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Research paper

Evaluation of Mechanical Characteristics based on Tool Pin Shapes in Friction Stir Welding of A6061-T6

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Abstract

Using 6061-T6 alloy sheets, which are high-strength age-hardening materials used in automobile parts, an analysis of the strength characteristics and integrity of welding joints was performed based on the changes in welding conditions such as rotation direction, stirring rate, and welding speed that are in turn dependent on the rotating tool pin during friction stir welding (FSW). Regarding the exterior of FSW specimens, which were fabricated by using rotating tools having A and B type pins, the joint formed when the tool shoulder rotates appeared on the overall friction welded surface of each specimen, regardless of the tool pin shape or welding state; pores or non-welded zones did not form. In other words, by observing the FSW specimens, satisfactory exteriors were found in general in all FSW conditions. As part of mechanical property evaluation, the maximum tensile strength measured was 199.1 MPa for the A type pin welding speed of 300 mm/min and rotation rate 3,000 rpm; the tensile strength of the A type pin was higher than that of the B type pin. As a result of measuring the microhardness, the distribution of hardness values were Hv104 and Hv111 in the case of 400 mm/min welding speed and 3,000 rpm tool rotation rate for the A type and B type pins, respectively, and Hv48 and Hv50, respectively, in the case of 200 mm/min welding speed and 2,000 rpm tool rotation rate. Observing the microstructures by using an optical microscope, the effect of pin type on microstructure was small; the stir zone was fine and uniform since plastic deformation occurred due to the rotation of the pin. In the thermal-mechanically affected zone, plastic deformation and partial recrystallization were observed. In the heat-affected zone, grains became coarse due to the heat produced during FSW.

Keywords: *A6061-T6, Friction Stir Welding, FSW, Tool Pin Shapes, Mechanical Characteristics*

1. Introduction

Friction stir welding (FSW) is a type of friction-based joining that uses the heat produced when two objects are rubbed together. Ever since TWI in the UK applied for a patent in 1991, interest has been rising rapidly in its application in the transportation machinery industry for airplanes and ships[1-4]. FSW is a non-heating solid-phase joining method that uses the friction heat produced on contacting surfaces by applying pressure along with rotational motion on the weld material[5]. When a certain temperature is reached before the contacting surfaces melt, if a pressure is applied, plastic deformation occurs that results in welding; thus, the joining strength is excellent and reliability good. Furthermore, coarse grains or intermetallic compounds caused by intense plastic deformation are difficult to form, and because heat is produced at the welded joint only, thermal efficiency is high compared to that of regular welding. FSW facilitates welding between different shapes and types of materials, and compared to the conventional welding methods, high-quality weld properties can be obtained, such as high tensile strength and superior fatigue properties of the joint.

Up until now, the studies on the FSW technology mostly pertained to processes such as tool design, though recently, interest has been increasing on the mechanical and corrosion characteristics of welded materials[6-7]. However, both qualitatively and quantitatively, not many studies have been reported on the mechanical characteristics of final weld materials based on welding conditions such as stirring rate or welding speed[8-10].

Therefore, in this study, using high-strength age-hardened A6061-T6 alloy sheets, which are used for automobile parts, an analysis was performed for the strength characteristics and welding integrity of joints based on the changes in welding conditions such as rotation direction, stirring rate, and welding speed, which are in turn dependent on the rotating tool pin in FSW.

2. Test Methods

2.1. Material used

Recently, aluminum alloy has being used in various industries, such as automobile, shipbuilding and aircraft because of characteristics of low density and high corrosion resistance. A6061-T6 is heat treatment materials so it has high strength and mostly used for assembly by mechanical fastening such as a bolting and riveting. The chemical composition and mechanical properties of A6061-T6 are shown in Table 1 and 2, respectively.

