

# Value Creation Through Enabling Technologies to Up-Cycle Aluminum Scrap

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## ABSTRACT

Many forms of aluminum scrap are down-cycled at end-of-life. Unfortunately, end-of-life processing of products containing aluminum is not optimized to allow for maximized reuse opportunities. By not creating value in our waste or scrap streams, one down-cycles rather than up-cycles, resulting in scrap surpluses and diminishing domestic utilization. The recycling loops of many old aluminum scrap classes are extensively open (not closed loop). With the advent of optoelectronic sorters and other enabling technologies, we can now up-cycle, and thus create value from scrap; these developments have transformed how one deals with end-of-life of products. The capabilities and limitations of metallic sorting systems and characterizing mixed scrap classes to enhance end of life recycling rates are reviewed and presented.

## INTRODUCTION

There are two distinct scrap aluminum designations; new and old. New scrap is defined as a secondary material stream that flows from a production line and is typically very clean and segregated based on composition. Some new scrap will mix and does require sortation, but this paper will focus on technologies to up-cycle old scrap. Old scrap is defined as a secondary material stream that results from obsolete products. Some old scrap classes like used beverage containers (UBCs), aluminum alloy wheels, and scrap from building and construction projects approach the cleanliness and degree of segregation of new scrap streams. However, a significant amount of old aluminum scrap is mixed together and commonly shredded to form smaller, workable scrap particulates. This scrap stream and the majority of other old scrap forms (strictly excluding UBCs) are recycled into secondary cast alloys. This means that wrought alloys will be recycled in an open-loop fashion and will form secondary cast in its second lifecycle. This is the current norm because cast alloys can absorb must larger amounts of alloying elements and contaminants in their solid solution matrix and still be functional. Chemistry specification limits are much tighter for wrought alloy families. The current paradigm is down-cycling this above ground ore, devaluing this critical resource, and it is not sustainable.

Optoelectronic sorters are commercially available and are continuously being improved to up-cycle shredded, mixed, metal scrap streams. The majority of shredded scrap metal streams result from auto-shred yards. At these sites, end of life vehicles (ELVs) are mixed with obsolete products from other sectors including consumer durables (*i.e. home appliances, white goods*), and machinery/equipment (*i.e. obsolete industrial equipment, lawn mowers etc.*). It must be noted that the mixture that is placed on the conveyor belt directed toward the hammer-mill shredder is determined by the market; supply of scrap and demand



that the shredders are working to satisfy. This work will focus on the shredded fraction and how this stream can be up-cycled through the utilization of these developing technologies.

From 2002 to 2014 an average of ~13 million vehicles were annually deregistered and scrapped in the U.S. (NADA 2015). Following deregistration, ELVs enter the first stage of the end of life treatment; dismantling. Worth noting, the transportation sector has represented a high-level model for the circular economy for quite some time. During life, cars are maintained to lengthen their lifetime. Once at a dismantling yard, auto-parts are removed that can continue to function in other vehicles. The most common parts that are removed for reuse include transmissions, engines, doors, trunks, hoods, and wheels. Once an ELV is picked for all of its reuse value and specific parts, like wheels and catalytic converters, are separated for the scrap metal value, the ELV is flattened and delivered to the shred-yard.

At the shredding site, the ELV will mix with other obsolete products. This mixture will be shredded and separated/sorted using a variety of techniques including air separation, magnetic separation, eddy-current separation, induction sorting and density separation (*i.e. heavy media separation, dry – sand or wet – media*). These sites will be referred to as scrap processors. Scrap processors do not engage in all forms of sortation. They process the material to the level required by their customers.

The Institute of Scrap Recycling Industries (ISRI) defines a scrap specification circular for the recycling industry to abide by. This circular is used to define compositions, and signify contamination limits. Magnets are used to sort shredded mixtures into two streams; ferrous and nonferrous metals/non-metals. After eddy-current separation, the nonferrous shredded scrap is termed Zorba. This nonferrous scrap stream is composed of aluminum alloys, copper, magnesium alloys, zinc, brass, some stainless steel (non-magnetic) and various non-metallic (*i.e. polymers, rubbers, rocks, dirt, organic paints, oils, wood, etc.*) (ISRI 2014). Zorba can be further separated based on its constituent's density. This is primarily accomplished through heavy-media separation, wet or dry, to separate the light/floating fraction from the heavy/sinking fraction. The floating fraction is 90-98% aluminum alloy with some magnesium and non-metallic (ISRI 2014, Kelly 2015). This is defined by ISRI as Twitch. The sinking fraction consists of everything else and is termed Zebra (ISRI 2014). To summarize, Zorba is separated into Twitch and Zebra.

