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Formability Evaluation of Recycle-Friendly Automotive Aluminum Alloys

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

Secat, Inc.

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.[1–4] 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.[3] The use of automotive aluminum quadrupled between 1991 and 2005.[3] It is expected to continue to climb at a rate of approximately 3.6–4.5 kg/vehicle for the near future.[2] Annual global vehicle production is expected to increase by 11 million to reach 67.8 million in 2009[3]; 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[3] 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" [5], 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[1], 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[3] 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[1]. 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[6,7] 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.[8] 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 dross 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.

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 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[7,8].

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*	010*	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.

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.

Another approach is to revisit the idea of developing some single versatile “unialloy” to better fit the likely recycled metal stream compositions for a large number of automotive components. Thus, the scrap stream could be simplified. This has previously proven difficult to achieve because of the diverging performance requirements of different automotive applications. Even within body panels, for example, the differing requirements for dent resistance in outer panels and optimized formability for inner panels continue 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 direction, but the impact of this concept on the challenge of recycling aluminum components will be long-term and evolutionary, not revolutionary.

CASE STUDY – FORMABILITY EVALUATION

Formability is one of critical properties for aluminum body panels and strongly depends on alloy composition and processing[10-12]. The forming limit in the sheet metal forming process is often set by the occurrence of necking, which leads to a local thinning of the sheet and possible further failure. Therefore, evaluation of the formability of sheet metal is required for the design of automotive parts and their manufacturing process.

TESTING METHOD— FORMING LIMIT DIAGRAM

The forming limit diagram has proven to be successful for a description of the phenomena. Figure 1 is a representative forming limit diagram with the two principal in-plane strains, major and minor strains, being plotted. The stretching of circumferentially clamped specimens to failure was employed over a hemispherical punch using a Tinius Olsen BUP. ASTM E2218-02 Standard Test Method for Determining Forming Limit Curves was adopted in the laboratory. Sheet samples with a width of 20–110 mm and different lubricants were used for different strain paths. Grids can be printed on the surface of the samples by electrochemical etching. After forming the parts, the strain near the necked or fractured area of each part was measured using Automated Strain Analysis and Measurement Environment (ASAME) to form a forming limit diagram.

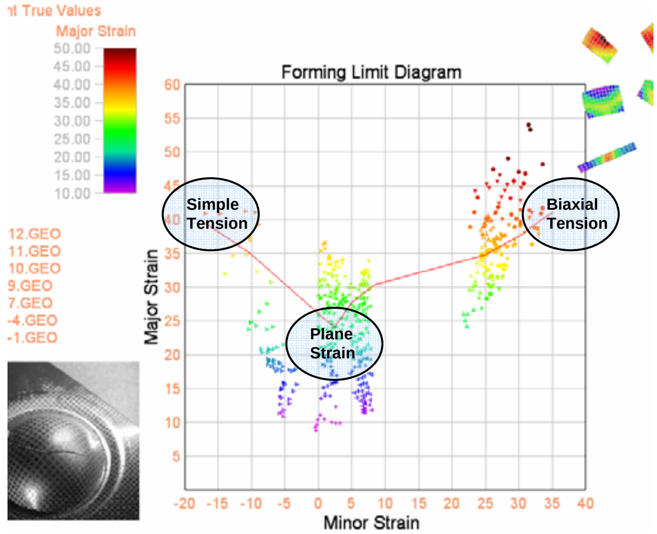


Fig. 1. Representative forming limit diagram.

The combinations of major and minor strains at the necking grids can be marked, and a curve can be created by these points. Below the curve, the deformation is uniform during stamping and becomes unstable above the curve; thus it is called a forming limit curve (FLC). The FLC (Figure 1) shows a “V” shape with the lowest major strain at plane strain condition.

The FLC is determined by the ability to distribute plastic deformation, i.e., the work hardening characteristics of the material. Thus the forming limit diagram is expanded with increasing work hardening coefficient and is also influenced by material thickness. The major metallurgical factors that affect the formability can be summarized as follows:

- Ductility: controlled by stress state, temperature, and inclusion level.
- Work hardening: controlled by temperature, solutes, and microstructure.
- Strength level: controlled by composition, grain size, solutes, and precipitates.
- Anisotropy: controlled by thermal-mechanical process and microstructure.
- Surface properties: controlled by oxide films, lubricants, and microstructure.

