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Friction Stir Welding Tool Geometries Affecting Tensile Strength of AA6063-T1 Aluminum Alloy Butt Joint

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Abstract

Friction Stir Welding (FSW) is a solid state welding that could successfully weld the difficult-to-weld-materials such as an aluminum alloy. In this welding process, the stirrer of the welding tool is one of the important factors for producing the perfect sound joint that indicates the higher joint strength. So, this report aims to apply the friction stir welding using various stirrer geometries to weld the AA6063-T1 aluminum alloy butt joint, investigates the mechanical properties of the joint and then compares the mechanical properties with the microstructure of the joint. An experiment was started by applying the friction stir welding process to weld a 6.3 mm thickness of AA6063-T1 aluminum alloy butt joint. A study of the stirrer geometries effect such as a cylindrical geometry, a cone geometry, a left screw geometry and a right screw geometry at a rotational speed of 2000 rpm and a welding speed of 50-200 mm/min was performed. The mechanical properties such as a tensile strength and a hardness of the joint were also investigated and compared with the microstructure of the joint. The results are as follows. A variation of FSW Stirrer shape directly affected the quality AA6063-T1 aluminum alloy butt joint. A cylindrical stirrer shape and a cone stirrer shape produced the void defect at the bottom part of the weld metal and initiated the failure of the joint when the joint was subjected to the load during the tensile test. Left and right screw stirrer shapes gave the sound joint with no void defect in the weld metal and affected to increase the joint strength that was higher than that of the aluminum base metal.

Keywords*: friction stir welding, aluminum, tool shape, tensile strength,*

1. INTRODUCTION

Friction Stir Welding is a solid state welding that is widely applied in various industries for welding the difficult to fusion weld such as aluminium and aluminium alloy. [1] When compared to the fusion welding,

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FSW could produce the mechanical properties of the weld metal that were not highly different from the base metal, prepared the finer equi-axed grain shape and did not produce the cast structure in the weld metal. The FSW process was applied to produce the sound joint in aerospace, automobile and shipping industries. [2] The principle of the FSW process is shown in figure 1. Recently, FSW was applied to weld various aluminum alloys and showed the high quality of weld metal such as the butt joint of A356 aluminum cast alloy [3], AA2017 aluminum alloy [4], AA5083 aluminum alloy [5], AA6082 aluminum alloy [6], Al-Li-Cu aluminum alloy [7], AA6063 aluminum alloy [8], [9] etc. These studies reported that the tensile strength of these weld metals were higher than that of the base metal.

The FSW principle as shown in figure 1 shows that one of the important factors that could produce the best combination of the materials at the joint interface is welding tool geometries. The variation of the welding tool geometries such as a stirrer shape, a stirrer length or a tool shoulder surface, etc. is expected for producing the weld metal as required. Recently, many research works have been introduced by the various welding tool geometries for producing the butt joint of aluminum alloy. Li *et al.* [10] designed the stirrer that had a shape of the right screw for observation of the combination between AA2024 and AA6061 aluminum alloy and showed a materials combination mechanism around the joint interface. Prado *et al.* [11] applied the right screw stirrer for welding the butt joint between 6061 aluminum alloy and the 20% Al_2O_3 ceramics and revealed that the butt joint could be produced but the wear rate of stirrer was high. Boz and Kurt [12] designed 4 shapes of FSW stirrer for welding the butt joint of AA1018 aluminum and found that the suitable combination of the aluminum in the weld metal of the joint could be successfully produced when the right screw was applied for welding. The bending test results also showed that the right screw specimen could be completely bent to 180 degrees without any fractures. Zhao *et al.* [13] comparatively designed the right screw cylindrical stirrer shape and the right screw cone stirrer shape for producing the butt joint of AA2014 aluminum alloy. The results showed that the right screw cone stirrer shape indicated the tensile strength of 75% of base metal and showed the best combination of aluminum in the weld metal.

