Friction Stir Welding of Aluminum Alloy to Steel

Aluminum alloy plate was successfully butt-joint welded to steel plate by friction stir welding

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ABSTRACT. The authors tried to butt-joint weld an aluminum alloy plate to a mild steel plate using friction stir welding.

This study investigated the effects of pin rotation speed, position of the pin axis, and pin diameter on the tensile strength and microstructure of the joint. The main results obtained are as follows:

Butt-joint welding of an aluminum alloy plate to a steel plate was easily and successfully achieved. The maximum tensile strength of the joint was about 86% of that of the aluminum alloy base metal. Many fragments of the steel were scattered in the aluminum alloy matrix, and fracture tended to occur along the interface between the fragment and the aluminum matrix. A small amount of intermetallic compounds was formed at the upper part of the steel/aluminum interface, while no intermetallic compounds were observed in the middle and bottom regions of the interface. A small amount of intermetallic compound was also often formed at the interface between the steel fragments and the aluminum matrix. The regions where the intermetallic compounds formed seem to be fracture paths in a joint.

Introduction

Energy savings and environmental preservation are important issues for us to resolve. Since reducing the weight of vehicles is one of the efficient measures, the use of the combination of steel and aluminum alloy has been increasing in fabricating vehicles. Under this situation, many trials to weld steel to aluminum alloy have been conducted. However, sound joints have not been produced so far, because hard and brittle intermetallic compounds were formed at the weld whenever steel was welded to aluminum by fusion welding.

At present, the following methods have been employed to produce a joint between steel and aluminum. One method utilizes a transition joint that consists of a steel plate welded in advance to an aluminum alloy plate by explosive bonding or rolling (Ref. 1). Others are solid-phase bonding methods, such as friction welding (Ref. 2), ultrasonic joining (Ref. 3), and rolling (Ref. 4).

The method using the transition joint, however, involves some difficulties in that the transition joint is not easy to produce and is expensive, and the joint is limited in shape. Rotary friction welding has the difficulty that at least one material to be joined should be circular in cross-sectional shape. Ultrasonic welding and rolling also have the shortcoming that they are applicable only to thin plate.

A new method has been tried in which the heat conduction from a steel plate heated by a laser beam melts the faying surface of an aluminum plate, resulting in welding the steel to the aluminum by the molten aluminum (Ref. 5). However, this method presents difficulties in that some brittle intermetallic compound is still formed and it is hard to control the heat input and the melting amount of the aluminum by laser irradiation. In addition, laser equipment is expensive.

Recently, a few preliminary studies have been reported on friction stir welding (FSW) — a process developed by TWI (Ref. 6) — of aluminum to steel butt joints (Ref. 7) and lap joints (Ref. 8).

In this paper, the authors applied FSW to produce a butt joint between aluminum alloy and steel, and are reporting the details of the joint performance.

KEYWORDS

Joining of Dissimilar Metals
Friction Stir Welding
Steel
Aluminum Alloy
Tensile Strength of a Joint

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Explanation of the Rotating Pin Position in the Friction Stir Welding Employed in this Study

Figure 1 is a schematic illustration to explain pin position in friction stir welding. Figure 1A is a bird's-eye view of the method, and B is a view of the cross section perpendicular to a weld interface.

A rotating pin is plunged into the aluminum as shown in the figure. Next, the rotating pin is pushed toward the faying surface of the steel and, consequently, the oxide film is mechanically removed from the faying surface by the rubbing motion of the rotating pin. Aluminum, which is in a fluid-like plastic state due to the heat generated by the friction of the rotating tool shoulder, adheres to the activated faying surface of the steel, so that joining between steel and aluminum is achieved. In this process, since the rotating pin is plunged into the softer aluminum and does not come in contact with the steel, the rotating pin shows minimal wear.

Welding by FSW is ordinarily completed through stirring by a rotating pin inserted around the center of the weld interface of butted base plates. A preliminary experiment proved that when the rotating pin was inserted around the center of the weld interface between the steel plate and the aluminum alloy plate, welding could not be achieved because of excessive wear of the rotating pin in a short duration. The wear caused insufficient stirring between the aluminum alloy and the steel. This point will be referred to later.