The FLC offers the chance to determine process limitations in sheet metal forming and is used to estimate 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.

REPRESENTATIVE ALLOYS

As shown in Table 1, aluminum alloys for automotive body panel applications could be divided into three categories: low alloying-Mg (6022); high alloying-Mg (5754 and 5182); and high alloying-CuMg sheet metals. To simplify the scrap stream, the first two categories appear to be better choice. Four aluminum sheets (Table 2) have been selected from the first two categories for formability evaluation.

Table 2. Four Aluminum Sheet Alloys Selected for Formability Evaluation.

Sheet	Alloy	Comments
#1	6022	Low alloying - Base alloy
#2	6022	Low alloying - Elevated Fe
#3	5182	High alloying - Base alloy
#4	5182	High alloying - Elevated Mn

The formability evaluation focuses on the effect of chemical composition variation in aluminum alloys (Table 2). As the scrap returns to the main stream of aluminum supply, the impurities such as Fe content will gradually increase based on the scrap mix with the cycles because of the contamination during the recycling process. The Fe content in #2 sheet metal was intentionally increased based on #1 alloy in order to investigate the effect of Fe elevation on the formability. Two 5182 alloys (#3 and #4) were also evaluated to determine the dependence of formability behavior on a small variation of Mn content.

TENSILE ANISOTROPIC PLASTIC BEHAVIOR

The results of tensile tests are of particular value for sheet metal forming operation. To study anisotropic behavior, specimens were taken from each sheet in three directions: rolling direction (0°), 45° to rolling direction, and transverse direction (90°).

The tensile properties were tested using calibrated Material Test System MTS 810 using calibrated transverse and axial extensometers (50-mm gauge length). A 25000 N load cell was used in the 0–2500 N calibration range. The cross-head speed was kept constant at 2.5 mm/min throughout the test. The work hardening exponent (n value) was calculated from the beginning of uniform plastic deformation until maximum load. The strain used for the plastic strain ratio (R value) calculation was at the beginning of uniform plastic deformation. The yield strength was at 0.2% offset. The elongation recorded is the plastic elongation until fracture. The tests were performed in accordance with ASTM E 8-04, E 517-00, and E 646-00.

As shown in Figure 2a, the elevation of Fe does not have a significant effect on tensile strength and yield strength, whereas the strength at 45° decreases slightly. The elongation of #2 sheet (higher Fe) at the rolling direction is almost the same as the #1 sheet, although a small difference is observed at 90°.

Figure 2b indicates that elevated Fe enhances anisotropy parameters R at 90° whereas it reduces R value at 0° and 45°. Therefore, the elevation of Fe lowers the directional variation while it keeps the average plastic anisotropy unchanged. The work hardening exponent n is slightly increased in the #2 sheet with elevated Fe.

The sheet with slightly more Mn displays higher tensile strength and yield strength at three different orientations in Figure 3a. The elongation of #4 sheet (higher Mn) at the rolling direction is almost the same as the #3 sheet, although a small difference is observed at 90°. Figure 3b indicates that elevated Mn barely affects anisotropy parameters R or work hardening exponent n.

Strain hardening and plastic anisotropy determine the distribution and uniformity of strain. A high strain hardening exponent is generally favorable, because it means that deformation will distribute more evenly on the sheet. The role of anisotropy is more complicated. Normally, a large average R value and small directional variation will be beneficial for a stamping operation.

FORMING LIMIT MEASUREMENTS

Figure 4 shows the comparison of FLCs in four different sheet metals obtained at the punch speed of ~ 5mm/min. WD-40, plastic film, and a combination were utilized for better lubrication to realize high major/minor strain without fracturing or necking.

