Light Metals 2015

ALUMINUM ALLOYS: DEVELOPMENT, CHARACTERIZATION AND APPLICATIONS

Development and Applications

SESSION CHAIR

Zhengdong Long
Kaiser Aluminum
Spokane, WA, USA

Light Metals 2015
Edited by: Margaret Hyland
TMS (The Minerals, Metals & Materials Society), 2015

Process Development for Stamping A-Pillar Covers with Aluminum

Jung Pyung Choi, Aashish Rohatgi, Mark T. Smith, and Curt A. Lavender
Pacific Northwest National Laboratory, 902 Battelle Boulevard, Richland, WA 99352, USA

Keywords: Aluminum, class-8 truck, A-pillar cover, lightweighting, hot-forming, paint-bake

Abstract

In this work, performed in close collaboration with PACCAR and Magna International (Stronach Centre for Innovation, SCFI), a 6xxx series aluminum alloy was used for the development of an A-pillar cover for the cab of a typical heavy-duty Class-8 truck. The use of Al alloy for the A-pillar cover represents an approximately 40% weight savings over its steel or molded fiberglass composite counterpart. For the selected Al alloy, a small amount of cold work (5% tensile strain), following prior hot-forming, was found to significantly improve the subsequent age-hardening response. The role of solutionizing temperature and rate of cooling on the age-hardening response after paint-bake treatment were investigated. For the temperature range selected in this work, higher solutionizing temperature correlated with greater subsequent age-hardening and vice-versa. However, the age-hardening response was insensitive to the mode of cooling (water quench vs. air cooling). Finally, a two-step forming process was developed where, in the first step, the blank was heated to solutionizing temperature, quenched, and then partially formed at room temperature. For the second step, the pre-form was re-heated and quenched as in the first step, and the forming was completed at room temperature. The resulting A-pillars had sufficient residual ductility to be compatible with hemming and riveting operations that occur during downstream cab assembly.

Introduction

The U.S. government regulations mandate that the automotive companies reduce vehicle exhaust emissions, improve occupant safety, and enhance fuel economy. Recent government and industry funded research efforts have focused on designing components using light-weight alloys, such as those of aluminum and magnesium, to simultaneously achieve the above objectives. Similar lightweighting efforts are underway for heavy-duty vehicles as well for potential benefits in increased freight efficiency and reduced fuel consumption.

Determining the right alloy for the body structure and hang-on panels has been the subject of considerable development effort [1]. For skin sheet materials such as A-pillar covers, the emphasis is on achieving a good balance of formability, strength after the paint-bake, and a high surface quality after the painting operation. Consequently, the age-hardenable 6xxxAl alloys with good paint-bake response are the primary choice for these applications [2].

The objective of this project was to demonstrate manufacturing of Al components, as a lightweight alternative to steel and molded fiber reinforced glass composite panels and components, for applications in Class 8 trucks. If successful, the use of Al components has the potential for weight savings of ~40% for applications in Class 8 trucks. However, current 6xxx series Al sheet alloys lack sufficient formability to allow their use in the manufacture of many aerodynamic cab components and structures. Current automotive grade 6xxx-series Al alloys are limited to the equivalent of 18-20% tensile elongation at room temperature whereas an equivalent elongation of over 40% is needed for some of the applications/components being addressed in this work. Another limitation in the widespread use of Al for truck components is the poor post-formed tensile properties (typically < 100 MPa yield) after hot forming processes. Thus, applications requiring higher post-formed strength for long-term fatigue and dent resistance are not suitable for such hot-formed Al components. Moreover, post-formed parts need to retain sufficient room-temperature ductility to ensure that they can be assembled with the rest of the structure via riveting and hemming operations. Therefore, there is a need to develop a manufacturing process that can achieve the required formability and the post-formed mechanical properties in Al alloys.

This paper will describe hot/cold forming process development at PNNL to fabricate A-pillar covers out of a 6xxx Al alloy. Mechanical property characterization and electrical conductivity measurements on the formed A-pillar covers is also described. The Al alloy used in this work was developed by Novelis, for PACCAR's Class-8 trucks while the final prototype parts, using PNNL's processing routes, were fabricated at Magna International-SCFI.

