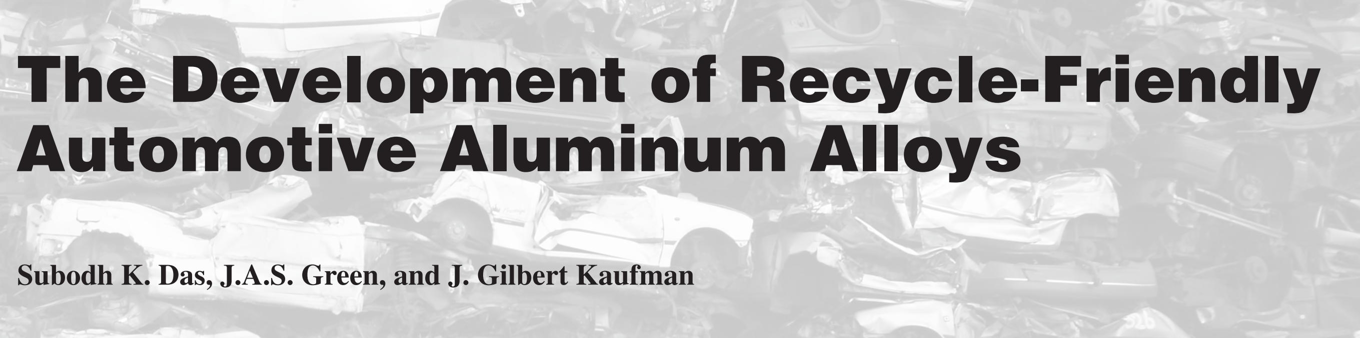

The Development of Recycle-Friendly Automotive Aluminum Alloys

Subodh K. Das, J.A.S. Green, and J. Gilbert Kaufman

The continuing growth of aluminum alloy usage in transportation applications, notably passenger automobiles and minivans, and the demonstrated economic benefits of recycling aluminum-rich vehicles increase the need to seriously consider the desirability of designing recycling-friendly alloys. This article focuses on that aspect of the recycling process for passenger vehicles. The goals are to illustrate the opportunities afforded by identifying and taking full advantage of potential metal streams in guiding the development of new alloys that use those streams. In speculating on several possible aluminum recovery practices and systems that might be used in recycling passenger vehicles, likely compositions are identified and preliminary assessments of their usefulness for direct recycling are made. Specific compositions for possible new recycle-friendly alloys are suggested. In addition, recommendations on how the aluminum enterprise, including industry, academia, and government, can work together to achieve the aggressive but important goals described here are discussed.

INTRODUCTION

In a 2005 article, S. Das[1] presented an overview of a recycling-friendly world in which all aspects of product recycling were addressed and challenges were laid down to maximize the ecological and economic advantages of this new stage for the aluminum industry. In that article, Das pointed out that included among the principal challenges that must be dealt with in creating this ideal recycling world are: improving the recovery of used aluminum components for recycling; improving and more fully automating shredding and sorting technology and making it more broadly available; significantly broadening the range of available aluminum alloys that will perform well in quality products when they are produced directly from recycled metal; and identifying useful by-products to handle residual elements unable to be used in recycled metal, such as iron.

It was further noted that the first, second, and fourth challenges are receiving considerable attention due to the efforts of the Aluminum Association and metal recovery businesses such as Huron Valley Steel Corporation (HVSC, Belleville, Michigan).[2] The greatest unanswered challenge is the third challenge: providing some new types of recycle-friendly alloys, defined in this case as those amenable to direct recovery from recycle remelts and reusable without significant processing or composition supplement with new primary aluminum. It is this last subject with which this article deals, with special focus on the automotive industry.

The high volume of recycled aluminum coming from automotive components exceeded the recycled metal coming from used beverage cans for the first time in 2005.

THE DRIVING FORCES

It is particularly appropriate to focus on automotive recycling in addressing the subject of recycle-friendly alloys because of the increase in secondary metal (i.e., remelted from recycling centers) coming from recycled automotive vehicles. As illustrated by W.T. Choate and J.A.S. Green,[3] the high volume of recycled aluminum coming from automotive components exceeded the recycled metal coming from used beverage cans for the first time in 2005. The *Aluminum Industry Roadmap*[4] also illustrates the importance of these trends and of efforts to address the technology requirements from primary production to finished products.

