Wrought Aluminum Technologies for Automobiles

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Automobiles are using more aluminum products in response to ever increasing requirements for fuel-efficient, environmentally-friendly, vehicles. A variety of new technologies are being developed for aluminum products. This article introduces the current status and trends of aluminum product technologies, with the main focus on sheets, extrusions, forgings and their peripheral technologies.

Introduction

The Kyoto Protocol was ratified in 1997 and led to increased global attention to environmental issues. Approximately 20% of the total carbon dioxide emissions in Japan are due to automobile exhausts and improvements of automobile fuel economy are strongly desired. A target has been set of a 22.8% improvement of fuel economy for gasoline-fueled vehicles by 2010 compared to the 1995 level.[1)] On the other hand, weights of vehicles are increasing year by year due to improvements in collision safety and mounting of various information devices. Weight reduction has therefore become a major subject among automobile manufactures.[2)] Aluminum alloys are effective materials for the reduction of vehicle weight and are expanding their applications (**Figure 1**: Japan Aluminum Association). In the past the main aluminum products were castings such as engines; however wrought aluminum products are finding more applications these days in sheets including exterior panels such as hoods and heat insulators, in extrusions including bumper beams, and in forgings including suspension parts.

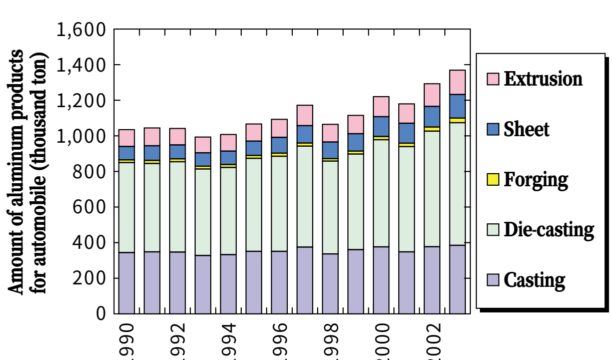


Fig. 1 Trend of amount of aluminum products used for automobile

We, as an all-round supplier of aluminum products in a variety of forms, have developed not only materials with improved properties, but also peripheral technologies such as forming and joining, to make them suited for aluminum properties that are different from steels. This article describes technological trends in aluminum sheets, extrusions and forgings and explains peripheral technologies including numerical analysis and joining technology.

1. Technological trends in aluminum sheets for automobiles

The total annual demand for aluminum sheet for automobiles is approx. 130 thousand tons (2003 fiscal yr.) and more than a half of the demand is occupied by heat exchangers such as radiators. Slightly less than 30 thousand tons of aluminum sheet is used for automobile bodies. This chapter outlines the application of aluminum sheets to automobile bodies, aluminum alloys for panels, and their application technologies. More details are described in the reference 3).

1.1 Application of aluminum to automobile panels

Aluminum panels were first applied domestically to the hoods of MAZDA RX7 in 1985 and since then have been applied mainly to sports cars and luxury vehicles. Recently, however, they are becoming to be used in mass-production cars and their applications have expanded from conventional hoods to backdoors, trunk lids, roofs and doors. **Figure 2** shows the trend of aluminum panel applications to automobiles. North America

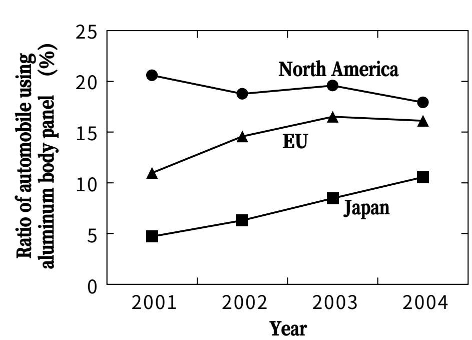


Fig. 2 Ratio of automobile using aluminum body panel

Table 1 Chemical compositions of aluminum alloys for auto body panels

Alloy	Si	Fe	Cu	Mn	Mg	Alloy code of Kobe Steel
AA6016	1.0-1.5	<0.50	<0.20	<0.20	0.25-0.60	KS6K21
AA6022	0.8-1.5	0.05-0.20	0.01-0.11	0.02-0.10	0.45-0.70	
AA6111	0.7-1.1	<0.40	0.50-0.90	0.15-0.45	0.50-1.0	KS6K31
AA5022	<0.25	<0.40	0.20-0.50	<0.10	3.5-4.9	KS5J30
AA5023	<0.25	<0.40	0.20-0.50	<0.10	5.0-6.2	KS5J32
AA5182	<0.20	<0.35	<0.15	0.20-0.50	4.0-5.0	5182

