessed 15 April 2018].

[20] J. M. Cullen, "Circular Economy: Theoretical Benchmark or Perpetual Motion Machine?," *Journal of Industrial Economy*, 2017.

[21] D. Altenpohl, in *Aluminum: Technology, Applications, and Environment*, Warrendale, PA, TMS-AIME, 1998, p. 61.

[22] R. Peterson, "Reducing chlorine usage in furnace fluxing: two case studies," in *Light Metals 1995*, Warrendale, PA, TMS-AIME, 1995, p. 1197.

[23] P. Waite, in *Light Metals 2002*, Warrendale, PA, TMS-AIME, 2002, p. 841.

[24] P. Waite, "Improved metallurgical understanding of the Alcan Compact Degasser after two years of industrial implementation in aluminum casting plants," in *Light Metals 1998*, Warrendale PA, TMS-AIME, 1998, p. 791.

[25] Jaguar Land Rover Limited, "Jaguar Land Rover - Novelis' recycled aluminum cars (REALCAR)," 24 July 2017. [Online]. Available: http://www.circulary.eu/project/jaguar-realcar/.

[26] Ford, "Ford, Alcoa collaborative on more formable and design-friendly next-generation aluminum alloys," 14 September 2015. [Online]. Available: https://media.ford.com/content/fordmedia/fna/us/en/news/2015/09/14/ford-alcoa-collaborate.html.

[27] A. Graf and Constellium, "The Case for Aluminum in Body-in-White Design," *Light Metal Age*, pp. 38-39, October 2015.

Appendix A: Supplementary Background

Aluminum Production

Primary Production

Primary metal production is referred to metal produced from ore in deposits extracted from the earth's crust. The first step in producing aluminum from raw materials is bauxite mining. Mining normally happens in tropical and sub-tropical countries in open-pit mines. Bauxite consists mostly of hydrated alumina and a range of iron oxides. The second step in aluminum production is known as the Bayer process where alumina (Al_2O_3) is produced from bauxite ore. Alumina is also known as aluminum oxide, aloxide, aloxite and alundum. The third step consists of smelting through the Hall-Héroult process where alumina is refined into pure aluminum metal. The process consists of using carbon anodes and a molten cryolite salt bath to separate the oxygen from the aluminum. The aluminum settles in the bottom of the melt where it moved into the next step of the process. The pure aluminum metal is then casted into ingots, which can be used to make wrought, cast or extruded products [9].

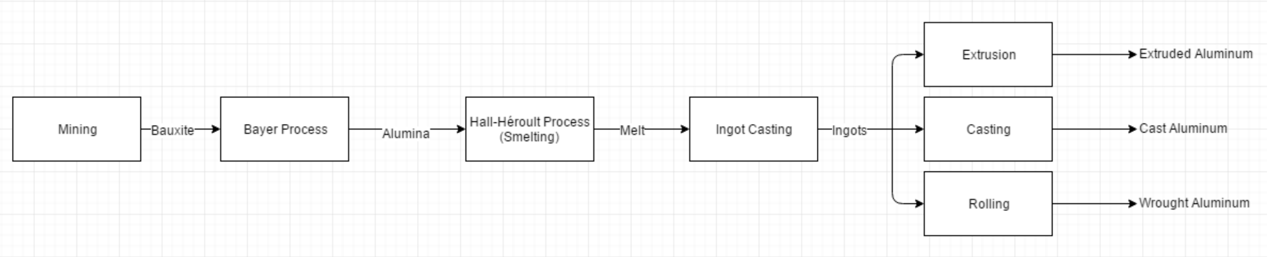


Fig. 13: Aluminum Primary Production.

Wrought Alloy System

Wrought alloys are those that have been turned into consumer products by solid-state processing including rolling, extruding and forging. Wrought alloys mostly consists of at least 90% aluminum or sometimes at least 95% aluminum. There are eight different classes depending on main alloying elements [9].

- *1xxx* alloys: The purest class, contain 99% or more aluminum. Used in electrical and chemical applications, and packaging foil. Due to its high aluminum content, it is very hard to produce through recycling.
- *2xxx* alloys: These contain 1% to 6% copper and other elements including iron, magnesium, manganese and silicon. The highest strength class normally used in aircraft and fasteners.
- *3xxx* alloys: These contain up to 1.5% manganese and between 0.7% to 0.8% iron. Mostly known for being used in the body of aluminum cans. These display strain hardening and anticorrosive properties.
- *4xxx* alloys: These contain up to 13% silicon. Mostly used in forging and welding, it shows high wear resistance. Due to its high silicon content, its scrap is valued in secondary cast production.
- *5xxx* alloys: With contents of magnesium of up to 5.5%, these alloys are known for their corrosion resistance, toughness and weldabilty. These are found everywhere from bridges to

the lids of cans. Since magnesium is the easiest alloying element to be refined from aluminum, its recycling of this alloy group can result in wrought recycled alloys easier than the other groups.

- *6xxx* alloys: Can contain up to 1.5% magnesium and 1.8% silicon. Used in architecture and automotive applications. Like in 4xxx alloys, high silicon contents also present an issue for recycling.
- *7xxx* alloys: can contain from 1.5% to 10% zinc, up to 3% magnesium and 2.6% copper. Used mostly in aviation industry, these present extremely high toughness and strength but low corrosion resistance.
- *8xxx* alloys: Includes any alloying element not seen in the other classes such as lithium, boron, nickel, tin and vanadium.

Table XIII: Wrought Aluminum Alloy Designation System.

Alloying Series	Principal Alloying Element
1xxx	At Least 99% Aluminum
2xxx	Copper
3xxx	Manganese
4xxx	Silicon
5xxx	Magnesium
6xxx	Magnesium and Silicon
7xxx	Zinc
8xxx	Other Elements

Cast Alloy System

Cast alloys, as their name suggests, are those that have been casted or produced from a melt. Cast alloys tend to have more variety in their compositions compared to their wrought counterparts. The classifications are similar to those of the wrought system as the main alloying elements for each classification by number remain the same [9].

- *1xx.x* alloys: These are composed of at least 99% aluminum similar to the *1xxx* wrought class. These tend to be used to make ingots that in turn serve as material for re-melting and creating other alloys.
- *2xx.x* alloys: These contain from 3.5% to 10.7% copper, the main alloying element. Can also contain significant levels of iron, magnesium, nickel or silicon. They demonstrate high-temperature strength but require heat treatment to prevent stress-corrosion cracking.
- *3xx.x* alloys: Contain silicon levels from 4.5% to over 20% and copper levels ranging from 0.5% to 5%. Sometimes, magnesium is added from 0.5% to 1.5% and nickel from 0.5% to 3.0%. The silicon helps with fluidity and casting by reducing shrinking porosity in casting and the copper and magnesium provide solid solution hardening.
- *4xx.x* alloys: Contain levels of silicon at the range of 3.3% to 13% with smaller levels of other elements compared to the *3xx.x* class. Copper, iron and nickel can also be present.
- *5xx.x* alloys: Includes 3.5% to 10.5% magnesium. Lower levels of iron, silicon and zinc are used.