Experimental

Materials and Welding Conditions

Plates of 2-mm-thick SS400 mild steel (hereafter, Fe) and A5083 (Al-0.5 Mg-0.5 Mn wt-%) aluminum alloy (hereafter, Al) were welded. The ultimate tensile strength of the A5083 base metal was about 275 MPa and that of the SS400 was about 455 MPa. The shape and dimension of both plates was rectangular and 140 mm in length and 40

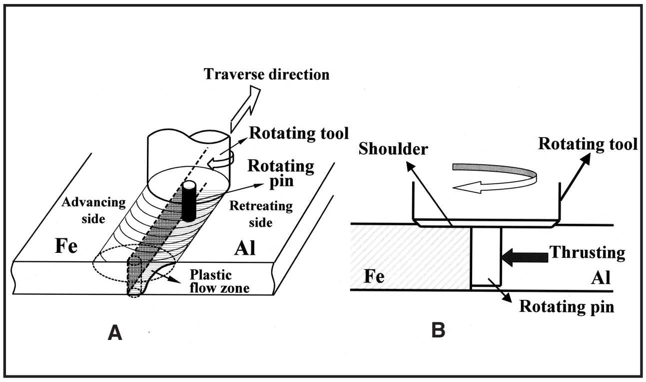

Fig. 1 — Schematic of the rotating pin position in this study: A — Bird's-eye view of the method; B — view of the cross section perpendicular to the weld interface.

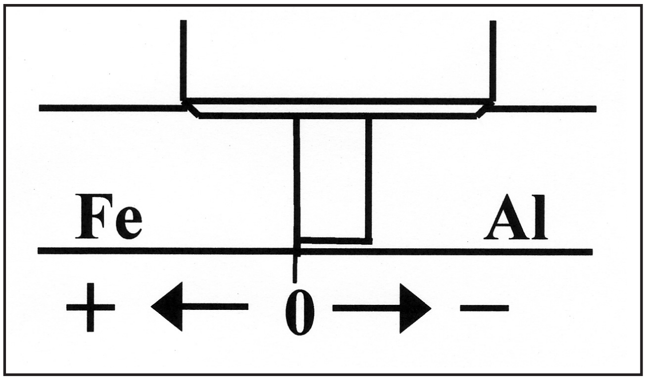

Fig. 2 — Schematic explaining the relationship between the pin position and the coordinate.

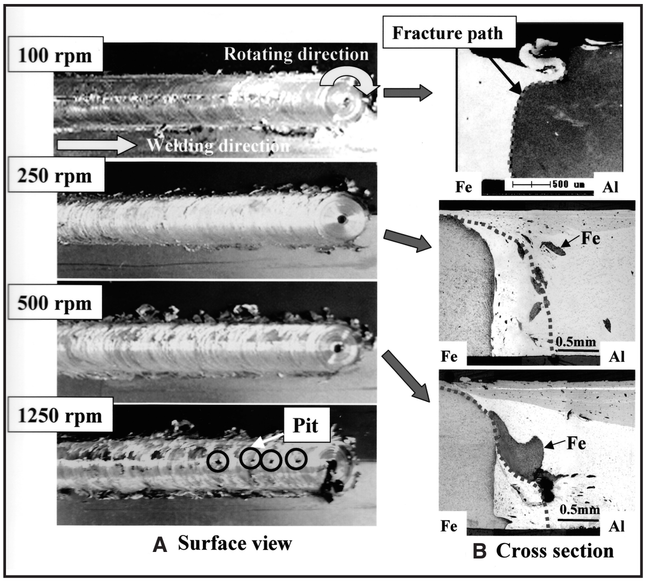

Fig. 3 — Effects of pin rotation speed: A —surface view; B — cross-sectional structure with the fracture path indicated by a dashed line in the welds.

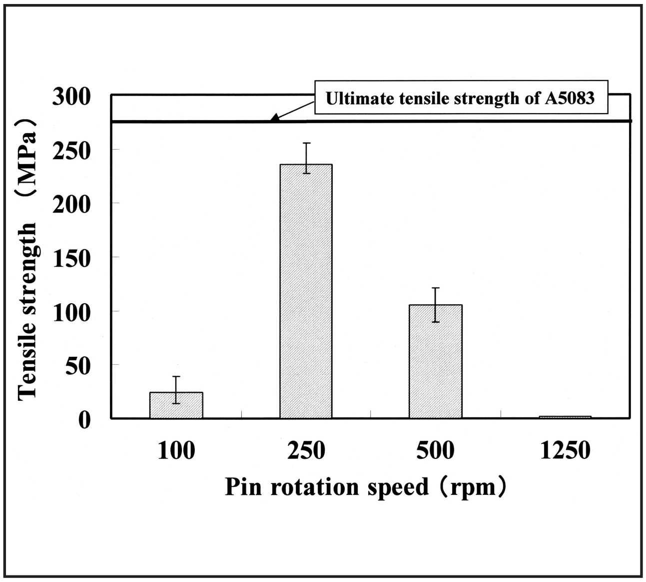

Fig. 4 — Relation between pin rotation speed and joint tensile strength.

mm in width. The 140-mm-long faying surface of each plate was polished with 400-grit emery paper, and then mounted in a jig to make a butt joint.