The majority of Zorba produced is exported out of the U.S. to developing countries like China, India and Turkey (Bray 2014). Not many scrap processors in the U.S. sort this auto-shred stream into Twitch and Zebra. If Twitch is being separated from Zorba, it is safe to assume this material will be domestically utilized. Twitch purchased by secondary smelters in the U.S. is charged to form secondary aluminum cast alloys that are not safety-relevant (Lovik 2014). In 1996, the U.S. produced 97,000 metric tons (MT) of aluminum auto-shred scrap and ~60% of that stayed domestic. In 2012, the U.S. produced 1.5 million MT of auto-shred scrap and ~7% stayed domestic (Bray 2013, USITC 2014). Although exporting this material may be a short-term solution for current business models, it has been forecasted that the global production of auto-shred will reach a surplus by the year 2025 and this surplus value will increase to 28% by 2050 if no changes are made to the secondary aluminum processing industry (Lovik 2014). Currently, there is minimal up-cycling of Twitch to form a broadened spectrum of secondary alloys beyond 380. This up-cycling can be accomplished through the involvement of optoelectronic sortation systems, namely x-ray transmission (XRT), x-ray fluorescence (XRF) and laser induced breakdown spectroscopy (LIBS). These technologies will be discussed in detail. These are all automatic sorting processes which can be defined as



the automated separation of mixed materials based on measured and detected differences of material property.

### **X-ray Transmission (XRT)**

Dual energy x-ray transmission (DE-XRT) is capable of sorting metallic particulates based on differences in atomic density (Khoury 2017). XRT can easily sort the heavy and light fraction of Zorba as a dry method. A major drawback of heavy-media separation is that it is a wet method which requires maintenance of the media density and a recovery system for this ferrosilicon slurry. The second is that magnesium alloys will float to the surface along with the aluminum alloys as the specific gravity of the media being used is typically maintained at 3.5 (Gaustad 2012). Magnesium in this case can be viewed as an impurity if it is not required in the downstream product. If this is the case, then a de-magging process must be employed to remove the magnesium content after separation during secondary smelting or re-melting. Even considering the most common secondary cast alloy 380 the Mg content must be between 0.10-0.35 wt. %, so by mixing in wrought alloys (*i.e.* 5000 series) with higher Mg content and bulk Mg alloys contamination can result if open-loop recycling is being practiced (Velasco 2011). XRT is investigated here as a mechanism to separate out this undesired Mg content. These XRT systems can knowingly detect when a bulk impurity (*i.e.* a steel screw) is compounded on the scrap particulate which is critical to tramp element mitigation and control (Mesina 2007).

During scrap processing, the XRT would fit seamlessly after the non-ferrous scrap stream moves through the eddy-current separators. A conveyor belt system would carry the scrap to the sorter's feeding mechanism (*i.e.* vibratory platform, rotary ejection etc.) which allows for proper scrap distribution on the analysis belt. A scanning system (*i.e.* laser, 3D camera) or, simply the x-ray source itself, alerts the ejection system of the scrap particulate's belt location. The x-ray source tube and the x-ray detection system are positioned below and above the conveyor belt, respectively. Once the belt location and density differences are known, the ejection system is alerted to either fire the compressed air or pneumatic hammer system to induce separation or to allow the scrap piece to fall if the material's density does not meet the pre-programmed criteria. With this equipment, the ejection distance must be controlled, pneumatic hammers must be used or multiple material passes are required to sort beyond an ejection fraction and a dropped fraction.

### **X-ray Fluorescence (XRF)**

This technology utilizes x-ray fluorescence detection from an unknown sample to identify chemical composition as a function of signal intensity at elemental-specific energy levels. In more detail, low energy x-ray radiation is fired at the scrap streams which leads to the excitation of a low-energy electron causing it to eject from orbit. A higher energy electron quickly fills the vacancy at the lower energy state and with this jump, an elemental specific fluorescence is released. An energy dispersive x-ray sensor is used to detect this release of fluorescence and alerts the computational system of the signal intensity. This computational system is accompanied by a sorting algorithm and both work together, on the order of milliseconds, to send instructions to the ejection system on how to handle every single scrap piece detected dependent upon a preset criteria input to the system before processing.