Table 2 Mechanical properties of automotive aluminum sheets produced by Kobe Steel

Alloy code (Kobe Steel)	TS (MPa)	YS (MPa)	El. (%)	After baking YS (MPa)	Application parts
KS6K21	240	125	29	200	Outer
KS6K31	275	130	32	165	Inner
KS5J30	275	135	30	155	Outer/Inner
KS5J32	285	135	33	155	Outer/Inner
5182	270	125	29	140	Inner

and Europe precede in the use of aluminum panels but the gap has narrowed rapidly in the last few years.

1.2 Features of aluminum alloy sheets for automobile panels

The aluminum alloys for panels are required to have various properties including strength, formability, bendability, surface characteristics and weldability. The 2000 series (Al-Cu-Mg) and 7000 series (Al-Mg-Zn) alloys were used in early days and 5000 series (Al-Mg) and 6000 series (Al-Mg-Si) alloys are mostly used these days. **Table 1** shows the AA specifications of chemical composition for typical aluminum alloys used for panels and **Table 2** shows the properties of our representative alloys for panels.

The 5000 series are non heat treatable alloys and special 5000 series alloys, AA5022 (KS5J30) and AA5023 (KS5J32), are used for panels.

The 6000 series alloys are heat treatable and have bake-hardening (BH) features which increase strength during paint baking. They are also free from stretcher-strain (SS) marks after forming. Because of those features, the 6000 series alloys are used for outer panels which require dent resistance and surface qualities. Lower temperatures (around 170℃) and shorter times (around 20 min) are used for paint baking in Japan compared to the USA and Europe. We have developed a 6000 series alloy and its manufacturing process having high bake-hardenability at low temperatures **(Figure 3)**.[4] The BH is the most critical feature of 6000 series alloys and further improvement will continue in the future.

The 6000 series alloys for automobile panels fall into two categories. Copper-containing AA6111

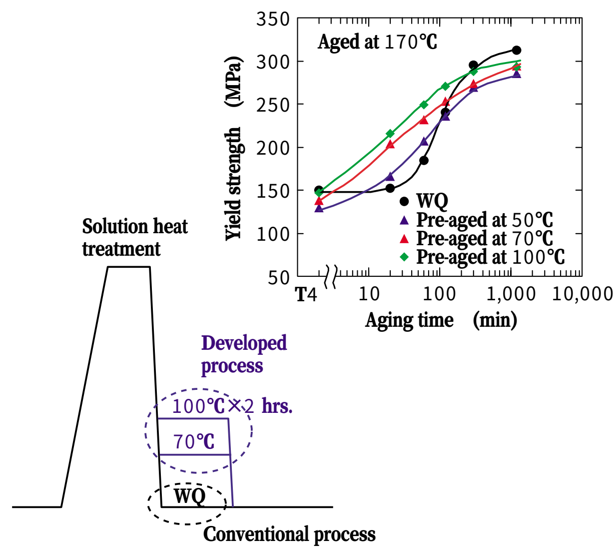


Fig. 3 Effect of pre-aging on bake hardenability in 6000 series alloys

(KS6K31) and AA6022 (KS6K21) which contains almost no copper. The non-copper types are more commonly used in Japan for their high filiform corrosion resistance and the copper-containing types are used where drawability is required.

The biggest issue for 6000 series alloys is their lower formabilities compared to 5000 series alloys and steels. Outer panels, especially, are subject to hemming (bending) and domestic automobile manufacturers prefer to use flat-hemming for visual quality. The severe bending conditions of hemming can cause cracks. More development will be required to improve the hemming performance of these alloys.

1.3 Application technologies of aluminum alloy sheets to automobile panels

Generally, aluminum alloys have lower

elongations, r-values and Young's modulus compared to steels. Shapes which can be formed by steel sheets can cause aluminum sheets to crack, wrinkle and to spring-back, restricting the shapes and designs of automobile bodies. In order to improve this, it is essential to develop forming and fabrication technologies suited for aluminum alloys.