The rotating tool used in this study was made of high-speed tool steel (SKH57). It had a 15-mm-diameter shoulder and an unthreaded pin 2 mm in diameter and 1.9 mm long, as shown in Fig. 1. Welds were made with the pin rotating clockwise at speeds of 100 to 1250 rpm. The pin transverse speed, that is, welding speed, was 25 mm/min. The Al plate was located on the retreating side as shown in Fig. 1. After the rotating pin was inserted into the Al plate, the pin was thrust toward the Fe faying surface by the distances of –0.2 mm to 2 mm (zero is at the position where the pin side face is located just at the Fe faying surface, and the offset is defined as shown in Fig. 2).

A tensile test was employed to estimate the tensile strength of the joints and the fracture path. The tensile test specimens perpendicular to the weld interface were machined from the welds. The welded area was located in the center of the tensile specimen.

Metallographic samples were produced from the welds and etched with only an etchant of 3% Nital. Etched samples were examined using optical microscope and scanning electron microscope (SEM) with X-ray energy-dispersive spectroscopy (EDS).

Results and Discussion

Effect of Pin Rotation Speed on Joint Tensile Strength

First, the surface and cross-sectional structure of welds were examined when pin rotation speed was varied under the pin offset of 0.2 mm. Figure 3 shows the surface appearances and cross-sectional structures of the welds. The relation between joint tensile strength and pin rotation speed is shown in Fig. 4.

When pin rotation speed was too slow, i.e., 100 rpm, the pin wore out in a short time due to insufficient heat generation and insufficient plasticization of the Al. Consequently, about a quarter of the weld interface was welded; the balance of the joint was welded only on the surface. The fracture path (shown by a dotted line) of the tensile specimen produced under these conditions was along the interface where there was incomplete fusion between Fe and Al, so that the tensile strength of these specimens was low. Pin rotation speed of 250 rpm made a good joint, showing the maximum tensile strength of about 240 MPa, which was about 86% of the Al base metal tensile strength. The fracture path of these specimens was along the interface between the Al matrix and the Fe fragments (indicated by arrow in Fig. 3) scattering in the Al ma-

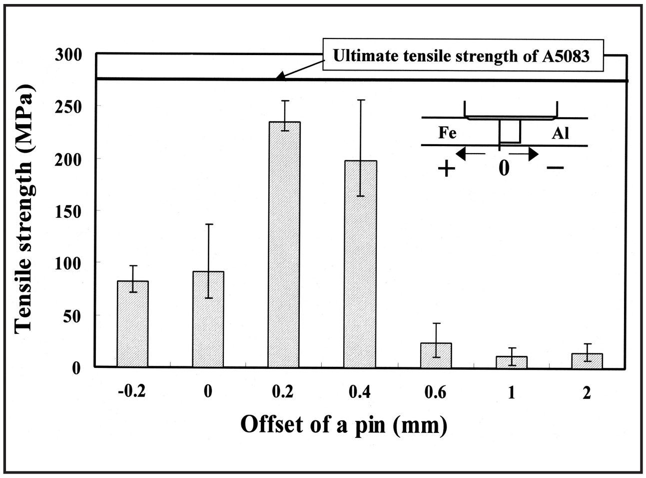

Fig. 5 — Relation between pin offset and joint tensile strength.

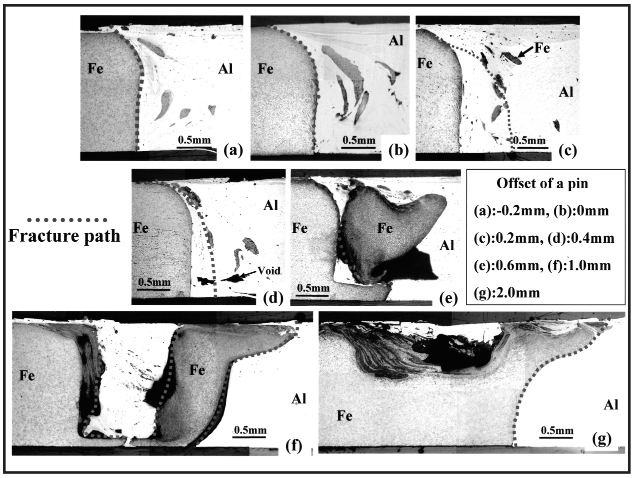

Fig. 6 — Effects of pin offset on the microstructures and fracture paths of welds.

