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Role of twinning and slip in cyclic deformation of extruded Mg–3%Al–1%Zn alloys

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The low-cycle tension–tension fatigue properties of extruded Mg–3%Al–1%Zn alloy plate have significantly different features in twinning-dominated samples and dislocation-dominated samples. The twinning-dominated samples show more pronounced cyclic hardening and longer fatigue life than those of the slip-dominated samples. The elongated lifetime of the twinning-dominated samples may be due to the roughness-induced crack closure.

Keywords: Magnesium alloy; Low-cycle fatigue; Twin; Failure

Magnesium alloys are a potential structural material with a high specific strength, good machinability and recyclability [1]. These advantages make it very attractive for the transportation industry. As structural materials in service, magnesium alloys are usually subjected to cyclic deformation, leading to catastrophic fracture after a certain period of time. Therefore, the cyclic deformation behavior of these materials needs to be further investigated for safety reasons.

Most magnesium alloys have a hexagonal close packed (hcp) crystal structure and a very limited number of slip systems at room temperature. Besides slip, twinning is another important plastic deformation mode in magnesium alloys. As such, the fatigue properties of magnesium alloys differ markedly from those deformed predominantly by slip, such as pure copper and aluminum alloys. Yin et al. [2] reported that the hysteresis loops of extruded AZ31 alloy were asymmetric between the compression and tension cycle. This indicated that twinning and detwinning alternates with the cycle loading, i.e. most deformation twins can detwin under reversal loading [2,3]. Twinning–detwinning led to complicated cyclic deformation and fatigue behavior of magnesium alloys [2–7]. The well-known Manson–Coffin relationship is not applicable to magnesium alloys under the strain-controlled loading conditions. Matsuzuki and Horibe [6] observed that the fatigue results of AZ31 exhibited a bi-linear tendency in the Manson–Coffin curve. This indicated that the twinning process was dominant at greater strain amplitude, whereas dislocation slips were dominant at lower plastic strains. Concurrently, Li et al. [8] found that the fatigue properties of magnesium alloys were dominated by dislocation slip when the strain amplitude was less than 0.5%, and by twinning process when the strain amplitude was greater than 0.5%. Tokaji et al. [9] proposed a model of cyclic slip deformation to explain the surface crack initiation in high cycle fatigue; however, Yang et al. [10] observed that secondary cracks were along twin bands in extruded AZ31 magnesium alloy. These investigations suggested that both dislocation slip and twinning played an important role in the cyclic response of magnesium alloys. This gives rise to an interesting question: what kind of deformation mechanisms are intrinsically beneficial to resist fatigue cracking?

An important difference between twinning and slip deformation is that twinning is polarized. As the c/a ratio of a hexagonal magnesium lattice (1.624) is less than $\sqrt{3}$, tension twins are activated easily by c-axis tension. Therefore, twinning is the dominant deformation mechanism during tensile loading parallel to c-axis, whereas slip is the dominant deformation mechanism during tensile loading vertical to c-axis. In the present study, low-cycle tension–tension fatigue properties of a extruded AZ31 alloy sheet (Mg–3%Al–1%Zn, wt.%) have been investigated. The average grain size is about 80 μm. The initial texture exhibits the combined features of

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the typical rolling and extrusion textures, shown in Figure 1a. There are two major texture components, one with the basal poles parallel to the plate normal and the other with the basal poles parallel to the transverse direction. When the tensile loading is parallel to the extrusion direction, the *c*-axis in most grains is vertical to the loading axis and slip is the dominant deformation mechanism (designated as SD samples). In contrast, when the tensile loading is parallel to the transverse direction, the *c*-axis in many grains is parallel to the loading axis and twinning is the dominant deformation mechanism (designated as TD samples). As such, the samples for tensile and fatigue tests were cut along the extrusion direction and transverse direction, respectively.