2.2. Tool pin shape

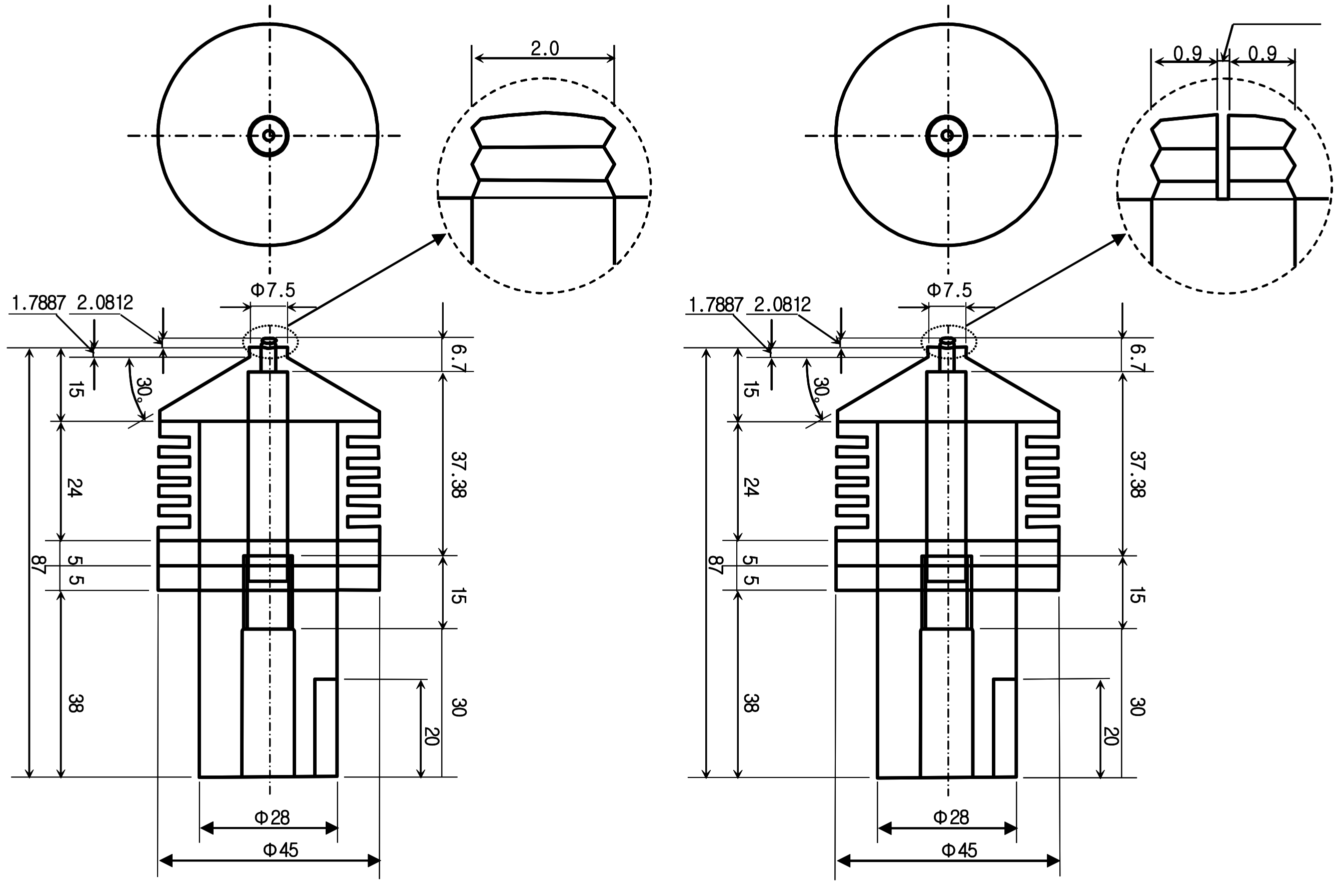
The most important factors in FSW are the material and shape of the tool and pin. Since high frictional heat and shear stress occurs at the tip of the tool, SKD61 or martensitic stainless steel

Table 1 Chemical composition of base metal

Materials	Si	Mn	Mg	Cu	Cr	Fe	Al
A6061-T6	0.58	0.12	1.1	0.22	0.20	0.35	Bal.

Table 2: Mechanical properties of base metal

Materials	Yield strength (MPa)	Tensile strength (MPa)	Elogation (%)	Hardness (Hv)
A6061-T6	335	359	10	125