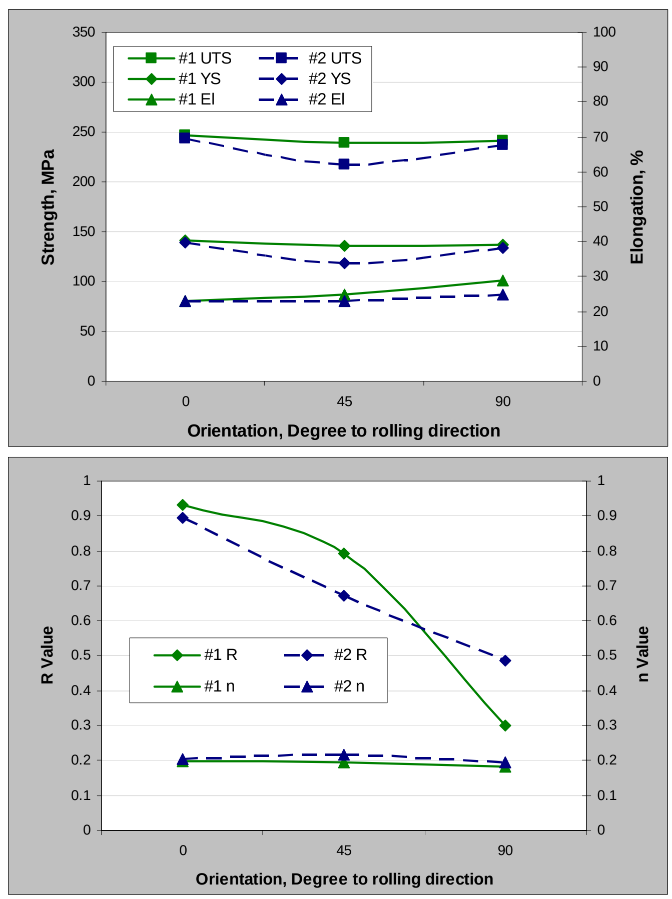


Fig. 2. Effect of Fe on tensile plastic behavior showing (a) strength and ductility and (b) anisotropy and work hardening.

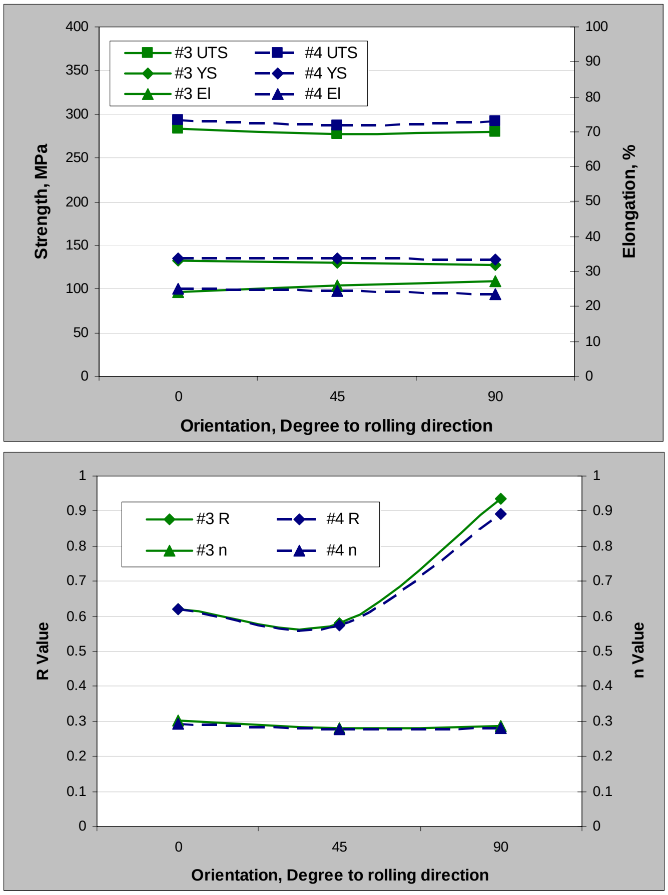


Fig. 3. Effect of Mn on tensile plastic behavior showing (a) strength and ductility and (b) anisotropy and work hardening.

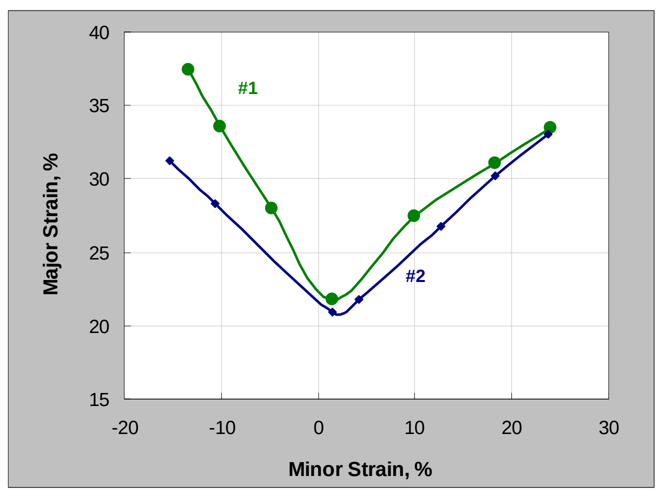
The forming limit curve of #2 sheet shifts down as compared to #1 sheet (Figure 4a). This suggests that the elevation of Fe in 6022 alloy leads to the deterioration of formability. The result is not encouraging, but also not surprising because Fe has been considered as one of harmful impurities to formability in aluminum alloys.

