

Development of Aluminum Subframe Using Hot Bulging and Vacuum Die Casting

Fumiaki FUKUCHI*
Tsutomu OGAWA*

Takanori YAHABA*
Haruyuki IWASAKI*

Hiroshi AKIYAMA*
Izuru HORI**

ABSTRACT

The world's first aluminum subframe that is composed of bulge-formed members and die cast members welded by MIG has been developed.

The bulging employed a newly developed hot process with superior formability together with an alloy developed for the hot process. The die casting employed a newly developed vacuum die casting process and alloy which has superior weldability. A method of MIG welding was established after the weldability of these new alloys was researched. The developed subframe achieved a 20% cost reduction and 10% weight reduction while keeping functional performance equal to or better than the company's conventional aluminum subframe.

1. Introduction

The achievement of weight savings in automobiles is becoming increasingly necessary in order to contribute to the preservation of the global environment and the conservation of energy resources, in addition to improving dynamic performance. To respond to this need, aluminum subframes which are 35% lighter than conventional steel subframes are already being employed in some models.

However, the aluminum subframes currently in use are assembled by MIG welding with brackets press-formed from aluminum sheets to cradles formed from aluminum pipes at room temperature. The total number of parts used is high and the weld lengths are long, putting limits on the cost reductions that can be achieved.

The aim of the research described in this paper was to reduce costs by integrating parts. Hot bulge forming and vacuum die casting were studied as methods of achieving the desired integration of parts, and materials were optimized for these new production processes. Hot bulge forming is a new bulging method which was developed to enable an increased degree of freedom in the formation of aluminum pipes. Research continued with study of the MIG welding performance of the materials produced using the new methods, resulting in the creation of welding technology.

2. Development Goals

The following development goals were established for the new subframe:

- (1) Number of parts: 50% reduction against conventional subframe
- (2) Welding length: 50% reduction against conventional subframe
- (3) Weight: Equivalent to or lower than conventional aluminum subframe
- (4) Cost: 20% reduction against conventional subframe

The project aimed to reduce the number of parts and the welding length by employing hot bulge forming for the members and vacuum die casting for the brackets and the members, enabling parts to be integrated. Figures 1 to 4 show the configuration of the parts of the new subframe, while Tables 1 and 2 show the methods applied in the production of each part.

The subframe supports the suspension and supplements the rigidity of the body, and was therefore required to display an equivalent level of strength and toughness within the suspension, and an equivalent level of impact absorption performance to the body. The positioning of the joints between parts was optimized to enable these requirements to be satisfied. In addition, the integration of parts has increased dimensional accuracy after welding.

