# The Latest Trends in Aluminum Alloy Sheets for Automotive Body Panels

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*Automobiles tend to become heavier as the safety and comfort features are improved. On the other hand, the demand for higher fuel efficiency and lower environmental impact is also rising. This has directly influenced the trend toward the weight reduction of automobiles and the increase in applications of light aluminum alloys in automotive body panels. This paper reports on developments and trends in aluminum alloy sheets for automotive body panels.*

## Introduction

Automobiles are becoming heavier in order to satisfy requirements such as safety (e.g., collision safety and pedestrian protection), drivability, comfort and larger interior space. Meanwhile, automobiles have to meet more stringent regulations against exhaust emissions, including $CO_2$ and $NO_X$ emissions, to protect the environment. The European Commission, for example, has announced a policy to reduce $CO_2$ emissions down to 140 g/km or less by 2008 and to 130g/km or less by 2012. Japanese regulations to reduce $CO_2$ emissions will also be tightened to a level comparable to that of the European Commission by 2012. Thus, reducing fuel consumption is now imperative for all the automobile manufacturers.

Various measures are taken to reduce fuel consumption including new power trains involving hybrid systems or advanced diesel engines. Above all, automotive weight reduction is regarded as one of the most effective means for decreasing fuel consumption. One hundred kilograms of weight reduction improves fuel consumption by 1 km/L, according to the Japanese 10-15 mode measurements[1]. Automotive weight reduction has been achieved traditionally by reducing thickness of steel-sheet body panels by increasing the strength of the steels, however, this approach is limited because of the resultant reduction in panel stiffness. For this reason, lighter materials are being studied extensively to replace the steels. Especially, aluminum alloys have started to be used for various automotive parts for its low specific gravity (approximately 1/3 of steel). Now the use of aluminum alloy is not limited to conventional castings such as engine blocks, but extends to hoods, trunk lids, outer panels such as doors and protection covers including heat insulators[2)-5)]. The present paper describes the latest trends and developmental status of aluminum alloy sheets for automotive panels.

## 1. Aluminum body panels for vehicles

In 1985, the Mazda RX-7 applied aluminum alloy sheet for its body panel (hood) for the first time in Japan. Since then, aluminum panels have been used mostly for sport cars and luxury sedans until early 1990s. Honda Motor Co., Ltd. presented the all-aluminum body NSX for the first time in the world. Subsequent collapse of bubble economy reduced the applications of aluminum panels to new models, however, aluminum panels started to be used again in around 1999 when global environmental issues became a major concern. **Table 1** lists the vehicle models in Japan using aluminum panels as of 2006. More recently, aluminum panels are being used for a wider variety of models, such as the Toyota Crown (**Fig. 1**), Toyota Prius, Subaru Legacy, Nissan Fuga (Infiniti M35/M45, **Fig. 2**)[6)] and Nissan Skyline

**Table 1** Examples of aluminum closer panels for automobiles

| Car maker | Model | Application parts |
|---|---|---|
| TOYOTA | CROWN | Hood |
| | CROWN MJ | Hood |
| | PRIUS | Hood, Back-door |
| TOYOTA(LEXUS) | LS | Hood |
| | GS | Hood |
| | SC | Hood, Roof |
| | IS | Hood |
| DAIHATSU | COPEN | Hood, Roof |
| NISSAN | FUGA | Hood, Door, Trunk-lid |
| | CIMA | Hood, Trunk-lid |
| | SKYLINE | Hood |
| | STAGEA | Hood |
| | Fairlady Z | Hood |
| SUBARU | LEGACY | Hood, Back-door |
| | INPRESSA | Hood |
| | FORESTER | Hood |
| MAZDA | RX-8 | Hood, Rear-door |
| | ROADSTER | Hood, Trunk-lid |
| HONDA | LEGEND | Hood, Trunk-lid, fr-fender |
| | S2000 | Hood |
| MITSUBISHI | LANCHER Evo. | Hood, Roof, Trunk-lid |
| | PAJERO | Hood |
| | AUTORUNDER | Roof |