The most common applications for XRF sorting systems involve the ejection of copper alloys from Zebra streams and stainless steel (SS) alloys from subsequent mixed SS streams. Heavy elements (*i.e.* Fe, Cu, Zn)



are easily detected; lighter elements (*i.e. Mg, Al, Si*), that have a lower characteristic energy, are harder to differentiate (Ridall 2015). The sort of light metal alloys becomes even more challenging when considering the signal attenuation that results from the surface contamination (*i.e. paint, oils, lubricants, inorganics, etc.*) on many of these scrap particulates (McDowell 2016). In addition, the air that separates the scrap pieces and sensors absorbs the low-energy secondary x-rays (Habich 2017). However, aluminum scrap mixtures can be sorted using this technology when a sorting criteria is set based upon the heavy element content in solution and this will be discussed here.

### **Laser-Induced Breakdown Spectroscopy (LIBS)**

LIBS automated sorting systems have been under development since before 2001 (Gesing 2001), but this sorting technology has not surfaced as a commonly used up-cycling solution for mixed scrap streams. This may change, however, due to the forecasted increase of aluminum consumption in the transportation sector. LIBS technology will be critical for closing the auto-Al recycling loop. LIBS, at first, will be used for the sortation of 5000 and 6000 series aluminum wrought alloys off of the production line that mix during body and closure sheet manufacturing. In addition to this, with help from a spot-cleaning pre-ablation laser, LIBS technology will be operated to upgrade old Al scrap mixtures.

In this automated system, a sensor first detects the presence of a specific particle, then this particle is hit with a laser pulse. These pulses create local, luminous plasmas (*i.e. atomic emissions*) that are detected (Cui 2010). This emitted light, upon its breakdown, is analyzed spectroscopically using an optical fiber, a polychromator and a photodiode that are connected to a computer system for an instantaneous elemental composition detection (Cui 2010, Gurell 2012). Werheit et al. have researched a 3D scanning LIBS system for aluminum cast and wrought alloy recycling. Sorting measurements of old Al scrap were taken in this study. After 20% of the data were discarded as outliers, wrought and cast scrap samples were identified with an accuracy greater than 96%. The second study conducted by this group involved the sortation of 8 different Al alloys of production scrap that required a high analytical precision. A mean identification correctness was reported as greater than 95% for these wrought alloys (Werheit 2011). Incorrectly sorted alloys must be kept at a minimum as wrought and cast products are limited by very different alloying specifications. This paper will discuss some sorting options that are made possible by this recycling technology. One limitation of the LIBS sorting system is that it is a spot treatment which means the scrap particulates must be placed in a straight line at an appropriate distance apart so the cleaning laser and analytical laser can pulse the surface of each piece. In other words, a vibratory feeder as used for the XRT and XRF cannot be used with this equipment as more precise belt placement is required due to the laser technology. Currently, commercial use of LIBS sorters in Japan sort into a cast fraction, and 2000/3000/5000/6000/7000 series wrought (Harita 2016).

## **METHODOLOGY**

### **X-ray Transmission (XRT)**

Steinert's x-ray sorting system, the XSS T, was used to sort a ~2400 lb. Twitch sample. The objective of this sorting study, conducted by Steinert technicians, was to eject the cast fraction and allow the wrought fraction to drop before the splitter. Ultimately, the compositional differences between these two fractions were under investigation. The sorted scrap was delivered to WPI for compositional analysis. The sorted



cast and wrought fractions were sampled using a cone and quartering technique resulting in 2 - 100 lb. samples. Each of these 100 lb. samples were reduced to 5 – 20 lb. samples, then melted in an induction furnace and casted into optical emission spectroscopy (OES) pucks. Using a Spectro Maxx OES, the compositional differences between the sorts were analyzed.