* Tochigi R&D Center

** Honda Engineering Co., Ltd.

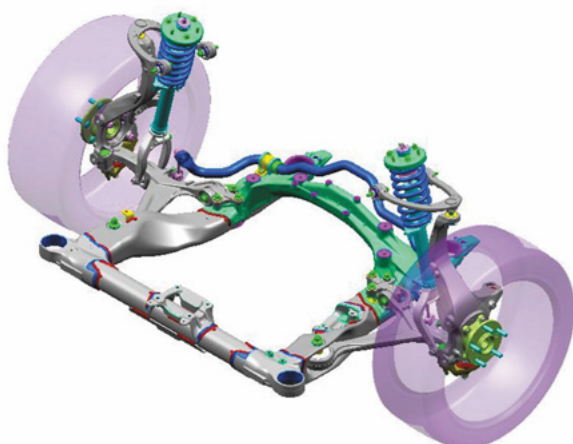


Fig. 1 Front chassis system



Fig. 2 Rear chassis system

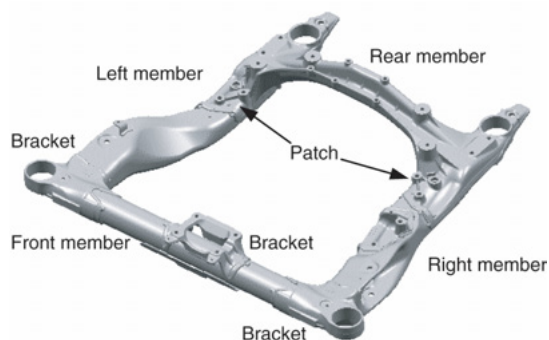


Fig. 3 Front subframe components

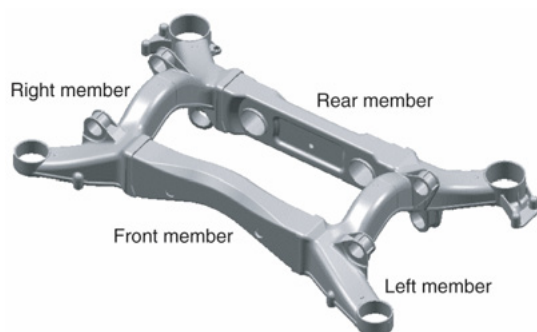


Fig. 4 Rear subframe components

Table 1 Application of process and alloy to front subframe components

Parts	Process	Alloy
Front member	Extrusion	Al-Mg
Rear member	Vacuum die casting	Al-Si-Mg
Left member Right member	Hot bulging	Al-Mg
Brackets	Squeeze die casting	AC4CH-T6
Patch	Stamping	A5052P-O

Table 2 Application of process and alloy to rear subframe components

Parts	Process	Alloy
Front member Rear member	Hot bulging	Al-Mg
Left member Right member	Vacuum die casting	Al-Si-Mg

Weight savings were achieved by increasing rigidity, optimizing the layout of the closed sections, and reducing thickness, chiefly in the structural parts. In particular, the employment of hot bulge forming enabled the sectional modulus of the bulge-formed members to be increased. In addition, the use of die casting enabled the thickness of the die cast members to be reduced and excess thickness to be eliminated.

3. Hot Bulge Technology

3.1. Issues in the Conventional Production Process

Bulge forming is a well established technique in the formation of pipes. The hydro-forming method, which uses liquid pressure in formation, is particularly widely used in the manufacture of subframes, and can be used with all materials. The adoption of this method enabled integrated formation of the cradles, which were formerly produced by welding a large number of pressed parts, considerably reducing the number of parts employed. However, because the conventional bulging process is a plastic forming process conducted at room temperature, in other words a cold process, the formability limit is comparatively low. The ratio of change of circular length (the ratio of the circular length of the original pipe to the circular length after formation) provides an index of formability, and in the case of conventional bulge forming is about 130%. This makes it difficult to achieve further integration of structural parts.

3.2. Development of a Hot Bulging Production Method

To solve this issue, the project focused on the characteristics of aluminum when heated in order to improve formability. As Fig. 5 shows, these studies demonstrated that when aluminum is heated to 510 °C, transformation resistance (pressure resistance) is reduced to 1/10 the figure the material displays at room temperature, and elongation is increased by a factor of six⁽¹⁾⁻⁽³⁾.

Exploitation of these characteristics by bulge forming while the pipe is heated (hot bulge) has increased the ratio of change of circular length to 190%, 1.5 times the ratio achieved using the conventional forming method. This has made it possible to form complex shapes and integrate parts.

In addition, the internal pressure during hot bulge formation is less than 1/100 that of hydro-forming, and this has enabled production facilities to be reduced in size.

In the hot bulge forming method, the change in dimension of the material during forming does not give an accurate indication of the thickness of the material after forming, and the reduction in thickness is particularly noticeable in parts with complex forms. To design hot bulge-formed parts, it is therefore necessary to predict the distribution of thickness after forming. A shape simulation technique was developed which takes into consideration the properties of aluminum when heated and the characteristics of the bulge forming process.

Because temperature and the velocity of strain have significant effects on the properties of aluminum, the parameters employed in the analysis were established on the basis of the results of tests of the properties of the material under temperature and strain conditions close to those experienced during actual forming. In addition, the boundary conditions and forming conditions with the most significant effect on the distribution of thickness were identified, and a database of measurements displaying excellent reproducibility was compiled. This research has enabled predictions of thickness accurate to within $\pm 10\%$. Figures 6 and 7 show a comparison of the result of the prediction of thickness in a simulation and the distribution of thickness in a formed part.

