Upcycling of Low-Quality Aluminum Automotive Scrap– The DNA of Twitch

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ABSTRACT

As our consumption of aluminum (Al) continues to grow, the demand to maximize the use of Al scrap grows proportionally. The challenge is to create value from waste, including low-quality scrap. Automotive Al scrap from auto shredders dubbed "twitch," is an amalgamation of Al alloys traditionally melted and downcycled to a low-value alloy. The Advanced Casting Research Center (ACRC) is working towards upcycling twitch to develop a high value green Al alloy made from 100% twitch utilizing liquid metallurgy methodologies and computational tools/software utilizing thermodynamic and kinetic databases (Integrated Computational Materials Engineering-ICME). Twitch has been collected over a period of time from the two coasts of USA–giving a geographical and temporal perspective. A dynamic analysis of twitch has been collected and the metallurgical pathways to upcycle to high value Al alloys is presented and discussed.

Keywords: green alloy, automotive, end-of-life vehicles, ELV, recycling, twitch, zorba, elemental composition, temporal, geographical, Integrated Computational Materials Engineering, ICME

INTRODUCTION

The International Energy Agency (IEA) requires a 250 Mt CO_2e decrease from the aluminum industry under the Beyond 2 Degree Scenario creating immense pressure on the Al industry to further promote sustainable practices.[1,2] Per the United States Environmental Protection Agency (USEPA), CO_2e (carbon dioxide equivalent) means the number of metric tons of CO_2 emissions with same global warming potential as 1 metric ton of another greenhouse gas. Two avenues emerge to mitigate the environmental footprint of Al: the first involves the reduction of emissions associated with primary Al processing, and the other entails the utilization of recycled Al. The former works to reduce the energy demand in primary aluminum production. This focuses on analyzing the life cycle of aluminum production and novel technologies and processing methods to reduce the energetically taxing process of producing aluminum from bauxite. The other aspect of decarbonizing the aluminum industry is expanding the use of aluminum scrap. Aluminum scrap is infinitely recyclable and can be used to make secondary Al. Secondary Al is recycled from aluminum containing scrap.[3] Secondary Al circumvents the electrolysis process and typically needs minimal treatment for remelting. The use of secondary or "recycled" aluminum allows Original Equipment Manufacturers (OEMs) to reduce their environmental footprint by roughly 95%.[4] The reduced footprint from using secondary aluminum renders it appealing to the Al industry. However, there is a disconnect in using low value Al scrap for structural applications (i.e., upcycling Al scrap). Understanding where low value Al scrap originates from and researching how to upcycle it is crucial to utilizing more secondary Al and thus reducing the CO_2 footprint of the Al industry.

Electrification of the transportation industry across the globe is increasing the need for light weighting of the fleet. Lighter vehicles have a longer travel time and lead to increased efficiencies for the consumer.[5,6] Aluminum usage in cars and trucks has increased significantly during the last decade, and that trend is increasing with time.[7] In 2000, the average weight of Al per vehicle was merely ~258 lbs./vehicle, whereas the projection for year 2030 is ~570 lbs./vehicle.[8] Moreover, the mix of Al extrusions, sheet, and castings used in the vehicle implies a large variety of alloys that are utilized for light weighting the structure. Specifically, the alloys that are utilized range from wrought 1xxx to 7xxx, to cast 3xx series. In 2019, 27 million cars were recycled across the globe, of which 12 million came from the US.[9] To understand the complexity and limitations of aluminum recovery in the automotive sector, a clear understanding of how a vehicle is deregistered and recycled is necessary as well as the metallurgical characteristics of the scrap that is available from end-of-life vehicles (ELV).

The process begins when an ELV is sent to a dismantler where hazardous materials and reusable parts are removed from the vehicle. The ELV is then flattened, shredded and sorted into different material streams. Typically, other post-consumer scrap streams are mixed into the ELV shred. The shred is fed through magnetic, air, and eddy-current separators (ECSs) to attain the nonferrous auto shred designated by the Institute of Scrap Recycling Industries, Inc. (ISRI) as zorba. A majority of zorba is exported to developing countries and the remainder is further sorted via density separation into zorba and twitch. The zorba fraction is the heavy nonferrous scrap typically containing copper, zinc, and brass whereas the twitch fraction is light nonferrous scrap mainly Al and magnesium (Mg). The journey for end-of-life vehicles (automotive) is shown in Figure 1.

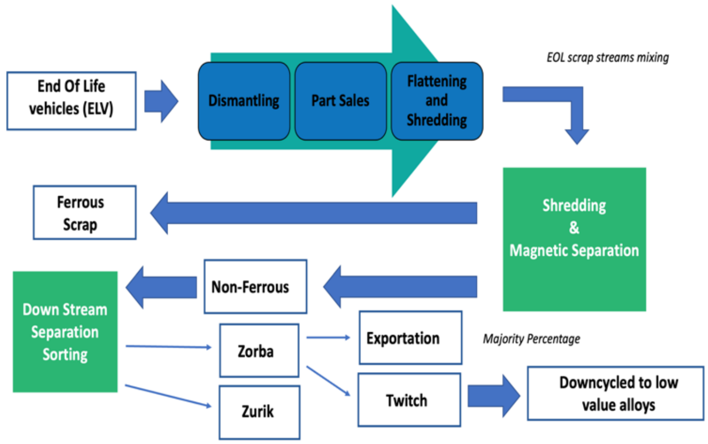

Figure 1. Pathway of end-of-life vehicles (ELVs).

