Aluminum Recycling—An Integrated, Industrywide Approach

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The aluminum industry is a leading proponent of global sustainability and strongly advocates the use of recycled metal. As the North American primary aluminum industry continues to move offshore to other geographic areas such as Iceland and the Middle East, where energy is more readily available at lower cost, the importance of the secondary (i.e., recycled metal) market in the U.S. will continue to increase. The purpose of this paper is to take an integrated, industry-wide look at the recovery of material from demolished buildings, shredded automobiles, and aging aircraft, as well as from traditional cans and other rigid containers. Attempts will be made to assess how the different alloys used in these separate markets can be recycled in the most energy-efficient manner.

INTRODUCTION

In his recent book *Aluminum Recycling,*[1] Mark Schlesinger points out that in traditional extractive metallurgy, the raw material used to produce a metal is mined from the earth and then is separated from other gangue minerals and impurities. In aluminum recycling, however, the ore body consists of scrap metal found on the ground rather than in it. He further notes that scrap comes with its own variety of gangue and impurities such as paint coatings and metal attachments, as well as dirt and other contaminants. So, while the recycling process still requires some refinement and expenditure of energy, the amounts of effort and energy involved are much less than those in refining mined ores.

The aluminum industry "Vision" document,[2] published in 2001, notes that the electrical energy embedded in metallic aluminum can be considered to be an "energy bank" because it can be essentially recovered during recycling. Thus, from a sustainability viewpoint, aluminum recycling is tapping into a convenient "urban mine" of material that enables reuse while saving energy and reducing environmental impacts. This urban mine analogy is becoming increasingly real as the amount of aluminum in vehicles continues to increase in order to improve performance, reduce weight, increase fuel efficiency, and enhance safety.

See the sidebar for background on aluminum recycling.

How would you…

…describe the overall significance of this paper?

This paper introduces the concept and suggests several implementable ideas to design and commercialize recycle-friendly aluminum alloys for key market sectors.

…describe this work to a materials science and engineering professional with no experience in your technical specialty?

Most of the aluminum alloys used in the commerce today have been designed and sold commercially using primary and pure aluminum, pure alloying elements, and sometimes special elements to meet perceived customers needs. This practice is not economically and environmentally sustainable as it leads to a larger carbon footprint and lower recycling rates for the aluminum industry products.

…describe this work to a layperson?

In order to achieve the sustainability goals of a manufacturing industry, each of the commercially sold product(s) to its intermediate or ultimate customer(s), must be designed and processed keeping the recyclability in mind during the entire phase of its product life cycle.

MODELING THE URBAN ALUMINUM MINE

Modeling, together with some life cycle assumptions, has also been used to explore the impact of recycling on the overall U.S. metal supply.[10] This "urban mine" model assumes that the amount of scrap that will become available in a given time frame can be predicted based on the amount of material sold into specific markets and the typical life cycle of material in these markets. For instance, building components, automobiles, and beverage cans have useful lives that are, respectively, ~50, ~15, and ~0.2 years, and the amount of metal that is sold to these markets is known and can be forecast into the future with some assurance.

Existing industry data has been used for the model. The model inputs include primary production data from 1893, secondary production data from 1913, and imports from 1911. These data are merged with market information for the last 40 or 50 years in order to project future U.S. metal supplies. The model also projects information based upon the market size and growth rates from 1990 to 2000. Specifically the percentage of the overall market and the average growth rate over the decade were, respectively: transportation (37%, 9.8%), containers and packaging (23%, 0.3%), consumer durables (8%, 4.8%), building and construction (15%, 2.6%), electrical (8%, 3.0%), machinery and equipment (7%, 4.8%), and others (2%, 1.7%).

Considerable insight has been gained from the macro-model of the urban mine.[10] A major conclusion is that the automotive area, driven by the number of vehicles (~15 million per year) and the growing amount of aluminum used per vehicle, will dominate the future scrap source picture.

RECYCLING CHALLENGES BY MARKET APPLICATION

Capturing the metal in the recycling process represents only a part of the overall recovery process. A more significant challenge is preserving the economic value of the alloying ingredients by recycling specific wrought alloys into the same or similar wrought alloys. The ideal is to recycle a specific alloy back to the identical alloy, as with beverage cans; the value of the alloy is maximized.

Transportation Recycling—The Major Recycling Opportunity

As noted in the Modeling section and in Reference 10, the transportation area is the biggest market for aluminum and the scrap generated from used autos and trucks now exceeds that from recycled beverage cans. Specifically, according to the *Aluminum Statistical Report*[11] the transportation market sector consumes ~8.7 million pounds or 33.9% of North American production. Over the period 2001–2005, the annual growth rate of aluminum in this market has been 5.4%. This growth is driven by the need to save weight, increase fuel efficiency, and enhance safety. The drive toward "sustainable mobility" is increasing, and the aluminum recycling potential from the automotive sector is enormous.