Source : Japan Aluminum Association


Source：Toyota Motor Corporation

**Fig. 1** Example of application of aluminum hood (TOYOTA CROWN)

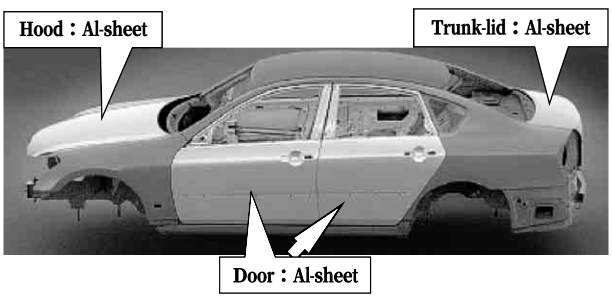


**Fig. 2** Example of application of aluminum body panel (NISSAN FUGA)[6]

(Infiniti G35). Many aluminum panels are used for hoods or bonnets. Recent models employ aluminum panels for trunk lids, rear doors and roofs[7), 8)].

In Europe, automotive use of aluminum raised sharply between 2000 and 2002. Aluminum alloy panels are now used for more than 2.5 million vehicles every year. The Renault Clio (sold as “Lutecia” in Japan) is a high volume model employing an aluminum alloy panel for its hood, and about forty thousand vehicles of the model are produced every month. Other examples of high volume models include the Mercedes-Benz E-class and BMW 5 series, both of which are produced in volumes greater than twenty thousand a month. Furthermore, the uses of aluminum alloy panels in those vehicles are expanding. The BMW 5 series, for example, has an all-aluminum frame and panels for the structure in front of its A-pillar. Audi presented, as early as 1992, an all-aluminum body car, the Audi A8, having a space frame structure and is regarded as a forerunner in the use of aluminum panels for automobiles. In 2006, after presenting the Audi A2 and new Audi A8, the company started using a hybrid material structure for the new Audi TT model, in which steel sheets are partially used with an aluminum space frame and joined together. The expanding automotive use of aluminum in Europe seems relevant to the more stringent regulation on $CO_2$ emissions which becomes compulsory in 2012.

## 2. The developmental status of aluminum alloy sheets for automotive panels

**Table 2** shows the development history of aluminum alloy sheets for automotive panels[9)]. In Japan, Al-Mg alloys with minor addition of Zn were first used when aluminum alloy sheets started to be used for automobiles in 1985. Around the same time in EU and USA, either 2000 series (Al-Cu) alloys or 6000 series (Al-Mg-Si) alloys with minor addition of Cu were used to serve the purpose. Currently, as the requirements for automotive panels has diversified, 6000 series (Al-Mg-Si) alloys are predominantly used worldwide with a few exceptions of 5000 series (Al-Mg) alloys. This is because the requirements for the material properties now include not only strength and formability, but also corrosion resistance, hemming formability, surface characteristics and weldability.

**Table 3** presents the compositions and properties of typical aluminum alloys used for automotive panels[8)]. The 6000 series alloys constitute the mainstream of alloys used for automotive panels because they are heat-treatable and their strengths can easily be controlled by heat treatments. In addition, the 6000 series alloys may also be adapted to exhibit bake hardening which occurs during the baking step after painting in the automotive manufacturing process. The bake hardening features of the alloys improve dent resistance and enables reduction of the sheet thickness and weight. The bake hardenability depends on the baking conditions which differ slightly by countries. The baking process is treated at higher temperatures, around 180 to 200˚C, in EU and USA, while the treatments at lower temperatures for short period (e.g.,170˚C x 20 min) are preferred in Japan. The alloys for outer panels are required to harden under the baking conditions described above, however, conventional 6000 series alloys were unable to harden sufficiently under such conditions. Extensive studies[10)-12)] revealed that pre-aging steps as shown in **Fig. 3** provides bake

**Table 2** Development history of aluminum sheets for automotive panels

| | 1985～1990 | 1990～1998 | 1999～2005 |
|---|---|---|---|
| JAPAN | ●Al-Mg Series alloy<br>High strength &<br>High formability | ○Al-Mg Series alloy<br>AA5022, AA5023<br><br>○Al-Mg-Si Series alloy<br>High bakehardability<br>High formability | ◎Al-Mg-Si Series alloy<br>High bakehardability<br>High formability<br>Hemming<br>SS mark free<br>○Al-Mg Series alloy |
| US & EU | ●Al-Cu Series alloy<br>AA2036, AA2008<br><br>●Al-Mg-Si Series alloy<br>AA6009, AA6010 | ○Al-Mg-Si Series alloy<br>AA6022, AA6016<br><br>○Al-Mg-Si Series alloy<br>AA6111 | ◎Al-Mg-Si Series alloy<br>AA6022, AA6016 |