- *7xx.x* alloys: These require zinc levels of 2.7% to 8.0%. Magnesium and chromium can also be present at 0.5% to 2.0% and 0.2% to 6% respectively.
- *8xx.x* alloys: Include 5.5% 7.0% tin and 0.7% to 4.0% copper. These are much less common than the others in the series.

Table XIV: Cast Aluminum Alloy Designation System.

Alloying Series	Principal Alloying Element
1xx.x	At Least 99% Aluminum
2xx.x	Copper
3xx.x	Silicon and Copper and/or Magnesium
4xx.x	Silicon
5xx.x	Magnesium
7xx.x	Zinc
8xx.x	Tin
9xx.x	Other Elements

Manufacturing Technologies

Casting

Casting is a process in which a molten material flows into a mold and is allowed to solidify taking the shape of the mold. The complexity of casting can range from simple gravity pouring into an open mold to more complex processes such as semi-solid slurries that are then injected into a closed metal mold. Casting offers advantages such as reducing component cost through creating parts with complex internal and external geometries, reducing assembly required and post casting processing with near net shape. The limitations include lower mechanical relative to wrought metals (due to large-scale porosity and/or inclusions in solidification), a need for larger dimensional tolerancing than wrought processes and significant safety issues address when handling molten metal [16]. Relevant parts produced through casting include engine blocks, and cylinder heads [17].

Extrusions

Extrusion is a manufacturing process that consists of pushing a billet of material through a die orifice using a ram. It can be done at room temperature or at elevated temperatures. The material takes the shape of the die orifice. Extrusion can produce any part of a constant cross-sectional geometry including tubes, channels and bars.

Extrusions are increasing in automotive applications with the increase of aluminum usage as light alloys have better extrudabilty than steel (steel has poor extrudabilty which has limited extrusion as a process to fabricate steel parts). Aluminum extrusions are used in a range of components including drive shafts, body structure, suspension components, intake manifolds, bumpers, seats, and doors. Extrusions can help improve with weight savings but tends to require appropriate design for crash energy management to meet safety requirements [16].

Aluminum extrusions usage is expected to grow to 49 pounds per vehicle in 2020 from 36 pounds per vehicle in 2015 including an increase of 65% (~6 lbs) in crash management parts and 100% (4.4 lbs) in extruded Body-In-White components [2].

Sheet Metal Stamping

Stamping processes consist of changing the shape of sheet metals blanks into a desired form using a die and mechanical press. Stamping requires the development of the associated tooling including the die, fixtures and transfer mechanisms that depend on the desired part geometry [8]. Stamping starts with the use of a rolled coil provided by mills that is later cut into pieces that are then blanked. Blanking is the stamping process where a sheet is cut into closed shape that is to be used in a future operation. The piece that is formed is called the blank. Blanking differs from punching or piercing, as the part being scrapped in blanking is the outer piece, while in punching, the part being scrapped is the centerpiece. Blanking is the initial stage since a sheet has to be cut into a general shape before it is formed.

Blanks are then formed, also known as sheared, and punched to deform plastically it into a desired shape. The excess material around the part is then trimmed. Through this process, lubrication is required, normally in the form of oil even though water is sometimes used.

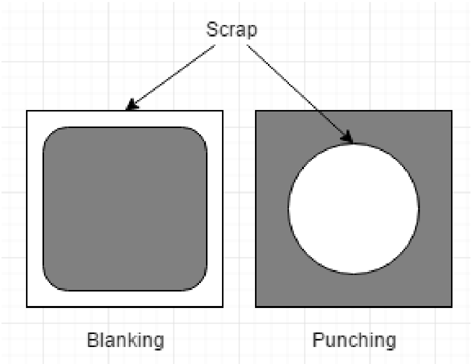


Fig. 14: Blanking vs. Punching.

Progressive stamping lines or transfer press lines can be used for stamping. In progressive stamping, the desired form is achieved through a series of operations performed as different stations of a single press. The part being formed remains connected to the coil until the final station of the line where it is cut off from the carrying web.

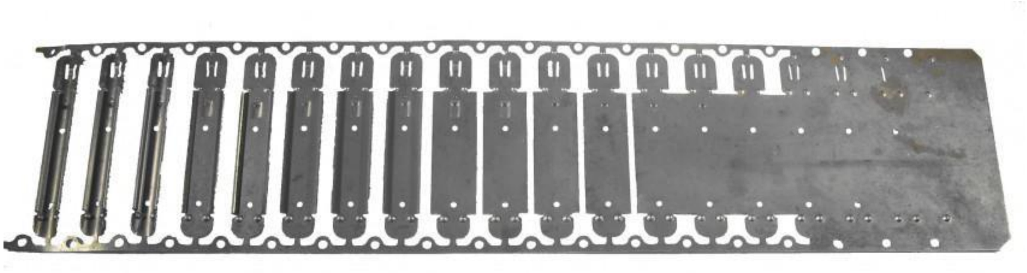


Fig. 15: Progressive Stamping.

A transfer press line is used for larger part sizes including automotive closures and structural elements. It uses robotic arms or other mechanisms to transfer the metal sheets or blanks from one station or press into another. The number of stations depends on the part geometry and material being used. Typical stations include drawing (forming), punching and trimming stations. Light alloys, including aluminum, tend to have limited formability especially when subjected to high shear. This results in the need for more stamping operations with less drawing for a single part [16].

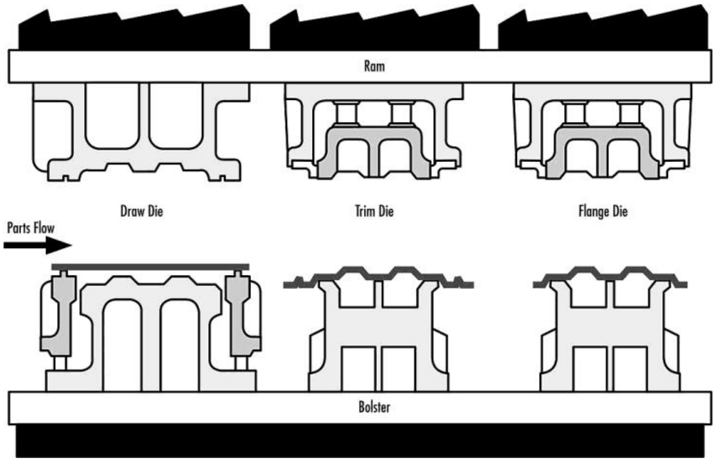


Fig. 16: Transfer Line Stamping.

