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Strain localization in friction stir welded magnesium alloy during tension and compression deformation

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ABSTRACT

As a solid-state process, friction stir welding can avoid solidification problems and therefore has great potential in welding of Mg alloys. However, strong texture is usually formed in Mg welds, which results in localized plastic deformation, and significantly deteriorates the mechanical properties of welds. The present paper seeks to understand the characteristics of strain localization in deformed Mg welds and underline mechanisms. AZ31 Mg alloy sheets were friction stir welded and then were subjected to transverse tensile and compressive deformation. During the transverse deformation, severe and complex strain localization was observed in Mg welds during tensile and compressive deformation, which resulted in "concave–convex" appearances in longitudinal section. The largest strain corresponds to the region easy to activate basal slip for both kinds of deformed samples. Extension twinning contributed the strain in the side of stir zone for tension but in the center of stir zone for compression. The characteristics of strain localization were explained based on the activation of basal slip and extension twinning with respect to local texture.

1. Introduction

As a solid-state process, friction stir welding (FSW) can avoid solidification problems associated with conventional fusion welding, and has great potential in welding of Mg alloys [1,2]. After FSW, the grains of Mg alloys can be largely refined [3–5], which is beneficial for the improvement of strength and ductility. However, for hexagonal close packed Mg alloys, strong texture was usually formed in stir zone (SZ) [6–10], which causes strong anisotropic mechanical properties for the weld [4,5,11–13]. Park et al. [6] reported that tensile deformation was preferentially concentrated at the interface between SZ and unaffected base material (BM). Many successive studies confirmed that the strain localization is not an isolated case but rather typical for FSW Mg alloys [14–16], and it can significantly deteriorate the strength as well as ductility. Therefore, it is important to clarify the mechanism underlying the strain localization.

Park et al. [6] found that the basal planes in the fractured region of FSW AZ61 alloy were inclined to loading direction at $\sim 45^\circ$ and thus the Schmid factor (SF) for basal slip should be high. So they believed that the profuse activation of dislocations should be the reason giving rise to the strain localization. On the other hand, $\{10\text{–}12\}\langle -1011\rangle$ extension twins have been observed in the SZ-side [14,17,18], which could also give rise to the strain localization. Moreover, the contraction deformation in SZ-side was mainly occurred in welding direction (WD), which caused an "emboss-ment" toward WD in SZ-center [16]. The current paper seeks to expand understanding of the strain localization characteristics in deformed Mg welds and their correlations with local texture and deformation mechanism. In addition to applying transverse tensile test as usually did by other researchers, we also applied transverse compressive test on the weld. By comparative analyses on the tensile and compressive samples, the contributions of slip and twinning on the strain localization can be better understood.

2. Experimental

A hot-rolled commercial AZ31 Mg alloy sheet (Mg–3%Al–1%Zn) with the thickness of 6 mm was joined by FSW. A cylindrical thread pin tool with a probe length of 5.7 mm, a pin diameter of 5 mm and a shoulder diameter of 15 mm was used. The welding was conducted with the tool tilt angle of 2.5° at a rotation rate of 1600 rpm and a welding speed of 600 mm/min. Dog bone-shaped specimens with nominal gage dimensions of 25 mm × 5 mm × 4.5 mm were prepared for transverse tensile tests, and rectangular

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prism specimens with nominal dimensions of 10 mm × 5 mm × 5 mm were prepared for transverse compressive tests. All the tests were performed at a strain rate of $1 \times 10^{-3}\ s^{-1}$ at room temperature. To evaluate the microstructural evolution and strain localization, the tensile and compressive tests were interrupted at 5% strain.

3. Results and discussion

The texture distribution across weld zone (WZ) in the original joint was studied by electron backscatter diffraction (EBSD) and the results are shown in Fig. 1. The texture distribution on retreating side (RS) was reported to be almost symmetrical with that on advancing side (AS) [7,16]. Fig. 1 confirms that the *c*-axis is nearly parallel to WD in SZ-center and nearly parallel to transverse direction (TD) in SZ-side. In the region close to SZ-side the *c*-axis is inclined ~45° to TD and hence basal slip is very likely activated due to a favorable orientation factor. Hereinafter, this region was referred to the region easy to activate basal slip (designated EABS region) [16].

The drastic texture change in the various parts of WZ caused different macroscopic plastic strain during the transverse tensile and compressive test. As shown in Fig. 2, severe non-uniform macroscopic plastic deformation is observed in the FSW joint samples with 5% strain, especially on the normal direction (ND)-TD plane (longitudinal section). This kind of non-uniform plastic deformation was not found in the as-received samples. Obvious "concave–convex" appearances are exhibited on the ND-TD plane of the FSW samples, and the features of the non-uniform plastic deformation are different between the tensile and compressive samples. Moreover, the surfaces of the deformed samples appear different on the obverse and reverse sides.

