

# Formability Evaluation of Recycle-Friendly Automotive Aluminum Alloys

Subodh K. Das, Weimin Yin, Xiyu Wen, Yansheng Liu and Shridas Ningileri  
Secat, Inc.

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## ABSTRACT

Aluminum consumption in automotive applications has maintained consistent growth in the past 30 years and is expected to continue to climb to meet the growing demand for more energy-efficient vehicles. Recycling post-consumer aluminum to build new vehicles will further reduce manufacturing life-cycle energy consumption and emissions leading to significantly lower production costs. To take full advantage of recycling automotive aluminum alloys, a guideline for the recycling practice and design of recycle-friendly alloys such as cost benefits is needed, while meeting the property requirements. Formability is one of critical properties for aluminum vehicle body panels and strongly depends on alloy composition and processing. The forming limit curve (FLC) offers the opportunity to determine process limitations in sheet metal forming and is used in the estimation of the stamping characteristics of sheet metal materials. The comparison of deformations on stamped metal sheets with the FLC leads to a security estimation of the stamping process. Numerical analysis has also been applied to simulate the forming process of automotive parts and to predict the forming behavior of aluminum alloys. A combination of numerical analysis and the FLC comparison can serve as a good guideline to optimize the recycling process and alloy compositions of automotive aluminum alloys.

## INTRODUCTION

Aluminum has made great strides in taking a portion of the automotive spotlight from steel, especially considering its relatively recent entry into the automotive industry.<sup>1-4</sup> A recent global study by Ducker Research Company on aluminum content in light vehicles showed that the aluminum content has maintained consistent, uninterrupted, annual growth for the last 30 years.<sup>3</sup> The use of automotive aluminum quadrupled between 1991 and 2005.<sup>3</sup> It is expected to continue to climb at a rate of approximately 3.6–4.5 kg/vehicle for the near future.<sup>2</sup>

Annual global vehicle production is expected to increase by 11 million to reach 67.8 million in 2009<sup>3</sup>; with a 3% annual growth rate, aluminum consumption could be even greater in this industry.

The rise in energy costs and the need for emissions reduction worldwide make aluminum more attractive for automotive applications. Aluminum has been used increasingly by the automotive industry to reduce vehicle weight without sacrificing performance and safety. The oil crisis in the 1970s made people aware of the need for fuel-efficient cars, and recent energy price hikes demand speedy action for weight reduction. This further drives the increased use of aluminum, which already has been applied in a variety of parts, including the engine, body, hood, and front end.

The Ducker report<sup>3</sup> stated that 61.9% of North American-built passenger car and light truck aluminum content is castings for components such as engine blocks, cylinder heads, and manifolds. Another 12.9% of the aluminum content is in the form of foil, largely for heat exchangers such as the radiator. The remaining aluminum applications include wheels (15.7%), exterior trim and interiors (4.6%), chassis and suspensions (2.6%), closure panels (1.2%, mostly hoods), body structures (0.7%), and bumper systems (0.4%).

Further increase in aluminum content will rely more on the development of aluminum alloys for automotive body panel applications. Although aluminum alloys exhibit many advantages compared to steel their formability and production cost pose challenges to both the aluminum and automotive industries. As the volume of recycled aluminum coming back into the metal stream increases, some new demands are placed upon the science of alloy development to optimize the utility and cost-effectiveness of the reuse of the recycled metal. Developing recycle-friendly alloys is essential in building sustainable automotive and aluminum fabrication industries.

So far, the identification of recycling-friendly new alloys has received little attention and, in fact, is considered impractical by some because of the generally negative effects of impurity elements. However, the potential economic and environmental benefits warrant serious consideration to explore this new approach. This article will review the current status of automotive aluminum recycling and will take an integrated, industry-wide approach to look at formability and chemistry to develop recycling-friendly aluminum alloys for sustainable automotive applications.