Experimental

A 6xxx series Al alloy, specifically developed for PACCAR cab structure applications, was provided by Novelis with the designation X608. The objective was to form an A-pillar cover using a 1.27 mm thick alloy sheet. Two sets of preliminary tests were done before the final production of the prototype A-pillar cover.

In the first set of tests, the as-received material (T4 condition) was subjected to a simulated paint-bake heat-treatment (180°C-20 minutes) with/without cold-forming to 5% tensile strain. The as-received and paint-baked samples were tested in quasi-static tension to determine the baseline properties of the alloy.

In the second set of tests, a series of hot forming experiments were conducted in a three-dimensional prototype tray die design (Fig. 1) to evaluate different forming temperatures and post-forming cooling steps. Hot forming was done at either 500 or 540°C with post-form cooling obtained by forced air or water quenching. All the formed samples were cold formed to 5% strain and then paint-baked (180°C-20 minutes).

The final prototypes of the A-pillar cover were fabricated by Magna International-SCFI. A two-step forming process was used where, in the first step, the blank was heated to solutionizing temperature (525°C), quenched, and partially formed at room temperature. For the second step, the pre-form was re-heated and quenched as in the first step with the final forming being completed at room temperature. Some as-formed A-pillar covers were subjected to the paint-bake treatment (180°C-20 minutes).

The uniformity of thickness of the A-pillar covers was measured using an Olympus Panametrics 37DL PLUS with D79X series dual element transducer that was re-calibrated with a standard after every 10 measurements. Samples, extracted from both as-formed and paint-baked pillars, were characterized by quasi-static tension tests, hardness tests (Rockwell, H-scale) and eddy-current electrical conductivity testing. The electrical conductivity measurements were performed using an Olympus Nortec 500D eddy current system with a 0.75" diameter probe and 60 kHz frequency. The measured values were considered to be accurate within ±0.5% International Annealed Copper Standard (IACS).

Result and Discussion

Baseline tests

The baseline tensile properties of the Al alloy, determined from the first set of experiments, are shown in Table I. The data in Table I show that the as-received T4 material (solution heat-treated) has the lowest yield and ultimate tensile strength. Subjecting the as-received material to paint-bake increases its yield strength and UTS due to precipitate hardening by ~36% and 14%, respectively, with only a minor reduction in elongation. If the as-received material is pre-strained to 5% *prior* to paint-bake, the post-paint-bake yield strength and UTS increase by additional 25% and ~5%, respectively, beyond the values achieved without the 5% pre-strain. The total elongation is also greater with 5% pre-strain than without the pre-strain. The greater strength and ductility in the 5% pre-strained + paint-baked samples, relative to the paint-baked sample without the pre-strain, can be explained by the effectiveness of the dislocations (generated during 5% pre-strain) in increasing the kinetics of precipitation during paint-bake. The 6xxx alloy tested here is a "compositionally lean" alloy and hence, the small amount of cold-work before paint-bake demonstrated its significance in enhancing the strength and ductility in this alloy.

Prototype Tray Tests

Forming trials were done on a prototype tray to simulate the 3D geometry of the A-pillar cover and the temperatures anticipated during the final stamping process. Hot forming at temperatures above 500°C enabled the Al alloy to achieve the required level of formability. Fig. 2 shows the bottom view of the hot-formed tray and the final tray after the room-temperature forming step. As seen in Fig. 2, the prototype tray showed significant draw-in which was primarily due to the limitation of the forming equipment's ability to apply binder force to the sheet along the length. The resulting plastic deformation, as determined from thickness measurement, was found to be in the 5 to 15 percent range depending on the location in the tray. Table II shows tensile test results for the samples machined from the flat bottom of the trays that were formed using different combinations of hot-forming temperatures and the cooling method, followed by room-temperature forming and paint-bake heat-treatment.

