Low-Cycle Fatigue Deformation Behavior and Evaluation of Fatigue Life on Extruded Magnesium Alloys

K. Shiozawa, J. Kitajima, T. Kaminashi, T. Murai and T. Takahashi

Abstract

To evaluate fatigue deformation behavior and fatigue life of extruded magnesium alloy, total strain-controlled and stress-controlled low-cycle fatigue test of three extruded magnesium alloys, AZ31, AZ61 and AZ80, were performed in ambient atmosphere at room temperature using smooth round bar specimen. Mean tensile stress during total strain-controlled fatigue process and mean compressive strain during stress-controlled fatigue process appeared due to asymmetry of yield stress between tension and compression. The values of mean stress and mean strain appeared on three alloys were associated with the ratio of compressive yield stress to tensile one, which resulted in mechanical twinning in the compressive phase. Fatigue criteria proposed previously considering the mean stress effect were evaluated in terms of fatigue life predictions based on the experimental results. Also, an energy-based model taken into account of plastic and elastic energy density was discussed to predict the fatigue lives obtained from total strain- and stress-controlled fatigue experiments.

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Keywords: Low-cycle fatigue; Strain-control; Stress-control; Magnesium alloy; Mean strain; Mean stress; Hysteresis loop

1. Introduction

Magnesium alloys, having some excellent properties such as low density, high specific strength and stiffness and so on, have received more concerns as very attractive materials for structural components.

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required weight reduction, energy saving and reduction of the environmental loads to the globe. With development of extruding and rolling technology in present-day, wrought magnesium alloys are expected to use of mechanical components under high oscillating load, instead of using cast magnesium alloys which have disadvantages in defects such as casting porosity, cavity and microscopic shrink hole. For application of the wrought alloys to load-bearing components, it is important to evaluate fatigue properties. It is already recognized for extruded magnesium alloys to result a strong anisotropy of mechanical properties, which is caused by both a crystallographic nature in hexagonal close packed lattice structure and fibre texture with basal plane aligned parallel to the extruded direction by mechanical processing. Because of the limited number of active slip systems, twinning system operates for plastic deformation \[1-4\]. Fatigue behavior of metals is basically controlled by plastic deformation and cyclic deformation irreversibility in microscopic level. But there has not been found a study about a fatigue behaviour which has taken into account the specific deformation mechanism in wrought magnesium alloys. In this study, both of total strain and stress controlled low-cycle fatigue tests of the extruded rod of three types of materials, AZ31, AZ61 and AZ80, were carried out in ambient atmosphere at room temperature to investigate the cyclic deformation behavior and evaluate the fatigue life.

2. Experimental Procedures

2.1. Testing materials and specimen

The materials used in this study were commercial Mg-Al-Zn magnesium alloys, AZ31, AZ61 and AZ80. The chemical composition of these materials (in mass percentage) is given in Table 1. The bar with 16mm in diameter was extruded from a billet of 160mm diameter (an extrusion ratio of 99.4:1) under the extrusion ram speed of 5m/min for AZ31 and 1.5m/min for AZ61 and AZ80 at temperature of 623K. The specimen as shown in Fig. 1 was machined from the extruded bar and used for the fatigue tests. The surface of the gauge section was mechanically polished along the longitudinal direction by emery paper up to mesh #2000 and finally buff polished before fatigue test, for attaining smooth surface. The mechanical properties determined by tensile test were summarized in Table 2. Compressive 0.2% proof stress obtained with an incremental-step loading and unloading test (ISLUT) \[5\], Vickers hardness and grain size were included in this table.

