A study on the Friction Stir Welded Non-ferrous Alloy

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Abstract—Friction stir welding (FSW), which is a new-type solid state welding technology, has been successfully used in aluminum alloys, magnesium alloys and copper. To study the properties of friction stir welded zinc-based non-ferrous alloys, Zn-0.5Cu alloy plates were butt welded by FSW. The results show that Zn-0.5Cu alloy plates with 5 thickness can be successfully welded by FSW. The joint efficiency of weld joint can reach over 95% at appropriate weld process parameters.

1. INTRODUCTION
As a new-type welding technology, friction stir welding (FSW) has attracted more and more interest. The basic principle of FSW, as shown in Figure 1, is to insert the welded part by rotating a special shape of mixing head, then move forward along the interface to be welded of the pieces, and heat the material to be welded to the thermoplastic state through the stirring and friction of the tool and pin. The material in the plastic state is stirred around under the drive of high-speed rotation of the tool, and the material diffusion connection formed a dense solid-state connection between metals under the combined action of heat engine [1].

![Fig.1. Basic principle of the FSW process.](image)

In past studies, it has been confirmed that magnesium alloys [2-3], aluminum alloys [4-6] and other non-ferrous metals [7-9] can be successfully welded by FSW. However, there are limited studies on friction stir welding for zinc alloys. Nishihara [10] has studied friction stir welding of superplastic Zn-22Al alloy. And the microstructure and properties of friction stir welded joints of Zn-22wt.%Al alloy...
were researched by Tsutomu [11]. Due to excellent corrosion resistance, electrochemical performance, damping performance and friction resistance, zinc alloy has been widely used. Its consumption is regarded as the second only to aluminum and copper in non-ferrous metals. While the few studies on other zinc-based alloys by friction stir welding has been reported. In the paper, the Zn-0.5Cu alloy plate with 5 thickness were butt welded by FSW, and the tensile properties of welds were also tested.

2. EXPERIMENTAL DETAILS

2.1. Base material (BM)
Zn-0.5Cu alloy plates, base material (BM), are with dimensions of 195 mm (length) × 60 mm (width) × 5 mm (thickness), and the BM is with chemical composition of 0.5 %Cu and balance Zn in weight percent. The mechanical properties, such as ultimate tensile strength (UTS), Yield strength (YS) and elongation of the BM, is shown in Table 1.

| Ultimate tensile strength (UTS, MPa) | Yield strength (MPa) | Elongation (%) |
|-----------------------------------|---------------------|----------------|
| 277                               | 231                 | 5.3            |

2.2. Welding process
Zn-0.5Cu alloy plates were butt welded on LT-XJ1510-05 static gantry type friction stir welding machine, as shown in Figure 2, at rotation rate of 800 rpm and welding speed of 350 mm/min. The tool, as shown in Figure 3, is with tool shoulder diameter of 15 mm and pin length of 4.7 mm. During FSW, the shoulder plunge depth is of 0.2 mm and the angle of tool is at 2.5 °.

2.3. Properties test
All the transverse tensile specimens of the weld joint and BM were prepared by wire-electrode cutting. The size of transverse tensile specimens is shown in Fig. 4. Three tensile specimens of weld joints and the BM were cut. And the average test value of three samples was as the test results of the weld joints. At room temperature, the tensile tests were done on Sansi CMT-5105 mechanical tester with a crosshead speed of 1 mm/min.

![Fig.2. LT-XJ1510-05 static gantry type friction stir welding machine.](image-url)
3. RESULTS AND DISCUSSIONS

3.1. Welds appearance

Figure 5 shows the surface appearance of the friction stir weld joint. From this figure, the weld joint is glassy and slippery with a few flash. The weld joint is good moldability without galling and voids. Thus, it can be seen that Zn-0.5Cu non-ferrous alloy can be successfully welded by FSW.

3.2. Mechanical properties

Table 2 shows the mechanical properties of the weld joint at room temperature. It can be seen that the ultimate tensile strength (UTS) of the weld joint is lower than that of the BM from Table 1 and 2. It is probably because the grain growth and some oxide layers in the boundary between nugget zone and thermomechanically affected zone, the same as magnesium alloys, which has been reported by Gharacheh et al. [12] and Lim et al. [13]. This also indicates that the joint efficiency of Zn-0.5Cu alloy with thickness of 5 mm reaches over 95 %, which is the ratio in percentage of the UTS of weld joint to the UTS of BM, when the rotation rate is of 800 rpm and the welding speed is at 350 mm/min. It is obvious that the UTS of weld joint for Zn-0.5Cu alloy can be near to that of the BM at appropriate welding process parameters.

| Specimens       | Ultimate tensile strength (UTS, MPa) | Joint efficiency (%) |
|-----------------|--------------------------------------|----------------------|
| Weld joint-1#   | 264                                  | 95.3                 |
| Weld joint-2#   | 265                                  | 95.7                 |
| Weld joint-3#   | 265                                  | 95.7                 |
| Average value   | 264.7                                | 95.6                 |
Figure 6 shows the typical micrographs of tensile fracture surfaces for the BM and weld joint by SEM. From Fig. 6(a), a large amount of dimples and some tear ridges are observed in the tensile fracture of the BM, which exhibits ductile fracture being primary and brittle fracture being auxiliary. It can be seen from Figure 6(b) that the tensile fracture presents river pattern with some obvious fracture gullies and dimples are formed in the tensile fracture of the weld joint. Thus, the fracture mode of Zn-0.5Cu alloy weld after FSW presents brittle fracture being primary and ductile fracture being auxiliary.

