APPLICATION OF THE RECYCLING INDICES TO THE IDENTIFICATION OF RECYCLE-FRIENDLY ALUMINUM ALLOYS

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Abstract

The Aluminum Recycle Index (ARI) has recently been proposed to measure the relative energy value to be recovered through recycling aluminum alloys and to aid in identifying recycle-friendly compositions. In the past, aluminum alloys were designed based solely upon the target performance requirements and the elemental alloying additions needed to achieve them. It was assumed that whatever base metal requirements were needed would come from primary aluminum, to which the needed alloying elements would be added. Little or no consideration was given to what will happen when a product made of the alloy reaches the end of its life, and becomes available for recycling.

Today, this approach is being replaced by one in which recycling characteristics are included in alloy design. The fact that as much as 35 (check?) percent of the metal available to produce alloys comes from recycled metal makes this factor much more important than before. So recyclability is increasingly being considered along with performance requirements in designing new alloy compositions.

This approach is enhanced by recognizing the relative recycle-friendliness of existing alloys with the ARI. An additional factor, introduced herein for the first time, is the Recycle Production Index, RPI, which indicates the relative degree to which an alloy may be produced entirely from recycle remelts. In the paper which follows, the basis or the ARI and RPI are described, and some applications of their use are illustrated.

Introduction

It has been the usual procedure in the design and development of new aluminum alloys to focus entirely upon the performance requirements needed for the specific application to which the alloy will be targeted. Decisions on what elemental alloying additions were needed have been based upon judgments of what would be needed to achieve the required performance characteristics for the target application, usually properties such as design strengths, fracture toughness, resistance to atmospheric environments and/or susceptibility to stress-corrosion cracking.

Generally, in the past little attention if any was given to what happens when the products produced of an alloy reach the end of their useful life and are available for recycling. In fact until recently, many products were not even considered for recycling, for example those from aerospace, rail car, and building and construction applications

In addition, it was taken for granted in the past that the base metal requirements needed to produce the new alloy would come from new primary aluminum production, to which the needed alloying elements would be added. Little or no recognition was given to the possibility that some alloys might be produced partly or entirely from recycled metal, thereby avoiding the relatively high energy requirements needed to produce the needed primary metal.

Now, for the first time, the old approach to alloy design is being replaced by one in which recyclability is considered along with performance in developing new alloys. It might be termed a more recycle-friendly alloy design technique.

This new approach can be aided by recognizing two attributes of the potential new alloy design:

- The Aluminum Recycle Index, ARI - The relative desirability or recycling an alloy in terms of recovering the maximum stored energy invested in the alloy, and
- The Aluminum Production Recycle Index, RPI – The relative ease of producing an alloy from recycled metal remelts.

These two characteristics will be described in more detail below, and illustrations of their application will be provided.

Background

As noted above, in the past, little consideration has been given to the recycling characteristics of an alloy during its development. Recently, a series of recommendations have been to illustrate how the relative recyclability of a composition may be considered in developing new alloys [1-12]. The net result should be more cost-effective recycling of aluminum alloy products.

Historically, the recycling of aluminum beverage cans has been well accepted, and provides an excellent example of true recycling, i.e., the remelted metal goes back into the same beverage can products [1-4]. This is in contrast to the recycling of some materials in which the recycled content can not be directly reused for the same product, and so is diverted into some lower quality product. Aluminum offers the approach in which products other than just used beverage cans can be truly recycled, i.e., put back into the production of the same products, so the cycle is virtually endless.

The opportunity for the application of this approach to a variety of aluminum products has now been recognized and gradual implementation seems likely. Recommendations have been put forward for widely used aluminum alloy products such as automotive and truck components [4, 5], building and highway construction components [6, 7], and aircraft components [8].

All of these approaches include attention to the other important aspects of the most cost-effective recycling including:

- Increasing the recovery of recyclable products,
- Automated shredding,
- Automated color or electronic sorting of the shredded volume,
- The use of optimized remelting technology, and
- Improved modeling of the recycled metal flows.

The underlying driving forces for recommendations to recycle in the most cost-effective manner are the major benefits of aluminum recycling itself, which include:

1. The reduction in the need for primary aluminum, and therefore the saving of energy,
2. The reduction of emissions associated with primary production, and
3. The elimination of landfill wastes.

These benefits have been quantified by a comprehensive life cycle analysis conducted by the aluminum industry [13], including the analysis of 15 unit processes in some 213 plants worldwide. It was demonstrated that the production of primary aluminum, when all the electrical generation and transmission losses and transportation fuels are accounted for, requires about 45 kWh of energy and emits about 12 kg of CO_2 for each kilogram of new primary metal produced. On the other hand, the recycling of aluminum requires only about 2.8 kWh of energy and emits only about 0.6 kg of CO_2 for each kilogram of metal [14.15].

A useful way of looking at this is that every time aluminum is recycled, 95 percent of the energy banked in the metal during the initial smelting process is recovered, with only minor losses, and about 95 percent of the environmental emissions are saved. It is the energy recovery component of the aluminum recycling process fact that has led to consideration of the aluminum products in use and becoming available for recycling as an **aluminum energy bank** [14-16].

In Mark Schlesinger's recent book "***Aluminum Recycling***" [15], he noted 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 contrast, with aluminum recycling, much of the "ore body" consists of the used aluminum products on top of the ground rather than in it; these aluminum products are what can be referred to as our **urban mine**, Such scrap aluminum products come with their own variety of impurities, e.g., paint coatings, metal attachments, and dirt or other contaminants. So, while the aluminum recycling process still requires some refinement and expenditure of energy, the total effort and energy involved is much less than (only 5 percent of) that involved in the traditional mining, refining, and smelting to produce primary aluminum.