**Table 3** Chemical compositions and mechanical properties of aluminum alloys for automotive body sheet

| Alloy | | Chemical compositions (wt%) | | | | | | | | Mechanical properties | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | TS (MPa) | YS (MPa) | El. (%) | n-Value | r-Value |
| 5000 series | AA5022 | 0.25 | 0.40 | 0.20～0.50 | 0.20 | 3.5～4.9 | 0.10 | 0.25 | 0.10 | 275 | 135 | 30 | 0.30 | 0.67 |
| | AA5023 | 0.25 | 0.40 | 0.20～0.50 | 0.20 | 5.0～6.2 | 0.10 | 0.25 | 0.10 | 285 | 135 | 33 | — | — |
| | AA5182 | 0.25 | 0.35 | 0.15 | 0.20～0.50 | 4.0～5.0 | 0.10 | 0.25 | 0.10 | 265 | 125 | 28 | 0.33 | 0.80 |
| | AA5052 | 0.25 | 0.25 | 0.10 | 0.10 | 2.2～2.8 | 0.15～0.35 | 0.10 | — | 190 | 90 | 26 | 0.26 | 0.66 |
| 6000 series | AA6022 | 0.8～1.5 | 0.05～0.20 | 0.01～0.11 | 0.02～0.10 | 0.45～0.7 | 0.10 | 0.25 | 0.15 | 275 | 155 | 31 | 0.25 | 0.60 |
| | AA6016 | 1.0～1.5 | 0.50 | 0.20 | 0.20 | 0.25～0.6 | 0.10 | 0.20 | 0.15 | 235 | 130 | 28 | 0.23 | 0.70 |
| | AA6111 | 0.7～1.1 | 0.40 | 0.5～0.9 | 0.15～0.45 | 0.50～1.0 | 0.10 | 0.15 | 0.10 | 290 | 160 | 28 | 0.26 | 0.60 |

