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Emerging Trends in Aluminum Recycling: Reasons and Responses

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1. Abstract

The growth in aluminum usage in transportation applications, the decline in aluminum beverage can recycling, and the increasing reliance of the domestic fabrication industry on secondary aluminum have combined to create new needs in both the materials design and processing space. This presentation will detail the history and future projections for aluminum recycling, emphasizing the increasing importance of mixed scrap streams in the makeup of secondary aluminum. To most economically utilize these scrap streams, new approaches to developing acceptable materials processed to control properties suitable for an expanded range of applications are needed. How the aluminum enterprise, including industry, academia, and government can work together to meet these important but aggressive targets and transform recycling from strictly an environmental imperative to an economic development opportunity will be discussed.

2. Introduction

An increasing amount of the aluminum going into the production of aluminum alloy products for many applications is coming from recycled products. In a recent modeling study of the industry, Choate and Green (1) illustrated that most of the increase is coming from recycled automotive components, which in 2005 is expected to exceed for the first time the recycled metal coming from used beverage cans. The Aluminum Industry Roadmap (2) illustrates the importance of these trends and of the efforts to address the technology to address them 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.

As Choate and Green (1) demonstrated, 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. It is to the industry and a national advantage to maximize the amount of recycled metal, both from the energy-savings and the reduction of dependence upon overseas sources (now about 40% of U.S. consumption) and also from the ecological standpoint, since recycling emits only about 4% as much CO_2 as primary production.

Secat, Inc., the Center for Aluminum Technology (CAT) and Sloan Industry Center for a Sustainable Aluminum Industry all based at The University of Kentucky, Lexington, Kentucky have also demonstrated the economic advantages of recycling to American municipalities. It is to be noted that trashed cans contribute about $600 million to the nation's trade deficit each year (Fig. 1).

By increasing the aluminum recycling by 1%, the economic saving to the US is $12 million/year which will approach $600 million /yr if we can recycle all the available aluminum.

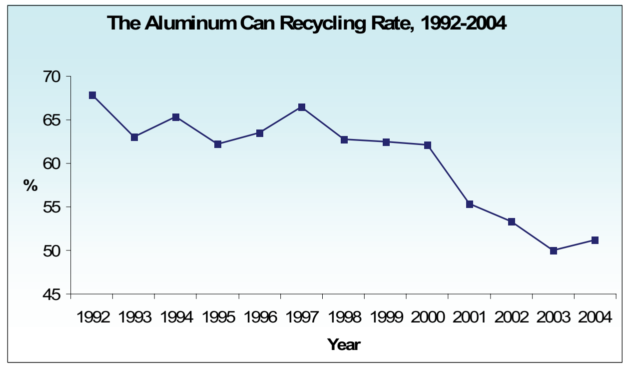

Fig.1 National Aluminum Beverage Can Recycling Rate Trends

Such savings support the building of new recycling plants, each employing many people with high paying manufacturing jobs. It also contributes to the savings of trillions of BTU's per year. For the U.S as a whole, it has the potential of significantly decreasing our reliance of overseas sources of primary aluminum metal.

Today, in order to meet the performance requirements of many alloy and product specifications, much of the recycled metal must be "sweetened" with the more costly and energy-intense primary metal before it can be re-employed in many applications. The specialty alloys required for a number of applications require such strict controls on impurities that recycled metal can not be used without modification. The result is that, in many cases (except beverage cans), recycled metal tends to be used primarily for lower grade casting alloys and products. While a certain amount of this is acceptable, the recycle-friendly world will only be truly optimized when the recycle loop is closer to a closed loop within a number of product lines.

The net result of these observations makes it clear that as a nation and as a world we need to be looking forward to all means of maximizing the advantages of a recycling-friendly world. That includes defining the characteristics of such an environments and addressing the technological needs to make it happen, as presented below.

3. Ideal Recycling World

In the ideal aluminum industry, recycling of all used aluminum components would be the standard, 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 of the U.S. on overseas production minimized.

Recycled aluminum would be readily recovered and processed, utilizing automatic sorting and shredding technology to put it in the best possible form for reuse in new products.

A wide array of aluminum alloys compatible with the incoming composition of recycled metal would be available, so the opportunities for direct use of the recycled, shredded, and sorted metal would be optimized. There would be a number of high-value applications, like beverage cans, into which the recycled metal would flow. In such situations, product made directly from the recycled metal would readily meet both specification composition and mechanical property limits of the intended applications.

