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Designing Aluminum Alloys for a Recycle-Friendly World

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Introduction

Recycling aluminum alloys has been shown to provide major economic benefits. As a result, it is appropriate for the aluminum industry and the U.S. as a whole to identify, develop, and implement all technologies that will optimize the benefits of recycling.

This paper will focus primarily on alloy design for optimizing the reuse of recycled metal; this is both the most forward looking area as we move toward a more recycle-friendly world, and the most overlooked for its potential in maximizing the recycle loop. Some specific approaches to alloy design for recycling are put forth, and some specific compositions for evaluation are proposed. Options for moving forward to further capitalize on the advantages of aluminum recycling are also addressed.

Background

Aluminum recycling in North America is a mature, well-developed economy. Aluminum recycling gained momentum after World War II following rapid economic and industrial growth, and especially after the introduction of the aluminum beverage can with its easy-open end. While today's recycling metals markets also include ferrous metals like iron and steel, and nonferrous metals like copper and brass, aluminum recycling is the engine of recycling economics.

Today an increasing amount of the aluminum going into producing new aluminum alloy products is coming from recycled products. Choate and Green[1] have illustrated that much of the increase is coming from recycled automotive components. In 2005, for the first time, recycled scrap coming from automotive products is expected to exceed that coming from used beverage cans (UBCs). *The Aluminum Industry Roadmap*[2] illustrates the importance of these trends and efforts to address the technology from primary production to finished products, and Fielding's recent article in *Light Metal Age*[3] illustrates how one segment of the industry, the extrusion business, is approaching the challenge.

The increase in recycled metal becoming available is a positive trend, as secondary metal produced from recycled metal requires only about 2.8 kWh/kg of metal produced while primary aluminum production requires about 45 kWh/kg produced. It is to the aluminum industry's advantage to maximize the amount of recycled metal, for both the energy-savings and the reduction of dependence upon overseas sources (now about 40% of U.S. consumption). Increasing the use of recycled metal is also quite important from an ecological standpoint, since producing aluminum by recycling creates only about 4% as much CO_2 as by primary production.

The significant economic advantages of aluminum can recycling have also been demonstrated in a joint study of a representative American community by Secat, Inc., the Center for Aluminum Technology (CAT), and the Sloan Industry Center for a Sustainable Aluminum Industry (CSAI), all of which are located at the University of Kentucky in Lexington. For each 1% increase in the amount of aluminum cans recycled, the economic savings to the U.S. economy is $12 million/year. It was shown that this could approach $600 million to offset the U.S. trade balance if all available aluminum cans could be recycled.

Savings such as these are significant enough to support the construction of new recycling plants, adding a significant number of high-paying jobs. The additional recycling also contributes to energy savings of 1 trillion BTU/year. Such major impacts have the potential to significantly decrease our reliance on overseas sources of primary aluminum metal.

Today, much recycled aluminum must be "sweetened" with more costly and energy-intense primary metal before it is reused in order to meet the performance requirements of most alloy and product specifications. The result is that, in most cases other than beverage cans, recycled metal tends to be used primarily for lower grade casting alloys or wrought products. While a modest amount of this will always be acceptable, the full benefits of a recycle-friendly world can only be realized when the recycle loop is closer to a closed loop for a number of product lines.

These observations lead to the conclusion that as an industry we need to be looking forward to every opportunity for maximizing the advantages of what we are calling a recycle-friendly world.[4] In the discussion that follows, we will begin to develop the characteristics of such a world, and then to identify and address the technological challenges of optimizing that environment.

Characteristics of the Recycle-Friendly World

In the ideal recycling world of the aluminum industry:

- Recycling of all used aluminum products and components would be the norm, and the total content of recycled products would increasingly approach the total required by U.S. consumption. The amount of primary production required would be reduced, and therefore the dependence by the U.S. on overseas production minimized.
- Recycled aluminum would be processed utilizing automatic sorting, shredding, and separation technology to facilitate its reuse in new products.
- A variety of existing and new aluminum alloys would be available with compositions compatible with the composition of most recycled metal. The opportunities for direct use of the recycled, shredded, and sorted metal would be optimized.
- Parallel to the existing situation with beverage cans, there would be a number of high-value applications into which the recycled metal would flow. The resultant product made directly from the recycled metal would meet the required composition and mechanical property specification limits for those applications.

