

Development of Friction Stir Welding Technology for Subframe for Fuel Cell System

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ABSTRACT

In order to save weight and increase productivity, the FC subframe developed for vehicle mounting of the fuel cell system employed in the FCX Clarity fuel cell vehicle is constructed from both extruded and cut parts produced from 6000 series aluminum alloy. Friction stir welding (FSW) was used to weld the main structural parts of the subframe. FSW was applied to 12 types of lap joints and one type of butt joint. Five tools were developed for the lap joints and one tool for the butt joints. The strength of lap joints formed using FSW can be diminished by the infiltration of the material in the bottom sheet into the material in the top sheet, a phenomenon referred to as “hook.” The project discussed here clarified the mechanism of this phenomenon, and reduced its occurrence by forming grooves on the probes of the welding tools. In addition, in the case of butt welds of forms with radii, the occurrence of elongated cavity was controlled without the use of filler metal by having the center of the tool approach the thickest side of the material.

The use of these methods has enabled the achievement of a 17% weight saving against a conventional subframe using stamped parts.

1. Introduction

Friction stir welding (FSW) involves a lower heat input than arc welding (such as MIG welding and TIG welding) and other types of fusion welding, and enables reduced distortion. Although the method has been applied mainly to railway rolling stock, instances of use in

automotive parts⁽¹⁾ have been limited to suspension arms, hoods, tailgates, doors, and other components that open and close. The application of FSW on components with a hollow cross-section, such as the subframe, has not advanced. This is because the heavy load applied during joining can deform the workpiece and end up producing joining imperfections.

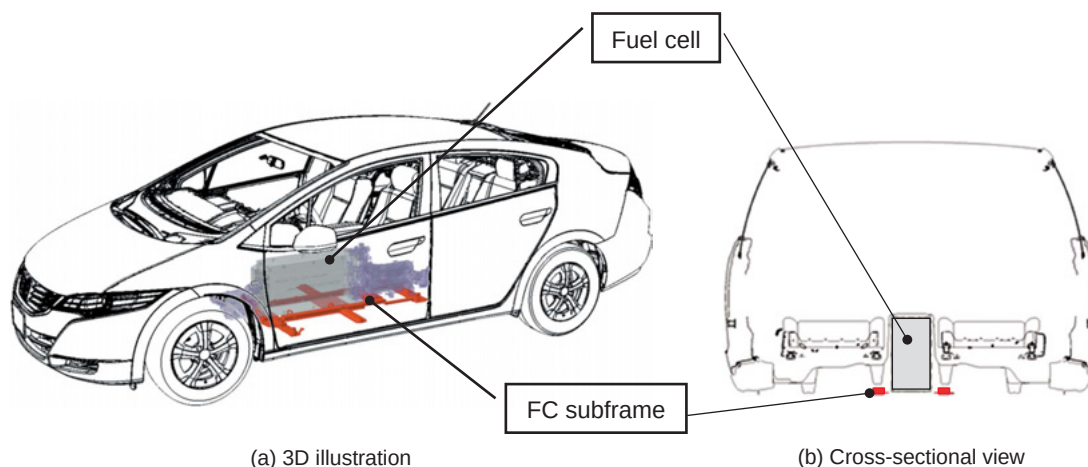


Fig. 1 Positioning of FC subframe in Honda FCX Clarity

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The FC subframe used in the FCX Clarity, as shown in Fig. 1, is installed under the floor to hold and protect the fuel cell system. Since saving weight was a priority, aluminum alloy was used for all component parts. With conventional aluminum parts, however, there was an issue of deformation as a result of arc welding. FSW was therefore adopted as the joining method for the main structural parts. This was intended to reduce deformation due to joining and was also expected to save weight by simplifying joint structures and optimizing wall thicknesses.

Lap joints were used for the joint structure so that dimensional errors in the parts being joined, from when the parts were manufactured, could be absorbed. In order to obtain the necessary joint strength, linear welding was used. There are few cases, however, of linear welding in lap joints using FSW.

Here, therefore, linear welding techniques for FSW lap joints and butt joints were developed for that purpose. Suitable structures for lap joints were also designed and implemented.

This paper provides an overview of the development of those FSW techniques.

