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Microstructure and Tensile Strength of Butt Joint between AA6063 Aluminum Alloy and AISI304 Stainless Steel by Friction Stir Welding

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Abstract

This study presents the experimental results of the Friction Stir Welding (FSW) of AA6063 aluminum alloy and AISI304 stainless steel butt joint by varying the welding parameters such as the rotating speed and the welding speed. The main results are as follows. The variation of the welding parameters produced various characteristic interfaces and had distinct influences on the joint properties. Increasing the rotating speed and the welding speed decreased the joint tensile strength because it produced the defect on the joint interface. The optimum welding parameter that could produce the sound joint was a rotating speed of 750 rpm and the welding speed of 102 mm/min with the tensile strength of 71 MPa.

Keywords: friction stir welding, aluminium, steel, tensile strength, Microstructur

1. INTRODUCTION

A lower specific weight metal part is replaced with a higher specific weight metal part in an automobile structure due to the requirement to increase vehicle efficiency, decrease energy consumption and preserve the environment [1], [2]. This replacement tends to increase an amount of the dissimilar materials joint in the automobile structure. However, the fusion welding of the dissimilar materials joint still encounters the problem due to the differences in material properties. The difference in chemical composition of the materials tends to form a brittle intermetallic compound (IMC) on the weld metal and deteriorates the joint strength. The difference in modulus of elasticity tends to form a high stress concentration and stress discontinuity at the joint interface and the work-piece. The difference in a thermal conductivity of the

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materials during the welding produces a thermal stress on the work-piece that could directly decrease the joint strength [3]. Therefore, the optimum welding process to produce the weld of the dissimilar materials joint should be carefully considered.

Friction stir welding (FSW) is a solid state welding that was invented for welding a difficult-to-fusion-weld-metal such as aluminum and aluminum alloy [4]. This FSW process has been applied successfully for welding various parts in industries such as an aerospace, automobile and shipping [5]. Presently, continuous research and development are done to improve the weld properties. The characteristics of the FSW process are as follows. Firstly, a rotating welding tool is inserted into the joint plate until the shoulder of the welding tool touched the upper surface of the joint. Secondly, the friction between the welding surface and the materials produces the frictional heat that softened the materials around the rotating probe and under the shoulder of the welding tool. Thirdly, the softened materials are in a plastic-fluid-like state around the rotating probe and under the shoulder of the welding tool. Fourthly, when the welding tool was moving along the joint butt line, the plastic-like materials were pressed, stirred and combined together with the trailing edge of the rotating tool to be a weld metal as shown in figure 1.

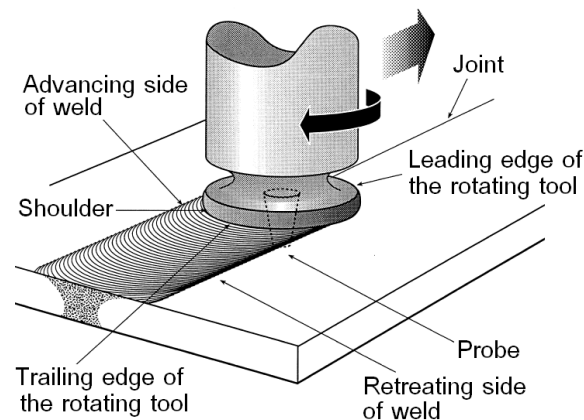


Figure 1.FSW process principle [5]

Friction stir welding has been applied to weld the dissimilar aluminum/steel joint as follows. Kimapong and Watanabe [6] welded the butt joint between A5083 aluminum alloy and SS400 steel and reported the tensile strength of the butt joint that was about 86% of the base aluminum tensile strength. These researchers also welded the lap joint of between A5083 aluminum alloy and SS400 steel by various FSW parameters and reported that the main effect that decreased the joint strength was the IMC thickness of the joint interface [7,8]. This IMC formation was also observed at the weld metal of Al6061 aluminum alloy and AISI1018 carbon steel and could be classified as Fe_4Al_{13} and Fe_2Al_5 IMC but no relation between these IMCs phases and the joint strength was reported [9]. Furthermore, Uzen et al. [10] welded 6013-T4 aluminum alloy to X5CrNi18-10 stainless steel and reported that the fatigue strength of the joint was about 30% of the base aluminum strength. Weld metal microstructure was consisted of the stir zone, thermo-mechanical zone and heat affected zone that was similar to a typical microstructure of FSW aluminum weld metal.

