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Low-cycle fatigue characteristics of rolled Mg–3Al–1Zn alloy

Sung Hyuk Park [a], Seong-Gu Hong [b,*], Byoung Ho Lee [c], Wonkyu Bang [d], Chong Soo Lee [a,**]

[a] Department of Materials Science and Engineering, Pohang University of Science and Technology, Pohang 790-784, Republic of Korea
[b] Division of Industrial Metrology, Korea Research Institute of Standards and Science, Daejeon 305-340, Republic of Korea
[c] Sheet Products & Process Research Group, POSCO Technical Research Laboratories, Pohang 790-785, Republic of Korea
[d] Magnesium Project Team, Research Institute of Industrial Science and Technology, Pohang 790-785, Republic of Korea

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ABSTRACT

Fatigue characteristics of rolled Mg–3Al–1Zn (AZ31) alloy were investigated by performing the low-cycle fatigue test along the rolling direction. The alloy was found to have a strong basal texture so that the fatigue deformation was predominated by the alternation of twinning and detwinning during each cycle, and this made the cyclic stress response unstable and introduced a non-zero mean stress and/or strain depending on the loading condition. An energy-based concept was successfully used to predict the low-cycle fatigue life because a plastic strain energy density was found to have good characteristics as a fatigue parameter; it was stabilized at the early stage of fatigue life and nearly invariant through entire life. In the life prediction model, the effect of mean stress was appropriately considered.

1. Introduction

Because environmental problems are emerging as an internationally important issue, regulation to limit carbon dioxide emissions of vehicle is becoming tougher recently. Therefore, applications of light materials have received considerable attention in automotive industry to improve energy efficiency. Magnesium alloys, which are the lightest among all commercial structural materials, are the most attractive candidate in applications of automobile parts for reducing weight by substituting aluminum or steel components. A majority of these applications have used die-cast Mg alloys, however, wrought Mg alloys manufactured by the processes such as rolling, extrusion, and strip-casting are recently receiving wide interest due to their superior mechanical properties than the cast one [1]. These components are generally used under service condition of cyclic loading or vibration. Accordingly, it is an important factor to understand the fatigue properties. Although many researches on the low-cycle fatigue behavior of wrought Mg alloys have been performed recently [2–8], research to predict the low-cycle fatigue life behavior is still lacking [7,8].

In wrought AZ31 Mg alloys, asymmetric hysteresis loop and non-elastic unloading behavior have been reported due to the repeated activation of the twinning and detwinning during cyclic straining. These natures induced the development of non-zero mean stress affecting the fatigue characteristics and the ambiguity in determining the plastic strain amplitude from a stress–strain hysteresis loop. This makes it difficult to express the fatigue life with the Coffin–Manson type model defined by plastic strain range at zero stress which is generally used to predict the low-cycle fatigue [8]. Cyclic plastic strain energy models based on the analysis of the hysteresis loop have been developed by several researchers [9–12] and successfully extended to the uniaxial and multiaxial low-cycle fatigue characteristics of various materials [13–15]. Criteria based on total strain energy composed of elastic and plastic energy were found to be in good agreement with experimental results under complex loading state with mean stress [16]. However, it is still questioned whether the proposed criteria well predicts low-cycle fatigue life of Mg alloys whose hysteresis loops are severely distorted due to the different deformation mechanisms during tension and compression.

In this study, it was attempted to understand the low-cycle fatigue deformation behavior of rolled AZ31 Mg alloy in relation with the twinning–detwinning characteristics and to verify the fatigue life behavior based on the earlier proposed energy-based criteria.

2. Material and experimental procedures

The material used in this study was a hot-rolled AZ31 Mg plate with 50 mm in thickness, which was homogenized at 400 °C for 4 h. The chemical composition of the alloy was 3.6 Al, 1.0 Zn, 0.5 Mn, and the balance Mg (in wt.%). The average grain size was about 30 μm. X-ray diffraction test revealed that a strong basal texture

* Corresponding author. Tel.: +82 42 868 5868; fax: +82 42 868 5032.
** Corresponding author. Tel.: +82 54 279 2141; fax: +82 54 279 2399.
E-mail addresses: sghong@kriss.re.kr (S.-G. Hong), cslee@postech.ac.kr (C. Soo Lee).

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with most basal planes aligned parallel to the rolling plane was developed. More detailed information on the texture developed can be found elsewhere [7].

For tensile test, cylindrical specimens with a gauge length of 25 mm and a gauge diameter of 6 mm were prepared, and those for compression test were with a diameter of 10 mm and a height of 12 mm. Cylinder axis of all specimens was located parallel to the rolling direction. Quasi-static tension and compression tests were carried out at room temperature with a strain rate of $5 \times 10^{-3}\ s^{-1}$ and using INSTRON 8801 and Gleeble 3500 testing machines, respectively.

Specimen for low-cycle fatigue tests had a gauge length of 10 mm and a gauge diameter of 5 mm aligning cylinder axis in the rolling direction. INSTRON 8801 testing machine was also used to perform the strain and stress-controlled fatigue tests with a frequency of 1 Hz in laboratory air at room temperature. Strain signal was measured and controlled by an extensometer attached to the sample. A sine wave with the stress ratios, $R_\sigma = \sigma_{min}/\sigma_{max}$, of 0 and -1 was used for the stress-controlled tests and a triangular wave with the strain ratios, $R_\varepsilon = \varepsilon_{min}/\varepsilon_{max}$, of -1 and 0.5 was employed for the strain-controlled tests. For fatigue tests under $R_\varepsilon = -1$, six different levels of strain amplitude ranging from 0.3% to 1.2% were used, while under $R_\varepsilon = 0.5$, five levels of strain amplitude ranging from 0.3% to 0.5% were used. The fatigue life of the specimen was defined when a tensile peak stress dropped by an amount of 30% as compared to that at half-life or as the separation of the specimen.