2. FSW and Circumstances of FSW Application

The FSW technology was developed by The Welding Institute Ltd. (TWI) in the United Kingdom in 1991⁽²⁾. Figure 2 shows the welding tool (hereafter the tool) with the pointed tip known as a probe. In order to make a join, this tool is rotated at high speed and pressed against the material being worked on until the shoulder portion touches the material. The material around the probe and the shoulder are softened by the frictional heat, and the plastic flow produced by the rotation of the tool leads to the material being joined in a solid state.

This technology is said to be suited mainly to use with aluminum alloys, copper alloys, magnesium alloys, and other metals with low melting points.

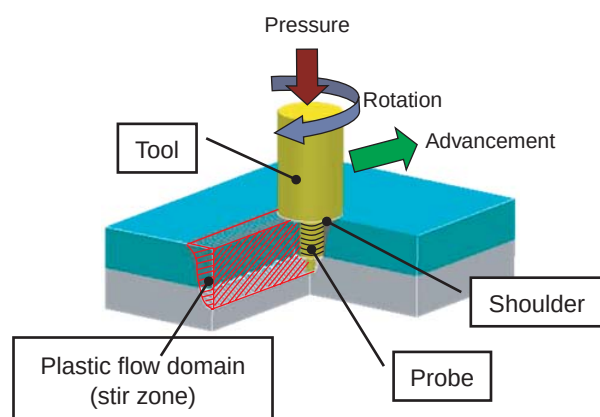


Fig. 2 Schematic illustration of FSW

Characteristics of FSW include:

- (1) It is a solid phase join that does not melt the materials being joined.
- (2) It produces little joint deformation.
- (3) Blowholes and other internal quality imperfections produced by melting and solidification do not occur.
- (4) In the case of aluminum alloys, shielding gas is not needed.
- (5) Filler metal is not needed.
- (6) Fumes, spattering, and the like do not occur.
- (7) A large amount of electric power is not needed.

Drawbacks of FSW include the following⁽³⁾:

- (1) Rigid clamping is necessary.
- (2) The allowable range of gaps between workpieces is narrow.
- (3) It is challenging to make fillet joints and other such joins of members with complex shapes.
- (4) A hole remains at the end of the weld.
- (5) It is limited for use with metals that have low melting points.

Making the most of the above characteristics, Japan has seen an increase in cases of FSW being used in particular⁽⁴⁾ with railway rolling stock made from aluminum alloy. This involves many long parts as much as 20 m in length, which necessitates measures against deformation during welding when undergoing conventional fusion welding. The application of FSW, which results in little deformation, not only increases productivity, it is also able to save energy and provide a clean work environment.

The automotive field also shows an increase in the number of cases⁽⁵⁾ of FSW being used, such as resistance spot welding for spot joining on doors, hoods, and other aluminum alloy components.

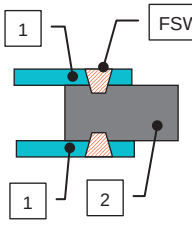
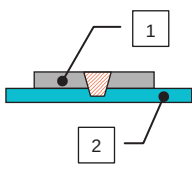
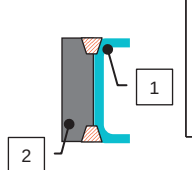
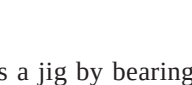
3. FC Subframe

3.1. FC Subframe Structure

Figure 3 shows the FC subframe materials and components, and Table 1 shows FSW weld structures. The components basically consist of combinations of aluminum alloy extruded parts and cut solid parts (hereafter solid parts). Table 2 shows the cross-sectional shape of the extruded parts. Many cross-sections are hollow and complex. The cross-section circumscribed diameters range from 36 to 214 mm. The parts are made thin, with thickness ranging from 1.3 to 3.5 mm. In order to achieve material quality that balances extrudability and strength, A6N01S-T5⁽⁶⁾ was used. For the solid parts, the priority was placed on strength and A6061P-T651⁽⁷⁾ was used. For the stamped parts used in attaching components, A5052P-O⁽⁷⁾ was used for strength and formability, while A6063S-T5⁽⁶⁾ was used for other attaching parts.

