Constant ΔK Fatigue Crack Growth Tests under Programmed Humidity Cycle Conditions—As a Tool to Evaluate the Effect of Humidity on Fatigue Crack Growth of Al–Li Alloys—

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The effect of the relative humidity of the laboratory air on the fatigue crack growth rate in 8090 Al–Li alloys has been examined. The constant ΔK fatigue crack growth tests under programmed humidity cycle conditions were carried out to quantify the extent of the increase in fatigue crack growth rates due to the relative humidity. The obtained results are compared to the da/dN – ΔK relationships obtained from the constant amplitude dynamic load fatigue crack growth tests. It was found that the intrinsic fatigue crack growth rate increase with the relative humidity, but the extent of the increase was found to be considerably small compared to the growth rate difference between the laboratory air and vacuum conditions. The constant ΔK test at a high stress ratio under programmed humidity cycle conditions was effective for detecting the relatively small humidity effect on the fatigue crack growth rate.

KEY WORDS: Al–Li alloy; fatigue crack growth; humidity; constant ΔK test; crack closure.

1. Introduction

Fatigue crack growth in metallic materials is affected by the loading conditions, the microstructure and the test environment. The effects of the test environment have been examined in terms of corrosion fatigue under corrosive conditions, such as in aqueous solution or salt water.^{1–7)} Recently, fatigue crack growth tests have been carried out in inert atmospheres or vacuum conditions in order to examine the basic mechanism of fatigue crack growth.^{1,2)} The results of these tests suggest that laboratory air is a relatively corrosive environment compared to an inert gas atmosphere or a vacuum.

The extent of the effect of a gaseous environment depends on the combination of gases and materials, and the partial pressures of the gases. For example, it has been reported that the fatigue crack growth rates for steels and titanium alloys are increased in hydrogen atmosphere due to hydrogen embrittlement. In contrast, the fatigue crack growth rates for aluminum alloys do not increase in hydrogen gas, but increase in water vapor.^{5–7)} This is believed to be due to hydrogen embrittlement in the fatigue crack tip region. The hydrogen is produced by the reaction between water vapor and the virgin metal surface created at the crack tip following cyclic plastic deformation, and it penetrates

into the plastically deformed region at the crack tip. This effect is a problem, particularly in fatigue crack growth in high-strength aluminum alloys used in aircraft. Therefore, it is crucial to examine the effect of humidity, *i.e.*, the quantity of water vapor in laboratory air, on the fatigue crack growth rates for these alloys.

Al–Li alloys with low density, high modulus and high strength are attractive replacements for conventional high-strength aluminum alloys such as the 2xxx and 7xxx series. Over the past ten years, it has been reported that commercial Al–Li alloys have superior fatigue crack growth resistance. This is due to the enhanced roughness-induced crack closure effect, resulting from the tortuous fatigue crack growth path. The origin of the tortuous crack path morphology is considered to be the preferential crack growth along the (111) slip plane. This was demonstrated by carrying out a fatigue crack growth test in a vacuum. However, the fatigue fracture surface produced by fatigue crack growth in a water vapor atmosphere is reported to be a mixture of (110), (100) and (111) planes.²⁾ This indicates that water vapor changes the crack growth path, and consequently controls the magnitude of roughness-induced crack closure and the resultant fatigue crack growth rates. Therefore, in order to examine the effect of humidity (water vapor) on the fatigue crack growth rate we should distinguish

intrinsic effects such as hydrogen embrittlement at the crack tip from extrinsic mechanistic effects such as crack deflection and the resultant roughness-induced crack closure.

The effect of humidity on the fatigue crack growth rate can be quantified using the $da/dN-\Delta K_{\text{eff}}$ relationship, which is obtained from the constant amplitude dynamic load fatigue crack growth tests and crack closure measurements in the laboratory air with the fixed relative humidity conditions. The constant amplitude dynamic load fatigue crack growth test at a high stress ratio, in which the roughness-induced crack closure effect is considered to be negligible, can also provide the data concerning the intrinsic humidity effect. However, the extent of the humidity effect is considered to depend on the ΔK levels since the quantity of the virgin metal surface created at the crack tip, which is concerned with the reaction with water vapor is a function of the ΔK at the crack tip.

