Effect of test frequency on fatigue strength of AZ31 alloy

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Abstract. Investigation of fatigue strength of extruded AZ31 magnesium alloy was performed by ultrasonic fatigue tests (test frequency about 19500Hz) and taken to compare with conventional tension-compression fatigue tests (20Hz). The fatigue life under ultrasonic loading exhibits longer than the conventional one. Effects of ultrasonic frequency on the S-N curve, crack initiation and growth behaviour of AZ31 alloy is discussed. This work would be useful for improving the ultrasonic fatigue test method to observe the fatigue behaviour in very high cycle regime.

1. Introduction

In recent years, especially since the beginning of the new century, magnesium alloys so called “the 21th century’s engineering materials” which are the lightest commercial structural alloys attract many interests. With high specific strength, high stiffness ratio, good heat dissipation, good damping capability and recycling ability, these alloys have a good prospect application for automobile and aerospace structural parts as we know the engine, power transmission and car body.

During their lifetime, some of the components have to survive more than $10^8$ cycles. Therefore, fatigue strength and fracture mechanism of the alloys in very high cycle regime are of tremendous interest [1, 2]. On the other hand, significant improvements have been achieved for pursuing accelerated fatigue tests under ultrasonic resonance. For this reason, ultrasonic method is increasingly applied in order to investigate fatigue lives at very long cycle regime and explore the crack propagation behaviour [3, 4], where experiments by conventional machines are time-consuming and expensive. However, the influence of ultrasonic frequency on small crack behaviour in magnesium alloys has not been adequately studied for the prediction of fatigue damage. It is dangerous especially at giga-cycle fatigue life region [5]. Nowadays the continuum damage mechanics approach with numerical simulation is widely applied for studying the fatigue behavior [6-11]. The comparison between the estimated crack initiation by numerical models developed with the Finite Element Analysis (FEA) and the total experimental lifetime can be used to evaluate the effect of the frequency between ultrasonic and conventional fatigue test. This valuable method is considered a feasible and effective for the future work of this study.
The objective of the present study is, therefore, to investigate the fatigue strength and the small crack behaviour of extruded AZ31 magnesium alloy in the very high cycle domain under ultrasonic fatigue. The effects of frequency on the small crack behaviour and fracture mechanism are evaluated by comparing the results with those under conventional fatigue.

2. Materials and Methods

2.1. Ultrasonic fatigue test method

Schematic figure of principle of our test system is shown in Fig.1. Firstly, the power generator converts 50 or 60 Hz voltage signal into 19.5 kHz ultrasonic electrical signal. The electrical signal turns to mechanical vibration with longitudinal ultrasonic waves in the same frequency by piezoelectric converter inside the power generator. The mechanical displacement is induced to generate the stress amplitude. In this case, the specimen is designed with first mode frequency of 19.5 kHz, which is related to the specimen length. With applying this resonant vibration, the specimen gets a maximum displacement at the end and maximum stress in the central section. Finally, an ultrasonic horn and cone that amplifies the mechanical vibration generating from the converter in order to obtain the required stress amplitude in the middle section of the specimen. The stress amplitude is pre-selected and kept constant during the test.

Schematic diagram of our test system is shown in Fig. 2. There are also other devices composing the ultrasonic fatigue test machine. They are mainly divided into two parts: the recording system which includes control unit and cycle counter; the measuring system which includes the displacement sensor and thermometer. This test machine allows testing load ratio of $R = -1$.

![Figure 1. Schematic illustration of ultrasonic fatigue test.](image1)

![Figure 2. Schematic diagram of ultrasonic fatigue test system.[12](image2)

2.2. Material and experimental

The material used was a extruded magnesium alloy AZ31 with a chemical composition (in wt. %) of 3.05Al, 1.04Zn, 0.39Mn, and balance Mg. Yield stress (0.2% proof stress), $\sigma_y$ and tensile strengths at room temperature were 197 MPa and 286 MPa, respectively, and the elongation was 5.07%. The mean grain size of the alloy was 16.1 μm.

The ultrasonic fatigue system was tuned to resonate at a frequency of ~19.5 kHz. A longitudinal standing wave was excited in a circular taper dumbbell specimen, introducing a sinusoidal, cyclic loading along the specimen with the maximum displacement (the minimum stress amplitude) at either end of the specimen and a displacement node (the maximum stress amplitude) in between, as shown in Fig. 1. The maximum stress amplitude is obtained at the displacement node of the specimen, which can be calculated from the maximum displacement at the free end of the specimen, and the dynamic Young's
modulus of the alloy. The displacement is measured by LK-G5000 laser sensor by Keyence Corporation. The dimensions of the fatigue test specimen are shown in Fig. 3.

Prior to fatigue testing, the curved surface of the specimens are polished by ~20 μm in depth after emery paper grinding in order to remove worked layer and to better observe surface damage. The observation of fatigue damage and the measurement of surface crack length are conducted directly under an optical microscope or under a scanning electron microscope (SEM). The crack length was defined vertical to the loading direction on the specimen surface.