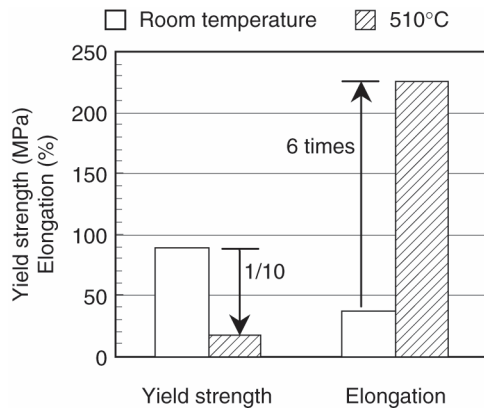


Fig. 5 Influence of bulging temperature on yield strength and elongation

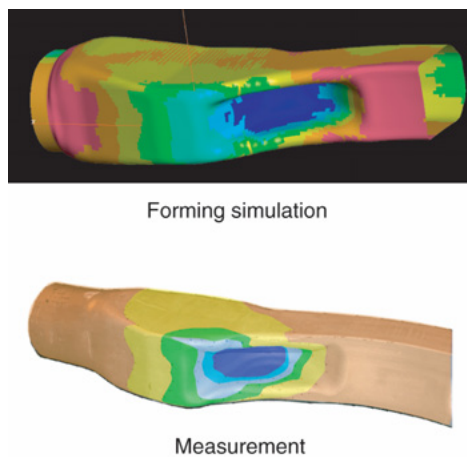


Fig. 6 Comparison of thickness distributions by forming simulation and measurement

In addition, an axial inserting procedure has been added to the forming process. The resulting improvement in the flow of the material has been verified as having an effect on controlling the reduction in the thickness of the material following formation. As Fig. 8 shows, increasing the amount of insert replenishes the material and lowers the rate of reduction of thickness. The division of control of internal pressure and the insert stroke into multiple steps has enabled thickness targets to be achieved, in particular in complex shapes. Figure 9 shows the values employed in a simulation of the control program for internal pressure and insert during forming and the results of application of control.

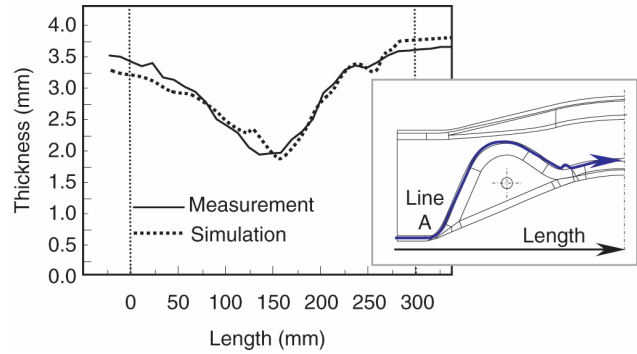


Fig. 7 Thickness distribution on line A

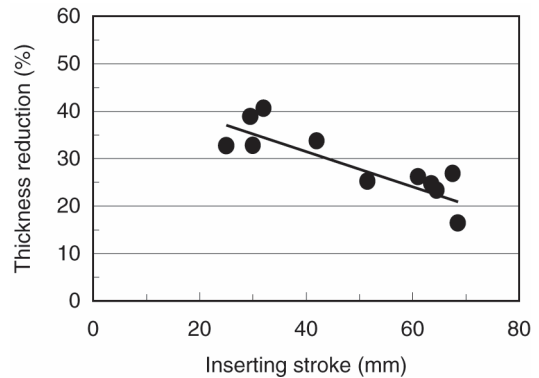


Fig. 8 Influence of inserting stroke

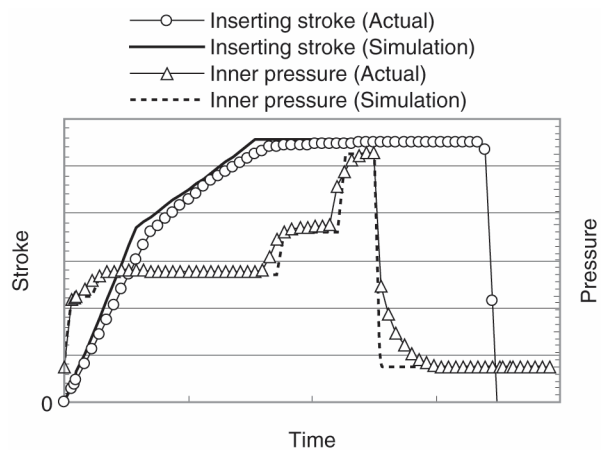


Fig. 9 Control of inserting stroke and inner pressure

3.3. Development of Material for Hot Forming Process

Because there was a possibility that grain growth (abnormal growth of crystal grains) and cavities which would cause material properties to decline might occur during forming if the former materials were employed in the hot bulge process, a new Al-Mg material was developed for use in hot forming.

