The effect of load ratio on fatigue life and crack propagation behavior of an extruded magnesium alloy

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Abstract

Fatigue experiments were carried out in laboratory air using an extruded magnesium alloy, AZ31, to investigate the effect of load ratio on the fatigue life and crack propagation behavior. The crack propagation behavior was analyzed using a modified linear elastic fracture mechanics parameter, M. The relation crack propagation rate vs. M parameter was found to be useful in predicting fatigue lives at different R ratios. Good agreement between the estimated and the experimental results at each stress ratio was obtained.

1. Introduction

Magnesium alloys are candidates as structural materials due to their high specific strength and good damping capacity [1]. For example, when they are used as car parts, weight saving of the car body and reduction of fuel consumption can be expected, since they are the lightest among metals. Further, a better driving feeling can be obtained because oscillation of the car body can be reduced due to their good damping capacity. However, before utilizing magnesium alloys for machines and structures, a determination of fatigue lives and crack propagation behavior of the alloys at different load ratios is required.

There already have been a number of investigations concerning the fatigue properties of magnesium alloys. For example, Goodenberger and Stephens [2] have provided basic information concerning the fatigue behavior of the cast magnesium alloy, AZ91E-T6 in laboratory air. Hilpert and Wagner [3] have carried out experiments to determine the degree of degradation in fatigue resistance due to corrosion of the AZ80 magnesium alloy as a function of various surface treatments such as electro-polishing, grinding, machining and shot peening. Eiseneimer et al. [4] have studied the fatigue behavior of AZ91 magnesium alloy that had been processed using a vacuum die casting method. They reported that the fatigue cracks were initiated at casting defects in the material, and that the crack growth behavior was influenced by the microstructure of the material. Shih et al. [5] performed fatigue experiments on the extruded magnesium alloy AZ61A, and reported that fatigue cracks were initiated at surface or near-surface inclusions, and that the initial crack growth behavior was affected by the microstructure.

Until now, empirical relations, Gerber and Goodman diagrams have been utilized for evaluation of the effect of mean stress on fatigue lives, however, theoretical methods to analyze the effect of R ratios on the fatigue lives are very few and limited. McEvily et al. [6] proposed a modified linear elastic fracture mechanics approach. This method was originally developed to analyze both the long through and short fatigue crack propagation behavior. Then the method was shown to be able to predict crack growth behavior under multiple two-step loading condition [7] and in different materials [8–9].

In the present study, fatigue tests were conducted on an extruded magnesium alloy to investigate fatigue lives (S–N curves) and crack propagation behavior under different stress ratios, R. The modified linear elastic fracture mechanics approach was applied to analyze the crack propagation behavior of the extruded magnesium alloy AZ31 and to predict S–N curves at different R ratios. Comparison between experimental and calculated results reveals that the approach proposed by McEvily et al. [6] is effective and useful in analyzing the short fatigue crack propagation behavior at different R ratios including negative R ratios.
2. Material, specimens and experimental procedures

2.1. Material

The extruded magnesium alloy AZ31 was used in this investigation. Its chemical composition is listed in Table 1. A cylindrical billet with a diameter of 200 mm was extruded into a round bar with a diameter of 70 mm, an extrusion ratio of 10. Table 2 lists the extrusion conditions under which the alloy was processed. Fig. 1 shows the microstructure of the material used in the present study. The average grain diameter of the material after extrusion was 9 μm, and its aspect ratio was about 0.8.

2.2. Experimental procedures

2.2.1. Specimens and fatigue testing machine

In the present study two types of fatigue tests were used. Rotating bending fatigue tests (\( R = -1 \)) at 30 Hz and axial-load fatigue tests at 10 Hz were conducted in laboratory air at room temperature at stress ratios, \( R = 0.1, -1, \) and \(-2\). Fig. 2a and b shows the specimen shapes and dimensions of the rotating bending fatigue tests and axial fatigue tests, respectively. For the rotating bending fatigue tests, round bar specimens with a minimum diameter of 5.6 mm were used (stress concentration factor 1.04). For the axial-load tests, round bar specimens with a minimum diameter of 4 mm were used (stress concentration factor 1.06). The specimen surfaces were polished to a mirror-like finish using emery papers and diamond paste prior to fatigue tests to eliminate any effect of the roughness of the specimen surface on the fatigue results, and to facilitate the observations of crack propagation on the specimen surfaces. Monotonic tension and compression tests were also conducted using a similar specimen as shown in Fig. 1b. Its gauge length was 5 mm.