For the research and development of the FSW butt joint between aluminum and stainless steel, however, a few studies have been done and reported so far. In this study, the butt joint between AA6063 aluminum alloy to AISI304 stainless steel was friction stir welded using various rotating and welding speeds. Tensile strength and microstructure of the joint were investigated to achieve the optimum welding parameter.

2. EXPERIMENTAL PROCEDURE

Materials used in this study were a rolled plate of AA6063 aluminum alloy and AISI304 stainless steel that had a chemical composition as shown in Table 1. A dimension of the plates was a thickness of 3 mm, a length of 150 mm and a width of 75 mm as shown in figure 2 (a). The butt surfaces of the plates were mechanically polished by the emery paper grit number 400 and cleaned with acetone as shown in figure 2 (b). The plates were set to be a butt joint in a jig that was firmly clamped on the moving table of the vertical milling machine, and were fixed with Fe plate at the advancing side of the joint [6].

Table 1. Chemical composition of the experimental materials (wt%).

Element	Fe	Al	Mg	C	S	Cr	Si	Mo	Mn	Ni
AA6063	-	Bal.	0.40	-	-	0.01	-	-	0.05	-
AISI304	Bal.	-	-	0.04	0.02	17.11	0.45	0.08	1.31	7.22

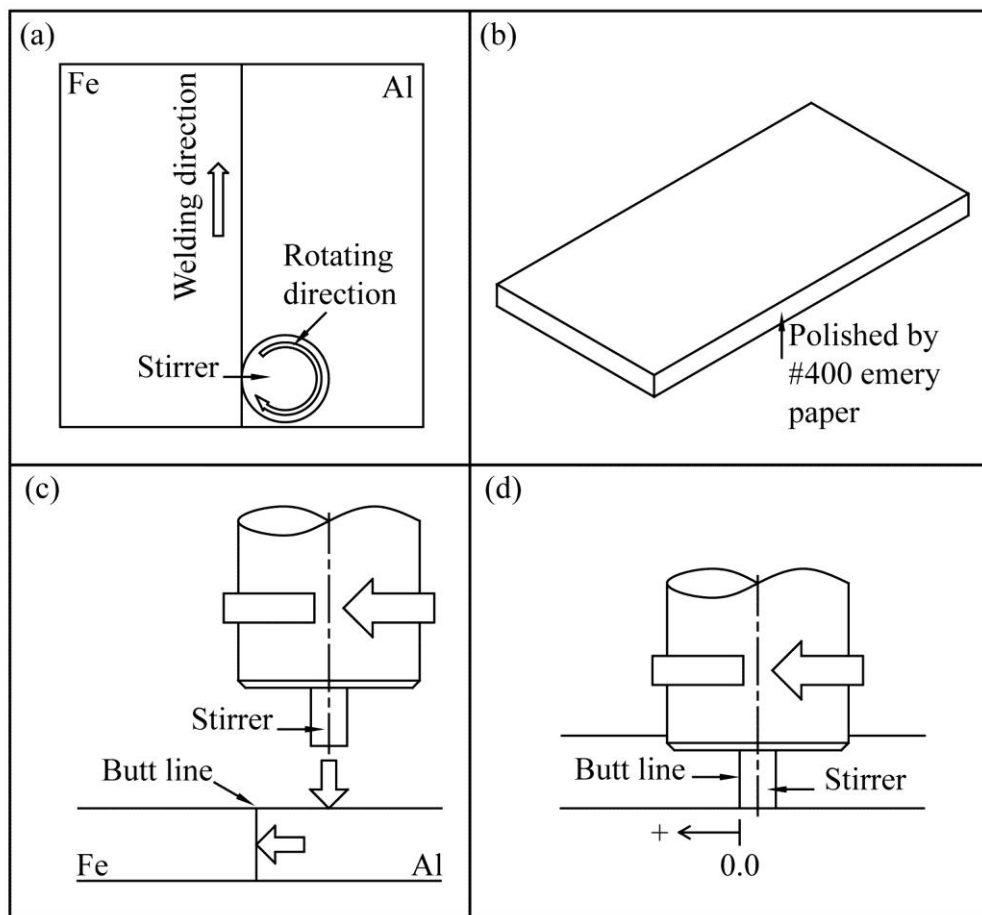


Figure 2. Welding setup: (a) the configuration of the butt joint, (b) preparation of the butt surface, (c) the welding tool insertion steps, and (d) the stirrer location set up.

