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Influence of sampling design on tensile properties and fracture behavior of friction stir welded magnesium alloys

Dejia Liu [a], Renlong Xin [a,b,*], Liyun Sun [a], Zheng Zhou [a], Qing Liu [a,b]

[a] College of Materials Science and Engineering, Chongqing University, Chongqing, China
[b] National Engineering Research Center for Magnesium Alloys, Chongqing University, Chongqing, China

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ABSTRACT

Dissimilar joints of ZK60 and AZ31 alloys were obtained by friction stir welding (FSW). Two types of sampling designs were employed for transverse tensile tests to evaluate the tensile properties and fracture behavior of the joints. One kind of samples was machined excluding the upper part of the weld zone (WZ) and named as the stir zone (SZ) sample. Another kind was machined including the entirety of WZ and named as the entirety sample (EN sample). Both types of samples have strength higher than the base alloy AZ31 but lower than the base alloy ZK60. The tensile properties of the EN sample are slightly better than those of the SZ sample. Significant differences in fracture behaviors were observed between the two types of samples. The fracture of the SZ sample initiated at the boundary of transition zone (TZ)/SZ in retreating side (RS) and propagated toward the SZ. However, the EN sample fractured in advancing side (AS), close to the “hard” material of ZK60 alloy, with more complex fracture morphology. A comprehensive characterization of microstructure and texture distributions was carried out to explain the deformation and fracture behaviors. The grains in the SZ-side are favorably oriented for basal slip or extension twinning, being the weak position during the transverse tensile tests. The grains in the side of crown zone (CZ) have the *c*-axis tilted toward the normal direction (ND), being harder for extension twinning compared with those in the SZ-side. A triple junction region was clearly observed adjacent to the interface of TZ/WZ in AS, but it was not observed in RS. The grains in the triple junction region were significantly refined but inhomogeneous among the various parts. The texture of the triple junction region was close to that of the CZ-side, but with a tendency to tilt toward that of the SZ-side. This observation confirmed that the triple junction region was located between the SZ-side and CZ-side of the WZ. Significant differences in the grain size and Schmid factor (SF) distributions for slip and twinning were observed among the different parts, which could cause deformation incompatibility, generate stress concentrations and accelerate fracture in the triple junction region in AS.

1. Introduction

As a solid-state joining technique, friction stir welding (FSW) was invented at The Welding Institute (TWI) of the United Kingdom in 1991 [1,2]. It is advantageous to join light metals such as Al and Mg alloys [3–6]. The basic concept of FSW is remarkably simple. As shown in Fig. 1a, a rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of plates to be joined and subsequently traverses along the joint line [7–9]. The welding process was finished under the hybrid effects of friction heat and force [10,11]. Because of the different thermo-mechanical histories experienced at various regions in a joint, several distinct zones with different microstructures can be distinguished, which consist of base metal, transition zone (TZ) and weld zone (WZ) [12,13]. In addition, the WZ can be divided into the upper part and the lower part as shown in Fig. 1b, named as the crown zone (CZ) and stir zone (SZ), respectively [14,15]. It can be speculated that there are significant differences in the microstructure and texture between the CZ and SZ due to a relatively large cylindrical shoulder and a smaller profiled pin causing a quite different heat and force in the upper and the lower parts of the WZ [16].

Tensile test is a common method to examine the welding quality and has been used to analyze FSW joints by many scholars [17–20]. Several kinds of tensile specimens were used and the tension direction was different as well [21–24], but most of the tensile specimens, with a relatively large sample size, were tensioned along the transverse direction (TD) [18,23,25]. For these tests two specimen geometries were used; to study the effect of

* Corresponding author at: Chongqing University, College of Materials Science and Engineering, Sha Zheng Jie 174#, Sha Ping Ba District, Chongqing, China. Tel.: +86 23 65102179; fax: +86 23 65106407.
E-mail address: rlxin@cqu.edu.cn (R. Xin).

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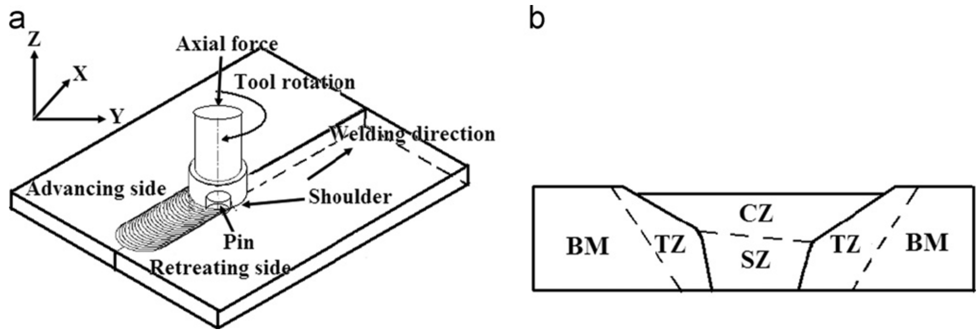

Fig. 1. Schematic drawing of friction stir welding process (a); (b) distinct regions in the FSW joint.

texture on the mechanical behavior of FSW joints, for example, the CZ part was usually excluded in the tensile specimens [25,26]. Hereafter, this kind of specimens is named as the SZ sample. Another kind of sampling is to include the entirety of the WZ, hereafter named as the entirety sample (EN sample). The EN sample is usually prepared by grinding the top surface of the WZ, which is commonly used to examine the joint efficiency [18,20,23]. Because of the different regions included in the two types of samples, it is expected that differences in the tensile properties and fracture behaviors are observed. However, this issue has rarely been discussed in previous reports.