One of the methods of improving the formability of aluminum alloys is a method of using their temperature dependence of plastic deformation, which utilizes higher elongations at temperatures either higher or lower than ambient temperature. The high-temperature blow-forming, which utilizes high elongations of aluminum alloys at elevated temperatures, has been used for small-scale production of panels and has achieved improved productivity recently. This method is applied to the front fender and trunk lid of Honda Legend (2004).[5)] The high-temperature blow forming gives better formability than steel sheets and provides a good example of a combination of material and forming technologies of aluminum.

1.4 Future application of automobile panels

The needs to reduce weight of automobile bodies will encourage more panels to be made of aluminum. Almost 20 years have passed since an aluminum alloy was used for an automobile panel for the first time; however, the materials and their application technologies are still under development. Further developments are expected in the future.

2. Technological trends in aluminum extrusions for automobiles

Aluminum extrusions can have complex cross-sectional shapes having a variety of thickness distributions, which are not obtainable for steels, and are gaining attention as effective products to reduce automobile weights. Aluminum extrusions for automobiles, first applied to heat-exchangers of air-conditioners, have expanded their applications to underbody and engine parts. More recently, applications to structural members such as bumper-beams are progressing. This chapter describes our status and future developments of aluminum extrusions in relation to the recently growing applications. References 6)-8) give more details of the technological trends.

2.1 Usage of aluminum extrusions in automobiles

According to the statistics of the Japan Aluminum Association, the domestic shipping volume of aluminum extrusions has been staying at a level of one million tons/year in total; however the volume of extrusions for automobile applications has increased steadily. For example, it increased by approx. 50% from fiscal 1995 (94,000 tons) to fiscal 2003 (139,000 tons).

In our case, more than 50% of total shipping volume (including cast bar) was employed in products for automobile applications in 2003.

2.2 Applications to safety members

We started volume production of safety members, such as bumper beams and door beams, in the early 1990s. Historically those parts had been made of steels. We started development of those products because the required properties and shapes were considered to be appropriate for aluminum extrusions. **Figure 4** shows an example of the aluminum bumper beam.

Since bumper beams are fixed at positions far from the gravity center of vehicles, the reductions of their weights are effective in improving drivabilities of vehicles. Because of this more aluminum alloys have recently been applied to bumper beams.

We have produced a number of bumper beams using 6000 series alloys; however, strong demands for further weight reduction and safety improvement are encouraging us to develop bumper beams made of 7000 series alloys with higher strength.

2.3 Development and use of extrusion materials

Generally, the extrusion productivities of 7000 series alloys are lower than those of 6000 series alloys. The productivities of 7000 series alloys had to be improved to reduce costs before the alloys

Fig. 4 Example of aluminum bumper beam

could be applied to safety members.

We have continued development of 7000 series alloys through optimization of alloying elements, while continually developing production technologies to improve the productivities based on microstructure control. The main focal points of the developments were;

- homogenization of billets,
- isothermal extrusion process for both optimum microstructure and productivity and
- die design technologies.

As a result, we have developed a 7000 series alloy which reduces weights of bumper beams by 15% (reduction depends on conditions) compared to 6000 series alloys.

7000 series alloys, however, have high susceptibilities to stress corrosion cracking (SCC). We have lowered the SCC susceptibility of the alloy through microstructure control by optimizing alloying elements, extrusion conditions and heat treatment. We have performed, with our users, a variety of corrosion tests under assumed conditions and have proved the immunity of our products. The first production batch of 7000 bumpers has passed over 12 years without any trouble. We will continue to develop products focusing on microstructure control.

2.4 Design technologies for safety members

Conventionally the role of materials manufacturers was to produce materials specified by users at reasonable costs in a stable manner. This role of material manufacturers still continues; however, increasingly the material manufacturers are required to consider the characteristics of actual parts and to make counter proposals.

More specifically, material manufacturers are requested to propose optimum structures based on requirements provided by CAD data such as collision performance requirements and layout conditions. In the case of bumper beams, material manufactures have to design not only cross-sectional shapes of extrusions but also the whole bumper structure, taking into account other parts such as the energy absorber on the front surfaces and the stays which fix bumpers to bodies.

Developments of bumpers and door beams are deeply connected to safety regulations since those parts are heavily involved in the performances of front and side collisions of automobiles. In the past, the main goal of a bumper beam was to meet regulations such as PART 581 which specifies the crash damage of the body at the time of low speed collisions (2.5-5 mph).

