Technical Trends in Aluminum Alloy Sheets for Automotive Body Panels

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Aluminum alloy sheets are increasingly being used for automotive bodies to reduce their weights and are required to have excellent mechanical properties, joining performance and corrosion resistance. For outer panels, Kobe Steel has been working to improve the performance of 6000 series (Al-Mg-Si) alloys in bake hardenability, formability, and surface quality after stamping. For inner panels and structural members, the application of Ti/Zr surface treatment is being promoted to meet the requirements for the durability of adhesive bonding, which are mainly adopted by non-Japanese automakers. This paper introduces developments in the application of aluminum alloy sheets to automotive bodies and developments for overcoming technological issues.

Introduction

The typical characteristics of aluminum alloys include, in addition to low specific gravity, good corrosion resistance, ease of recycling, high electrical conductivity, good thermal conductivity, and non-magnetic properties. With these advantages, aluminum is being used in various applications as industrial goods and parts.

Meanwhile the weight reduction of automotive bodies has been a challenge in reducing CO_2 emissions, increasing the cruising distance of electrical vehicles, and coping with the increasing weight due to the addition of safety equipment,[1] and the replacement of steel sheet, which has been mainly used so far, with the lightweight material is being studied. Under such circumstances, aluminum alloy sheets, in particular, has been used for various parts of vehicles, including outer panels and structural members, since the 1980s, and the demand for aluminum alloys is expected to increase further in the field of transportation equipment.[2]

In order to maximize the benefits of body weight reduction by the use of aluminum alloy, it is considered necessary to propose not just material substitution, but also comprehensive technology combining the design of structural parts and the material technology to realize it.

This paper introduces the status of the use of aluminum alloy sheets in automobile bodies and the progress being made at Kobe Steel to overcome technological issues.

1. Status of aluminum alloy sheet use in automotive bodies

In North America and Europe, aluminum alloy sheets were rapidly adopted from 2000 to 2002, and are now applied to mass-produced models. In addition, to cope with weight reduction and strengthened collision safety regulations, the use of high strength steel sheets and aluminum alloy sheets is being studied to find the most suitable placement in the body-in-white for each material.[3]

In Japan, in 1985, aluminum alloy hoods were applied for the first time to the Mazda RX-7®, and in the first half of the 1990s, the use of aluminum outer panels progressed mainly in sports cars and luxury cars. In recent years, they have been adopted for mass-produced vehicles, and the number of applicable parts such as trunk lids, back doors, and roofs has also increased. In China, which boasts the world's top automotive production volume, there is a growing need for the weight reduction of vehicles against the background of strengthened fuel efficiency regulations.

The Kobe Steel Group is expanding the production capacity to meet the demand for aluminum alloys in the transportation segment, which continues to grow significantly in Asia, including Japan and China. (For details, see the article on this issue, pp.5-10.)

The materials for automotive panels have various performance requirements, such as bondability and corrosion resistance, as well as mechanical properties. Therefore, Kobe Steel has developed materials with optimized chemical compositions and production conditions in accordance with the applied parts. The chemical compositions and required characteristics of typical aluminum alloy sheets for automotive panels are shown in **Table 1** and **Table 2**, respectively. The 5000 series alloy with a high Mg content has excellent formability and is used for various parts exemplified by inner panels. Outer panels are required to have excellent bake hardenability[Note 1)], press formability and surface quality after stamping. Taking into account the balance of these required characteristics, 6000 series (Al-Mg-Si series) alloys containing Si higher than

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[Note 1)] Age hardenability in heat treatment at relatively low temperature and for a short time

Table 1 Chemical compositions of aluminum alloys for automotive body panel

(mass%)

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Al
AA6014	0.30-0.6	<0.35	<0.25	0.05-0.20	0.40-0.8	<0.20	Bal.
AA6016	1.0-1.5	<0.50	<0.20	<0.20	0.25-0.60	<0.10	Bal.
AA6022	0.8-1.5	0.05-0.20	0.01-0.11	0.02-0.10	0.45-0.70	<0.10	Bal.
AA6111	0.6-1.1	<0.40	0.50-0.9	0.10-0.45	0.50-1.0	<0.10	Bal.
AA5022	<0.25	<0.40	0.20-0.50	<0.20	3.5-4.9	<0.10	Bal.
AA5052	<0.25	<0.40	<0.10	<0.10	2.2-2.8	0.15-0.35	Bal.
AA5754	<0.40	<0.40	<0.10	<0.50	2.6-3.6	<0.30	Bal.
AA5182	<0.20	<0.35	<0.15	0.20-0.50	4.0-5.0	<0.10	Bal.