(a) Type A (b) Type B

Fig. 1: Different type of tool pin shapes in FSW

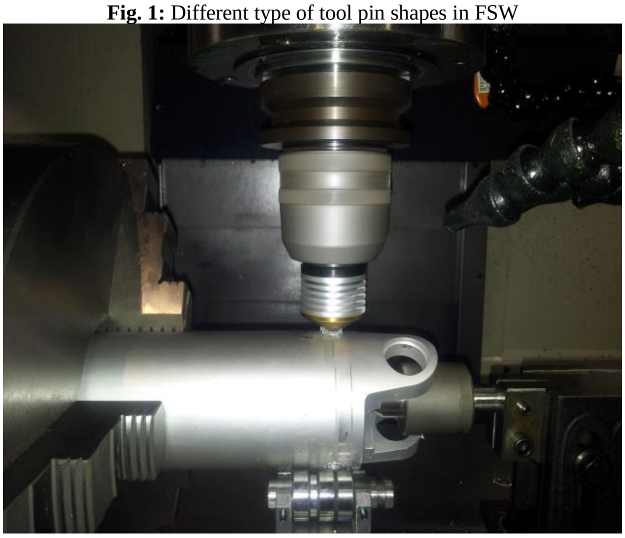


Fig. 2: FSW of aluminum tube

Fig. 3: Tool pin of FSW

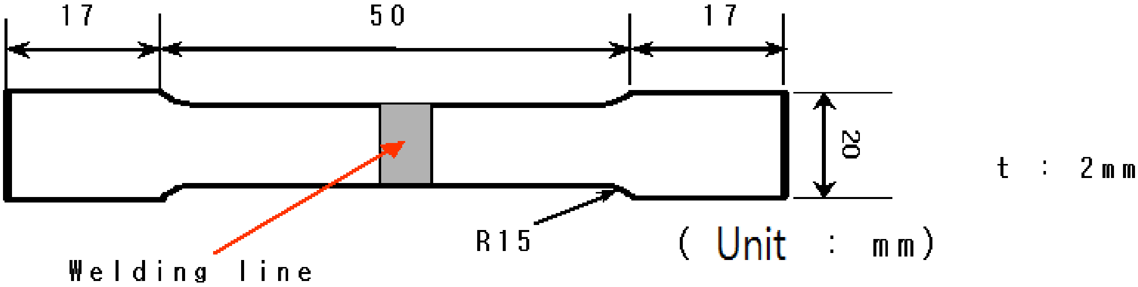


Fig. 4: Tensile strength specimen

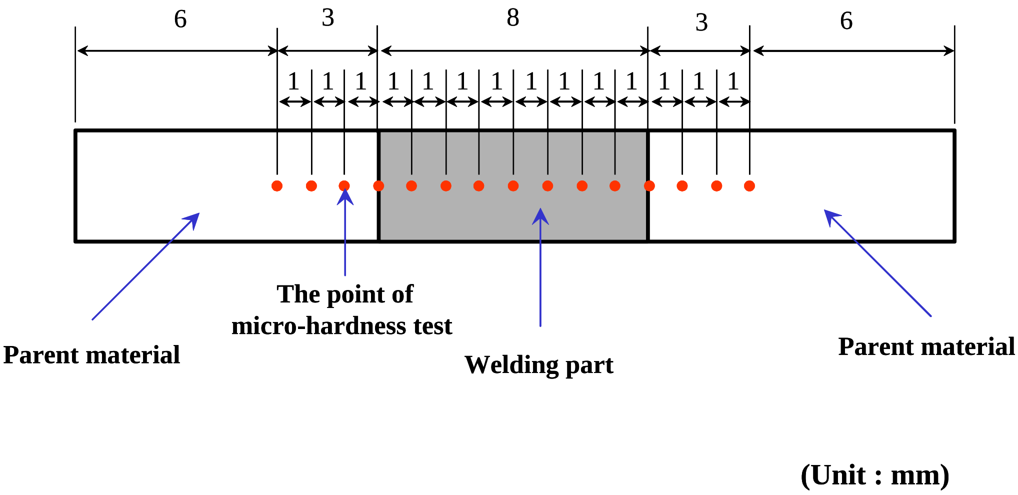
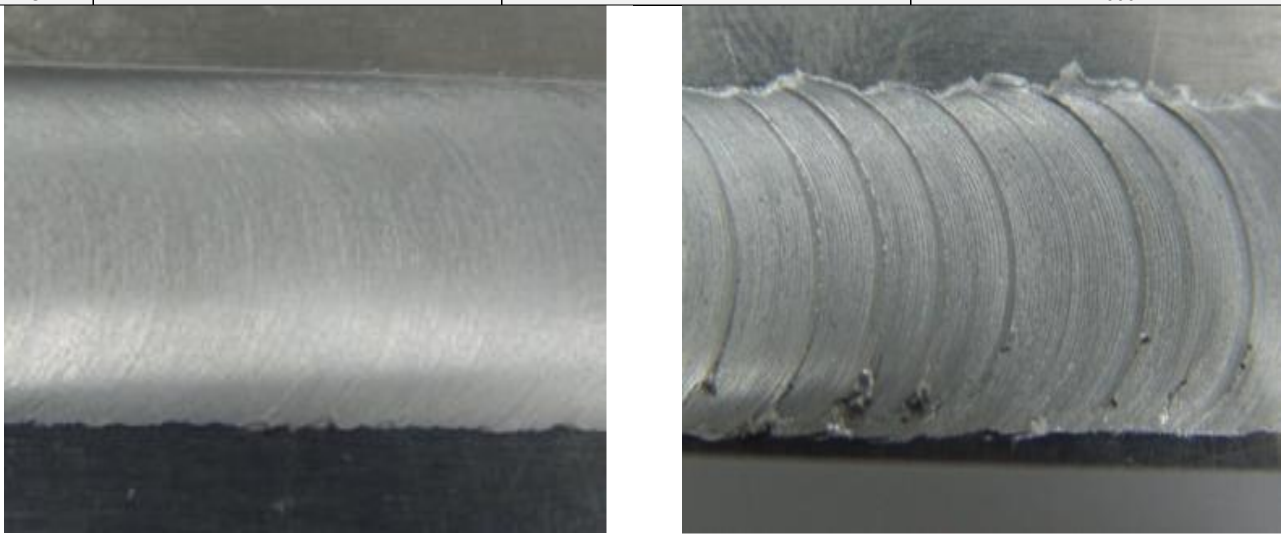