The "waste" product from auto shredders that contains the most amount of Al alloys is twitch which has been used as the feedstock to produce secondary Al alloys. Twitch is an amalgamation of Al alloys ranging from 8-12 high value and low value alloys, see Table 1. Presently, much of the twitch is used by secondary aluminum producers to produce 380/390 diecast alloys having wide compositional specifications.[10] However, this is considered downcycling as there are many high value alloys in twitch that are currently not being reclaimed and melted together to form a low-quality alloy.

Table 1. Alloy Distribution from Two Twitch Samples[6]

Alloy/ Alloy Family	Twitch 1	Twitch 2
319	5%	7%
356	3%	3%
380	16%	31%
413	4%	6%
3000	1%	1%
5000	8%	8%
6000	26%	20%
7000	2%	1%
Other	34%	20%

At present, there is much industrial focus on reclaiming the alloys from twitch with advanced sortation technologies coupled with artificial intelligence and machine learning.[11,6] These include sortation technologies such as XRT (X-ray Transmission), XRF (X-ray Fluorescence), and LIBS (Laser Induced Breakdown Spectroscopy). Much has been published on these technologies.[12-14] Sortation of a wide variety of feedstocks is an engineering challenge and adds to the overall cost of the recovery and recycling operation. The Al industry needs to transition in maximizing the potential of the twitch stream. With the number of light vehicles reaching end of life (EOL), it is imperative that twitch is upcycled. There would be an advantage in directly melting (without any sortation) and applying liquid metallurgical processing to separate out unwanted phases as well as add elements to bring the composition of the melt in tune with the desired final composition generated from 100% scrap. The term "liquid metallurgical processing" refers to traditional molten metal processing technologies coupled with processing technologies that separate out unwanted phases as well as add elements to bring the composition of the melt in tune with the needed final composition. Again, the intent is to alleviate sortation of the feedstock, and to directly melt and apply liquid metallurgical processing to produce green Al alloys from 100% scrap.

To establish the efficacy of liquid metallurgical processing for upcycling of twitch it is imperative to understand the geographical and temporal variation of the twitch feedstock, or the "DNA" of twitch. This will identify the bad actors and establish which liquid metallurgical processing methodologies need to be employed. In this work, the dynamic (temporal and geographical) chemical analysis of the melted twitch scrap stream is presented measured via spectrometric analyses. As an additional validation to the chemical analyses of the melted twitch, VALIS Insights Inc.[15] analyzed the twitch feedstock (unmelted) from all 4 quarters (both coasts) via laser induced breakdown spectroscopy (LIBS). These results are being compared to the optical emission spectroscopy (OES) analyses from the melted twitch.

METHODOLOGY AND EXPERIMENTAL PROCEDURES

TWITCH COLLECTION, MACRO-ANALYSIS AND SAMPLING

Twitch was collected from the East Coast region (mostly from Pennsylvania to Georgia) from Radius Recycling (previously Schnitzer Steel Industries, Inc.), and from the West Coast (mostly California and Southwest region) from Radius Recycling and SA Recycling, LLC. The campaign commenced calendar year 2023, and 200 lbs.

(90Kg) was obtained each quarter (Q). From that 200 lbs, 100 lbs. (45 kg) were used for the melted bulk analysis while the remainder was used for LIBS analysis. This work presents the data from Q1 (January-March), Q2 (April-June), and Q3 (July-September) bulk melted analysis. Additionally, the data for West Coast (WC) Q1 LIBS analysis of unmelted twitch is also presented.

The makeup of twitch consisted of components ranging in size from 1.5 to 8+ in. (4 to 20+ cm), Figure 2. A detailed size distribution was not conducted, however, the parts that were in this size range mainly had their origin from cast components, whereas the larger parts found in twitch mainly had their origin from extruded and thus wrought alloys.

Figure 2. Visual representation of twitch.

With a such a large variety of twitch sizes and compositions (cast versus wrought), it is apparent that how the twitch is sampled and melted will be a significant factor. For example, if the twitch that is being melted comprises mostly of small parts versus large parts, two different outcomes will result. To validate this hypothesis, a batch of twitch consisting of small parts and another batch consisting of large parts were melted and analyzed. Table 2 shows the compositional differences between these two populations. This complexity in range of compositional spread mandated a rigorous methodology for sampling prior to melting based on statistics to ensure an unbiased analysis of the melted twitch.

