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Effect of Pre-Strain on the Fatigue Behavior of Extruded AZ31 Alloys

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Abstract. An attempt is made to rationalize the effect of pre-strain history on fatigue behaviors of AZ31 magnesium alloy. Axial fatigue tests were conducted in the extruded and pre-compressioned AZ31 alloy under low cycle total strain control fatigue conditions. The pre-strain process influences the plastic deformation mechanism activated during fatigue deformation, especially during tensile loading, by enhancing the activity of detwinning mechanism. The low-cycle fatigue lifetime of extruded AZ31 alloy can be enhanced by the pre-compression process. And the hysteresis energy was successfully used to predict the low-cycle fatigue lifetime.

1. Introduction

The first systematic research works on the effects of pre-strain on cyclic behavior had been performed 40 years ago [1]. And there exists a threshold pre-strain for easy-cross-slip metals. Below this threshold, the cyclic stress-strain response doesn’t depend on the pre-strain. Above it, the cyclic plastic response strongly depends on the pre-strain. While for planar-slip metals, the cyclic behavior is always sensitive to the pre-strain[2]. Contrary to other industrial materials, most magnesium alloys are with hexagonal close packed (hcp) crystal structure and they have 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. [3] reported that the hysteresis loops of extruded AZ31 alloy were asymmetric between the compression and tension cycle. This indicated that twinning and detwinning alternated with the cycle loading. Twinning-detwinning led to complicated cyclic deformation and fatigue behavior of magnesium alloys [3-8]. These investigations suggested that twinning-detwinning played an important role in the cyclic response of magnesium alloys. Then pre-strain of magnesium alloy induced change in the twinning-detwinning characteristics, and influenced the fatigue deformation behavior. The main objective of this investigation was to rationalize the effect of pre-stain on fatigue behavior of an extruded AZ31 alloy.

2. Experimental

The starting material for this study was an extruded rod of commercial AZ31 (Mg-3wt.%Al-1wt.%Zn) alloy. Specimens for pre-compression process with a gauge size of 95mm in length and 20mm in diameter were prepared from the extruded rod, where their cylindrical axes were parallel to the extrusion direction. After
pre-compressioning these specimens to the strain values of 3% and 5%, they were remachined to tension (2x3x10 mm3), and fatigue (14x6x5 mm3) specimens.

All tests were conducted with an Instron-8801 testing machine. A strain rate of 5×10^-4/s was used for tensile tests. The cyclic frequency was 1Hz. Also, the fatigue experiments were carried out at room temperature under the strain ratio S = -1. Before testing, the samples were polished with 2000 grit silicon carbide abrasive paper, followed by electropolishing using a solution comprising 15 ml HClO4, 50 ml glycol and 180 ml ethanol to eliminate the residual stress of the surface layer. The microstructure and morphology of the specimens were characterized by optical microscope and a Quanta-200 scanning electron microscope. X-ray diffraction (XRD) was performed using a D/Max-1200X diffractometry with Cu Kα radiation operated at 20kV and 100mA, in order to identify the crystallographic orientation.

3. Results and discussion

The microstructures of the as-extruded and pre-strained AZ31 alloy are shown in Figure 1. The average grain size in initial state is approximately 30µm. The pre-compression process introduces plenty of twins into the microstructure. And with the progress of deformation, the twins initiated, gradually grew, and intersected with each other.

![Figure 1](image1.png)  
**Figure 1.** Optical microstructures and XRD scans from the longitudinal planes of (a) the as-extruded (b) 3% pre-compression, and (c) 5% pre-compression materials.

To gain insight into the texture evolution of the material, the X-ray diffraction (XRD) is employed. Figure 1(a) shows the crystallographic orientation of as-extruded sample. The intensity of the (0002) peak, (denoted as I(0002)/I(1010) ratio [9]), is about 0.22, so the initial texture can be roughly considered as having a ring fiber texture with the basal planes parallel to the extrusion direction. This initial texture does not allow any twinning under tensile loading but twinning under compressive loading. As the \{10 \overline{1} 2\} twinning induces a crystallographic lattice reorientation of 86.3° in the twinned region, the intensity of basal poles aligned perpendicular to the ED (i.e., initial texture) gradually became weak with increasing pre-compression. On the contrary, the intensity of basal poles aligned parallel to the ED (i.e., twin texture) gradually increases because of the formation and growth of twins. As shown in Figure 1(b) and (c), the I(0002)/I(1010) ratio in 3% pre-compression specimen is about 0.35, while the I(0002)/I(1010) ratio in 5% pre-compression specimen is about 0.52. Hence, it is reasonable to conclude that the pre-compression specimen has a higher total volume fraction of \{10 \overline{1} 2\} twins than the extruded specimen. The twin texture will be favored for detwinning during...
subsequent tensile loading because it undergoes tension parallel to the c-axis. This causes a significant decrease in flow stress.

Figure 2 presents the tensile and compressive stress-strain curves of pre-strained AZ31 alloys and Table 1 summarizes the mechanical properties. It is interesting to note that the as-extruded specimen yield at much higher strength as compared to the pre-strained specimen during the tensile deformation, and vice versa in the compression test. This asymmetric feature has been found to be due to the different deformation mechanisms which vary with the orientation of specimen and the direction of loading [5].

For HCP magnesium with a c/a ratio of approximately 1.622, tensile twinning on the \{10\overline{1}2\} plane is activated by a compressive stress parallel to the basal plane or a tensile stress perpendicular to the basal plane [4]. Accordingly, specimen deformed by twinning reveals much lower yield strength than that deformed by slip. Consequently, the lower tensile yield stress, shown in Figure 2, indicates that twinning is the dominant deformation mechanism which arises from twins produced by pre-compression. Also, the as-extruded specimen showed the parabolic hardening of slip-dominated deformation, whereas the pre-strained specimen showed the sigmoidal (S-shaped) hardening of twin-dominated deformation [5]. The yield strength of the as-extruded is about 155MPa, decreasing to 66 and 54MPa for 3% pre-compression and 5% pre-compression, respectively.