Because residual stress from the process of formation of the original material and heat energy during heating causes recrystallization in the original material, grain growth is a difficult phenomenon to avoid in heat forming extended materials. In this project, Cr, which has been shown to be effective in grain fining⁽⁴⁾, was added to the material to control grain growth. As Fig. 10 shows, grain growth has been controlled through the addition of the optimum amount of Cr. Conditions for the forming process were also studied to control grain growth. The temperature in forming has a significant effect on this phenomenon, as can be seen in Fig. 11, and the temperature at forming and the time taken in the process were therefore optimized.

Cavities are microscopic vacancies originating at the interfaces of intermetallic crystallization phases or triple grain boundary points in the matrix of the original material when it undergoes a large amount of forming process. The black points in the photograph of the aluminum microstructure shown in Fig. 12 are cavities. In studying a means to reduce the occurrence of cavities, the project first determined the upper limit for the cavity ratio (the ratio of the area of cavities to the total area of a surface used in measurements) at which satisfactory materials performance could still be ensured. Next, to enable the occurrence of cavities to be controlled, the relationship between the amount of Fe and Si added and the cavity ratio was clarified. As Fig. 13 shows, reducing the amount of Fe and Si reduces the intermetallic crystallization phases, consequently reducing the cavity ratio. This relationship was employed in establishing the acceptable range for the volume of Fe and Si components.

The techniques discussed above enabled the development of an Al-Mg alloy which displays identical properties to the conventional alloy even after hot forming.

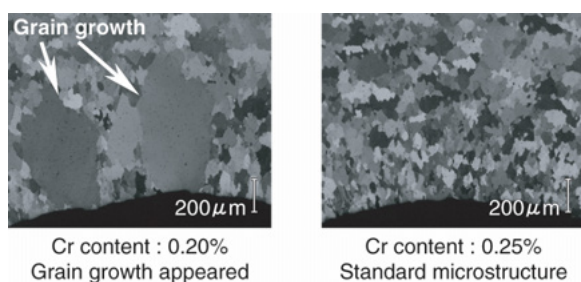


Fig. 10 Influence of Cr content on grain growth

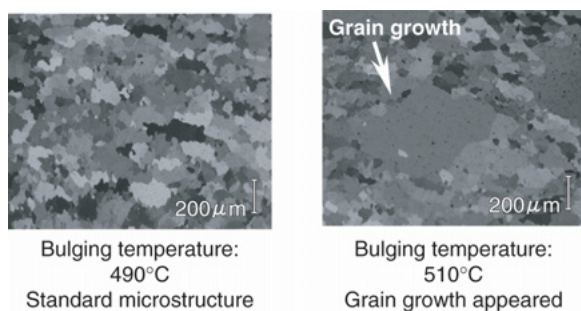


Fig. 11 Influence of hot bulging temperature

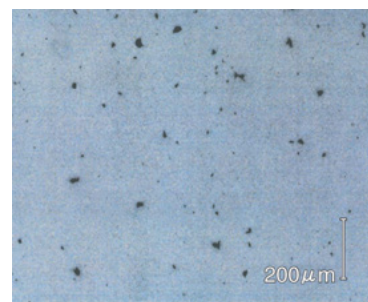


Fig. 12 Cavity in aluminum microstructure

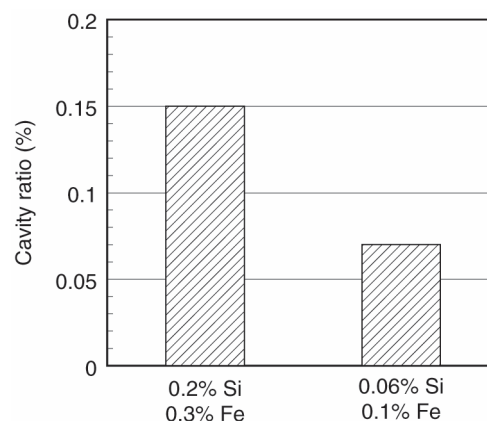


Fig. 13 Influence of Fe and Si content on cavity ratio

4. Vacuum Die Cast Technology

4.1. Issues of Conventional Production Method

The die is filled with molten metal instantaneously, and this makes it difficult to reduce the amount of casting defects such as oxide inclusions and blowhole occurring in the casting and ensure a level of die cast quality appropriate for use in an automotive subframe. In addition, gas is easily trapped in the mold, and the gas content of the casting is normally higher than 20 cm³/100 gAl. For this reason, when the casting is welded, numerous blowholes occur in the welding bead, and ensuring welding strength is another issue. There are few examples of the use of die casts in a subframe, and even fewer examples of their use in a welded structure.