A welding tool was made of JIS-SKH57 tool steel that had a shoulder diameter of 25 mm, a stirrer diameter of 5 mm and a stirrer length of 6.1 mm as shown in figure 3. The welding process steps were as follows. The rotating stirrer was firstly inserted along the Z axis at a location that was about 2 times of the

stirrer diameter. The rotating stirrer was inserted until the tool shoulder plunged at about 0.1 mm depth from the upper surface of the aluminum plate. Secondly, the rotating stirrer was moved to the butt surface as shown in figure 2 (c). The location that the stirrer side was touching the butt surface was 0.0 mm of the thrusting distance as shown in figure 2 (d). Thirdly, the welding tool was moved along the butt line for producing the weld metal of the butt. The welding parameters of this study were the rotating speed of 280-830 rpm, the welding speed of 22-114 mm/min, the thrusting distance of +0.1 mm. When the butt joint was welded, the joint was mechanically prepared for the joint strength and microstructure investigation. The tensile strength test specimen was defined with the welding line at the center of the specimen and had the configuration as shown in figure 4. A cross section of the joint that was perpendicular to the welding line was mechanically polished and then, investigated by a light optical microscope and a scanning electron microscope.

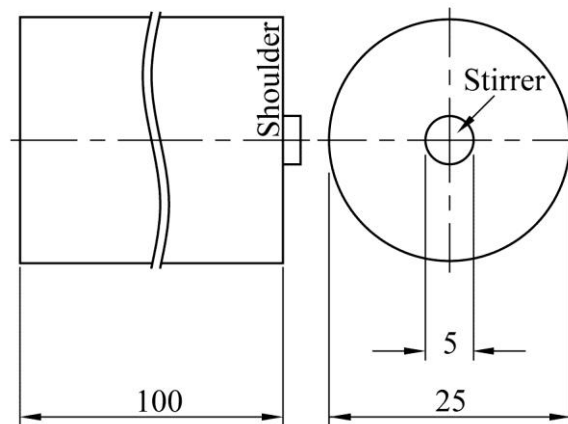


Figure 3. A configuration of a welding tool.

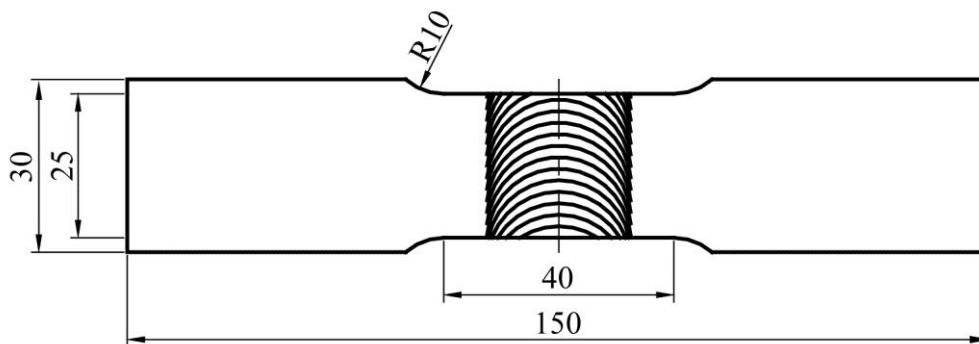


Figure 4. A configuration of a tensile strength test specimen.

