Properties of Friction Stir Welded 3003-H17 Aluminum Alloy at High Travel Speeds

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Abstract. As a new-type technology of solid state welding, friction stir welding (FSW) has a very good prospect for application. However, the welding speed is low in the practical application, and most of the time the welding speed is less than 500 mm/min, which hinders the large-scale commercial application of FSW. In this paper, 3003-H17 aluminum alloy plates of 5 mm thickness were butt welded by high speed FSW with travel speed at 1500 and 3000 mm/min and a constant tool rotation speed. The results show that 3003-H17 aluminum alloy can be successfully butt welded by high travel speed. And the UTS of weld joint decreases when the travel speed increases from 1500 mm/min to 3000 mm/min at a constant tool rotation speed of 2000 rpm and shoulder plunge depth of 0.2 mm. The joint efficiency reaches 87% at travel speed of 1500 mm/min, tool rotation speed of 2000 rpm and shoulder plunge depth of 0.2 mm.

1. Introduction
Friction stir welding (FSW) is known as an innovative welding technology after laser welding, and it is being concerned by many researchers and engineering personnel. Figure 1 shows the working principle of the friction stir welding process.

![Fig. 1 Working principle of the friction stir welding process](image-url)
FSW is successfully used to weld aluminum alloys [1-8], magnesium alloys [9-17], titanium alloy [18-19], zinc alloy [20], cooper [21] and other materials [22]. FSW is the most successful application on aluminum alloys. 3003 aluminum alloy is in common use. AA 3003 aluminum alloy with a thickness of 3 mm were friction stir welded at travel speed of 200 mm/min and the microstructural evolution and mechanical properties of weld joints were investigated, as reported by Tan et al [23]. Aydin et al [24] investigated friction stir welds of 3003-O aluminum alloy in 3mm thickness with travel speed of 40–112 mm/min during welding. However, in the previous researches, the travel speed is almost lower than 300 mm/min, which reduces welding efficiency. In this study, 3003-H17 aluminum alloy plates with 5 thickness were welded by FSW at high travel speed of 1500 and 3000 mm/min. And the mechanical properties of weld joints were tested and analyzed.

2. Experiment

Base material (BM). 3003-H17 aluminum alloy plates were with the size of 600 mm*200 mm*5 mm (length, width, and thickness, respectively). Table 1 shows the chemical composition of the BM. The ultimate tensile strength (UTS), yield strength (YS) and elongation of BM is of 171 Mpa, 121 Mpa and 21.5%.

Welding processes. 3003-H17 aluminum alloy plates were butt welded by FSW at a constant tool rotation speed of 2000 rpm, and the high travel speed were at 1500 and 3000 mm/min, and for simplicity, the weld joints were marked as joint-1500 mm/min and joint-3000 mm/min corresponding to the travel speed of 1500 and 3000 mm/min, respectively. Figure 2 shows the tool used in the study of FSW for 3003-H17 aluminum alloy plates. The diameter of tool shoulder is at 16 mm, and the diameter and length of pin is at 6 mm and 4.7 mm, respectively. The tool angle is of 2.5° and shoulder plunge depth of 0.2 mm during welding.

Hardness test. The surface hardness of the friction stir weld specimens was measured at transverse direction with a 500 g load for 10 s.

Tensile test. All the transverse tensile specimens were with gauge length of 60 mm, as shown in Fig. 3. The tensile tests were on Sansi CMT-5105 mechanical tester at crosshead speed of 1 mm/min at room temperature. Five tensile specimens of the BM and weld joints were prepared and tested. The average value of five specimens was used as the test value. The tensile fracture of weld joints was observed by JSM6510 scanning electronic microscopy (SEM).

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

| Mn  | Cu  | Fe  | Si  | Zn  | Others | Al  |
|-----|-----|-----|-----|-----|--------|-----|
| 1.21| 0.12| 0.38| 0.08| 0.02| <0.15  | Bal.|

Fig.2. The tool used for FSW
3. Results and discussions
Welds appearance. The surface appearance of weld joints are shown in Fig. 4. It is seen from the figure that the welds are glassy and slippery with a few flash, and without volids and gallings. The weld joints are with beautiful welding gap.