However, this detrimental effect of Fe on the formability of 6022 alloy is not observed for 5017 alloy based on a report by Sillekens, W. H. and Sano, T. [10] In this report, a certain amount of Fe up to 1.4% did not cause the decline of formability in recycled aluminum alloy 5017. This study was carried out to develop a unialloy for beverage can application, which is of particular interest for closed-loop recycling (i.e., using the reclaimed materials to replace primary aluminum and fresh alloying elements). Reclamation of used beverage cans either involves alloy separation or the production of a mixed composition. Thus, the alloying elements Mg and Mn in 5017 alloy are intermediate to accommodate the composition of can lid and can body. An expected increase in Fe content is adopted with double and triple the normal content (0.45%) in can body alloy[9]. The supposition that the formability of the material would deteriorate with an increasing amount of Fe was not confirmed in the study. The alloy with a double content of Fe (0.94%) showed higher formability at simple tension condition, and the alloy with a triple content of Fe (1.4%) displayed better formability at plane strain condition. The alloy with normal content Fe (0.45%) exceeded in formability for biaxial tension condition. This study on the effect of Fe on formability of 5017 alloy is very encouraging and suggests the development of alloys less sensitive to the amount of impurities such as Fe. This will be beneficial for recycling aluminum alloys in a long run, and thus is recycle-friendly.

Figure 4b shows the comparison of FLCs in 5182 alloy with a varying Mn content. Formability at plane strain condition does not change. A slight shifting of the curves is noticed in #3 base alloy from #4 alloy with higher Mn content. The formability decreased slightly in the drawing condition (the left part of the curve with tension in the major strain direction and compression in the minor strain direction), whereas it improves for the stretching condition (right part of the curve with tension in both directions). This suggests that the alloy would have a good tolerance for a small variation of Mn content.

NUMERICAL SIMULATION

Formability of an automotive part (vehicle fender) was assessed using the numerical method and compared with the measured FLC, as shown in Figure 5. The stamping was run at room temperature with a load of 50 tonnes.



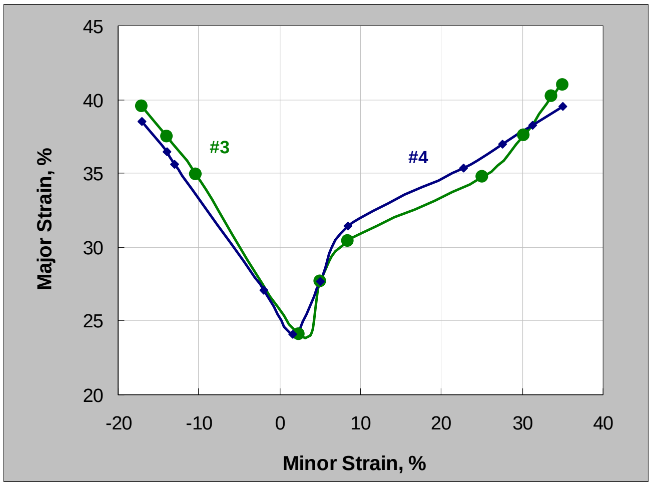
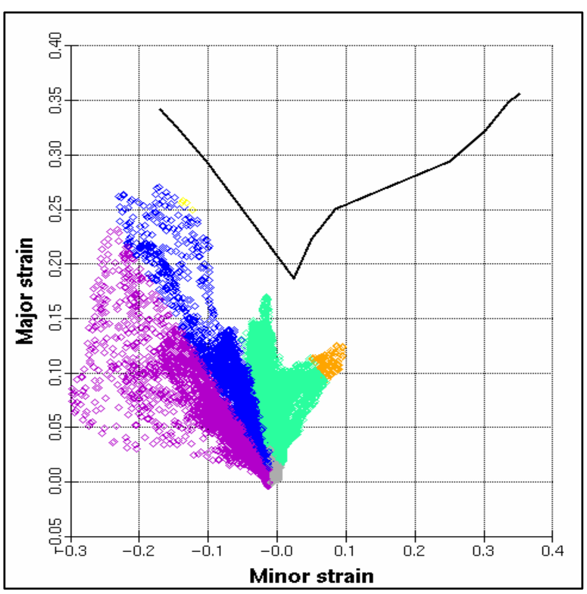


Fig. 4. Forming limit diagrams showing (a) the effect of Fe and (b) the effect of Mn.

