

Development of Steel and Aluminum Continuous Welding Technology Using FSW and Application to Subframes

Tetsuya MIYAHARA*

Mitsuru SAYAMA*

Takanori YAHABA**

Shousuke OHHAMA*

Tsunehisa HATA*

Tsutomu KOBAYASHI*

ABSTRACT

Continuous welding technology that uses Friction Stir Welding and has a welding strength equal to or above that of MIG welding was developed to weld together steel parts and aluminum parts, and at the same time technology was also developed to rustproof areas where dissimilar metals are welded. In order to apply this welding technology to mass production, an original welding system using an industrial articulated robot was developed, and application was realized with an efficiency and investment equivalent to that of conventional MIG welding. In addition, an inspection system using a highly sensitive infrared camera and laser beam was also developed as a non-destructive in-line system to assure joint strength. This technology was applied to the front subframe, which is a structural component of mass-production vehicles. As a result, compared to the previous model, the weight was reduced by 25%, the rigidity of the suspension mounting point was increased by 20%, the vehicle's dynamic performance was enhanced, and electrical power consumption during the welding process was reduced by 50%.

1. Introduction

Recently, needs are increasing to reduce vehicle weights and to conserve energy in the production stage from the viewpoints of reducing carbon emissions, conserving energy, and enhancing fuel economy performance and dynamic performance in order to protect the global environment. The function required of the front subframe is to possess sufficient support rigidity to support the suspension, power plant, and steering gear box. In addition, the subframe must also contribute to steering stability performance, vibration and noise performance, and collision performance. For these reasons, automotive manufacturers are actively researching and developing welding, structural, material and other technologies to efficiently achieve a good balance of the required performances with reduced weight and low cost⁽¹⁾. One method of reducing weight is to mechanically join aluminum members to aluminum subframes and steel subframes. Conventional subframes have mostly used MIG welding, so there was a limit to how much energy consumption could be reduced in the manufacturing stage. Furthermore, mechanical joining

methods are point connections, so weight reduction and increases in rigidity are also limited, which makes it a challenge to greatly enhance dynamic performance.

This development focused on Friction Stir Welding (hereafter "FSW"), which consumes less electrical power and has a lower running cost in the manufacturing process compared to MIG welding, and developed dissimilar-metal welding technology to take the place of conventional MIG welding and mechanical joining. Generally speaking, sufficient joint strength cannot be obtained when welding together steel and aluminum, so these dissimilar metals could only be joined mechanically or bonded using adhesive. In addition, dissimilar-metal welding technology using FSW is being actively researched^{(2), (3)}, but there are no known cases of practical application, and insulating technology for rustproofing also has not yet been established. Furthermore, the known cases of FSW use large welding equipment, which requires a large installation area and high infrastructure investment. Therefore, a space-saving welding system was developed that can be applied to existing plants and production lines with low infrastructure investment, and which also has a production tact equivalent

* Automobile R&D Center

** Honda Motor Co., Ltd.

to that of MIG welding in consideration of application to mass production of 1500 units or more per day. In addition, ultrasound tests and other techniques are known as non-destructive methods of observing the inside of FSW joints, but in subframes the joints are located inside the various members, so they cannot be easily checked. This made it necessary to develop non-destructive inspection technology that can accurately inspect the inside of joints in a short time, so an original inspection system was constructed.

2. Dissimilar-Metal Welding Technology Development Goals and Parts Development Target Values

The goals of this technical development were the following four items.

- (1) Establishment of technology for welding together the dissimilar metals of steel and aluminum
- (2) Establishment of rustproofing technology
- (3) Establishment of a mass-production welding system using industrial robots
- (4) Establishment of non-destructive inspection technology and an inspection system

Next, the following target values were set to realize mass production of hybrid subframes comprising both steel and aluminum members.