Fig. 5 Measuring Points of micro-vickers hardness

Table 3 Parameters with travel and spin speed

No.	Pin type	Travel speed (mm/min)	Spin speed (rpm)
1			3000
2		400	2500
3			2000
4			3000
5	A	300	2500
6			2000
7			3000
8		200	2500
9			2000
10			3000
11		400	2500
12			2000
13			3000
14	B	300	2500
15			2000
16		200	3000
17			2500

18			2000



(a) A type pin, 200mm, 3000rpm FSW Condition (b) B type pin 400rpm, 2000rpm FSW Condition

Fig. 6 : FSW Results On Different Moving & Tool Rotating Speed

(STS440C) is usually used since they have excellent dynamic and static properties at high temperatures; depending on the welding material, the tool shape varies. In this study, to set up the variables when performing FSW on A6061-T6, the welding speed was changed to 200-400 mm/min, and the rotation rate to 2000-3000 rpm. Furthermore, FSW was performed according to the shape of the tool pin.

In general, the variables affecting the mechanical properties and weldability in FSW include the tool rotation rate (rpm), welding speed (mm/min), shape of the pin, joint constraints, size of the tool shoulder, tool shape, and tilting angle. Fig. 1 shows the respective tool pin shapes used in FSW. To determine the welding and mechanical property changes in the materials through the changes in the rotating tool during FSW, a groove was cut on the center part of the rotating tool pin. In addition, a heat radiator was fabricated on the body of the rotating tool to easily dissipate the heat produced during FSW. The diameter of the welding tool shoulder part was 7.5 mm, while that of the tip was 2 mm. Furthermore, the specimen had a size of 170 mm × 50 mm × 3 t, on which butt-joint FSW was carried out. Fig. 2 shows aluminium tube welding in FSW. Fig. 3 shows tool pin in FSW. Table 3 shows the stirring rate and welding speed according to the tool pin shape.

2.3 Mechanical Properties

After FSW, tensile and microhardness tests were conducted to evaluate the mechanical properties. The tensile test specimens were fabricated as shown in Fig. 4, and using the Instron 4206 tensile tester, the test was carried out at the rate of 1mm/min. Furthermore, for the microhardness test, measurements were taken at 15 positions with 1mm gaps at the center of the joint cross-section as shown in Fig. 5; the magnification used for hardness test was 40, and pyramid particles of size 135° were used. In addition, to check for defects such as pores and welding cracks at the joints and the welding state at the cross-section of the joint, an optical microscope (×15) was used for magnification and observation. Here, surface etching was performed on the cross-section of the joint, and precision polishing by using rough polishing (#400), micropolishing (#2000), and aluminum oxide. For etching, the cross-section of the joint was examined using Keller solution.

3. Result

3.1 Exterior and macro test

With respect to the exteriors of the FSW specimens, which were fabricated by using rotating tools with A and B type pins, the joints formed when the rotating tool shoulder part spins appeared on the entire friction welded surface of each specimen, regardless of the tool pin shape or welding condition; pores or non-welded zones were not observed. In other words, satisfactory exteriors of the FSW specimens were observed in general in all the conditions. Fig. 6 represents the magnified images of the joints when the moving speed and rotating speed were changed. As shown in Fig. 6 (a), when the moving speed is low and the rotating speed high, the joint showed slight rotation patterns; on the other hand, as shown in Fig. 6 (b), when the moving speed was high and the rotating speed low, the rotation patterns that appeared on the surface of the joint bead had rough shapes. Depending on the A and B type pin shapes, the welded surface bead shapes showed a difference, and, under the condition of low moving speed and high rotating speed using A type pin, the weld bead shapes appeared beautiful. Furthermore, it is thought that such differences in bead shape affect tensile strength and microhardness.