Above discussion shows that the suitable combination of the materials at the joint interface directly affected to improve the FSW joint strength. Therefore, this article aims to study the effects of FSW stirrer shape on the joint strength and compare the relation between the microstructure and the mechanical properties of the joint.

2. EXPERIMENTAL PROCEDURE

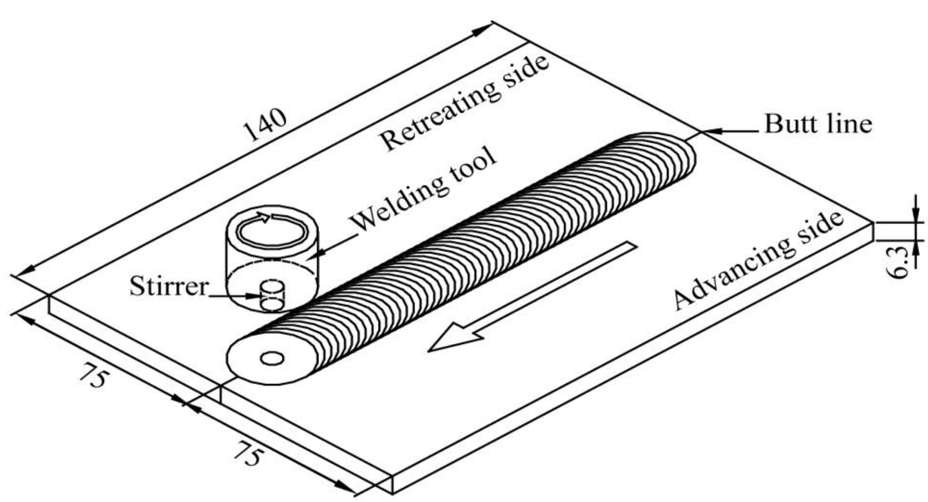


Figure 1. Dimension of the butt joint. (unit: mm)

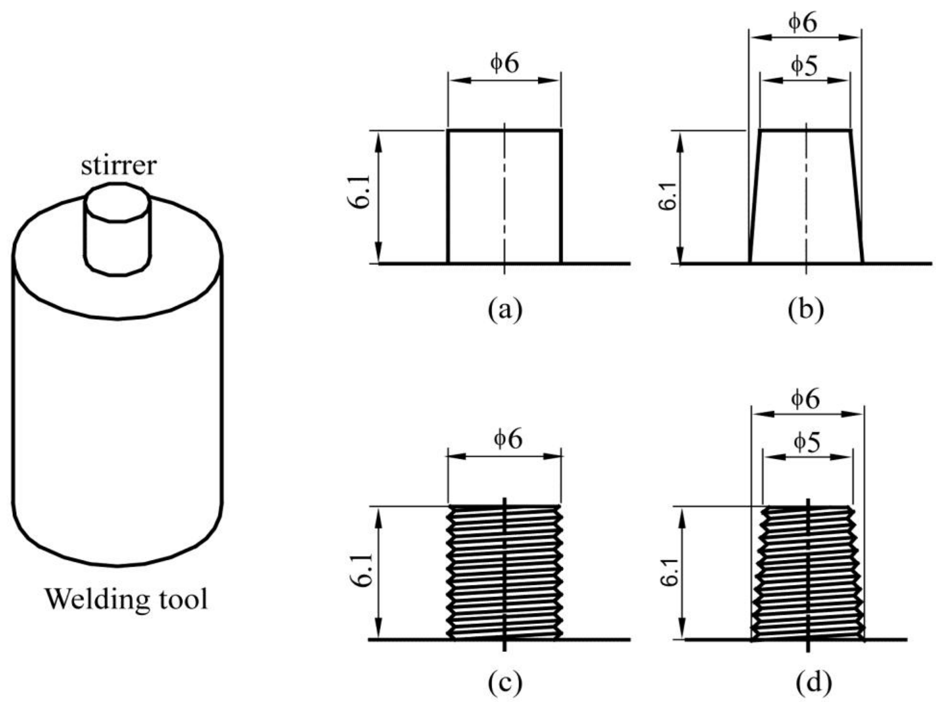


Figure 2. Dimension of the stirrer: (a) an unthread cylindrical stirrer, (b) an unthread cone stirrer, (c) a right screw cylindrical stirrer and (d) a right screw cone stirrer. (unit: mm)