Joining

Typically, the step following casting, extruding and stamping is assembly. Multiply joining methods exist and their application depends on the materials and geometry of the parts being joined. The following section discusses some of the common methods used in lightweight vehicles.

Welding

There are two types of welding: liquid phase or fusion welding and solid phase welding. Liquid phase welding consists of locally heating the materials to be joined to their liquid phases and then allowing cooling under pressure to form a joint. Three main liquid phase welding processes are used in industry. The first is resistance spot welding where an electric current is passed through two electrodes and the sheets to be joined creating intense heat that locally melts and fuses the materials. This method presents an issue when oxide layers are present (the case with aluminum) or if oil is present (from stamping and forming operations) since the contact between the electrodes and the materials should not be disturbed. Materials with different melting temperatures (steel and aluminum) are also difficult to join with this method, as the difference does not allow for optimal fusion. The second method is arc welding where the heat required for joining is produced by an electrical arc between an electrode and the parts to be joined. The electrode can be either a consumable rod or wire that also melts and supplies filler material or a non-consumable rod that only conducts electricity. This method also requires proper electrode contact and can be difficult to use with oil or an oxidized layer. The third method is laser welding that uses focused light to transfer heat to the joint. This method requires precise fits with very little mismatch and has high operating costs making it less common than the previous two.

Apart from liquid phase welding, solid phase welding exists. This method does not melt the materials, the weld quality tends to be superior, distortion and residual stresses are less and the process is more environmentally friendly as there are no fumes, glares or reflected laser beams associated. The most common method involves using a non-consumable rotating welding tool that generates heat through friction at the point where materials are to be joined. The materials become soft enough to be mixed by the rotating tool.

In any welding procedure, it is important to note that the materials might undergo property changes at the heat-affected zone (HAZ). The HAZ can develop different crystal structure that can be much more brittle than the rest of the structure [16].

Mechanical Joining

Bolds and nuts are not very common in automotive applications even though these offer advantages in disassembly. Self-piercing riveting, clinching and seaming are more common.

Self-piercing riveting involves the use of semi-tubular rivet that is pierced through two sheets producing a mechanical interlock between the two. It is mainly used to join aluminum sheets but can also be used to join steel and aluminum [16].

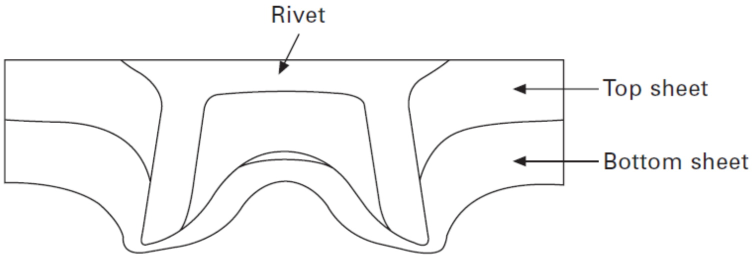


Fig. 17: Self-Piercing Rivet.

Clinching also mechanically interlocks two sheets but does not use rivets. A punch and die is used to form an interlocking button [16].

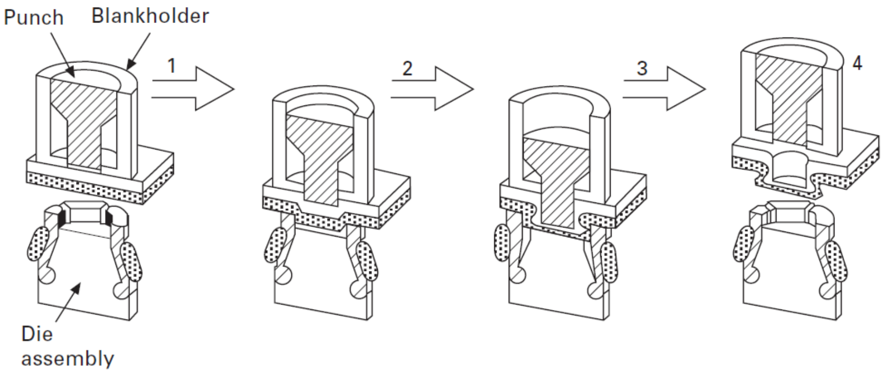


Fig. 18: Clinching Mechanism.

These two methods, even though extremely useful in joining ductile materials, present esthetic limitation as the rivets and buttons are not flush to the rest of the material. Seaming is a joining process that also improves esthetics. It is used to join the edges of inner and outer panels of hoods, doors and other outer components.

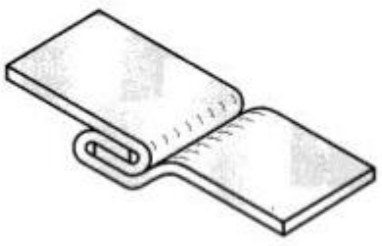


Fig. 19: Seaming of Two Metal Sheets.

Adhesive bonding

There are multiple advantages to using adhesives compared to welding and mechanical joining. One of them is its continuous localized joining that result in more uniform stress distribution and high-energy distortion. Another is good noise and vibration dampening. The adhesives many times act like a seal to prevent water and debris from invading the joint area. There are disadvantages associated to adhesives such as surface preparation and heat-curing requirements that affect the material properties by unwillingly reducing residual stresses generated in forming that improve strength properties [16].

Combination

It is important to note that in most cases aluminum joining is done through multiple of the aforementioned processes. An example is weld-bonding and rivet-bonding where adhesives carry most of the load but are accompanied by localized welds or self-piercing rivets to improve crashworthiness. Another example is the use of adhesives at seamed edges where the adhesives are used to seal the component at the joint. Most adhesives need to be cured at high temperatures but manufacturers keep this in mind and place the adhesives before heat treatment or welding so curing and heat treatment can occur simultaneously (useful in heat treatable sheet). This solves the issue of unwillingly changing mechanical properties of the part by curing as a final step [16].

Recycling

Downcycling, Recycling and Upcycling

The term recycling is understood to be the process where waste materials are converted into new materials. This general definition of recycling has proved to be problematic through the years, as it does not encapsulate all the complexities and possible scenarios that result from attempting to reprocess old materials.