There are a number of challenges to be met to create the recycling friendly world, as discussed below.

4. Challenge Areas

4.1 - The principal challenges that must be dealt with in creating this ideal recycling world include the following:

a. Improving the recovery of used aluminum components for recycling;
b. Improving and more fully automating the shredding and sorting technology, and making it more broadly available;
c. Significantly broadening the range of available aluminum alloys that will perform well in quality products when they are produced directly from recycled metal;
d. Identifying useful byproducts to handle elemental residual unable to be used in recycled metal, e.g., Fe.

Satisfactory progress is being made in addressing items a, b, and d on this list of challenges. Examples include, on item b, the laser induced breakdown spectroscopy (LIBS) developed and applied by Huron Valley Steel Corp. (HVSC) applied to the shredding and sorting of aluminum and aluminum alloys (4), and, on d, the identification and optimization of aluminum alloy containing relatively high iron content for deoxidizing steel (de-ox).

However little is being done on Item c above, addressing the development of a broader range of aluminum alloys suitable for direct production from recycled metal while performing admirably in service. That challenge is the focus of the remainder of this presentation.

4.2 – There are a number of more detailed challenges facing any effort to increase the number of aluminum alloys and applications suitable for direct production from recycled metal, among them the following:

- With the exception of recycled beverage cans, 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 silicon (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 refinement of the metal to achieve acceptable impurity levels for products other than castings, including sheet, plate, forgings, and extrusions.

- Many premium alloys utilized today, especially in the aerospace industry where requirements for exceptionally high ductility and toughness are common, call for very tight composition controls on both iron (Fe) and Si. Impurity levels above 0.10-0.15% Fe or 0.15-0.25% Si are unacceptable, for example, in premium high toughness aerospace alloys. High performance automotive alloys generally 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.

- Elements other than Fe may be expected to gradually increase with time and may require special attention; Magnesium (Mg), Nickel (Ni) and Vanadium (V) are three examples.

- Typical compositions of recycled metal today based upon eight representative studies by Adam Gesing of Huron Valley Steel Corp. (HVSC) (4) are shown (Table 1) in weight %. HVSC is capable of separating wrought and cast alloy scrap, so four samples were of representative wrought separations, three of representative cast separations, and one of the two mixed (wrought and cast alloys).

Table 1 Representative composition of aluminum alloys

LOT	Al	Cu	Fe	Mg	Mn	Si	Zn	Others
Wrought1	97.1	0.11	0.59	0.82	0.21	0.51	0.45	0.19
Wrought2	96.7	0.30	0.60	0.60	0.20	0.90	0.50	0.10
Wrought3	93.1	0.95	1.01	0.89	0.12	2.41	1.25	0.27
Wrought4	93.1	1.20	0.70	0.70	0.30	2.60	1.20	0.20
Cast 1	83.5	4.40	1.10	0.40	0.30	8.0	1.90	0.40
Cast 2	86.0	3.90	1.00	0.10	0.20	6.30	2.30	0.30
Cast 3	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

The results above illustrate several of the fundamental problems in reusing scrap aluminum as shown below:

- Even segregated wrought scrap can have relatively widely varying compositions; Wrought 3 and Wrought 4 lots above, for example, have higher Cu (from more 2xxx alloys) and higher Zn (from more 7xxx alloys) in the mix than did Wrought1 and Wrought 2 lots. It appears that auto bumper alloys like 7029 and auto body sheet alloys like 2036 were more highly represented in the wrought lots 3 and 4.
- Some lots of wrought recycled metal (lots 1 and 2) match existing wrought alloys reasonably well, e.g., 3005, 3104, 3105 and 6061, and can be readily reused; other like lots 3 and 4 will be more difficult to use directly.
- Cast alloy scrap differs significantly from wrought alloy scrap, notably with higher total alloy content, notably

higher Si content, and depending upon which cast alloys are involved, higher Cu (from 380.0 and 390.0) and Zn (from 7xx.0 cast alloys).

- Compositions resulting from mixed wrought and cast scrap will be more difficult to use directly, except perhaps in some casting alloys.