3.2. Tensile test

As a result of the tensile test, fractures occurred in the FSW zone of each specimen. Table 4 shows the tensile strength, elongation, and modulus according to the tool pin shape after FSW. Fig. 8 shows ultimate tensile strength graph. The maximum tensile strength was measured to be 199.1 MPa at 300mm/min welding speed and 3,000 rpm rotation speed with the A type pin. Compared to the B type pin, the A type pin showed higher tensile strengths.

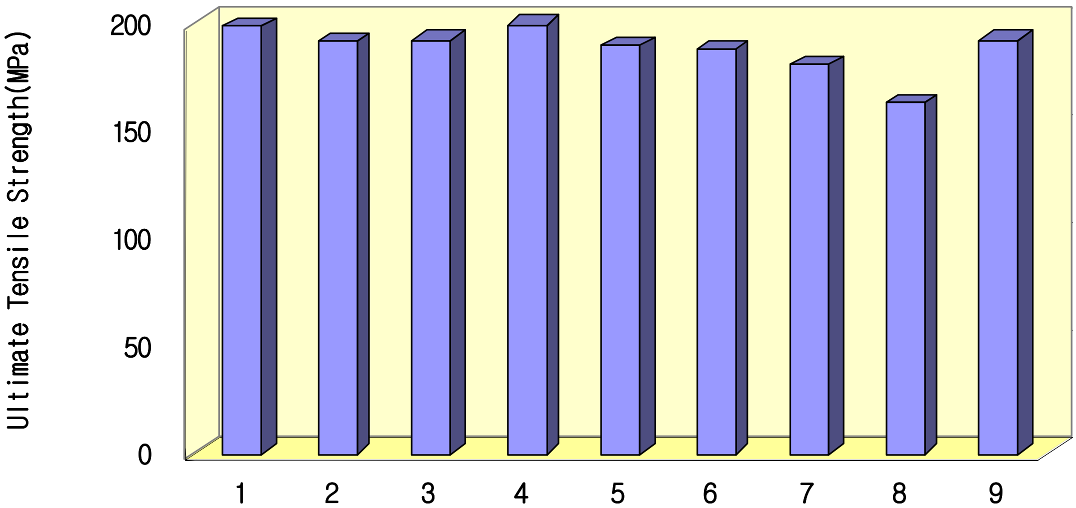
At 400 mm/min and 4,000 rpm for the A type pin, the elongation was 6.9%, which was the highest, but the difference in elongation between the A and B type pins was very small. Overall, the tool rotation rate and welding speed did not show much difference across different conditions, and the fracture of the tensile specimen occurred at the joints. It was concentrated in the heat-affected zone (HAZ) or thermo-mechanically affected zone (TMAZ), where the hardness values were measured to be lower than those at the center of the joint.

(a) Welding speed low, tool rotation rate(rpm) high (b) Welding speed high, tool rotation rate(rpm) low

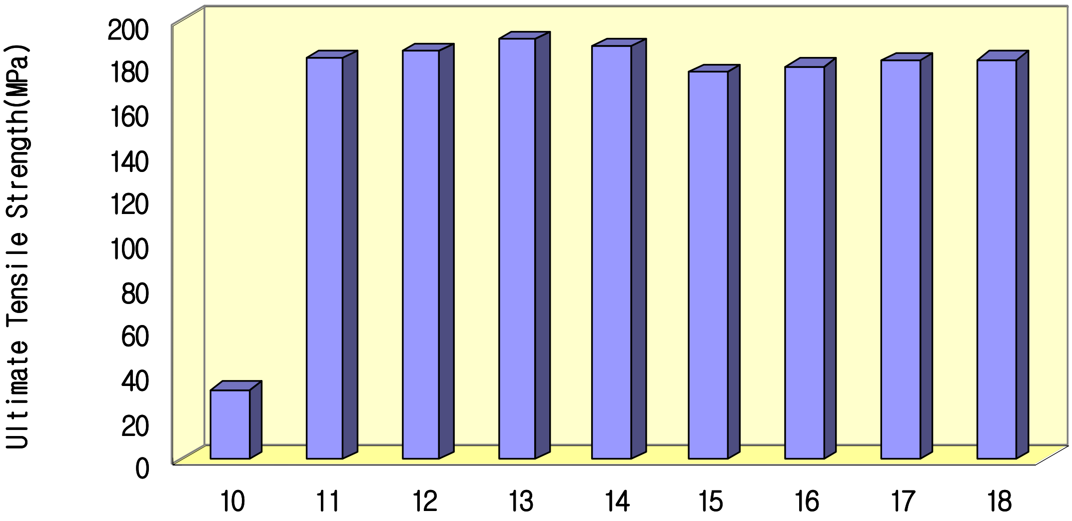
Fig. 7 : FSW Results On Different Moving & Tool Rotating Speed