Challenges in Achieving the Recycle-Friendly World

There are a number of challenges to be met to create the recycling friendly world. Among the key challenges are the following:

- Maximize recovery of used aluminum products and components for recycling
- Automate and optimize pre-sorting, shredding, and separation technologies, and make them broadly available
- Identify more useful by-products to handle elemental residual unsuitable for reuse in recycled metal, e.g. Fe
- Broaden the number of available aluminum alloys

whose specifications will readily directly accept recycled metal and will perform well in high-quality, value added products

Progress has been and is still being made in addressing the first three challenges. An example of greatly improved shredding and sorting technology is the laser induced breakdown spectroscopy (LIBS) developed and being utilized by Huron Valley Steel Corp. (HVSC).[5] An excellent example of a by-product utilizing aluminum containing relatively high iron content is the "de-ox" for deoxidizing steel during its production, getting significant amounts of undesirable Fe out of the aluminum system.

The fourth challenge, the identification of new alloys that will more readily utilize recycled aluminum, has received little attention, and in fact is considered impractical by some because of the generally negative effects of impurity elements in aluminum on certain properties such as fracture toughness. However, the potential economic and environmental benefits are sufficiently great that we believe it is indeed useful to consider this approach. Addressing this last challenge is the main focus of this paper.

In the following sections, we will focus on the challenges facing the direct application of recycled aluminum alloys to high quality aluminum products, a possible rationale for creating and evaluating new, more recycle-friendly alloy compositions, and proposing specific action to create progress in this approach.

The Nature of Recycled Metal

As a starting point in considering the challenges faced in directly utilizing recycled aluminum scrap, it is appropriate to look at representative compositions observed in such metal.

Some representative compositions of recycled aluminum reported by Adam Gesing of HVSC are shown in weight % in Table I. HVSC is capable of pre-sorting wrought and cast alloy scrap, so four samples were chosen of representative wrought separations, three of representative cast separations, and one of the two mixed (wrought and cast alloys).

LOT	Al	Cu	Fe	Mg	Mn	Si	Zn	Others
WroughtA	97.1	0.11	0.59	0.82	0.21	0.51	0.45	0.19
WroughtB	93.1	0.95	1.01	0.89	0.12	2.41	1.25	0.27
CastA	83.5	4.40	1.10	0.40	0.30	8.0	1.90	0.40
CastB	88.4	2.50	0.75	0.58	0.26	5.18	1.27	1.09
MixedW&C	90.1	2.30	0.80	0.50	0.20	4.50	1.20	0.30

Table I. Representative composition of recycled aluminum.

These representative compositions illustrate several of the fundamental complications in directly reusing scrap aluminum:

- Even when wrought scrap has been segregated, individual lots can have relatively widely varying compositions; for example, WroughtB has higher Cu (possibly from more autobody alloy 2036 alloy) and higher Zn (possibly from more bumper alloy 7029) in the mix.
- Some lots of wrought recycled metal like WroughtA match existing wrought alloys reasonably well, e.g. 3005, 3104, 3105, and 6061, and can be readily reused; others like WroughtB do not and will be more difficult to use directly.
- Cast alloy scrap can vary greatly in composition, and is likely to differ significantly in composition from wrought alloy scrap. Note the differences in Cu, Si, and Zn between CastA and CastB. Note also the higher Si content compared to WroughtA and B, typical of castings, and higher Cu (from 380.0 and 390.0) and Zn (from 7xx.0 cast alloys) depending upon which cast alloys are involved.
- Compositions resulting from mixed wrought and cast scrap (MixedW&C) will be more difficult to use directly because of their combinations of higher Si, Cu, and Zn, except perhaps in some casting alloys.