Table 2. Sampling Distribution of "Large" & "Small" Twitch

Twitch Batch	Si	Fe	Cu	Mn	Mg	Zn
Small particles	7.85	0.74	3.29	0.24	0.95	1.44
Large particles	2.11	0.34	0.57	0.18	0.75	0.36

Utilizing Yamane's formula[16] (Eqn.1) the finite population size was set at 100 to represent 100 lbs. of twitch that had to be melted for analysis. Yamane's formula dictates that with a finite population size one can determine the necessary sample size (n) given the population size (N) and the acceptable population size (e). However, the issue of representative sampling did not lie with statistical sampling but rather with the fracture behavior of the aluminum components in the twitch stream. Carrying out a deeper analysis of the part size distribution in twitch, coupled with discussions with recyclers[17] it became apparent that the mechanical properties and fracture behavior of the scrap Al is significant. Cast aluminum tends to break up into smaller pieces while wrought particles tend to fracture in larger pieces. Additionally, many recyclers tend to size gate their twitch particles when selling it to maximize customer needs as the compositional demand vastly vary (Table 2).[17] Separating twitch particles by size can allow smelters to utilize twitch in a more cost efficient manner by enabling them to target their compositional specifications.

$$n = \frac{N}{1+N(e^2)} \qquad \text{Eqn. 1}$$

Representing the twitch chemistry in a lab environment is a challenging feat due to the sheer volume of twitch that needs to be melted. Without understanding the correct ratio of cast and wrought alloys in a representative sample of twitch it is improbable to correctly represent it. For this work a 50/50 split of large and small twitch parts was considered as representative of the whole.

MELTING

The twitch was cleaned in a mixture of water and industrial degreaser and preheated at 230F (110C) for 3 hours. This was done to remove any organic material on the surface and to remove trapped moisture. Ingot molds and an OES mold were preheated to 662F (350C) for 3 hours. Melting was conducted at the ACRC foundry using an Inductotherm 35kW unit. The starting batch of 100 lbs. (45kg) was separated into 4 smaller batches of 25-30 lbs. (11.3-13.6 kg). This was simply done as a limitation of the melting crucible used. A final melt was prepared by taking an even weight from each batch. In this manner, a representative and an unbiased ingot was prepared for analysis of the melted and cast twitch. Ingots were cast at 1364F (740C) and OES samples for compositional analyses were poured at 1328F (720C).

CHEMICAL AND MICROSTRUCTURAL ANALYSIS

Compositional analysis was conducted with the Ametek Spectro Lab S Optical Emission Spectrometer. Five samples from each twitch ingot were tested to attain a representative elemental composition. Samples were prepared using a Buehler SimpliMet 4000 Mounting Press. Samples were polished using a Buehler AutoMet 250 polisher. Optical micrographs were taken with using an Evident Scientific DSX1000 Digital Microscope.

PARTICLE ANALYSIS

Particle analysis was conducted using a SciAps Z-902 Alloy+ Analyzer. To prepare a sample for analysis a localized section of a twitch particle was ground, creating a surface capable for characterization.

ICME (INTEGRATED COMPUTATIONAL MATERIALS ENGINEERING)

Thermodynamic and Scheil solidification analyses was performed using Thermocalc-Software with the TCal 8.1 Al alloy database.

RESULTS AND DISCUSSION

DROSS

Melting twitch produces higher levels of dross than traditional primary or cleaner secondary aluminum melts. In the latter, in general, one finds that ~1-2.5% of the weight of the starting metal is found in dross.[18] For example, in a 100 lb. (45 kg) primary aluminum melt, one would expect 1-2.5 lbs. (0.45-1.13 kg) of dross formed. The dross resulting from melting twitch is more on the order of 10% which is significant, Table 3. While this study did not include an in depth analysis of the dross levels produced there are melting processes in industry that can reduce the levels of dross formed in secondary smelting.[19] The dross collected from melted twitch that was processed during our experiments was found to contain unmelted metallic pieces, ferrous pieces, glass, refractories as well as the product of runaway oxidation of magnesium.[20] The black dross formed from melted twitch is named "switch" referring to ***s***ludge obtained from twitch.

Table 3. Percentage Switch from Melted Twitch [Sum of 4 batches of Twitch melted, 100 lbs. (45Kg) total]

Quarter *(WC- West Coast; EC – East Coast)*	**Percentage of Switch**
Total Switch from WC Q1 melt	12.2%
Total Switch from WC Q2 melt	11.6%
Total Switch from WC Q3 melt	10.4%
Total Switch from EC Q1 melt	13.6%
Total Switch from EC Q2 melt	10.6%
Total Switch from EC Q3 melt	12.2%

Given the elevated amount of switch formed during melting of twitch it is important to address potential applications of switch, as the goal is to create value from waste. The switch chemistry exhibits significant variability, ranging from unmelted pieces, ferrous pieces, glass residue, and various other refuse, rendering the application of switch challenging. Nonetheless, switch can be processed at reclamation facilities where it can undergo series of processes aimed at recovering the entrapped aluminum within.[18]

ELEMENTAL QUARTERLY ANALYSIS

Figure 3 shows the results of the chemical analysis of melted twitch from the three quarters: wt.% vs. elements, Q1, Q2 and Q3 from both East Coast and West Coast Twitch feedstock, respectively. The blue color represents the WC whereas the red color represents the EC. The major constituents that are present in the twitch stream are silicon (Si), iron (Fe), copper (Cu), manganese (Mn), magnesium (Mg), and zinc (Zn). One can observe a consistent trend in the major elemental constituents in melted and cast twitch scrap stream.