Table 4: Tensile strengths result of A type and B type

No.	Pin type	Welding condition		Mechanical Properties			Fracture mode
		Speed (mm/min)	Spin (rpm)	Tensile strength (MPa)	Elongation (%)	Modulus (MPa)	
1	A	400	3000	197.8	6.9	5,334	Thermal effect part
2			2500	190.9	6.7	5,684	Thermal effect part
3			2000	191.3	5.8	5,649	Thermal effect part
4		300	3000	199.1	6.2	5,586	Thermal effect part
5			2500	189.0	6.1	5,305	Thermal effect part
6			2000	186.8	6.1	5,653	Weld center line
7		200	3000	180.0	6.8	5,228	Thermal effect part
8			2500	162.2	4.7	8,746	Thermal effect part
9			2000	191.2	6.8	4,983	Thermal effect part
10	B	400	3000	161.4	4.5	5,998	Weld center line
11			2500	182.3	4.3	5,474	Weld center line
12			2000	184.8	5.0	5,646	Thermal effect part
13		300	3000	190.6	6.1	5,895	Thermal effect part
14			2500	187.4	4.2	9,903	Weld center line
15			2000	175.4	3.7	9,210	Weld center line
16		200	3000	178.3	5.8	7,688	Thermal effect part
17			2500	181.2	5.0	7,829	Thermal effect part
18			2000	181.5	5.2	5,853	Thermal effect part

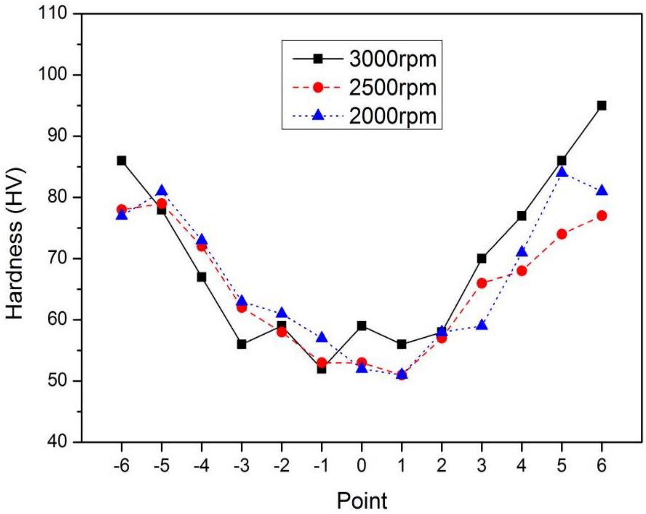


(a) "A" type tip FSW test result

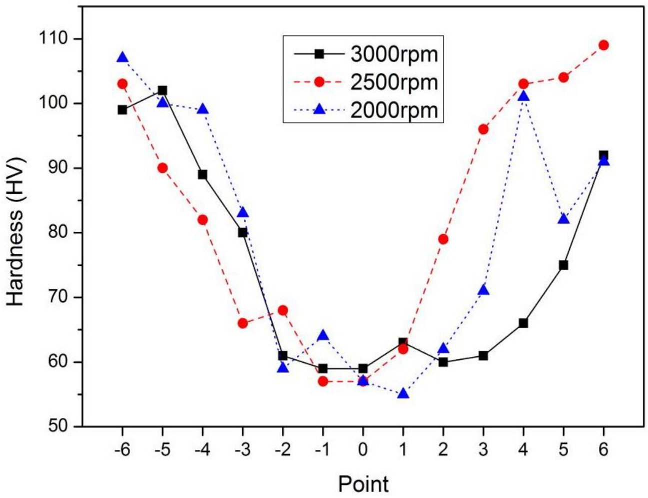


(b) “B” type tip FSW test result

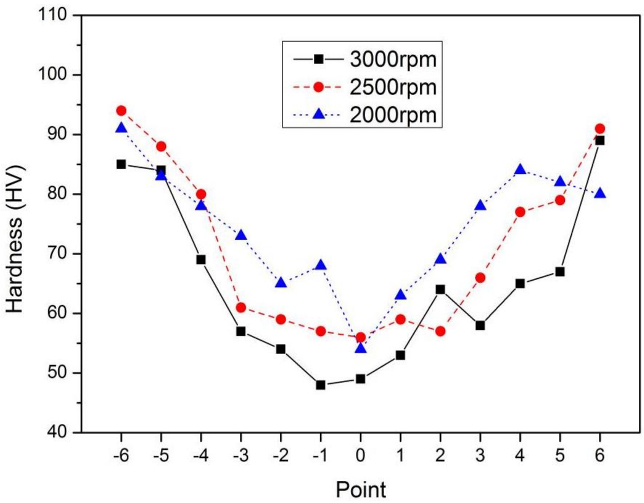
Fig. 8 : Results of tensile strength test