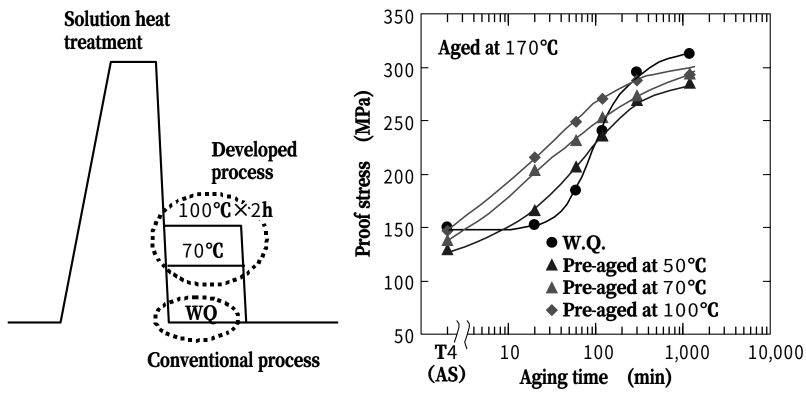


**Fig. 3** Effects of pre-aging on bake hardenability in 6000 series alloys

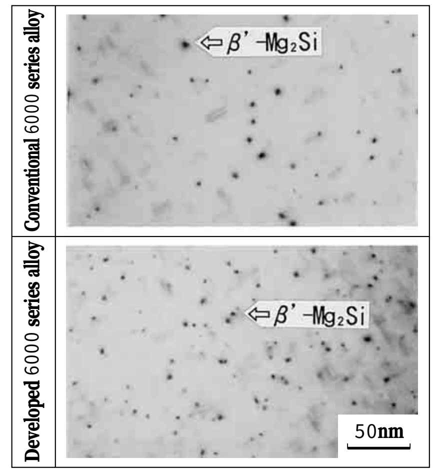


**Fig. 4** TEM microstructures of aged 6000 series alloys (aged at 180 °C for 60min)

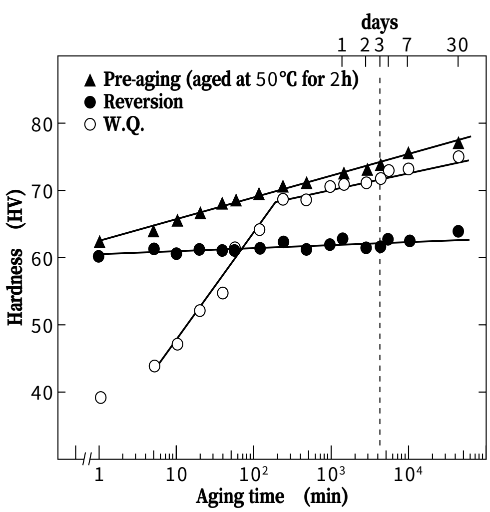


**Fig. 5** Effect of reversion process on natural aging in 6000 series alloy

hardenability at low temperatures, which otherwise has been difficult to achieve. A short period process of reversion treatment at a low temperature is also reported to provide bake hardening[13)-15)].

The proof stress of a 6000 series alloy depends on the distribution (size and density) of fine precipitates (intermediate β', $Mg_2Si$) formed during aging treatment. The distribution is largely affected by the content of Mg and Si, major alloying elements, as well as by aging treatment conditions. A dense distribution of fine precipitates as shown in **Fig. 4** is required to achieve a high proof stress. The figure represents the microstructure of a newly developed alloy which can be hardened during low temperature baking. Such distribution is obtained by an excessive addition of Si which is the major alloying element. Because of this, excessive amounts of Si are added to the aluminum alloys practically used for automotive panels, such as A6022 and AA6016. Most of the 6000 series alloys for automotive panels developed in Japan also contain Si in excessive amounts. In addition, Cu is also effective in making the precipitate distribution fine and homogenous[16)].

An alloy in 6000 series is naturally aged to increase its proof stress when left at room -temperature for a long period of time. The increase in proof stress may adversely affect workabilities such as press formability and bendability. To prevent such change in strength over time, a process has been developed involving a reversion or stabilization treatment. As shown in **Fig. 5**, the process yields only minimal hardening after a time elapse of several hours[15)]. Another issue with 6000 series alloys is hemming. Outer and inner panels are often hemmed together for automotive parts such as hoods and trunk lids. The process for making such parts generally comprises a down flange (90˚ bending) step, pre-hemming (135˚ bending) step and hemming (180˚ bending) step. Cracks may occur during the process under severe bending condition

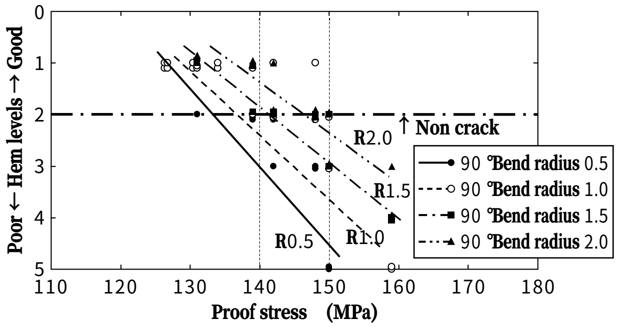


**Fig. 6** Effects of proof stress and 90 °bend radius on flat hemming formability in 6000 sieres alloys

with a small bending radius and / or thin outer panel thickness. To prevent such cracking, much effort has been spent for improving the bendability. The cracking is reported to occur due to relatively large precipitate existing in the crystal grain and / or at the grain boundaries[17]. Also, bendability is reported to deteriorate when shear zones and second phase particles are formed in a matrix, or when the amount of the shear band and the second phase particles is large[18]. In other words, bendability is considered be improved by adjusting material properties through controlling of the second phase which precipitates during heat treatment. Another approach for improving bendability relates to processing method. The alloy sheets of 6000 series can be bent without cracking by increasing the bend radius for the down flange (90° bending) step as shown in **Fig. 6**[19].

Many panel products in Europe are mechanically joined together after down flange step without being bent 180°, however, flat hems as produced in Japan are being introduced to improve aesthetics.