Table I. Baseline 6xxx Novelis Al alloy sheet tensile properties (average of minimum three test specimens).

Condition	0.2% Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)
AR	135	228	23.6
AR+PB	184	260	21.2
AR+5% CF+PB	230	274	27.1

*AR: As received (T4); PB: Paint bake (180°C for 20 minutes); CF: Cold forming (room-temperature)

Table II. Tensile test results for hot/RT-formed tray materials (average of four tests, using ASTM sub-size specimen geometry).

Forming Conditions	0.2% Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)
HF 500°C/AC+CF+PB	119.7	210.3	22.9
HF 500°C/WQ+CF+PB	121.4	211.2	22.8
HF 540°C/AC+CF+PB	140.8	241.8	22.9
HF 540°C/WQ+CF+PB	144.8	245.0	22.8

*HF: Hot forming; CF: Cold forming; AC: Air cooling; WQ:

The results in Table II show that for a given forming temperature, the mode of cooling (air cooling vs. water quenching) did not affect the mechanical properties. However, increasing the hot-forming temperature from 500°C to 540°C resulted in a ~18% and ~15% increase in the yield strength and UTS, respectively. Such increase in the post-paint-bake strength with increasing hot-forming temperature is likely due to greater concentration of alloying elements being in solution at the higher forming temperature. Thus, during subsequent water quenching/air cooling, a relatively larger concentration of solutes in the metastable solid-solution produced a proportionately larger precipitation strengthening after the paint-bake treatment. It is noted that all the samples demonstrate sufficient tensile ductility (>22% elongation) suitable for downstream riveting and hemming operations.

Final A-pillar Cover Prototype Fabrication

A solid model of the A-pillar cover is shown in Fig. 3. This component is currently manufactured as a sheet molding compound (SMC) part because it cannot be formed from the X608

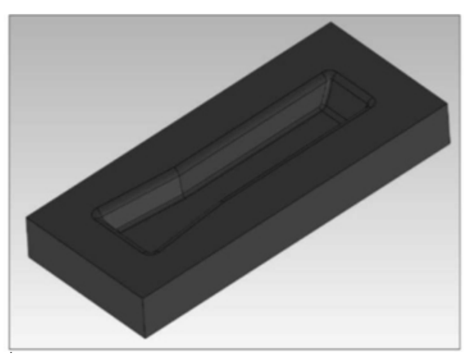


Figure 1. Three-dimensional prototype tray component die design.

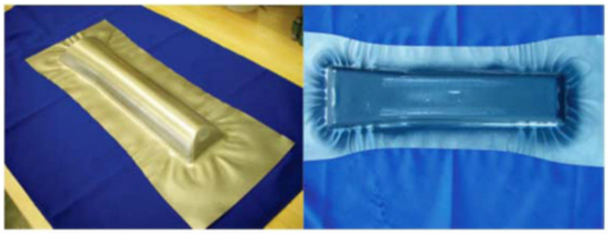


Figure 2. Bottom view of hot formed tray (left) and final formed tray (right) showing sheet draw-in around the perimeter.

Figure 3. Solid model of the A-pillar cover (~650 mm overall component length).

aluminum sheet using conventional room-temperature stamping methods. The SMC component presents a number of drawbacks compared to an Al part, including a 40 percent increase in weight, and is not fully compatible with the series of assembly and finishing operations used in the cab assembly process.

The forming tools were built, and using the results from the baseline tests and the Prototype Tray tests at PNNL, the final fabrication was performed by Magna International-SCFI. The A-pillar covers were fabricated in two steps and Fig. 4 shows pictures of the two-stage forming tools. In the first step, the Al blank was heated to a target temperature of 525°C, water quenched, and then partially formed at room temperature. The preform was re-heated to the 525°C, water quenched, and fully formed in the next room-temperature forming step.

<u>Evaluation of A-pillar Covers</u>

Prototype A-pillar covers, in the as-fabricated state and after

Figure 4. Views of forming tools used to fabricate A-pillar covers.

