Properties of High Speed Friction Stir Welded 6063-T6 Aluminum Alloy

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Abstract. Friction stir welding (FSW) is known as a revolutionary welding technology, which has come to the forefront in recent years. The low welding speed affects the efficiency of friction stir welding (FSW) and hinders the large-scale commercial application of FSW. In order to improve the welding speed and promote the application of FSW, 6063-T6 aluminum alloy plates were friction stir welded with welding speed of 3000 mm/min. The properties of welds were also tested and analyzed. The results show that the alloy plates can be successfully welded by FSW with high speed welding speed, and the tensile strength of weld can reach over 71% that of the base material.

1. Introduction
Friction stir welding (FSW) is known as another revolutionary welding technology after laser welding. FSW produces weld joints by using a non-consumable and rotating welding tool to locally soften the workpieces under the effect of friction and plastic work. The working principle is as shown in Figure 1. Compared with the traditional fusion welding, FSW avoids many of the difficulties related to a change in state, such as volumetric changes and variations of gas solubility [1]. So the favorable characteristics of FSW compared to the arc welding processes are with improvement of weldability, cosmetic appearance, fatigue property, corrosion resistance, stress corrosion cracking performance, static strength and ductility [2]. FSW can reduces distortion and residual stress. As a solid state welding technology, FSW has great application prospect in aluminum alloy [3-13], magnesium alloy [14-24], and other products [25-28]. However, low welding speed, below 1000 m/min, limits the commercial application of FSW. 6061-T6 sheets with thickness of 1.2 mm and 2 mm by high speed FSW of 3000 mm/min were studied [29]. While there are few reports on high speed FSW of 6063 aluminum alloy plates which are widely used in industry. In the study, 6063-T6 aluminum alloy plates with were successfully friction stir welded with welding speed of 3000 mm/min.
2. Experiment

Base material (BM). 6063-T6 aluminum alloy plates of 3 mm thickness were butt friction stir welded at high speed of 3000 mm/min. The plates are with length of 200 mm and width of 60 mm. The chemical composition of the BM is of 0.58 % Mg, 0.46 % Si, 0.21 % Fe, 0.05 % Cu, 0.04 % Mn, 0.04 % Zn, 0.03 % Ti and balance Al in weight percent.

Welding process. Figure 2 shows the tool for FSW in the study. The tool is with shoulder of 11 mm in diameter, and the pin is with length of 2.7 mm and diameter of 4.1 mm. The tool angle is at 2.5° during welding. A constant welding speed of 3000 mm/min, shoulder plunge depth of 0.15 mm and different rotation rates were used in the study. The rotation rates were of 2500 rpm and 3000 rpm, respectively. And the welds are noted as weld-2500 rpm and weld-3000 rpm, respectively.

Hardness test. Hardness of the friction stir welds at transverse direction was measured with a 500 g load for 10 s.

Tensile test. Transverse tensile samples with gauge length of 60 mm were prepared, as shown in Figure 3, and all the tensile samples of weld joints were milled before testing. The tensile tests were on Sansi CMT-5105 mechanical tester at room temperature with crosshead speed of 1 mm/min. In order to reduce the test error, three tensile specimens of the BM and joints were cut and tested. The average value of three specimens was used as the test value. And the tensile fracture surfaces of welds were observed by VEGA3-type scanning electronic microscopy (SEM).
3. Results and discussions

Welds appearance. The surface appearance of high speed friction stir welds are shown in Fig. 4. It is seen that the welds are good formability with a few flash and without macro defects such as void and galling. Excessive flash is a kind of surface defects, which is caused by excessive shoulder plunge depth and mistake of welding seam at the process of FSW. While a few flash can certify for adequate shoulder plunge depth, resulting in better performance of welds. If the thickness of welded plates is basically the same, the length of the pin matches the thickness of the workpiece to be welded, and the shoulder plunge depth is got under control in perspective, a few flash can be got in the welds of FSW. Key hole produces resulted by the absence of base metal when the tool is drawn out at the end of welds.