2.2.2. Fatigue crack propagation tests

2.2.2.1. Short surface crack.

The propagation rates of the short surface crack, crack propagation behavior of the long face cracks that initiated and propagated on the specimen surfaces during both the rotating bending fatigue process and the axial fatigue process were investigated using the replication technique. Crack opening stress intensity factor, \( K \), was also investigated using the round type compact tension specimens as shown in Fig. 3. Crack lengths were measured using a travelling microscope at a magnification of 40.

The following expression [12] was used for calculations of the stress intensity factor, \( K \)

\[
K = \frac{P}{tW^{1/2}} \times \left( \frac{2 + \pi}{\pi} \right) \left( 0.76 + \frac{4.8\pi}{7} \pi x_0 + \frac{11.43}{1} \pi x_0^2 - \frac{4.08}{1} \pi x_0^3 \right) \left( 1 - \pi x_0^2 \right)^{1/2}
\]

(2)

where \( x = a/W \), \( a \) is a crack length, and \( W \) is a specimen width.

Crack opening stress intensity factor, \( K_{op} \), during a loading cycle was determined based on the unloading elastic compliance method [13] by affixing strain gauges ahead of the crack tip.

3. Experimental results

3.1. Monotonic tension and compression tests

Fig. 4 shows the stress vs. strain relationships for both tension and compression tests. As can be seen from the figure, the yield strength under compression is lower than that for tension. Table 3 lists the mechanical properties of the material under tension and compression tests. In the compression tests, the specimen (4.5 mm in diameter and 8 mm in gauge length) used failed due to buckling at the maximum compressive load. A similar result was also reported by Muller and Muller [14]. They suggested that twinning is concerned with the above difference between the yield strength in tension and the one in compression, but a detailed mechanism is unknown at present.

3.2. Fatigue tests

3.2.1. S–N curves

Fig. 5a and b shows S–N curves for the different \( R \) ratios, \( R = 0.1, -1 \) and \(-2\). Those results were obtained from the axial fatigue tests and also from the rotating bending (RB) fatigue tests. In Fig. 5a and b, the maximum stress \( \sigma_{\text{max}} \) and stress amplitude \( \sigma_a \) are taken as the vertical axes, respectively. Similar S–N curves between the axial fatigue tests and the rotating bending fatigue tests are seen. S–N curves for \( R = -1 \) and \( R = -2 \) bend at \( 10^7 \)–\( 10^9 \) cycles. From Fig. 5a, the maximum stress \( \sigma_{\text{max}} \) at a constant fatigue life decreases with a decrease in the value of \( R \).

However, in Fig. 5b, the reverse is true, i.e., the stress amplitude \( \sigma_a \) at a constant fatigue life increases with a decrease in the \( R \) value.

The relationship between stress amplitude \( \sigma_a \) and mean stress \( \sigma_m \) was drawn using the data from Fig. 5. Fig. 6 shows the results.
We can see that the experimental data appear fit better with the Gerber diagram \[15\] represented by Eq. (3) rather than with the modified Goodman diagram \[15\] represented by Eq. (4). To extend this finding, the data for the magnesium alloy AZEM2230 and ZE41A obtained by Hotta and Saruki \[16\] were also plotted in Fig. 6b, where the vertical and horizontal axes are normalized by the tensile strength of the material, \(r_B\). Upon considering all data it is not possible to state that the relation \(r_a vs. r_m\) for the extruded magnesium alloy is categorically described by either the Gerber diagram or the modified Goodman diagram in view of the scatter. However, our experimental and theoretical results (Fig. 11) fit better with the Gerber diagram than with the modified Goodman diagram. To confirm this point, further experimental studies are needed.

\[
\begin{align*}
\sigma_a &= \sigma_w \left(1 - \frac{\sigma_m}{\sigma_B}\right)^2 \\
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### 3.2.2. Crack growth behavior

#### 3.2.2.1. Short surface crack growth behavior under rotating bending fatigue process, \(R = -1\).

Successive observations of the specimens surface during the fatigue process were performed to investigate the crack propagation behavior under the rotating bending fatigue tests of \(R = -1\).