As Choate and Green also demonstrated,[3] the increase in available recycled metal is a very positive factor, as secondary metal produced from recycled products requires only ~2.8 kWh/kg of metal produced whereas primary aluminum production requires ~45 kWh/kg of metal produced. For the year 2003, this tranlates to an energy saving of 1.72×10^{11} kWh/y. In addition, because recycling emits only ~5% as much CO_2 as primary production, the ecological advantages are as great as the energy savings advantages.

Therefore, as pointed by Das[1] and Green and Choate,[3] it is to the advantage of the aluminum industry to maximize the amount of recycled aluminum alloys being employed in new production. An added benefit to the United States is a reduced dependence on overseas sources of aluminum, which currently constitute ~40% of U.S. consumption through imports.[5]

There is one additional important driving force for increasing the options available for directly reusing recycled secondary metal: reducing post-remelting process costs. Today, most recycled metal must be "sweetened" with more costly and energy-intense primary metal in order to meet the performance requirements of many alloy and product specifications before it is used to produce new products. The specialty alloys required

Table I. Nominal Compositions and Impurity Limits of Representative Automotive Components (wt.%)

Parts	Alloy	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
Body Panels	2010	~96	0.50*	0.50*	1.0	0.25	0.70	0.15*	0.30*	0.05*
	5754	~95	0.40*	0.40*	0.10*	0.40*	3.1	0.30*	0.20*	0.15*
	6022	~97	1.2	0.12	0.06	0.06	0.60	0.10*	0.25*	0.15*
	6111	~97	0.8	0.40*	0.70	0.28	0.75	0.10*	0.15*	0.10*
Structural Elements	6005	~98	0.75	0.35*	0.10*	0.10*	0.50	0.10*	0.10*	0.10*
	6063	~98	0.40	0.35*	0.10*	0.10*	0.68	0.10*	0.10*	0.10*
Bumpers	7116	~93	0.15*	0.30*	0.80	0.05*	1.10	0.05*	4.7	0.05
	7129	~93	0.15*	0.30*	0.70	0.10*	1.65	0.10*	4.7	0.05
Cast Parts	A356.0	~92	7.0	0.20*	0.20*	0.10*	0.35	0.05*	0.10*	0.20*
	360.0	~89	0.9.5	2.0*	0.6*	0.35*	0.50	0.10*	0.50*	0.10*
	A380.0	~85	8.5	1.3	3.5	0.50*	0.10*	0.10*	3.0*	0.10*

* Maximum limit; other values are nominal amounts.

for numerous applications require such strict controls on impurities that recycled metal cannot be used without significant 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. Although this is acceptable to a certain extent, the recycle-friendly world would greatly benefit economically and energy-wise from directly reusing the remelted alloys with little or no post-processing.

Thus, there are significant economic, energy-saving, and ecological driving forces encouraging the aluminum industry and the automotive industry to take recycling automotive vehicles very seriously.

IDEAL AUTOMOTIVE RECYCLING WORLD

There are several critical steps in the ideal system of recycling automotive vehicles. First, recycling of all discarded vehicles would be the standard. This is happening today to an increasing extent through vehicle recycling centers and, in European markets at least, automobile manufacturers that are willing to take back their vehicles. Next, known and obvious aluminum components in vehicles, such as bumpers, wheels, and body panels, would be regularly disassembled and retained separately for remelting to the degree practical. Ideally they would also be separated by alloy class (e.g., 5xxx, 6xxx, etc.). The remainder of the vehicle would be put through an automated shredding and sorting technology, such as laser-induced breakdown spectroscopy,[2] that does not require any extra purification steps before the aluminum is recycled into high-performance products. The aggregates of recovered components and shreddings would be remelted using the most efficient processes to reduce dross and maximize recovery. Finally, appropriate melts of reusable compositions would be targeted for direct reuse, and others would be pooled for reprocessing as required.

The key new feature here is that new alloy options for potential direct reuse in vehicle components, either cast or wrought, would be available. These would become available as a result of considerations dealt with in the remainder if this article.

THE SPECIFIC CHALLENGES

The two key challenges in optimizing the recycling of automotive alloys and products are controlling the dismantling and presorting processes to maximize opportunities to control metal stream composition and developing new alloys or modifications of existing alloys that come directly from the metal streams.