2.2. Fatigue testing method

Closed-loop servo-hydraulic axial fatigue testing machine was used in this study. Total strain controlled low cycle fatigue tests have been conducted under fully-reversed tension-compression loading, \(R_{\theta} = \frac{\sigma_{\min}}{\sigma_{\max}} = -1\), of the triangular wave form and the strain rate of 0.2%/s in ambient atmosphere at room temperature. Nominal strain of the specimen was measured and controlled with a clip-on extensometer having an axial 5mm gauge length attached to the test specimen at the gauge section. All total strain controlled cyclic fatigue tests were initiated in tension. Number of cycles to failure was defined as the number of cycles when the maximum tensile stress in hysteresis curve decreased to three quarters of the

| Table 1 Chemical compositions of materials tested (mass %) |
|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Al   | Zn  | Mn  | Fe  | Si  | Cu  | Ni  | Mg  | 
| AZ31 | 3.10 | 0.93 | 0.33 | 0.001 | 0.005 | 0.001 | Bal |
| AZ61 | 6.30 | 0.61 | 0.28 | 0.005 | 0.012 | 0.001 | Bal |
| AZ80 | 8.53 | 0.57 | 0.17 | 0.005 | 0.012 | 0.001 | 0.0008 | Bal |

Fig.1 Shape and dimensions of specimen.
ordinary value appeared in the middle of fatigue cycles. On the other hand, stress controlled low cycle fatigue tests have been performed under fully-reversed tension-compression loading, $R_i = \frac{\sigma_{\min}}{\sigma_{\max}} = -1$ of sinusoidal wave form and frequency of 0.05Hz in ambient atmosphere at room temperature. Stress of the specimen was monitored by load cell.

3. Experimental Results and Discussion

3.1. Low cycle fatigue life

Experimental results obtained from the tests under the condition of stress-controlled and total strain-controlled low-cycle fatigue were summarized in Fig. 2. Fatigue life under stress-controlled fatigue test depends on the ultimate tensile strength of the tested materials, but that under total stress-controlled fatigue test does not depend and fatigue strength of AZ31 is smaller than those of AZ61 and AZ80. Fig. 3(a) shows the experimental relationship between plastic strain range $\Delta \varepsilon_p$, which was obtained from a hysteresis loop at 0.5 $N_f$, and number of cycles to failure, $N_f$, that is Coffin-Manson low, Eq. (1). Relations of $\Delta \varepsilon_p$-$N_f$ are linearized with log - log coordinates in both conditions of fatigue test. From this figure, fatigue lives of three kinds of materials tested under the stress-controlled fatigue condition are controlled by plastic strain range. On the other hand, fatigue life obtained under total strain-controlled fatigue test shows the dependency of tested materials and is different with that of stress-controlled one.

$$\Delta \varepsilon_p N_f^{\alpha_p} = C_p \quad (1)$$

Values of fatigue ductility exponent, $\alpha_p$, and coefficient, $C_p$, in Eq. (1) were different among tested materials. Fig. 3(b) shows $\alpha_p$ and $C_p$ with relating the ratio of 0.2% offset yield stress in tension and compression, $\sigma_{0.2}^T / \sigma_{0.2}^C$. Value of $\alpha_p$ obtained from the total strain-controlled fatigue test takes 1.43 ~ 1.13

### Table 2 Mechanical properties of tested materials

<table>
<thead>
<tr>
<th></th>
<th>Proof stress $\sigma_{0.2}$ (MPa)</th>
<th>Tensile Strength $\sigma_0$ (MPa)</th>
<th>Elongation $\delta$ (%)</th>
<th>Tension $\sigma_{0.2}^T$ (MPa)</th>
<th>Compression $\sigma_{0.2}^C$ (MPa)</th>
<th>$\sigma_{0.2}^C / \sigma_{0.2}^T$</th>
<th>Vickers Hardness, HV</th>
<th>Grain size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ31</td>
<td>209</td>
<td>232</td>
<td>19.2</td>
<td>200</td>
<td>65</td>
<td>0.235</td>
<td>54.0</td>
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<tr>
<td>AZ61</td>
<td>227</td>
<td>298</td>
<td>19.2</td>
<td>230</td>
<td>100</td>
<td>0.435</td>
<td>59.8</td>
<td>13.7</td>
</tr>
<tr>
<td>AZ80</td>
<td>226</td>
<td>329</td>
<td>15.4</td>
<td>225</td>
<td>159</td>
<td>0.667</td>
<td>62.0</td>
<td>16.0</td>
</tr>
</tbody>
</table>