Therefore, the constant ΔK fatigue crack growth test is considered to be the most straightforward testing method for the present purpose. However, a number of fatigue crack growth tests must be carried out under fixed humidity conditions in order to examine the dependence of the fatigue crack growth rate on the humidity. An alternative method is to keep the fatigue crack growth rate constant using the constant ΔK conditions and change the humidity conditions systematically during the test.

The purpose of the present study is to examine the effect of the relative humidity of the laboratory air on the fatigue crack growth rate in 8090 Al-Li alloys. The constant ΔK fatigue crack growth tests are carried out under programmed humidity cycle conditions to quantify the extent of the increase in fatigue crack growth rates due to the relative humidity. The results are compared to the $da/dN-\Delta K$ relationships obtained from the constant amplitude dynamic load fatigue crack growth tests in the humid laboratory air or vacuum conditions.

2. Experimental Procedures

2.1. Materials

8090 Al-Li alloys (the Al-Li-Cu-Mg-Zr system), obtained from Alithium, Japan, was used in this study. The chemical composition is as follows: Li 2.61, Cu 1.25, Mg 0.87, Fe 0.05, Si 0.03, Zr 0.12 and Al balance (in mass%). The alloy was subjected to a two-step heat-treatment process at 723 K for 24 h and 813 K for 6 h, and then hot-rolled to form a plate 22 mm thick at an initial temperature of 753 K. The plate was solution treated at 793 K for 1 h, water quenched and then stretched by 2.4%. The alloy was peak-aged at 423 K for 24 h. **Figure 1** shows a three-dimensional optical micrograph of the grain structure of a sample taken from the mid-thickness area of the plate. The grain structure is highly anisotropic and the grains are typically 1 000 μm long, 100 μm wide and 10 μm thick. The $\{111\}$ pole figure for the mid-thickness region indicated that the material has a predominantly brass-type texture. The uniaxial tensile properties (longitudinal L direction) were

Fig. 1. A three dimensional optical micrograph of the grain structure machined from the mid-thickness area of an 8090 Al-Li alloy plate.

Fig. 2. Geometry of the CT specimen (a) and the orientation of CT specimens in the L-T and T-L orientations (b).

as follows: 0.2 % proof stress, 416 MPa; UTS, 511 MPa; elongation to fracture, 6.1 %.⁸⁾

2.2. Fatigue Crack Growth Tests

1) Specimens

Compact tension (CT) specimens, with a thickness (B) of 8.5 mm and a width (W) of 30 mm were machined from the mid-section of the plate in the L-T and T-L orientations as shown in **Fig. 2**.

2) Constant Amplitude Dynamic Load Fatigue Crack Growth Tests

To obtain the basic $da/dN-\Delta K$ relationships, constant amplitude dynamic load fatigue crack growth tests were

Fig. 3. A block diagram of the fatigue crack growth testing system.

performed, in general accordance with ASTM E647-93, using a closed-loop servo-hydraulic testing machine with load control. All tests were performed under sinusoidal loading at a frequency of 10 Hz with a stress ratio of $R=0.1$ or $R=0.8$. The testing temperature was 296 K. The tests were carried out in the fixed relative humidity condition or vacuum. The humidity control procedure is described later. The tests in vacuum was carried out in dynamically pumped vacuum (6.0×10^{-5} Pa) using the closed-loop servo-hydraulic testing machine equipped with a vacuum chamber. The crack length was monitored using a direct current potential drop apparatus equipped with a polarity switching facility in order to eliminate any thermoelectric effects. An on-line, interactive computer system was used to control the test conditions and to record fatigue crack growth rate (da/dN) vs. ΔK data. A block-diagram of the experimental system is shown in Fig. 3.

3) Crack Closure Measurements

The crack closure was evaluated by measuring the crack opening displacement (COD) using a clip gauge. During the closure measurements the frequency was reduced to 0.1 Hz. The load-COD relationship was measured at various ΔK levels during the fatigue crack growth tests.

4) Constant ΔK Fatigue Crack Growth Tests under Controlled Relative Humidity Conditions

The constant ΔK fatigue crack growth tests were performed by reducing the amplitude of the dynamic load to keep ΔK constant as the crack length increased. The tests were carried out under sinusoidal loading at a frequency of 10 Hz with a stress ratio of $R=0.8$.

