TWINNING AND DUCTILE FAILURE OF Mg-3Al-1Zn

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Abstract

In general, magnesium alloys display lower ductilities than other metal systems that display equivalent strength. Some authors have suggested that twinning plays a role in this phenomenon. In the present work two series of samples cut in different directions from an extruded bar are examined to test this idea. One series was cut to favour \( \{012\} \) twinning, the other to suppress it. The reduction in area measured in tensile tests performed at temperatures between room temperature and 250°C showed negligible difference between the two series of samples. The series in which \( \{012\} \) twinning was not favoured displayed copious amounts of twinning that was assumed, based on EBSD analysis, to be on the \( \{011\} \) plane. These twins were associated with flow localization and void formation and are thus likely to play an important role in ductile failure.

Introduction

The degree to which magnesium alloys can be subjected to room temperature deformation is limited. One of the main reasons given for this in the literature is that there is an insufficient availability of deformation systems. However, the material does display some plasticity, which testifies to the fact that it does have enough deformation systems for generalized plastic deformation. The material readily undergoes deformation twinning and this contributes to its plasticity. However, it is known that in certain instances, at least in other metals, twinning can lead to the onset of ductile failure \cite{1}. Perhaps there is something about the twinning modes in magnesium that serves to hasten failure. The present work examines this idea through two series of tensile specimens cut in different ways from an extruded bar of Mg-3Al-1Zn (AZ31). One series was cut to favour \( \{012\} \) twinning, the other to suppress it.

Experimental Method

The experiments employed in the present study were conventional tension and compression tests. These were carried out on an as-received bar of Mg-3Al-1Zn (AZ31). The bar was 75 mm in diameter and the texture and initial microstructure proved to be typical of extruded material (Figure 1). It can be seen that the \( c \) axis is distributed perpendicular to the extrusion direction and that the grain size is quite fine, \(<8 \mu m \) (linear intercept).

![Figure 1. Microstructure (linear intercept grain size = 8 \( \mu m \)) and basal pole figure (levels: 1,2, 4) for the commercial AZ31 bar employed in the present study.](image)

Tensile samples with a gauge dimension of 4.5×15 mm were cut from the as-received bar in two ways. One series was such that the tensile direction was aligned with the extrusion direction while the other was perpendicular to it. The samples cut perpendicular to the extrusion direction (and loaded in the radial direction) are expected to display greater amounts of \( \{012\} \) twinning. The tests were performed at a constant strain rate of 0.01 s\(^{-1}\) and test temperatures in the range ambient to 250°C were employed. Prior to testing, the samples were held for 15 min in an infrared furnace to equilibrate the temperature. Following testing, the samples were cooled in forced air beginning approximately 2 s after the test. A creep strain measurement device was employed to measure the strain in the gauge length throughout the test.

After testing, the surfaces of all specimens were ground with 1200 grit SiC paper. Polishing was then carried out with diamond paste through a sequence of 15, 6, 3 and 1 \( \mu m \) for optical metallographic observation. Electron Backscatter Diffraction (EBSD) mapping was used for micro-texture measurement. For this purpose, the specimens were mechanically polished with a Colloidal Silica Slurry and etched with a solution of 10 ml HNO\(_3\), 30 ml acetic acid, 40 ml H\(_2\)O and 120 ml ethanol for 10 seconds.
Results

The optical microstructures of selected samples were inspected just outside of the neck in samples tested to failure for signs of deformation twinning. More twinning was evident in regions for the series of samples cut perpendicular to the extrusion direction. These were the samples expected to favour \{10\bar{1}2\} twinning (see Figure 2). For tests performed at 150°C, the frequency of twinning was noticeably less than seen at room temperature. Some twins were evident in the samples strained along the extrusion direction and these were, in general, thinner and straighter than those in the other series.

Figure 2. Optical micrographs taken approximately 2 mm outside of the neck for samples tested at a strain rate of 0.01 s\(^{-1}\). a) parallel to extrusion direction, ambient, b) perpendicular to the extrusion direction, ambient, c) parallel to extrusion direction, 150°C and d) perpendicular to the extrusion direction, 150°C.

The cross sectional area of the fracture surface was measured following tensile failure and this was used to determine the reduction in area. The values obtained for all of the present tests are summarized in Figure 3 where the reduction in area is given in terms of the strain to failure as a function of test temperature. No discernable difference between the two series of samples can be detected. It thus appears that the influence of \{10\bar{1}2\} twinning on the ductile failure is negligible.

Inspection of the microstructures developed in the series of samples tested such that \{10\bar{1}2\} twinning was not favoured, i.e. along the extrusion direction, showed an increase in the twin frequency near to the fracture surface. An image of the sample tested at room temperature is given in Figure 4. Near to the fracture surface it appears as if the twins join in a co-operative manner into shear bands. The twins in this sample etch dark in their interior.

Figure 3. Influence of test temperature on the strain to failure seen in the present extruded samples of AZ31 bar.

Figure 4. Twinning and shear bands evident in a sample of AZ31 bar tested to failure along the extrusion direction (horizontal) at room temperature at a strain rate of 0.01 s\(^{-1}\).