The following targets were established in this project in order to solve these issues:

- (1) Achievement of a high level of casting quality, commensurate with use in an automotive subframe
- (2) Development of a die cast alloy with excellent weldability

4.2. Achievement of Casting Quality

The project first studied optimization of mold patterns and casting conditions to enable improvement of casting quality. Figure 14 shows an example of the simulations of the flow of molten metal employed to analyze the effect of the position of the gate and overflow and changes in the casting conditions. Pattern A was predicted to trap a great deal of gas, while in pattern B the molten metal fills the mold uniformly, reducing the amount of trapped gas. The area of the gate was increased to enable filling of the die in a shorter time. In terms of casting conditions, the speed of injection of the metal into the mold has been increased (during high-speed injection, to more than twice the speed employed in the

former method) to fill the mold in a shorter time, and the temperature of the die has been controlled.

Next, to reduce the amount of gas in the castings, the volume of die lubricant and tip lubricant, which produce gas, has been reduced, and the pressure in the die was reduced to create a vacuum (vacuum die casting), as shown in Fig. 15.

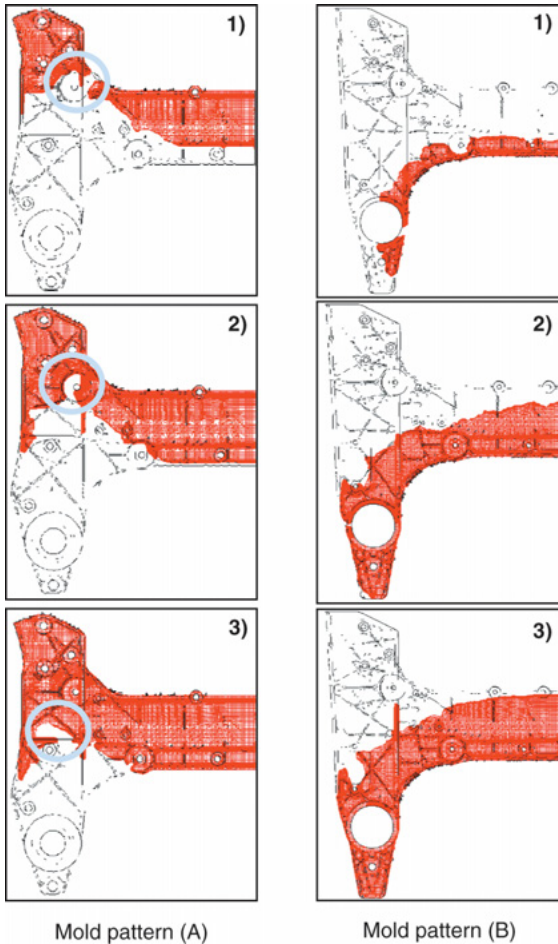


Fig. 14 Comparison of mold patterns by flow simulation of molten metal

Vacuum circuits have been positioned at several points, including the part of the die that is filled last, the most effective positioning for reducing the amount of trapped gas⁽⁵⁾, and the internal pressure has been reduced to less than 5 kPa. Optimization of the timing of the pressure reduction has further reduced the amount of trapped gas, resulting in the achievement of a gas content of less than 3 cm³/100 gAl as shown in Fig. 16. 85-90% of this gas is H₂, with the remainder made up of N₂ and other gases.