From the dynamic analysis it can be inferred that there is increased variability in the amounts of Si, Cu, Mg, and Zn which are caused by the variations in the mix of cast vs. wrought scrap. From a temporal perspective the elements seem to follow a trend of similar compositions except for EC Q1 having significantly higher amounts of Mg and Zn. The EC Q1 supplier did not utilize extensive downstream separation technologies, therefore the result could be increased amounts of light alloys such as Mg alloys contaminating the twitch.

The variability in strengthening elements namely Cu and Mg can stem from the downstream sorting technologies being used. Certain downstream separation operations remove extra Cu wiring or Mg alloys from the twitch, and different recycling plants have different processes in place. From the geographical analysis indicates that the EC Q2/Q3 supplier used downstream sortation technologies to reduce the levels of Cu and Mg. This can be inferred due to the fact that when melting EC Q2/Q3 there was less Cu wires in the melt and reduced burning of Mg alloys. The excess levels of Cu could also be indicative of larger amounts of cast alloys namely 380. From a temporal perspective the Si is rising in the WC and decreasing in the EC Twitch streams. This could be due to the increased/decreased amount of cast alloys being sampled. However, it is not possible to come to a conclusion regarding the change in elements without a larger study in sampling.

Finding the representative sample size in twitch especially the ratio of cast vs. wrought is crucial to ensure a representative twitch stream. Particle size analysis can elucidate the alloy family distribution and is needed to establish a protocol how to sample twitch accurately. The Si content level in twitch strongly indicates a prevalence of cast alloys. This is substantiated by the fact that wrought alloys have an upper limit of 0.9 wt.% Si in the 6xxx series. The difference in the average Si content ~5.29 wt.% suggests a predominance of cast alloys in the twitch stream. Sortation aims to reclaim the value of twitch by separating out the "high value" alloys from the twitch stream. In contrast, liquid metallurgy aims to harness the full spectrum of alloys present within the twitch aiming to upcycle the entire stream. Figure 4 shows the average elemental composition of all the melted twitch, from both East and West coast streams and for all three quarters studied, Q1, Q2, and Q3. Table 4 gives the data in a tabular form, showing that melted/cast twitch ingot has about 91% Al, with ~5-6% Si, ~0.6%Fe, ~1.5% Cu, and ~0.9% Mg and Zn.

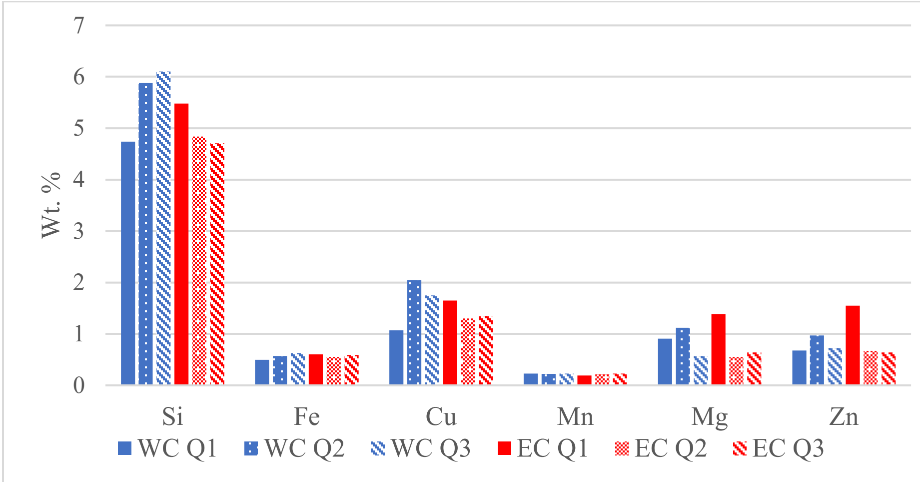

Figure 3. Quarters 1-3 elemental analysis of melted twitch.

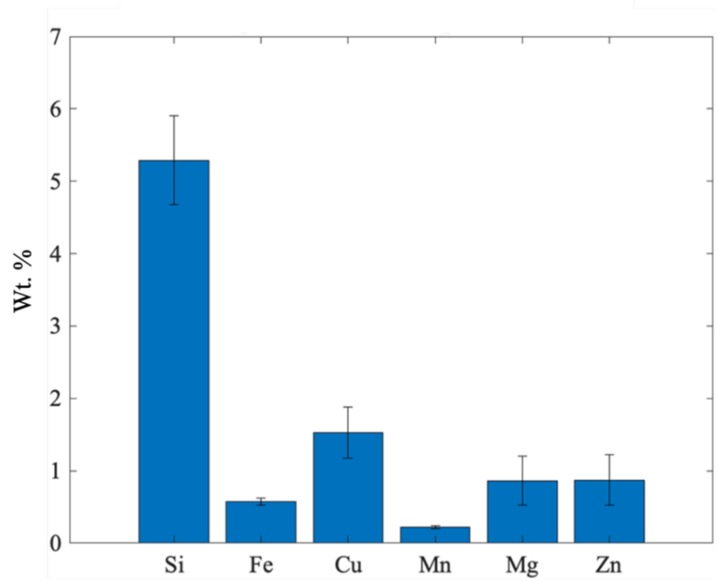

Figure 4. Average elemental composition of twitch (Q1-Q3, for both EC and WC).