BENEFITS OF AND BACKGROUND ON ALUMINUM RECYCLING

The conventional benefits that are cited for aluminum recycling are energy savings, emissions reductions, and the elimination of landfill wastes. A comprehensive life cycle analysis conducted by the industry under USCAR guidance, and which involved analysis of 15 unit processes in 213 plants worldwide, verified these savings.[3] Specifically, it was shown that the production of primary aluminum, when all electrical generation, transmission losses, and transportation fuels are accounted for, requires ~45 kWh of energy and emits ~12 kg of CO_2 for each kilogram of metal. On the other hand, the recycling of aluminum requires only ~2.8 kWh of energy and emits only ~0.6 kg of CO_2 for each kilogram of metal. Thus, ~95% of the energy and ~95% of the environmental emissions are saved when the metal is recycled. The energy banked in the metal during the initial smelting process is recovered, with minor losses, each time the material is recycled.

A newer and more critical benefit of aluminum recycling is that it helps to maintain a viable North American aluminum fabrication industry. With the declining aluminum primary industry, the secondary industry based upon recycling now provides the bulk of domestic metal to the downstream fabrication industry.

Historically, since the start of the aluminum industry in 1888, some amount of recycling has always occurred. It has been estimated that ~70% of all the aluminum that has ever been made is still in active use.[4] But, it was not until the advent of the aluminum can in 1965 and the buy-back programs of the Reynolds Metals Company that recycling became part of the public awareness. The success of the beverage can spawned the secondary, or recycling, industry. The large number (~10,000) of recycling centers that emerged nationwide during the 1970s and 1980s has given way to fewer but more active recycling companies with curbside collection of all recyclables that go to municipal recycling facilities (MRFs). There are now some 300 MRFs representing more than half the U.S. population and this phenomenon has generated a subsidized dealer market for aluminum cans, along with other recyclable items.

For the U.S. market, an increase of 1% in aluminum can collection is equivalent to a saving of $12 million, so renewed effort is being put in that direction. For example, the Aluminum Association and the Can Manufacturing Institute have formed the Aluminum Can Council to develop educational and promotional programs. Other groups have also been active in this effort, notably Secat, Inc., the Center of Aluminum Technology at the University of Kentucky, and the Sloan Industry Center for a Sustainable Aluminum Industry to focus on recycling issues. This consortium has already addressed some of the cultural and societal factors that that influence recycling.[5–7]

Another new development has been the advent of the industrial shredder. The shredding of large industrial scrap such as automobiles, refrigerators, freezers, and other large machinery has been complemented by the developments by Huron Valley Steel Corporation[8,9] of color sorting and laser induced breakdown spectroscopy, making it possible to analyze the emitted plasma light from a scrap sample and determine its chemical composition. In the future, it should be economically feasible to separate and sort aluminum scrap on an alloy-by-alloy basis by virtue of the developments on an industrial scale.

Automotive recycling is relatively complex due to the large number of alloys used. In a parallel paper,[12] the authors have explored an ideal automotive recycling scenario addressing these issues. Among the alloys widely used are Al-Cu (2xxx) alloys 2008 and 2010 for body sheet; Al-Mg (5xxx) alloys 5022 and 5754 for body sheet; Al-Mg-Si (6xxx) alloys 6111 for body sheet and 6063 for structural components, including frames; and Al-Zn-Mg (7xxx) alloys like 7029, 7116, and 7129 for bumpers. Casting alloys like A356.0, 360.0, and A380.0 are used for engine and other mounting components. It is apparent from an examination of the compositions of these alloys[12] that the high-Zn 7xxx alloys are not compatible with the other alloys, and the relatively high Cu in the 2xxx alloys will not fit well with the 5xxx and 6xxx alloys

Thus the potential importance of pre-shred dismantling becomes clear. Ideally, all vehicles would be recycled and would be subject to a pre-shred disassembly process where large components of known alloy composition (i.e., wheels, bumpers, engine blocks, perhaps body sheet components like hoods, deck lids, and door panels) would be removed and segregated for remelting. Hand-held chemical analyzers could aid preliminary separation and sorting of alloys. As one example, the batching of all bumpers together—grouping alloys 7029, 7116, and 7129—would probably yield a melt that could be directly reused for bumpers as a 7xxx alloy.[12] The remainder of the auto hulk would be shredded, subjected to laser-induced breakdown spectroscopy (LIBS) sorting,[8,9] and remelted, using the most efficient processes to reduce dross losses and maximize recovery. Of course, if/when shredding technology develops to the point where individual alloys can be identified and separated, pre-shred disassembly may not be warranted.

