Microstructure and mechanical properties of Mg-Mn alloys by friction stir welding

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Abstract: Mg-Mn alloy is welded by friction stir welding technology to manufacture liquid-cooled components in radar equipment. The effect of welding processes on microstructure and mechanical properties of Mg-Mn alloy was analyzed. The results show that the rotation speed has little effect on the microstructure when it is above 1200 rpm. The strength is increased by the increase of rotation speed from 900 rpm to 1500 rpm. The highest ultimate tensile strength is about 175 MPa. Most of the welding joints show brittle fracture during tensile test.

1. Introduction

Liquid-cooled components are typical structural and functional integrated components in radar equipment. There are liquid-cooled channels of various shapes inside, and a large number of electronic components are installed outside. When working, the fast-flowing liquid can take away the heat produced by the electronic components on the liquid-cooled component through the liquid-cooled channel. Common liquid cooling components are mainly composed of liquid cooling channels and cover plates, as shown in figure 1. The welding process is often used to connect the cover plate with the channel to form a closed channel. In practical applications, leakages often occur at the welding joints of the liquid-cooled channel, which greatly threatens the normal operation of the electronic equipment. Therefore, the liquid-cooled channel welding technology is one of the key points in the manufacturing process of the liquid-cooled components [1,2]. In addition, with the continuous development of radar technology, many liquid-cooled components are manufactured by magnesium alloys in order to meet the need for weight reduction [3,4]. Therefore, a credible welding technology of magnesium alloys is important to support these applications. However, conventional fusion welding methods always show dissatisfactory performance. As the magnesium alloys display high thermal expansion coefficient, high thermal conductivity and solidification shrinkage in a molten state. Consequently, the joints welded by fusion welding method often contain porosity, oxidation, hot cracks and so on [5-7].
Figure 1. (a) Typical structure of liquid-cooled components; (b) Friction Stir Welding process.

Friction Stir Welding (FSW) is a solid-state welding technique without melting base materials. It can eliminate problems appearing in the fusion welding process of magnesium alloys and obtain good quality joints [8,9]. Therefore, welding of magnesium alloys by FSW has been widely investigated, especially the Mg-Al-Zn alloys, such as AZ31, AZ91 and AZ61. Most of these studies focus on microstructure and mechanical properties of the joint [10-17]. The microstructure of FSW joints consists of four distinct microstructural zones, the heat affected zone (HAZ), the thermo-mechanically affected zone (TMAZ), the stir zone (SZ) and base material (BM). Grains in the SZ are fine and equiaxial with a relatively high dislocation density [10-13]. Mechanical properties of joints, such as tensile properties, hardness, and fracture feature are often related to the welding process parameters. For example, good joints properties are obtained by increasing rotation speed and larger shoulder diameter [14-17].

Although the FSW process offers many advantages, very limited numbers of investigations were carried out so far on FSW of Mg-Mn alloys, which is also a kind of magnesium alloy widely used in various industrial fields [18-20]. In this work, liquid-cooled components are made by a Mg-Mn (MB8) alloy and are welded by the FSW. The rotation speed of FSW pin is adjusted during FSW process. Microstructure and mechanical properties of joints are studied.

2. Experimental methods
Liquid-cooled components were manufactured by MB8 magnesium alloy with a nominal chemical composition of Mg-2.5Mn-0.3Al (wt.%). Liquid-cooled channels and cover plate shapes are shown in figure 1. The thickness of the cover plate is about 3 mm. The liquid-cooled channel is CNC-milled, the cover plate is processed by wire cutting, and the connection between the liquid-cooled channel and the cover plate is FSW technology.

FSW operations were carried out using a computer numerical controlled FSW machine (FSW-LS-09, Shanghai Space fight Manufacture Co. Ltd.). The welding tool was fabricated from a tool steel and consisted of a shoulder and a pin. The tool shoulder is 10 mm in diameter. The pin is 1.5
mm in diameter with a length of 2.5 mm. During FSW, tool rotational speed was chosen in a wide range, from 600, 900, 1200, 1500 to 1800 rpm respectively, whereas the tool travel speed was kept constant at 80 mm/min. Samples were cut from liquid-cooled components after FSW with dimensions of 190 × 20 × 3 mm.