### **X-ray Fluorescence (XRF)**

A 50 lb. Twitch sample composed of 50% aluminum cast and 50% aluminum wrought was used to test the lowest compositional threshold limits of Steinert's XSS F system. For this test, the scrap material was sorted on the lowest possible criteria for alloying elements Cu, Zn and Fe. This preset program ejected a particulate if the alloying composition met the low signal overlap for one or more of the three elemental requirements. Samples were extracted to melt and form OES pucks for further chemical analysis. This study was conducted to determine what the system defines to be a "high enough" copper, zinc and iron alloying content to induce particle ejection when the sorting criteria is set at the lowest possible level. In this study, a vibratory feeder laid scrap particulates on a conveyor belt at an appropriate distance from one another for sensing. This conveyor belt was moving at 2 m/s.

### **Laser-Induced Breakdown Spectroscopy (LIBS)**

Using an XRF gun, ~400 aluminum alloy scrap pieces within a Twitch scrap sample were analyzed. The individual pieces were weighed, their surfaces were cleaned with a table-top grinder and each scanned to determine the weighted Si, Cu, Zn, Fe, Mg, and Al content. Once these data were extracted from the XRF gun, a sorting model was applied to simulate a LIBS automated system. A 100% efficiency assumption was made and all Mg and steel alloy particulates were removed from the data set. Compositional limits were set through use of an IF-THEN algorithm and various sorts were made to investigate the opportunity to form further secondary Al alloys beyond 380. Gray et al, a research group at Worcester Polytechnic Institute, advised by the authors of this paper, have laid the framework for using LIBS technology to sort Twitch into preset compositional bins to form secondary 319 and 360 aluminum alloys (Gray 2016). From this work, specific scatter plots were prepared and will be presented here which highlight 2D alloying element relationships that exploit possible sorting criteria for the LIBS system as applied to Twitch scrap streams. In the near future, empirical data will be collected on the effectiveness and efficiency of the automated LIBS systems that are under development.

## **RESULTS AND DISCUSSION**

### **X-ray Transmission (XRT)**

The automated XRT has proven to be effective in sorting low alloy content aluminum from high alloy content aluminum. This sort predominantly consists of sorting wrought from cast, but as an example some 356 could be observed in the wrought fraction due to low Cu/Zn/Fe content and some 7000 series wrought could be observed as being ejected into the cast fraction due to the high Zn content. The ejected fraction was mainly cast and the resulting composition is shown in **Table 1**. This mixture could be used to form high Cu containing Al cast alloys.

**Table 1: Cast ejection – XRT.**

CAST	Fe	Cu	Zn	Al	Si	Mg
EJECTION	0.80	3.3	1.8	84	8.8	0.21



The dropped fraction (*i.e. particulates that did not meet the preset sorting criteria*) resulted in the composition shown in **Table 2** after a 20 lb. sample that contained a significant amount of bulk Mg alloy was removed from the initial 100 lb. sampling. The bulk magnesium content in the light fraction of Twitch must be carefully monitored in order to avoid contamination. This impurity may be considered as beneficial if a secondary 5000 series alloy is being produced. This composition with silicon addition and with some dilution can form low Cu cast alloy, or with strictly dilution some secondary 5000 (with Mg addition)/6000 wrought alloys can be produced.

**Table 2: Dropped wrought – XRT.**

WROUGHT DROP	Fe	Cu	Zn	Al	Si	Mg
w/o Mg Impurity	0.46	0.45	0.18	95	2.7	1.1

### X-ray Fluorescence (XRF)

This system succeeded in reducing the amount of Cu, Zn and Fe in the bulk chemistry of the scrap when processing at the lowest threshold for each element. From this 50 lb. Twitch sample 48.7% was ejected and is labeled Al + Cu/Zn/Fe and 51.3% dropped and is labeled Al + No Cu/Zn/Fe. This sorting criteria, set for one material pass, proved to be effective in producing a bulk chemistry capable of forming a stream that could broaden the secondary aluminum alloy spectrum. The results comparing these two fractions are shown in **Table 3** along with the weight percent of cast vs. wrought in each ejection/drop. The dropped material without Cu/Zn/Fe is a suitable scrap class for secondary foundries trying to form low Cu/low Fe cast components or semi-products based on these three elements. However, the Si content presented in **Table 4** for the dropped, low Zn/Cu/Fe content is too low for secondary cast and too high for wrought alloys that are used in the automotive sector. Further dilution or Si addition would be required to achieve one or the other.