- (1) Weight: reduction of 10% or more compared to the previous model
- (2) Number of component parts: reduction of 30% or more compared to the previous model
- (3) Rigidity of the suspension mounting point: increase of 10% or more compared to the previous model
- (4) Electrical power consumption during the welding process: reduction of 30% or more compared to the previous model
- (5) Cost: equivalent to that of the previous model

3. Steel and Aluminum Welding Method and Welding Mechanism

FSW, which enables bonding with low heat input, was selected as the method of welding the dissimilar metals of steel and aluminum. As shown in Fig. 1, FSW is solid-

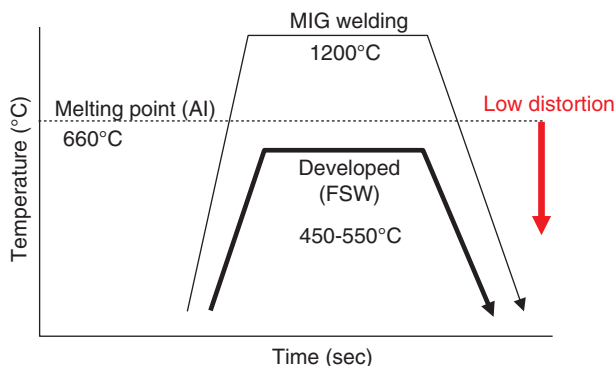


Fig. 1 Welding temperature of FSW

state welding at a temperature below the melting point, which enables suppression of the formation of coarse and brittle intermetallic compounds (hereafter “IMC”). The joint is formed as shown in Fig. 2 by applying pressure from the aluminum side to insert the tool while rotating the tool. As a result, the aluminum side is stirred, the tip of the probe destroys and removes impurities such as the galvanization, cathodic electrodeposition, and sealer on the steel surface to reveal the bare surface of the steel, and IMC are formed to bond the metals. The IMC composition was confirmed by the electron diffraction pattern to be $\text{Fe}_4\text{Al}_{13}$. In addition, it was also confirmed that the IMC thickness is suppressed to approximately $1\ \mu\text{m}$. Figure 3 shows the confirmation results using a Scanning Electron Microscope (SEM) and a Transmission Electron Microscope (TEM). In order to set the appropriate FSW joining conditions, it is important to stabilize the plastic flow and control the probe insertion position, and consideration must also be given to structural advantages due to differences in the shape of the hook created by the plastic flow in the FSW stirring area. Regarding the joining condition settings, the

