Materials Science Forum Vols. 519-521 (2006) pp. 1239-1244
online at http://www.scientific.net

Designing Aluminum Alloys for a Recycling Friendly World

Dr. Subodh K. Das

President, Secat, Inc; 1505 Bull Lea Rd., Lexington, KY, 40511, USA

skdas@secat.net

Keywords: aluminum, alloy development, recycling, ecology,

Abstract. Recycling aluminum alloys has been shown to provide major economic benefits, as a result it is appropriate for the aluminum industry and the United States as a whole to identify, develop, and implement all technologies that will optimize the benefits of recycling. This paper will focus primarily alloy design for optimizing the reuse of recycled metal; this is both the most forward looking as we move toward a more recycling 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 of the advantages of aluminum recycling are also addressed.

Background

Aluminum recycling in North America is one of the well-developed and mature metals recycling economies in the world. While today's recycling metals markets also include ferrous metals like iron and steel, and non-ferrous metals like copper and brass, aluminum recycling is the engine of recycling economics.

Choate and Green [1] have illustrated that an increasing amount of aluminum utilized today 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. The Aluminum Industry Roadmap [2] illustrates the importance of this trend. 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 of metal produced. Increasing the use of recycled metal is also quite important from the ecological standpoint, since producing aluminum by recycling creates only about 4% as much CO_2 as by primary production.

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) found that for each 1% increase in the amount of aluminum cans recycled, the economic savings to the US economy is $12 million/year. The additional recycling also contributes to energy savings of 1 trillion BTU/year. Such major impacts have the potential to significantly decrease our reliance of overseas sources of primary aluminum metal.

These observations illustrate that as an industry we need to be looking for opportunities to maximize the advantages of a "recycling-friendly world" (3). In the discussion below, we will identify and address the technological challenges associated with doing so.

Characteristics of The "Recycling Friendly World"

In the ideal recycling world of the aluminum industry:

- The total content of all recycled products would increasingly approach the total required new consumption. The dependence on overseas production would be 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 suitable for direct reuse of most recycled metal.
- Parallel to the existing situation with beverage cans, there would be a number of high-value applications into which the recycled metal would flow, meeting the required specification limits and performance requirements for those applications.

Challenges in Achieving the "Recycling Friendly World"

Among the key challenges to be met in creating this ideal recycling friendly world are the following:

- Maximize recovery of used aluminum products and components for recycling;
- Automate and optimize the pre-sorting, shredding, and separation technologies;
- Identify more useful byproducts to handle elemental residual elements, e.g., Fe.
- Broaden the number of available aluminum alloys whose specifications will readily 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. The fourth, the identification of new alloys that will more readily accept recycled aluminum has received little attention. However the potential economic and environmental benefits are sufficiently great that we believe it should be addressed, and is the main focus of this paper.

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 Gesing of Huron Valley Steel Corp. (HVSC) [4] are shown in Table 1. HVSC is capable of pre-sorting wrought and cast alloy scrap, so two samples were of wrought separations, two of cast separations, and one mixed.

Table 1: Representative composition of recycled aluminum, in weight %

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

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

- Individual lots of scrap can have relatively widely varying compositions, e.g., WroughtB above has higher Cu (possibly from 2036 alloy) and higher Zn (possibly from 7029).
- 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 do not.
- Cast alloy scrap can vary greatly in composition, and differs significantly from wrought alloy scrap. Note the higher Si content compared to WroughtA & B, typical of castings, and also higher Cu (from 380.0 and 390.0) and Zn (from 7xx.0 cast alloys).
- 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.

Thus, with the exception of segregated recycled beverage can scrap, recycled aluminum may involve a mixture of alloys from a fairly wide variety of applications, including a selection of castings containing rather high percentages of Si. While most of this metal may be used in new castings, there is a significant challenge in its use as 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 modestly 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 system equipment. 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.
It should be noted elements other than Fe may also be expected to increase with repeated recycling and to require special attention, e.g., Mg, Ni and V.

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 2:

Table 2: Typical recycled casting alloys

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.