**Table 3: Steinert's XSS F results for Cu, Zn and Fe simultaneous low threshold ejection.**

Sample	Wt. % Cast	Wt. % Wrought	OES Zn composition	OES Cu composition	OES Fe composition
Al + Cu/Zn/Fe	72%	28%	0.88	1.7	0.55
Al + No Cu/Zn/Fe	26%	74%	0.027	0.051	0.30

**Table 4: Steinert's XSS F complete alloy composition results.**

Sample	Zn	Cu	Fe	Si	Mn	Mg	Cr	Ni	Ti	Pb	Sn	Other	Al
Al + Cu/Zn/Fe	0.88	1.69	0.55	7.2	0.14	0.29	0.040	0.040	0.070	0.020	0.010	0.050	89
Al + No Cu/Zn/Fe	0.030	0.050	0.30	2.9	0.19	0.55	0.030	0.040	0.060	--	--	0.030	96



## Laser-Induced Breakdown Spectroscopy (LIBS)

The LIBS automated system is capable of sorting by aluminum alloy regardless of form. To date, the research team has not conducted any hands-on testing. A sample of scrap Twitch has been analyzed and preliminary 2D sorting criteria for a LIBS system has been determined. Balance must be achieved when utilizing the LIBS technology as it applies to a mixture of scrap that could contain over 30 aluminum alloys. As it is not feasible to sort into 30+ alloy streams, a balance must be met where compositional ranges are targeted from which a secondary alloy can be formed with minimal dilution or additive requirements to meet specification, and the percent ejected that meets the sorting criteria should be maximized.

A scatter plot comparing the silicon and magnesium content in each of the Twitch particulates is shown in **Figure 1**. Four 2D sorting criteria are circled and presented in **Table 5**. Each of these sorts were chosen based upon clusters observed in the data set or upon the effort to form a specific secondary alloy. The sorting criteria is what the IF-THEN algorithm applied to the data set and the percent sorted value is the weight percentage of all particulates that met these criteria. Since each scrap particulate was weighed and an alloying weight percentage was supplied by the XRF gun, a weighted bulk chemistry was easily calculated and is also presented in **Table 5**. Circle one represents the selection criteria for the secondary formation of 6061. At present time, producing wrought from old scrap streams is not practiced, but to increase the sustainability of automotive scrap this need be performed in the future. The sorting criteria for circle two results in a Si content that is 2.5 wt.% too high and a Cu content that is 0.4 wt.% too low to form secondary 319. However, with dilution using low silicon Al scrap and pure Cu scrap, this composition could be altered to form this alloy. This is not an ideal procedure; further sortation criteria must be utilized to make this sort more feasible. Circle three shows another cluster that can be focused on to form secondary 6000 series alloys. There would need to be some compositional alterations here as well, including Zn and Si reduction depending upon which exact alloy in the series is being formed. Finally, the cluster in circle 4 can be used to form 5000 series wrought alloys with some dilution to lower the silicon content.



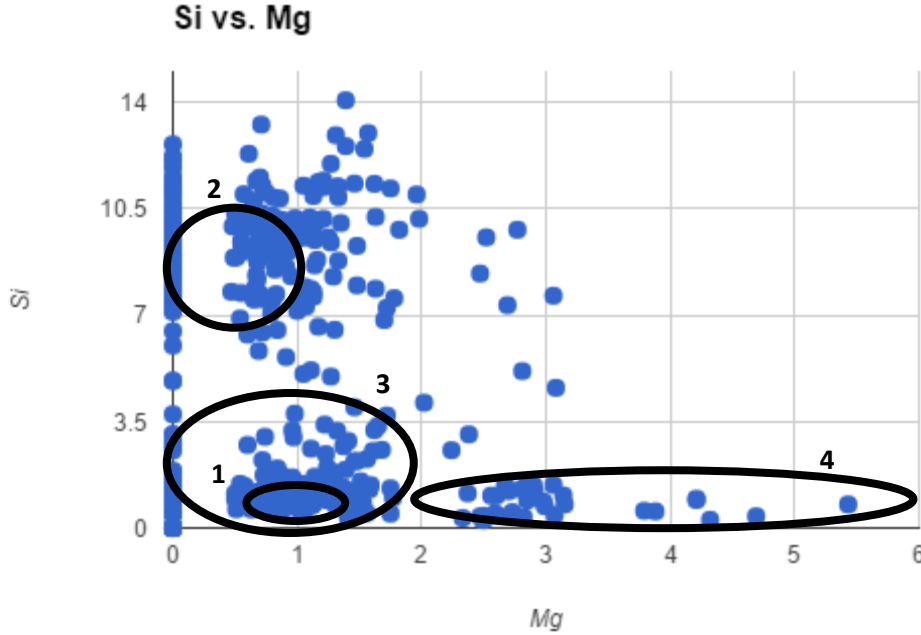


Figure 1: Si vs. Mg for all Twitch particulates.