The Importance of Dismantling and Presorting Vehicle Components

Table I summarizes the nominal compositions of representative wrought and cast alloys that would most likely be encountered during vehicle recycling. A comprehensive discussion of all the characteristics and applications of the various alloys series can be found in References 6–15.

There are other alloys that might be included in this summary, but these are sufficient to demonstrate the importance of the concept of disassembly and separation of the major components. For example, the high zinc content in bumper alloys greatly complicates the reuse of a melt containing these alloys for any components involving 2xxx, 5xxx, or 6xxx alloys. Additionally, the exceptionally high silicon content of the castings works against mixing with sheet or extrusion alloys; as a group, however, they may be rather readily reused as castings.

Some caveats must be recognized in regard to the strong emphasis on pre-shred dismantling. First, the operation of the industrial shredders is dominated by the greater economic need to produce uniform steel scrap, and so the collection of nonferrous material is sometimes compromised by the primary needs of the shredder operators to supply the needs of the steel industry. Second, vehicle owners often upgrade their vehicles (e.g., wheels), and in so doing modify the recycling process. Also, there are numerous types of wheels, such as cast or forged wheels, with different alloy compositions so there is no guarantee that a vehicle at end-of-life has retained the original equipment manufacturer (OEM) components. Accordingly, any auto component sorting based on an original design specification may be flawed. Third, the economics of after-market trading may require that certain components be stripped and traded or sold before the hulk is shredded. There is little consideration of alloy composition, and all of these activities are driven by opportunities for higher-value sales. The dismantlers may well use hand-held analytical devices to analyze the key alloy additions in a specific component but the stripped components may be batched by designations such as “low copper” or “high zinc,” which do not necessarily correspond to the Aluminum Association specifications of a specific alloy series. Finally, the dismantlers and recycling companies often use internal proprietary specifications that can be different from the conventional Aluminum Association alloy series.[15]

However, it is highly desirable when creating the maximum value and cost effectiveness of a vehicle recycling plant to incorporate the dismantling and presorting capability to a practical degree. Failure to do so will force significant additional costs in post-processing of the metal and very likely the need for substantial additions of primary metal.

It is also appropriate to recognize that there are a few historical factors that limit what can be done with remelted metal, adding to the challenge of creating directly recyclable alloys. These will be dealt with in the alloy discussions that follow but it is useful at this point to note some of the challenges facing any effort to increase the number of aluminum alloys and applications suitable for direct production from recycled metal. One such challenge is that many premium alloys used today, especially in the aerospace industry where requirements for exceptionally high ductility and toughness are common, call for very tight iron and silicon composition controls. For example, impurity levels above 0.10–0.15% iron or 0.15–0.25% silicon are unacceptable in premium high-toughness aerospace alloys and even in some automotive alloys in use today (see Table I). Wrought high-performance automotive alloys generally restrict both silicon and iron to 0.40% maximum. Both elements are difficult to control in recycled metal and tend to increase modestly the more often the metal has been recycled. Elements other than silicon and iron may be expected to gradually increase with time and may require special attention. Magnesium, nickel, and vanadium are three examples.

Typical compositions of current recycled metal based on eight representative studies by Adam Gesing of HVSC[2] are shown in Table II. Huron Valley Steel Corporation separates 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). The results illustrate several of the fundamental problems in reusing scrap aluminum if significant disassembly and pre-sorting is not carried out. First, even segregated wrought scrap can have relatively widely varying compositions; wrought 3 and wrought 4 lots in Table II, for example, have higher copper (from more 2xxx alloys) and higher zinc (from more 7xxx alloys) in the mix than do wrought 1 and wrought 2 lots. It appears that auto bumper alloys like 7029 and auto body sheet alloys like 2010 were more highly represented in the wrought 3 and 4 lots.