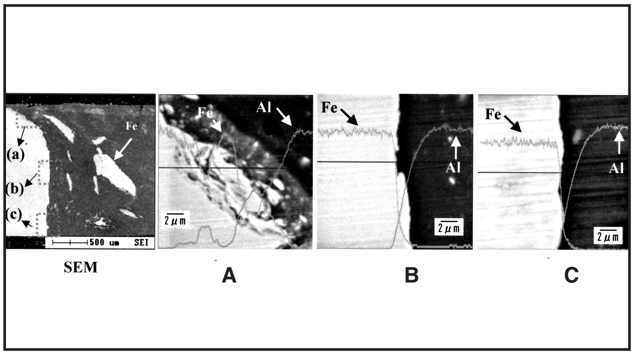

Fig. 7 — SEM images and line analyses of Fe and Al around the interface between the steel and the aluminum alloy: A — upper position; B — middle position; C — bottom position.

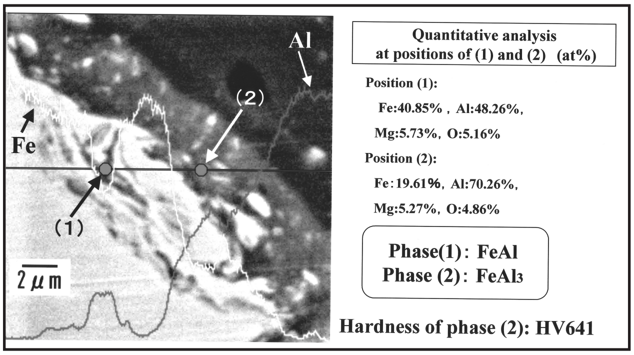

Fig. 8 — Quantitative analyses of the phases at the positions indicated by (1) and (2).

trix. Energy-dispersive spectroscopy analysis revealed that the chemical composition of the fragments was identical with that of SS400 Fe base metal and the fragments in the Al came from the Fe.

At a pin rotation of 500 rpm, the surface morphology of the weld was similar to that in the case of 250 rpm rotation speed; however, the joint strength was much lower than that at 250 rpm rotation speed.

At the faster pin rotation speed of 1250 rpm, oxidation occurred during the welding process due to Mg in the Al base metal; however, there is no direct evidence of oxidation of Mg in the Al. The weld could not be completed and the joint fractured during machining to make a tensile test specimen. The fracture surface appeared to be heavily oxidized and appeared to be burned.

According to the above results, a pin rotation speed of 250 rpm was adopted thereafter as the optimal rotation speed for the welding experiments.

The Effect of Pin Offset on Joint Tensile Strength

Figure 5 shows the effect of pin offset on the tensile strength of a joint made under the conditions of a 25 mm/min welding speed and a 250 rpm pin rotation speed.

When the offset was zero or negative, that is to say, the side face of the pin just contacted the Fe faying surface or was located in the Al matrix, the joint tensile strength was low, but higher than when the offset was larger than 0.6 mm. Maximum joint strength was obtained at 0.2-mm offset. As offset was increased, joint tensile strength decreased.

Pin Offset, Cross-sectional Structure, and Fracture Path

Figure 6 shows the cross-sectional structures and fracture paths of the joints made at various pin offsets. When the offset was zero or negative, removal of the oxide film from the Fe faying surface was probably insufficient, so that fracture of the joint occurred along the interface between Fe and Al.

As the pin offset became positive, the joint strength increased and reached a maximum strength at an offset of 0.2 mm. The fracture path of the joint shifted from the Fe/Al interface to the Al matrix. When the offsets were 0.6 and 1 mm, Fe fragments scattering in the Al matrix became larger and some voids were formed, resulting in a decrease in joint strength. Fracture in the joint made with a 1-mm offset occurred along multiple paths as shown in Fig. 6, and the pin wore out in a short duration. The weld with the 1-mm offset using a 2-mm-diameter pin is typical of conventional FSW; however, a sound joint was not produced under this condition. At an offset of 2 mm into the Fe the pin wore out in a much shorter time and, consequently, only the upper region of the joint was welded and joint tensile strength was low.

Analysis and Observation of Joint Cross-sectional Microstructure

Cross-sectional Microstructure Perpendicular to a Weld Interface

Maximum tensile strength was obtained in the joint made under the following welding conditions: 25 mm/min welding speed, 250 rpm pin rotation speed, and 0.2-mm pin offset. Scanning

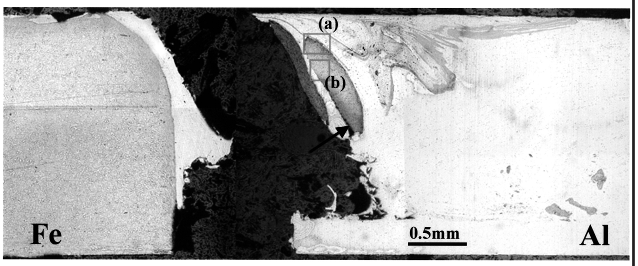

Fig. 9 — Cross-sectional view of the broken part of the joint after tension test. Fracture occurred along the interface between the steel fragment and the aluminum matrix.