Fig. 4. Surface appearance of weld joints with travel speed at (a) 1500 mm/min and (b) 3000 mm/min.

Hardness distribution. Figure 5 shows the typical hardness distribution profile across the weld center measured along the mid-thickness. The BM of 3003-H17 aluminum alloy is with hardness of 50~51 HBS10/500. Compared with the BM, the hardness of weld joints is higher after FSW. The hadness value of the weld joint at travel speed of 1500 mm/min is higher than that of the weld with travel speed of 3000 mm/min. The highest hardness in the weld at travel speed of 3000 mm/min is with about 62 HBS10/500. The lowest value of surface hardness is at the advancing side of the weld joint, and the highest value of hardness is in the nugget zone. This is because that there are sufficient plastic deformations in the nugget zone, resuting in fine grains and improving the hardness [5-7]. While at the advancing side of welds, there are lower friction heat and plastic deformations that leads to grain coarsening.

Tensile properties. Figure 6 shows mechanical properties of the weld joints at different travel speeds. It is seen that all the ultimate tensile strength (UTS) of weld joints is lower than that of the BM, and UTS of the weld joint at travel speed of 1500 mm/min is higher than that of the weld joint at travel speed of 3000 mm/min when the tool rotation is a constant speed of 2000 rpm. When the travel speed is at 1500 mm/min, the average joint efficiency that is a ratio of UTS of welds to UTS of BM reaches 87%. During FSW, once the tool starts to travel along the welding joint, friction between the shoulder/ pin and the welded metals and plastic produce heat to maintain sufficient softening and flowing in the BM when the travel speed is suitable. If the travel speed is too high, the plastic metals at the weld are not fully stirred and flow, The heat generated by plastic deformation and friction is too
late for heat conduction, resulting in uneven heat in the upper and lower layers of the weld joint, which leads to decrease of UTS for weld joints. In other words, the UTS of weld joint is decreasing with increasing travel speed from 1500 mm/min to 3000 mm/min as a result of the generation of insufficient heat input, when the tool rotation speed is at a constant value of 2000 rpm and the shoulder plunge depth is at constant of 0.2 mm. Sakthivel et al [13] reported that the UTS of weld joint for commercial-grade aluminum plate decreased from 80 Mpa to 71.6 Mpa with increasing of travel speed from 50 mm/min to 175 mm/min.
Figure 7 shows the fracture morphologies of tensile samples of weld joints. From the figure, it can be seen that all the tensile specimens of weld joints failed with basically 45° shear fracture at the advancing side (AS). During FSW, there is strong shear deformation at AS due to rotation of the shoulder and pin[5]. The typical micrographs of tensile fracture surfaces for friction stir welds by SEM is shown in Fig. 8. As can be seen from the figure, there are dimples with some tear ridges in the tensile fracture, which is with plastic fracture mostly and brittle fracture little quasi-cleavage fracture.

Fig. 7. Fracture morphologies of weld joints with different high travel speeds

(a) Travel speed of 1500 mm/min  (b) Travel speed of 3000 mm/min

Fig. 8. SEM micrographs of welds with different high travel speeds

(a)  (b)
4. Conclusions
3003-H17 aluminum alloy plates can be successfully butt welded by FSW at high travel speed of 1500~3000 mm/min. The UTS of weld joint decreases when the travel speed increases from 1500 mm/min to 3000 mm/min at a constant tool rotation speed of 2000 rpm and shoulder plunge depth of 0.2 mm. The joint efficiency reaches 87% at travel speed of 1500 mm/min, tool rotation speed of 2000 rpm and shoulder plunge depth of 0.2 mm. High speed friction stir welding of 3003-H17 aluminum alloy provides a reference model for other aluminum alloys. Friction stir welding with high travel speed can contribute to commercialized application of the newtype welding technology.

Acknowledgements
This work was supported by the China Postdoctoral Science Foundation (2019M652830) and Dongguan postdoctoral fund. The author would like to thank Professor Guojun Zhang and Yu Huang for their guidance and assistance during the study. And the author also wishes to thank Mr. Yuanjin Tang for his help in the course of your research.

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