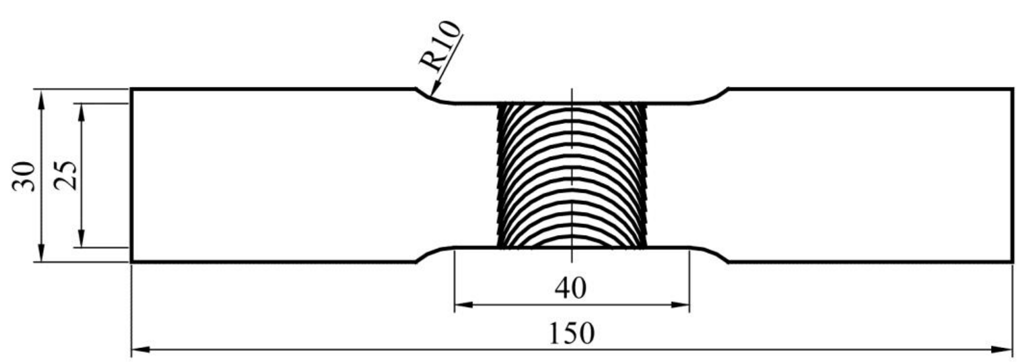
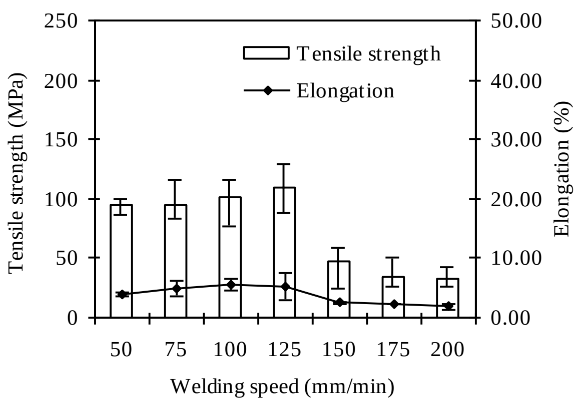


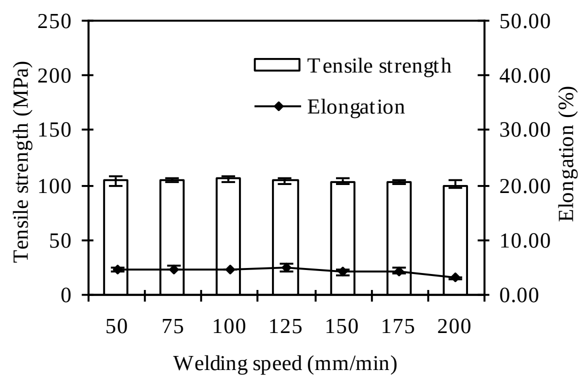
Figure 3. Dimension of the tensile strength of the specimen. (unit: mm)

The material in this experiment was a rolled plate of AA6063-T1 aluminum alloy. The chemical composition of the aluminum alloy was consisted of 95.92%Al-4.0%Mg-0.05%Mn-0.01%Cr-0.02%Cu (weight%). The plates that had a dimension of 75 mm in width, 140 mm in length and 6.3 mm in thickness, were prepared and firmly clamped to be a butt joint in a jig as shown in figure 1. A butt joint that was clamped in a jig was located on the moving table of the CNC vertical milling machine and used as a welding machine in this study. A welding tool was made of JIS-SKD11 and had a shoulder diameter of 25 mm, a stirrer diameter of 6 mm and a stirrer length of 6.0 mm. The stirrer shape was designed into 4 geometries that consisted of an unthreaded cylindrical stirrer geometry (hereafter, Type I stirrer), an unthreaded cone stirrer geometry (hereafter, Type II stirrer), a right screw cylindrical stirrer geometry (hereafter, Type III stirrer) and a right screw cone stirrer geometry (hereafter, Type IV stirrer) as shown in figure 2. The welding process parameters were a rotating speed of 2000 rpm, a welding speed of 50-200 mm/min and a tool tilt angle of 2 degrees. The joints that were welded by various welding parameters were mechanically prepared as tensile specimens as shown in figure 3 for investigation of the tensile strength, fracture location and elongation of the joint. After welding, light optical microscopy was used to characterize the microstructure of the joints. The light optical microscopy specimen was mechanically polished by an emery paper up to 2000 grit number and then finally polished by 1 micron diamond paste. The polished specimen was chemically etched by the solution mixture of 30%HNO_3+10%HF+60% H_2O.