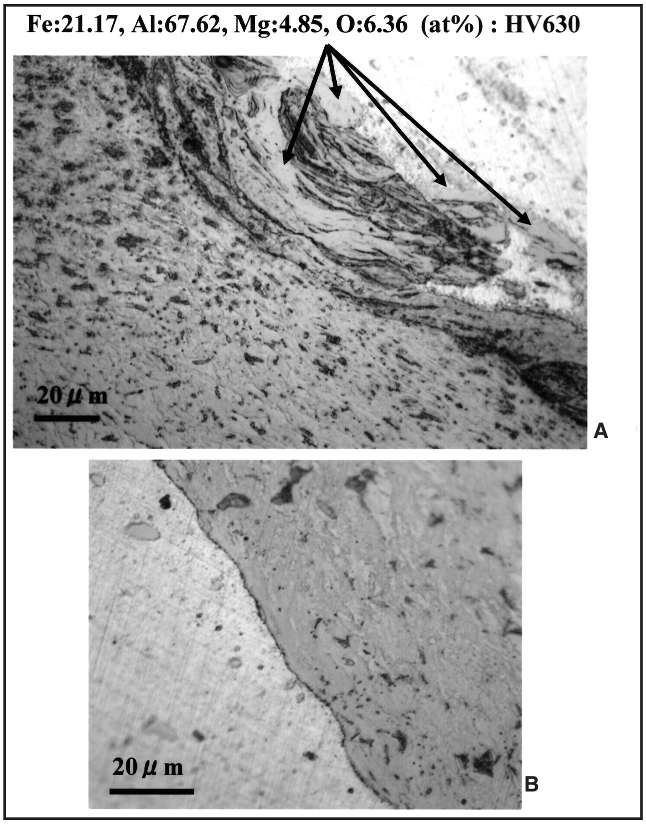

Fig. 10 — Enlarged optical micrographs of parts (a) and (b) in Fig. 9. Intermetallic compounds appeared at part (a) of the interface between the steel fragment and the aluminum matrix. No intermetallic compounds appeared at part (b).

electron microscope observations of the microstructure and the EDS analysis with the weld produced under these conditions were performed on the cross section perpendicular to the weld interface to examine whether intermetallic compounds were formed at the interface between the Fe and the Al.

Figure 7 shows enlarged SEM photographs and EDS line analyses of Fe and Al elements corresponding to the upper (A), central (B), and bottom (C) regions as shown in the photograph at the far left. Judging from the SEM photograph and EDS analysis, no intermetallic compounds were observed at the central and bottom regions of the interface between Fe and Al. However, the EDS line analysis of Fe and Al suggests that intermetallic compounds were formed at the upper region of the interface. Figure 8 shows the EDS quantitative analysis results at points 1 and 2 in the upper region of the interface. The chemical compositions of points 1 and 2 are 40.85%Fe-48.26%Al-5.73%Mg-5.16%O, and 19.61%Fe-70.26%Al-5.27%Mg-4.86%O (at-%), respectively. It appears that the intermetallic compounds of points 1 and 2 are FeAl and $FeAl_3$, respectively, based on this analysis and the Fe/Al phase diagram (Ref. 9). The hardness of the intermetallic compound of 2 was HV641.

A small amount of intermetallic compounds was observed at the upper region of the Fe/Al interface where the temperature was the highest during welding. As for the temperature, Ulysse (Ref. 10) has shown that the temperature at the upper region rubbed by the shoulder of a rotating tool is higher than the other regions in the weld.

Tensile testing of these joints showed that cracking tended to occur initially at the upper region of the joint and propagated toward the bottom region. The intermetallic compounds formed at the upper region of the Fe/Al interface appear to reduce the joints' strength.

Figure 9 shows an optical micrograph of a cross-sectional view of a fractured tensile specimen near the Fe/Al interface. This photograph shows that the fracture occurred along the interface between the Fe fragments and the Al matrix, and that the incipient cracking (indicated by an arrow in the photograph) occurred at the interface between the Fe fragment and the Al matrix. This suggests that cracking and fracture tend to occur at the interface between the Fe fragment and Al matrix.