Downcycling, a term popularized in the 2002 book: *Cradle to Cradle: Remaking the Way We Make Things,* is the reprocessing of a material into a new product of lesser quality or value [3]. This reduction of quality or value results in the new material to be used for an alternative, but many times similar, purpose. Downcycling occurs in almost all known materials including metal, glass, paper and plastics. This process is what typically occurs when processes are referred to as recycling. This presents an issue as downcycling implies that the material's quality will continue to degrade and will not result in its indefinite use but only delay its inevitable disposal. Downcycling occurs due to technical and economic limitations of recycling processes. Many times, it is not possible to maintain the quality after reprocessing as it happens with paper and plastic. With paper, the fibers length, associated with higher quality, shorten each time it is reprocessed until the material has to be discarded. With plastic, the polymer chains degrade making it impossible to remake the same product. Other issues include the commingling of materials that with technological limitations reduce the materials' value. This is the case with glass and metal. Glasses of different colors (green, blue and clear), which have different color agents (oxides), are mixed into a single stream or bin. This then requires an extra step in processing to segregate the colors into different bins or streams. This extra step can be difficult as the technology required can be either nonexistent or too expensive to justify the associated costs to prevent downcycling. The commingled material is then reprocessed into a material of lower quality as this proves to be more cost-effective for material recyclers. In the case of glass, a popular example, it is using mixed glass as filling material in construction projects. This is also the case in metals as different grades or alloys are mixed elevating the cost associated with segregation and purification [18]. The use of wrought scrap (new and old) to produce cast alloys is sometimes considered a type of aluminum downcycling as the purity of wrought alloys is perceived as higher than that of cast alloys. This is due to the tighter compositional requirements in wrought alloys compared their cast counterparts.

The opposite of downcycling is considered upcycling, where a discarded material is used to create a product of higher quality or value. Even though possible, the same issues that are presented when trying to prevent downcycling arise including associated costs and technological limitations. Many examples exist of upcycling but these remain extremely subjective, as comparing the value of different products is matter of current needs and perspective. An example is popular crafts seen on websites such as Pinterest where old items are repurposed such as using an old jar as a new desk plant pot. Even though creative, this is not what is perceived by technical experts when the term is referenced. A better example where materials processing does occur is that of *Toast Ale*, a brewery in London that collects the crusty ends of bread loafs from sandwich-making factories to make beer in the Ancient Babylon tradition [19]. Even though this has gained attention from the media, it demonstrates the subjectivity of upcycling as pure “upcycling” would imply that new and higher quality bread would be made from the discarded bread. In other industries, such as metals and glasses, upcycling can be perceived, at first glance, as the purification of unwanted contents from the material. An example would be the removal of an element from a melt to produce an alloy or melt of purer composition. This again can prove problematic, as this is not always the objective because producers see value in making products of lower purity as these do have a profitable market. In the case of aluminum recycling, the production of cast alloys is considered valuable and many times desirable making it difficult to deem definitely producing cast alloys from wrought scrap as downcycling. Upcycling is challenged when the energy requirement of purifying or improving a used material’s quality is higher than that of harvesting from primary or raw sources as higher energy requirements tend to be associated to higher carbon footprints [20].

Aluminum Recycling

Scrap Handling

Scrap can come in a range of shapes and sizes from small wiring scrap to large pieces of stamping scrap. Size can be a limiting factor when processing scrap as automated sorting equipment tend to require consistent particle size for proper functioning and other equipment such as furnaces have limitation on the size of the fed material. The process of reducing oversized particles into the proper size for further processing is known as comminution. Aluminum, as most metals, has to be torn apart to reduce its size and this is carried out by using shears, impact and rotary shredders with the latter being more common as these results in more consist particle size and higher volume processing capabilities. Shredding is also an important part of liberating scrap. Liberated scrap is free of any attached pieces of other materials, typical when bolted, welded or attached to other materials.

At any stage of processing, scrap could be agglomerated to reduce its density, especially during transport, as volume capacity is a limiting factor. The two most common methods of agglomeration are baling and briquetting. Baling is when the scrap is compressed by a hydraulic baler producing a cohesive bulk or bale of metal. The metal is deformed during this process and normally has to be shredded again for future processing. Baling can result problematic as bales can contain a varying amount of contaminates including moisture, grease and oil. The other popular method of agglomeration is briquetting. This method is ideal for small scrap of high surface to volume ratios (prone to oxidation when melting) such as metallic dust, boring, turning and other machining scrap [9].

Fig. 20: Bale Composed of Crushed Aluminum Cans.

Fig. 21: Briquettes of Aluminum Dust.

Sortation

Multiple sorting methods exist depending on what is trying to be removed from the scrap stream. One of the major concerns is the iron content, also known as irony. Most common, for the removal of ferrous content, is using drum magnets and overhead belt magnets. These separate scrap pieces made of iron and steel or nickel-based alloys if present. Scrap that is both composed of aluminum and ferrous material (due to bolting, welding or other fastening) can be processed through sweat melting where the scrap is heated to the aluminum's melting temperature but the steel making the aluminum melt away from the scrap.

Air sorting is useful when trying to remove lighter particles such as plastics and paper where an upward flow of air blows away the lighter material leaving the metal behind.

Heavy media separation is used to remove other contaminants that might be too heavy for air to blow away such as wood. It consists of submerging the scrap into a fluid of a density in between that of aluminum and the contaminant. The depending on the fluid and contaminant, one of the materials will float and other will sink. The issue of humidity remains as water-based fluids are used (see Hydrogen).

The last and surprisingly common method is hand sortation. Extremely effective when the desired result is the separation of general materials classes such plastics, glass and metals. This is extremely common in municipal recycling facilities where single stream recycling from curbside collection is initially processed. In some cases, the staff carrying out the process can be trained to distinguish even between metal types (ferrous and non-ferrous, cast vs noncast, etc.), but advanced tasks such as sorting between alloys of the same kind (wrought vs wrought) remains difficult if not impossible through simple visual assessment. (Knowledge of the scrap stream can make this possible, as certain scrap (characteristics, shape, texture, etc) can be associated to previous understanding of that scrap alloying designation) [9].

Decoating

Aluminum scrap is often exposed to organic materials such as oils from stamping operations. Multiple issues arise from charging oily material directly into melting furnaces such as the organic substances burning creating health hazards such as smoke and soot, increased aluminum oxidizing from the heat released in the combustion can create melt losses of up to 5% and the formation of dioxins that are hazardous in extremely small amounts. To prevent these and other harmful effects, two main methods have been devised for coatings removal. The first involves long exposure to low temperatures (480-520 C). This method can result in incomplete decoating in addition to unoxidized char. The second method involves rapid heating to temperature just below the melting point (590-620 C) for short exposures. Even though more effective, if the exposure is too long then unwanted oxidation can occur [9].