Many studies indicated that fracture usually occurred at the transition region of the advancing side (AS) during the transverse tensile test of FSW/FSP Mg alloys [14,18–20,26]. Yet, the reason for this behavior has not been fully understood. In a recent study, it was found that fracture did not always initiate in the AS of the dissimilar FSW joint of ZK60 and AZ31 [27], but it was dependent on the material arrangement. This fracture initiated in the RS when the AZ31 alloy was set in the RS and the ZK60 was set in the AS. The reason has been attributed to the lower strength of AZ31. It is interesting to note that the tensile specimen used in that study excluded the CZ part, being SZ sample. To better understand the factors affecting the joint strength of the FSW Mg joints, it is desirable to investigate and compare the fracture behaviors of the joint with the two different sampling designs as mentioned above. This is the main purpose of the current report.

2. Experimental procedures

Hot-rolled commercial AZ31 Mg alloy (Mg–3%Al–1%Zn) plates with a solution treatment and cast ZK60 Mg alloy (Mg–5.2%Zn–0.5%Zr) plates aged at 175 °C for 10 h were used as the initial materials. The thickness of the welded plates was 6 mm. A cylindrical thread pin tool with a probe length of 5.45 mm, a pin diameter of 5 mm and a shoulder diameter of 15 mm was used in the present investigation. FSW was conducted with the tool tilt angle of 2.5° at a rotation rate of 800 rpm and a welding speed of 100 mm/min. Before welding, the plates were polished by abrasive paper and cleaned with acetone. The stirring tool proceeded along the centerline of the two plates. The joint with ZK60 alloys in the AS and AZ31 alloy in the RS was served as the subject of this study.

After welding, the cross-section of the joint vertical to the welding direction (WD) was chosen for microstructure characterizations. Microstructure was examined by optical microscopy (OM) and scanning electron microscope (SEM). Moreover, electron back-scatter diffraction (EBSD) was used to analyze the evolution of grain orientations in various regions of the joint. The EBSD detector was an HKL Channel 5 Systems equipped by a field-emission gun SEM (FEI Nova 400). The samples for OM and SEM were etched with a solution consisting of 2 ml distilled water, 2 ml

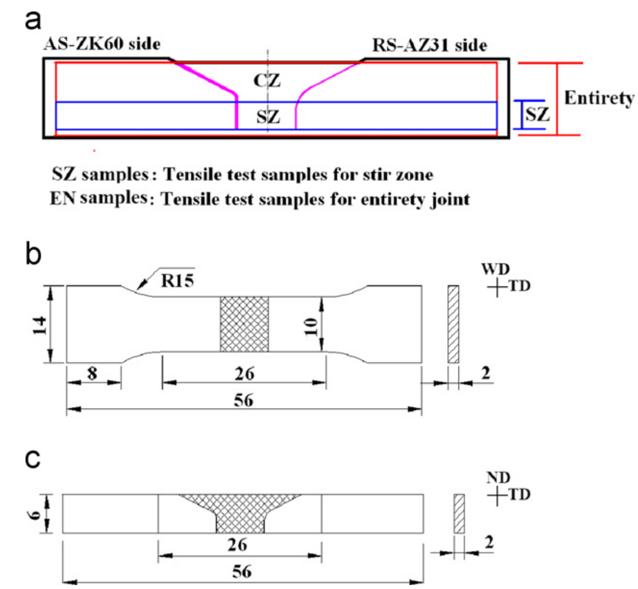

Fig. 2. Schematic diagram for the tensile test samples sampling design (a); (b) dimensions of SZ samples and (c) dimensions of EN samples.

glacial acetic acid, 14 ml ethanol and 0.84 g picric acid. The samples for EBSD analyses were polished at 20 V in a commercial polishing solution AC2 at 20 °C. The EBSD step size was 1 μm. Pole figures were obtained based on an EBSD scan area of approximately 150 × 150 μm^2.

Two types of specimens for transverse tensile tests were machined from the joint. The sampling design and dimensions were shown in Fig. 2. The SZ sample was machined excluding the upper part of the WZ and cut with about 1 mm away from the bottom surface of the FSW plates (see Fig. 2a). The EN sample was machined from the entirety of WZ, the upper part of the WZ being grinded by abrasive paper to obtain a smooth surface. The transverse tensile test was performed at a strain rate of $1 \times 10^{-3}\ s^{-1}$ at room temperature. Each kind of test sample was repeated three times to get representative results.

3. Results

3.1. Tensile properties and fracture behaviors

The cross-section of the dissimilar joint is shown in Fig. 3. Welding defects such as cracks and porosity are not observed indicating that ZK60 and AZ31 alloys are successfully joined by FSW. Three regions including the base metals, TZ and WZ are observed at the joint. The upper and lower parts can be distinguished in the WZ, which are named as the CZ and SZ, respectively. Moreover,