As a new type of solid-state joining technology with wide adaptability, FSW is more suitable for joining light alloy and other difficult materials than traditional fusion welding. The advantages of FSW are as described below [1, 14]. Firstly, the welding temperature is low, the microstructure in heat affected zone does not change significantly, and the deformation after welding is small. Secondly, it can realize one-time high quality welding of long weld and thick plate. Thirdly, it is especially suitable for high quality welding of special materials such as hot crack sensitive materials. Fourthly, there is no smoke, no radiation, no splash, no arc during welding, green and environmental protection. Fifthly, there is no need for welding wire, complex pre-treatment before welding, shielding gas and groove before welding. Compared with the traditional fusion welding, FSW process can significantly improve the weldability, fatigue property, cosmetic appearance, corrosion resistance, stress corrosion cracking performance, static strength and ductility of weld joints.

Welding process parameter is one of the most important factors affecting the joint performance. During FSW, rotation rate, welding speed, shoulder plunge depth and angle of tool are four important welding process parameters when the tool is determined. As
a very important process parameter in the FSW process, rotation rate has an significant effect on the frictional heat. If the too low rotation rate is selected, there is without sufficient frictional heat in the welds to promote effective thermoplastic flow, it is very easy to appear hole defects, tunnel flaw, lack of penetration and other defects [1]. With increasing rotation rate, friction heat source is increased, thermoplastic flow layer gradually increases from top to bottom to decrease the hole, tunnel flaw, lack of penetration and other defects. When the speed rises to a certain value, the hole, tunnel flaw, lack of penetration and other defects disappears, and the internal structure of weld joint is compact and uniform without weld defects such as the hole, tunnel flaw, lack of penetration. But when the rotation rate is too high, the temperature of materials around the pin and under the shoulder is too high, which is to cause the formation of defects such as coarsening grain and excessive flash. That being said, rotation rate is not as high as better. It should be noted that the influence of rotation speed on weld joints’ performance is not isolated. For the same material, when different tools are used for welding, the optimal rotation speed is different [14]. It is necessary to comprehensively consider the heat production in the process of friction stir welding, to ensure that the base metal to be welded has enough heat input, and to prevent overheating, so as to obtain excellent welding joints. The selection of rotation speed is restricted by welding speed. For the industrial friction stir welding of non-ferrous metal products, there are certain requirements for welding speed. If the welding speed is too fast, firstly it can lead to poor formation and weld defects such as tunnel flaw, lack of penetration and so on. Secondly, too fast welding speed requires higher equipment and operators and increases production cost [14]. But when the welding speed is too slow, it is possible to have defects in the weld joints due to unreasonable welding specifications, and it leads to inefficient production. Therefore, the selection range of welding speed should be considered from the aspects of welding quality, welding efficiency and joint performance. For FSW of non-ferrous alloys, there is an optimal parameter specification area between rotation rate and welding speed. The existence of this optimal specification area indicates that the weld formation and performance depend on the friction heat generated by the mixing head on the unit length weld, and the time of plastic state for the weld joint. When the different tool is used, different parameter matching is required between rotation rate and welding speed. Furthermore, welding assembly state and surrounding environment also directly affect the heat production and temperature field distribution in the welding process. So the optimized parameters of rotation rate and welding speed needs a case by case analysis for the friction stir welded specific non-ferrous products. In the process of friction stir welding, the shoulder plays a closed role in the formation of the weld. When the material reaches the plastic state, with the tool moving forward, the plastic material is driven around the axis by the tool, and the material flows from front to back. The plastic flow of the material fills up the space behind the tool to form a plastic connection. If the shoulder plunge depth is too small, on the one hand, it will produce internal holes, on the other hand, it will make the back welding poor, which will reduce the strength of the joint. While if the shoulder plunge depth is too large, it will make the surface morphology worse, and will cause the thinning of the weld. So the appropriate shoulder plunge depth is necessary to weld successfully. Angle of tool is important to obtain high quality weld joints for FSW.

4. CONCLUSIONS
Zn-0.5Cu non-ferrous alloy plates with 5 thickness can be successfully butt welded by FSW. With rotation rate of 800 rpm, welding speed of 350 mm/min and shoulder plunge depth of 0.2 mm, the joint efficiency of weld joint reaches over 95 %. The fracture mode of weld joint exhibits brittle fracture being primary and ductile fracture being auxiliary, while the BM presents ductile fracture being primary and brittle fracture being auxiliary. Friction stir welded Zn-based non-ferrous alloys have good quality, which can contribute to accelerate the improvement of FSW technology and promote the commercial application of FSW in non-ferrous metal, along with alluminum alloys and coppers.
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