Table 5: Sorting criteria analysis - Si vs. Mg.

Sort number	Target composition	Wt. % of Twitch used to attain target comp.	Si	Cu	Fe	Zn	Mg	Al
1	Mg: 0.8 – 1.2 Si: 0.4 – 0.8	4.5%	0.62	0.060	0.31	0.016	0.96	98
2	Mg: 0 – 1 Si: 6 – 10	31%	9.0	2.6	0.97	1.3	0.43	86
3	Mg: 0 – 2 Si: 0 – 4	33%	1.3	0.12	0.47	0.59	1.1	96
4	Mg: 2 – 6 Si: 0 – 2	8.0%	0.83	0.041	0.43	0.027	2.97	96

A scatter plot comparing Cu and Zn is shown in **Figure 2** with a more detailed analysis of the sorting criteria in **Table 6**. Circle one exposes a cluster that accounts for 53.9% of the entire mixture. However, this mixture contains a Si content that is too low to form a low Cu cast alloy (*i.e.* 356) and too high to form a 5000 or 6000 series wrought alloy. Therefore, this sorting criteria must be combined with a Si limitation or Si addition/dilution. The second circle shows a cluster that can be targeted to form 380 family which may not be desired as this is a low value secondary alloy that can be produced from a non-sorted Twitch. The composition that results from cluster three can be used to form secondary 384 with some de-magging. Although clusters result when plotting this 2D relationship, incorporation of other sorting instructions will be required.



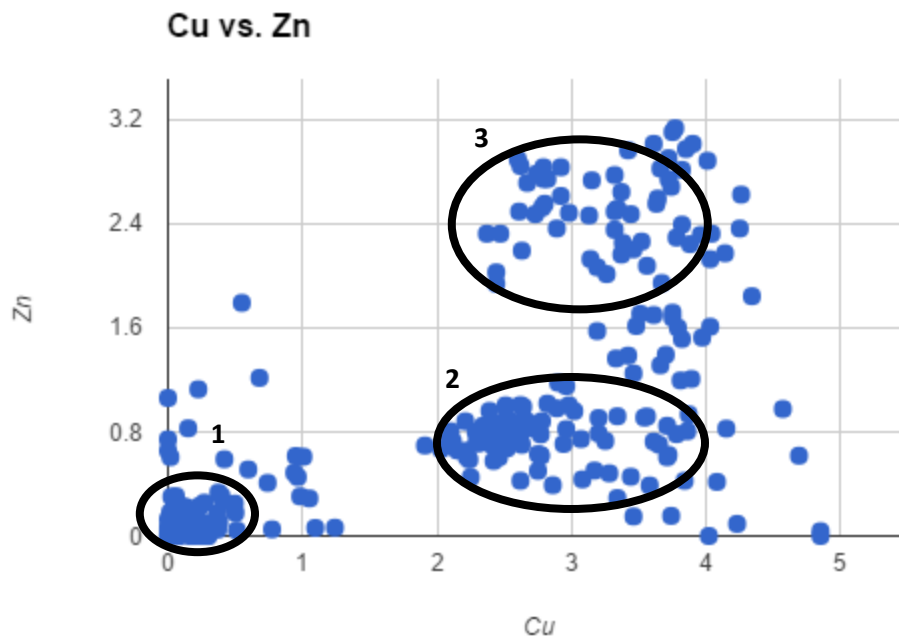


Figure 2: Cu vs. Zn for all Twitch particulates.

Table 6: Sorting criteria analysis - Cu vs. Zn.