The crack length, \(2a\), as a function of number of cycles \(N\) at stress amplitude of 150 MPa is shown in Fig. 7 for the two different cracks (solid and open circles). The crack represented by the solid mark coalesced with other cracks at about 50,000 cycles, showing a sudden increase in crack length at the point. As can be seen from the figure, cracks are initiated at an early fatigue stage, i.e., 5–10% of fatigue life. This result means that the total of fatigue life \(N_f\) can be approximated as the crack propagation life, \(N_p\).

### Table 3

**Mechanical properties.**

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3.2.2.2. Long through crack growth behavior, \( R = 0.1 \). Fig. 8a shows the relationship between the rate of crack propagation \( da/dN \) and stress intensity factor range \( \Delta K \) for the long through-thickness crack. In the figure, the relation \( da/dN \) vs. \( \Delta K \) is also plotted, where \( \Delta K_{\text{eff}} \) is the effective range of the stress intensity factor, i.e., \( K_{\text{max}} - K_{\text{op}} \), where \( K_{\text{op}} \) is the stress intensity factor at the crack opening level. The crack closure behavior was evaluated by using strain gauge attached ahead of the crack tip during fatigue crack propagation test based on the elastic compliance method [11]. From the figure, the threshold value \( \Delta K_{\text{effth}} \) can be estimated as 1.15 MPa m\(^{1/2}\).

The log–log plot between \( da/dN \) and \( \Delta K_{\text{eff}} - \Delta K_{\text{effth}} \) is shown in Fig. 8b. As can be seen from the figure, the relation can be represented by a straight line with a slope of 2, and therefore the following relation was obtained.

\[
\frac{da}{dN} = A(\Delta K_{\text{eff}} - \Delta K_{\text{effth}})^2
\]

where \( a \) is the crack length, \( A \) is a material-environmental constant equal to \( 4 \times 10^{-9} \) (MPa)\(^{-2}\).

4. Analysis of crack growth behavior based on the modified linear elastic fracture mechanics approach

In order to make use of Eq. (5) in the short crack range, modification is necessary since short fatigue cracks differ from large cracks in the following three aspects [17]:

(a) In the short crack regime, small scale yielding conditions are not applicable, and a modification for elastic–plastic conditions is needed.

Irwin [18] proposed that the linear elastic approach could be extended to include elastic–plastic behavior, i.e., those cases where the crack tip plastic zone size is large with respect to the crack length, by increasing the actual crack length, \( a \), by one-half of the plastic zone size. If the plastic zone size is taken to be that as defined by Dugdale [19], then the modified crack growth length, \( a_{\text{mod}} \), is given as

\[
a_{\text{mod}} = a + \frac{1}{2} \left( \sec \frac{\pi}{2} \frac{\sigma_{\text{max}}}{\sigma_Y} - 1 \right) = a + \frac{1}{2} \left( \sec \frac{\pi}{2} \frac{\sigma_{\text{max}}}{\sigma_Y} + 1 \right) = a F
\]

where \( \sigma_{\text{max}} \) is the maximum stress in a loading cycle, \( \sigma_Y \) is the yield strength, and \( F \) is termed the elastic–plastic correction factor.

(b) Crack closure in the wake of a newly formed crack is zero, but as the crack grows, the crack closure level increases to the level associated with a macroscopic crack in a distance of the order of 1 mm.

Fig. 8. Long through crack propagation behavior tested at \( R = 0.1 \).
The level of crack closure developed in the wake of a crack varies from zero for a newly formed crack up to $K_{opmax}$ for a macroscopic crack. The following expression has been proposed \cite{20} to describe this transient in crack closure behavior:

$$\Delta K_{op} = (1 - e^{-k(\theta)}) (K_{opmax} - K_{min})$$

(7)

where $\Delta K_{op}$ is the value of $K_{op} - K_{min}$ in the transient range, $k$ is a material constant (units m$^{-1}$) which determines the rate of crack closure development, and $\theta$ is the length of the newly formed crack (units m), and $K_{opmax}$ is the magnitude of the crack opening level associated with completion of the transient period of growth. The value of $\theta$ when $K_{opmax}$ is reached is generally less than a millimeter.