Recent safety assessments, such as IIHS (Insurance Institute for Highway Safety), have more stringent criteria which require not only the low speed collision characteristics required by the regulation but also require energy absorption characteristics at medium speed collisions. The requirements by the assessments also need to be satisfied since their evaluations determine the commercial values of automobiles.

As described above, more sophisticated design capabilities are required by material manufacturers, to enable material manufacturers to make counter proposals that reflect more integrated concepts including extrusion productivity, cross-sectional shapes for higher formability of bumper beams, and parts assemblies. This allows us to provide users with products which are optimized for low cost and weight.

An example of technological trends in bumper beams has been described. The applications of aluminum to automobile structures are expected to increase further. We will continue developments of semi-finished products by exploiting not only the microstructure control technologies but also forming technologies, and will respond to ever-increasing needs for weight and cost reductions.

3. Technological trends in aluminum forgings for automobiles

The annual domestic production of aluminum hot forgings is approx. 30 thousand tons and is smaller than other formed aluminum products. About 80% of the volume is occupied by automobile applications, which have increased by 60% in the last three years (**Figure 5**: a statistics by Ministry of Economy, Trade and Industry). The increase is mainly attributed to the increase in the applications of forgings to passenger vehicle suspensions. The underbody parts improve not only fuel economy through weight reduction but also ride qualities, handleability and performance[9], and have been

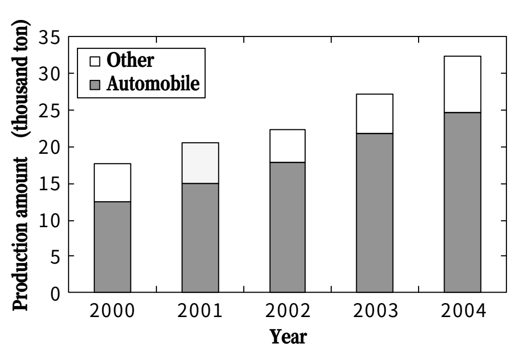


Fig. 5 Production amount of aluminum hot forging

used increasingly, especially in luxury vehicles. This chapter introduces the trends of suspension parts and describes our light-weight design technology, material development, production technology and global approach.

3.1 Technological trend of suspensions

A suspension with high stiffness improves the vehicle's handleability while deteriorating ride qualities. Suspensions of various structures are used depending on types of vehicles. An example of suspension structure is shown in **Figure 6**.[10) **Table 3** summarizes suspension parts and their production methods of a high-end model car released in 2004.

A suspension consists of such parts as a knuckle, upper-arm, lower-arm and lower-link. Knuckles and upper-arms require stiffness dominantly and castings with improved toughness are often used. Advancements in vacuum die-casting have enabled a development of single-construction lower links.[11) Lower arms, on the other hand, are subjected to higher stress and limited in their design due to interference with other peripheral parts. They employ mainly forgings which have higher strength and toughness.

In recent years suspensions are becoming more complicated and advanced for improved ride qualities, drivabilities and reductions of vibration and noise. They include such components as adaptive hydraulic rubbers and high-performance dampers and four-wheel steering. Further reduction of weight will be pursued by utilizing materials and design technologies.

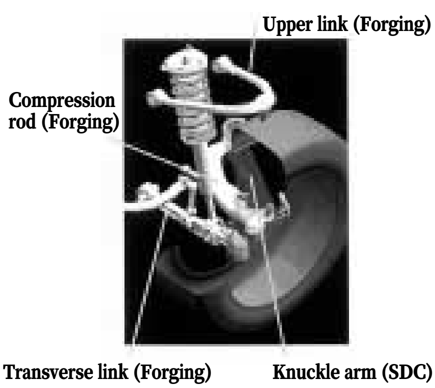


Fig. 6 Multilink type front suspension[10)

Table 3 Aluminum suspension parts and their production

Car	F/R	Type	Parts	Method
A	Front	Double wish bone	Knuckle	Squeeze casting
			Lower arm	Forging
			Upper arm	Forging
	Rear	Multi link	Carrier	Squeeze casting
			Lower link	Vacuum die-casting
			Upper arm	Forging
B	Front	Double wish bone	Knuckle	Forging
			Lower link	Forging
			Upper arm	Forging
	Rear	Multi link	Carrier	Gravity casting
			Lower link	Vacuum die-casting
			Upper arm	Forging
			Link lower front	Extrusion
			Control arm	Forging