Table 4. Distribution of Major Elements of Twitch

	Si	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**
WC Q1	4.74	0.50	1.07	0.23	0.91	0.68
WC Q2	5.88	0.57	2.05	0.22	1.12	0.97
WC Q3	6.10	0.63	1.75	0.23	0.57	0.73
EC Q1	5.48	0.60	1.65	0.19	1.39	1.55
EC Q2	4.84	0.55	1.30	0.22	0.55	0.67
EC Q3	4.71	0.59	1.35	0.23	0.64	0.64

	Si	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**
Average of all twitch Melted *(Q1 -Q3, both EC and WC)*	**5.29**	**0.57**	**1.53**	**0.22**	**0.86**	**0.87**
Std.Dev	0.61	0.05	0.35	0.02	0.34	0.35

Table 5. Classification of 380 per LIBS (wt%)

Si	**Fe**	**Cu**	**Mn**	**Mg**
12.28	1.02	3.23	0.13	0.12
Zn	**Ni**	**Cr**	**Ti**	**Pb**
1.57	0.05	0.04	0.05	0.26

MINOR ELEMENTS IN TWITCH

It is important to address the minor alloying elements or impurity elements of the melted/cast twitch as these have significant ramifications in the resultant structure and properties. The melted/cast twitch that was analyzed contained chromium (Cr), nickel (Ni), titanium (Ti), lead (Pb), and tin (Sn), and the data are given in Figure 5. Some of these elements are trace alloying elements; namely Cr, N, and Ti. Nickel and Cr can be found in ferrous scrap namely stainless steel that can be mixed in with the twitch. The Sn is used in casting applications to reduce friction between bushing and bearing applications to reduce overheating. However, an unprecedented element is Pb. Lead is a toxic impurity element that has a maximum tolerance of 0.1 wt%.[21] However under the Restriction of Hazardous Substances (RoHS) standard there are exemptions that allow Pb tolerances up to 0.4 wt.% composition stems from Pb-bearing Al scrap. Regardless, an important consideration is the removal of Pb from molten twitch prior to casting. Removing Pb from the system is an imperative goal as the industry strictly regulates the amount of toxic impurity elements allowed in the system. The first step is to identify the source of Pb and evaluate the effectiveness of liquid metallurgy to remove it in the molten state.

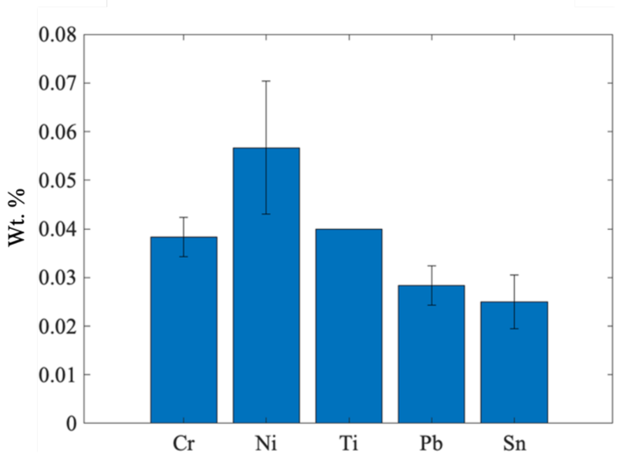

Figure 5. Minor elements found in twitch (Q1-Q3, for both EC and WC).

PARTICLE ANALYSIS

In conjunction with a melted bulk analysis, LIBS characterization of twitch particles (not melted) was conducted to examine the alloy distribution that lies in the twitch stream. Such a detailed LIBS analysis of each particle will assist in identifying the source of impurity elements such as Fe or Pb. Figure 6 shows a pie chart breakdown of the alloy families found in WC Q1. There is a large amount of 380, 3105, and 6063 in the stream analyzed. Additionally, there is 356 and various 4xxx and 5xxx series in the stream. The particle analysis shows a significant portion of the alloys as wrought alloys, however, from the melted bulk analysis the chemistry is not comparable. The particle analysis shown in Figure 6 contradicts the chemistry of melted/cast twitch, Figure 4 and Table 4. It should be noted that LIBS analysis is based on particle size, and thus for all future analyses weight-based metrics for LIBS needs to be applied. Specifically accounting for the weight of the particles being analyzed, as the results may be skewed. Analyzing particles by weight will give a clearer representation of the actual distribution of particles in the twitch stream as the particle mass is more indicative of the alloy diversity in the twitch feedstock.