4.3- Comparisons with Existing Aluminum Alloys

4.3.1 – Cast Alloy Scrap - As noted earlier, recycled metal from castings can often be used directly in new cast products, usually of the 3xx.0 and 4xx.0 series, because the impurity limits tend to be relatively high and almost all contain relatively high silicon, which improves their flow characteristics in the dies. Examples of some of the scrap-tolerant casting alloys include the following (Table 2):

Table 2 Representative cast aluminum alloy composition

ALLOY	Cu	Fe	Mg	Mn	Si	Zn	Others
B319.0	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	0.50-1.5	1.2 max	0.70-1.3	0.35 max	11.0-13.0	0.35 max	- -
C443.0	0.6 max	2.0 max	0.10 max	0.35 max	4.5-6.0	0.50 max	0.25 max

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 contents will be a challenge. Nevertheless, casting alloys as a whole have higher impurity limits than wrought alloys and will be more tolerant for direct recycling.

4.3.2 – Wrought Alloy Scrap - The extent of the current opportunity as well as the challenge in directly reusing recycled wrought alloy scrap without “sweetening” with primary metal is much greater. This can be illustrated by comparing the compositions above with those of several wrought commercial alloys already recognized as good consumers of scrap, below (Table 3):

Table 3 Some suggested alloy composition

ALLOY	Cu	Fe	Mg	Mn	Si	Zn	Others
3005	0.30 max	0.7 max	0.20-0.8	1.0-1.5	0.6 max	0.25 max	0.15 max
3104	0.8 max	0.6 max	0.8-1.3	0.8-1.4	0.6 max	0.25 max	0.15 max
3105	0.30 max	0.7 max	0.20-0.8	0.30-0.8	0.6 max	0.40 max	0.15 max
6061	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 noted earlier, material from Wrought 1 and Wrought 2 lots could reasonably be utilized in alloys like 3105 and 6061. Even for these alloys, the maximum limit on “Others” may be a challenge, as that value for Wrought 2 is slightly in excess of the limit.

Scrap from Wrought 3 and Wrought 4 lots could not be directly reused without some more flexible impurity limits, as addressed in Section 6.

Material from the Cast lots could not be used directly for any of these wrought alloys or any others for that matter.

An additional elemental impurity problem needs to be recognized, and that is the general trend for Fe content in scrap reused over and over to increase gradually, primarily through pickup from scrap handling system equipment. With only a few exceptions, Fe is an impurity in wrought alloys today, and is an ideal candidate for application to alternate products. An excellent example of such a product is the use of high Fe-bearing aluminum as a deoxidizing agent for steel production. Maximization of this capability will benefit both the aluminum and steel industries and add to the life-cycle benefits to aluminum operations. Another possible approach to the increased Fe content is to make use of the affinity of Zr for Fe, resulting in a heavy particle that sinks to the bottom of crucibles during processing. Combining this Fe-Zr product with Mg and perhaps other undesirable impurities like Ni and V may also improve their impact on resulting recycle content.

See Section 5 below on optimized recycling alloys for some options to address these challenges.

5. Alloys Designed with Recycling in Mind

As noted above, an ideal component of maximization of resources in recycling would be the availability of a larger number of aluminum alloys suitable for a wide variety of applications that do not require any extra purification step before they are recycled into high performance products. That is largely the case with beverage cans if the recycle scrap is not mixed with any other material.

Such an approach will call for some “tailored” alloys, enabling broader specification limits on alloying elements such as copper (Cu) and magnesium (Mg) plus higher max limits on Fe, Si, and other impurities while still providing the performance properties required for the intended applications.

Application of the laser induced breakdown spectroscopy (LIBS) developed by Huron Valley Steel to screen scrap with certain combinations of the desired elemental additions may permit some relaxation of the broadest interpretation of the guidelines above, but it is useful to look at the most useful long-term trends when such technology may not be available.

Adopting the approach of alloy optimization for recycling requires several steps. Potential phases in a development program are:

1. Identify with increasing precision the range of expected current and future recycled metal content, utilizing the feedback from organizations such as HVSC that are already capitalizing on the economics of recycling. Perform a mass balance to the extent practical indicating the relative volumes of various scrap compositions to be expected;

2. Identify 5-7 basic candidate compositions of alloys that would accept recycled metal directly and have acceptable/desirable performance characteristics for a wide variety of applications, including structural components for bridges and buildings, high-temperature applications, and architectural usage; and

3. Evaluate the performance of these candidate alloys in representative production lots, including especially the following along with the usual tensile and design properties, in order to assess their abilities to meet the requirements of representative applications as compared to existing alloys (5-10):
    - Atmospheric corrosion resistance
    - Stress-corrosion crack growth
    - Toughness, with tear tests and/or fracture toughness tests (for thick sections)
    - Formability tests, with bulge, minimum bend, and hemming tests

   It is recognized that there will be some negative effects; the question is the degree to which such alloys are still useful for some high volume applications.