Table 2 Properties required for automotive aluminum body panel

Applications	Properties
Outer	Yield strength after paint bake
	Surface qualities after stamping (Roping/S-S mark free)
	Formability
	Hemming property
	Anti-filiform corrosion property
Inner	Deep drawing performance
	Joining property
	Adhesion property

the stoichiometric composition are the ones most often used. It is mainly non-Japanese automakers that require durability after adhesive application for inner panels and structural members.

2. Required characteristics of aluminum alloys for automotive bodies and development status at Kobe Steel

2.1 Bake hardenability

For outer panel material, lower strength is required, with a view to ensuring shape accuracy after stamping with suppressed spring back. On the other hand, the final products are required to have high strength in order to maintain the dent resistance [Note 2)] with reduced thickness. Hence, 6000 series alloy sheets are mainly used because of their gaining strength during the heat treatment of paint baking in the automotive production process. The age hardenability during paint baking at a relatively low temperature for a short time is called bake hardenability. As improvement measures, pre-aging[4)] and a reversion process[5)] have been proposed. These heat treatment processes are performed in order to control the nanoscale material structure formed by Mg and Si, which are the main additive elements in 6000 series alloys.

Kobe Steel is working to develop a new process for the further improvement of the bake hardenability of 6000 series alloys,[6)] to optimize the chemical compositions and production conditions,[7)] and furthermore, to establish a microstructural analysis technology for clarifying the mechanism. **Fig. 1** shows 3D distribution maps of Mg and Si atoms aggregated in a 6000 series alloy along with the results of hardness measurement.[8)] The three-dimensional distribution in the figure was obtained by a fine region analysis apparatus that can three-dimensionally image the atomic arrangement inside the material. As is shown in Fig. 1, the hardness, and the number of atomic aggregations, including Mg and Si, with diameters of several nanometers, have increased with the increasing holding time at the room temperature. In other words, it has been clarified that this very small change in structure is responsible for the change in hardness that takes place during holding at the ambient temperature.

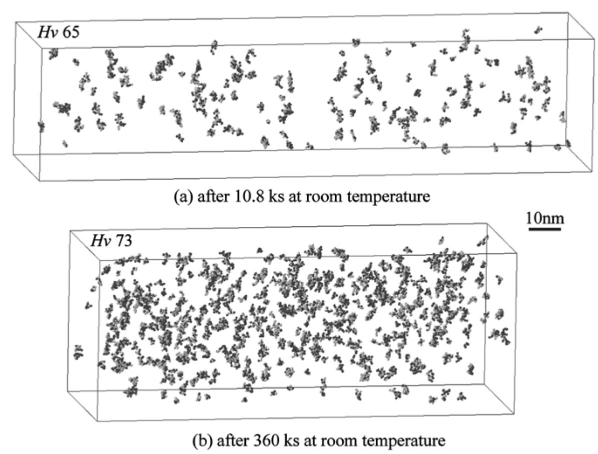

Fig. 1 3D distribution maps of Mg and Si atoms aggregated in Al-Mg-Si alloy and Vickers hardness [8)]

[Note 2)] Resistance to being dented when hit by pebbles, etc.

2.2 Formability

In general, the formability of 6000 series alloy sheets at the room temperature is regarded as inferior to that of mild steel sheets. For improvement, Kobe Steel is trying to raise the forming limit by developing press technology suitable for aluminum alloy sheets and is also developing materials with excellent formability. In such efforts, it has been found that a newly developed material with an optimized amount of additive elements such as Mg, Si, and Cu and produced under optimized conditions shows excellent elongation and work hardening characteristics. As the mechanism of this phenomenon, the dislocation growth during tensile deformation and kinetic recovery behavior have been clarified.[9)]

These efforts to improve the formability of aluminum alloy sheets are believed to enable complex-shape parts to be made of aluminum, improving the merchantability of vehicles with realized vehicle design needs and to contribute to the reduction of the total cost with a decreased parts count.

2.3 Improvement of surface quality after stamping

In 6000 series alloy sheets, a parallel concave-convex pattern called roping may appear in the rolling direction on the sheet surface after stamping (**Fig. 2**). For the sake of vehicle appearance, roping must be suppressed even in the high strain region, as the shape of the stamping parts has become more complex in recent years.