As seen by the compositions presented above, all contain relatively high silicon, and their impurity limits tend to be relatively loose. For all most alloys, the “Others” contents in scrap samples are higher than desired. .

Wrought Alloy Scrap – The compositions of several of the most useful alloys for direct use of recycled metal are shown below in Table 3.

Table 3: Examples of wrought aluminum alloys.

ALLOY	Al	Cu	Fe	Mg	Mn	Si	Zn	Others
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.

As for cast scrap, the maximum limit on “Others” presents a challenge; the “Others” total in WroughtA (Table 1) exceeds that limit for all of these alloys. The challenge of reusing recycled wrought alloy scrap without “sweetening” is greater than in cast alloys.

These examples illustrate why the concept 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 (a) relatively broad specification limits on major alloying elements such as Cu and Mg plus (b) more tolerant (i.e., higher) limits on Fe, Si, and other impurities, without significant restriction on performance characteristics for many applications.

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

1. Utilizing the experience of organizations already in the aluminum recycling business, such as HVSC (5), identify more precisely and with higher probability the likely sources and expected ranges of compositions of current and future recycled metal content;
2. With the results of the study in Phase 1, perform a mass balance indicating the anticipated volumes of various scrap compositions to be expected;
3. Based upon the projected mass balance, identify candidate alloy compositions that could most directly utilize the anticipated recycled metal and provide desirable performance characteristics for a wide variety of applications; and
4. Experimentally produce and statistically evaluate the performance of the candidate alloys, including atmospheric and stress corrosion resistance, toughness, and formability.

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.

Rationale for Recycling-Friendly Aluminum Alloy Compositions

Employing the concepts overviewed above, the following sets of parameters are proposed as a possible rationale for creating more recycling-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

Candidate Recycle-Friendly Aluminum Alloy Compositions

In order to further explore these concepts and encourage further discussion of the merits and limitation of such approaches, we have used the above rationale to propose several candidate recycle-friendly compositions below. The resultant candidates are shown below in Table 4:

Table 4: Some candidate compositions for recycle friendly alloys.

ALLOY	Si	Fe	Cu	Mn	Mg	Zn	Others
3xxx	0.7	0.6	0.4	1.0-1.5	0.8-1.5	0.5	0.3
4xxx	10.0-14.0	1.0	0.5-1.5	0.3	0.8-1.5	0.5	0.3
5xxx	0.7	0.6	0.3	0.05-0.35	2.0-3.0	0.5	0.3
6xxx	0.3-1.0	0.6	0.3	0.3	0.4-1.0	0.5	0.3

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

- 3xxx - Heat-exchanger tubing, chemical piping
- 4xxx - Forged or cast engine parts
- 5xxx - Tankage plate; housing components
- 6xxx - Extruded structural components

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 recycling of aluminum leads to some important conclusions for the aluminum industry throughout the world:

1. Optimized technologies for the recovery, shredding, sorting, and remelting of aluminum scrap should continue to be exploited.
2. Serious consideration and study should be given the development of new aluminum alloys designed for application directly from recycled aluminum, while providing performance capabilities for a wide variety of applications. The following steps should be included:
    a. Identify more precisely and with higher probability the sources and expected ranges of compositions of current and future recycled metal content, and perform a mass balance indicating the anticipated volumes of scrap compositions to be expected;
    b. Based upon the projected mass balance, identify candidate alloy composition limits that would most effectively directly utilize the anticipated recycled metal;
    c. Experimentally produce and statistically evaluate the performance of the candidate alloys, including atmospheric corrosion resistance, stress-corrosion crack growth, fracture resistance, and formability, as compared with industry needs [5-9]

Secat, Inc. is in the process of forming 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

Acknowledgements

The author gratefully acknowledges valuable input and advice from J.G. (Gil) Kaufman, VP Technology, The Aluminum Association (Ret.); Dr. John A.S. Green, VP Technology, The Aluminum Association (Ret.); Dr. Warren Hunt, Technical Director, TMS; and Dr. Wayne Hayden, ORNL (Ret.).

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