For the tensile sample, SZ-side exhibits "concave" appearance and SZ-center exhibits "convex" appearance on the obverse side of the ND-TD plane, while the non-uniform plastic strain is less obvious on the reverse side. For the compressive sample, "convex" appearance is exhibited in SZ-side and slight "concave" appearance is in SZ-center, as seen on the obverse side of the ND-TD plane. Similarly the "concave–convex" appearance is hardly seen on the reverse side. Furthermore, the contours of the "concave" or "convex" shapes formed in SZ-side are asymmetrical between AS and RS for the tensile and compressive samples. This is clearly revealed on the obverse side of the tensile sample in Fig. 2. The reason is associated with the different texture distribution in the transition region between AS and RS. The edges of the contours (indicated by dashed arrows) should correspond to the interface between SZ and BM. The different texture distributions on AS and RS is ascribed to the different material flows during the welding.

To quantitatively compare the non-uniform macroscopic plastic deformation, the thickness changes in WD were measured on the tensile and compressive samples. For simplicity of comparison, the relative thickness change in BM is assumed to be zero. The measured line is ~2.5 mm away from the bottom surface. As shown in Fig. 3, a "W" shape is seen in the thickness curve for the tensile sample, while an "M" shape is seen for the compressive sample. For the tensile sample, the EABS region (~ ±2 mm from SZ-center) has the maximum thickness decrease (~240 μm), while for SZ-side (~ ±3 mm from SZ-center) the thickness decrease is ~100 μm. The thickness change in SZ-center is almost zero, implying that the "convex" appearance in SZ-center is relative to SZ-side, not really embossed compared with BM. For the compressive sample, the thickness is increased almost in the entire WZ (Fig. 3b). The region with the maximum thickness increase (~160 μm) also corresponds to the EABS region (~ ±1.5 mm from SZ-center), and SZ-side (~ ±2.5 mm from the SZ-center) has the thickness increase of ~90 μm. Dissimilar with the tensile sample, there is also a large thickness change (~130 μm) in SZ-center of the compressive sample.

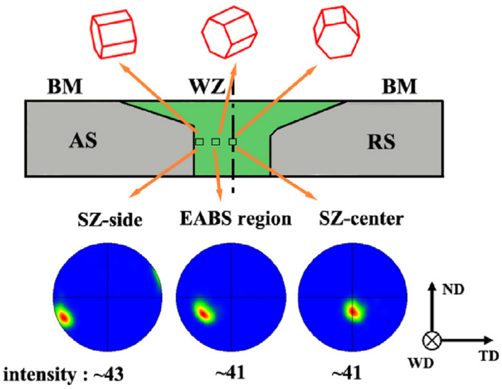

Fig. 1. {0001} pole figures from SZ-side, EABS region and SZ-center. The crystal orientation was illustrated by the hexagonal prisms.

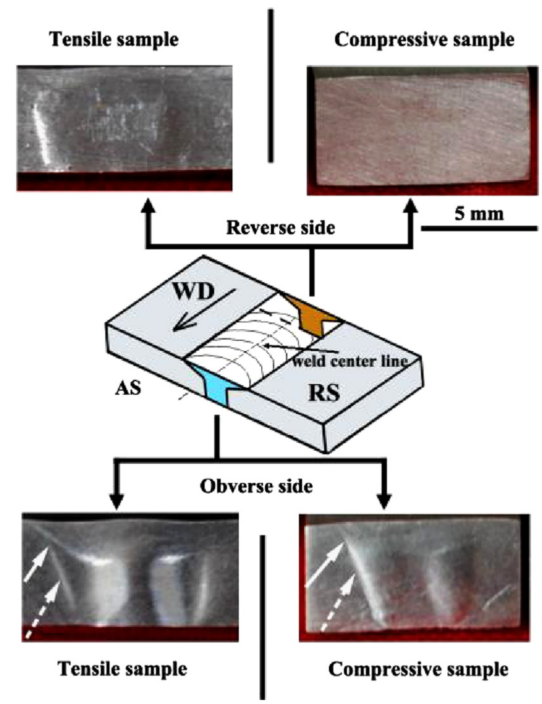

Fig. 2. Macrographs of the ND-TD plane (longitudinal section) of the weld subjected to 5% tensile and compressive deformation.

Microstructural evolution was examined by EBSD on the 5% strained samples and the orientation maps are shown as the insets in Fig. 3. The red lines in the maps indicate {10–12} extension twin boundaries. A large number of extension twins are seen in SZ-side of the tensile sample. The volume fraction of twins is ~44% in SZ-side as estimated by calculating the texture change due to twinning [19]. However, for the compressive sample the largest numbers of twins are seen in SZ-center with volume fraction of ~43%, which contributes to the thickness change. Some extension twin boundaries are also observed in EABS region for both tensile and compressive samples but the volume fraction is relatively less, 8–22%.

Basal slip and extension twinning are the most easily activated deformation mechanisms for Mg alloys at room temperature. Their competition can be evaluated by comparing SFs. For basal slip, shear is non-directional meaning that SF is equal for the tensile and compressive tests. But for extension twinning, SF can be