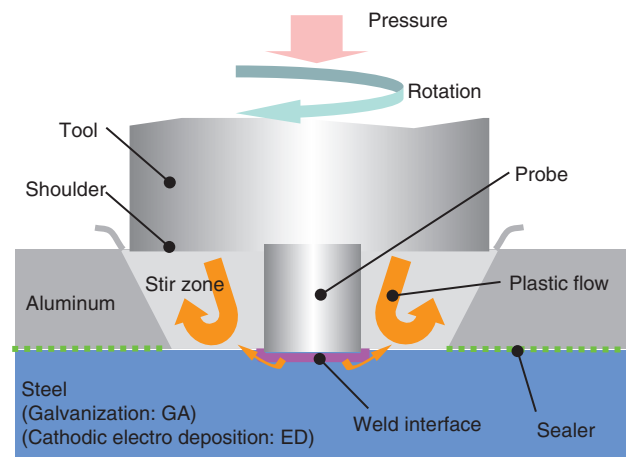


Fig. 2 Cross-sectional structure of Steel and Aluminum FSW

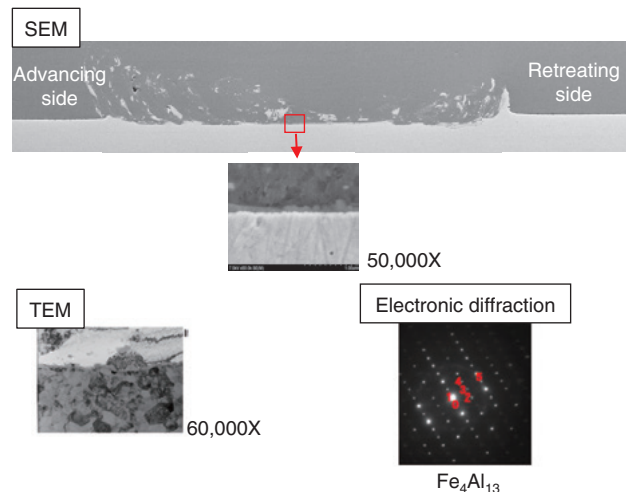


Fig. 3 Observation of IMC

shaded area in Fig. 4 was found to be the appropriate range based on the relationship between the rotations and the feed speed. Insertion position control is particularly important when welding dissimilar metals. When the probe insertion position is too shallow, impurities are not adequately discharged from the boundary, and a stable joint boundary cannot be obtained. Conversely, when the probe insertion position is too deep, even if impurities can be adequately discharged from the boundary surface, the contact between the steel and the probe is too strong, resulting in an excessively large hook or other factors that may reduce the strength. In addition, this also leads to a drop in probe durability, so it was necessary to set an appropriate range.

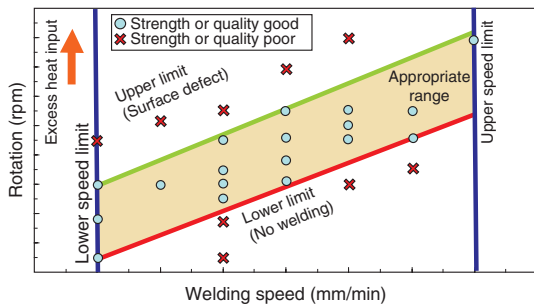


Fig. 4 Range appropriate FSW conditions

4. Rustproofing Technology

Figure 5 shows a schematic cross-section of a welding part. There is no cathodic electrodeposition around the joint between the dissimilar metals or on the steel surface in the edge area, and the galvanization and aluminum are in direct contact with each other. A structure that fills the gap between the steel and aluminum with sealer was used to prevent water or other substances from entering and corroding this type of welded joint between dissimilar metals. Table 1 lists the functions and physical properties required of the sealer. From these viewpoints, a single fluid denatured silicon-based sealer material was selected. Next,

Table 1 Required functions and properties for sealer

	Required function	Required property
(1)	Shut off from corrosion factors (water and corrosion current)	Water tightness, adhesion, and insulation
(2)	No failure to depend on frictional heat	Thermal stability
(3)	No failure to depend on market degradation	Durability over environment and vibration
(4)	Minimum investment in equipment and minimum cost for production control	One part agent providing cold curing

Fig. 6 shows the welding procedure. The sealer is applied before welding in order to completely fill the gap, and the coating diameter and position are also optimized. The joint strength with and without sealer was compared, and the sealer was confirmed to have no effect on the strength. In addition, Fig. 7 shows cross-sectional photos of the area around the joint after a 120-cycle test in a Cyclic Corrosion