Enlarged views of parts (a) and (b) in Fig. 9 are shown in Fig. 10A and B, respectively. A gray phase (indicated by an arrow) is observed at part A, and the phase composition analyzed quantitatively by EDS was 21.17%Fe-67.62%Al-4.85%Mg-6.36%O (at-%). It seemed from the composition and the hardness (HV630) that the phase was $FeAl_3$ intermetallic compound. However, there were also interfaces in which no intermetallic compounds appeared as shown in Fig. 10B.

Cross-sectional Microstructure Parallel to a Weld Interface

Figure 11 shows the SEM photographs of the cross-sectional microstructure parallel to the weld interface of the joint discussed in the previous section. A cross section was made about 700 µm from the Fe/Al interface for metallurgical analysis. The SEM photograph shows that Fe fragments are lined in rows in the Al matrix.

Scanning electron microscopy photographs of the fracture surface of this joint are shown in Fig. 12. Figures 12A and B are a macrophotograph and an enlarged SEM photograph, respectively. The uneven Al fracture surface suggests that fracture occurred along the interface between the Fe fragment and the Al matrix, as discussed in the previous section. Figure 12C is an enlarged SEM photograph showing a dimple pattern that indicates ductile fracture occurred.

The Effect of Rotating Pin Diameter on Joint Strength

In the previous sections, the 2-mm-diameter rotating pin was used to make a joint. In this section, the effects of various pin diameters on joint strength are examined. Joints were made using pins of 1, 3, and 4 mm diameter under the welding conditions of 0.2-mm pin offset, 250-rpm pin rotation speed, and 25-mm/min welding speed. The relation of pin diameter to joint strength is shown in Fig. 13. A pin of 1 mm diameter wore out in such a short duration that a sound joint could not be produced. The tensile strength and the microstructures of joints made using a pin of

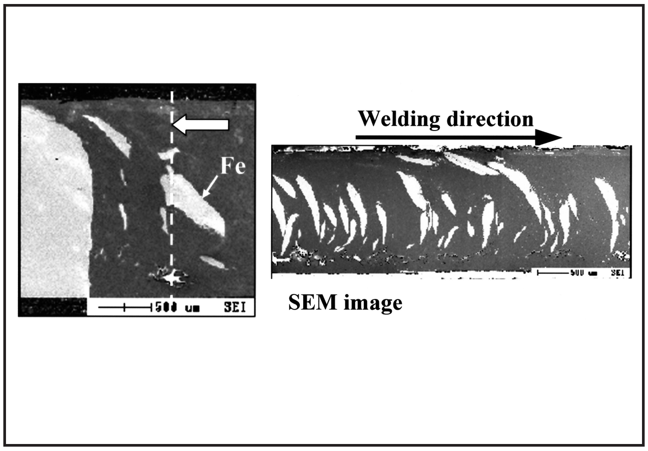

Fig. 11 — Cross-sectional SEM image longitudinal to welding direction. Many steel fragments are observed in the aluminum matrix.

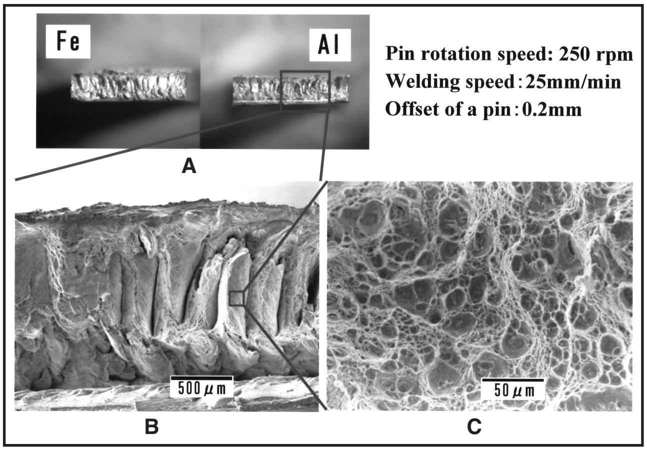

Fig. 12 — Fracture surface of the weld made under the optimal welding conditions: A — macrophoto of fracture surface; B — SEM image of fracture surface; C — enlarged SEM image of B. Fracture seems to occur along the interface between the steel fragments and the aluminum matrix, and a dimple pattern is observed in the fracture surface.