3.2 Analytical design of suspensions

For aluminum suspensions we offer the lightest-shape designs for the provided strength specifications, based on elasto-plasticity structural analysis. We scrutinize material properties and optimize boundary conditions, which are keys to improving analytical accuracies. Since suspension arms are mounted with rubber bushes and adaptive hydraulic rubbers, the spring properties of those bushes have to be understood before setting the boundary conditions. For this purpose we perform not only the evaluations of the bush performances themselves, but also bench tests to evaluate the load-displacement characteristics of assembled suspension arms, and develop databases to improve analytical accuracies. **Figure 7** shows a comparison between a simulation and an experimental result of the suspension load test. The simulation can be adjusted to the experimental result by scrutiny of boundary conditions such as rubber properties.

Table 4 shows an example of shape optimization in which the arm-section shapes of web thickness, fillet radius and corner radius are optimized for the weight of a rear upper arm. A 13% weight reduction is achieved for a given strength specification by optimizing the cross-sectional shape.

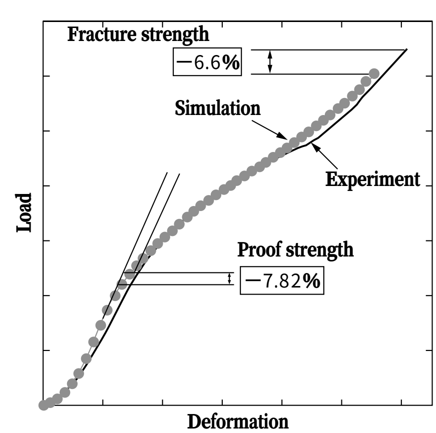
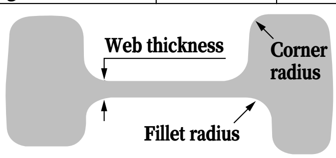


Fig. 7 Comparison between simulation and experiment of suspension load test

Table 4 Weight vs. arm-section shape

	Conventional	Improved
Web thickness (mm)	8	4
Fillet radius (mm)	15	5
Corner radius (mm)	5	4
Weight ratio	100	87



3.3 Development of 6000 series high strength aluminum alloys

The materials properties required for suspension parts are high stiffness, strength, fatigue strength, elongation, impact value and corrosion resistance. The strength is governed either by fatigue-strength or proof-strength depending on specifications. From safety perspective the suspension arms are required to deform largely rather than to fracture for shock absorbing. For this purpose forgings of 6000 series alloys are predominantly used for suspension arms because of their high strengths, toughnesses and reliabilities.

We developed a high-strength cast billet alloy, KS651, which is more economical than extruded bar, and started volume production in 1991. We also have newly developed KD610 which has strength higher than 6061 by 40%. The high strength has been achieved by the optimization not only of chemical compositions but also of homogenizing, forging and heat-treatment conditions to refine precipitates to prevent coarsening of re-crystallized grains and to increase sub-grain boundaries. **Figure 8** shows mechanical properties of KD610 compared to those of 6061 and KS651. KD610 allows almost 20% weight reduction compared to 6061 in a strength-controlled design. In addition, KD610 alloy has lower corrosive erosion compared to KS651 because of the optimized composition and heat-treatment which reduce coarse crystallites.

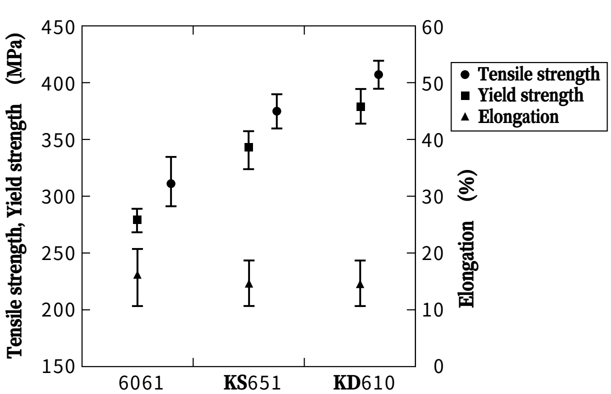


Fig. 8 Mechanical properties of developed 6000 series

3.4 Suspension production technology

We started production of suspensions using a 6300 ton mechanical press in 1991 and currently have four mechanical press lines to accommodate demand which started to increase in 2000. Each line is comprised of five process steps; preheat, buster, blocker, finisher and trim. Work pieces are transferred by robot hands from a step to the next.