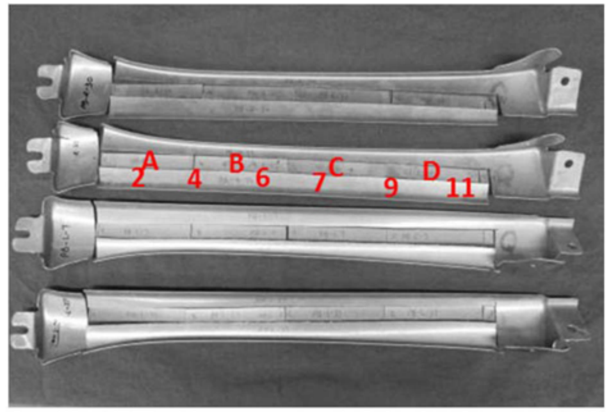


Figure 5. Photograph of several A-pillar covers with cut sections showing the locations where the tensile coupons were obtained from along a cover's length.

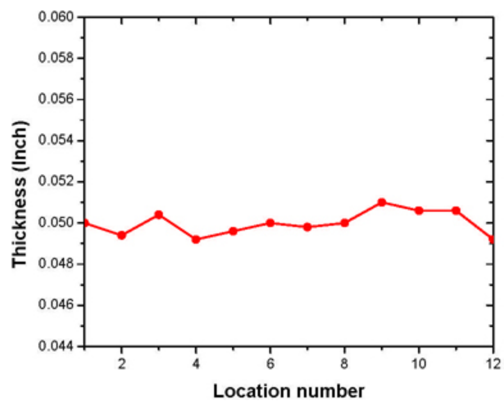


Figure 6. Sheet thickness, measured with an ultrasound gauge, along the length of an A-pillar cover. (0.050" = ~1.27 mm).

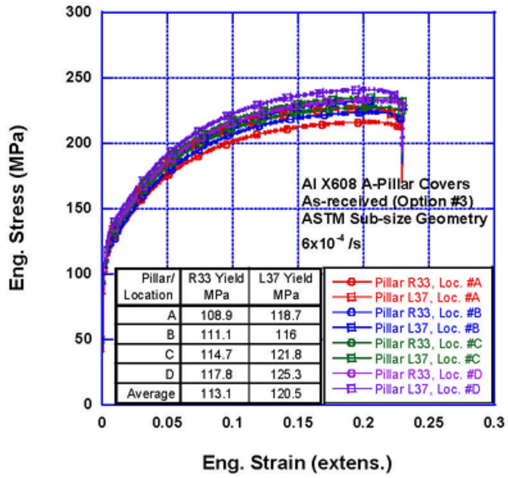
paint-bake treatment (180°C for 20 minutes), were evaluated at PNNL through tensile testing, hardness measurements and electrical conductivity measurements. Measurement locations for the above tests were marked along the A-pillar cover length, as shown in Fig. 5.

Fig. 6 shows the results of thickness measurement along the length of one of the A-pillar covers. As seen in Fig. 6, the average A-pillar cover thickness is ~1.27 mm which is identical to the original sheet thickness thus, implying that the forming was essentially a drawing operation with almost no stretching. As shown below, the thickness of the A-pillar cover is several times greater than the "skin-depth" of the eddy current transducer used here and hence, suitable for evaluation by this technique.

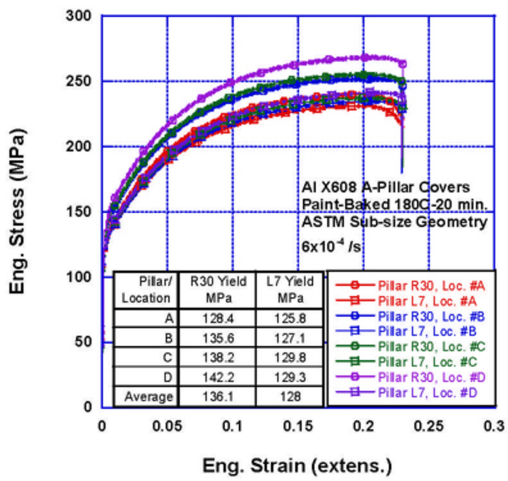
The standard penetration depth (skin depth) is given by Eq. (1)

$$\delta_{std} = \frac{1}{\sqrt{\pi f \mu \sigma}} \qquad (1)$$

where, f is the frequency, μ is the absolute magnetic permeability of the conductor, and σ is the electrical conductivity of the