The simulation of the stamping process of the vehicle fender shows that the deformation of the aluminum sheet mainly is in the deep drawing condition. In both #3 and #4 sheet metals, the FLCs are well above the deformation caused by the stamping process; thus both aluminum sheets are safe for manufacturing of the vehicle fender.

Further analysis on maximum thinning, maximum thickening, and maximum strain was performed for extra safety evaluation. The maximum thinning of sheet #3 and sheet #4 is 18.3% and 20.3%, respectively. The thinning occurs near the corner of the fender. With the limit of maximum thinning, sheet #3 will be safer for this application. However, maximum thickening and maximum plastic strain in #3 sheet are larger than those in #4 sheet. Careful consideration is needed for all the technical requirements.



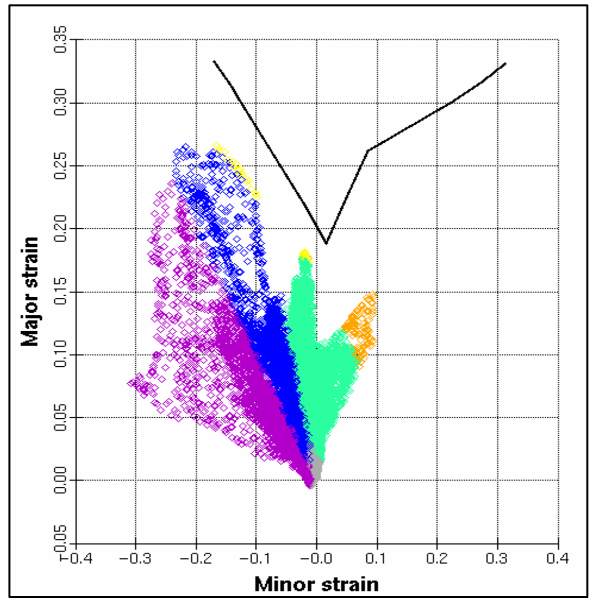


Fig. 5. Formability assessment of an automotive part with (a) #3 sheet and (b) #4 sheet.

CONCLUSION

Formability is a critical consideration for selecting a suitable alloy for automotive body applications. The sustainability of aluminum and automotive industries demands recycle-friendly aluminum alloys, which tend to have a higher tolerance of impurities and variation of alloying elements.

The current formability evaluation focuses on the effect of chemical compositions in aluminum alloys, including the impurity Fe, which will gradually increase with the reclamations because of the contamination during the recycling process. Two 5182 alloys were also evaluated to determine the dependence of formability behavior on a small variation of Mn content because the fluctuation of the alloying element Mn may happen due to the resource of recycled materials.

Formability deteriorates with an Fe content increase. The alloying element Mn improves the formability in biaxial tension condition, whereas it reduces the formability in simple tension condition.

Numerical simulation has also been applied to the stamping process of a vehicle fender to predict the forming behavior of aluminum alloys. The simulation results show that the aluminum alloys are safe for manufacturing the vehicle fender, with caution on maximum thinning in the alloy with higher Mn content and maximum plastic strain in the base alloy. A combination of numerical analysis and the comparison with the FLCs can serve as a good guideline to optimize the recycling process and alloy compositions of automotive aluminum alloys.

Further efforts are needed to develop recycle-friendly alloys with higher tolerance of impurities and fluctuation of alloying elements. Advanced manufacturing techniques, such as better lubrication and warm forming, may be necessary for using recycle-friendly alloys in the future.

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CONTACT

Subodh K. Das is the president and chief executive officer of Secat, 1505 Bull Lea Road, Lexington KY 40511. He is also director for the Center for Aluminum Technology, executive director for the Sloan Industry Center for a Sustainable Aluminum Industry, and adjunct professor of mechanical engineering and chemical & materials engineering at the University of Kentucky. Dr. Das can be reached at (859) 514-4989; fax (859) 514-4988; e-mail: sdas@secat.net.