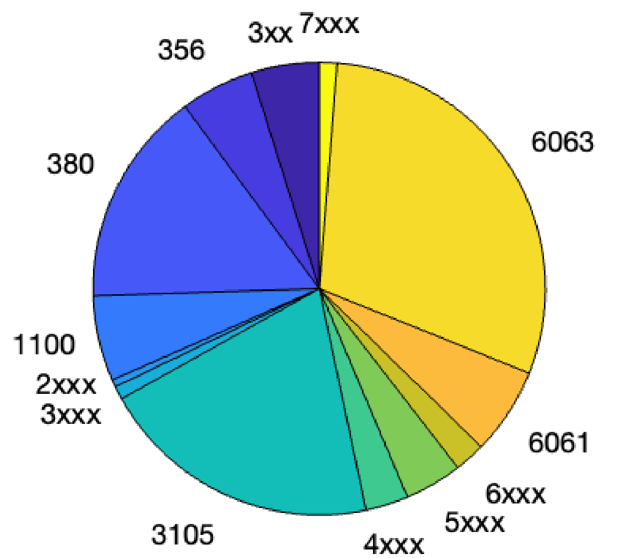

Figure 6. LIBS analysis of all particles and components in WC Q1 unmelted twitch stream.

Table 5 presents the average chemistry of 380 measured by LIBS since it is the major contributor of impurity and trace elements. As expected, 380 has a high tolerance for Fe~1.02%, Cu~3.23%, Zn~1.57%, and Si, which should be ~7.5-9.5%, is out of specification at ~12.28%.

A noticeable impurity element found in 380 is Pb. Whether the Pb is an elemental constituent of the alloy, or whether it is present on the surface of a particle from an artifact is being investigated. If the former, liquid metallurgical processing technologies can be utilized to dilute the Pb. If the latter, a mechanical cleaning or an alternative solid separation methods need to be used prior to melting and casting the twitch.

MICROSTRUCTURAL ANALYSIS

As shown in Figures 3 and 4, Si is a predominant alloying element in melted/cast twitch. In addition, minor elements are also present such as Cu, Mg, and Zn, which are key in strengthening of the alloy. However, there is an optimum level of these strengthening elements that should be targeted, as in excess they can reduce ductility of the alloy. Considering the composition of melted/cast twitch (Table 4), one can expect that it should have a high ultimate tensile strength but low elongation values due to the presence of brittle intermetallic phases. Figure 7 is the Scheil solidification curve - fraction solid versus temperature for the average melted/cast twitch composition. As can be seen, multiple Fe-containing phases, Si eutectic, and Cu-containing phases precipitate out during solidification.

The Scheil solidification curve (Figure 7) gives valuable information about the phases that form and at what temperature they precipitate out during the solidification journey. It can be noted that after the initial precipitation of FCC Al (represented as FCC_A1) the favorable Fe phase α-$Al_{15}(Fe,Mn,Cr)_3Si_2$ forms (represented as Al15Si2M4). However, the more dominant Fe phase is the deleterious β-Al_5FeSi phase (represented as Al9Fe2Si2), which precipitates next. Additionally, towards the end of solidification the quaternary Q-$Al_5Cu_2Mg_8Si_6$ (represented as Q_ALCUMGSI) and the binary θ-$AlCu_2$ (represented as Al2CU_16) precipitate out; these are known to increase strength but reduce ductility.[22] The solidification curve shows a variety of phases that are forming in the matrix ranging from iron containing intermetallics, to the Si eutectic (represented as DIAMOND_A4) to strengthening precipitates like Mg_2Si (represented as MG2SI_C1).

Figure 8 shows micrographs of the melted/cast twitch microstructure. Figure 8a shows an overview of the microstructure, while Figure 8b shows specific intermetallic phases. The microstructure indicates the "bad actors" and the deleterious phases/intermetallics that need to be removed. For example, the sharp platelet intermetallics are the β-AlFeSi[23] phase markedly reduce mechanical properties of the alloy. In addition, different copper phases are observed. The initial hypothesis was that Fe would have been the most prohibitive element, however the mixture of Cu, Mg, and Zn indicates that an abundance of strengthening elements may reduce ductility and have negative ramifications on dynamic properties.