Kobe Steel conducted deformation analysis using crystal plasticity theory on the basis of the actual texture information for 6000 series sheets and investigated in detail the deformation behavior of the sheet cross-section shape associated with tensile deformation. As a result, the roping is considered to be partially attributable to bending deformation caused by inhomogeneous stress distribution in the sheet cross-section, in which specific crystal orientations such as Goss orientation and Cube orientation are distributed un-uniformly.[10)] On the basis of these analysis results, a production process has been established to further improve the uniformity of the crystal orientation distribution, and materials have been developed that can suppress roping even in the parts with complex shapes.

The conventional method of evaluating roping involves applying prescribed tensile deformation, applying stone grinding and/or painting, and visually evaluating the level of concaveness/convexness that appears; thus the problem with this method is that it depends on the skill of workers. It was against this backdrop that Kobe Steel developed a method of quantifying the degree of roping by performing frequency analysis on the three-dimensional shape measured on the deformed sheet surface and separating and analyzing the in-plane wavelength.[11)] **Fig. 3** shows the relationship between the roping index value, which is the ratio of the intensity of the wavelength component in the rolling direction to the average intensity of the wavelength component in all directions, and the conventional visual evaluation results. An excellent correlation has been recognized between the two, and it is considered that the new method of quantitatively evaluating roping can replace the conventional method and improve the efficiency of material development.

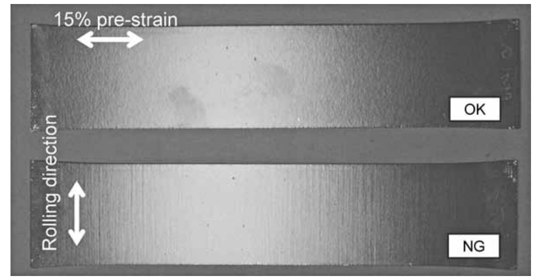

Fig. 2 Appearance roping test piece (15% pre-strain, after spray coating)

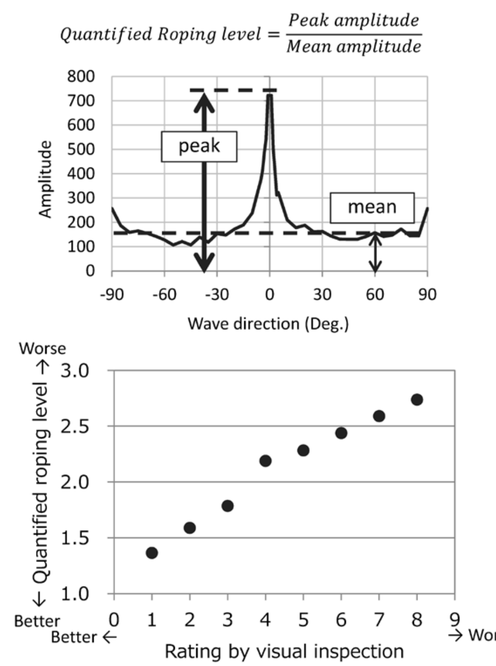

Fig. 3 Relationship between quantified roping level and rating by visual inspection

2.4 Adhesive durability

In Japan, aluminum alloy sheets for automobile panels are generally shipped out as materials that have been subjected to pickling, or other procedures to remove the oxide film formed during the heat treatment, so as to improve paintability, adhesion properties, and weldability.[12] On the other hand, outside Japan, surface treatment may be applied to improve durability when adhesive is applied. This is to prevent the adhesive from peeling off at the interface under the influence of the harsh market environment to which adhesive joints are assumed to be exposed, so as to ensure the reliability of adhesive properties.[13] It is known that proactive use of adhesives improves rigidity, collision safety, noise suppression, vibration characteristics (NVH properties), and the like. In Europe, adhesives are being used frequently for such purposes.[13]

Specific surface treatments include Ti/Zr treatment applied in Europe and Alcoa 951 treatment applied at the material stage in North America.[13] Of these, Ti/Zr treatment is a technology widely used by non-Japanese automakers, mainly in Germany. In the process as shown in **Fig. 4**, an oxide film of Ti and Zr is formed on the deoxidized surface of aluminum alloy.[14]

Fig. 5 shows examples of fractured bond surfaces after a shear tensile test performed following the evaluation of adhesive durability (using epoxy adhesive; 3,000 hours of salt spray).[15] The surface with pickling-only shows a metallic luster caused by interfacial fracture, whereas the Ti/Zr-treated material has no metallic luster, exhibiting cohesive failure. **Fig. 6** shows the results of a study on the influence of the cohesive failure ratio on Ti/Zr film mass, wherein the Ti/Zr film mass is defined as the total amount of Ti and Zr metal components on the Ti/Zr-treated material surface.[15] The cohesive failure ratio is about 30% for the pickling-only material, and the cohesive failure ratio improves as the amount of Ti/Zr film increases, reaching a maximum at 5 to 10 mg/m^2. The cohesive failure ratio decreases as the Ti/Zr film mass increases further. This is considered to be due to the fact that, as the film mass increases, fracture occurs easily inside the Ti/Zr film.[13]