6. Some Approaches to Recycling-Friendly Alloy Compositions

It seems useful at this stage to consider some preliminary candidates for recycling-friendly alloys based upon what we know already from the HVSC data and other sources. In this consideration, attention will be given primarily to wrought alloy compositions because, as noted earlier, casting alloys already can be produced in rather large quantities from recycled cast products. The greatest challenge is direct use of recycled wrought products.

6.1 – Rationale for Recycling-Friendly Aluminum Alloy Compositions

As noted above, the challenge is to define alloy specifications that can readily met utilizing recycled aluminum with no addition of primary metal, and, only if necessary, the addition of alloying elements. In developing some candidate compositions below, the following rather basic guidelines have been utilized:

- Select alloying elements that are commonly and successfully used in alloys of the various series, e.g., 2024 or 2219 in the 2xxx series, or 7005 in the 7xxx series.
- Adjust the limiting maximum levels on impurities (i.e., elements not added intentionally) to the levels of those elements typically found in recycled metal

6.2 – Candidate Compositions for Recycle Friendly Aluminum Alloys

Six preliminary candidate wrought alloy compositions that might be reasonably made from recycled and shred-sorted wrought products with at minimum the addition of some alloying elements are shown in Table 4 below:

Table 4 Suggested recycle-friendly aluminum alloys

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

In this initial list, one composition has been selected from each major alloy series. Other candidates might well be devised by adjustments in the major alloying elements and/or the addition of other minor alloying elements.

Please note that these are preliminary candidates, and it is recognized that the completion of Phase 1 described in Section 5 above, identifying to higher precision the compositions of incoming scrap, current and future, may result in significant changes in these candidate alloys. It may also lead to a focus on several different candidates from specific series that show maximum fit with the incoming metal (e.g., the 3xxx, 5xxx, and 6xxx series representing the highest volumes of recycled metal).

The application targets for these candidate compositions are much the same as their existing counterparts with tighter limits, recognizing that these are not likely to be suitable for the more fracture-critical items. However the possibility exists that they may perform quite satisfactorily in such applications as chemical plant piping (A-2xxx), heat-exchanger tubing (B-3xxx), forged or cast engine parts (C-4xxx), rolled and extruded structural components (D-5xxx and E-6xxx), and even for non-critical aircraft components (F-7xxx).

As noted earlier, application of the LIBS technology developed by HVSC to screen scrap with certain combinations of the desired elemental additions may permit some relaxation of the broadest interpretation of the guidelines above, but it is useful to look at the most useful long-term trends when such technology may not be widely available.

6.3 - Unialloy

Another approach that might be considered, and one that has been studied to considerable degree in the past, is the development of one or two "unialloys," that is alloys that meet all the requirements for a large application like aluminum beverage packaging, automotive components or architectural components.

Unialloy concept was first developed by Golden Aluminum (11) in late 1980s, focused on alloy AA5017 with 2% Mg and .7% Mn. The concept was derived from the idea that unialloy had an average weighted composition of can body alloy AA3004 and can end alloy AA5182. This recycling idea achieved limited application due to economic and commercial factors. In the current environment of rising price of primary aluminum and its alloying elements such as magnesium, manganese and copper coupled with the societal desire for enhancing recycling rate of products; it is time to rethink applicability and commercialization of the unialloy concept.

This has proven difficult to achieve because of the diverging performance requirements of different applications. Even within autobody panels for example, the differing requirements for dent resistance in outer panels and optimized formability for inner panels continues to lead to two different types of alloys being used (6111 heat treated for high outer panel dent resistance and 5754 annealed for maximum formability for inner panels, for example).

The approach above of selecting "recycle-optimized" alloys from each series may lead to a master list of several recycle-friendly alloys.