Table II. Typical Compositions of Current Recycled Metal (in wt.%)[2]

Lot	Al	Cu	Fe	Mg	Mn	Si	Zn	Others
Wrought 1	97.1	0.11	0.59	0.82	0.21	0.51	0.45	0.19
Wrought 2	96.7	0.30	0.60	0.60	0.20	0.90	0.50	0.10
Wrought 3	93.1	0.95	1.01	0.89	0.12	2.41	1.25	0.27
Wrought 4	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 Wrought and Cast	90.1	2.30	0.80	0.50	0.20	4.50	1.20	0.30

In addition, some lots of wrought recycled metal (lots 1 and 2) match reasonably well existing lower-end wrought alloys used for building and construction (e.g., 3005, 3104, 3105, and 6061) and can be readily reused as such, although the lots would not be too directly useful as automotive scrap. Others, like lots 3 and 4, are more difficult to use directly in any applications. As noted from Table I, cast alloy scrap differs significantly from wrought alloy scrap, notably with a higher total alloy content, higher silicon content, and, depending on which cast alloys are involved, higher copper (e.g., from A380.0) and zinc (from 7xx.0 cast alloys).

> **An ideal component of resource maximization in recycling would be the availability of several new aluminum alloys that likely fit recycled metal streams and do not require any further post-processing for reuse.**

Finally, compositions resulting from mixed wrought and cast scrap are the most difficult to use directly, except perhaps in some casting alloys.

Alloys Designed with Automotive Recycling in Mind

As noted, an ideal component of resource maximization in recycling would be the availability of several new aluminum alloys that likely fit recycled metal streams and do not require any further post-processing for reuse. That is largely the case with beverage cans today if the recycled scrap is not mixed with other material.

Adopting the approach of new alloy optimization for automotive recycling requires several steps that potentially could be phases in a development program. First, one must identify with increasing precision the range of expected current and future recycled metal content, assuming various disassembly and pre-sorting plans and using the feedback from organizations such as HVSC that are already capitalizing on the economics of recycling. A mass balance must be performed to the extent practical. The mass balance would indicate the expected relative volumes of various scrap compositions.

Next, 5–7 basic candidate alloy compositions must be identified that would accept recycled metal directly and have acceptable/desirable performance characteristics for reuse in a variety of auto applications. Finally, the performance of these candidate alloys must be evaluated in representative production lots to assess their abilities to meet the requirements of representative automotive applications as compared to existing alloys.[6–15]

These evaluations would include atmospheric and salt-water corrosion resistance, formability (with bulge, minimum bend, and hemming tests), and finishing characteristics, response to paint-bake aging where needed, along with the usual tensile and design properties. There may be some negative impacts on some characteristics, but the question is the degree to which such alloys are still useful for some high-volume applications.

Table III. Potential New Recycle-Friendly Automotive Alloys (in wt.%)

Alloy	Si	Fe	Cu	Mn	Mg	Zn	Others
RCBS mix	0.70	0.40	0.50	0.25	1.20	0.20	0.20
RCBS2xxx	0.25	0.25	1.00	0.25	0.80	0.12	0.20
RCBS5xxx	0.20	0.20	0.08	0.20	2.80	0.15	0.20
RCBS6xxx	1.00	0.15	0.30	0.15	0.70	0.08	0.20
RCSE6xxx	0.60	0.20	0.08	0.60	0.08	0.08	0.15
RCB7xxx	0.10	0.15	0.75	0.08	1.35	4.70	0.20
RCCP3xx.x	8.50	1.20	1.00	0.25	0.30	1.00	0.40

SPECIFIC APPROACHES TO RECYCLING-FRIENDLY ALLOY COMPOSITIONS

It is useful at this stage to consider some preliminary candidates for new recycling-friendly automotive alloys based on potential pre-sorting plans and what is known already from the HVSC data and other sources.[2] It is important to recognize that this information is speculation based upon presumed representative alloy mixes, and this subject needs to be revised when better mass balances are performed and the efficacy of the presorting techniques is proven.

Also, it is appropriate to emphasize that these discussions are focused on recycled components from vehicles recovered after their driven life; there is no question that in-plant scrap of all of these alloys can be collected, recycled, and reused directly, subject only to possible contamination from handling equipment.

Body Sheet Alloys

Based on the information in Table I, a potential remelt mix from body sheet components remelted as a group would be something like the recycled body sheet (RCBS) alloy mix shown in Table III. The RCBS mix composition may be useful as a body sheet composition and would likely respond to solution heat treating and aging. The iron and copper levels would not be a serious problem, given the performance of 6111. This composition may justify performance evaluation.