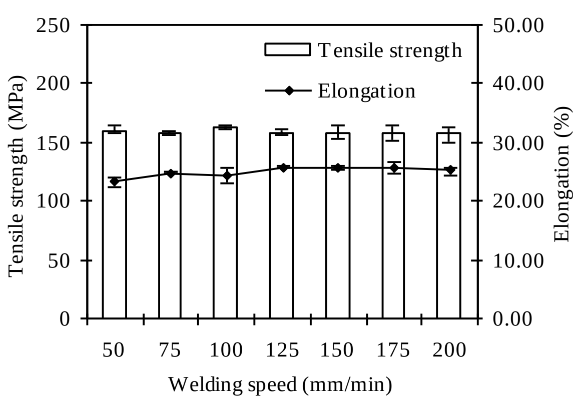
3. RESULTS AND DISCUSSION



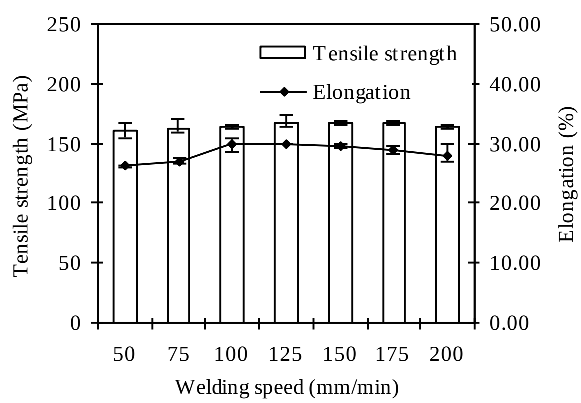
(a) Type I stirrer



(b) Type II stirrer



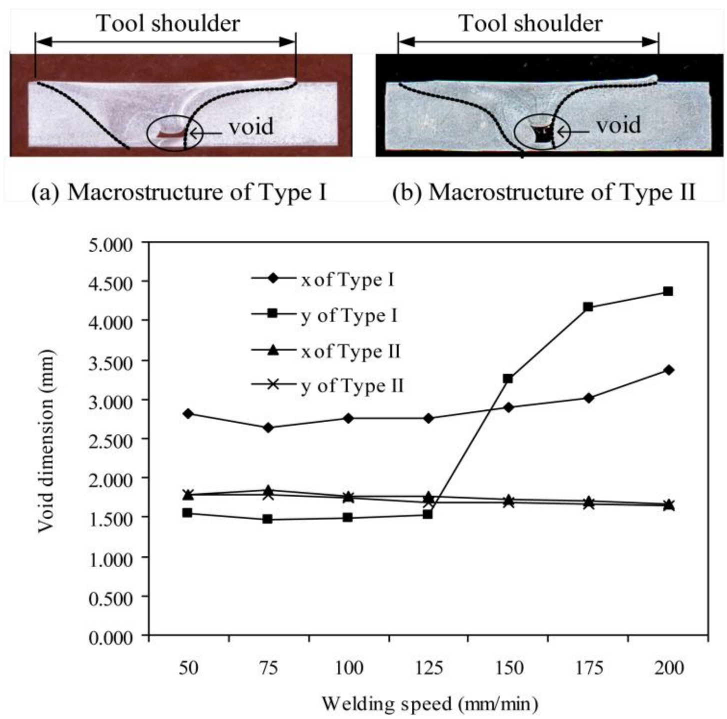
(c) Type III stirrer



(d) Type IV stirrer

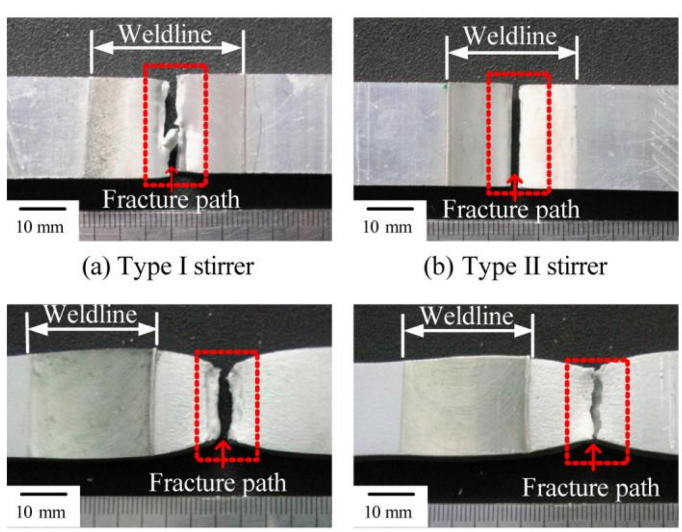
Figure 4. Relation between tensile strength, elongation, welding speed and strirrer type.

Figure 4 shows the relation between the tensile strength, elongation, welding speed and various stirrer shapes of the welding tool that were applied to weld the butt joint of AA6063-T1 aluminum alloy. The tensile strength test results showed that Type I stirrer had the maximum tensile strength of 110 MPa and the elongation of 5.36% as shown in figure 1 (a). The tensile strength of the joint produced by Type I stirrer increased when the welding speed was increased. However, the tensile shear strength of the joint produced by Type I stirrer decreased when the welding speed was faster than 150 mm/min. The variation of tensile strength of the joint was because of the formation of void at the bottom part in the weld as shown in figure 5 (a). Measurement of the dimension of the void (x and y axis) at the bottom of the weld and comparison of the void dimension under various welding speeds, found that the void dimension was related to the tensile strength of the joint and the welding speed. The void dimension was slightly decreased when the welding speed increased, but was dramatically increased when the welding speed increased as shown in figure 5 (c).



(c) Relation of void dimension , welding speed and stirrer type