Although conventional fatigue tests involving full tension–compression cycles may be ideal for evaluating fatigue behavior and fatigue life in actual applications, the mixture of twinning and slip makes it impossible to distinguish their roles. For example, the dislocation slip is dominant in tension for SD samples, whereas twinning is dominant in compression. In the present work, fatigue tests were performed in tension cycles with a strain ratio of $S = 0$. All tests were conducted using an Instron-8801 testing machine in laboratory air at room temperature. The gauge dimensions of the tensile samples were $2 \times 3 \times 10\ mm^3$. The initial strain rate was $5 \times 10^{-4}\ s^{-1}$. A dog-bone sample, measuring 16 mm in gauge length, 14 mm in gauge width, and 4 mm in thickness, was used for all tension–tension fatigue tests. The cyclic frequency was 1 Hz. Before testing, the samples were polished with 2000 grit silicon carbide abrasive paper, followed by electropolishing using a solution comprising 15 ml $HClO_4$, 50 ml glycol and 180 ml ethanol to eliminate the residual stress of the surface layer. The fracture morphologies were observed with a Quanta-200 scanning electron microscope. To clarify the texture, (0 0 0 2) pole figure was measured using X-ray diffractometer (model Philip X'pert PRD) with Co Kα radiation.

Figure 1b shows the engineering stress–strain curves of the samples TD and SD under tensile loading. The tensile yield strengths of the TD and SD samples are about 55 and 114 MPa, respectively. The elongation of the TD sample is nearly 20%, higher than that (~15%) of the SD sample. The yield strength of the SD sample is about two times that of the TD sample during the tensile deformation. This marked difference can be attributed to the easier twinning for the TD samples in tension [7,11,12]. Also, the SD sample showed the parabolic hardening of slip-dominated deformation, whereas the TD sample showed the sigmoidal (S-shaped) hardening of twin-dominated deformation [12,13].

Representative hysteresis curves are shown in Figure 2a and b for SD and TD samples at total strain amplitude of 0.25%. The hysteresis loops of the SD sample, in Figure 2a, are symmetric; this is usually the result of the dislocation slip-dominated deformation in most materials [14]. In contrast, the hysteresis loops of the TD sample were asymmetric, shown in Figure 2b. Upon the initial tensile yielding at ~55 MPa, the sample showed little hardening and the maximum tensile stress at 0.5% was ~60 MPa. This type of strain-hardening plateau is typical of magnesium alloys which are deformed by twinning [11,15]. Upon unloading, a significant pseudoelasticity was observed which was caused by detwinning [2,3].

Figure 2c shows the cyclic stress responses of the TD and SD samples with increasing cyclic number. It can be seen that under the same total strain amplitude, the cyclic stresses of the SD samples are always higher than those of the TD samples. This can be explained by the tensile strength of the SD samples being higher than that of the TD samples. Apparently, the TD sample shows much greater cyclic hardening than that of the SD sample. This may be caused by the residual twins in the fatigue process of the TD samples. Although most twins are removed via detwinning, there are some residual twins that existed, which gradually increased with increasing cycles [3]. The residual twins subdivided the initial grains into small ones, which strengthened the alloys.

Figure 3 shows the curves of total strain amplitude vs. number of cycles to failure. It is apparent that the low-cycle fatigue lifetime of the TD samples is higher than that of the SD samples under the strain-controlled tension–tension fatigue tests. This indicated that twinning-dominated deformation improved the low-cycle fatigue life compared with that of dislocation slip-dominated deformation. In order to show the fatigue crack behavior, the macroscopic fracture morphologies and the corresponding three-dimensional illustrations of the crack profiles of the SD and TD samples are inserted in Figure 3. When dislocation was the dominant deformation mechanism, the cracking behavior was similar to tensile cracking, whereas when twinning was the dominant deformation

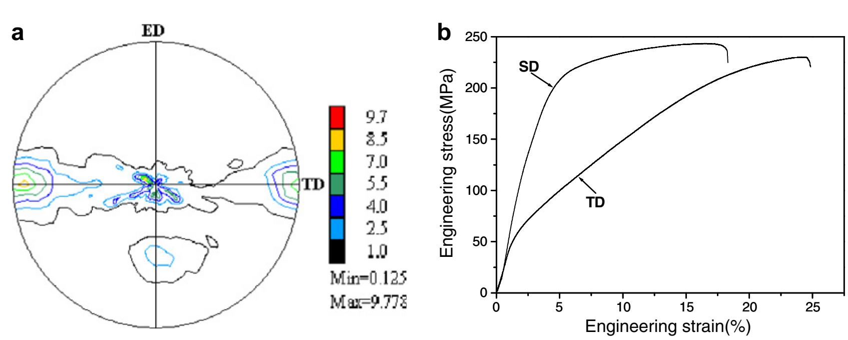

Figure 1. (a) {0 0 0 2} pole figure for extruded AZ31 alloy; (b) the tensile stress–strain curves of the TD and SD samples.