The main structural parts were constructed by inserting solid parts into extruded parts and joining them using FSW. This construction was adopted so that the solid parts

Table 1 FSW weld structures in FC subframe

	Part 1		Part 2	
	Material 1	Thickness (mm)	Material 2	Thickness (mm)
	A6N01S-T5	1.3	A6061P-T651	
		1.5		
		2.0		
		3.0		
		3.5		
	A6N01S-T5	2.0	A6N01S-T5	2.0
			A6063S-T5	2.0
			A5052P-O	1.2
			A5052P-O	2.0
	A6N01S-T5	3.0	A5052P-O	1.0
			A6063S-T5	2.0
	A6N01S-T5	2.0	A6961P-T651	7.0

would function as a jig by bearing the load from the tool during joining. Another purpose is to absorb the error from lengthwise processing of extruded parts.

The joints in conventional FC subframes were formed using resistance spot welding and MIG welding. These methods had limits on the thickness of the plates they could join, however, and they could not be optimized. They also resulted in more complex joint structures that were incompatible with weight reduction.

The present structures were designed with FSW in

mind. They were intended to save 10% or more weight by such means as simplifying the joints, eliminating joint flanges, and optimizing the wall thicknesses of extruded parts. Another goal was to discontinue corrective work after joining.

The present FC subframe has 48 lap joints with the structure of thick solid parts inserted into extruded parts, 14 lap joints joining two thin plates, and four butt joints with solid parts joined to the side surfaces of extruded parts.

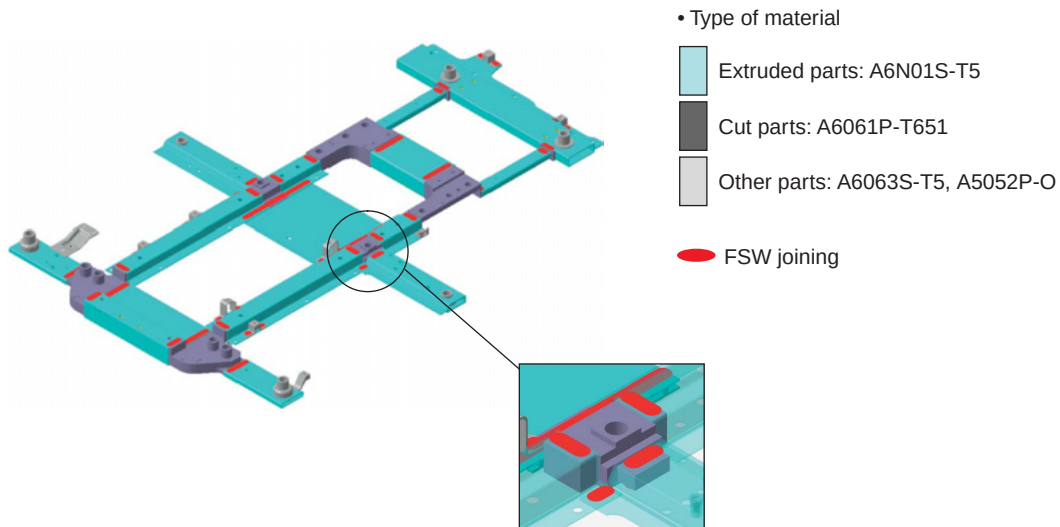


Fig. 3 Components of FC subframe

Table 2 Cross-sectional shape of extruded frames

Cross-sectional view	Circumcircle diameter (mm)	Minimum thickness (mm)	Thickness of FSW weld (mm)
	36	1.5	1.5
	73	2.0	2.0
	99	1.3	1.3
			2.0
	111	2.0	3.0
	111	2.0	2.0
			3.5
	156	2.0	2.0
	190	2.0	2.0
			3.0
	214	2.0	2.0
			3.0

3.2. Issues in Joint Structures

It was found that when the FSW tool used for butt joints is used for a lap joint, the tensile strength is reduced. This mechanism is illustrated in Fig. 4. The rotation of the tool generates frictional heat that softens the material, and the reverse screw effect of the probe generates a downward plastic flow. The material that flows downward along the probe is blocked by the bottom sheet so that it flows outward and up. The upward flow of material around the outer margin of the zone of plastic flow lifts up the softened material in the periphery as though dragging that material along with it. The result is the hook phenomenon, in which material from the bottom sheet infiltrates the top sheet in a wedge-like manner. The boundary of unjoined material is moved up into the top

sheet just as it is by infiltration, so that the thickness of the bottom sheet is reduced by the amount of material removed from the original plate thickness by the hook, thus lowering the tensile strength.