To minimize internal friction induced temperature rise, ultrasonic fatigue tests were performed in a pulse-pause manner with pulse length varied in a range of 100 ms and pauses 3000 ms. The surface temperature at the most stressed node section of the specimen was monitored during the tests using an infrared thermal tracer. The maximum temperature rise is controlled below 3 °C during the testing. The influence of pulse-pause loading on the fatigue strength of the alloy was ignorable. Fatigue tests were carried out at ambient temperature under a load ratio of $R = -1$.

![Figure 3. The geometries of the fatigue test specimen. (mm).](image)

### 3. Results and Discussion

#### 3.1. Relationship between stress and fracture life

![Figure 4. S-N plot of extruded AZ31 in ultrasonic fatigue tests. Results of conventional axial tension compression test of 20 Hz [13] are also plotted for comparison.](image)

Fig. 4 shows the fatigue life of extruded AZ31 alloy under ultrasonic loading, the circular one represents data of present work. The triangle one represents data of Shiozawa [13] with extruded AZ31 alloy under conventional axial tension compression loading with 20 Hz and a load ratio of $R = -1$. For the material
used in current research and Shiozawa’s work, the yield stress $\sigma_b$ are 197 MPa and 209 MPa, respectively [13]. Strength of the materials in these two work has a little bit different. In order to get a better comparison, the ratio of $\sigma_m/\sigma_b$ is used to present the fatigue strength, where $\sigma_m$ is the stress amplitude. Fatigue strength of current work is greater than the conventional one. It shows the existence of the effect of ultrasonic frequency. Shiozawa’ data appears to have a continuous decreasing trend in the very high cycle regime and it exhibits a step-wise behaviour [13]. In case of present work, the plots shows a continuous decreasing trend insufficiently.

In the cyclic loading of $10^6$ to $10^7$ cycles, there is no fatigue limit which different from the traditional fatigue test data, parts of the samples cracks after $10^8$ cycles in Shiozawa’s work. For present work, one sample which under 136 MPa ultrasonic loading, undergone near$10^8$ cycles.

The fatigue strength exhibited in present work is larger than that of conventional data. The effect of loading frequency on the fatigue behaviour is considered to be obvious when the yield stress ratio ($\sigma_m/\sigma_b$) is smaller than 1.2 [14]. The reason is due to the behaviour of cyclic hardening and softening of the metallic materials [14]. The yield stress ratio of magnesium alloy always smaller than 1, and the ratio of the two materials compared in this paper is 0.69 (material used for ultrasonic test in present work) and 0.9 (conventional test alloy), respectively. These materials have a behaviour of cyclic softening and the frequency effect is remarkable. Besides, another major frequency effect is the temperature increasing caused by the plastic deformation under high frequent loading. In the present study, the specimens are cooled by the pulse-pause manner of the test machine. The influence of temperature on fatigue strength is considered to be limited. Other factors of the frequency effect need further investigation.

3.2. Crack growth behaviour

![Figure 5. Crack length a vs. number of cycles](image1)

![Figure 6. Crack length a vs. fatigue ratio N/Nf](image2)

Fig. 5 shows the relationship of the crack length and number of cycles with different load stress of 136 and 168 MPa. The crack grows much faster under the higher stress. After the crack grow to 1 mm, the crack growth rate gets a remarkable increasing, irrespective to the loading stress. For both higher and lower stress, the crack initiated at the early stage of fatigue cycle. The relationship of the crack length and the ratio of number of cycles to whole lifetime cycles (Fig. 6) shows crack propagation period (crack length $\leq$ 1 mm) takes up more than 80% of the total fatigue life, and then in the rest of less than 20% life, the crack grows from under 1 mm to near 10mm rapidly. The fracture observation shows no notable difference in different load stress (136 MPa and 168 MPa).

3.3. Fracture surface

After testing, the fractured sample takes to observation by scanning electronic microscope (SEM). Fig.7 shows the scanning electronic micrographs of the fracture surface of specimen at 124 MPa cyclic loading.
which survived more than $10^7$ cycles. An interior crack initiation site was observed, and it is different from the lower cycle fatigue crack behaviour which is rarely observed of interior crack initiation. It turned out that it would be important to investigate the very high cycle fatigue behaviour of AZ31 alloy, which may surfer up to $10^8$ or $10^9$ stress cycling in the service life of the structural components. The crack initiation mechanism may change from the surface initiation to interior initiation.

![Figure 7. Scanning electronic micrographs of fracture surface of specimen with interior crack. $\sigma_m=124$MPa, $N_f=9.32*10^7$ cycles.](image)

4. Conclusion
The fatigue test of an AZ31 extruded magnesium alloy in the long lifetime regime conducts at ultrasonic frequency at room temperature. The fatigue behaviour and crack propagation are examined and compared. For this study, the following conclusions can be drawn.

1. Loading frequency affects the fatigue strength of this extruded magnesium alloy.
2. Interior crack was recognized in the specimen which did not fail after cycling near $10^8$ cycles, implying that the importance to investigate interior crack initiation in the very high cycle fatigue region.
3. Cracks initiated at the very beginning of fatigue cycling and the suppression of early crack propagation becomes significant under low stress levels. It is fund that more than 80% of total fatigue life is consumed in nucleating and growing cracks smaller than 1 mm.

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