Figure 5. A void dimension in weld metal produced by Type I and II stirrer.



(c) Type III stirrer (d) Type IV stirrer

Figure 6. Fracture path of the tensile strength specimen.

This void initiated the fracture of the tensile specimen from the bottom to the upper surface of the joint as shown in figure 6 (a) and directly deteriorated the tensile strength of the joint. Furthermore, it was found that the void in the weld metal was similar to the void or the incomplete part in the weld metal of FSW AA2025 aluminum alloy butt joint [10] and 6063-T6 aluminum alloy butt joint [14]. However, no relation between void dimension and tensile strength of the joint was reported. Mishra and Ma [15] reported that the void could be neglected if the serious flow of the materials that was moving around the stirrer was produced and to produce the turbulent flow, the tool tilt angle should be increased [13].

Type II stirrer was designed to increase turbulent flow around the stirrer and under the tool shoulder. It also had some advantage for decreasing the inserted force of the welding tool to the joint in FWS process [15]. However, this stirrer could not remove the void at the bottom part of the weld metal as shown in figure 5 (b). The void formation in the weld is smaller than that was formed in the weld metal of Type I and seemed to be normal when the welding speed increased. However, this void trended to initiate the fracture from the void to the upper surface of the joint as shown in figure 6 (b). The maximum tensile strength and the elongation of the joint produced by Type II stirrer was 106 MPa and 4.66%, respectively, at the welding speed of 100 mm/min.