Impurities

The following section discusses common impurities found in molten aluminum. Their presence and concentration vary depending on the origin of the material (primary material, old or new scrap).

Hydrogen

Hydrogen in molten aluminum results from the reaction of water vapor and molten aluminum or magnesium (in scrap melts) [21].

$$3\ \mathrm{H_2O} + 2\ \mathrm{Al} = \mathrm{Al_2O_3} + 6\ \mathrm{H}$$

$$\mathrm{H_2O} + \mathrm{Mg} = \mathrm{MgO} + 2\ \mathrm{H}$$

Both reactions are favored thermodynamically and are only halted by an oxide skin on the melt surface. Conditions that encourage this reaction include high humidity, melt turbulence that disturbs the oxide skin and wet charge material that makes water vapor directly available to the melt. Hydrogen concentrations tend to be higher in secondary melts than primary melts due to humid or wet scrap or the use of fossil fuel furnaces that release humidity as product of fuel combustion [9].

To remove hydrogen from a melt is has to be transformed into gas phase.

$$2\ \mathrm{H} = \mathrm{H_2}\ \mathrm{(g)}$$

Hydrogen degassing can be enhanced by reducing the partial pressure of H_2 in the gas (either by using a vacuum or bubbling gas into the melt), raising the temperature (results into higher energy costs and raises H solubility) and generating a higher surface area by adding little bubbles to the melt. Molten aluminum will degas naturally but not to the necessary extent for acceptable quality, so purposeful degassing of some kind is required [9].

It is believed that the use of chlorine gas boosts hydrogen removal but it remains doubtful, as HCl is thermodynamically less stable than $AlCl_3$ [22].

$$2\ \mathrm{H} + \mathrm{Cl_2} = \mathrm{HCl}\ \mathrm{(g)}$$

Reactive Metals

This group includes all alkali and alkaline earth metals but three elements matter the most: sodium, calcium and magnesium.

Sodium, calcium and lithium arise in primary melts from the Hall-Héroult processes where aluminum is generated in electrolytic cells from alumina in baths of molten sodium and lithium salts. Since this process is only used in primary production, secondary melts contain little to no sodium and lithium. Calcium can arise in old scrap secondary melts since automotive scrap that has been exposed to calcium-based road de-icing salts can end up in the mix. The “sweetening” or addition of primary material to secondary melts is common, allowing for calcium and lithium to end up in secondary melts.

Demagging is the process of removing magnesium from a melt. Magnesium arises mostly in secondary melts from its use as an alloying element. It is important to note that magnesium is more expensive than aluminum so its removal is not always desired. When the goal is the production of high magnesium alloys, demagging is not encouraged.

Chlorine gas is added to aluminum melts to react with calcium and sodium impurities resulting in sodium chloride and calcium chloride that floats up to the surface salt slag.

$$\mathrm{Ca} + \mathrm{Cl_2} = \mathrm{CaCl_2}\ \mathrm{(slag)}$$

$$\mathrm{Na} + \frac{1}{2}\mathrm{Cl_2} = \mathrm{NaCl}\ \mathrm{(slag)}$$

Chlorine also reacts with magnesium to form magnesium chloride (a key reaction in demagging of molten aluminum).

$$\mathrm{Mg} + \mathrm{Cl_2} = \mathrm{MgCl}\ \mathrm{(slag)}$$

However, chlorine can react with react with aluminum to produce aluminum chloride vapor, which in turn reacts with the humidity in the air to produce hydrochloric acid vapor. These reactions and the general use of chlorine gas present various environmental concerns, which have led to need to find a suitable replacement for chlorine gas as a refining agent [9].

$$2\ \mathrm{Al} + 3\ \mathrm{Cl_2} = 2\ \mathrm{AlCl_3}\ \mathrm{(g)}$$

$$2\ \mathrm{AlCl}\ \mathrm{(g)} + \mathrm{H_2O}\ \mathrm{(g)} + 6\ \mathrm{HCl(g)}$$

Inclusions

Inclusions are solid particles suspended in molten aluminum. Their size and number depends on a variety of things especially the quality of the scrap being melted and the impurities in that scrap. There are two types of inclusions: exogenous and indigenous. As their name implies, exogenous inclusions are those that already exist before melting such as furnace dirt. These tend to be larger than their counterpart causing more problems during solidification, but their size also makes them easier to remove. Indigenous inclusions are those formed by chemical reactions in the melt such as the formation of alumina from the presence of dissolved oxygen. Generally, secondary melts have more inclusions than primary melts as scrap tends to be exposed to more contaminants. The size of the scrap also affects inclusion concentration as smaller scrap has higher surface area to volume rations resulting in more dirt and contaminant exposure [21].

There are three methods to remove inclusions. The first being sedimentation as inclusions naturally settle at the bottom of a melt. Even though useful for larger inclusions, its rate can be an issue for small inclusions as the settling rate is correlated to inclusion size. The second method is flotation through bubbling the melt. This is convenient as this procedure is necessary in degassing and reactive metal removal. Even through flotation is effective enough to meet many quality specifications; many times, there is a need for further processing to remove the smallest inclusions. The third and most effective method is filtration. There are two types of filters: cake and deep-bed. The first functions using pores smaller than the inclusions to be removed piling them up into a cake of increasing thickness. These filters are highly effective but experience pressure drops due to the cake requiring the melt to be forced through the filter. This makes their use impractical and expensive resulting in these being used only or low volume applications. Deep filtration functions by the attachment of inclusions to the inside walls of the filter. There is no cake formation thus no pressure drop problems. This only works if the inclusions are smaller than the pores of the filter requiring large inclusion size removal prior to filtration. This can be achieved through flotation or the use of dual filters with a large pore filter followed by a small pore filter [9].

Flow Processing

The following section describes the steps for molten aluminum processing. It is important to note that not every single recycling facility is the same (such as the melting and casting furnaces being the same and the crucible pretreatment being skipped) but tend to follow a similar progression.