Microstructure features of FSW joints were characterized by optical microscopy. For the microstructural investigation, each specimen was first polished with sandpaper of 450 to 1200 grits and then mechanically polished with 3 and 1 μm diamond oil-suspension. After polish, specimens were etched for 1~2 s by a solution, which was composed of 4.2 picric acid, 10 mL acetic acid, 10 mL water, and 70 mL ethanol. Specimens for the tensile test were cut from the welded samples perpendicular to the welding direction. Dimension and shape of tensile test specimens were prepared according to ASTM-E8 standard [21]. Tensile tests were conducted at room temperature using a universal tensile test machine at a strain rate of 5 mm min⁻¹.

3. Results and discussion

3.1. Macrostructure

The macro-welding seam features of FSW are presented in figure 2.

![Figure 2](image)

**Figure 2.** (a) macro-welding seam at a rotation of 1800 rpm. (b) macrostructure of welding seam cross section at a rotation of 1800 rpm.

The images of welding seam at rotation of 1800 rpm are shown in figure 2 (a) and (b). As shown in figure2 (a), the surface of the welding seam has a neat onion ring texture, which is a typical character of FSW. No visible cracks, holes or other defects appear on the welding seam surface. In figure2 (b), the shape of the weld zone in specimens is conical which is the same as the shape of the pin. This phenomenon suggests that the pin may dominant material flow during FSW. According to Bahrami et al., the inadequacy of material flow and insufficient material consolidation in the weld zone will result in this phenomenon [22]. The detailed characteristics of the weld area are further studied by examining the weld zone under an optical microscope for the different welding parameters.

3.2. Microstructure

The optical images of cross-section for specimen obtained at a rotation of 1200 rpm and a speed of 80 mm/min by FSW are presented in figure3 (b)-(d). The optical images of cross-section for specimen obtained at a rotation of 1800 rpm and a speed of 80 mm/min by FSW are presented in figure 3 (e)-(f).
Figure 3. Optical micrograph of samples: (a) base materials, (b)-(d) different areas of the weld cross-section with a rotation of 1200 rpm, (e)-(f) different areas of the weld cross-section with a rotation of 1800 rpm.

Figure 3 (a) shows base material optical microstructure. Many large grains with size more than
30μm co-exist with many small grains with size about less than 10μm. The distribution of grains is not homogeneous.

Figure 3(b)-(f) is different areas in weld cross-section which are often referred to as heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) and stir zone (SZ). From the micrographs, it is obvious to find that grain size in the different weld cross-section is different. The average grain size in HAZ is much larger than TMAZ and SZ. As known to all, HAZ is influenced by the heat input of the welding process. However, in HAZ, little difference in grain size is observed after welding at different rotation speeds, as shown in figure 2(b) and figure 2(e). So it can be inferred that the rotation speed has little effect on the grain size in HAZ in the range of 1200-1800 rpm.

The micrographs of TMAZ welded by 1200 rpm and 1800 rpm are shown in figure 2(c) and figure 2(f). Both TMAZs are characterized by a mixture of large grains and small grains without elongate grains. This means TMAZ subjects to the influence of severe plastic deformation and large grains may break up to small grains. As no elongated grains are observed, dynamic recrystallization process may occur in the TMAZ. It also should be noticed that the rotation speed has little effect on the grain size in the TMAZ.

Finer grains are presented in stir zone (SZ) when compared with other regions of joints, irrespective of the FSW process, as shown in Fig 2 (d). This phenomenon can be correlated to the severe deformation induced by the high rotation of pin and insufficient heat input that is not enough to support grain growth [15]. On the other hand, according to [23], good thermal conductivity and low thermal capacity of magnesium alloy also restricted the growth of grains in the welding zone. It also should be noticed that the rotation speed has little effect on the grain size in SZ. Therefore, rotation speed has little effect on the microstructure structure when the rotation speed is above 1200 rpm. This character is helpful during engineering applications.