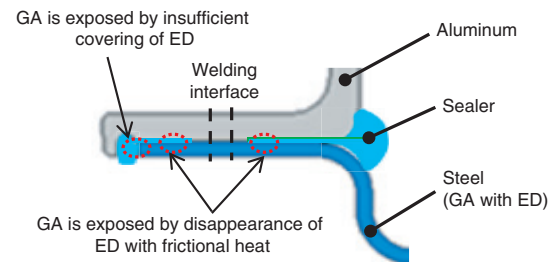


Fig. 5 Schematic cross section of welding part

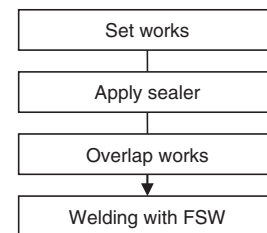


Fig. 6 Welding flow process

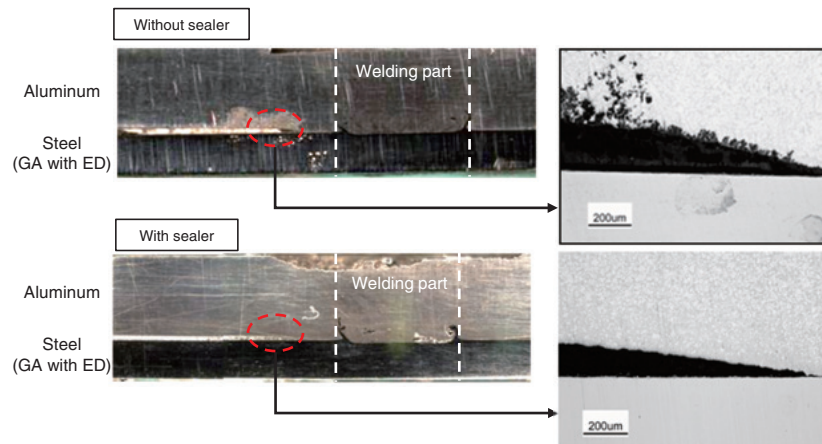


Fig. 7 Cross-sectional photos of welding test pieces with and without sealer after 120 cycles CCT

Tester (CCT). Corrosion with a maximum depth of 0.4 mm occurred on the aluminum side of the test piece without sealer, but corrosion did not occur on the test piece with sealer. In this manner, joint rustproofing effects can be obtained by using sealer. Furthermore, sacrifice corrosive protection effects maintain the rustproofing effects even if the cathodic electrodeposition on the back side of the joint peels off.

5. Robot FSW Technology

FSW continuous welding is generally performed using a large gate-type welding machine^{(4), (5)}. This is because a large load is applied to the tool during welding, so a highly rigid machine is necessary. Applying this type of large machine to mass production requires a large installation area (Fig. 8) and large investment, which makes introduction to existing plants and production lines difficult. Therefore, it was decided to develop a welding unit that requires a small installation area and suppresses investment by using an industrial articulated robot. There are cases of research on FSW continuous welding using articulated robots^{(6), (7)}, but to date it has been considered necessary to develop special

robots with a high rigidity able to withstand the large loads during welding. In particular, when performing FSW continuous welding on the subframe structure in this study, the load in the axial direction of the tool is 10 kN or more. However, instead of developing a special robot that can withstand this load, the FSW welding system shown in Fig. 9 was developed with the aim of not placing a high load on the robot. This welding system eliminates the robot load in the axial direction of the tool by mounting an FSW unit with a highly rigid C-shaped frame structure onto a robot. In this welding method, a steel part and an aluminum part are set in a supported welding jig, and the FSW welding unit welds together the parts by clamping the work together with the jig. In addition, the jig side of the C-shaped frame is a roller, which enabled sufficiently reducing the load generated in the weld advancing direction to within the allowable load range of the robot. Furthermore, the welding speed is also equivalent to that of general MIG welding, thereby achieving the production tact in conventional mass production.

The robot used performs 6-axis control, but the developed system incorporates two axes (welding tool rotation and insertion position) into the robot's own control system,

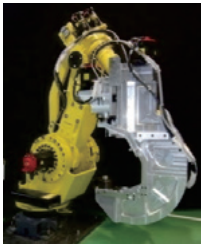
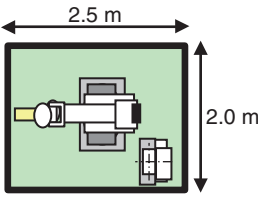
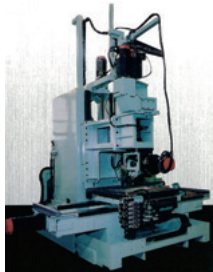
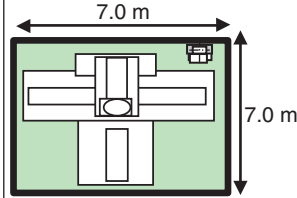
FSW unit of C-gun type robot		FSW unit of marketing	
Appearance	Ground contact size	Appearance	Ground contact size
	 Equipment height: 2.5 m		 Equipment height: 5.0 m