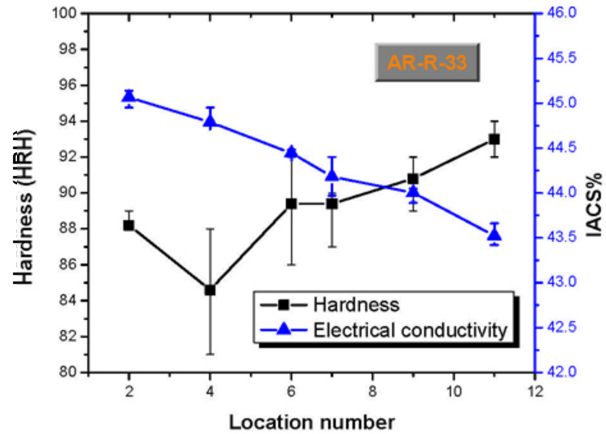


(a)

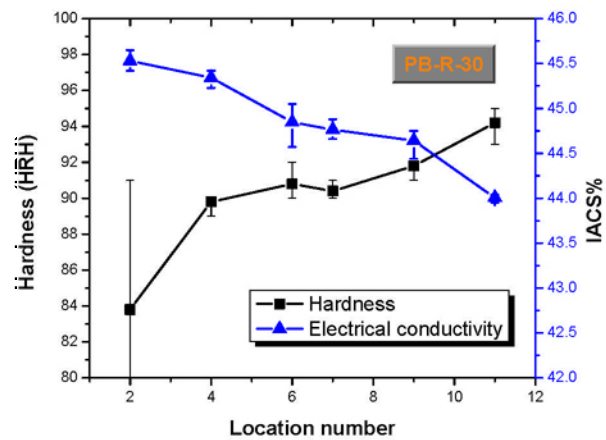


(b)

Figure 7. Quasi-static stress-strain data of A-Pillar covers in the (a) as-received (AR) and (b) paint-baked (PB) conditions.



(a)



(b)

Figure 8. Rockwell hardness and electrical conductivity in an (a) as-received (AR) and (b) paint-baked (PB) A-pillar cover.

material. The absolute magnetic permeability can be obtained from relative permeability data and the permeability of air as:

$$\mu = \mu_0 \times \mu_r \quad (2)$$

From Eq. (1) and Eq. (2), the skin depth of aluminum at 60 kHz is about 0.3 mm (0.012") which is several times lower than the sheet thickness. Hence, potential error in conductivity measurements on account of sheet thickness was not a concern in the current work.

Tensile tests of samples cut from the A-pillar covers are shown in Fig. 7. The failure strain exceeded the physical limits of the extensometer and hence, extensometer strain >23% could not be recorded. As a result, the specimens "appear" to fail abruptly at 23% strain. The plots in Fig. 7 show that the tensile strength of the test coupons increases as one moved along the length of the A-pillar cover (from location #A to #D). Since Fig. 6 shows a uniform thickness along the A-pillar cover's length with almost no plastic strain, the strength variation along the A-pillar cover's length shown in Fig. 7 was unexpected. This variation in the strength along the A-pillar cover's length is likely due to non-uniform heating/thermal gradient during the solutionizing heat-treatment in the furnace. Thus, the location exposed to somewhat higher temperature (location #D) will result in a stronger age-hardening response than the location in the "cooler" part of the heating furnace.

Figure 8 shows the hardness and eddy current conductivity plotted as a function of location on the A-pillar cover. It is seen that the electrical conductivity decreases with increase in hardness along the A-pillar cover's length (e.g. as shown in Fig. 5).