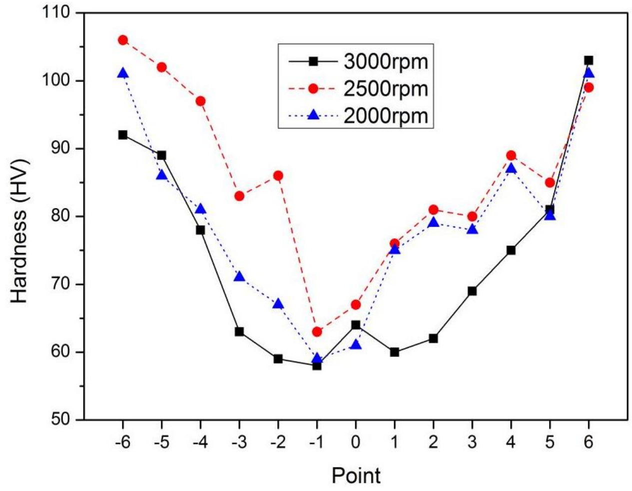
(a) A Type (200mm/min)



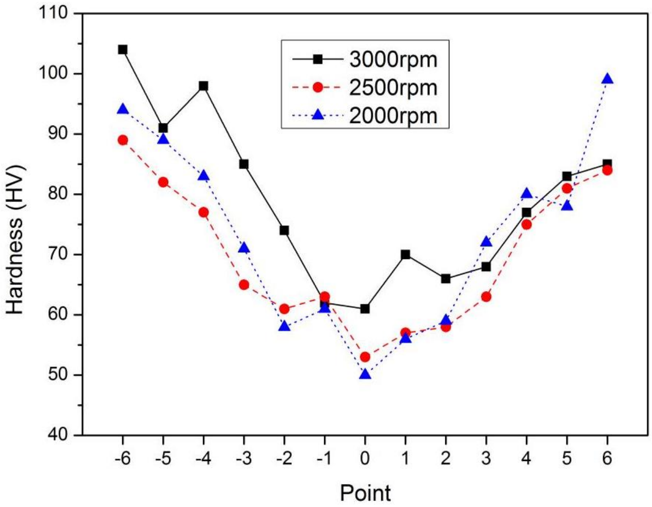
(b) B Type (200mm/min)



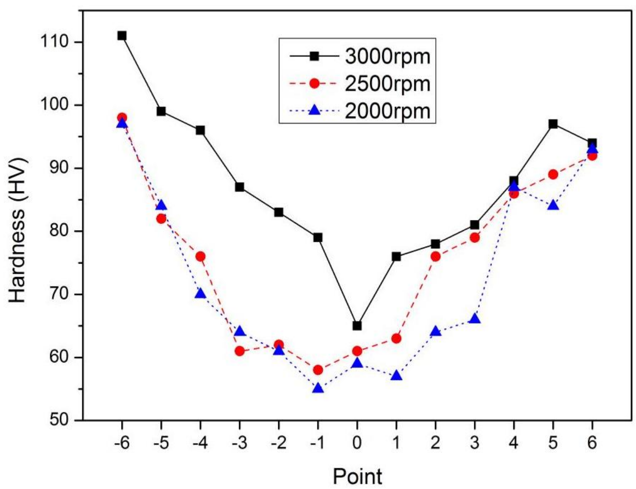
(c) A Type (300mm/min)



(d) B Type (300mm/min)

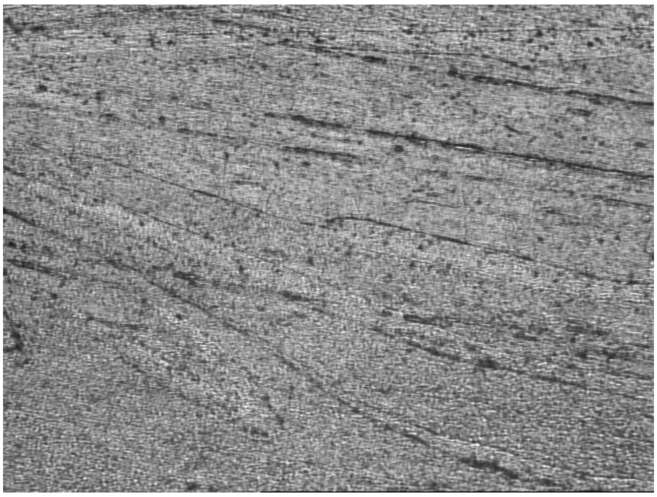


(e) A Type (400mm/min)