Cost reductions of cast billets and increase of material yields have been the major issue since the material cost occupies 50% of the total cost. The billet cost was reduced significantly by the development of continuous horizontal billet-casting and scrap recycling technologies in 2001. Improvement of material yield has been achieved by developing two-cavity molds for I-shaped links and L-shaped upper-arms, by optimizing buster (rough) shapes and by introducing bending and roll-forming processes.

3.5 Global approach

As a part of globalization, we inaugurated a forging plant at Bowling Green, Kentucky and started production in June, 2005. The plant has the same process as the one used in the Daian Plant with minor modifications and is the first aluminum forging plant in the USA having the integrated capabilities of billet casting, forging, heat treatment and inspection. In the USA, there have been many suspensions using aluminum castings; however, applications of forged aluminum to suspensions are limited. Forged aluminum suspension parts, which are more promising in weight reduction than castings, are getting more attentions in the USA than in Japan and are expected to grow in their production scale that may exceed the scale of Japan.

4. Numerical analysis and joining technology

In addition to materials and production technologies, we are actively developing technologies such as numerical analysis and joining which are indispensable for the application of aluminum to automobiles. Numerical analyses are useful to obtain solutions for problems on formed products. Practical examples are shown in the second and third sections of this article. Here we review the trends and an example of numerical analyses including structural analysis. As for joining technology, technical trends in the automobile area and a few recent topics are reviewed.

4.1 Numerical analysis technology

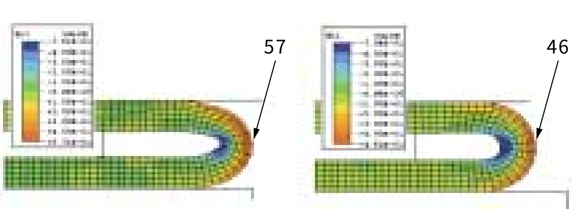
Recently numerical analyses have been adopted widely in forming technologies of aluminum. For automobile panels improvement of formability has been the major subject and numerical analyses have been applied to design molds to control material flow while preventing wrinkles and cracks. They have been used also to optimize the press conditions and lubrications.[12)]

Embossed aluminum sheets are used mainly in Europe for shielding of automobile exhausts. Such embossed sheets have characteristics totally different from those of plain sheets and numerical analyses are used for the forming successfully.[13)]

Cracking has been an issue for the flat-hemming process of hood-outers. To prevent cracking during the hemming process, control of the yield strength and reduction of work-hardening during the process are effective. Also effective is the modification of bending process. **Figure 9** shows a result of an analysis of the effect of bending radius r_d of the first step of hemming process[14)], showing a larger r_d reduces cracks and possibility of failures during the hemming process.

Aluminum roofs are usually joined to steel frames and the difference in thermal-expansion between aluminum and steel sometimes causes distortions during the heating for paint baking. Prevention of the distortion is also being considered by numerical analysis.[15)]

Wrinkles often occur during the bending process of extrusions. Numerical analyses enable predictions of critical bending radii for bend extrusions with complicated cross sectional shapes without wrinkles. The analyses assume hollow extrusions to be assemblies of plate elements fixed at the extrusion corners and determine the plastic-buckling limits of the elements.[16)] A wrinkle limit diagram for aluminum extrusion of 6063-T1 is shown in **Figure 10** as an example. The plots in the diagram show results of FEM analyses and the