Figure 5 shows a cross-sectional photograph of a lap joint. It can be seen that the plastic flow zone has spread outward from the tool center to form a trapezoidal shape. Figure 6 is a cross-sectional photograph showing the top sheet forced upwards in order to illustrate clearly how the hook process has induced infiltration of the boundary of unjoined material into the top sheet. In this case, the hook height accounts for 1.60 mm of the 2.89 mm of the top sheet. The remaining thickness of the top sheet has been reduced to half or less that of the original plate, so that the tensile strength of the joint portion is also one-half or

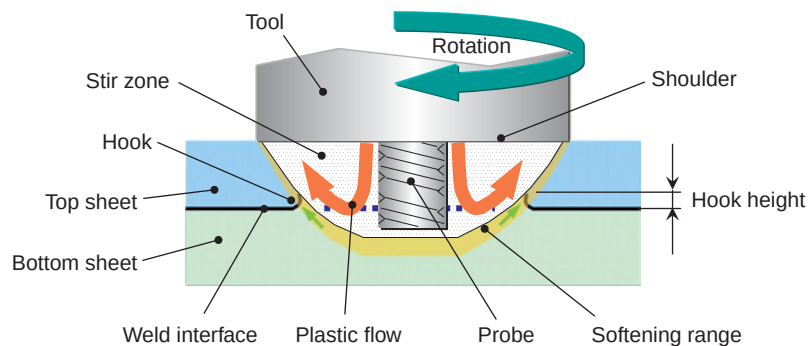


Fig. 4 Mechanism of FSW for lap joint

less of the strength of the parent material in the original plate.

Figure 7 presents a schematic view of a butt joint. It shows how the curvature of the angular edge areas of the extruded part is joined just as it is. Figure 8 is a cross-sectional photograph showing that an elongated cavity has formed. A hole like this is generally thought to form because of insufficient heat input⁽⁸⁾, but in this case the

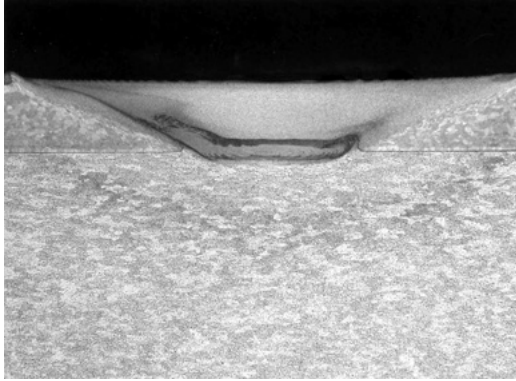


Fig. 5 Cross-sectional micrograph of FSW at lap joint

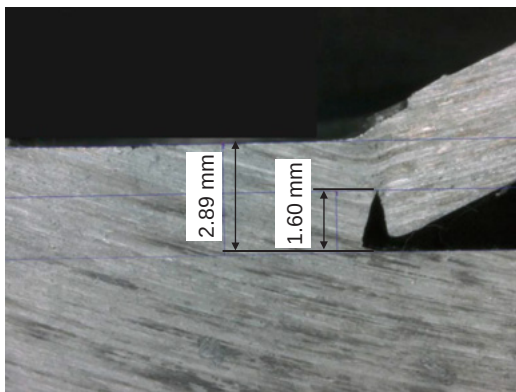


Fig. 6 Cross-sectional micrograph of FSW at lap joint when top sheet is forced upwards

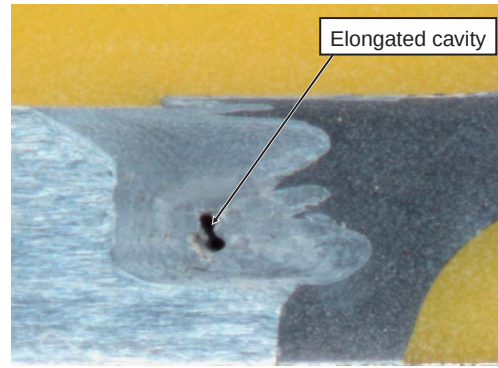


Fig. 8 Cross-sectional micrograph of elongated cavity

origin is probably the cavity formed because of the curvature of the angular edge area of the extruded part. Since FSW does not allow weld reinforcement, such holes are thought to form because there is insufficient material to fill the cavity resulting from the curvature of the angular edge area of the extruded part. This imperfection can lead to reduced tensile strength, and it therefore had to be addressed for the development of practical applications.

