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Characteristics of long {10-12} twin bands in sheet rolling of a magnesium alloy

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Sheet rolling was performed at room temperature on a friction-stir-welded Mg alloy. Long twin bands comprising small {10-12}<-1011> twins (average size $\sim$7 μm) were revealed. Based on the long twin bands identified, the grain boundary disorientation and strain accommodation between neighboring twins and global Schmid factors were assessed. The results indicate that these factors are favorable for the formation of such long twin bands in the applied rolling deformation.

Keywords: Twinning; Schmid factor; Strain accommodation; Variant selection; Magnesium alloy

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Twinning is an important deformation mechanism for Mg alloys of hexagonal close packed structure, in which there are insufficient operative slip systems to offer continuous deformation, especially at room temperature [1,2]. During plastic deformation processes, the lattice rotation and grain subdivision by twinning can largely affect the microstructure evolution and strain hardening behaviors [3]. It is known that the propensity and characteristics of twins are highly sensitive to grain orientations with respect to applied loading deformation. For example, a {10-12} extension twin most likely takes place when a tensile (compressive) stress is applied parallel (perpendicular) to the *c*-axis, and the morphology and variant selection of twins can vary largely in different strain paths [4,5]. Understanding of the twinning characteristics in various applied deformation conditions is desirable for improving the deformation ability of Mg alloys.

Recently, Baird et al. revealed a highly localized twinning pattern during three-point bending tests [6], which was different from most previous studies. In the compression zone of their samples, {10-12} twins were localized in bands, each band comprising high-density twins, but twins were absent between the bands. The formation of such localized twin bands could have significant impacts on the formability of Mg alloy sheets. Based on in situ electron backscatter diffraction (EBSD) examinations, they have discussed the possible mechanisms for such localized twin bands in the three-point bending samples. Despite the above efforts, the understanding of twinning characteristics (e.g. variant selection) and mechanisms (e.g. Schmid factor, local strain effect) in localized twin bands is limited.

In the present work, long twin bands comprising small {10-12} twins connecting together end to end were observed in the rolling process of Mg alloys. The main goal is to analyze the characteristics and variant selections of the {10-12} twins for understanding the mechanism of such long twin band formation during rolling. Specifically the correlations between neighboring twinning plane normals and twinning shear directions were precisely described by a geometrical compatibility parameter (m') as previously used in titanium [7–9], and an effective Schmid factor based on previous work [10–13] for rolling was also employed to understand variant selections of the twins in the long twin bands.

The material used in this work is a friction-stir-welded joint of Mg–3Al–1Zn alloy. The welding center contains equiaxed grains with an average size of $\sim$9 um and presents a strong basal texture with the (0 0 0 1) poles inclined $\sim$25° from the welding direction (WD) (see Fig. 1a). Similar characteristic microstructure and texture have been revealed in friction-stirred Mg alloys [14–17]. Cold rolling was applied on the Mg joints to improve joint strength. The general microstructure evolution during rolling and its effects on mechanical properties have been reported elsewhere [18]. The

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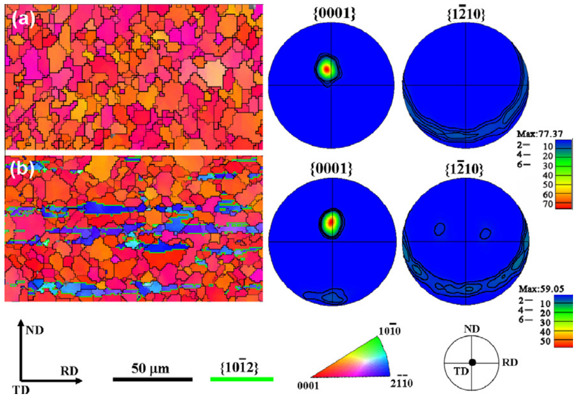

Figure 1. Microstructure and texture of the friction-stir-welded Mg joint (a) before and (b) after rolling. The black lines in the maps indicate grain boundaries above 15° and the green lines indicate the {10-12} twin boundaries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

present work focuses on the characteristics of some localized long twin bands formed during rolling of the Mg joints. The microstructure of the rolled sample was characterized by EBSD analysis on the RD–ND planes. Here, RD and ND refer to the rolling direction and normal direction of the rolled sample, respectively. So the WD of the joint is placed parallel to the transverse direction (TD) during the rolling.