Fig. 8 Comparison of FSW units

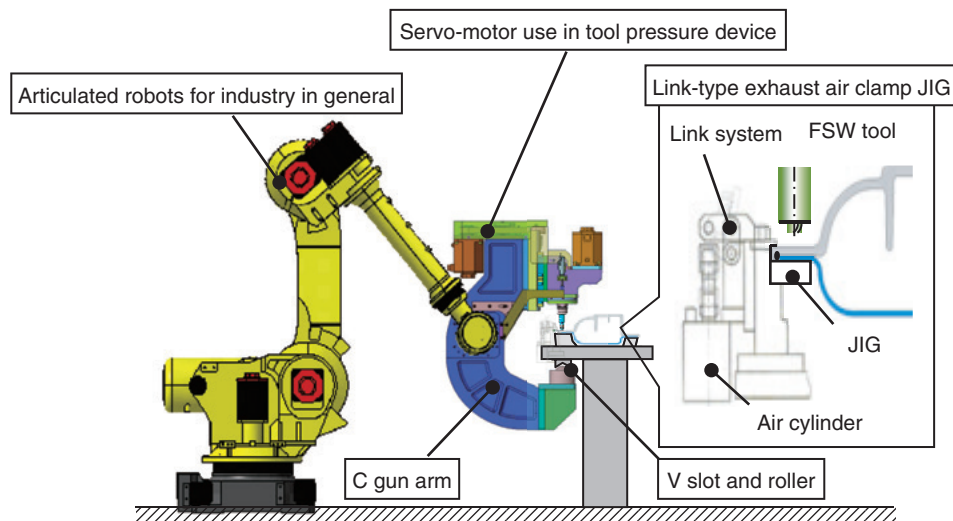


Fig. 9 FSW equipment appearance

and performs integrated control. This realizes a simple system that does not require a special control unit or other devices for welding. This system can be taught both online and offline in the same manner as a normal robot, and two- or three-dimensional welding programs can be easily created. In addition, the welding tool rotations and insertion position, the welding speed, and other parameters are controlled collectively, which enables constant monitoring of the welding status and real-time quality control.

The ability to use industrial robots enables production with stable quality in existing plants and production lines. In addition, this FSW welding system is highly versatile and can also be used to weld aluminum-to-aluminum structures.

6. Non-destructive Inspection Technology and Inspection System

It was decided to perform both condition control that includes monitoring of the welding status, and in-line non-destructive inspection that enables inspection of every unit as quality control for areas where dissimilar metals of steel and aluminum are welded. Existing non-destructive inspection technology is unable to accurately judge the quality of dissimilar-metal joints in a short time, so a new inspection system was developed by incorporating a laser excitation system onto the base of a thermal image analyzer using optical excitation. This system uses the principle of active thermography, and includes a heat source suited to the subject materials. Active thermography is a technology for visualizing the information in the lamination direction (plate thickness direction) when heat energy is applied to a material. When a material absorbs applied heat energy, locations (cavities, defects, boundaries, etc.) that differ from the base material (normal areas) radiate heat energy as self-energy. This phenomenon is measured using a high-performance infrared camera, and visualized by performing frequency analysis. Conventional excitation methods had the issue that when applied to materials with high thermal conductivity such as aluminum, the heat diffusion was greater than the heat transfer speed in the depth direction,

so accurate measurement was not possible. Therefore, a laser device with high energy irradiation and easy output adjustment (power density, time control) was incorporated to construct a system for welding the dissimilar metals of steel and aluminum parts (Fig. 10). In addition, the following features were taken into account for application.

6.1. Cross-sectional Structure of Joints

The cross-sectional structure of dissimilar-metal joints can be classified into three areas as follows (Fig. 11).

- (a) An area with high thermal conductivity where IMC are formed
- (b) An area where IMC are not formed, but the dissimilar metals are closely adhered and the thermal conductivity is lower than that in area (a)
- (c) An area with greatly reduced thermal conductivity due to the presence of sealer, cathodic electrodeposition, an air layer, and other factors

This system detects the differences in the reflected energy phase from each of these areas, and is used to determine the welding quality.