As described above for the variation of tensile strength as a function of location on the A-pillar cover, a similar variation in the hardness along an A-pillar cover's length (as shown in Fig. 8) is attributed to the temperature variations within the furnace during solutionizing heat-treatment. Sheet locations subjected to a higher temperature were likely to have complete dissolution of the solute atoms and result in greater precipitation hardening during subsequent ageing. On the other hand, the locations heated to a lower temperature would be expected to show lower precipitation hardening response on account of incomplete dissolution of solutes.

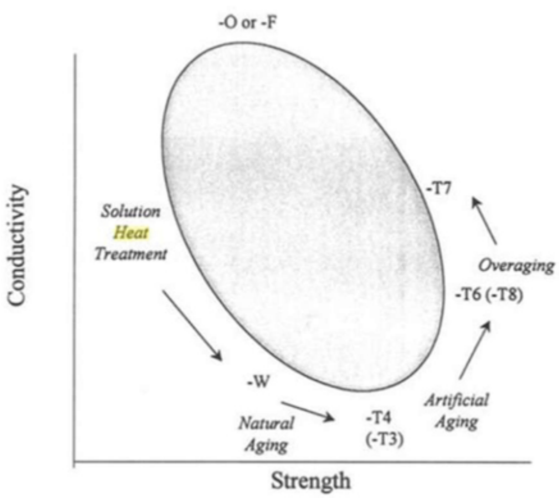


Figure 9. Changes in electrical conductivity and strength with heat treatment [5].

The data in Fig. 8 also shows that an increase in hardness corresponds to a decrease in electrical conductivity in both as-received and paint-baked conditions. The explanation for the trend in electrical conductivity observed in Fig. 8 requires additional work since the hardness-conductivity trend for X608 Al alloy is not available in the literature. Further, existing literature on Al alloys suggests that the hardness-conductivity trend is not linear, as schematically shown in Fig. 9, and may be alloy specific as well. For example, Tariq et al. [3] observed an increase in both conductivity and hardness in AA2014 Al alloy, associated with Guinier-Preston GP zone formation and θ' precipitation during artificial ageing. On the other hand, Wu et al. [4] observed a decrease in conductivity and increase in hardness in AA7050 Al alloy associated with GP zone formation. Moreover, the conductivity-hardness trend changed with further progress of precipitation [4]. Thus, an explanation of the hardness-conductivity trend observed in X608 requires additional work on this alloy with a focus on understanding the relationship between the precipitation sequence, hardness and electrical conductivity.

Conclusions

1. A hot/cold forming process was developed to successfully form A-pillar covers for Class-8 truck's cab using a 6xxx series Al alloy. The resulting A-pillar covers represent ~40% weight savings over those conventionally made by steel or sheet-molding compound.

2. A correct solutionizing temperature for 6xxx Al alloys is essential to maximize the precipitation hardening response following the paint-bake heat-treatment. Thus, higher solutionizing temperature correlates with higher post-paint-bake strength, and vice-versa. However, the paint-bake response was insensitive to the differences in the cooling mode (water quench or air cooling employed in this work).

3. Non-uniformity in the temperature distribution during solutionizing is believed to be the cause for variations in the strength, hardness and electrical conductivity of the A-pillar covers along their length. However, the hardness-electrical conductivity relationship for X608 needs to be determined to clearly understand the post-formed properties.

Acknowledgments

The Pacific Northwest National Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy under contract DE-AC05-76RL01830. This work was sponsored by W. Joost in association with the U.S. Department of Energy, Office of Vehicle Technologies, as part of the Lightweight Materials program. This work was done in collaboration with PACCAR, Magna International-Stronach Center for Innovation and Novelis, and the authors are grateful for the technical discussions and assistance provided by K. Dunn and N. Larson at PACCAR, B. Kokosza & B. Shulkin at Magna International-SCFI and A. Brooks at Novelis. Technical support provided by PNNL staff: E. Stephens, N. Karri, K. Mattlin, M. Dahl, T. Kafentzis and A. Guzman, is acknowledged.

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