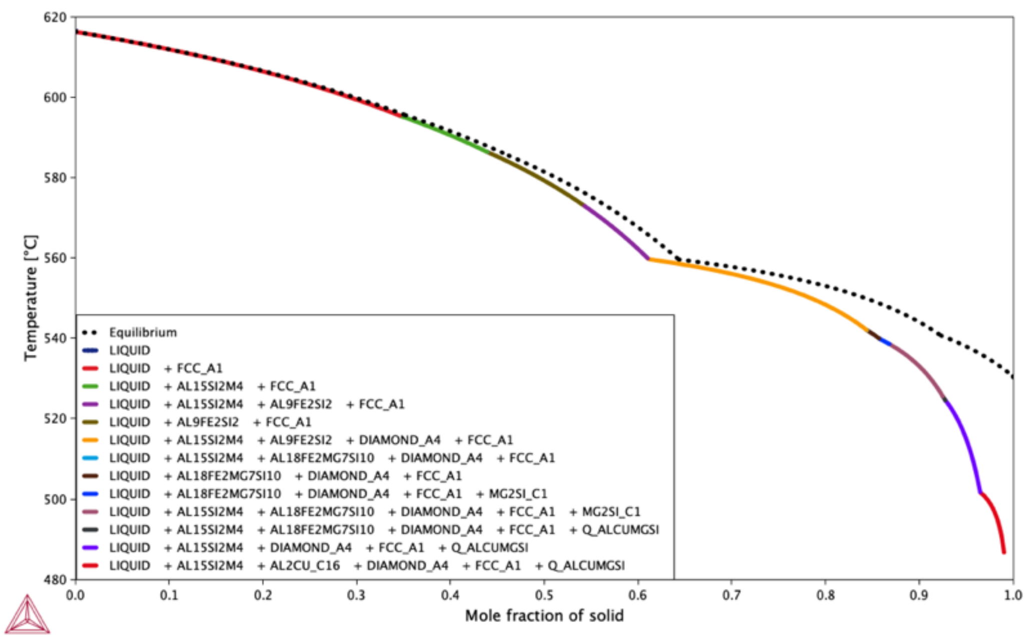

Figure 7. Scheil solidification path of twitch alloy.

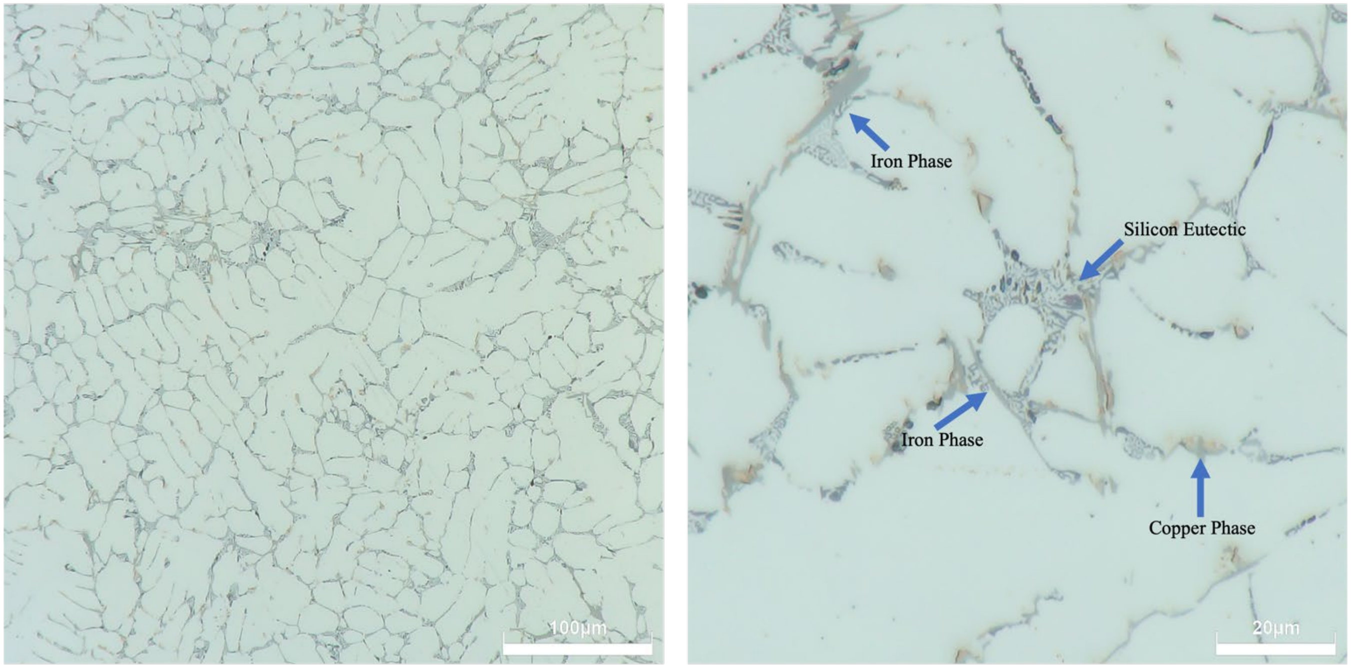

Figure 8.(a) Macrostructure of melted/cast twitch showing the typical dendritic cast structure, (b) The various phases that are found in melted/cast twitch and the presence of deleterious intermetallic phases.

UPCYCLING TWITCH

The next phase of this work is to focus on liquid metallurgical processing methodologies (Table 6) to produce a system of green alloys from 100% scrap (twitch) in an upcycling modality rather than downcycling. With the general composition of twitch attained, and the contaminating elements identified (Fe, Pb, and excess amounts of Cu, Mg, and Zn) the next step is to determine the chemical and physical characteristics of the phases and elements that need to be removed. For example, density, volume fraction of the phase present, size distribution of the deleterious phases, electrical and magnetic properties, surface energy considerations, etc. The latter will be important factors to consider in determining the appropriate liquid metallurgical pathways to pursue.