A more favorable condition would exist, of course, if the body sheet components of different alloy types (i.e., 2xxx, 5xxx, and 6xxx series) could be presorted with portable spectrometric devices, leading to three potential compositions, RCBS2xxx, RCBS5xxx, and RCBS6xxx, as shown in Table III, and assuming some mixture with other alloys of the same series.

Not surprisingly, these compositions would all likely be recyclable into essentially the same alloys, although perhaps with higher impurity levels in some cases.

Structural Elements

Some structural elements, like the automotive seat backs and tracks, would likely be extruded 6061 or 6063 shapes and thus be readily recognizable for whatever presorting seems practical. The main structural frames of some vehicles would also likely be these 6xxx alloys, but it is unlikely that the frames could be incorporated into a disassembly program before general shredding.

Assuming some pre-shred dismantling of extruded shapes could be done, a potentially rather useful remelt composition would result, something like RCSE6xxx (Table III). This type of composition would seem to be directly reusable for extrusions with properties intermediate to those of 6005 and 6063, and impurity levels would seem to be adequately under control. An interesting sidelight is that this composition might also be reusable with recycled 6xxx body sheet panels for either body sheet or extruded components.

Bumpers

There should be little problem presorting bumpers, and the likely remelt composition could look something like RCB7xxx (Table III). Obviously this composition is very similar to the original bumper 7xxx bumper alloys and could be directly reused as bumper components.

Cast Parts

With the exception of wheels, most of which are A356.0-T6-type, the variety of castings potentially involved elsewhere in automobiles (e.g., for internal automotive motor housings and supports) is large enough that even with presorting of cast from wrought components, their reuse is perhaps the largest challenge. However, casting compositions are also typically the most tolerant of impurities, and so there is a helpful trade-off.

Speculating from the alloy list in Table I, the remelt composition from presorted casting might look something like RCCP3xx.x (Table III). This composition is amazingly close to commercial alloys such as 328.0, which are heat treatable and have reasonably good strengths and casting characteristics. Thus, for this casting mix the reuse potential for remelted automotive castings back into cast parts seems very high.

Obviously, the results will differ with other mixes, and the importance of mass balances based on castings used in older vehicles will be useful in identifying reuse opportunities. This is important because historically (and therefore likely in the early years of auto recycling) the total aluminum used in vehicles was about 75–85% castings.

UNIALLOYS

An approach that commonly comes up when automotive aluminum component recycling is discussed is the possibility of developing one or two “unialloys,” alloys that meet all of the requirements for a large number of automotive components.

This has proven difficult because of the diverging performance requirements of different automotive 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 use of two different alloy types (e.g., 6111 heat treated for high outer panel dent resistance and 5754 annealed for maximum formability for inner panels). Some progress is being made in this matter, as companies like Toyota use alloy 6022 for both inner and outer body components, but the impact of this concept on the challenge of recycling aluminum components will be long-term and likely more evolutionary than revolutionary.

CONCLUSIONS

The advantages of maximizing the opportunities for the direct reuse of remelted aluminum components from recycled automobiles are very clear in reducing the amount of post-processing required and shortening the recycle/reuse loop. From the foregoing discussion, one can conclude that for optimized reuse of wrought and cast aluminum alloys from recycled vehicles, there is much to gain by adopting a disassembly and presorting technique that provides separate alloy and/or component metal pools. Other commercial priorities may make this impractical, but it will maximize the achievable gains of recycling aluminum alloys in vehicles. Also, if disassembly and presorting is adopted, the compositions likely to result from these pools are highly likely to be reusable as existing or modestly modified new aluminum alloys. And finally, some compositions that are likely to result from remelting presorted components differ from existing alloys, but may be completely adequate in terms of performance for reuse in similar applications. Once such compositions are better known from the mass balances performed as recommended here, the potential of these remelt compositions should be experimentally evaluated.

To capitalize on this opportunity, mass balances should be performed based on the historical studies of aluminum content in automotive vehicles, such as the Ducker reports,[16] to better identify the likely potential metal pools resulting from various disassembly and presorting plans. In addition, new alloy compositions found from the mass balance to likely result from recycling various presorted components should be evaluated experimentally to assess their suitability for direct reuse.

One can conclude that for optimized reuse of wrought and cast aluminum alloys from recycled vehicles, there is much to gain by adopting a disassembly and presorting technique that provides separate alloy and/or component metal pools.

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