4. Joining Technology

4.1. Addressing the Lap Joint Issue

In order to prevent a reduction in the tensile strength of the lap joint, it is crucial that the hook process be contained. One conceivable method for containing hook is to weaken the plastic flow in a longitudinal direction.

First of all, reducing the rotational speed of the tool appears likely to weaken plastic flow in the longitudinal direction. If the tool rotates slowly, however, it will not generate the heat required to form the join, which will therefore result in unstable joints. Figure 9 shows the cases of lap joints formed in 6000-series aluminum alloy with varying tool rotation speeds and welding speeds.

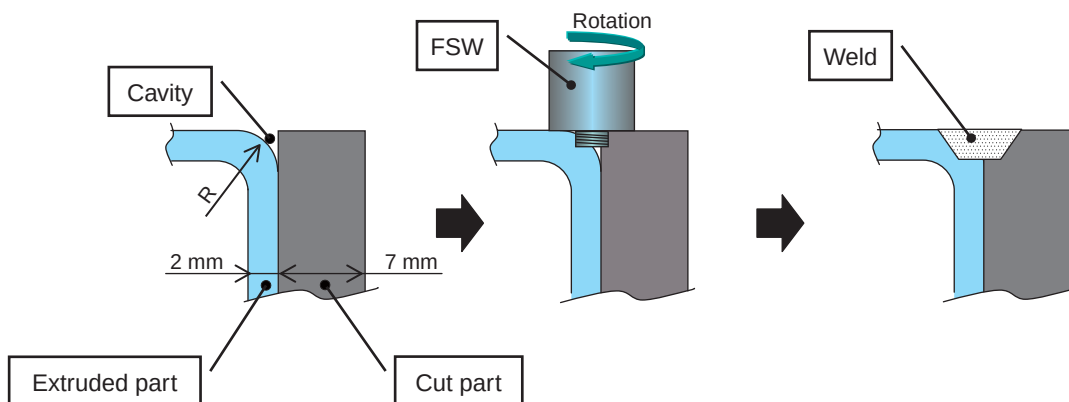


Fig. 7 Cross-sectional image of FSW butt joint

When the tool rotation speed is 1000 rpm, good join quality was obtained with the welding speed of 100–150 mm/min. When the tool rotation speed was decreased to 800 rpm or less, however, the heat input was inadequate and the joints were unstable. When the tool rotation speed was 1100–1200 rpm and the welding speed 100 mm/min, good quality joints were not obtained. It is likely that the excess heat generated at high revolutions results in imperfections from surface gouging and excessive winding up.

The shape of the probe on the developed tools is shown in Fig. 10. It was decided to add grooves like those of a thread-cutting tap to the probe in order to maintain the rotational speed required to form a join and weaken the plastic flow. Grooves in the probe would ordinarily promote plastic flow, but these grooves were devised to divide up and weaken the plastic flow by retaining the softened metal inside the grooves. When the downward plastic flow produced as a result of the screw effect is weakened, the plastic flow that moves upward while spreading outward, thereby generating the hook, is also weakened. The tip of the probe was also hollowed out in a concave form that is linked to the grooves, so that the solid volume of the tool at the probe tip is reduced. This can also be expected to have the effect of lowering the pressure exerted on the material from the periphery of the probe. This was intended to lower the pressure from the probe tip and reduce the force exerted on the periphery to spread it outward in order to contain the plastic flow. By incorporating these design purposes into the probe shape, it was expected to contain the hook phenomenon, even at tool rotating speeds, that generate the frictional heat required to form a join.

4.2. Results of Lap Joint Study by Simulation

A CAE analysis was carried out utilizing general-purpose thermal flow modeling and analysis software

(FLUENT from ANSYS, Inc.) to confirm the effects of tool shape on plastic flow.

CATIA V5 was used to prepare a model of conditions when the tool is inserted in a region of the parent material with a diameter approximately 1.3 times that of the tool shoulder. The automatic mesh generation function of the thermal flow modeling and analysis tool (FLUENT for CATIA V5 from ANSYS, Inc.) was used to generate a mesh for analysis. With the density and coefficient of viscosity set as constant physical properties, the tool was assigned rotating speeds and analyzed in a steady state.

Figure 11 presents typical cross-sections showing the differences in flow direction and flow rate distribution obtained from the simulation of tools with and without grooves. Here, the maximum flow rate, defined as 1, is a dimensionless number.