## 3. Forming technologies of aluminum sheets for automotive panels

Aluminum alloy sheets are less formable than steel sheets because of their low elongations, n-values, r-values and modulus of elasticity. A shape that could be formed by steel sheet may not be formed by aluminum alloys without causing cracking, wrinkling, or spring back. Thus, aluminum alloy sheets may impose restrictions on the design of shapes with their lower degree of freedom in forming.

When compared to steel sheets, aluminum alloy sheets exhibit proof stress and tensile strengths almost equivalent to those of mild-steel, however, their elongations are much smaller. **Fig. 7** shows stress-strain curves of typical aluminum alloy sheets (5000 and 6000 series) used for automotive panels. Also included is the curve for a mild steel. As can be seen from the figure, the aluminum alloys have significantly smaller elongations after maximum loads are reached (the elongations called "local elongations") compared to the steel. The difference in local elongation is considered to be the cause of the different formabilitites between aluminum alloys and steel. The following describes the measures taken to improve the formabilitites of aluminum alloy sheets.

### 3.1 Strechability

**Fig. 8** depicts the relation between the $LDH_0$ (LDH : Limit Drawing Height) and tensile strength for aluminum alloys and steels. The $LDH_0$ is defined as the height at which a fracture occurs when a rectangular blank is press-formed using a spherical head punch. The vicinity of the fractured portion is in a plane-strain region. The results indicate that the stretchability of aluminum alloy sheets is inferior to that of steel sheets.

### 3.2 Drawing formability

**Table 4** shows the results of cylindrical drawing tests

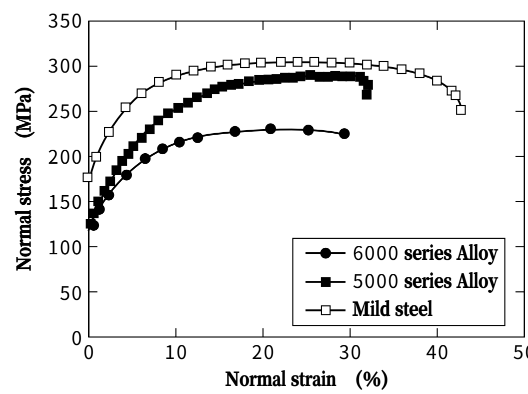


**Fig. 7** Stress-strain curves of aluminum alloys and mild steel

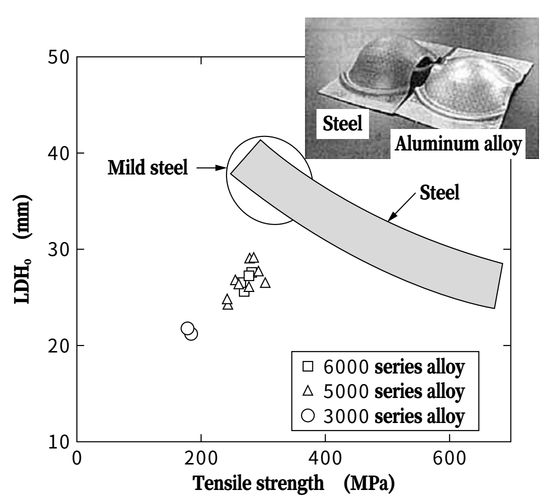


**Fig. 8** Relationship between $LDH_0$ and tensile strength of typical aluminum sheet and mild steel

Table 4 Comparison of drawing formability of aluminum sheet and mild steel (die inner diameter : 100mm)

| Alloy | Drawing ratio (LDR) | Drawing height $H/D_d$ |
|---|---|---|
| 5000 series alloy-1.0t | 1.86 | 0.67 |
| 6000 series alloy-1.0t | 1.81 | 0.65 |
| Mild steel-0.8t | 2.15 | 0.97 |

as represented by limit drawing ratio (LDR) and drawing height, measured for sheets of aluminum alloys and a mild steel. The LDRs for the aluminum alloys are smaller than the value for the mild steel. The drawing heights of the aluminum sheets are about 70 % of that of the steel.

### 3.3 Wrinkling sensitivity

**Fig. 9** shows the results of conical cup forming tests performed on the sheets of aluminum alloys and a mild steel. When low blank holding forces (BHFs) are applied, the aluminum alloy sheets exhibit wrinkling behaviors similar to that of the mild steel. However, higher BHFs, such as applied to steels, cause aluminum alloy sheets to crack. This limits the forming of aluminum alloy sheets compared to steel sheets. Some measures against wrinkling and cracking should be taken for the forming of aluminum sheet, because their modulus of elasticity is rather small (1/3 of steel) which makes them more prone to buckling. In addition, as indicated by their low r-values, aluminum alloys tend to fracture more easily once local deformations occur[20].