(f) B Type (400mm/min)

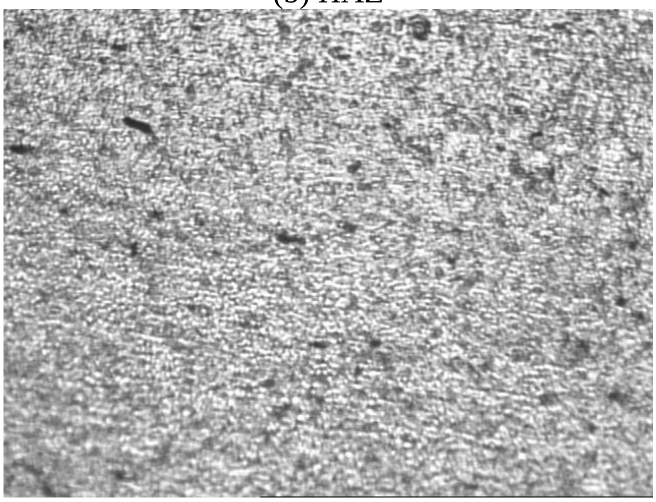
Fig. 9: Result of microhardness measurements



(a) Stir zone

(b) HAZ

(c) TMAZ



(d) Base metal

Fig. 10 Cross sectional views of friction stir welded A6061-T6 (×100)

3.3. Microhardness

The distributions of hardness values were Hv104 and Hv111 for the A and B type pins, respectively, at the welding speed of 400 mm/min and tool rotation rate of 3,000 rpm, and Hv48 and Hv50 in the case of 200 mm/min welding speed and 3,000 rpm rotation rate. The hardness value was generally low in the stir zone, and it was determined that it had an influence on the fracture occurring in the entire stir zone.

3.4. Microstructure

Fig. 9 shows the microstructures of the cross-sections of the FSW zones. For both A and B type pins, the same microstructures were observed. The microstructures are divided into the stir zone (SZ), TMAZ, HAZ, and base metal, and depending on the tool rotation rate and weld speed, various shapes of the deformed structure were observed in the SZ and adjacent areas. The effect of pin shape on microstructure was very small, and various shapes of the deformed structure were observed in the SZ and adjacent areas, depending on the welding speed. The effect of pin shape on microstructure was very small; the SZ was fine and uniform, because plastic deformation occurred due to the rotation of the pin. Both plastic deformation and partial recrystallization were observed in the TMAZ. As the tool rotation rate and welding speed increased, dense precipitates appeared due to the stirring caused by the rotation of the tool during FSW. In the HAZ, grains became coarse due to the heat produced during FSW. It was determined that such coarse grains affected the tensile strength and microhardness of the FSW zone. Furthermore, typical onion ring shapes were observed in the SZ.

4. Conclusion & Discussion

The following results were obtained from the tests for evaluating the mechanical properties for different rotating tool pin shapes when FSW was performed on A6061-T6.

1) When FSW was performed on A6061-T6 based on the rotating tool pin shape, i.e., A or B type pin, the A type pin showed a better exterior bead than the B type pin.

2) As a result of the tensile test, fractures were observed in the friction welding zone of each specimen, and the maximum tensile strength measured was 197.8 MPa for the A type pin conditions of 400 mm/min and 3,000 rpm.

3) Based on the microhardness test, a generally low hardness distribution was observed in the FSW zone in all the specimens. Furthermore, the A and B type pins showed Hv104 and Hv111, respectively, in the case of 400 mm/min welding speed and 3,000 rpm tool rotation rate, and Hv48 and Hv50, respectively, in the case of 200 mm/min welding speed and 2,000 rpm tool rotation.

4) By observing the microstructures using an optical microscope, the effect of pin shape on microstructure was determined to be very small; the SZ was fine and uniform since plastic deformation occurred due to the rotation of the pin. Both plastic deformation and partial recrystallization were observed in the TMAZ. In the HAZ, grains became coarse due to the heat produced during FSW. It was determined that this had an influence on tensile strength and microhardness.

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