Another very important driving force for maximizing recycling is the changing geopolitical scene of aluminum production [10, 17]. For much of the industry's early history, the United States (USA) was the world's largest producer of primary aluminum. However, as illustrated in Figure 1, the USA has gone from being the first to now being the fourth largest primary aluminum producer. Just since the year 2000, China and Russia have emerged as the two largest producers. While no longer the leading primary aluminum producer, the USA remains the world's largest consumer of aluminum. According to the United States Geological Survey (USGS) Minerals Yearbook, US aluminum consumption in 2005 was 6,460,000 metric tones.

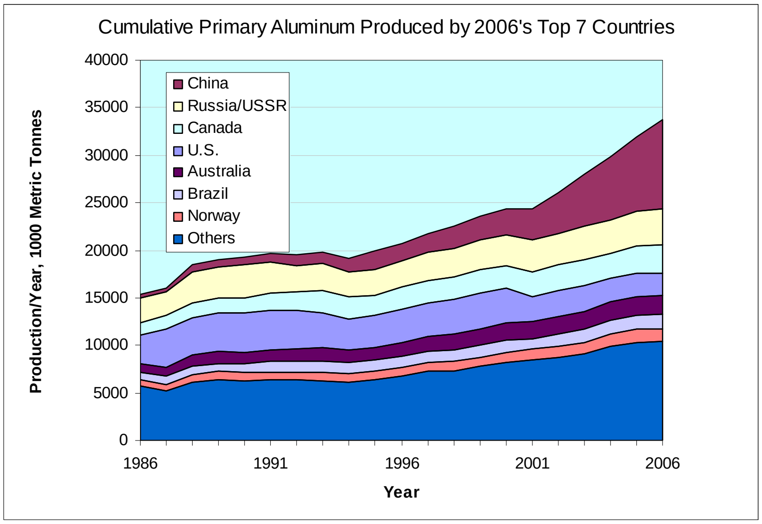

Figure 1. Primary Aluminum Production per Year by Top 7 Nations in 2006.

Consistent with this shift, the USA remains the largest fabricator of aluminum products but now must import a large amount of the primary aluminum it consumes. This is a critical aspect of the discussion of the importance of recycling, as maximizing the ability to cost-effectively recover and directly reuse recycled aluminum metal reduces USA dependence on imports. This fact reinforces the concept of recovered aluminum products being our urban mine with their energy content being our energy bank. It also reinforces the importance of retaining scrap aluminum in the USA, and as much as possible in the hands of fabricators who will reuse the scrap aluminum for new products whenever practical as contrasted to the usual pattern of permitting it to go to offshore sales.

In dealing with recycling challenges, whether the development of new alloys or in evaluating recycling opportunities and practices for existing alloys, the use of the Alloy Recycling Index (ARI) as a quantitative description of the relative ease and value of recycling of a composition, plus the Recycled Aluminum Production Index (RPI) as a measure of the ease of production of an alloy from recycled metal can be useful tools. It is on this last point that the remainder of this paper is focused.

The Aluminum Alloy Recycling Index, ARI – a measure of the value of recycling an alloy

The Aluminum Recycling Index, ARI, as introduced in Reference 18, is defined as follows:

> ARI is a measure of the stored energy banked in an aluminum alloy during its initial production, and therefore a quantitative measure of the value and desirability of used, end-of-life products made of the alloy to be recycled and directly reused if feasible. Because the energy involved in producing the alloying elements is relatively small, ARI is based solely upon the energy content associated with the aluminum in the alloy being recycled.

ARI is determining by calculating the nominal aluminum content of an alloy based upon the nominal composition and operating limits for the alloys as published by the Aluminum Association in *Aluminum Standards & Data, ASD* [19]. Using this reference, the nominal aluminum content is calculated as follows for each alloy:

1. The nominal alloy content is calculated by summing the nominal alloy additions, which are the mid-range of the specific alloying additions (e.g., the limits for Cu in 2018 are 3.5-4.5%, so the nominal value of 4.0% is used, and added to the other nominal alloying additions);
2. To the sum of the nominal alloying content from Step 1 is added the sum of the mid-range of the impurity limits (e.g., for 2018, the upper limit on Fe as an impurity is 1.0%, so 0.5% is used, and added to all of the other stated impurity limits); no account is taken for “other” or “all other” elements categories.
3. This total of nominal alloying content (Step 1) plus nominal total impurity content (Step 2) is subtracted from 100% to give the nominal aluminum content or ARI.

Tables 1 and 2 at the end of the paper present ARI values for a number of representative wrought and cast aluminum alloys, respectively. As defined, the higher the value of ARI for an alloy, the higher is the stored energy content in the alloy and, hence, the greater value and desirability of recycling that alloy. The lower the ARI value, the lesser energy content stored in the alloy, and the lesser value in recycling the alloy because of the increased likelihood that additional processing will be required to productively use the remelted metal. It is important to recognize, however, that a lower ARI does not mean that such alloys should not be recycled (in fact, they should), but that recycling them will not be as straightforward. Reinforcing this is the fact that even the lowest rated alloys have an ARI of 80 or more: they are at least 80 percent aluminum, valuable for recovery.

Some descriptive ranges of ARI have also been proposed to reflect the various levels of ease and desirability of recycling on individual alloys, as [presented in Table 3. Two sets of ranges are proposed, one for wrought alloys and one for casting alloys. The reason for the difference in application of the ARI ranges to wrought and casting alloys is the higher tolerance for Si in casting alloys than in wrought alloys. Thus the casting alloy ratings are more forgiving of relatively high Si contents, which are present in amounts greater than 4 percent in almost all aluminum casting alloys; Si contributes to good flow characteristics of the molten alloy, enabling it to completely fill complex casting molds.