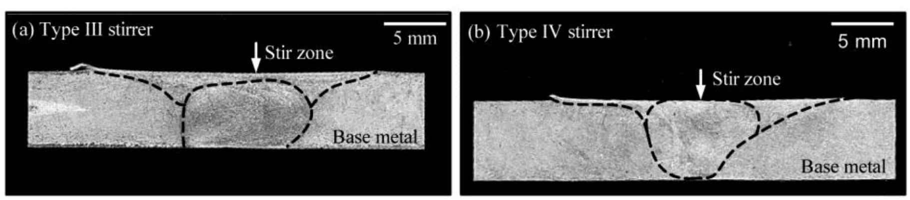


Figure 7. Macrostructure of the joints produced by various stirrer shapes.

The joint that was welded by Type III and IV stirrer could remove the void at the bottom in the weld metal. Macrostructure in figure 7 shows the sound metal without the void that was the initiation point of the fracture in the tensile test specimen as occurred in the joint produced by Type I and II stirrers. This was the reason that the joint produced by Type III and IV stirrers gave the higher tensile strength when compared to Type I and II stirrers. The weld metal of the joint produced by Type III and IV stirrers were stronger than the base metal as the fracture locations were found in the base metal as shown in figure 6. This was causing the tensile strength and the elongation of the joints, as shown in figure 3. The maximum tensile strength and the elongation of the joints produced by Type III stirrer were 163 MPa and 25% of the welding speed of 100 mm/min. The maximum tensile strength and the elongation of the joints produced by Type IV stirrer were 106 MPa and 25% of the welding speed of 100 mm/min.

Figure 8 (a) shows the macrostructure of the joint produced by the right screw cylindrical stirrer, the rotating speed of 2000 rpm, the welding speed of 100 mm/min, which was the optimum condition in this study. (AS=Advancing side and RS=Retreating side) The macrostructure showed the sound joint without the defect in the weld metal and also showed the circle of the materials that was called “nugget” at the center of the weld metal. This area was formed because of the serious turbulent flow of the aluminum that was forced, sheared and pushed by the screw stirrer. 5 locations on the macrostructure in figure 8 (a) were examined for revealing the microstructure of the joint and showed the microstructure as follows.

Figure 8 (b) shows the microstructure of the AA6063-T1 aluminum alloy base metal that had an irregular grain shape and size. The grain size of the base aluminium alloy that was followed ASTM E112 [16] – Linear interception method, was 33.39 microns. The boundary between Thermo-mechanical Affected Zone (TMAZ) and the stir zone (SZ), is shown in figure 8 (c). This location was treated by the frictional heat and caused to have more regular and round grain shape than that of a microstructure of base metal [3,7,10]. The microstructure of the stir zone at location III to V in figure 8 (a) showed the dynamic recrystallization zone that was a regular round grain shape and showed the grain size of 18.49 microns as shown in figure 8 (d)-(e). When compared to the grain size of the weld that was produced by Type I stirrer, it was found that the grain size of this Type III stirrer was finer than that of Type I stirrer. However, the smallest grain size in this study was found at the location beneath the upper surface of the weld as shown in figure 8 (f).