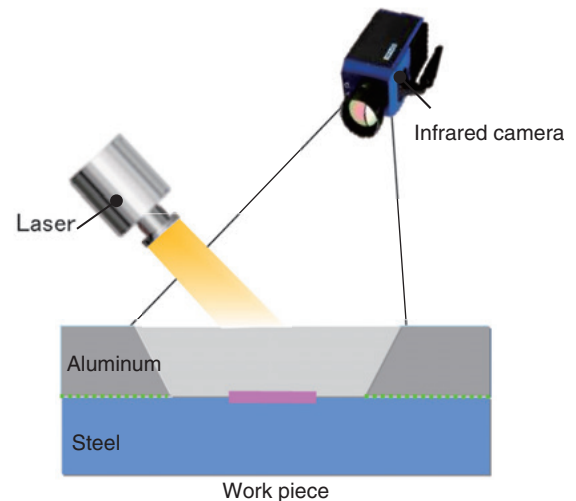


Fig. 10 Non-destructive inspection equipment

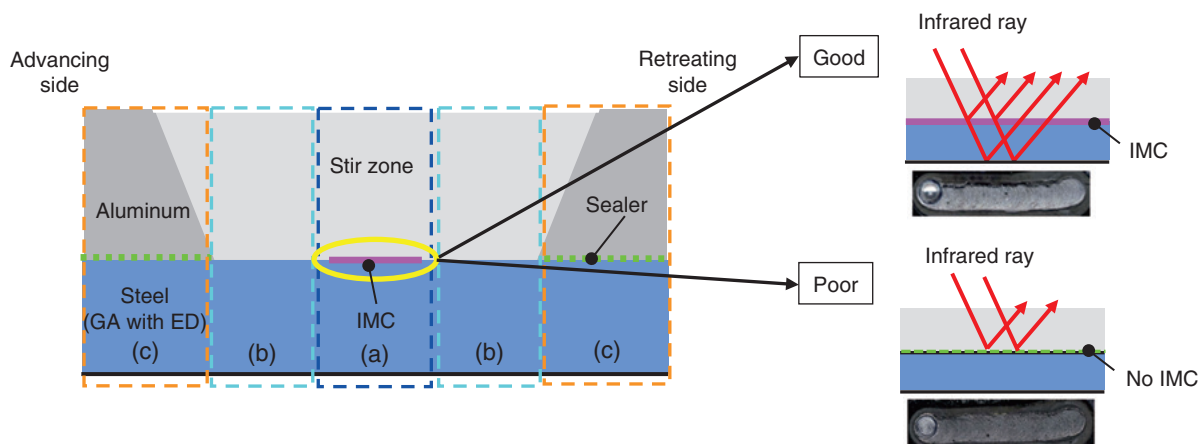


Fig. 11 Cross-section structure and judgment of welding

6.2. Steel and Aluminum Joint Structure

FSW joints are used for two-part structures with a steel part and an aluminum part, and three-part structures with two steel parts and one aluminum part. Therefore, the reflection method was adopted to enable measurement of all structures in the same manner (Fig. 12). In addition, the reflection method is affected by noise due to surrounding reflected light, so measurement conditions and judgment values were set and a re-measurement method was incorporated to increase the measurement accuracy with respect to reflected light.

Judgment criteria were set based on the relationship between the joint strength and the phase angle (Fig. 13), and adoption of this system enabled in-line inspection of all units.