Thus, with the exception of segregated recycled beverage can scrap, most recycled aluminum involves a mixture of alloys from a fairly wide variety of applications, including a selection of castings containing rather high percentages of Si. While there is generally no problem recycling most of this metal as castings, there is a significant challenge in shredding, sorting, and, in some cases, further refining of the metal to achieve acceptable impurity levels for products other than castings, including sheet, plate, forgings, and extrusions.

This is particularly true for any of the specialized alloys produced today, for example, those utilized in the aerospace industry where requirements for exceptionally high ductility and toughness are common. Such performance requirements call for very tight composition controls on both Fe and Si. Impurity levels above 0.15% Fe or 0.25% Si are unacceptable in premium aerospace alloys such as 7050, 7055, and 7475. Similarly some high performance automotive alloys (e.g. 5457 and 6111) restrict both Si and Fe to 0.40% maximum. Both of these elements (Fe and Si) are difficult to control in recycled metal, and tend to increase slightly the more often the metal has been recycled.

Fe in particular can be a significant challenge because of its tendency to increase gradually in metal recycled over and over again, primarily from pickup from scrap handling systems. As a result, Fe is an ideal candidate for application to alternative products, an excellent example of which is the use of high Fe-bearing aluminum as a deoxidizing agent for steel production. Optimization of this product will benefit both the aluminum and steel industries and add to the life-cycle benefits of aluminum operations. Another possible approach to the increased Fe content is to make use of the affinity of Zr for Fe, creating a heavy particle readily taken from an aluminum melt.[6]

It should be noted that elements other than Fe may be expected to gradually increase with repeated recycling and are likely to require special attention. Mg, Ni, and V are three examples, also potentially treatable with Zr.[6]

Using Recycled Metal in Existing Alloys

Cast Alloy Scrap: Recycled casting alloys can often be used directly in new cast products, notably those of the 3xx.0 and 4xx.0 series of the types illustrated in Table II.

As seen by the compositions presented in Table II, all contain relatively high Si, and their impurity limits tend to be relatively loose. However, even these relatively tolerant limits pose some challenge for direct recycle reuse. For all except 336.0, for which no "Others" limit exists, the "Others" contents noted in scrap samples are higher than desired. In the 4xx.x series, the tight Mg content will be a challenge. Despite these added challenges, casting alloys as a whole are more tolerant for direct recycling.

ALLOY	Al	Cu	Fe	Mg	Mn	Si	Zn	Others
B319.0	remainder	3.0-4.0	1.2 max.	0.10-0.50	0.8 max.	5.5-6.5	1.0 max.	0.50 max.
336.0	remainder	0.50-1.5	1.2 max.	0.70-1.3	0.35 max.	11.0-13.0	0.35 max.	- -
C443.0	remainder	0.6 max.	2.0 max.	0.10 max.	0.35 max.	4.5-6.0	0.50 max.	0.25 max.

Table II. Typical recycled casting alloys.

Wrought Alloy Scrap: The compositions of several of the most useful alloys for direct use of recycled metal are shown in Table III. It is clear from these limits that the challenge of reusing recycled scrap in wrought alloys without sweetening with primary metal is much greater than in cast alloys.

ALLOY	Al	Cu	Fe	Mg	Mn	Si	Zn	Othe
3005	remainder	0.30 max.	0.7 max.	0.20-0.8	1.0-1.5	0.6 max.	0.25 max.	0.15 max.
3104	remainder	0.8 max.	0.6 max.	0.8-1.3	0.8-1.4	0.6 max.	0.25 max.	0.15 max.
3105	remainder	0.30 max.	0.7 max.	0.20-0.8	0.30-0.8	0.6 max.	0.40 max.	0.15 max.
6061	remainder	0.15-0.40	0.7 max.	0.8-1.2	0.15 max.	0.40-0.8	0.25 max.	0.15 max.