Table 3 – Definitions of ranges of Aluminum Recycle Index for aluminum alloys

	ARI		
Descriptor	Wrought Alloys	Casting Alloys	ARI Descriptor Definition
Optimum	97-100	95-100	At or near maximum stored energy; easy to recycle under any conditions; will mix readily with all alloys; if segregated, may be directly reused
Excellent	96-97	90-95	Near maximum stored energy; easy to directly recycle into the same or

			similar products; will mix readily with most other alloys
Good	95-96	87-93	Very high stored energy; may be recycled for direct reuse in same or similar product if alloy segregation done before remelting
Fair	93-95	84-86	High stored energy but no easily recycled except to lower performance alloys unless segregated prior to remelting
Difficult	90-93	80-83	Relatively lower stored energy; more difficult to recycle except to castings unless segregated prior to remelting
Unlikely	<90	<80	Lowest stored energy; rather difficult to recycle except with post-processing to remove some problem elements

Some criteria underlying the ARI ranges are as follows:.

Relatively high ARI for alloys with:

- Relative high purity and therefore few contaminants to future remelts
- Relatively low alloying levels and therefore the greater likelihood to be compatible with other compositions potentially in the same remelt mix
- For casting alloys only, alloys with moderate Si compositions and relatively few other alloying elements

Medium ARI for alloys that are

- Moderately high in alloying content and associated impurity and insoluble constituent content
- Used in applications where pre-shred segregation prior to remelt seems practical (e.g., automotive wheels and bumpers).
- For casting alloys only, alloys with high levels of Si and relatively few other alloying elements

Lowest ARI for alloys with:

- Relatively high alloys content in one or more elements, or
- Alloying additions undesirable in most remelts (e.g., Ag, Be, ,Pb, Li)
- For casting alloys, alloys with very high Si plus relatively high Cu, Sn, or Zn.

It is appropriate to note that most if not all of the troublesome elements can be dealt with in recycling the products, but require additional processing. Ag and Pb would likely end up in the furnace sludge because of their high density. Bi and Li would be handled like the alkali and alkali earth metals, and be fluxed out with argon/chlorine combinations. Pb and Sn melt at relatively low temperatures, and can be separated out relatively easily. Be is a large negative because of toxicity, and would be best kept out of the recycle remelt; fortunately it is only in weld wire alloys and would not likely occur in large quantities in any case.

The potential usefulness of the ARI includes the following determinations:

- Which existing alloys can be most readily recycled for direct reuse, as in beverage can recycling, or readily combined with other like alloys for other high-value applications;
- Which alloys are more difficult to recycle and reuse without significant reprocessing unless methods of segregation of alloys in advance of mass shredding are introduced; and
- Which alloys are the most difficult to recycle because of the presence of undesirable elements like Ag, Be, Bi, Pb, or Li, or because of the presence of very high levels of elements like Cu, or Zn, and of the associated intermetallic compounds.

In addition, and key to this discussion, the Alloy Recycling Index would be helpful during new alloy design in indicating which existing alloys would be most readily compatible with the new composition being considered from the recycling perspective.

In summary, the ARI is a measure of the energy stored in an alloy, and therefore the desirability of recycling it. The adoption of an Alloy Recycling Index is proposed to aid in maximizing the aluminum industry contribution to a green environment by reducing energy use and CO_2 production by reducing the need for new primary aluminum while continuing expansion to new applications.

The Recycling Production Index, RPI - a measure of relative ease of producing an alloy directly from recycle remelts

There is a second aspect of recycle-friendliness that is not directly defined by the ARI: the ease with which alloys might be produced directly or with minimum processing from recycle remelts and utilized in the production of the same product or another high value product. This characteristic is defined by the Recycling Production Index, or RPI, and is graded into only four categories:

- High (H) – Readily produced from recycle remelts with little or no additional processing
- Medium (M) – Readily produced from recycle remelts of scrap segregated at least by alloy series (e.g., 1xxx, 2xxx, 3xxx, etc), or with minimum additions of new primary metal
- Low (L) – More difficult to recycle from recycle remelts unless scrap was segregated by alloy, and may require significant post-processing
- Unlikely (U) – Composition does not lend itself to production from recycle remelts because of high-purity requirements, large amounts of alloying elements, or the presence of undesirable elements like Ag, Be, or Li,

Two factors define this RPI characteristic, the amount alloying elements, as with ARI, and the impurity levels, the latter acting opposite to their effect on ARI. Thus alloys with relatively tight limits on impurities get a relatively low score with regard to being producible from a recycle remelt. On the other hand, alloys with relatively tolerant (i.e., higher) limits on impurities, combined with relatively low to medium amounts of alloying elements rate relatively high as far as opportunities for direct production from recycle remelts. Examples include 3004, 3105, 5050, 6061, and 6063.

Ratings of the alloys with respect to RPI are shown in the right-hand column of Tables 1 and 2.

Two quick illustrations will help demonstrate the difference between high value of ARI and high value of RPI:

- 1050 has an ARI = 100 because it is usually a very positive addition to any recycle mix; however, because of the high purity required it is unlikely the alloy itself could ever be produced from a recycle remelt, and so the RPI for 1050 is "low."

- A356.0 gets a relatively high ARI for a casting because it would be a relatively positive addition to any recycling remelt. However because of its relatively tight limits on impurities, it is very unlikely A356.0 could ever be produced directly from a recycle remelt, and so its RPI is "low."

In general, alloys with a very low ARI will also have a relatively low RPI.

Several of the alloys in Tables 1 and 2 are footnoted with respect to ARI and RPI because they would get relatively higher ratings in this respect if they are able to be produced from recycling operations in products made of those alloys were segregated prior to remelting. For example, automotive alloys used for body sheet and bumpers might be reused directly from recycle remelts if these parts are dismantled and segregated prior to remelting as part of the automotive recycling process.