Because of the issues unique to aluminum sheets, the forming technologies of steel cannot be applied as-is to the forming of aluminum sheet in most cases. Thus, it is essential to develop technologies designed to form aluminum alloy sheets. The press forming of a 6000 series alloy, for example, involves optimizing the die shape for the alloy, increasing the accuracies of the die contact face and lowering the bead height (1/2 of steel). A BHF control method is reported to be effective in improving dimensional accuracies of the shapes formed[21].

The temperature dependence of superplastic deformation is also utilized in the forming of aluminum alloy sheets. Some aluminum alloys have unique characteristics of exhibiting significantly large elongations at temperatures either higher or lower than room temperature. The characteristics may be exploited in the forming of aluminum alloys. **Fig. 10** depicts the temperature dependence of the mechanical properties of a 5000 series (Al-Mg) alloy. Hot-blow forming utilizes the large elongation of aluminum alloy sheet at elevated temperatures. The method is practically used in forming complex shapes which may be difficult to form even with steel sheets. However, the approach takes long process time and its application has been limited. Recent development has shortened the process time of hot-blow forming. Honda Motor Co., Ltd., adapted the process to the forming of front fenders and trunk lids for the Honda Legend[22]. On the other hand, a low temperature forming technology has also been developed utilizing the large elongation at lower temperatures, a unique characteristics of aluminum alloy.

Since aluminum alloys have smaller local elongation compared to steel, aluminum sheets tend to break more easily when local deformations occur during press forming. Solid lubricant serves to improve stretch flangeability and drawing formability of aluminum alloy sheets. Various, commercially available, lubricant of wax and dry film are applied to aluminum sheet in Europe to form automotive panels[23].

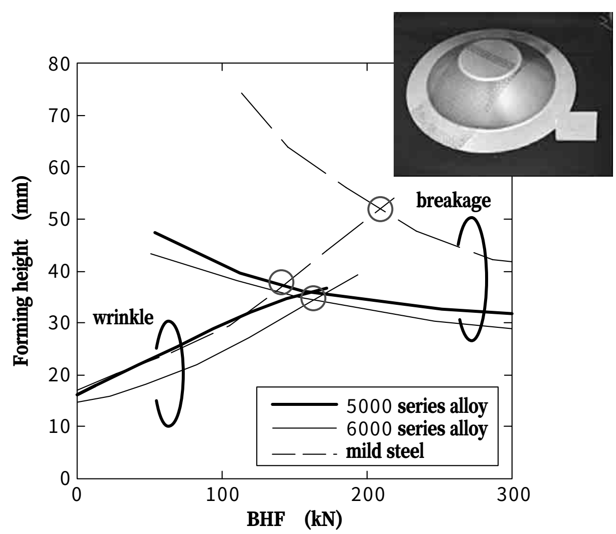


**Fig. 9** Relationship between forming limit height and BHF of conical cup forming (punch dianeter:100mm, die inner diameter:200mm)