In the endeavor of developing a novel green alloy, the reduction of iron from the melted/cast twitch is not an option; β-AlFeSi is detrimental to the resultant properties.[24, 20] Over the years, separation technologies have been developed and utilized in various fields outside of metallurgy. The chemical engineering industry with a vast experiential base in unit processes and unit operations is a rich resource for the development of liquid metallurgical technologies. Technologies to separate out unwanted phase and intermetallics are briefly reviewed here to establish some context.

Gravity sedimentation uses gravity to separate denser phases. Sludge, primarily the Fe rich phase[15] – i.e., α-$Al_{15}(Fe,Mn,Cr)_3Si_2$ sediments to the bottom.[26]

Filtration is another technology that can be used to remove phases either through deep bed filters, or foam filters.[27] In deep bed filters, separation occurs due to the differences in the flow velocity profile of the intermetallics and the melt in the fluid stream.[28] Whereas in foam filters, it relies for the phase to be separated and be held up above the filter surface and form a "cake."[27]

Centrifugal force is another means of separating phases from the melt; denser phases being forced to the outer perimeter of the crucible, whereas lighter phases being forced to the inner core of the melt. This technology has been used to efficiently remove iron rich phases from the melt with up to 75% removal rates.[29] Parameters that influence separation efficiency include G-Force, melt temperature, and overall composition of the melt.

Electromagnetic (EM) separation is another effective mode for separation, relying on induced Lorentz forces. The principle is that when a uniform EM force is applied to the melt, it is compressed and a pressure gradient forms. The non-conductive particles move in the opposite direction of the EM force and separate out. Table 6 is a summary of the liquid metallurgical technologies that are potential candidates to remove unwanted phases from melted twitch.

Table 6. Summary of Liquid Metallurgical Processing Techniques

	Centrifugal Treatment	Filtration	Electromagnetic Separation	Gravity Sedimentation
Concept	Centrifugal force moves intermetallics to outside wall	Porous filters used to trap/block intermetallics	Apply nonconductive EM forces to intermetallics pushing them to melt surface	Partial solidification to form intermetallics
Underlying Physics	Centrifugal Force	Intermetallics size, diffusion, surface force retention	Lorentz Force	Density of phases
Criteria	G-Force, Density, Stokes Law, Temperature, Viscosity of fluid	Filter material and size, temperature	Lorentz Force, Power Coefficient, Stokes Law, Archimedes gravitation	Temperature, Density of phases

Liquid metallurgical techniques can be utilized to remove Fe and Si from the system.[29] The reduction of Fe is beneficial for the resultant mechanical properties as there would be less precipitation of the deleterious β-AlFeSi intermetallic. While the reduction of Si would reduce the overall castability of the green alloy, it would on the other hand improve its mechanical properties. Reducing the amount of Si would alleviate the presence of the Q-phase (AlCuMgSi). Specifically, with reduction of Si from melted/cast twitch, the potential exists to produce wrought-like alloys such as 6061 and others. In the next phase of the ACRC project being pursued at University of California, Irvine, (UCI), these pathways are being studied to examine feasibility for purifying twitch.

There is much historical legacy when it comes to Al alloy development going back to Wilm in 1906.[31] In the quest of upcycling twitch, it is important to keep in mind that in addition to the potential of making a known alloy from twitch, one needs to be open to the opportunity to make a new alloy, a high-integrity green alloy, that is completely novel and leverages the value in twitch from 100% scrap, and reduces carbon footprint.

CONCLUSIONS

To upcycle twitch, a detailed compositional study was conducted to account for all major and minor elements in the scrap feedstock. A temporal and geographical compositional study was conducted to study the variability of the twitch feedstock. The intent is to alleviate sortation of the feedstock, and to directly melt and apply liquid metallurgical processing to produce green Al alloys from 100% scrap. From this work, we can conclude that:

- Major elemental constituents in melted and cast twitch are Si, Cu, Fe, Mg, Mn, and Zn. Specifically, ~ 91% Al, with ~5-6% Si, ~0.6%Fe, ~1.5% Cu, 0.22% Mn, and ~0.9% Mg and Zn.
- Minor elemental constituents in melted and cast twitch are Ni, Ti, Cr, Sn, and Pb.
- The Al industry has a tight tolerance for Pb. The Pb seems to stem from the 380 alloy family.
- The LIBS analysis of WC Q1 shows a variety of alloys in the twitch stream but the stream is mainly 3xx, 3xxx, and 6xxx alloys however more research needs to be conducted with LIBS analysis measuring by weight instead of particle size.
- Twitch feedstock consists of small and large parts, the smaller ones emanating from cast components, whereas the larger ones from extrusions or wrought alloys.
- The variability in elements can stem from a misrepresentative sampling bias, thus further research needs to elucidate the most accurate way to sample twitch.
- The melted/cast composition suggests a high UTS but low ductility because of Fe, Cu, Mg, and Zn.
- Removal of unwanted phases via liquid metallurgy creates potential to produce high value alloys from 100% twitch.

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