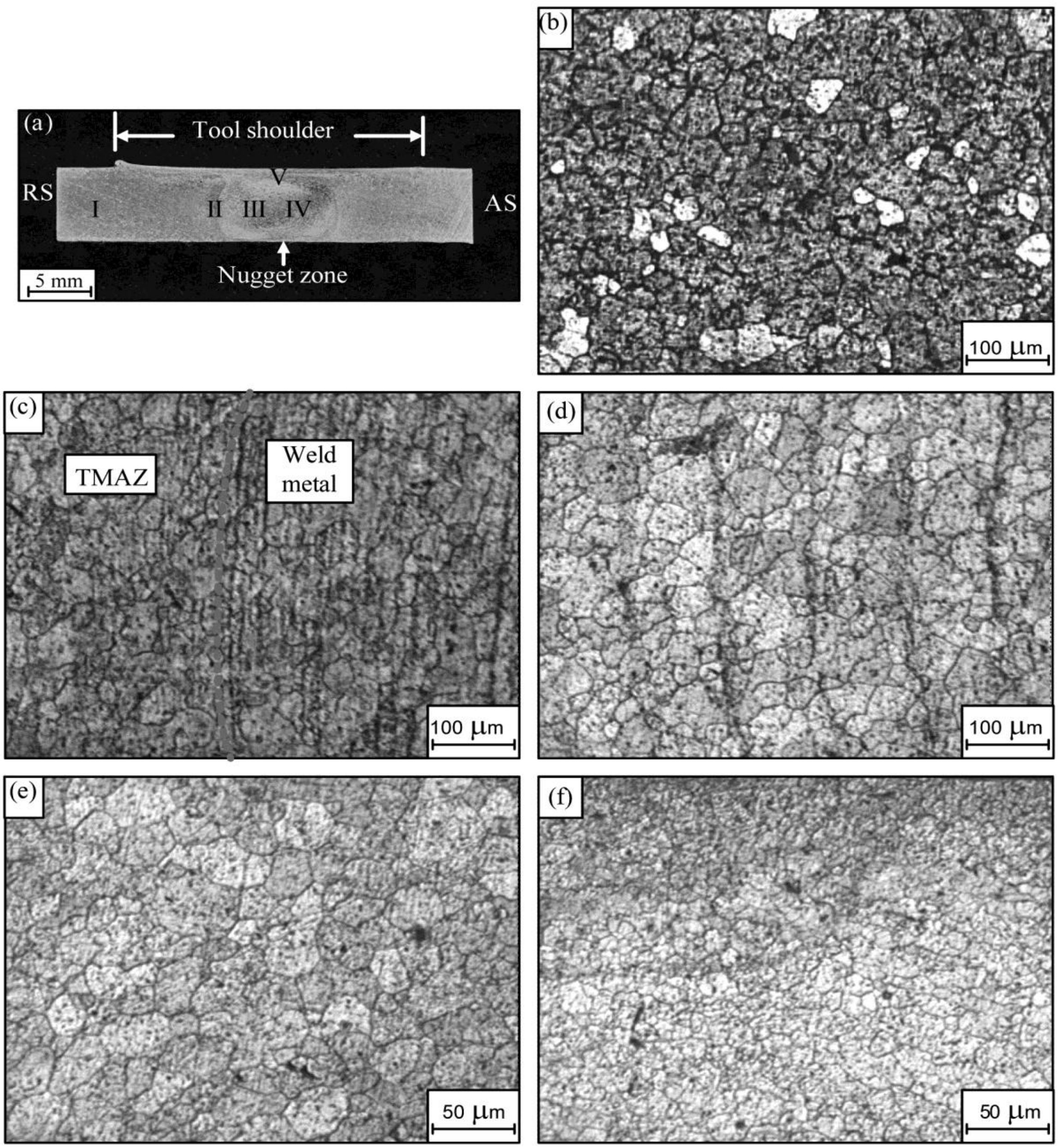


Figure 8. Microstructure of Type III Stirrer: (a) Macrostructure, (b) base metal, (c) TMAZ+Stir zone, (d) stirs zone, (e) Nugget zone, and (f) beneath the tool shoulder.

4. CONCLUSION

The butt joint of AA6063-T1 aluminum alloy was friction stir welded using various welding parameters consisted of the stirrer shapes and the welding speeds. After welding, the joint was prepared and investigated for the butt joint properties. The summarized results are as follows.

1. The cylindrical and cone pin shapes produced the incomplete weld and directly initiated the fracture to occur at the middle of the weld.
2. The left and right screw pin shapes could produce a sound weld and increased the tensile strength of the joint.
3. The optimum welding condition that produced the tensile strength of 168 MPa, was the welding condition with the left screw pin, the rotating speed of 2000 rpm and the welding speed of 125 mm/min, were applied.
4. The microstructure of the joint that was produced by a left screw pin produced a finer re-crystalline grain than that of a base metal.

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