It is recognized, however, that some variability of shredded material in most commercial recycling operations will result from material coming from a variety of applications, such as washers, refrigerators, and structural components, and thus prejudging most recycled alloy mixes is difficult. However, it is quite possible that even when a variety of recycled components are mixed together, useful alloy remelts may be obtained, especially if the alloys are in the high-recyclability category.

That discussion leads directly into the subject of recognizing new recycle-friendly alloys that might be produced from recycle remelts, as covered in the next section.

Application of Recycling to New Alloy Development

As noted earlier, tentative recommendations have been put forward for recognizing the compositions resulting from remelting various aluminum alloy products, notably automotive and truck components [4, 5], building and highway construction components [6], and aircraft components [8]. These recommendations were summarized in Reference 12, and are summarized below to illustrate the usefulness of ARI and RPI

A brief discussion follows of those major markets as listed below in Table 4.

Table 4 – Market/Product/Alloy Matrix for Aluminum Alloys

	Rolled Products	**Extrusions**	**Forgings**	**Castings**
Electrical	1350, 5005, 6101, 6201	- -	- -	- -
Beverage Cans and Packaging	1100, 3X04, 5182	- -	- -	- -
Building and Construction	3X05, 505X 5083, 5086	6061, 6063, 6082	- -	- -
Transportation -Vehicles	5022, 5754, 6022, 6111	6063	- -	360.0, 380.0, A356.0
Transportation – Railroad Cars	505X 508X 6061 6063			
Transportation - Aircraft	2X24, 7X75	2X24, 7X75	2X24, 7X75	A201.0, A356.0, A357.0

Electrical Conductor Alloy Recycling

Since most, if not all, aluminum electrical conductors would be dismantled as well as installed and erected by electrical contractors, the first step in maximizing their recycling should not be difficult. Such contractors should collect dismantled conductors by type, and return them in batches to their suppliers. While life cycles are usually quite long in the electrical market, say 15-20 years, the potential value in recycling this component of the urban aluminum mine is significant.

The feasibility for direct reuse of scrapped electrical conductors after they are remelted should also be fairly high as the alloys most likely to be encountered, 1350, 6101, and 6201, are all relatively lightly alloyed, as alloying detracts from the electrical properties. The result is that a remelt of any mixture of these alloys is very likely to be directly reusable as either 6101 or 6201, with any 1350 in the mix helping keep impurities low. If the three alloys are separated initially, they could of course be directly recycled back to the original conductor product. So both ARI and RPI are quite high for electrical remelts, the latter assuming reasonable segregation prior to melting as described herein.

Beverage Can Alloy Recycling

There are essentially two alloys involved in the highly engineered aluminum beverage can, namely 3004/3104, an Al-Mn alloy for the body, and 5182, an Al-Mg alloy, for the tab and can lid [4, 11]. The ARI values for these alloys are relatively high (97.0 for 3004, 94.5 for 5182) because alloying elements of the two alloys are quite compatible when the whole can is remelted. The Si, Fe, Cu and Mn values of 5182 are all lower than those for 3004 and thus do not cause any impurity incompatibilities when melted together. The Mg level in 5182 is considerably higher than in 3004. However, Mg is volatile at the temperatures involved in the remelting process and also some Mg is lost in the fluxing and purification stages. As most as the remelts are derived from recycled beverage cans, both ARI and RPI for 3004 would be high.

Hence, the recycling of remelted beverage cans to 3004 body stock is relatively straightforward to accomplish with only some minor loss of magnesium. In fabricating new cans, the new lid 5182 material is generally supplied from primary alloy, so its RPI is low.

The recycling and recovery of alloys from the automotive, railcar, and building and construction, and aircraft and aerospace markets are all relatively more complex than the electrical and beverage can markets discussed above, with greater elemental incompatibilities and different impurity issues, as illustrated in the following sections.

Automotive, Truck, and Trailer Recycling

As noted earlier, since 2005 the automotive and truck market represents the largest and fastest growing market for aluminum in the U.S. since 2005. The scrap generated from used autos and trucks now exceeds that from the recycling of beverage cans, and the margin will continue to increase. Thus this market offers the greatest opportunity for economic recycling. Clearly, much of the future supply of recyclable aluminum is driving around on our roads today, our mobile urban mine.

Automotive alloys are included in Tables 1 and 2. The relatively high Cu content of the 2xxx alloys will not blend well with the 5xxx and 6xxx alloys, and the high Zn content of the 7xxx alloys is not compatible with any of the other alloys. As a result, even with the best LIBS sorting [20, 21], shredding a whole vehicle and remelting all of the aluminum together will likely result in a composition that will be difficult or impossible to reuse directly as wrought alloys, and even perhaps a challenge to utilize for castings.

If as suggested in Reference 5, large, easily accessible vehicle components, such as bumpers, wheels, and perhaps even body panels, are removed prior to shredding and segregated for separate remelting, the resultant remelts may be directly reused. The remainder of the auto hulk would then be shredded, sorted and remelted using the most efficient processes to reduce dross losses and maximize recovery.

If the pre-shred dismantling and segregated remelt approach is adopted, and alloys are segregated at least into 2xxx, 5xxx, 6xxx and 7xxx alloys series or if sheet can be separated from extruded shapes, remelt compositions such as those illustrated in Table 5 may be generated.