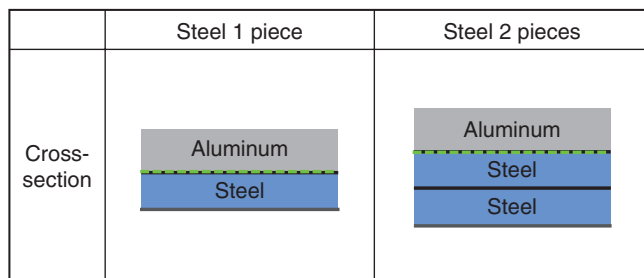


Fig. 12 Steel construction

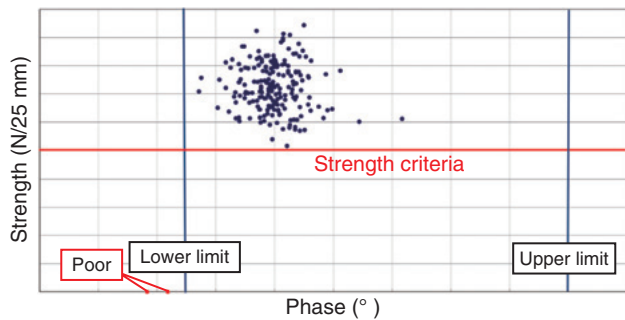


Fig. 13 Measurement result of non-destructive inspection

7. Structure of Hybrid Subframe Using Dissimilar Metal Welding Technology

The subframe functions to support the suspension, power plant and steering gear box (Fig. 14), and it also provides sufficient support rigidity and contributes to control in collision mode. Figure 15 and Table 2 show the structure and the material composition. The rear member is made of aluminum diecast to provide and increase support rigidity for the power plant and steering gear box with the aim of reducing both the weight and the number of component parts. In addition, this aluminum diecast rear member was also positioned to increase the rigidity of the suspension lower arm mount that has a high contribution to dynamic

Table 2 Materials of hybrid subframe for FSW

Steel parts		Aluminum parts	
Part name	Material	Part name	Material
Side member upper right-hand side	JAC270C	Rear member	Equivalent ADC3
Side member upper left-hand side			
Side member lower right-hand side			
Side member lower left-hand side			

performance. Steel sheet material is used for the side member lower to stabilize energy absorption and prevent the subframe from separating in the event of a collision. In the previous model, steel sheet member and aluminum diecast member components were joined mechanically using multiple bolts. The hybrid subframe has a structure with flanges formed from the various steel sheet members and aluminum diecast members, and these dissimilar metal flanges are welded using FSW. This reduces both weight and cost and saves energy.

The newly developed rear member is 3.2 times heavier and has a product projection area 2.4 times that of the member of the previous model (Fig. 16). Modification of the product shape and use of a compact casting plan enabled

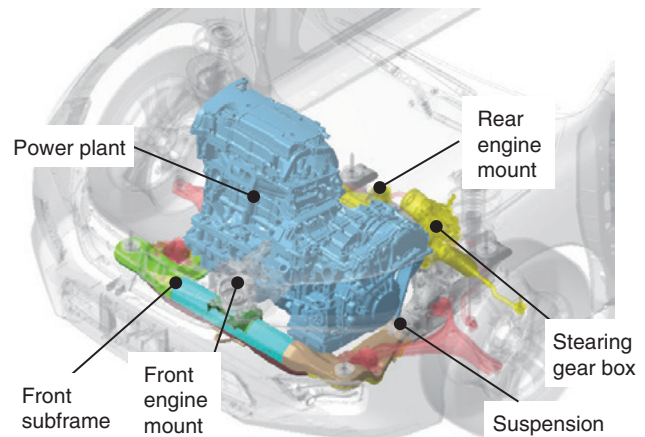


Fig. 14 Front subframe position of vehicle

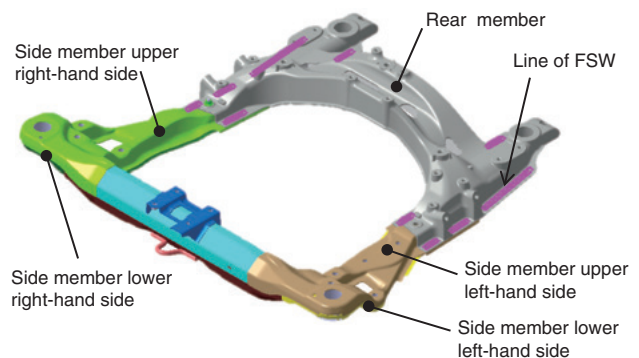


Fig. 15 Hybrid subframe components (after FSW)