## ACCELERATING DRIVING FORCE OF ALUMINUM RECYCLING

Based on the 2002 U.S. Department of Energy report of "U.S. Energy Requirements for Aluminum Production: Historical Perspective, Theoretical Limits and New Opportunities"<sup>5</sup>, aluminum has been referred to as an "energy bank." Once the energy has been invested in it through the smelting process, it can be effectively drawn upon again through recycling. It requires 45 kWh to produce 1 kg of primary aluminum (produced from ore), whereas the same amount of secondary aluminum produced from recycled metal requires only 2.8 kWh. Primary aluminum production consumes 2% of the worldwide electricity supply, and one-third of the total energy consumption in primary aluminum production comes from coal-generated electricity.

Air pollution from primary aluminum production creates large amounts of gaseous emissions and solid and liquid wastes, such as carbon dioxide and nitrogen oxide. Air toxic emissions and solid wastes can be minimized by environmentally friendly practices such as recycling aluminum scrap, which can reduce 95% of the carbon dioxide emission as well as 95% of the energy consumption compared to mining, refining, and smelting the metal from the original bauxite ore. The elimination of the need to generate additional energy will also result in a reduction of mercury emissions coming from coal combustion at power generation plants.

It is estimated that whereas annual production of primary aluminum from bauxite is 32 million tonnes, there are still 400 million tonnes of the metal in use that will eventually be available for recycling. Today, the secondary aluminum stream is becoming an even more important component of aluminum production and is attractive because of its economic and environmental benefits, which can significantly improve the sustainability of the aluminum fabrication industry.

Utilization of recycled aluminum would not only lower emissions and reduce landfill use, but also represents an untapped economic opportunity that reduces dependence on overseas sources. In the United States, shipments of aluminum in the form of wrought and cast products have increased from 9.5 million tonnes in 1995 to 11.6 million tonnes in 2005, whereas primary aluminum production has

been decreasing from 3.4 million tonnes to 2.5 million tonnes. Although imports have increased, secondary aluminum has become a more important component of metal supply. Secondary aluminum benefits the aluminum fabrication industry by using low-cost, recycled aluminum instead of expensive primary aluminum. To survive in this competitive market of high energy and raw material costs and relatively low prices for finished goods, aluminum producers must minimize conversion costs while maximizing the recoverable metal units.

## GROWING OPPORTUNITY IN AUTOMOTIVE ALUMINUM RECYCLING

The transportation area is now the biggest market for aluminum, and the scrap generated from used automobiles now exceeds that from the recycling of beverage cans. Specifically, according to the Aluminum Statistical Report<sup>1</sup>, the transportation market sector consumes 3,939,543 tonnes or 33.9% of the U.S. and Canadian production (statistics are now jointly published). During the period 2001–2005, the annual growth of aluminum in this market was 5.4%.

The use of aluminum in passenger cars<sup>3</sup> is on the increase with the use in both trucks and buses and in trailers and semi-trailers significantly increased. For instance, the annual growth rate for the period 2001–2005 for passenger cars, trucks and buses, and trailers and semi-trailers was 2.8%, 11.0% and 14.7%, respectively<sup>1</sup>. All this growth is driven by the need to reduce weight, increase fuel efficiency, and enhance safety.

The recovery of material from vehicles at the end of their useful lives (assumed to be 15–18 years) has been accelerated by the advent of the industrial shredder and by the activities of companies like Huron Valley Steel Corporation (HVSC). Gesing and coworkers at HVSC have developed several sorting procedures<sup>6,7</sup> and now commercially market a wrought alloy-cast alloy separation and a 3105 alloy mix. HVSC has also demonstrated that the laser-induced breakdown spectroscopy (LIBS) tool is a powerful technology for alloy identification and separation, which can, in fact, separate material on an alloy-by-alloy basis, although this is not yet commercially viable. So, the recycling potential from the automotive sector is enormous. Further, the time scale is not as long as that of buildings and airplanes and is such that a considerable amount of material would be available annually. On the other hand, automotive recycling is very complex because of the large number of alloys being used, the huge potential for alloy incompatibilities, and the fact that dismantling may also confuse alloy identification.