Table 5 – Potential New Recycle-Friendly aluminum alloys from segregated automotive batch remelts

Remelt Source	Si, %	Fe, %	Cu, %	Mn, %	Mg, %	Zn, %	Others,%	ARI	RPI
All body sheet panels	0.7	0.4	0.5	0.25	1.2	0.2	0.2	~98	M/H
2xxx body sheet panels	0.25	0.25	1.0	0.25	0.8	0.12	0.2	~98	M/H
5xxx body sheet panels	0.20	0.20	0.08	0.20	2.8	0.15	0.2	~96	M/H
6xxx body sheet panels	1.0	0.15	0.30	0.15	0.7	0.08	0.2	~98	M/H
All structural members	0.6	0.20	0.08	0.60	0.08	0.08	0.15	~99	M/H
7xxx bumper components	0.10	0.15	0.75	0.08	1.35	4.0	0.20	~95	M/H
Cast components	8.5	1.2	1.0	0.25	0.3	1.0	0.4	~90	M/H

All of these remelt compositions from segregated melts, except the bumper stock with relatively high Zn content rate an ARI of 95 or more, being relatively recycle friendly. More important perhaps all would receive a very high RPI rating (M/H – medium high) for their ability to be produced from recycle remelts. Even the bumper stock would rate highly in this respect if it is made from segregated 7xxx alloy remelts.

The difficulties in implementing this pre-shred disassembly and pre-sorting approach for vehicles by vehicle recyclers are recognized to be fairly significant, but the potential economic gains are extremely attractive and powerful enough to justify careful evaluation plus added effort to ensure the scrap aluminum stays in the USA.

Obviously, these complications would all be eliminated if the use of relatively similar alloys throughout the whole body system could be implemented, the “unialloy” approach.. This is difficult because of the diverse requirements of different components but some progress has been made. An example is the use of a 6xxx like 6022 alloy for all body sheet applications, the O temper for inner body panels requiring maximum formability, and the T4 temper for outer body panels requiring maximum dent resistance. In this case, the aluminum remelt composition from all chassis components including the 6063 and 6061 extruded shapes should be quite readily reusable for the production of new chassis components. Even when mixed with metal from remelted 319.0 and/or 356.0 castings, relatively useful compositions would result. Careful consideration of alloy choices to assure compatibility will always improve recyclability.

Buildings and Construction (B&C) Recycling

Because the life cycles of buildings and highway structures are so long, generally considered to be 30-50 years, this market segment (the third largest for aluminum) has generally not received much attention concerning recycling until recently [6,7]. Newer architectural designs are increasing the use of aluminum to make buildings more energy efficient through the use of sun screens, cladding and shades, curtain wall construction and advanced window designs, so B&C usage is likely to increase more rapidly along with the value of the associated embedded urban aluminum mine.

Investigators at the Technical University of Delft [7] have documented the opportunities for recycling aluminum components during the demolition of buildings of nine different types located in six different countries in Europe. Among the findings were the following:

- The average aluminum collection rate for the nine buildings was found to be about 96%.
- Even though the aluminum content of the buildings was less than 1%, there was still significant mass of aluminum available for recovery,
- Most aluminum, including that added to buildings during refurbishment, is located on or near the periphery of the building and is easy to recover, e.g. roof-top air conditioners, sun shades and awnings, etc.,
- Non–residential high rise buildings and factories contain 1-2 orders of magnitude more aluminum than residential buildings,
- Residential construction in warm climates contains about 20 times more aluminum than in cold climates, with future architectural designs are likely to increase this amount,
- There is a potential for direct reuse of some components; aluminum alloy windows, for example, could be immediately reused in new construction after cleaning,
- Recycling during demolition would significantly reduce the amount of material going to landfill, for which in Europe are increasing due to limited space, and
- Recycling during demolition also increases the amount of clean and segregated aggregate available for future building projects, thereby saving the need for additional quarrying operations.

If the approach of recovering aluminum components from building and structural demolition is implemented, several judgments can be made about potential remelt mixes from segregated rolled and extruded components. For the rolled products, the principal alloys would likely be sheet of alloys like 3105 and the 5xxx series, including 5052, 5083 and 5454. For the extruded products, the alloys would be almost exclusively 6061 and 6063. Segregated remelts would likely lead to compositions something like those in Table 6:

Table 6 - – Potential new recycle remelt alloys from B&C and structural applications

Remelt source	Si, %	Fe, %	Cu, %	Mn, %	Mg, %	Cr, %	Zn, %	Ti, %	ARI	RPI
All B&C components	0.45	0.45	0.15	0.8	1.6	0.15	0.20	0.1	~96	M/H
Rolled sheet & plate	0.4	0.4	0.15	0.6	2.5	0.15	0.25	0.10	~97	H
Extruded shapes	0.5	0.5	0.2	0.12	0.8	0.15	0.15	0.12	~97	H

All three of these compositions have a very high ARI for recycling and at least a M/H RPI rating so long as they were produced from segregated remelts.. Some advantage is gained if the 5xxx and 6xxx panels are pre-sorted and remelted separately, as indicated by the slightly higher ARI for the segregated alloy types. The segregated compositions would also rate very highly (RPI = H) for their ability to be fabricated from recycle remelts.

It appears there could be value in recognizing all three of these compositions as new alloys or modifications of existing alloys.

Aircraft and Aerospace Alloys Recycling

Aerospace alloys are the most highly alloyed and expensive in the whole portfolio of aluminum alloys. Their ARI values, therefore are relatively low, but their high alloy content may maker them useful to recover if the added value from the alloying can be retained.

Aircraft alloys fall primarily into two categories: (a) the Al-Cu or 2xxx series, like 2014, 2024, and 2219, and (b) the Al-Zn-Mg-Cu alloys of the 7xxx series, like 7050, 7075, and in earlier years, 7178.

As demand for recycled aluminum continues to increase, thousands of obsolete aircraft fabricated have been sitting in “graveyards,” such as those in the southwest U.S. providing a large urban mine of valuable metal. Cost-effective recycling of aircraft alloys for reuse the aerospace applications is complex because, as noted above, they typically contain relatively high levels of Cu and Zn, among others, plus the fact that for new applications many of the alloys must contain very low levels of impurities to optimize performance characteristics like fracture toughness and corrosion resistance..