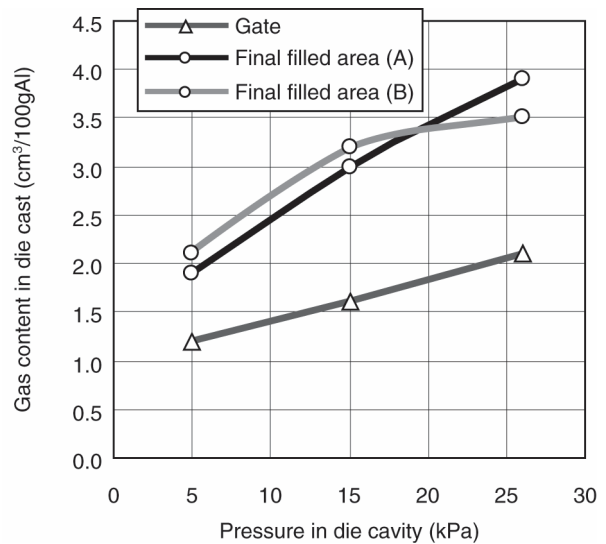


Fig. 16 Relation between pressure and gas content in die cast

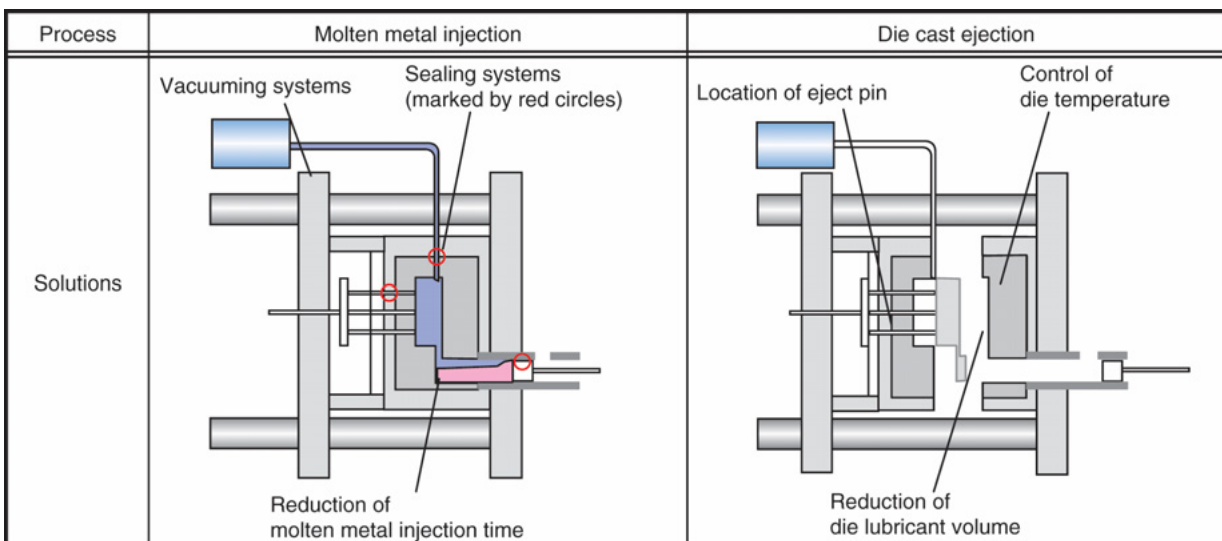


Fig. 15 Outline of solutions for vacuum die casting

4.3. Development of Die Cast Alloy

An Al-Si-Mg alloy is widely used in the casting of subframes. This alloy is strong and displays excellent castability. After a study of the required design properties of the material employed in the new subframe, this alloy was used as a base in the development of a new die casting alloy. T5 was adopted as the heat treatment, to eliminate the necessity of correcting the strain occurring in the application of the T6 solution treatment.

In establishing the composition of the new alloy, the effect of the amount of Si and Mg in the material was first studied. ASTM test pieces produced by a 200 ton die cast machine were used to evaluate the properties of the material, and the conditions employed in the T5 heat treatment were also investigated. Next, flat sheet test pieces were produced and the bead quality and joint strength after welding were studied to evaluate weldability. On the basis of the results of these tests, the basic composition was established based on an Al-Si hypoeutectic alloy, and the range of Mg content was set to enable design property targets to be satisfied. The Fe and Mn content was established through consideration of the anti-soldering performance of the material. Anti-soldering can normally be ensured with an Fe content of over 0.8 wt% and an Mn content of over 0.4 wt%^{(6),(7)}. The synergistic effect between Fe and Mn was considered in the design of the new alloy, and a range for these components has been established which ensures anti-soldering performance but does not affect toughness. Figure 17 shows the microstructure of the newly developed alloy. As this photograph shows, the Al-Si eutectic microstructure and the

amount of precipitation of inter-Al-Mn-Si compounds has been reduced against the former alloy.

In terms of mechanical properties, as Fig. 18 shows, the new alloy shows an excellent balance of tensile strength, yield strength, elongation and impact value. The reduction of cold flaking in comparison to the former alloy has reduced the level of variations occurring in these properties.

5. Aluminum Welding Technology

In addition to the composition of the alloy and the quality of the materials, the quality of aluminum welding is significantly affected by all the elements of the welding process, including the filler metal employed. It is therefore necessary to establish optimum conditions for each material being welded.