Table III. Examples of wrought aluminum alloys.

Even for these alloys, the maximum limit on "Others" will present a challenge in reusing recycled scrap. The "Others" total in WroughtA above exceeds the limits for all of these alloys.

These examples illustrate why the approach of designing recycle-friendly alloys is so appealing.

Developing and Evaluating Recycle-Friendly Aluminum Alloys

The goal of identifying new recycle-friendly aluminum alloy compositions is to increase the opportunities to directly or with only minor modification reuse recycled scrap aluminum products. Such an approach requires compositions with relatively broad specification limits on major alloying elements such as Cu and Mg, plus more tolerant (i.e. higher) limits on Fe, Si, and other impurities. A further goal is to accomplish this without significant restriction on performance characteristics for many important applications.

Fully developing this approach requires several important steps. As described in another paper on this subject,[4] the needed phases of such a development program include the following:

Phase 1: Utilize the experience of organizations already in the aluminum recycling business, such as HVSC, to identify more precisely and with higher probability the likely sources and expected ranges of compositions of current and future recycled metal content.

Phase 2: Based upon the results of the study in Phase 1 plus market projections for products such as aluminum beverage cans and motor vehicles, perform a mass balance indicating the anticipated volumes of various scrap compositions to be expected.

Phase 3: With a projected mass balance in hand, identify[5-7] candidate alloy composition limits that would most effectively directly utilize the anticipated recycled metal and seem likely to provide acceptable/desirable performance characteristics for a wide variety of applications.

Phase 4: Experimentally produce and statistically evaluate the performance of the candidate alloys— including especially atmospheric corrosion resistance, stress-corrosion crack growth, toughness (with tear tests and/or fracture toughness tests for thick sections), and formability tests with bulge, minimum bend, and hemming tests—along with the usual tensile and design properties, in order to assess their suitability for representative applications as compared to existing alloys.[7-12]

It is recognized that there are likely to be some negative effects of higher impurity levels where required, but these may not be important for many high-volume applications. A critical assessment of this particular point will be a major thrust in Phase 4.

Separation technologies such as LIBS to screen scrap with certain combinations of the desired elemental additions may permit some greater flexibility in the candidate compositions, but it will still be useful to look at the long-term alloy requirements where such technology may not be available.

Rationale for Recycle-Friendly Aluminum Alloy Compositions

Employing the concepts overviewed, the following set of parameters are proposed as a possible rationale for creating more recycle-friendly aluminum alloy composition limits:

- For major alloying elements in a particular series (e.g. Cu in the 2xxx series, Si and Mg in the 6xxx series, etc.), propose relatively broad specification limits.
- For limits on impurities (elements not usually required or desired, e.g. Fe, Ni, and V), propose more tolerant (i.e. higher) limits. To the degree potentially practical, adjust the maximum limits on impurities to the levels of those elements typically found in recycled metal.

Candidates for Recycle-Friendly Aluminum Alloy Compositions

In order to further explore these concepts and encourage further discussion of the merits and limitations of such approaches, we have used the stated rationale to propose several candidates for recycle-friendly compositions.

An alloy was selected from each major series, targeting alloying contents that are commonly and successfully used in that series, e.g. 2024 or 2219 in the 2xxx series or 7005 in the 7xxx series. The ranges for the major alloying elements were broadened, and the maximum limits on impurities were increased to the levels representative of what seems to be typically found in recycled metal. The resultant candidates are shown in Table IV.

ALLOY	Si	Fe	Cu	Mn	Mg	Zn	Others
A(2xxx)	0.7	0.6	5.5-7.0	0.2-0.4	0.7	0.5	0.3
B(3xxx)	0.7	0.6	0.4	1.0-1.5	0.8-1.5	0.5	0.3
C(4xxx)	10.0-14.0	1.0	0.5-1.5	0.3	0.8-1.5	0.5	0.3
D(5xxx)	0.7	0.6	0.3	0.05-0.35	2.0-3.0	0.5	0.3
E(6xxx)	0.3-1.0	0.6	0.3	0.3	0.4-1.0	0.5	0.3
F(7xxx)	0.5	0.6	0.5-1.2	0.3	2.0-2.8	4.0-6.0	0.3

Table IV. Candidates for recycle-friendly alloys.