Another option is to revisit the idea of developing some single versatile "unialloy" that could meet many of the requirements for a large number of automotive components, thus simplifying the scrap stream. This has proven difficult to achieve because of the diverse performance requirements of different components. However, some progress has being made, as companies like Toyota use alloy 6022 for both inner (-O temper, greater formability) and outer (-T4 temper, greater dent resistance) body components.

Table I. Nominal Compositions of Potential New Recycling Friendly Alloys Resulting from B&C Product Sorting and Remelting

Alloy	Al,%	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
505X	~96.0	0.4	0.4	0.15	0.6	2.5	0.15	0.25	0.1
606X	~96.0	0.5	0.5	0.2	0.12	0.8	0.15	0.15	0.12

Building and Construction—A Hidden Opportunity

The third largest market sector for aluminum, after transportation and containers/packaging, is the building and construction (B&C) market that also includes highway structures (e.g., lamp posts, signs, bridge decks). This market has not received much attention in regard to recycling, primarily because the life cycles of buildings and highway structures are so long, ~30–50 years, plus the smaller amounts of aluminum previously used in B&C applications. Newer architectural designs, however, have emphasized the value of aluminum to make buildings more energy efficient through the use of sun screens, cladding and shades, curtain wall construction and advanced window designs, and the potential value of recycling. The aluminum components have increased.

Recent studies at the Technical University of Delft[13] have provided a comprehensive evaluation of recycling during the demolition of nine types of buildings located in six countries in Europe. In this study, conducted under EU regulations and employing ISO-certified protocols and contractors, the deconstruction and demolition of the buildings was closely monitored and comprehensive data were collected.

The following conclusions were among those drawn from the Delft study, all supporting the recycling of aluminum components from B&C structures:[13]

- The average aluminum collection rate for all nine buildings was 95.7%.
- Even though the aluminum content of the buildings was <1%, there was still a substantial mass of aluminum available for recovery.
- Much of the aluminum in a building is on the periphery (e.g., air conditioners, sun shades and awnings, etc.) and is easy to recover.
- Non-residential high-rise buildings and factories contain much more aluminum, by 1–2 orders of magnitude, than residential buildings.
- Residential construction in warm climates contains ~20 times more aluminum than in cold climates (i.e., sun shades, reflectors). Future architectural designs are anticipated to increase this amount.
- Recovery is enhanced when a subcontractor is involved who wishes to reuse some components (i.e., windows), directly.

An examination of the *2005 Aluminum Statistical Review*[11] indicates that the 3.7 billion pounds of metal in this market is almost equally divided between extruded shapes and sheet products. The workhorse alloys for B&C extrusions are Al-Mg-Si alloys 6061 and 6063.[14,15] Alloy 6061 provides the best combination of strength, cost, weldability, and corrosion resistance, while alloy 6063 is more readily extrudable with lower strength and lower cost. By contrast, for B&C sheet and plate, the most widely used alloys are the Al-Mg 5xxx series, ranging from 5050 with ~1.5% Mg to 5456 with ~4.5% Mg. These alloys are characterized by excellent corrosion resistance, toughness, weldability, and moderate strength. While the 5xxx and 6xxx alloys can usefully be remelted together, it is clearly desirable to separate the 5xxx alloys from the 6xxx alloys prior to melting to most efficiently reuse the alloying constituents.

It is fortuitous that the 6xxx alloys are primarily extrusions and the 5xxx alloys are primarily sheet and plate. Thus a rudimentary sorting of 5xxx from 6xxx alloys can be achieved by merely separating structural extrusions from sheet and plate materials at the demolition site.[16]

It is useful to speculate upon the alloy content likely to result if the approach of separating the sheet and plate components from the extrusions components is adopted. Table I illustrates two potential output compositions from remelting these two separations, designated 505X and 606X. These are speculative illustrations; a mass balance based upon the expected inputs by alloy and product would lead to more precise projections.

The projected average 505X composition in Table I is similar to a 5052-type alloy, with higher Si and Zn impurities, plus a higher Mn content (0.6% vs. a max. of 0.1 for 5052). Based upon the known performance of commercial 5xxx alloys, all of these three variances may be acceptable for direct reuse of this composition in many products. The Si and Zn impurities are not likely to be troublesome, and the high Mn content may lead to slightly higher strength. It would be practical to define a new alloy based upon the likely output from B&C recycled sheet and plate that could be reused directly in B&C applications, as well as others perhaps.