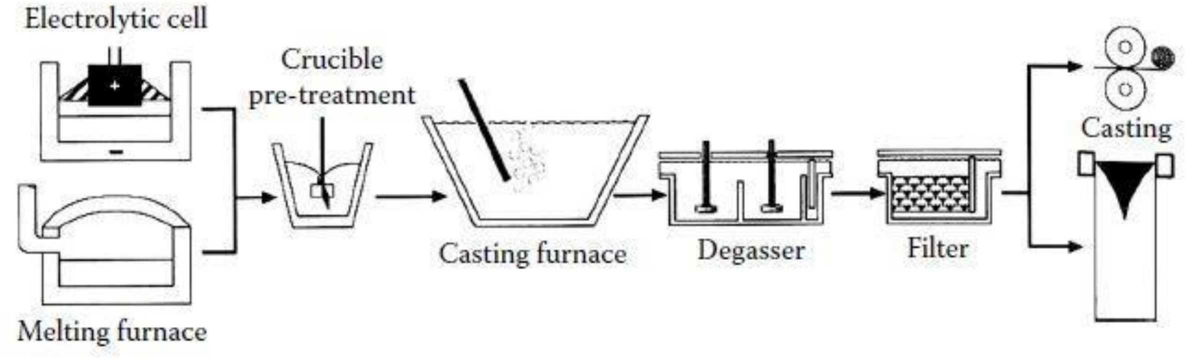


Fig. 22: General steps taken in aluminum smelting and recycling. Electrolytic cells is used in primary production and the melting surface in secondary production [23].

Demagging is performed in melting furnaces using chlorine gas. The use of crucible pretreatment is not universal but may hold advantages for alkali removal. In many facilities melting and casting may be done in the same furnace. Casting furnaces are mainly used for alkali removal and degassing but this can prove to be inefficient furnaces are designed with heat transfer properties in mind and not as chemical reactors. Degassing has now been minimized in casting furnaces and carried out with in-line degassers. In-line degassers offer an advantage as these are specially designed for process efficiency. Figure 23 shows the use of spinning gas injectors that increase bubble count and reduce bubble size improving degassing and particle flotation. The use of baffles improves the process as it creates a continuous multi-stage degassing process where the slag is not carried into the next degassing stage. Filtration is the last step where remaining inclusions are removed. After filtration is completed, the melt is then casted and worked (if wrought) into semi-fabricated products [9].

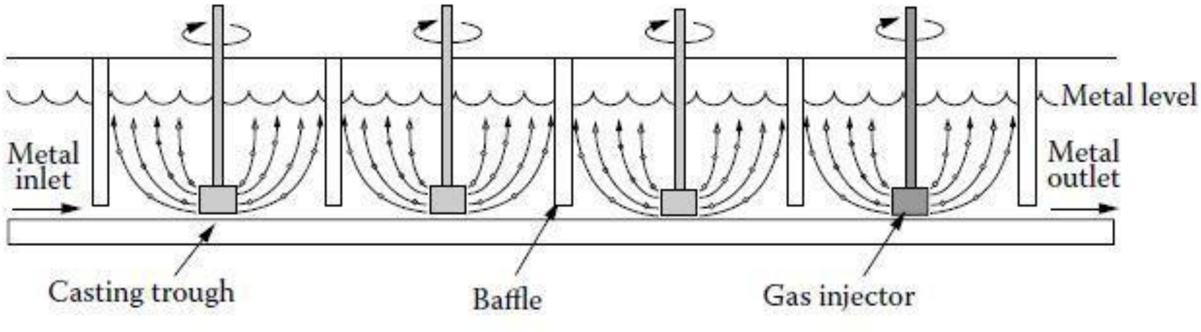


Fig. 23: Multistage In-Line Degasser [24].

Appendix B: Python Scripts and Sorting Algorithms

The following python script was used to make the 2D compositional graphs:

```
"""
Created on Mon Feb 26 12:08:22 2018

@author: Shady Zummar
"""
"""Import of required Packages"""
import pandas as pd
import matplotlib.pyplot as plt
import matplotlib.patches as patches



"""Import of Alloy Compositions"""
#The following section imports the alloy compositions from excel sheet in the same directory as a pd DataFrame
#It sets the index, color, linestyles, and also has the option to drop desired alloys
df1 = pd.read_excel('Alloy compositions.xlsx', sheetname='6XXX')
df1 = df1.set_index('Alloy')
#print(df1.index)
color = pd.DataFrame({'color':['b','b','r','b','r','g','g','k','k','k','k']}, df1.index)
linestyles = pd.DataFrame({'linestyles':[':','--',':','-','-.','--','-.',':','-','--','-.']}, df1.index)
df1 = pd.concat([df1, color, linestyles], axis=1)
#df1 = df1.drop([6111,5454,5754,5182,6182])
print(df1)

"""Imports of Bins Compsotions"""
# The follwing section imports the bin compositions from excel sheet in the same directory into a pd DataFrame
#It sets the index, color, linestyles, and also has the option to drop desired alloys
df2 = pd.read_excel('Alloy compositions.xlsx', sheetname='Bins')
df2 = df2.set_index('Bins')
color2 = pd.DataFrame({'color':['b','b','b','g','g','k']}, df2.index)
linestyles2 = pd.DataFrame({'linestyles':['-.','--',':',':','-.','-']}, df2.index)
df2 = pd.concat([df2, color2, linestyles2], axis=1)
print(df2)
print(df2.index)

"""Set difference to create spacing in graph"""
```

```
diff1 = 0.009
diff2 = 0.005

"""Inputs"""
#Choose which elements to use for graph and if to display bins, alloys or both
y_axis = "Cu"
x_axis = "Mg"
display = 'bins' #set to alloys, bins or both in string form

"""Create base figure"""
fig3 = plt.figure()
ax1 = fig3.add_subplot(111, aspect='equal') #Creates plot base

"""Bins"""
#Graph into figure
if display == 'bins' or display == 'both':
    for row in df2.index:
        ax1.add_patch(
                patches.Rectangle(
                        (df2.loc[row, x_axis + ' Min'] + diff2, df2.loc[row,y_axis + ' Min'] + diff2), df2.loc[row,x_axis + ' Max']-df2.loc[row,x_axis + ' Min']- 2*diff2, df2.loc[row, y_axis + ' Max']-df2.loc[row,y_axis + ' Min']- 2*diff2,
                        fill = False,
                        #facecolor = '0.9',
                        edgecolor = str(df2.loc[row, 'color']),
                        linestyle = str(df2.loc[row, 'linestyles']),
                        linewidth = 1.2
                    )
                )

"""alloys"""
#Graph Alloys into figure
if display == 'alloys' or display == 'both':
    for row in df1.index:
        ax1.add_patch(
                patches.Rectangle(
                        (df1.loc[row, x_axis + ' Min'] + diff1,df1.loc[row,y_axis + ' Min'] + diff1), df1.loc[row,x_axis + ' Max'] - df1.loc[row,x_axis + ' Min']-  2*diff1, df1.loc[row, y_axis + ' Max']-df1.loc[row,y_axis + ' Min']- 2*diff1,
                        fill = False,
                        #facecolor = '0.9',
                        edgecolor = str(df1.loc[row, 'color']),
                        linestyle = str(df1.loc[row, 'linestyles']),
```

```
                        linewidth = 0.5
                    )
                )
"""add labels and other formatting"""
plt.xlabel(x_axis + " [%]")
plt.ylabel(y_axis + " [%]")
#plt.title("Alloy Compositions: " + y_axis + " vs " + x_axis)

#Shrink current axis by 20%
box = ax1.get_position()
ax1.set_position([box.x0, box.y0, box.width * 0.8, box.height])

if display == 'bins':
    plt.legend(df2.index, loc='center left', bbox_to_anchor=(1, 0.5))
elif display == 'alloys':
    plt.legend(df1.index, loc='center left', bbox_to_anchor=(1, 0.5))
else:
    plt.legend(df2.index, loc='center left', bbox_to_anchor=(1, 0.5))

axes = plt.gca()
axes.set_xlim([-0.05 , float(df1[[x_axis + " Max"]].max(axis=0) + 0.1)])
axes.set_ylim([-0.05 , float(df1[[y_axis + " Max"]].max(axis=0) + 0.1)])
axes.set_aspect('equal')

ax1.tick_params(direction='inout', length=6, width=2)

"""save figure to current directory"""
fig3.savefig(display + ' ' + y_axis + " vs " + x_axis + '.png', dpi=300, bbox_inches='tight')
```