To capitalize on this urban mine, it seems potentially feasible to develop one or more aircraft recycling centers around the globe, including in the southwest U.S. [8]. Not only could the metal in the ‘graveyards” be recaptured, active aircraft being decommissioned could be flown to the nearest center for timely metal recovery.

If this approach to aircraft recycling were to be adopted, it seems clear that some sort of dismantling and presorting would be useful to maximize the value of the resultant remelts as contrasted to shredding an entire aircraft. One technique that seems practical would be to dismantle aircraft into certain logical component groups, as these typically are made of similar alloys of the same series. As example, landing gears, engine nacelles, tail sections, and flaps could easily be presorted, and wings separated from fuselages. Hand-held chemical; analyzers could be used to help sort the components by alloy type (2xxx or 7xxx). Such separations may be desirable anyway to permit removal of non-aluminum components before shredding.

Continuing this approach, it will be desirable at minimum to separate 2xxx and 7xxx alloy components. Potential remelts compositions from segregated remelts would likely look something like the first two lines in Table 8. For comparison, the likely type of composition that would result without pre-shred sorting of 2xxx and 7xxx alloys is included on the third line.

Table 8 – Potential Compositions of Remelted Recycled Aircraft Alloys With and Without Pre-Shred Sorting of 2xxx and 7xxx Components

ALLOY	Si, %	Fe, %	Cu, %	Mn, %	Mg, %	Zn, %	Others %	ARI	RPI
R2XXX	0.5	0.5	4.4	0.7	1.0	0.1	0.2	~94	M
R7XXX	0.2	0.4	2.0	0.2	2.5	6.0	0.2	~91	M/L
R2+7XXX	0.4	0.5	3.0	0.5	1.8	3.5	0.3	~91	U

If 2xxx and 7xxx alloys can be sorted successfully leading to the first two compositions as in Table 8, there may be some opportunities to re-use the recycled R2XXX metal in a 2024-like alloy, and the R7XXX composition for a 7075-type alloy. Upon the appropriate subsequent heat treatment, the properties of these alloys are likely to resemble those of 2024-T3 or T4 and 7075-T6, respectively. Subject to more thorough performance evaluation, there is reason to conclude that such remelted metal might be directly utilized in non-fracture-critical aerospace components or in non-aerospace applications such as railroad cars or truck bodies. Almost certainly the material could be reused in the form of castings where the compositional ranges are more tolerant of impurities.

The characteristics of the third composition (R2+R7XXX) that could result if no pre-shred sorting is carried out are difficult to estimate as they do not match any existing registered alloy, and some remedial beneficiation will very likely be required before it could be used for any application, even castings. There is considerable motivation for including the pre-sorting technology to its maximum advantage.

Naturally it would be even more desirable if it would be economically feasible to separate specific alloys, say 2014 from 2024 and 7050 from 7075. This would be another application for hand-held tools. Since newer aircraft will have more high-purity alloys like 2124, 2324, 7050, 7175, and 7475, it would also be highly desirable to be able to make a finer segregation based upon Fe content.

While some level of alloy sorting may possibly be achieved based upon Fe levels in recycled aircraft components, it is more logical at this point to assume that sorting will be initially limited to identifying only 2xxx and 7xxx series alloys.

Several other factors should be noted:

- The presence of specialty elements Ag, Be, and Li in aircraft alloys may require some extra post-processing steps. If these elements are not dealt with, it will be desirable to maintain the aircraft recycle stream separated from a general aluminum recycle stream.

- 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.

- Issues like the above illustrate the desirability of moving decommissioned aircraft to the recycle center as quickly as possible, while the alloy identification of specific components is well documented and current.

Market Review Wrap-up

In concluding the market review of potential opportunities for new recycle-friendly alloys, it is appropriate to note that the greatest likelihood of being able to take advantage of compositions resulting from the recycling of the end-of-life automotive vehicles, B&C structures, and aircraft would be through the institution of systems to control their collection and implement some types of pre-shred sorting and segregation of alloy types prior to remelting. To better define both the value of such measures and the actual compositions likely to result from such activities, mass flow balances and mathematical modeling of the aluminum flows through these markets will be needed.

While a detailed study of the opportunities to recycle railcars to take advantage of the substantial quantities of aluminum embedded therein, the situation there would seem to be very similar to that with ground vehicles. The separation of rolled and extruded components would like lead to useful remelt compositions, possibility even for direct reuse in structural applications.

Quantifying the Added Value from New Recycle-Friendly Alloys

It would be highly desirable to be able to quantify the specific value that would be added if the suggestions above about segregated remelts and recycle-friendly alloys. Regrettably that is difficult to do without more detailed information about metal movement and mass metal flow modeling. Specific mass flow information would be required for specific alloys and products within each market.

However, we are able to identify some specific processing steps that may be changed significantly or eliminated by pre-shred disassembly and segregation of components of like alloys before they are remelted, moving toward the possibility of having recycle remelts for direct reuse as existing or new recycle-friendly alloys. These include the following:

1. The ability to cast remelts directly into extrusion billets or sheet/plate ingots for immediate production of semi-finished products without intermediate furnace beneficiation or refining steps are needed;
2. The elimination or at least minimization of the need to add new primary metal to the recycle remelt to make it suitable for new product production; and
3. The elimination of steps to modify composition, e.g., remove Si, Fe, or Mg from the recycle remelt mix.

If verified with more detailed studies, it seems clear that savings of at least \$0.20-\$0.30 per pound would be accrued. The metal that comes from segregated scrap remelts could be valued as full-price alloyed aluminum.

Conclusions

Based upon the foregoing data and discussion regarding the recycling of aluminum alloy products, the following conclusions seem warranted:

1. There is great economic and environmental justification to maximize the effectiveness of the recycling of aluminum alloy products, notably:
   - 95% reduction in energy utilized and 95% less CO2 generated as compared with the production of primary metal, and
   - Reduction in dependence upon overseas sources of primary aluminum.