Samples for optical microscopy were sectioned, mounted, polished, and etched with the acetic picral solution (10 ml acetic acid + 4.2 g picric acid + 10 ml distilled water + 70 ml ethanol (99.5%)).

3. Results and discussion

3.1. Asymmetry of flow curves between tension and compression

The stress–strain curves obtained from tensile and compressive tests are presented in Fig. 1a. The curves characterize an asymmetric deformation behavior with significantly lower yield strength in compression as compared to that in tension. Because of the strong basal texture developed by hot rolling process and the direction dependency of twinning, plastic deformation by twinning occurs only under compressive loading. It is generally known that principal twinning system occurs under extension parallel to the *c*-axis of the hexagonal close-packed (hcp) unit cell or under compression perpendicular to the *c*-axis of hcp materials with the *c*/*a* ratio less than 1.732 [17,18]. In magnesium and its alloys having the *c*/*a* ratio of 1.624, it is not surprising to observe active twinning under compression perpendicular to the *c*-axis. As shown in Fig. 1b, the initial microstructure of AZ31 Mg alloy after homogenizing is free of twins. At a tensile strain of 10%, a small number of contraction twins with a needle-like narrow shape are localized along the shear bands (Fig. 1c). On the other hand, at a compressive strain of 10%, many wide extension twin bands are observed throughout the specimen because most hcp unit cells of the specimen were the state of *c*-axis extension during the compression (Fig. 1d).

3.2. Cyclic stress–strain behavior

Stress–strain hysteresis loops at the first two cycles and half-life under the total strain amplitude of 1% are shown in Fig. 2. Deformation anisotropy occurs in the stress–strain curves due to the plastic deformation by the twinning, as mentioned earlier, and this

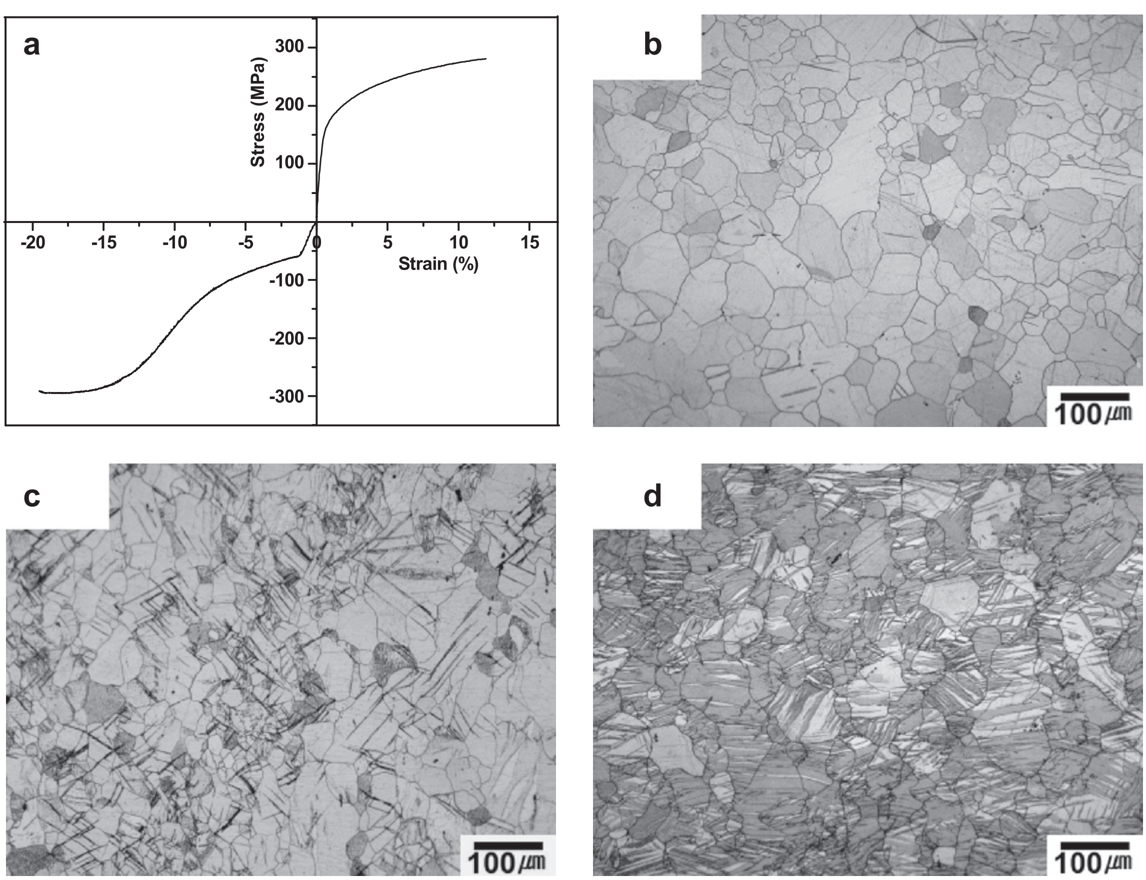

Fig. 1. Deformation anisotropy: (a) tensile and compressive stress–strain curves and optical micrographs of (b) the as-rolled, (c) 10% tensioned, and (d) 10% compressed materials.