Table 1. Mechanical properties of the extruded AZ31 Mg alloy with and without pre-compression.

| Sample          | TYS(MPa) | UTS(MPa) | CYS(MPa) | Elongation(%) |
|-----------------|----------|----------|----------|---------------|
| As-extruded     | 155      | 267      | 100      | 18            |
| 3% compression  | 66       | 267      | 109      | 12.5          |
| 5% compression  | 54       | 253      | 102      | 13.5          |

Representative hysteresis curves are shown in Figure 3(a) for the as-extruded sample at total strain amplitude of 0.3%. In the first cycle, the stress strain curve is asymmetric between tension and compression cycle. Upon the initial compressive yielding at ~90MPa, the sample showed little hardening and the maximum compressive stress at 0.3% was ~95MPa. This type of strain hardening plateau is typical of magnesium alloys which are deformed by twinning. Upon unloading, a significant pseudoelasticity was observed which was caused by detwinning [3,4].
The first tensile flow stress, as indicated by test results, is usually the preferred source for the mechanical property of a material. The maximum tensile stress and strain hardening exponent are both larger at tensile flow stress, which leads to the symmetric hysteresis loops. The residual twins gradually increase with increasing cycles so that the number of twins capable of detwinning decreases with increasing cycles [3,4]. As a result, after several cycles, it becomes insufficient to accommodate the imposed tensile strain by detwinning alone. This requires the activity of slip systems [10], which leads to the symmetric hysteresis loops. The total strain amplitude vs. number of cycles to failure for the pre-compression material is depicted in Figure 5. It is apparent that the low-cycle fatigue lifetime can be enhanced by the initial \{1012\} twins processed by pre-compression.

![Figure3](file://image.png)

Figure3. Evolution of the stress-strain hysteresis loops with the number of cycles (Δε/2=0.3%): (a) the as-extruded, (b) 3% pre-compression, and (c) 5% pre-compression materials.

For pre-compression materials, as described earlier, initial twins formed by pre-compression process serve as a source for the detwinning mechanism during tensile loading. With the aid of initial twins, the first tensile loading would be accommodated by the detwinning mechanism alone and lead to tensile strain hardening plateau, as shown in Figure 3(b) and (c). It is commonly recognized that the pre-compression process decreases tensile flow stress, as shown in Figure 4(a). The mean stress at half-life is taken as the representing one. However, the effect of pre-compression on the hysteresis loops was dependent on the amount of pre-compression and the number of cycles. The residual twins gradually increase with increasing cycles so that the number of twins capable of detwinning decreases with increasing cycles [3,4].

![Figure4](file://image.png)

Figure4. Mean stress (a) and plastic strain amplitude (b) at 50% of fatigue life in dependence on total strain amplitude.

From the detailed observations of fracture surfaces, examples of fractographs are shown in Figure 6(a) and (b) for the as-extruded sample and 5% pre-compression sample at strain amplitude of 0.2% in the fatigue crack initiation and stable propagation zone respectively. In Figure 6(a) the as-extruded sample shows irregular fracture surfaces going up and down in some random way. In contrast, the 5% pre-compression fracture mode is mostly faceted and brittle-like.
It is well known that tensile mean stress has a harmful effect on the fatigue resistance by accelerating crack initiation and propagation mechanisms, while the reverse is true for compressive mean stress [5]. Based on this model, Park et al. [10] explained the effect of mean stress on fatigue lifetime under total strain amplitude. Actually, the assessment of the fatigue performance is not quite straightforward. The effect of mean stress on fatigue lifetime, proposed by Evans [11], is only valid for stress-controlled fatigue. While under strain-controlled conditions, except for mean stress, plastic strain amplitude, \( \gamma_{pl} \), is another important factor influencing the fatigue lifetime. The amount of cyclic damage [12], \( \Gamma \), can be expressed as \( \Gamma = \sum_{i=1}^{4} \gamma_{pl,i} \). The variation of plastic strain amplitude does not follow the trend of mean stress. The extruded sample shows the highest mean stress, while its plastic strain amplitude is the lowest, shown in Figure 4(b).

The devised Morrow model, proposed by Ellyin and Kujawski [13], can be expressed as follows:

\[
\Delta W_i \cdot N_f^m = C
\]

where \( \Delta W_t, N_f, m \) and \( C \) are the hysteresis energy, fatigue life, and material constants, respectively. Fatigue life curve as a function of hysteresis energy is presented in Figure 7(b). It is clearly shown that the fatigue data for the pre-strained samples were well depicted with the total hysteresis energy. This implies that the total strain energy-based life prediction model provides a good prediction on the fatigue life behavior of the pre-strained Mg alloy.
Figure 7. The hysteresis energy (a) and life prediction using the energy-based model (b) of pre-compression materials.

4. Conclusions
From the above mentioned low-cycle fatigue study on pre-strained AZ31 alloy, the following conclusions can be drawn:
(1) The pre-compression process influences the plastic deformation mechanism activated during fatigue deformation, especially during tensile loading, by enhancing the activity of detwinning mechanism.
(2) The pre-strain process decreased the mean stress, but increased the plastic strain amplitude.
(3) The low-cycle fatigue lifetime can be enhanced by the pre-compression process. And hysteresis energy considering the mean stress can be used for the prediction of fatigue life.

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