2. To assist in this effort, it is useful to have a quantitative measure of the value of recycling specific aluminum alloys based upon their relative energy content, 95% of which is saved each time the metal is recycled. The Aluminum Recycling Index, or ARI, is the nominal aluminum content of an alloy calculated by subtracting the nominal alloy and impurity counts for an alloy from 100%, and a direct measure of the recoverable energy from recycling and avoiding the need for primary metal.

3. Based upon the ARI measure of recyclability and alloy content:
   - Alloys with lower alloy and impurity content are the easiest to recycle into new direct use products.
   - Alloys with primarily Si and/or Mg additions also provide many opportunities to be recycled directly into high value products.
   - Alloys with high Cu and/or Zn contents are relatively difficult to recycle into direct reuse products unless there are opportunities for pre-shred sorting and segregation of alloys or alloy types prior to remelting.
   - Alloys with elements like Ag, Be, Bi, Pb, and/or Li are relatively more difficult to recycle, requiring additional processing to remove the undesirable elements..

4. A companion indicator to the ARI is the RPI, an index indicating the relative potential for alloys to be produced directly from recycle remelts and therefore directly reused in producing either the same product or other high value products. Alloys with relatively high impurity limits rate higher in this respect, and those with relatively tight/low impurity limits rate lower.

5. Based upon a review of the opportunities to increase the cost-effectiveness of aluminum product recycling on a market-by-market basis, the following conclusions have been developed.

- For the electrical and beverage can markets, the opportunity for closed loop recycling and direct reuse of remelted metal exists, and no new alloy compositions are likely to be needed.
- For the automotive market, some recycled material may be incorporated into existing alloys or into new or established "sink" alloys with tolerant impurity specifications. An even more effective approach may be through judicious selection of alloys and tempers for various automotive components to increase compositional compatibility, as, for example using the same alloy in different tempers for inner and outer body panels.
- For the building and construction market, the demolition and segregation of sheet and plate from extruded shapes, and remelts of the segregated materials, lead to a 5xxx alloy from the sheet and plate elements and a 6xxx alloy from the structural and fascia extruded shapes, both likely directly reusable in comparable components.
- For airframe recycling, the establishment of aircraft recycling centers with the ability to segregate 2xxx and 7xxx alloys and remelt the segregated elements, leads to potentially new alloys in each of those two classes that might be directly reused in non-fracture-critical applications. The aircraft/airframe recycle stream would appear to be sufficiently distinct from the general aluminum recycle stream that it should be maintained separate
- To maximize the efficiency and effectiveness of both automotive and aircraft recycling, there is great importance in improving collection and control of end-of-life vehicles. This could be achieved by having more direct involvement or participation of the OEM in the overall process. This might be achieved by setting up dedicated recycling centers where obsolete vehicles and/or aircraft would be taken.

6. The reuse of recycled metal would be greatly facilitated by the availability of rapid, efficient, and low-cost techniques for the removal of excess impurities, especially Fe and Si, from the molten metal. These two elements, and possible some others used for grain-refining, e.g., Cr and V, might build up in recycled metal with time and repeated recycling.

7. At this time all of the above examples and the financial implications of adopting the approach are speculative based upon paper studies. For more definitive, quantitative, and reliable judgments of recycle remelt compositions, careful mass flow metal balances and mathematic modeling of likely future metal flows should be carried out for each of the markets discussed and also for the industry as a whole. Secat has proposed to undertake such studies collaboratively with interested organizations

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References

1. William T. Choate, John A.S. Green, "Modeling the Impact of Secondary Recovery (Recycling) on U. S. Aluminum Supply and Nominal Energy Requirements," ***Light Metals***, TMS 2004, p 913-918
2. S. Das, J. Long, W. Hayden, J. Green, W. Hunt, "Energy Implications of the Changing World of Aluminum Metal Supply," Journal of Metals, August 2004, pp. 14-17
3. S. Das, "Emerging Trends in Aluminum Recycling: Reasons and Responses," ***Proceedings***, TMS 2006, pp. 911-916
4. J.A.S. Green and M. Skillingberg, "Recyclable Aluminum Rolled Products – Building Blocks for a Sustainable World," Light Metal Age, August, 2006, pp 33-42
5. Subodh K. Das, J.A.S. Green, and J. Gilbert Kaufman, "The Development of Recycle-Friendly Automotive Aluminum Alloys," Light Metal Age, November, 2007, pp 47-51 .
6. S.K. Das, J.A.S. Green and J.G. Kaufman, "The Recycling of Aluminum from Building and Construction (B&C) Applications", ***Aluminum***, TMS 2008.
7. EAA Report "Collection of Aluminum from Buildings in Europe", Delft University of Technology, European Aluminum Association, 2004, www.eaa.net
8. S. Das, J. G. Kaufman, "Recycling Aluminum Aerospace Alloys," Light Metals 2007, pp. 1161-1165
9. S. Das, "Designing Aluminum Alloys for a Recycle-Friendly World," Light Metal Age, June 2006, pp. 26-29
10. S. Das and W. Yin, "Trends in the Global Aluminum Fabrication Industry," Journal of Metals, Feb. 2007, pp. 83-87
11. S. Das, "Recent Projects of the Sloan Industry Center for a Sustainable Aluminum Industry Promoting Aluminum Recycling," ***Light Metals***, TMS, 2007, pp. 1131-1140
12. Subodh K. Das, John A.S. Green, and J. Gilbert Kaufman, "Aluminum Recycling – An Integrated, Industry Wide Approach," to be published (update?).
13. ***Life Cycle Inventory Report for the North American Aluminum Industry***, AT-2 Report, compiled by Roy F. Weston, The Aluminum Association, Arlington, VA, Nov. 1998.
14. "Aluminum Industry Vision – Sustainable Solutions for a Dynamic World", published by the Aluminum Association, Arlington, VA 22209, 2001, p.17
15. Mark E. Schlesinger, ***Aluminum Recycling***, CRC Press, 2007, p.9c
16. ***Aluminum: Technology, Applications and Environment***, A profile of a Modern Metal, by Dietrich G. Altenpohl, edited by J.G. Kaufman and S.K. Das, The Aluminum Association, Washington, D.C. and TMS, Warrendale, PA, 1998, p.328-335.