3.3. Tensile properties
In most cases, materials with high strength often with low ductility. It is difficult to find a material with both high strength and high ductility. However, according to the Hall-Petch relation, grain refinement is considered as one of the most satisfying approaches to obtain materials with both high strength and high ductility. The obvious grains refinement in the stir zone might lead to the good mechanical performance of FSW joints. Therefore, uniaxial tensile tests were conducted under room temperature at a strain rate of $10^{-3}$ s$^{-1}$ in order to study the joint properties of FSW. The failure mechanisms were also analyzed based on the SEM images.
Figure 4. Stress–strain curves of uniaxial tensile test for welding joints obtained at fixed translational speed and rotation speed of 900 rpm and 1800 rpm.

The mechanical properties of joints obtained by FSW are presented in figure 4. It can be observed that from 900 rpm to 1500 rpm, increasing rotation speed results in higher strength. The specimen welded with rotation speed 1500 rpm presents the highest ultimate tensile strength of more than 175 MPa. This phenomenon can be explained by the fact that increasing rotation speed leads to an increase in heat input, which consequently improves the materials flow in the welding zone. On the other side, high rotation speed also leads to severe stir in the welding zone, and more refinement grains are produced, which also result in improvement of strength and stain. The character of the macrostructure and microstructure in welding joints also indicate this mechanical property. However, when the rotation speed is 1800 rpm, the strength becomes decrease. Too much heat input and low welding speed may result in refinement grains growth, which leads to strength decrease.

All the stress–strain curves of the samples exhibited a brittle behavior. For the purpose of analyzing the failure character of joints, tensile test samples were investigated by SEM.

Figure 5 presents the fracture samples obtained after tensile testing. The two samples were welded at rotation speeds of 1200 rpm and 1800 rpm.

Figure 5. Fracture images of samples after tensile tests, (a) welded at a rotation speed of 1200 rpm, (b) welded at a rotation speed of 1800 rpm.

From figure 5, it can be observed that both failures of samples occurred in the retreating side near the edge of the welding seam. From microstructure optical images of figure 3, the grain size in TMAZ is inhomogeneous with a mixture of small grains and large grains. A large number of dislocation
tangles presents in TMAZ as it undergoes non-uniform plastic deformation without recrystallization [5]. According to the report of M. Barmouz et al., the region with high dislocation density is apt to become a crack nucleation [24]. So it is reasonable to infer that the failure may locate in the TMAZ during the tensile test. In order to investigate character of the fracture, SEM images of samples after the tensile test are presented in figure 6.

Figure 6. SEM images of the fracture, (a) sample was welded at a rotation speed of 1200 rpm, (b) is a amplification of the circle area in (a).

Tear ridges and cleavage planes are found on the fractured surface in figure6(a). It is a symbol characteristic of a brittle fracture. Only a little of dimples are observed in the fracture surface as seen in figure6(b), which is an indication of the cup- and cone-type fracture. This type of failure pattern will occur only when the breakage of material is a ductile mode. However, dimples are far less observed in most of the fracture surface, which also gives evidence to the occurrence of brittle fracture during the tensile test.

4. Conclusions
In this study, MB8 magnesium alloy liquid-cooled components were welded by friction stir welding. Microstructural and mechanical properties of the joints were studied and the findings are as follows:

(1) MB8 magnesium alloy liquid-cooled components were successfully welded by FSW with different rotation speeds. The specimens exhibited typical neat onion ring texture and no visible cracks, holes or other defects appeared on the welding seam surface.

(2) When the welding speed is the same, and the rotation speed of the stirring pin exceeds 1200 rpm, the welding microstructure remains basically unchanged with the increase of the rotation speed.

(3) All welding joints exhibited a brittle behavior during the tensile test. The joints welded at a rotation speed of 1500 rpm present the highest ultimate tensile strength.
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