Similarly, the 606X-type represents a melding of 6061 and 6063 compositions, with variation to be expected based upon the mix of the two at a given time, which also appears potentially directly reusable; it would have useful structural strength when heat treated and aged and would be rather readily extrudable.

Thus, if component pre-sorting based upon separating rolled and extruded products is adopted during demolition, it seems likely that both output remelt compositions could be directly reused in B&C applications, including highway structures, with no further processing.

Recycling Aerospace Alloys—An Overlooked Opportunity

For decades, thousands of obsolete aircraft have been sitting in the southwest desert “graveyards,” while the demand for recycled aluminum increases. The discarded aircraft provide a large potential source of valuable metal. However cost-effective recycling of aircraft alloys is complex because aircraft alloys are typically relatively high in alloying elements like Cu (2xxx series) and Zn (7xxx series), and may contain low levels of minor elements to optimize fracture toughness.

Again it would seem that dismantling

Table II. Potential Compositions of Some Recycled Aircraft Alloys Assuming Pre-Sorting

Alloy	Al	Cu	Fe	Mg	Mn	Si	Zn	Others
R2xxx	~93	4.4	0.5	1.0	0.7	0.5	0.1	0.2
R7xxx	~90	2.0	0.4	2.5	0.2	0.2	6.0	0.2

and presorting would aid in maximizing the value of recycled aircraft aluminum.[17] One technique would be to dismantle aircraft into certain logical component groups, as these typically are made of alloys of the same series. As examples, landing gears, engine nacelles, tail sections, and flaps could be presorted, and wings separated from fuselages. Such separations may be desirable anyway to permit removal of non-aluminum components before shredding.

Guidance in dismantling and presorting would be available from aircraft manufacturers who can identify the alloys used in various components. If/when such information is not available, it may be possible to identify the various alloys with hand-held mobile spectrometers. Non-aluminum components may also be readily identified using this technique. If a useful level of discrimination and separation of 2xxx and 7xxx series alloys is feasible, the compositions of recycled metal are likely to represent something like those shown in Table II.

Based upon this hypothesis, there would appear to be opportunities for direct reuse of the recycled metal in new 2024-like and 7075-type alloys. Upon solution heat treatment and precipitation aging, the properties of these remelt alloys are likely to be similar to those of 2024 and 7075. Subject to more thorough performance evaluation, there is reason to conclude that such metal might be utilized in non-fracture-critical aerospace components or in other structural market application. If, on the other hand, 2xxx and 7xxx alloys cannot be sorted before remelting, the combination of Cu and Zn is likely to require some type of beneficiation of the remelt before being very useful, even in non-aerospace applications.

Two other factors should be noted at this stage.

- First, at least small quantities of several other wrought aluminum alloys like 2219 and 6061 and cast alloys like 201.0, A356.0, and A357.0 may go into any such recycle mix.
- Second, aircraft alloys typically have grain-refining elements such as Cr, Zr, and V present in small quantities (~0.1% or less), and the potential buildup of such elements in addition to Fe, Mg, and Si needs to be the subject of further study. This second factor will become increasingly important as newer aircraft alloys such as 2124, 2048, 7050, 7055, and 7085 enter the recycle mix.

CONCLUSIONS

In several major product areas, opportunities to enhance the recycled metal stream have been identified.

First, the potential secondary metal supply in the automotive vehicle market dwarfs all other product streams. The vehicle recycling process is complex because of the large number of both wrought and cast alloys involved. The primary opportunities to increase the value of recycled automotive aluminum arises from the ability to dismantle as many components of known alloy classes (e.g., bumpers, wheels, body sheet, castings) prior to shredding, and segregate them before remelting. Without such strategies, the recycled metal stream will be limited to the production of casting alloys, much of it overseas.

Next, in the area of building and construction, the aluminum components of buildings being demolished are readily recoverable for recycling, and can readily be sorted by extruded or rolled products, effectively separating Al-Mg-Si (6xxx) alloys from Al-Mg (5xxx) series alloys. Remelting these as segregated lots will provide compositions suitable for direct reuse in B&C applications.

Finally, if aircraft structures can be dismantled and presorted by Al-Cu (2xxx) and Al-Zn (7xxx) alloys, the segregated remelt compositions may be directly reusable in non-fracture-critical components.

More in-depth analysis and mass flow balances are needed to more precisely determine the likely compositions of recycled metal from each of these product areas to more precisely determine the realistic opportunities and likely remelt compositions. Secat has proposed to undertake such studies collaboratively with organizations such as HVSC and other interested market leaders.

ACKNOWLEDGEMENTS

The authors acknowledge the partial support of Qatar National Research Fund through a grant from College of the North Atlantic–Qatar, Doha, Qatar.

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