3. RESULTS AND DISCUSSION

Figure 5 shows the welding surface appearances of the butt joints between AA6063 aluminum alloy and AISI304 that were friction stir welded by various welding parameters. The surface appearances were classified into three types as shown in Figure 5 and Table 2. Type I of the welding surface showed the complete surface that had no defect on the surface. The surface was inhomogeneous and showed the contrast

area between aluminum and steel. The large size of the aluminum splash was found at the retreating side of the joint as shown in Figure 5 (a). This surface type was found at the lower rotating speed and the lower welding speed as shown in Table 2. Type II surface showed a smaller size of the aluminum splash when compared with Type I, and also showed a complete surface appearance as shown in Figure 5 (b). Type III of the surface appearance was different from the first 2 types of surface appearances because of some void and incomplete surface area was observed as shown in Figure 5 (c). The small aluminum splash was found at about the starting point on the welding line, but was not observed along the welding surface appearance. This type of surface appearance was found when the welding speed and the rotating speed were higher as shown in Table 2.

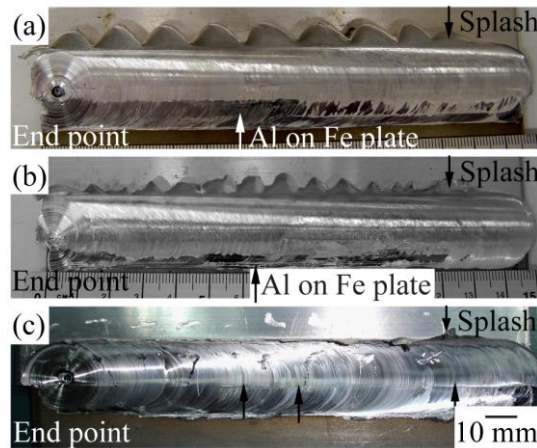


Figure 5. Surface appearances: (a) a complete surface with large contrast of the materials, (b) a complete surface with small contrast of the materials and (c) an incomplete surface.

Table 2. Classification of the welding surfaces.

Welding parameters		Welding speed (mm/min)				
		22	44	66	105	114
Rotating speed (rpm)	580	I	I	I	II	II
	750	I	II	II	II	III
	830	II	II	II	III	III

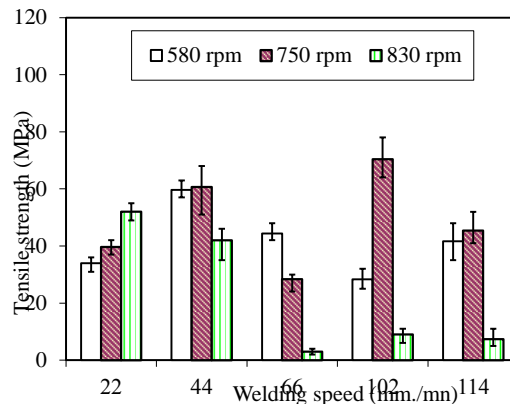


Figure 6. relation of welding speed, rotating speed and tensile strength.

Figure 6 shows the relation of the welding speed, the rotating speed and tensile strength of the butt joint between AA6063 aluminum alloy and AISI304 stainless steel. It was found that the tensile strength of the butt joint in this study was related to the completion of the surface appearances. The complete surfaces of the butt joint as shown in Figure 5 (a) and 6 (b) showed the tensile strength of 35-71 MPa but when compared with the incomplete surfaces as shown in Figure 5 (c), the tensile strength of the joint was not larger than 10 MPa. The optimum welding parameter in this study that indicated the tensile strength of 71 MPa was the rotating speed of 750 rpm, the welding speed of 102 mm/min and the thrusting distance of +0.1 mm. This maximum tensile strength was about 86% of the experimental base aluminum.