7. Some Caveats

The large bank of alloy design experience in the aluminum industry may well result in some skepticism about the probabilities of success and the seeming backward movement in the above approach of permitting higher levels of impurities in new alloy candidates. There is indeed some reason for the skepticism, as it is well known that optimizing fracture toughness, for example, requires tight impurity controls, especially on Fe and Si. So it is probably appropriate to acknowledge at the outset that it may be impossible to ever reach the stage where recycled metal will ever be used untreated for all aluminum alloy products such as fracture-critical components aerospace wings and wing spars; the fracture toughness requirements on these are simply too stringent to be met without tight impurity controls.

However, aerospace applications account for only about 8 percent of the total approximated 30-40 billion pounds aluminum used annually, and so the adoption of a recycle-friendly alloy system applicable to most other applications will still have a very great economic and ecological benefit in world consumption.

The performance requirements of many high-volume aluminum products, such as building and highway structures and chemical industry components, may well be satisfied by alloys with higher levels of impurities than presently mandated. In fact most such composition limits were set when the greater volume of production was primary metal and there was no need for higher impurity levels. The limits were not set by performance requirements, but by anticipated incoming metal compositions.

And finally we must acknowledge that such attempts at obtaining suitable performance requirements with the higher levels of impurities may not be successful. However any step in that direction will better enable the aluminum industry to maximize its recycling opportunities, and so the challenge of a new approach to alloy design is warranted.

8. Conclusions and Looking Ahead

The advantages of maximizing aluminum recycle rates and the ready reuse of the recycled metal to as wide a range of properties as possible leads to several important conclusions for the aluminum industry both in the US and throughout the world:

1. Avenues for recovery of aluminum scrap from as many products as possible should continue to be exploited; there are massive economic, energy, and ecological advantages to the communities and to the aluminum industry.
2. Development and application of enhanced shredding and sorting technologies such as the HVSC LIBS process should continue.
3. A focus on the most cost-effective remelting processes is justified, including the possibility of combining Fe with Zr and other impurities such as Ni and V in high-density particles that could be easily separated from the melt.
4. The production of alternative products such as Al-Fe de-oxidizing agents should be pursued to utilize that part of recycled aluminum products that cannot cost-effectively be used in the production of new aluminum alloys, to the benefit of both the steel and the aluminum industries.
5. The most overlooked aspect of maximizing recycled metal appears to be the development of new alloys tailored to meet composition and performance criteria when produced directly from recycled metal. A study of the type suggested in Section 5 above should be carried out to potentially add to the number of alloys available for direct recycling. Some candidate compositions have been suggested for such alloys with the intent to broaden this part of the discussion, and perhaps lead to interesting and economically attractive components to maximizing recycling efficiency and effectiveness.

Looking ahead, the challenge is identifying the most successful means of implementing the additional studies and development programs needed to maximize the benefits of recycling, as called for in Section 5 and Conclusion 5 of this paper. Accordingly it is proposed that the following steps be taken:

- An aluminum recycling "consortium" be identified or formed to consider options and opportunities to increase the overall effectiveness and efficiency of aluminum recycling and its benefits. The "consortium" should include representatives of
  - The municipalities and their representatives at the first line of collecting recycled metal;
  - The recyclers themselves (e.g., members of the Aluminum Association Recycling Division);
  - Fabricators and distributors of recycled products (e.g., auto and beverage can producers); and
  - End users of such recycled products.
- Secat, Inc is in the process of forming an aluminum recycling consortium to further the goals as outlined in this paper.
- The first two charges of the consortium should be to
  - Identify all means of maximizing the amount of aluminum products entering the recycling chain; and
  - Carrying out the paper study of alloy design optimization for recycling as described in Section 4 above, identifying the most likely high-volume recycle compositions, carrying out the resultant mass balance, and fine-tuning several candidate compositions that would take advantage of the anticipated recycle content.
  - Exploring opportunities to improve the quality of the melt by removal of high density particles formed by the combination of Fe with Zr and possibly other high density elements like Ni and V.
- The next logical step would be a complete evaluation of the physical, mechanical, corrosion, and fabricating characteristics of whatever optimized recycling candidate alloys are generated.

Successful application of these various approaches to maximizing the cost-effectiveness and efficiency of recycling processes should lead to increased opportunity to extend the life-cycle advantages of aluminum alloys, increase the usefulness of directly recycled alloys, and therefore increase the amount of metal that is directly reused without the addition of primary metal.

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