This research project therefore clarified the welding characteristics of the materials formed using hot bulging and vacuum die casting, and established appropriate conditions for MIG welding.

5.1. Weldability of Hot Bulge-formed Material

Because extruded pipes are used in the hot bulging process, the study of weldability focused on the quality of the surface. The lubricants and high temperatures employed in this production method cause an oxide film more than 100 nm thick to form on the surface of the material. This surface film makes the welding arc unstable and prevents sufficient melting of the bead, and must therefore be cleaned.

Figure 19 shows the results of studies of film cleaning.

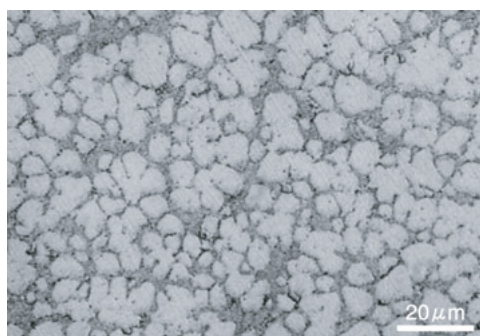


Fig. 17 Microstructure of developed alloy

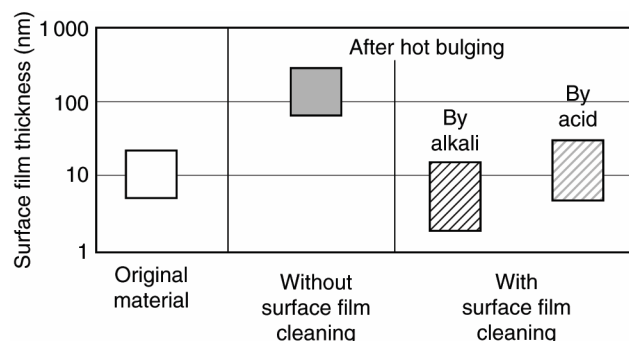


Fig. 19 Comparison of surface film thickness

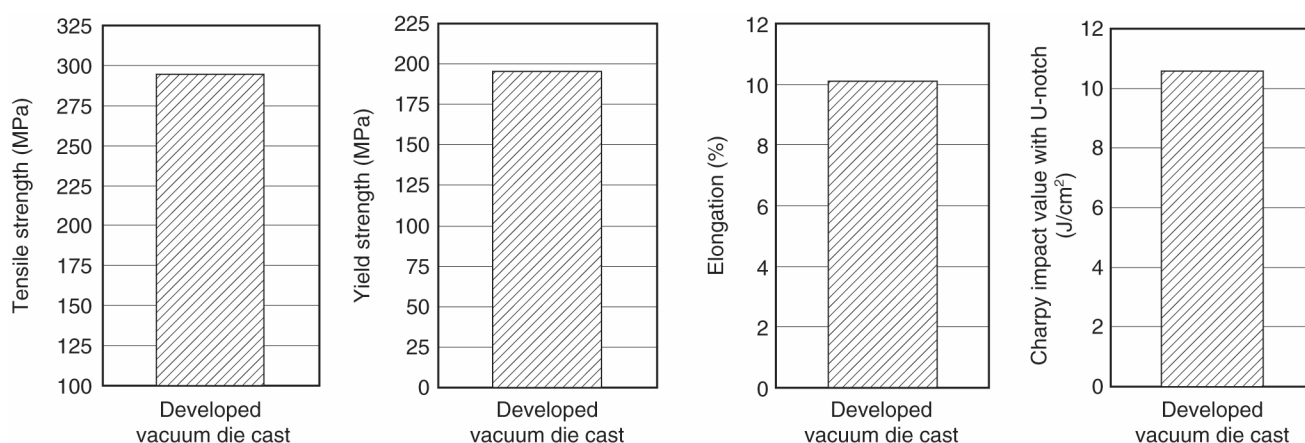


Fig. 18 Mechanical properties of developed vacuum die cast

These studies demonstrated that cleaning with alkali or acid reduced the thickness of the film to a level equivalent to that measured on the material before hot bulging.

Figure 20 shows the difference in welding quality with and without surface film cleaning. Removing the surface film and achieving a uniform state across the surface has stabilized the welding arc and increased the depth of melting of the bead.