(c) In the very short fatigue crack growth range, the stress for propagation is controlled by the endurance limit of the material rather than by the long crack threshold condition (Kitagawa effect \cite{21}).

Irwin \cite{22} has shown that the stress intensity factor, $K$, is related to the stress concentration factor, $K_r$, by the following equation:

$$K = \lim_{p \to \infty} \sigma_m \frac{\pi \rho}{4} = \lim_{p \to \infty} K_r \sigma \sqrt{\frac{\pi \rho}{4}}$$

(8)

where $\rho$ is the tip radius of the stress concentrator, $\sigma_m$ is the maximum stress at the tip of the stress concentrator, and $\sigma$ is the remote stress. In order to achieve the desired transition between the threshold level for fatigue crack growth and the fatigue strength, Eq. (4) is modified as follows:

$$K = \lim_{p \to \infty} K_r \sigma \sqrt{\frac{\pi \rho}{4}}$$

(9)

where $\rho$ is a material constant.

In the case of a panel containing a central crack under Mode I loading, $K_r$ is equal to $K_T = \left(1 + \frac{2}{\sqrt{p}}\right)$, and Eq. (5) becomes

$$K = \left(\sqrt{\frac{\pi \rho}{4}} + \sqrt{\pi \rho a}\right) \sigma$$

(10)

The material constant $\rho_0$ is converted to an effective length dimension, $r_e$, by postulating the following relationship:

$$\sqrt{\frac{\pi \rho}{4}} = \sqrt{2\pi r_e}$$

(11)

so that $r_e$ is equal to $\rho_0/8$ in magnitude. (The left hand side of Eq. (7) is obtained by equating the stress intensity factor $\sigma \sqrt{2\pi r_e}$ to the LEFM stress intensity factor, $\sigma \sqrt{2\pi r}$. Therefore $r_e$ is the distance from the tip of the crack to the point where the two stress intensity factors are equal).

In this modified approach $r_e$ is considered to be the effective length of an inherent flaw. In this interpretation of $r_e$, a newly formed crack is only significant when its length exceeds $r_e$, since for crack lengths less than $r_e$, the stress intensity factor associated with $r_e$ will be larger. It is pointed out that there is no relationship between $r_e$ and an actual defect. It is merely an adjustable parameter introduced, in order to deal with the Kitagawa effect in a quantititative manner.

The driving force for fatigue crack growth, $\Delta K$, is now generalized to take into account in geometries other than just the center-cracked panel, as well as possible elastic–plastic effects, as

$$\Delta K = \left(\sqrt{2\pi r_e F} + Y \sqrt{\pi a F}\right) \Delta \sigma$$

(12)

where the value of $Y$ depends upon the crack-shape. It is assumed that the initial crack-shape is semi-circular, then the value of $Y$ is 0.73 \cite{11}. The magnitude of $r_e$ is of the order of one micron. Its value is determined by setting a equal to $r_e$. $\Delta K$ equal to the effective range of the stress intensity factor at the threshold level, $\Delta K_{effth}$, which is taken to correspond to a crack growth rate of $10^{-11}$ m/cycle, and $\Delta \sigma$ equal to the stress range at the fatigue strength level, $\Delta \sigma_{EL}$ (10$^7$ cycles), i.e.,

$$r_e = \frac{[\Delta K_{effth}]}{\Delta \sigma_{EL}} \left[\frac{1}{2F(1 + \sqrt{2Y + 0.5Y^2})}\right]$$

(13)

With these modifications, Eq. (5) is written as

$$\frac{da}{dN} = A \frac{[\Delta K_{effth}]}{\Delta \sigma_{EL}(\Delta K_{effth} - (1 - e^{-\gamma})(K_{opmax} - K_{min}))(\Delta K_{effth})^2}$$

Eq. (14) can be written in simplified form as

$$\frac{da}{dN} = AM^2$$

(15)

where $M$, the net driving force for fatigue crack propagation, is the quantity within brackets in Eq. (6). Eq. (15) will be used in the following analyzes.

The rate of fatigue crack propagation in the present extruded magnesium alloy was analyzed using the $M$ parameter in Eq. (15). The values of parameters used for calculating $M$ are listed in Table 4. The values of $K_{opmax}$, $\Delta K_{effth}$, and $k$ were determined on the experimental data on the present extruded magnesium alloy AZ31 for the long through crack. The value of tensile strength $\sigma_y$ was used instead of the yield strength $\sigma_y$ for the calculations of $M$ at high $R$ ratios.