The following python script was used to determine compositional overlap:

```
Created on Tue Mar 13 16:51:10 2018

@author: Shady Zummar
"""
"""Import necessary packages"""
import pandas as pd



totalcount = 0
"""import necessary compositions from same directory"""
df1 = pd.read_excel('Alloy compositions.xlsx', sheetname='6XXX')
df1 = df1.set_index('Alloy')
elements = ['Si', 'Fe', 'Cu', 'Mg', 'Mn']

"""Nested loops for tolerance compatabilty check"""
#Nested loops check for toleracne compataiblity in each alloy with another. Three cases are checked for compositional overlap
for row in df1.index:
    for xrow in df1.index:
        totalcount = totalcount + 1
        if row != xrow: #ensures that not the same alloy is being compared
            count = 0 #Compatabilty count set to 0
            for element in elements: #checks different compositional overlap scenrios and adds one to count of true
                if df1.loc[row, element + " Min"] >= df1.loc[xrow, element + " Min"] and df1.loc[row, element + " Min"] <= df1.loc[xrow, element + " Max"] and df1.loc[row, element + " Max"] > df1.loc[xrow, element + " Max"]:
                    count += 1
                elif df1.loc[row, element + " Min"] >= df1.loc[xrow, element + " Min"] and df1.loc[row, element + " Max"] <= df1.loc[xrow, element + " Max"]:
                    count += 1
                elif df1.loc[row, element + " Max"] >= df1.loc[xrow, element + " Min"] and df1.loc[row, element + " Max"] <= df1.loc[xrow, element + " Max"] and df1.loc[row, element + " Min"] < df1.loc[xrow, element + " Min"]:
                    count += 1
            if count == 5: #if overlap is acheved for all 5 elements then the alloy presents composotional overlap
                print('overlap ' + str(row) + ' & ' + str(xrow))
                """else:
                    print('no overlap')"""

print(totalcount) #to check if all possible scenerios have been checked
```

The following script was used to determine alloy tolerance:

```
"""
Created on Sat Apr  7 18:52:52 2018

@author: Shady Zummar
"""
"""import necessary packages"""
import pandas as pd

"""Set Tolerance to Partial or Fully"""
tolerance = "Partial"



"""Import necessary alloy compositional from excel in same directory"""
df1 = pd.read_excel('Alloy compositions.xlsx', sheetname='6XXX')
df1 = df1.set_index('Alloy')
elements = ['Si', 'Fe', 'Cu', 'Mg', 'Mn']

"""Tolerance Check"""
totalcount = 0
tolerance_count = 0
for xrow in df1.index:
    for row in df1.index:
        totalcount = totalcount + 1
        if row != xrow:
            count = 0
            if tolerance == "Fully": #If full tolerance then the follwing condition is satisfied for each element
                for element in elements:
                    if df1.loc[xrow, element + " Max"] <= df1.loc[row, element + " Max"]:
                        count = count + 1
            elif tolerance == "Partial":
                for element in elements:
                    if df1.loc[xrow, element + " Min"] < df1.loc[row, element + " Max"]:
                        count = count + 1
            if count == 5: #if all elments are tolerant then the alloy is tolerant
                print(str(xrow) + ' -> ' + str(row))
                tolerance_count = tolerance_count + 1


print(tolerance_count)
```

The following script was used to create and sort through a digital scrap sample:

```
"""
Created on Fri Apr 13 17:34:03 2018

@author: Shady Zummar
"""

"""import necessary packages"""
import pandas as pd
import numpy as np

"""Import necessary compositions from same directory"""
df1 = pd.read_excel('Alloy compositions.xlsx', sheetname='6XXX')
df1 = df1.set_index('Alloy')
elements = ['Si', 'Fe', 'Cu', 'Mg', 'Mn']
df1 = df1.drop([6111,5454,5754,5182,6182])

"""set random seed to ensure consistency"""
np.random.seed(123)



"""create random scrap sample"""
#Creates 50 scrap samples of each alloy using two loops nested loops and saves as excel
scrap_sample = pd.DataFrame()
for alloy in df1.index :
        proto_random = pd.DataFrame()
        for element in elements:
            e_random = pd.DataFrame(
                    (df1.loc[alloy, element + " Max"] - df1.loc[alloy, element + " Min"]) * np.random.random_sample((50,
1)) + df1.loc[alloy, element + " Min"],
                    columns = [element])
            #print(e_random)
            proto_random = pd.concat([proto_random, e_random], axis=1,)
            #print(proto_random)
        proto_random.insert(5, 'Alloy', alloy)
        scrap_sample = pd.concat([scrap_sample, proto_random], ignore_index = True)
#print(scrap_sample)
writer = pd.ExcelWriter('Scrap Random Sample.xlsx')
scrap_sample.to_excel(writer)
writer.save()
```

```
"""Elements to take into account when sorting"""
sort_elements = ['Si',
                 #'Fe',
                 'Cu',
                 'Mg'#,
                 #'Mn'
                 ]
"""Sorting Algorithm"""
#Sorts the random scrap sample using the selected elements as criteria and saves to excel file with a sheet for each bin
sortbins={}
unsortedbins={}
writer = pd.ExcelWriter('Sorted_' + str(sort_elements) + '.xlsx')
total_count = 0
for alloy in df1.index:
    temp = pd.DataFrame()
    counter_temp = pd.DataFrame()
    for sample in scrap_sample.index:
        #print (alloy)
        compat = 0
        for element in sort_elements:
            if scrap_sample.loc[sample, element] <= df1.loc[alloy, element + " Max"] and scrap_sample.loc[sample, element] >= df1.loc[alloy, element + " Min"]:
                compat = compat + 1
        if compat == len(sort_elements):
            addition = scrap_sample.loc[sample,:]
            temp = temp.append(addition, ignore_index = False)
        if compat < len(sort_elements):
            sub = scrap_sample.loc[sample,:]
            counter_temp = counter_temp.append(sub, ignore_index = False)
    sortbins["sortbin_{0}".format(alloy)] = temp
    unsortedbins["unsortbin_{0}".format(alloy)] = counter_temp
    total_count = total_count + 1
    temp.to_excel(writer,str(alloy))
    counter_temp.to_excel(writer,"not " + str(alloy))

writer.save()
print(sortbins)
```