2.3. Control of the Relative Humidity of the Laboratory Air

The relative humidity of the laboratory air was controlled during the fatigue crack growth tests using the experimental cell shown in Fig. 4. A humidity generator (SRH-1R 135-TKD, Shinei Ltd., Japan) was set up-stream of the cell. Air with a controlled relative humidity was produced using the humidity generator and intro-

Fig. 4. An experimental apparatus for control of the relative humidity of the laboratory air.

duced into the cell. The relative humidity was measured at the outlet of the cell down-stream of the air flow using an electric capacity hygrometer. For the lowest humidity conditions the air from the humidity generator (below 1% RH) was introduced into a cold trap (203 K) and then reintroduced to the cell. In this case the hygrometer indicates the 0% RH reading because the lower limit of the reading of the electric capacity hygrometer used in the present study is 0.1% RH. This means that the relative humidity should be below 0.1% RH. Hereafter this condition is called "0% RH" just for convenience.

3. Results and Discussion

3.1. The Effect of Specimen Orientations on the da/dN - ΔK and da/dN - ΔK_{eff} Relationships

The da/dN - ΔK curves for T-L and L-T specimens, obtained at 30% RH, are shown in Fig. 5. The two curves are similar when the ΔK is above $6 \text{ MPa}\sqrt{\text{m}}$. Below this value, in the near-threshold regime, the L-T specimen exhibits slower growth rates than the T-L

Fig. 5. The da/dN - ΔK relationships for the T-L and L-T specimens obtained by constant amplitude dynamic load fatigue crack growth tests. ($R=0.1$, 296 K, 30% RH)

specimen.

The da/dN - ΔK curves were converted to da/dN - ΔK_{eff} curves ($\Delta K_{eff} = K_{max} - K_{cl}$) using the K_{cl} values obtained from the crack closure measurements. The da/dN - ΔK_{eff} curves are shown with the original da/dN - ΔK curves in Fig. 6. These curves show that the intrinsic fatigue crack growth rates, from which the contribution of roughness-induced crack closure is excluded, are comparable for the L-T and T-L specimens.

Even if the crack growth path profile is changed due to the humidity effect, thus altering the effect of roughness-induced crack closure, on the crack growth rate, the obtained da/dN - ΔK_{eff} curves reflect only the intrinsic fatigue crack growth rate. We can assess the effect of relative humidity on the fatigue crack growth rate using da/dN - ΔK_{eff} curves. In order to know the extent of the humidity effect on the fatigue crack growth rate a number of constant amplitude dynamic load fatigue crack growth tests must be carried out under fixed relative humidity conditions. It is not difficult to produce the relative humidity condition of over 20% RH. However, because of the limited ability of the humidity generator we found that the long-running fatigue crack growth tests at the fixed low humidity condition is quite difficult; the desiccant for producing the dry air saturates after 70 h operation. The restoration to recover the desiccant requires at least 5 h. Therefore, it was hard to obtain the reliable da/dN - ΔK curves over the wide range of ΔK at the low relative humidity conditions.

3.2. The Constant Fatigue Crack Growth Rate at the Fixed Relative Humidity Condition

An alternative method to examine the dependence of the fatigue crack growth rate on the relative humidity is to keep the fatigue crack growth rate constant using an experimental method based on the fracture mechanics. Under such conditions, the effect of relative humidity on the fatigue crack growth rate can be determined by changing the relative humidity systematically. The first thing that needs to be done in order to make this method viable is to eliminate the effect of roughness-induced

Fig. 6. The da/dN - ΔK relationships for the T-L and L-T specimens obtained by constant amplitude dynamic load fatigue crack growth tests, and the converted da/dN - ΔK_{eff} relationships using the measured crack closure stress intensity levels. ($R=0.1$, 296 K, 30% RH)

Fig. 7. Constant fatigue crack growth rates (da/dN) obtained by the constant ΔK fatigue crack growth test at the fixed humidity condition. ($\Delta K=2.5 \text{ MPa}\sqrt{\text{m}}$, $R=0.8$, 296 K, 60% RH)

crack closure. It is well known that the contribution of roughness-induced crack closure to fatigue crack growth is small at stress ratios above 0.5.