In a Gesing parallel paper, the present authors have explored an ideal automotive recycling scenario.<sup>8</sup> In this ideal situation, all vehicles would be recycled. Vehicles would be subject to a pre-shredding disassembly process where large components of known alloy

composition (e.g., bumpers and engine blocks) would be removed and retained separately for remelting. The remainder of the auto hulk would then be shredded and subject to LIBS sorting into streams that could then be remelted, using the most efficient processes to reduce gross losses and maximize recovery, and directly reused without further purification treatment.

In the real world, however, there is such a large range of alloys used in vehicles that the sorting process is hugely complex. Table 1 summarizes the nominal compositions of representative alloys that would most likely be encountered during recycling vehicles. A comprehensive discussion of all the characteristics and applications of the various alloys series can be found in Reference 8.

It is apparent from an examination of Table 1 that the high content of Zn in the 7xxx alloys is not compatible with other potential recycled alloys. Likewise, the relatively high content of Cu in the 2xxx alloys does not fit with the 3xxx, 5xxx, and 6xxx alloys. Another issue is that the values of Fe and Si generally increase over the longer term from the wear of industrial equipment; as a future issue, the content of Ni and V impurities also are likely to increase as the quality of coke used in primary smelting deteriorates, as is projected.

retained the original original-equipment manufacturer (OEM) components. Accordingly, any sorting of auto components based on an original design specification may be flawed. A third factor relates to the dismantlers and the after-market trading that precedes shredding of the hulk. Specific parts and components can be stripped and traded or resold. All these activities are driven by opportunities for resale, with little consideration of alloy composition. 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 Cu” or “high Zn,” which do not necessarily correspond to the Aluminum Association specifications of a specific alloy series. Finally, often the dismantlers and recycling companies operate using internal proprietary specifications that can be different from the conventional Aluminum Association alloy series.

For all the above reasons, the separation, sorting, and recycling of automotive alloys is complex. A more extensive disassembly and presorting are required at the dismantlers to ensure a better batching of material before remelting.

Table 1. Nominal Compositions (%) and Impurity Limits of Representative Automobile Components<sup>7,8</sup>.

| Parts               | Alloy  | Al  | Si    | Fe    | Cu    | Mn    | Mg    | Cr    | Zn    | Ti    |
|---------------------|--------|-----|-------|-------|-------|-------|-------|-------|-------|-------|
| Body Panels         | 5182   | ~94 | 0.20* | 0.35* | 0.15* | 0.50* | 4.5   | 0.10* | 0.25* | 0.10* |
|                     | 5754   | ~95 | 0.40* | 0.40* | 0.10* | 0.40* | 3.1   | 0.30* | 0.20* | 0.15* |
|                     | 2010   | ~96 | 0.50* | 0.50* | 1.0   | 0.25  | 0.70  | 0.15* | 0.30* | 0.05* |
|                     | 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 | 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.

The complexity of sorting and recycling all the alloys currently used in automotive applications is further compounded by several additional factors. First, the operation of the industrial shredders is dominated by the greater economic need to produce uniform steel scrap, and the collection of non-ferrous 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 such as the wheels, and in so doing modify the recycling process; there are numerous types of wheels (e.g., cast or forged wheels) with different alloy compositions so there is no guarantee that a vehicle at end of life has

## NEW PARADIGM IN AUTOMOTIVE ALUMINUM DEVELOPMENT

Tighter demands on material properties have led to an increased use of select alloying elements in controlled amounts and to a lowered tolerance of impurities in alloys. However, the stigma that impurities are always detrimental is not necessarily true. It is necessary to understand how a broader variety and a less strictly controlled amount of alloying elements will change these alloys.