17. Alcoa 2004 Sustainability Report, p. 10; <www.alcoa.com/global/en/about_alcoa/sustainability_report_2004/images/sr_online_final.pdf>
18. Subodh K. Das, John A.S. Green, and J. Gilbert Kaufman, “A Recycle Index for Aluminum Alloys,” ***ICAII Proceedings***, October, 2008.
19. ***Aluminum Standards & Data 2006***, The Aluminum Association, Arlington, VA, published periodically.
20. ***Aluminum Statistical Review for 2005***, The Aluminum Association, Arlington, VA 2005.
21. Adam Gesing et al, “Separation of Wrought Fraction of Aluminum Recovered from Automobile Shredder Scrap,” TMS Aluminum 2001.
22. Adam Gesing, Larry Berry, Ron Dalton, and Richard Wolanski, Huron Valley Steel Corporation, “Assuring Continued Recyclability of Automotive Aluminum Alloys,” ***Aluminum***, TMS 2002.

Table 1 – Values of ARI and RPI for some wrought aluminum alloys

Alloy	Nominal Alloying Content (1) %	Nominal Impurity Content (2) %	Sum Element Content (3) %	Nominal Aluminum Content (4) ARI, %	Notes re ARI	Potential From Recycle RPI (5,6)
1050	- -	- -	- -	99.5		U
1100	- -	- -	- -	99.0		U
1060	- -	- -	- -	99.6		U
1145	- -	- -	- -	99.5		L
1350	- -	- -	- -	99.5		U
2010	2.0	0.7	2.7	97.3		M
2011	5.5	0.8	6.3	93.7	a	M
2014	6.5	0.6	7.1	92.9		M
2024	6.5	0.9	7.4	92.7		M
2195	6.0	0.4	6.5	93.6	b	U
2219	6.9	0.5	7.4	92.6		M
3003	1.4	0.8	2.1	97.9		M
3004	2.2	0.9	3.1	97.0		H
3105	1.1	1.3	2.4	97.7		H
4043	5.2	0.8	6.0	94.0		H
4145	14.0	0.8	14.8	85.2		H
5050	1.4	0.8	2.2	97.8		H
5052	2.8	0.7	3.5	96.6		H
5086	4.6	0.7	5.3	94.7		M
5182	4.9	0.7	5.5	94.5		M
5456	6.0	0.7	6.7	93.3		M
5754	3.1	1.5	4.6	95.4		H
6005	1.2	0.4	1.6	98.4		L
6022	2.0	0.4	2.4	97.6		M
6061	2.1	0.7	2.8	97.2		H
6063	1.1	0.5	1.6	98.4		H
6101	1.2	0.4	1.6	98.4		U
6111	2.6	0.5	3.1	96.9		M
6201	1.4	0.4	1.8	98.2		L
7050	10.8	0.3	11.1	88.9	c	U
7075	9.9	0.8	10.7	89.3	c	M
7116	6.5	0.3	6.8	93.2	c	L
7129	7.7	0.4	8.1	91.9	c	L
7475	9.7	0.3	10.0	90.0	c	U
8017	0.9	0.1	1.0	99.0		L
8090	4.8	0.6	5.4	94.6	b	L

Notes See Table 2 for Notes content

Table 2 – Values of ARI and RPI for some cast aluminum alloys

Alloy	Nominal Alloying Content (1) %	Nominal Impurity Content (2) %	Sum Element Content (3) %	Nominal Aluminum Content (4) ARI, %	Notes re ARI	Potential From Recycle RPI (5,6)
201.0	6.3	0.2	6.5	93.6	a	U
242.0	7.5	1.5	9.0	91.1		M
295.0	5.6	1.0	6.6	93.4		M
319.0	9.5	1.9	11.4	88.6		H
354.0	11.1	0.4	11.5	88.6		M
355.0	6.8	1.0	7.8	92.3		M
356.0	7.3	1.0	8.3	91.7		M
A356.0	7.4	0.5	7.9	92.2		U
360.0	10.0	2.2	12.2	87.8		H
380.0	12.0	3.5	15.5	84.5		H
390.0	22.1	2.0	24.1	75.9	b	M
443.0	5.2	1.7	6.9	93.1		M
512.0	5.8	1.4	7.2	92.8		M
520.0	10.1	0.7	10.7	89.3		M
710.0	7.7	0.6	8.3	91.7	c	M
772.0	7.6	0.3	7.9	92.1		M
850.0	8.2	1.1	9.3	90.7	d	L
853.0	13.8	0.9	14.6	85.4	d	L

Notes:
[1] - Equal to sum of nominal alloying elements
[2] - Equal to 1/2 total impurity elements maximum limits
[3] - Sum of nominal alloying content plus nominal impurity content
[4] - ARI; Aluminum Recycling Index, Equal to 100% minus the sum of alloying content plus impurity content
[5] - RPI - the potential ability to produce this alloy from recycled scrap remelts
H – high; M – medium; L - low
[6] - Rating may be higher if being produced from closed loop scrap system

ARI Notes
a - Requires treatment for added Ni
b - Requires treatment for very high Si
c - Requires treatment for high Zn
d - Requires treatment for added Sn