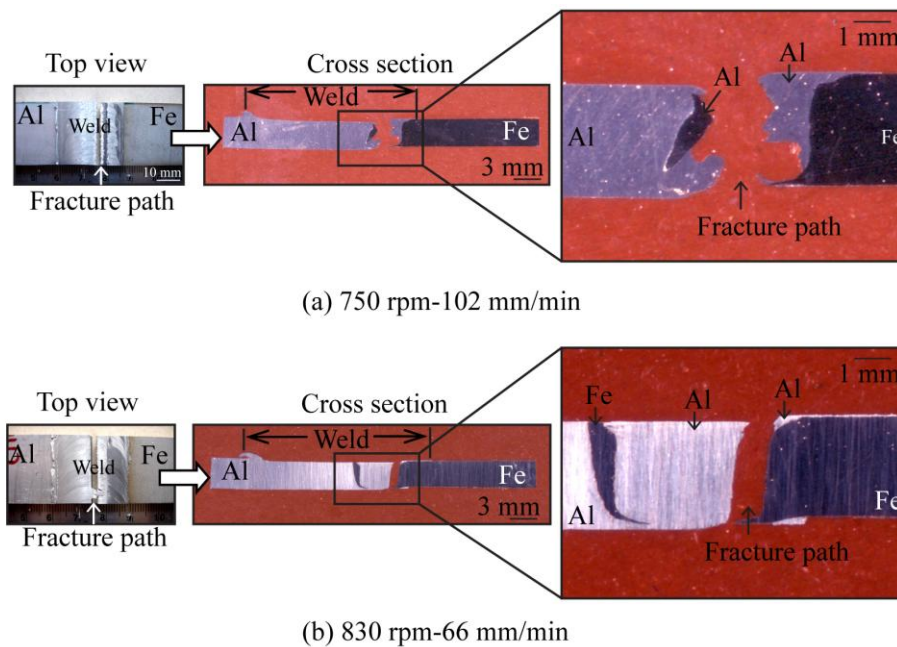


Figure 7. Failure location of tensile strength test specimen: (a) a higher tensile strength specimen and (b) a higher tensile strength specimen.

Figure 7 shows the failure location of the tensile strength test specimen between the specimens that indicated the maximum and minimum tensile strength. The photograph of the top view of the test specimen showed that the fracture location of the test specimens was occurring along the middle of the weld metals. However, when the cross section of the joint that was perpendicular to the welding direction was observed, the failure locations of the joint were different. The failure location of the test specimen that indicated maximum tensile strength occurred on the aluminum area of weld metal as shown in Figure 7 (a). The test specimen that showed this failure location was found when the surface appearance of the joint was completed as shown in figure 5 (a) and (b). The Comparison of the failure location with the minimum tensile test specimen as shown in Figure 7 (b), showed the failure location was occurring along the joint interface between aluminum and steel.

Figure 8 shows the microstructure of the joint that showed the maximum tensile strength (750 rpm-102 mm/min) in this study. The examined location was at the upper, the middle and lower location of the cross section of the joint interface as shown in Figure 8. The location I to III at the joint interface of the maximum tensile strength specimen showed the formation of combination phase and had a thickness of about 5 microns. This combination phase was chemically analyzed by the energy dispersive spectrometry (EDS) and

showed that the phase was FeAl intermetallic compound (45.28%Fe, 47.98%Al and 6.74%O, at%). When compared this IMC with Fe-Al phase diagram, it was equivalent to FeAl IMC that showed high ductile property, high strength and good corrosion resistance [13], [14]. This IMC formation at the joint interface showed a higher strength at the joint interface. The IMC formation that indicated the high strength at the joint interface was the reason that the joint failed at the aluminum weld metal. However, the IMC that was formed at the joint interface should be studied by the higher accuracy analytical equipment such as X-ray Diffractometer (XRD) or Transmission Electron Microscopy (TEM) for confirmation of the IMC phase in near future.