After rolling to ~7% reduction there are significant change in microstructure (see Fig. 1b). There are a few long bands (blue regions) running from left to right, and being nearly parallel to the RD. Crystallographic analysis confirms that the long bands consist of small {10-12} extension twins with the disorientation relation of 86° <1-210> with the parent grains. The (0 0 0 1) pole figure confirms that the {10-12} twins indeed take place, as a new intensity spot appears nearly 90° away from the original spot due to the parent grains. Considering the rolling geometry and twin orientation, the formation of such twins was probably made by the operation of compressive stress along the ND, not by the tensile stress along the RD. Recently, Suh et al. showed the importance of microscopic stress state on the formation of {10-12} twins during uniaxial tensile testing, which has the similar stress state to that during rolling [19]. Another important characteristic is that those twin bands appear to be highly localized. Away from these bands, twins are rarely observed, which is similar to the previous study in sheet bending of AZ31 Mg alloy [6]. In that study the bands run roughly 45° from top to bottom and the twin variants are aligned in two nearly perpendicular directions, while in the present study the bands are horizontal in the RD–ND sections, i.e. nearly parallel to the RD, and all the twin variants have twinning plane traces nearly aligned. Despite the above difference, the twins in both long twin bands mostly run through whole grains with the twins in neighboring grains being connected at grain boundaries (GBs). It was believed that the twin variants in neighboring grains of such long twin bands cannot be completely independent of each other.

To further and conveniently study the characteristics of these long {10-12} twin bands, a simplified treatment is done as follows: two neighboring twins are considered as an elementary unit, as schematically illustrated in Figure 2a, where twins T_1 and T_2 are generated from the parent grains M_1 and M_2, respectively, during the rolling process. The geometric relationship between the two active twinning systems in M_1 and M_2 are described in Figure 2b. Similarly with the previous studies [7–9], the geometric alignment of the two systems can be described by a geometric compatibility factor: $m' = \cos\psi \times \cos\kappa$, where ψ and κ are the angles between the two active twinning plane normals and shear directions, respectively. Based on EBSD orientation data the active twinning planes and their corresponding geometric parameters (ψ, κ and m') can be determined [20–22]. Table 1 displays the ψ, κ and m' of two neighboring twinning systems in one selected long twin band (denoted as STB), which contains nine extension twins connecting end to end. It is clear that both ψ and κ mainly distribute in a low angular range of below 15°, indicating that most active twinning planes are aligned well, and so are twinning shear directions. It is deduced that the low misalignment of twinning planes and twinning shear directions should be a beneficial factor for the formation of long twin bands. The same analysis was performed on the other three long twin bands and a similar characteristic was found, that is, nearly all active neighboring twins have their twinning planes normal and twinning shear directions in a low misalignment angular range of 0–15°. The geometric compatibility parameter (m') has been used to describe the transfer efficiencies of slip–slip [7], slip–twin [8] and twin–twin [9] between neighboring grains in titanium and its alloys. Recently it has also been used to explain the yield point elongation phenomenon due to twinning in Mg alloys [23]. If a higher m' (in general > 0.8) exists in two neighboring grains, the strain transfer across GB can be considered to occur easily. As shown in Table 1, an obviously larger m' (>0.9) of two active twinning systems was found for any two neighboring grains in the STB. A statistical analysis on m' of 43 neighboring twin pairs from four long {10-12} twin bands are presented in Figure 3a and b. It reveals that almost all twin pairs in the long twin bands have a larger m' exceeding 0.8 (except one being 0.79) and ~81.4% twin pairs have m' larger than 0.9. The above analysis indicates that the shear strains due to twinning can be transferred efficiently or accommodated consistently by forming such long twin bands.

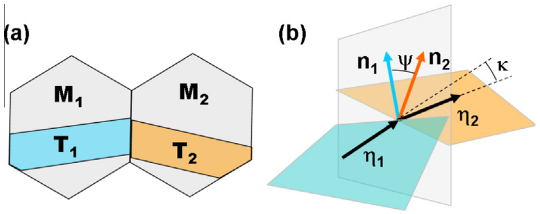

Figure 2. (a) Schematic illustrations of two neighboring twins (T_1 and T_2) in a twin band (M_1 and M_2 are the corresponding parent grains). (b) Geometric relationship between the active twinning systems in M_1 and M_2. n and η are the twinning plane normal and shear direction, respectively.