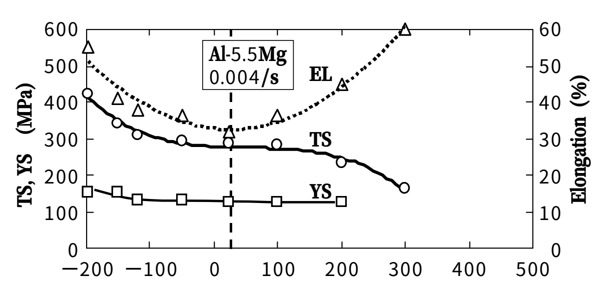


**Fig.10** Effects of forming temperature on mechanical properties in 5000 series alloys

**Table 5** Chemical compositions and mechanical properties of aluminum alloys for automotive structual parts

| Alloy | | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | TS (MPa) | YS (MPa) | El. (%) | Weldability | Corrosion resistance (SCC) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Chemical compositions (wt%) | | | | | | | | Mechanical properties | | | | |
| 5000 series | AA5052 | 0.25 | 0.25 | 0.10 | 0.10 | 2.2〜2.8 | 0.15〜0.35 | 0.10 | — | 190 | 90 | 26 | B | AA |
| | AA5182 | 0.25 | 0.35 | 0.15 | 0.20〜0.50 | 4.0〜5.0 | 0.10 | 0.25 | 0.10 | 275 | 125 | 28 | AA | AA |
| | AA5454 | 0.25 | 0.40 | 0.10 | 0.50〜1.0 | 2.4〜3.0 | 0.05〜0.20 | 0.25 | 0.20 | 240 | 110 | 24 | B | AA |
| | AA5154 | 0.50 | 0.50 | 0.10 | 0.50 | 3.1〜3.9 | 0.25 | 0.20 | 0.20 | 230 | 105 | 27 | A | AA |
| | AA5754 | 0.40 | 0.40 | 0.10 | 0.50 | 2.6〜3.6 | 0.30 | 0.20 | — | — | — | — | — | — |
| 6000 | AA6061 | 0.4〜0.8 | 0.7 | 0.15〜0.40 | 0.15 | 0.8〜1.2 | 0.04〜0.35 | 0.25 | 0.15 | 315 | 275 | 12 | C | B |

AA＞A＞BB＞B＞CC＞C
Good← →Poor

## 4. Development status of aluminum alloy sheets for automotive structures

**Table 5** lists the compositions and properties of aluminum alloys used for automotive structures. The aluminum alloys for structural parts require not only strength and formability, but also weldability and corrosion (stress corrosion cracking) resistance. Alloys in 5000 series are mainly used for the structural parts. It should be noted that the Mg content of these alloys is kept lower than that of alloys used for panels. The lower Mg content is to satisfy the above requirements, but causes to slightly lower strength and formability. To compensate the lower strength, transition metals, such as Mn and Cr, are added for crystal grain refinement. These alloy are employed to automotive sub-frames[2)-5)].

## 5. Other applications of aluminum sheets

For weight reduction, aluminum sheets are used for various automotive parts other than panels and structural parts. Examples include heat insulators and fuel tank protectors which insulate heat, noise and protect bodies from dirt. Also included are exhaust manifold covers in engine compartments. General-purpose aluminum alloys in 1000 series, or in 3000 series, are used for these parts. The alloys not only serve to reduce weight but also are comparable in terms of cost with plated steel sheets, justifying the aluminum alloys to replace steel[2)-5)].

## 6. Future prospect of aluminum alloy sheets for automotive panels

Needs for weight reduction will continue to increase with the progressing technologies for safety, environmental measures and comfort driving. Aluminum sheets are to be used for an increasing number of automotive panels. Further development of the alloys, along with their processing technology, are waited for, as well as their forming technology, in order to further expand the applications of aluminum sheet to panels other than hoods and applications to lower cost vehicles. Aluminum alloy should find its way not only as a lighter substitute of steel, but to provide additional values. For example, the "Impact Absorption Wave" hood of the Toyota Crown and the "Shock Corn" hood of the Mazda RX-8 not only serve to reduce weight, but also protect pedestrians at the time of collision[24)]. Thus, additional values of aluminum sheets are being pursued along with their weight reduction effect. Automotive applications of aluminum sheets are expected to expand and extend further.

## Conclusions

The latest trend and new technologies of aluminum sheets have been reviewed with major focus on automotive panels. In the needs for automotive weight reduction, aluminum will continue to be a major candidate for a lighter substitute material. Functional properties, as well as the weight reduction effect, will be required for aluminum alloys to be used for various automotive parts.

To expand the use of aluminum for automotive panels, forming technologies should be further improved to provide more degree of freedom to automotive design. Tribology is considered to be an area which needs to be pursued to further develop the applications of aluminum sheets. The formability can be improved by facilitating the material flow in dies by introducing lubricants with low friction coefficients.

Furthermore, enabling the joining between dissimilar materials, e.g. between steel and aluminum alloys, will promote the use of aluminum in a variety of parts.

Also important is to reduce the cost of aluminum parts for them to be used for various parts of mass produced vehicles. The cost reduction may involve the development of process technologies which simplifies process steps and simultaneously achieve the required quality. Unification and recycling of parts will also be needed.

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