The microtexture was inspected using EBSD in an attempt to identify the twin mode in the present samples. The indexing of the interiors of the thin twins proved to be difficult but in some instances Kikuchi patterns were able to obtained from the twin interior. The study revealed the presence of twins with boundaries consistent with \{10\bar{1}1\} twinning. Such boundaries are characterized by a 56° rotation around a \langle1\bar{2}10\rangle axis. In other cases, twins with a trace consistent with a \{10\bar{1}1\} habit plane displayed a orientation in their interior related to the matrix by a rotation near to that expected for \{10\bar{1}1\} twinning followed by re-twinning on \{10\bar{1}2\} in the twin interior. These boundaries are characterized by a rotation of 38° around a \langle1\bar{2}10\rangle axis [2]. In such instances the basal plane is frequently re-oriented so that the stress resolved on to it is greater. That is the basal plane becomes more favourably oriented for deformation following twinning. This has been pointed out previously in single crystal studies [2] and in a number of polycrystal investigations [3]. The two examples of these reorientations seen in the present material given in Figure 5 involve similarly dramatic increases in Schmid factor for basal slip; from ~0.05 to ~0.5.
It can be seen that the frequency of twinning is a strong function of temperature. At a temperature of 150°C, the twin frequency is very low up to strains of ~0.5.

Discussion

The fact that the strain to failure in the present samples is below a value of ~0.5 for temperatures less than 100°C is significant. Corelations between strain to failure in tensile testing and bendability and rollability show that the formability under these processes becomes quite limited for tensile failure strains less than 0.5. The present observations are quite possibly pertinent to the low formability of magnesium alloys generally seen at room temperature.

The high frequency of twins observed in the fine grained samples tested along the extrusion direction in the present work suggests a mode other than the common \{10\overline{1}2\} twinning mode. Twins consistent with twinning on the \{10\overline{1}1\} plane followed by re-twinning on the \{10\overline{1}2\} plane were observed. The difficulty in indexing these twins meant that statistics on their frequency could not be determined precisely. However, due to the uniform morphology of the twins and the sharp texture, it is assumed that most of the twins observed in observed in optical analysis of the samples tested along the extrusion direction come from the \{10\overline{1}1\} mode.

The occurrence of re-twinning in the twin interior reorients the basal plane to a favourable position for slip and the high local strain rates that are expected to follow have been linked to the failure of single crystals [2, 4]. Indeed, the present work is quite consistent with the idea that these twins lead to failure in the present samples. The twin frequency drops dramatically with temperature up to 150°C while at the same time the strain to failure increases from ~0.3 to around 1.0.

To determine if twins do indeed cause flow localization in the present material a rolled sample with a coarser grain size than employed here (~80 μm) was subjected to a tensile strain after being indented using a microhardness device. Material with a coarser grain size was required because of the poor resolution of the technique. Hardness indents were made, after the sample was strained by an elongation of 0.05, in the vicinity of twins that had the thin straight morphology typical of the \{10\overline{1}1\} mode. The initial and final grids are shown in Figure 7. It can be seen that additional twins formed following the pre-strain. It can also be seen that the twin in the middle of the image absorbed a high degree of local shear. The shear in this twin is estimated to be of the order of a shear strain of 3.4. This well in excess of the twinning shear (~0.13). The pole figures shown give the expected traces of the basal and \{10\overline{1}1\} planes. The alignment of the basal slip lines with the expected trace is obvious and it can also be seen that two of the families of twins are consistent with two of the expected traces of the \{10\overline{1}1\} planes.

The high degree of strain localization evident in this figure is likely to hasten failure. Indeed in a number of isolated instances twins displaying void formation were observed in the present study. An example of this is given in Figure 8.

Figure 5. EBSD analysis of double twins. a) and c) EBSD maps showing double twin boundaries (38°<0\overline{1}2\overline{1}0> +/- 7°) in white and shaded according to the Kikuchi band contrast. b) and c) Basal pole figures showing that the basal plane is more favourably aligned for slip in the twin interior. The tensile direction is horizontal and the pole figure reference frame is the same as for the images.

The favourable alignment of the basal planes for slip in these twins is likely to mean that they play an important role in the plasticity of the material. Given this importance, the frequency of twins was established by counting the twins in sections approaching the fracture surface. The results are plotted against strain (calculated from the cross sectional area) in Figure 6.

Figure 6. Change in Twin frequency per area of image plane seen with changing strain along the necked region of samples tested along the extrusion direction. The errors shown are approximate but reflect the difficulty in identifying and resolving the twins using optical microscopy.
Figure 7. Regions of intense local shear occurring in deformation twins on the \(\{10\bar{1}1\}\) plane in a rolled sample of AZ31. a) Initial image following a pre-strain of 0.05, b) same area as in a) but after the sample was strained to failure and c) corresponding pole figures showing the expected traces of the basal and two \(\{10\bar{1}1\}\) planes.

Figure 8. Example of a void forming in a twin in AZ31 bar tested to failure at room temperature.

Finally, it must be concluded that, if the failure of the samples tested along the extrusion direction is heavily influenced by the occurrence of twinning on the \(\{10\bar{1}1\}\) planes, then it is also likely that the same is true for the series tested perpendicular to the extrusion direction. The two series show very similar strains to failure. Such an eventuality is not out of the question because \(\{10\bar{1}2\}\) twinning re-orient the lattice in such a way that \(\{10\bar{1}1\}\) twinning is expected to be favoured in the new orientation. However, that the failure strains should be so similar for the two series is still difficult to rationalize.

Conclusions

- The occurrence of \(\{10\bar{1}2\}\) twinning in the early stages of tensile deformation does not seem to have a large impact on the strain to failure in tension.
- Twins formed in the latter stages of deformation in samples tested parallel to the extrusion direction are probably of the \(\{10\bar{1}1\}\) family.
- The frequency of these twins is a strong function of temperature and they accommodate local shear strains well in excess of the twinning strain.
- Such local shear is expected to contribute to the development of ductile failure but more study is required to verify this.

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References