(a) Downflange bending radius (b) r_d= 2.0 mm

Fig. 9 Numerical analysis results of flat hemming process

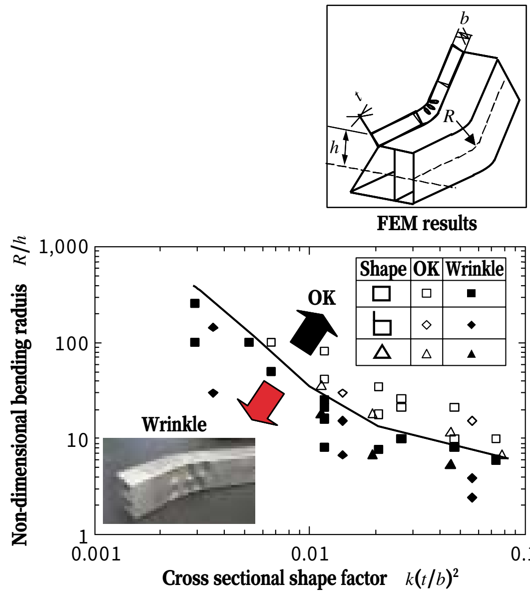


Fig.10 Wrinkle limit diagram for aluminum 6063-T1

solid plots show occurrences while the hollow plots show non-occurrences of wrinkles. The non-dimensional critical radius for wrinkle occurrence normalized by the distance h between the neutral axis and plate elements, R_{cr}/h, is determined by the elastic buckling coefficient k multiplied by the second power of the inverse of b/t, width-thickness ratio, $k(t/b)^2$. Cross-sectional shapes and bending radii to prevent wrinkles can easily be determined by this diagram.

Recently, structures that satisfy various regulations for front and side collisions are being considered from the safety stand point. Examples of bumpers and door beams are described in section two of this article. Besides, pedestrian protections are becoming important and hoods are being developed for the protection of pedestrians on impact in an accident.[17)]

4.2 Joining technology

Resistance spot welding (RSW) is the most common joining method of aluminum panels. Mechanical joining methods are also applied such as TOX®, TOG-L-LOC® which uses binding forces of plastic deformation and self-piercing rivets (SPR). Although the SPR has equal or higher joining performances compared to the RSW, special care has to be taken in the direction of piercing and lapping of materials for the joining strength when materials with different thicknesses are lapped together.[18)]

Recently a friction stir welding (FSW), spot type, technology has been developed and applied for the first time to MAZDA RX8. The spot type

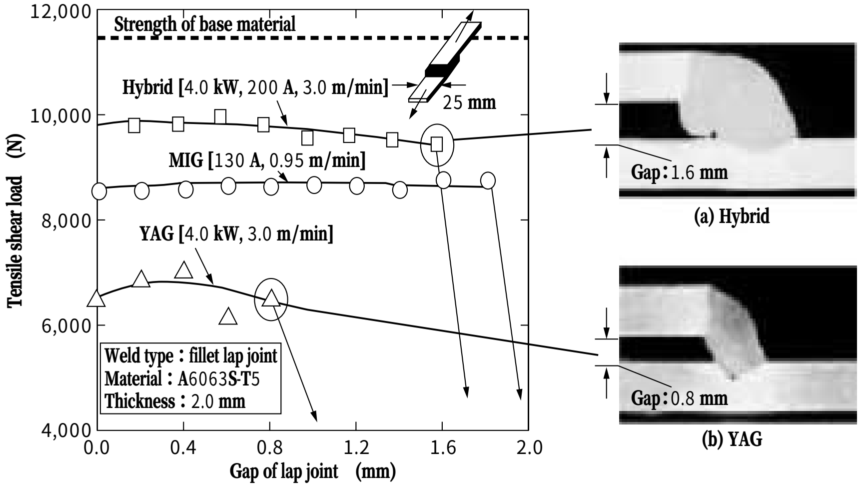


Fig.11 Relationships between tensile shear load and gap tolerances on fillet lap joints

FSW reduces joining energy significantly from the conventional RSW.

Laser welding has been developed for higher powers and better beam qualities. A high power, high-focusing YAG laser excited by a continuous oscillation lamp was developed several years ago, which enabled one-side welding and reduced distortion with its low heat input. The laser welding has started to be used for the lap joint of hood panels.

In order to expand the application of aluminum to structural members, continuous seam welding methods have been developed to ensure more welded volume. The hybrid welding of both laser and MIG welding methods has merits of gap-filling and high-speed[19] as shown in **Figure 11** and is used, for example, for the doors of VW Phaeton. The application of this method is expected to expand in the future.

Servo type pull-feed torches are used to prevent filler wire feeding troubles of MIG welding. The torches are retrofittable to existing power sources and robots of steel welding lines and have been developed for low-cost welding robot systems of aluminum.[20]

Conclusions

Recent application technologies of aluminum to automobiles have been described. Cost reduction is the major issue for aluminum products to be used more in the automobile applications. It is obviously important for an aluminum manufacturer to reduce cost of their products; however, total cost reduction will require application technologies of aluminum to draw the maximum benefit of using aluminum. Those technologies include cost and parts reductions of peripheral parts by utilizing recyclability and lightness of aluminum. We not only will keep supplying aluminum materials but also will promote cooperation with automobile and auto-parts manufacturers and develop aluminum technologies and products for automobile applications more comprehensively.

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