using the same casting machine as the previous model, casting of two parts with a single die, increasing casting quality and reducing costs. In addition, the FSW welding surface thickness accuracy has a large influence on welding quality. Therefore, the required mechanical properties were secured and thickness accuracy was enhanced by optimizing the casting plan and casting conditions, modifying the cross-section and rib shapes required for the subframe functions, and enhancing the fluidity. This eliminated machining of the FSW joint surface, which reduced costs. As a result, by adopting an aluminum diecast rear member, and by establishing and applying dissimilar metal welding technology using FSW, the number of component parts was reduced by 40%, the weight was reduced by 25%, and the rigidity of the suspension mounting point was increased by 20%. Compared to the previous model, the MIG welding length was also reduced, which enabled reduction of electrical power consumption during the welding process by 50%.

Part name	Bolt tightening member	Rear member
Model year	2008	2013
Figure		
Weight [kg]	2.62	8.41
Projection area [cm ²]	1008	2446
Casting machine/cavity	High vacuum diecast 3500 ton/2 cavity	High vacuum diecast 3500 ton/2 cavity

Fig. 16 Comparison of bolt tightening member and rear member

8. Conclusion

Technology for continuously welding dissimilar metals using FSW was developed, and mass-production technology was established. As a result, the following results were obtained.

- (1) The IMC mechanism of welded joints was clarified, and appropriate welding conditions were constructed.
- (2) Technology was established for rustproofing structures that use dissimilar metal welding technology.
- (3) A C-shaped frame and jig structure using an industrial articulated robot and robot control technology were developed, and a highly versatile mass-production welding system was established.
- (4) Non-destructive inspection technology was developed that incorporates a laser excitation system onto the base of a thermal image analyzer using optical excitation, and an in-line inspection system for mass production was established.

Compared to the previous model, these effects reduced the weight by 25%, reduced the number of component parts

by 40%, increased the rigidity of the suspension mounting point by 20%, and reduced electrical power consumption during the welding process by 50%. In addition, costs could also be reduced by 5%. Expanded application of dissimilar-metal welding technology and hybrid structure subframes in the future can contribute further to reducing vehicle weights and conserving electrical power in the manufacturing process.

References

- (1) Kobayashi, T., Sayama, M., Yahaba, T., Kato, T.: Development of Friction Stir Welding Technology for Subframe for Fuel Cell System, Honda R&D Technical Review, Vol. 21, No. 1, p. 49-57
- (2) Shimoda, Y., Tsubaki, M., Yasui, T., Fukumoto, M.: Effect of Material Flow on Formation of Weld Interface between Aluminum and Steel by Friction Stirring, Japan Welding Society, No. 89, p. 142-143, (2011)
- (3) Ogura, T., Saito, Y., Nishida, T., Nishida, H., Yoshida, T., Ohmichi, N., Fujimoto, M., Hirose, A.: Interfacial microstructure and its mechanical property in friction stir welded A3003/SUS304 dissimilar lap joint using WC tool, Japan Welding Society, No. 89, p. 120-121, (2011)
- (4) Tokisue, H., Shinoda, T., Kumagai, M.: FSW no jissui rei, FSW (Masatsu kakuhan setsugou) no kiso to oyo, Nikkan Kogyo Shinbunsha, p. 105-127, (2005) (in Japanese)
- (5) Japan Friction Welding Association: Friction Welding Technology, Nikkan Kogyo Shinbunsha, p. 191-193, (2006) (in Japanese)
- (6) Industrial Robot: An international Journal, Volume 31, Number 1, p. 55-63 (2004)
- (7) Industrial Robot: An international Journal, Volume 37, Number 1, p. 36-50 (2010)

Author



Tetsuya MIYAHARA



Mitsuru SAYAMA



Takanori YAHABA



Shousuke OHHAMA



Tsunehisa HATA



Tsutomu KOBAYASHI