It can be seen from Fig. 11 that when a groove is placed in the probe, the flow rate is reduced even at the same tool rotational speed. This is thought to occur because the groove induced the flow around the outer margin of the probe to be divided. It is apparent that the

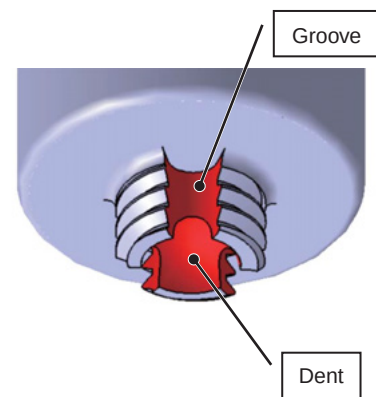


Fig. 10 Probe for developed tool

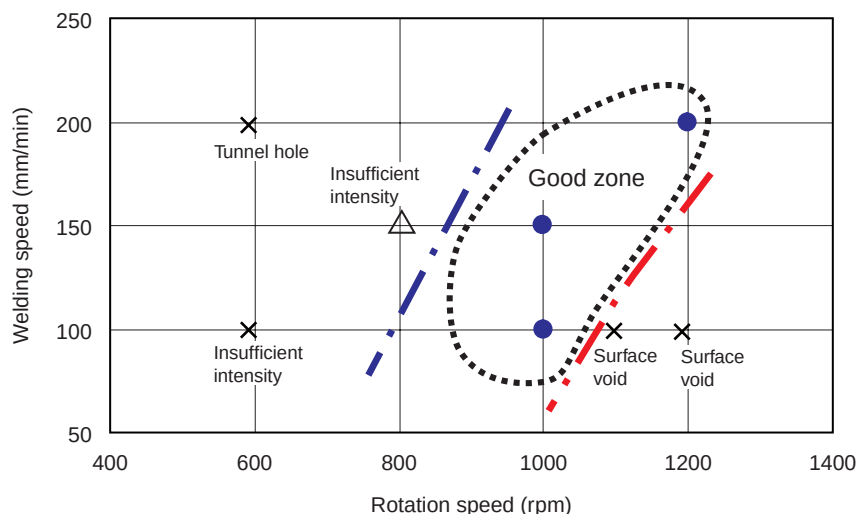
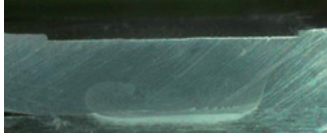
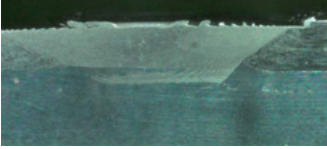
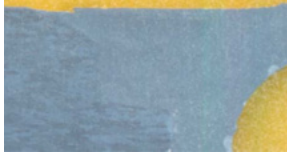


Fig. 9 Example of conditions for lap joint connection of 6000 series aluminium alloys

Table 3 Results of FSW using developed tools

No.	Joint	Type of material		Thickness (mm)	Cross-sectional micrograph	Joint efficiency
1	Lap joint	Top	A6N01S-T5	1.3		78%
		Bottom	A6061P-T6	28.0		
2	Lap joint	Top	A6N01S-T5	2.0		88%
		Bottom	A6061P-T6	28.0		
3	Lap joint	Top	A6N01S-T5	3.0		78%
		Bottom	A6061P-T6	14.0		
4	Lap joint	Top	A6061P-T6	2.0		71%
		Bottom	A6N01S-T5	3.0		
5	Butt joint	Right side	A6N01S-T5	2.0		91%
		Left side	A6061P-T6	7.0		