Fig. 2 S-N curve obtained from stress-controlled low-cycle fatigue test (a) and total strain range vs. fatigue life diagram obtained from total strain-controlled low-cycle fatigue test (b).
depending on the materials and decreases with increasing the value of $\frac{\sigma_{0.2}}{\sigma_{0.2}}^T$. These values are large as compared with many ferrous metals varied between approximately 0.5 and 0.7. Coefficient, $C_p$, is recognized widely as approximately equal to true fracture strain in tension for many metals but the values of tested materials under total strain-controlled fatigue condition, 26.4 ~ 13.0 are very large and depending on the value of $\frac{\sigma_{0.2}}{\sigma_{0.2}}^T$. Under the stress-controlled fatigue test, values of $\alpha_p$ and $C_p$ are 0.722 ~ 0.804 and 0.932 ~ 2.09, respectively, and increases with the value of $\frac{\sigma_{0.2}}{\sigma_{0.2}}^T$. It is considered from the experimental results that the exponent and coefficient in Coffin-Manson law depend on an anisotropy of the materials. Assuming the no difference of yield stress between tension and compression, value of $\alpha_p$ and $C_p$ will be 0.9 and 2, respectively, and take common values well known for many metals.

### 3.2. Change in stress and strain during fatigue process

Fig. 4 shows the change in strains during stress-controlled fatigue process and stresses during total strain-controlled fatigue process obtained from a hysteresis loop. From Fig. 4(a), the maximum strain, $\varepsilon_{\text{max}}$, and the minimum stress $\varepsilon_{\text{min}}$ were decreased rapidly in early stress cycles of fatigue life and
3.2. Fatigue life evaluation

The fatigue life evaluation is generally carried out by using fatigue damage parameters of stress, strain and energy-related terms. As shown in Fig. 3(a), low-cycle fatigue lives for three materials tested under stress-controlled loading can be predicted well with plastic strain range. But, those tested under total strain-controlled loading shows the dependency on materials and also difference from the fatigue life of stress-controlled loading, that is, strong dependency on the loading condition. This means that the low-cycle fatigue life for both loading conditions does not predict by mean of the plastic strain range-based data because of the tensile mean stress and/or compressive mean strain effects which are caused by anisotropic deformation during fatigue cycling. From the experimental results, it can be understand that tensile mean stress strongly affect on the fatigue resistance, however the effect of compressive mean strain is small because of small values of mean strain occurred during the stress-controlled low cycle fatigue cycling.

Fatigue life prediction methods considering the mean stress effect were proposed as Morrow, Lorenzo-Laird, Smith-Watson-Topper (SWT) and DIT model. Another fatigue life prediction method is strain energy-based model. Fig. 6(a) shows fatigue life curves as a function of plastic strain energy density, $\Delta W_p$, which is obtained as the area within the hysteresis loop at half-life. From this figure, the fatigue life of three materials cannot be predicted uniquely in the case of total strain controlled fatigue condition,
because that the damage induced by tensile mean stress, which takes a harmful effect on the fatigue resistance, is not regarded to $\Delta W_p$. To consider the mean stress effect, a tensile elastic strain energy density, $\Delta W_e$, was incorporated into $\Delta W_p$. Fig. 6(b) shows the comparison of the experimental data and the prediction with total strain energy density at half-life, $\Delta W_T (=\Delta W_p+\Delta W_e)$. All experimental results for different loading conditions are indicated within a factor of two scatter band, and the fatigue life can be expressed as follows:

$$\Delta W_T \cdot N_f^{0.735}=360$$

(2)

Same prediction form was proposed for rolled AZ31 alloy by S.H. Park et al [6], as fatigue exponent of 0.751 and material energy absorption capacity of 300 (MJ/m$^3$). Therefore, the total strain energy density-based fatigue life prediction method provides a good prediction for the extruded magnesium alloys.

4. Conclusions

(1) Tensile mean stress was appeared during the total strain controlled low-cycle fatigue and compressive mean strain was appeared under the stress controlled one, because of the difference of yield stress between tensile side and compressive side.

(2) Fatigue life prediction was successfully provided with the total strain energy density-based method for both loading conditions of total strain and stress controlled low cycle fatigue.

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References