Fig. 8 shows the log–log plot of the relation of $da/dN$ and $M$ for the short surface cracks. The data were obtained by the axial fatigue tests ($R = -1$ and $-2$) as well as the rotating bending fatigue tests ($R = -1$). For the case of $R = -2$, the values of $M$ were calculated using the compressive yield strength, $\sigma_y = 123$ MPa instead of the tensional yield strength, since the mean stress is compression for the case. In the figure, $da/dN$ vs. $\Delta K_{effth} - \Delta K_{effth}$ for the long through crack is also plotted for a comparison. As can be seen from this figure, no difference between the both relations can be seen (see Fig. 9).

In accord with Eq. (15), the value of the slope was set at 2. The relationship between $da/dN$ and $M$ can be expressed as

$$\frac{da}{dN} = 4 \times 10^{-9} \ M^2$$

(16)

5. Estimation of $S$–$N$ curves on the basis of the relation $da/dN$–$M$

It is possible to regard crack propagation life $N_p$, as equal to that of total fatigue life $N_T$, because the fatigue crack initiates early in the fatigue process. Crack propagation life can be estimated by numerically integrating Eq. (16) from an initial crack length $2r_e$ to a final crack length of 4 mm.

However, when we calculated the $M$ parameter for the case of $R = -2$ using the yield strength in tension rather than the yield strength in compression, the predictions disagreed with the experimental values. This disagreement between the estimated fatigue lives and experimental values is due to the large difference
between the tensile yield strength and the compressive yield strength, as shown in Fig. 4. Similarly, during fatigue cycling, the cyclic yield strength is also expected to be lower in the negative $R$ ratio region due to the occurrences of the twinned crystals introduced under compression. Better agreement was obtained when the compressive yield strength was used.

Fig. 10 compares the predicted and experimental behavior. As seen from the figure, the predicted $S$–$N$ curves agree well with the experimental data for a wide range of $R$ ratios, $R = -2$ to 0.1, with the yield strength in compression being used for $R = -2$. The yield strength in tension was used for other $R$ values.

Comparisons of the predicted results with the experimental ones were also made with respect to $\sigma_m$ vs. $\sigma_a$ where $\sigma_m$ indicates mean stress, and $\sigma_a$ means stress amplitude. The results are shown in Fig. 11, where three fatigue lives, i.e., $10^6$–$10^7$ cycles, $10^5$ cycles, and $10^4$ cycles are taken as parameters. Again, we can confirm that the predictions based on the $M$ parameter agree well with the experimental data, from the low cycle region, $10^3$–$10^5$ to the high cycle region, $10^6$–$10^7$.

In general the use of the modified linear elastic fracture mechanics parameter, $M$ is effective and useful for the analysis of the short fatigue crack propagation behavior as well as for predicting $S$–$N$ curves of the extruded magnesium alloy. However, for the case of the negative $R$ region of the alloy, the yield strength in compression should be used when analyzing short fatigue crack propagation based on the $M$ parameter. Further studies are needed to clarify the crack propagation behavior under the negative $R$ regions.

6. Conclusions

Fatigue tests were conducted using the extruded magnesium alloy AZ31 to determine the effect of load ratio on the fatigue lifetime. The following conclusions relating to extruded magnesium alloy AZ31 were reached:

(1) Fatigue cracks are initiated at an early fatigue stage, i.e., 5–10% of fatigue life, indicating that total of fatigue lives $N_f$ can be approximated as the crack propagation lives, $N_p$.

(2) The effect of mean stress on the fatigue strength was given approximately by the Gerber relationship. Further experimental studies are needed to confirm the above result.

(3) The modified linear elastic fracture mechanics parameter, $M$ is useful in the analysis of the short fatigue crack propagation behavior and for predicting the $S$–$N$ curves of the AZ31 extruded magnesium alloy.

(4) For the case of the negative $R$ ratios such as $R = -1$ and $R = -2$, compressive yield strength should be used in analyzing short fatigue crack propagation and in predicting the $S$–$N$ curves based on the $M$ parameter.

(5) Further studies are needed to clarify the crack propagation behavior at the negative $R$ regions.

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