It is understood that further studies of this type may lead to a greater variety of candidates for recycling compositions from some or all of the series. It is further recognized that the conclusions from the composition and mass balances studies suggested earlier may suggest focusing upon several different candidates from those series that have the best fit with incoming scrap metal (e.g. the 3xxx, 5xxx, and 6xxx series representing the highest volumes of recycled metal).

The target applications for the new recycle-friendly aluminum alloys include many of the same as for their existing counterparts with tighter limits. Examples may include:

- A(2xxx) - Truck structural members
- B(3xxx) - Heat-exchanger tubing, chemical piping
- C(4xxx) - Forged or cast engine parts
- D(5xxx) - Tankage plate; housing components
- E(6xxx) - Extruded structural components
- F(7xxx) - Non-critical aircraft components

As noted earlier, it is recognized that these alloys are not likely to be suitable for fracture-critical components, where higher levels of Fe and Si have been shown to degrade fracture resistance. However the likelihood exists that they may perform quite satisfactorily in applications such as those listed where service life is determined by other factors.

Since fracture-critical aerospace applications worldwide account for only a small percentage of the billions of pounds of aluminum used annually, the adoption of a recycle-friendly alloy group suitable for many other applications will yield great economic and ecological benefits.

While we must recognize that obtaining suitable performance requirements with the higher levels of impurities may not be entirely successful, all steps in that direction will better enable the aluminum industry to maximize its recycling opportunities, and so addressing the challenge of a new approach to alloy design is warranted.

Conclusions and Looking Ahead

The very significant economic and ecological advantages of maximizing the rate of and technology for recycling and reusing aluminum alloys leads to a number of important conclusions for the aluminum industry throughout the world. Among these conclusions are the following:

- Methods for the recovery of aluminum scrap from as many products as possible should continue to be exploited.
- The development and application of enhanced shredding and sorting technologies such as the HVSC LIBS process should continue.
- Strategies for the most cost-effective remelting processes should be pursued, including technologies to facilitate separation of undesired elements such as Fe, Ni, and/or V by combination with Zr.
- The development of alternative products such as Al-Fe de-oxidizing agents should be pursued to utilize that part of recycled aluminum that cannot cost-effectively be used in the production of new aluminum alloys.
- Serious consideration and study should be given to the development of new aluminum alloys designed for application directly from recycled aluminum, and still providing performance criteria required for a wide variety of applications, when produced directly from recycled metal.
- A study should be carried out to explore the potential of adding to the number of alloys available for direct recycling. This study should identify more precisely and with higher probability the sources and expected ranges of compositions of current and future recycled metal content.

With this information, a mass balance should be performed, indicating the anticipated volumes of various scrap compositions to be expected. Based upon this projected mass balance, 5-7 candidate alloy composition limits that would most effectively directly utilize the anticipated recycled metal could be identified. Candidate alloys could then be experimentally produced and their performance statistically evaluated, including atmospheric corrosion resistance, stress-corrosion crack growth, fracture resistance, and formability.

Formability tests should be conducted, including bulge, minimum bend, and hemming tests. Six potential candidate compositions for recycle-friendly aluminum alloys have been proposed with the intent of initiating the further discussion and evaluation of these concepts.

Secat, Inc. is in the process of communicating with customers, companies, and suppliers in order to form an aluminum recycling consortium to pursue the technical and economic goals discussed herein. It is anticipated that this effort will lead to maximization of the cost-effectiveness and efficiency of aluminum recycling processes. This in turn should increase the amount of recycled aluminum that is directly reused without the addition of primary metal, thereby increasing the life-cycle advantages of aluminum alloys.

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