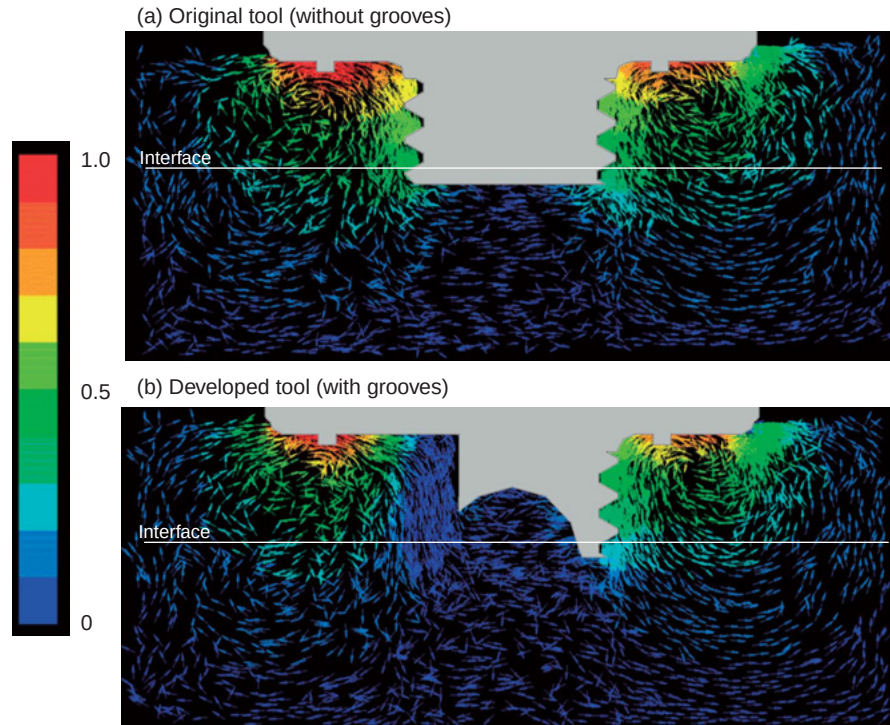


Fig. 11 Calculation of effectiveness of developed tool using CFD

flow is smaller inside the grooves, in particular. This suggests that the flow rate in the longitudinal direction will also be reduced, and the plastic flow weakened.

4.3. Addressing the Butt Joint Issue

The present butt joints had cavities produced by the curvature of the angular edge area of the material. In order to fill in those cavities, it was decided to displace the center of the tool approximately 0.5 mm toward the solid part. The reasoning was that this would cause the material to flow away from the solid-part side so that it could fill in the cavity. The joining conditions were also set so that the tool indentation amount would be deeper than usual on the reasoning that this would be effective in filling the cavity.

4.4. Results

The present FC subframe for use in the FCX Clarity has plates combined using 12 types of lap joints. Five types of tools were developed to match the upper plate thickness in those various combinations. These tools have grooves set into the probe. One tool for use with butt joints was developed.

Table 3 shows the verification results of the quality of joints made using the developed tools. Given the ability to contain the hook phenomenon, the ratio of the tensile strength of the joint to that of the parent material (hereafter joint efficiency) was 60% or more in every part of the 13 types of plate combination. The results from observation of cross-sections also confirmed that the hook phenomenon was being contained.

Figure 12 shows the finished FC subframe. The length of the FSW welds amounted to 2075 mm at a total of 66 locations. Distortion produced by the welding was very slight, enabling the attachment of welding jigs, without having to add an allowance for anticipated distortion. Parts accuracy requirements could also be satisfied without having to perform any corrective work after welding. This

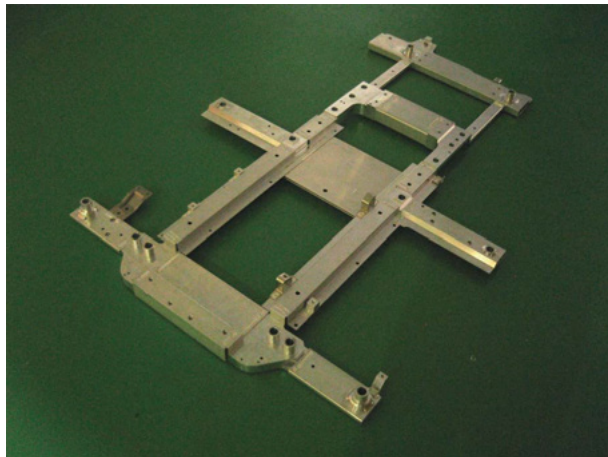


Fig. 12 Finished FC subframe

has curtailed corrective work processes, thus enabling greater work efficiency.

5. Mass Production Equipment

A brief introduction of the mass production equipment will be given here. Figure 13 presents a photograph showing an exterior view of the equipment. This system uses a general-purpose multi-axis robot for the FSW tool⁽⁹⁾. The FC subframe is set on a welding jig that is supported by two robots. The stationary FSW welding device clamps onto the workpiece and jig together and makes the join. The two robots simultaneously move the jig with the workpiece placed on it to form the welds. The device in this system is able to freely control the load on the FSW tool, and by accurately synchronizing its action with the movement of the robots, the system is able to produce stable joints. The FSW tool is attached to a highly rigid frame and on the jig side it bears the load from joining by means of rollers. This system is capable of forming joints easily in two dimensions by means of robot teaching, which also enables it to do three-dimensional welding work.