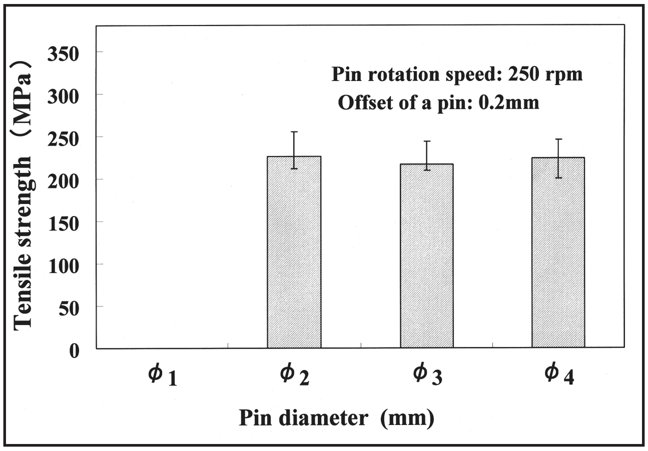

Fig. 13 — Relation between joint tensile strength and pin diameter..

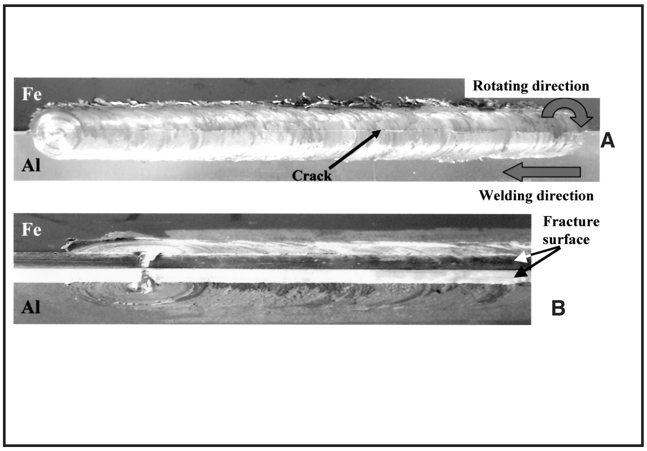

Fig. 14 — Surface view and fracture surface of the weld when welding direction was reversed, that is, the pin rotation direction was counterclockwise.

3 or 4 mm diameter were similar to those made using a 2-mm-diameter pin. It appears that rotating pin diameter has little effect on joint strength or microstructure.

The Effect of the Counterclockwise Rotation of a Pin

The effect of pin rotation direction on joint performance was also examined. The pin direction was reversed compared to the previously mentioned welds. With a counterclockwise pin rotation direction, the Al was located in the advancing side of the joint. The welding conditions consisted of a pin diameter of 2 mm, a pin rotation speed of 250 rpm, and a welding speed of 25 mm/min.

The top surface view of the weld made with a counterclockwise rotating pin is shown in Fig. 14A. It appears from this view that welding was successfully achieved. However, welding was restricted to the top surface and showed little bonding within the plate. Figure 14B shows a macrophotograph of the fracture surfaces of both Fe and Al sides. Both fracture surfaces appear flat and there seems to be no evidence of fusion on the butting surfaces.

The Fe faying surface polished with 400-grit emery paper was observed before and after welding to examine the surface morphology after rubbing by a rotating pin. Figure 15A and B shows the SEM photograph of the Fe polished faying surface before and after welding, respectively, with an offset of 0.2 mm. The photograph shows that the Fe polished surface was obviously rubbed with a pin, but fusion was not achieved. Figure 15C shows the Fe surface after welding with a pin offset of 0.4 mm. A more highly rubbed Fe surface was observed, but fusion welding was not achieved in this case, also.

It appears that fusion was not achieved with a counterclockwise pin rotation. The incomplete fusion can be explained using the schematic shown in Fig. 16. Figure 16A shows the case where the pin was rotated clockwise with the Fe plate mounted on the advancing side and the Al plate mounted on the retreating side. Figure 16B shows the case where the pin was rotated counterclockwise. When the pin rotates clockwise, the whirling Al, which is in a fluid-like plastic state, as shown by an arrow, is pressed to the Fe faying surface (indicated by a bold line) that has been already activated by the rubbing motion of the rotating pin and adheres to the Fe, resulting in welding of both plates. On the other hand, when the welding direction is opposite, as shown in B, the whirling Al in the plastic flow state, as shown by an arrow, is pressed to the Fe faying surface (indicated by a bold dotted line) that is not activated by a rotating pin, resulting in no welding.

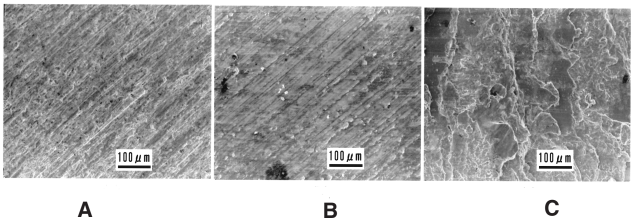

Fig. 15 — SEM photographs showing steel faying surfaces before and after welding when the welding direction was reversed: A — before welding; B — after welding with an offset of 0.2 mm; and C — after welding with an offset of 0.4 mm.