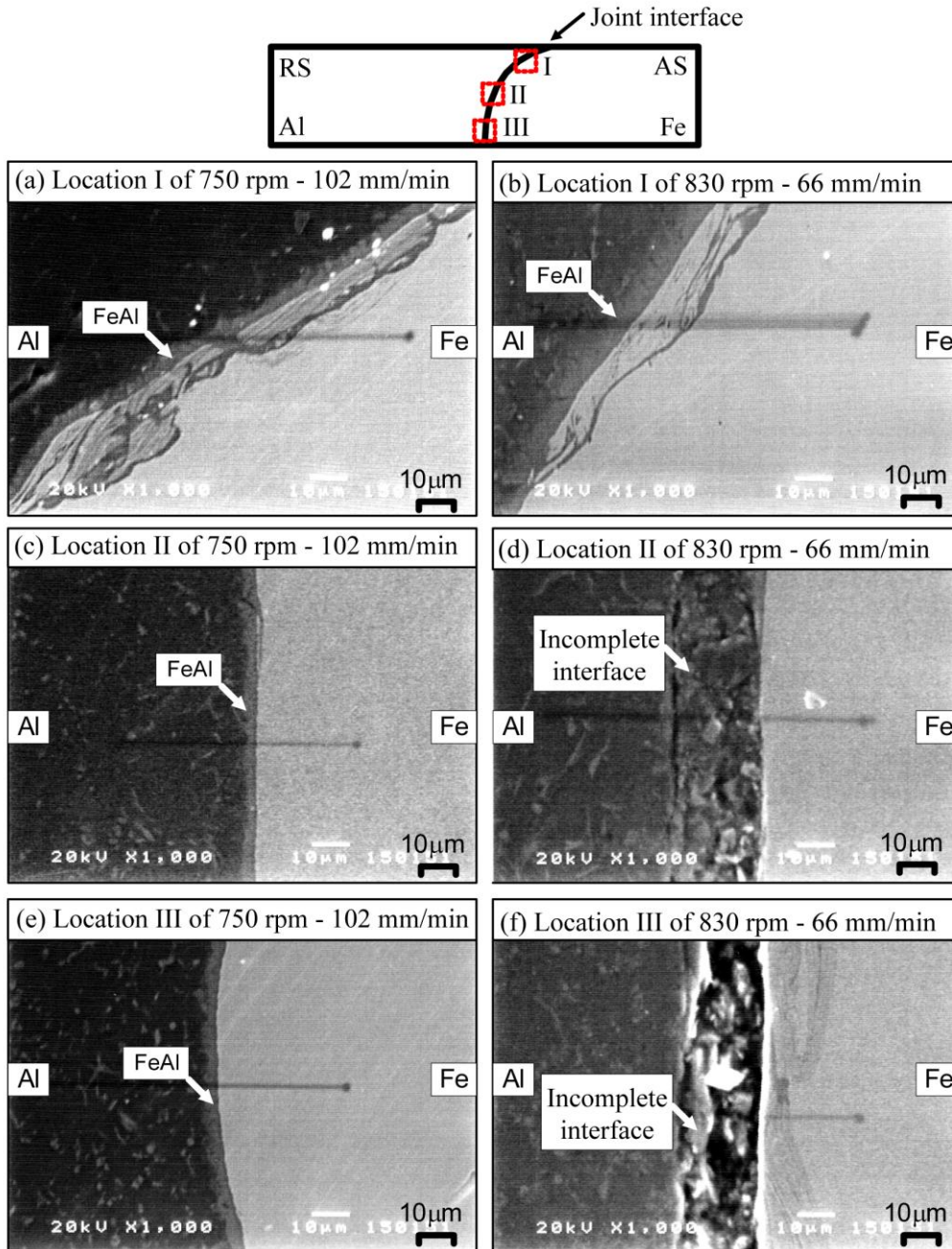


Figure 8. Interface structure of the butt joint that showed the maximum tensile strength (750 rpm-102 mm/min) and the minimum tensile strength (830 rpm-66 mm/min)

Figure 8 (b)-(f) show the microstructure of the joint that showed the minimum tensile strength (830 RPM-66 mm/min). At the location I of the joint as shown in Figure 8 (b) and (d), the joint interface showed the FeAl IMC (46.05Fe-51.33Al-2.61O, %at) formation that was thicker than that of the location I of the maximum tensile strength joint as shown in Figure 8 (a). The aluminum amount that caused the increased brittleness of the IMC was higher when compared with the joint interface in Figure 8 (a). The incomplete combination of the materials at the joint interface was found at the location II and III as shown in Figure 8 (d) and (f). This incomplete interface was the cause of failure of the joint and deteriorated the tensile strength of the joint interface.

4. CONCLUSION

This study applied the friction stir welding process for joining the butt joint between AA6063 aluminum alloy and AISI304 stainless steel. The welding process parameters that were a rotating speed of 280-830 rpm and the welding speed of 22-114 mm/min were applied to weld the butt joint. The summarized results are as follows.

- 4.1 Friction stir welding could produce the butt joint between AA6063 aluminum alloy and AISI304 stainless steel.
- 4.2 The optimum welding parameter that indicated the tensile strength of 71 MPa was the rotating speed of 750 RPM and the welding speed of 102 mm/min.
- 4.3 The increase of the rotating speed and the welding speed produced the incomplete bonding at the joint interface that was the initiation point of fail of the butt joint.
- 4.4 The FeAl IMC formation at the joint interface, increased the joint strength.

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