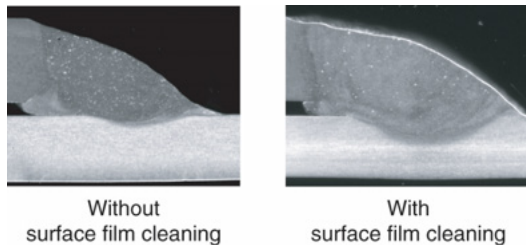


Fig. 20 Influence of surface film cleaning on welding quality

5.2. Weldability of Vacuum Die Cast Materials

As Fig. 21 shows, the gas content of the new vacuum die casts is less than $3 \text{ cm}^3/100 \text{ gAl}$, an identical level to that previously measured in a thixo die casting⁽⁸⁾. The relationship between gas content and welding bead quality is shown in Fig. 22. At a content of $6 \text{ cm}^3/100 \text{ gAl}$ blowholes occur, and at $8 \text{ cm}^3/100 \text{ gAl}$ numerous blowholes occur in the upper part of the bead. Because these blowholes reduce the effective throat thickness of the joint strength and cause the quality of the join to decline, in MIG welding it is necessary to ensure a gas content of less than $3 \text{ cm}^3/100 \text{ gAl}$. The use of the new die cast alloy reduces the occurrence of blowholes, and ensures excellent weld quality.

The results of measurements of the thickness of the surface film on the vacuum die cast using Auger electron spectroscopy showed a thickness of around 20 nm, with little effect on weldability.

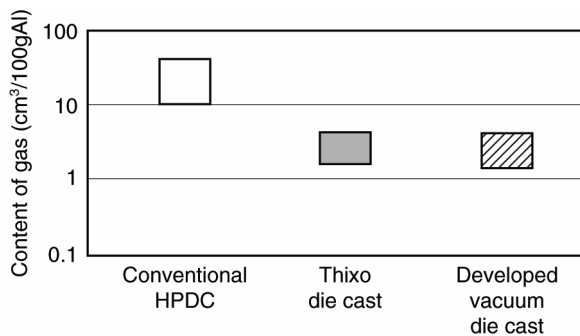


Fig. 21 Comparison of gas content

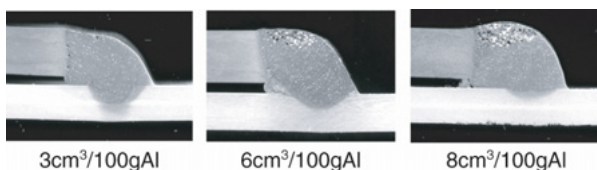


Fig. 22 Influence of gas content on blowhole

Welding conditions applicable to use with an automotive subframe were developed on the basis of these studies of the weldability of the newly developed materials. In addition, conditions were adjusted throughout the production process in order to ensure that these welding conditions could be achieved.

6. Conclusion

Hot bulge and vacuum die cast production techniques were developed as part of a project attempting to achieve cost reductions in aluminum subframes through the integration of parts. The following results have been achieved:

- (1) A lightweight and low-cost hybrid aluminum structure has been produced by MIG welding bulge-formed members and vacuum die cast members.
- (2) The development of a hot bulge process and an alloy for use in hot forming has enabled the achievement of a high degree of freedom in formation (1.5 times the ratio of transformation of circular length achieved with the former materials), making it possible to form complex shapes.
- (3) The development of a vacuum die cast process and an Al-Si-Mg die cast alloy has enabled the production of weldable die cast parts with excellent and well-balanced mechanical properties.
- (4) In MIG welding, the reduction of the thickness of the oxide film on the surface of the hot bulge-formed parts and the control of the gas content of the vacuum die cast parts to below $3 \text{ cm}^3/100 \text{ gAl}$ has ensured strength in the weld joints, and the conditions of welding have been optimized.

These developments have reduced the number of parts by 70%, welding length by 55%, weight by 10% and cost by 20% against conventional aluminum subframes.

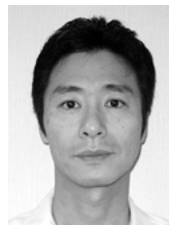
The authors hope that this research will result in the wider application of aluminum subframes and therefore contribute to automotive weight savings.

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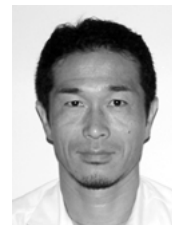
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■ Authors ■



Fumiaki FUKUCHI



Takanori YAHABA



Hiroshi AKIYAMA



Tsutomu OGAWA



Haruyuki IWASAKI



Izuru HORI