The interfacial fracture when an adhesive is applied has been attributed to the hydration of the material surface.[13] **Fig. 7** shows the effect of film mass, in the pickling-only material and in the Ti / Zr-treated material, on the amount of hydration, wherein the hydration amount of the pickling-only material is regarded as 1. Here, the hydration amounts of pickling-only material and Ti/Zr-treated material were determined by Fourier transform infrared spectrometer (FT-IR) analysis on the surface before and after holding in a humid environment

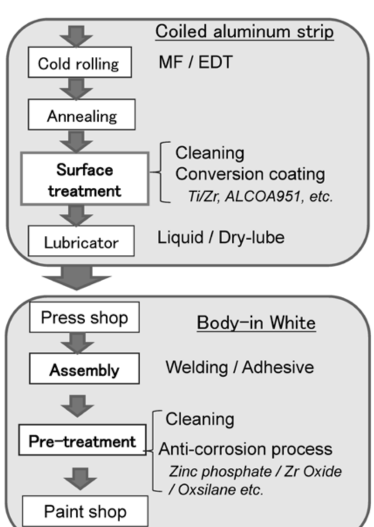

Fig. 4 Manufacturing process of aluminum sheet for automobiles (surface related technology)

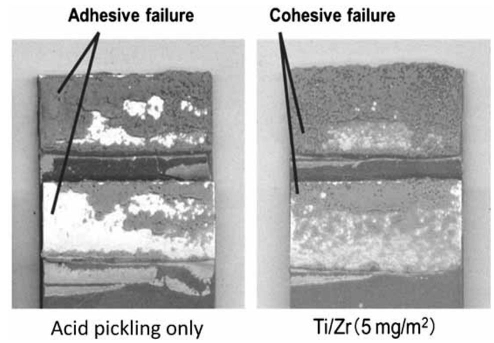

Fig. 5 Appearance of samples for adhesive durability test (Lap shear test)

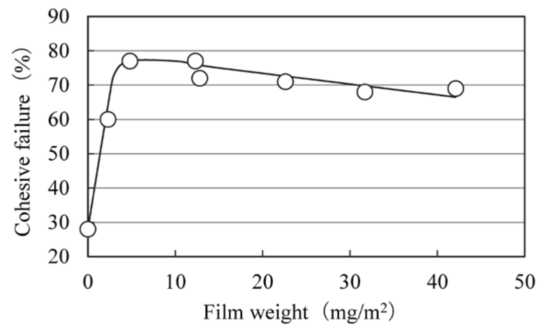

Fig. 6 Relationship between cohesive failure ratio and film weight

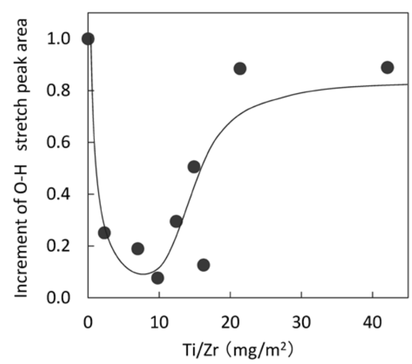

Fig. 7 Hydration variation with Ti/Zr film weight

(50℃, 95% RH, 24 hours) and by calculating the increase in the area of the peak of the OH stretching vibration observed near 3,400 cm^{-1}. These results confirm that the amount of hydration is suppressed by the increased film mass. It should be noted, however, that it tends to increase again when the film mass increases further.[15] This behavior corresponds to the evaluation results for adhesive durability.

The Ti/Zr-treated materials have been confirmed to exhibit conversion treatability and weldability characteristics equivalent to those of pickling-only materials.[14), 15)]

Conclusions

In recent years, the business environment surrounding automobiles has changed significantly. Along with technological innovation, new vehicle structures and parts are expected to be developed, and the role of aluminum alloy sheets as lightweight structural materials is expected to become increasingly important. In order to meet these needs, Kobe Steel is conducting research and development of aluminum sheet materials, and for that purpose, strong partnerships with customers have become more vital than ever before. The company strives to play a major role in reducing the weight of automobiles and protecting the global environment by promoting comprehensive R&D combining material development, component structure proposals for exploiting the characteristics of materials, and dissimilar materials joining technology for aluminum and high-strength steel sheets.

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