Sort number	Target composition	Wt. % of Twitch used to attain target comp.	Si	Cu	Fe	Zn	Mg	Al
1	Cu: <0.5 Zn: <0.4	54%	2.6	0.090	0.59	0.050	1.29	95
2	Cu: 2 – 4 Zn: 0.4 – 1.2	20%	9.4	2.7	0.95	0.75	0.72	85
3	Cu: 2 – 4 wt.% Zn: 2 – 3 wt.%	11%	8.9	3.2	1.1	2.6	0.53	83

The scatter plot when comparing Si and Cu results in two distinct clusters as shown in **Figure 3**. These clusters are described in more detail in **Table 7**. The first cluster can be used to form a secondary 6061 if dilution is used to lower the Si content or 6016 if a de-magging process takes place. These alloys are used to manufacture automotive extrusions and sheet, respectively. The second circle requires an alloy that has wide compositional requirements. If de-magging is used, secondary 384 can be produced and with silicon focused dilution secondary 319 can be formed.



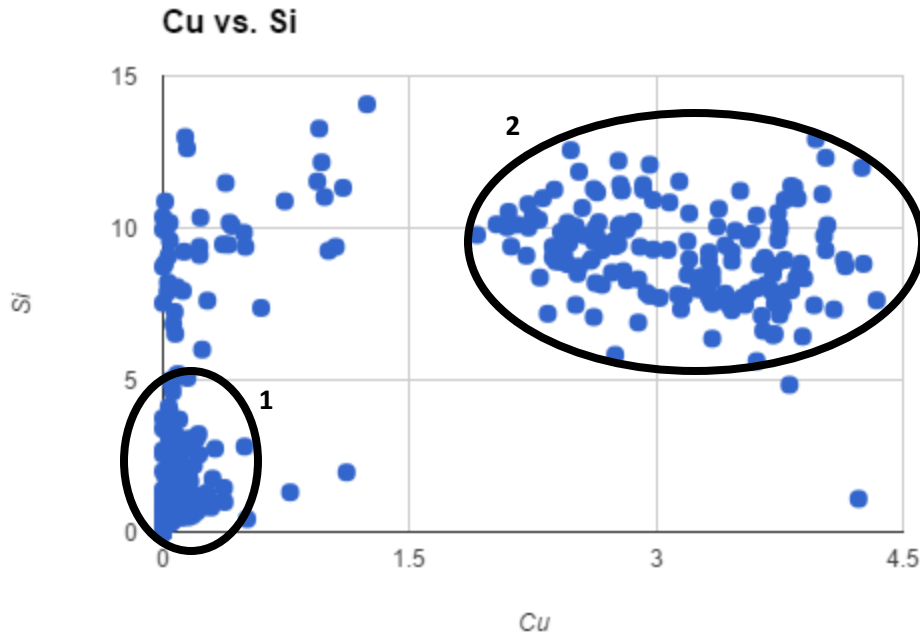


Figure 3: Cu vs. Si for all Twitch particulates.

Table 7: Sorting criteria analysis – Cu vs. Si.

Sort number	Target composition	Wt. % of Twitch used to attain target comp.	Si	Cu	Fe	Zn	Mg	Al
1	Cu: <0.6 Si: <5	47%	1.3	0.070	0.54	0.37	1.3	96
2	Cu: 1.9 – 4.5 Si: 5.5 – 13	38%	9.3	3.0	1.4	1.4	0.63	84

## CONCLUSION

It is clear that automated sorting systems can be used to up-cycle mixed aluminum scrap. However, careful attention to the sorting criteria is required. Many published articles cite the use of LIBS to sort into many alloy families or compositional bins (Harita 2016, Lovik 2014), however this may not be feasible considering the volumetric throughputs required to profit from up-cycling. Unfortunately, in the secondary metal production industry profit is key for any new technology or process to be implemented. There needs to be a solid business model in place for these automated sorting systems to take effect.

In summary:



- XRT can successfully sort into a light aluminum alloy fraction and a heavy aluminum alloy fraction based upon the alloying content. Some further sortation or post-sort processing will be required as discussed.
- XRF can sort based upon the heavy elements in the solid solution and promising results have been shown here.
- Further hands on work from the research team is required on a LIBS system to learn more about its efficiencies, capabilities, and limitations. Optimizing the sorting criteria from the current understanding with the 2D relationships discussed here is a must. LIBS is advantageous considering it can accurately detect all alloying elements but the throughput is lower than that of the XRT and XRF.

A balance must be met regarding throughput, fraction ejected based on of interest composition, and minimum post-sort processing/recipe adjustment. The sustainability of this scrap stream depends upon these developments.

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