Appendix C: Sorting Algorithm Output

Sorting using all elements:

Table IX: Sorting result when using all elements as criteria.

			Average Composition				
Sort	Incorrect Pieces	Accuracy [%]	Cu [%]	Fe [%]	Mg [%]	Mn [%]	Si [%]
6005	1	98.04	0.05	0.17	0.50	0.05	0.75
6016	23	68.49	0.09	0.21	0.45	0.09	1.23
6022	3	94.34	0.06	0.13	0.58	0.06	1.15
6061	0	100.00	0.28	0.35	0.99	0.06	0.60
6063	1	98.04	0.05	0.15	0.72	0.06	0.37
6111	0	100.00	0.72	0.20	0.78	0.26	0.85
6182	0	100.00	0.05	0.25	0.96	0.76	1.10
5182	0	100.00	0.08	0.19	4.57	0.33	0.09
5454	0	100.00	0.05	0.19	2.72	0.72	0.12
5754	0	100.00	0.05	0.20	3.05	0.26	0.19
5005 A	9	84.75	0.23	0.19	0.89	0.08	0.17

Note that all averages are within designated compositional range.

Sorting only using Magnesium and Copper:

Table X: Sorting result of other alloys when only using copper and magnesium as sorting criteria.

			Average Composition				
Sort	Incorrect Pieces	Accuracy [%]	Cu [%]	Fe [%]	Mg [%]	Mn [%]	Si [%]
6005	32	60.98	0.05	0.17	0.51	0.06	**0.92**
6016	80	38.46	0.07	0.20	0.47	0.07	1.03
6022	67	42.74	0.06	0.15	0.58	0.06	**0.89**
6061	13	79.37	0.28	0.32	0.99	0.06	0.51
6063	24	67.57	0.05	0.14	0.71	0.06	0.59
5005 A	64	43.86	0.23	0.25	0.91	0.06	**0.35**

Note that highlighted cells imply exceed acceptable compositions.

Appendix D: Other Content

Maps showing aluminum production and stamping plants:

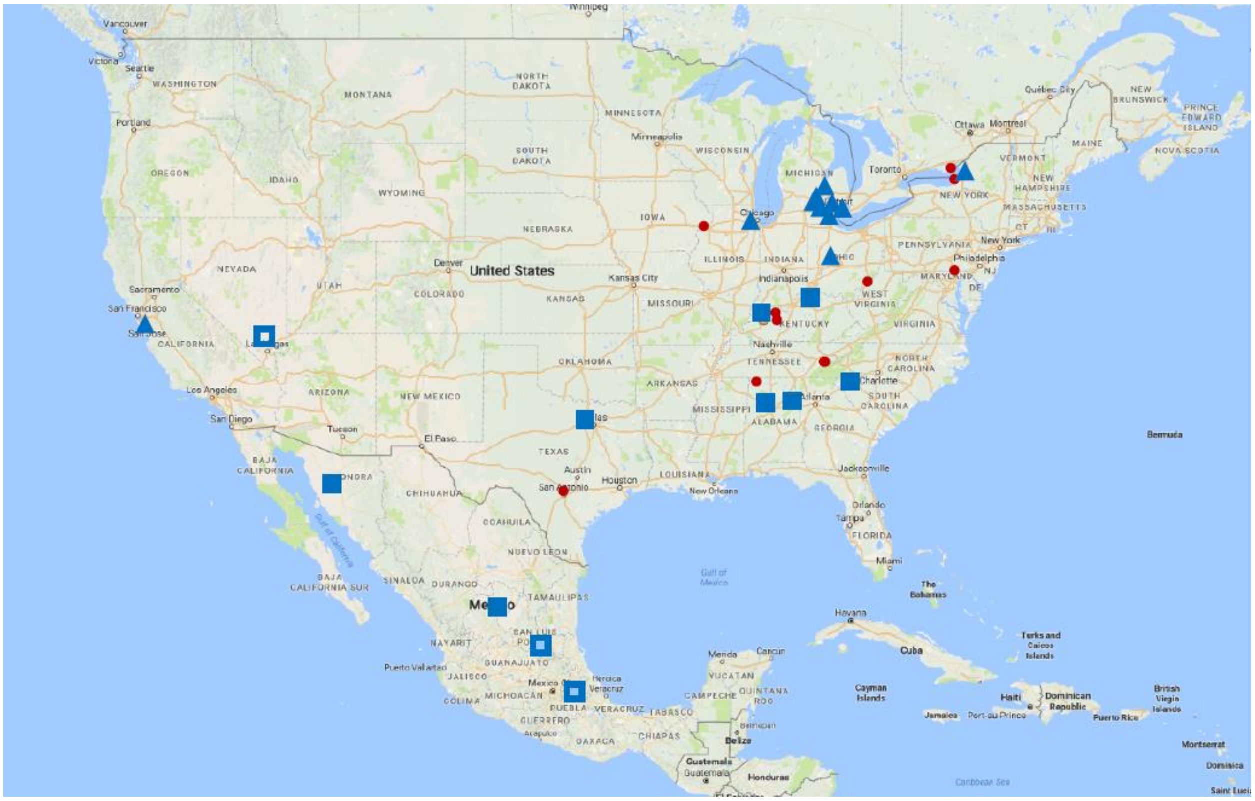


Figure 24: Aluminum Production and Consumption in North America. Producers (red circles), Consumers (triangles and squares)