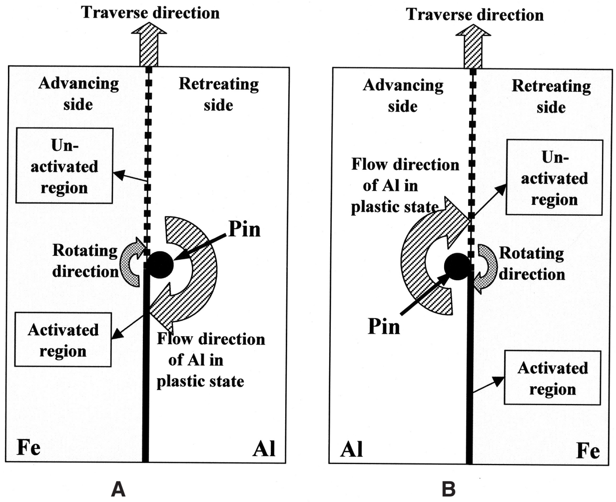

Fig. 16 — Schematic illustration showing plastic flow direction of aluminum for aluminum-to-steel FSW: A — clockwise pin rotation of a pin; B — counterclockwise pin rotation.

Conclusions

The authors applied friction stir welding in order to join an aluminum alloy containing magnesium to steel. In this study, the effects of pin rotation speed and pin offset toward the steel faying surface on the tensile strength and the structure of a joint were investigated. The following results were obtained.

1) Adjusting a rotating pin position to activate the faying surface of the steel enabled a joint to be produced between steel and an aluminum alloy. Welds were produced by placing the aluminum alloy on the retreating side of the joint.

2) There was an optimum rotation speed for the pin to make a sound joint. A lower rotation speed gave rise to an insufficient increase in temperature at the weld, so that the pin wore out in a short time. At a higher rotation speed, the temperature increase was so excessive that the magnesium in the Al alloy oxidized and resulted in an unsound joint.

3) The maximum tensile strength of the joint was obtained at the pin offset of 0.2 mm toward steel. At a larger offset, steel pieces scattering in the aluminum alloy matrix became larger in size and some voids were formed, resulting in a decrease in joint tensile strength.

4) Intermetallic compounds were not observed at the interface between the steel and the aluminum alloy. However, some intermetallic compounds were observed at the upper region of the weld where the temperature was higher due to the additional heat generated by the rotating tool shoulder. The intermetallic compounds formed at the upper region of the Fe/Al interface deteriorated the joint strength.

5) A minimum pin size was required to produce a weld. Pins that were too small in diameter, i.e., 1 mm diameter, could not produce a weld. Pin diameters from 2 to 4 mm showed similar joint tensile strength.

6) Welds could not be produced when the pin was rotated counterclockwise, i.e., the aluminum plate was mounted on the advancing side.

References

1. Maruzen. 1990. *Welding Handbook*. Edited by Japan Welding Society: pp. 496

2. Aritoshi, M., and Okita, K. 2002. Friction welding of dissimilar metals. *J. of Japan Welding Society* 71-6(2002): 432–436.

3. Watanabe, T., and Yoneda, A., et al. 1999. A study on ultrasonic welding of dissimilar metals, 1st and 2nd reports. *Quarterly J. of Japan Welding Society* 17-5(1999): 223–242.

4. Kouno. 2002. Manufacture of Al/SUS clad by vacuum rolling joining method and its properties. *J. Japan Welding Society* 71-6(2002): 427–431.

5. Katayama, S. 2002. Dissimilar materials joining by laser. *Welding Technology* 50-2(2002): 69–73.

6. Thomas, W. M., et al. Friction stir welding, international patent application PCT/GB92/02203.

7. Watanabe, T., Takayama, H., and Kimapong, K. 2003. Joining of steel to aluminum alloy by interface-activated adhesion welding. *Materials Science* forum, 426-432(2003): 4129–4134.

8. Yoshikawa, K., and Hirano, T. 2001. Numerically controlled friction stir welding in layered dissimilar metal materials of aluminum and steel. *Proceedings of the Third Symposium on Friction Stir Welding*, Kobe, Japan, September, pp. 1–11.

9. *Binary Alloy Phase Diagrams*, second edition, 1996. CD-ROM. Materials Park, Ohio: ASM International.

10. Ulysse, P. 2002. Three-dimensional modeling of the friction stir welding process. *International Journal of Machine Tools & Manufacture* 42(2002): 1549–1557.