Fig.3. Tensile specimen size

Fig.4. Surface appearance of welds with rotation rate at (a) 2500 rpm and (b) 3000 rpm.
Surface hardness. The typical hardness profile across the weld center measured along the mid-thickness is shown in Fig. 5. It can be seen that the hardness value of the BM fluctuates at 73~74 HBS10/500. After FSW, the hardness value in the nugget zone of welds is higher than that of the BM. At a constant welding speed of 3000 mm/min, the hardness value of weld-2500 rpm is higher than that of the weld-3000 rpm, as result of more frictional heat at the higher rotation rate of 3000 rpm. The highest hardness in the weld-3000 rpm is at 82 HBS10/500.

![Hardness test results of the BM and welds](image)

**Fig. 5. Hardness test results of the BM and welds**

Tensile properties. The average tensile strength, yield strength and elongation of BM is at 271 Mpa. Table 1 shows mechanical properties of the BM and welds at different rotation rates. It is seen that the ultimate tensile strength (UTS) of welds is less than that of the BM, and when the rotation rate is at 3000 rpm, the joint efficiency, which is a ratio of UTS of welds to UTS of BM, reaches 71 %. Forever, the UTS of welds at rotation rate of 3000 rpm is higher than that of welds at rotation rate of 2500 rpm. At the lower rotation rate of 2500 rpm, the heat generated by FSW is not enough to make the material in the welding area flow fully, which finally reduces UTS of welds. The increasing of rotation rate at a constant welding speed has contributed to the increasing of heat input. The peak temperature at the weld zone increase by ~40 °C with the rotation rate increasing from 300 to 600 rpm at a constant welding speed of 120 mm/min, which has been reported by Tang et al[30]. Rotation rate is a very important process parameter in the FSW process, which has an notable impact on the frictional heat. When the rotation rate is too low, there is without sufficient frictional heat leading to no thermoplastic flow, so the weld joint can not be successfully produced, it is easy to have hole defects, tunnel flaw and lack of penetration. Increasing rotation rate is conducive to improve the welding usability and weld joint property. But having a higher rotation rate is not the better. In the welding process, the effect of rotation speed on joint performance is not isolated.
The fracture morphologies of tensile samples of welds is shown in Fig. 6. From the figure, it appears that all the samples failed with basically 45° shear fracture at the advancing side (AS). That is because of strong shear deformation in the zone caused by rotation of the shoulder and pin[31]. Fig. 7 shows the typical micrographs of tensile fracture surfaces for welds by SEM. As can be seen from figure 7, dimples with some tear ridges are observed in the tensile fracture, and some fine smooth dimples left resulted by detaching of some small second phase particles. Therefore, the tensile fracture shows plastic fracture mostly and brittle fracture little quasi-cleavage fracture.

Table 1 Mechanical properties of the BM and welds

| Specimens     | UTS (MPa) | Average UTS (MPa) | Joint efficiency(%) |
|---------------|-----------|-------------------|---------------------|
| BM            |           |                   |                     |
| 1#            | 273       | 271               | /                   |
| 2#            | 269       |                   |                     |
| 3#            | 272       |                   |                     |
| Weld-2500 rpm |           |                   |                     |
| 1#            | 186       | 183               | 68                  |
| 2#            | 181       |                   |                     |
| 3#            | 183       |                   |                     |
| Weld-3000 rpm |           |                   |                     |
| 1#            | 191       | 192               | 71                  |
| 2#            | 192       |                   |                     |
| 3#            | 192       |                   |                     |

Fig.6. Fracture morphologies of welds with rotation rate at (a) 2500 rpm and (b) 3000 rpm.
4. Conclusions

6063-T6 aluminum alloy plates were friction stir welded with high welding speed of 3 m/min by butt. And the mechanical properties were tested and analyzed. The results show that compared with the BM, the UTS of welds is lower. And the joint efficiency can reach 71% when the rotation rate is of 3000 rpm and welding speed is of 3 m/min. As a widely used light alloy, 6063-T6 aluminum alloy is welded at high welding speed, which will give an impulse to industrialized application on large scale. High welding speed can significantly improve welding efficiency and reduce welding cost in the process of FSW, therefore it will help the enterprise improve productivity and competitiveness.

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Fig. 7. SEM micrographs of welds with rotation rate at (a) 2500 rpm and (b) 3000 rpm.
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