Quality management is implemented by monitoring the welding conditions, including the load on the FSW tool, its rotational speed, and the welding speed. Six types of tool are color-coded by their particular areas of application. The length of the probe and the shape of the tip are checked regularly.

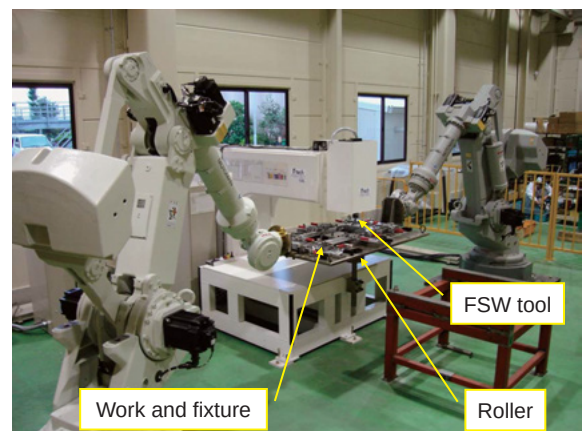


Fig. 13 Components of FSW machine

6. Conclusion

This FC subframe for use in the FCX Clarity achieves a 17% weight saving relative to the conventional subframe made from stamped aluminum alloy using resistance spot welding and MIG welding. It also achieved the reduction of corrective work. Productivity increased as a result.

- (1) The mechanism by which the hook phenomenon, generated by plastic flow in the FSW lap joint, reduces

the strength of the join was clarified. Flow modeling and analysis software were used to develop tools that contain the winding up phenomenon by means of grooves.

- (2) Using these tools, extruded parts made of 6000-series alloy and parts of various kinds of aluminum alloy were joined by FSW in lap joints and butt joints. Joint efficiency reached levels of 60% or higher.

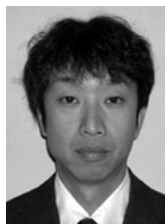
The robot welding system constituting a new mass production device is capable of controlling the welding load to perform stable welds. At the same time, this equipment is also capable of carrying out welding work in three dimensions. The system is producing FC subframes of stable quality.

Weight saving is a vital technology for the motor vehicle development of the future. Promoting widespread adoption of the present techniques can be expected to contribute to weight savings.

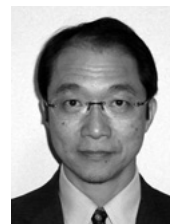
References

- (1) Tokisue, H., Shinoda, T., Kumagai, M.: FSW no Jisshirei, FSW (Masatsu Kakuhan Setsugou) no Kiso to Oyo, Nikkan Kogyo Shimbun, p. 129-161 (2005) (in Japanese)
- (2) Fujii, H.: Masatsu Kakuhan Setsugo no Genri to Tokutyō, Masatsu Kakuhan Setsugo (FSW no Subete), Sanpo Publications, p. 12-18 (2006) (in Japanese)
- (3) Tokisue, H., Shinoda, T., Kumagai, M.: FSW no Genri to Tokutyō, FSW (Masatsu Kakuhan Setsugo) no Kiso to Oyo, Nikkan Kogyo Shimbun, p. 11-12 (2005) (in Japanese)
- (4) Mori, H., Noda, M., Tominaga, T.: Current state on application of friction stir welding for rolling stock, Journal of Japan Institute of Light Metals, Vol. 57, No. 11, p. 506-510 (2007) (in Japanese)
- (5) Koga, S.: Zidosya e no Spot FSW no Tekiyo, Masatsu Kakuhan Setsugo (FSW no Subete), Sanpo Publications, p. 232-235 (2006) (in Japanese)
- (6) JIS H4100 : 2006, Aluminium and aluminium alloy extruded shape
- (7) JIS H4000 : 2006, Aluminium and aluminium alloy sheets, strips and plates
- (8) Fujii, H.: Masatsu Kakuhan Setsugo no Genri to Tokutyō, Masatsu Kakuhan Setsugou (FSW no Subete), Sanpo Publications, p. 22-24 (2006) (in Japanese)
- (9) JP, 2007-268558, A (2007)

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