In the present study, the stress ratio was fixed at 0.8; under these conditions, the roughness-induced crack closure should be negligible. In addition, relatively small ΔK values were chosen in order to suppress the contribution of the monotonic fracture mode, which is believed to operate under high K_{max} conditions.

Figure 7 shows the relationship between the crack growth rates and the crack length from the starter notch during the constant ΔK fatigue crack growth test at the ΔK of $2.5 \text{ MPa}\sqrt{\text{m}}$ for the 60% RH condition. The crack growth rate is kept constant very well during the test at the fixed relative humidity condition.

3.3. The Fatigue Crack Growth Rate under Programmed Humidity Cycle Conditions

The relative humidity was increased step by step or continuously during the constant ΔK test and the resultant increase of the fatigue crack growth rate was ex-

Fig. 8. Effects of relative humidity on the fatigue crack growth rates. ($\Delta K = 2.5 \text{ MPa}\sqrt{\text{m}}$, $R = 0.8$, 296 K)

Fig. 10. Effects of relative humidity on the fatigue crack growth rates under programmed humidity cycle conditions. ($\Delta K = 5.0 \text{ MPa}\sqrt{\text{m}}$, $R = 0.8$, 296 K)

Fig. 9. Effects of relative humidity on the fatigue crack growth rates under programmed humidity cycle conditions. ($\Delta K = 2.0 \text{ MPa}\sqrt{\text{m}}$, $R = 0.8$, 296 K)

Fig. 11. da/dN - ΔK relationships obtained under the vacuum condition and 80% RH laboratory air. ($R = 0.8$, 296 K)

aminated. The results obtained are shown in Fig. 8. The relative humidity values and the corresponding fatigue crack growth rates are plotted as functions of the crack length. The results clearly show that the fatigue crack growth rate increases with the relative humidity, and that a constant crack growth rate is obtained at a fixed relative humidity. However, the increment is found to be considerably small.

Figure 9 shows the da/dN -crack length relationship under programmed humidity cycle conditions. Since the applied ΔK is smaller than that in Fig. 8 the decreased crack growth rates are exhibited. Comparison between the humidity and the crack growth rate suggest that the change in crack growth rate is synchronized with the change in the relative humidity.

Figure 10 also shows the da/dN -crack length relationship under programmed humidity cycle conditions obtained at a relatively high ΔK of $5.0 \text{ MPa}\sqrt{\text{m}}$. The crack growth rates scatter largely in this condition. However, it is clearly demonstrated that the change in crack growth rate is synchronized with the change in the relative humidity.

3.4. Comparison of the Fatigue Crack Growth Rate among the Dry Air, Humid Air and Vacuum Conditions

The da/dN - ΔK curves obtained in the humid laboratory air (80% RH) and in vacuum are shown comparatively in Fig. 11. Both curves were obtained by the constant amplitude dynamic load fatigue crack growth tests at a stress ratio of 0.8, under the roughness-induced crack closure free condition. Significant increase in the crack growth rate is exhibited in the humid air.

The da/dN - ΔK_{eff} curve (previously appeared in Fig. 6) and the crack growth rates obtained under the constant ΔK condition (Figs. 8, 9 and 10) are shown with the two da/dN - ΔK curves in Fig. 12. Increased crack growth rates are observed for the da/dN - ΔK curves obtained at $R = 0.8$ at higher ΔK range compared to the da/dN - ΔK_{eff} of $R = 0.1$. This is due to the contribution of monotonic fracture mode which operates at high K_{max} conditions. The extent of the increase in fatigue crack growth rate due to the increase in relative humidity of the laboratory air is rather smaller compared to the difference between two extreme conditions, humid air and vacuum. The difference in the crack growth rates

Fig. 12. Effects of relative humidity on the fatigue crack growth rates. Obtained results exhibited in Figs. 6, 8, 9, 10 are shown collectively for comparison.

between the dry (near 0 % RH conditions) and humid air is less than one order. It is considered that the increment of the fatigue crack growth rate decreases as increase in the relative humidity, *i.e.*, the effect of humidity tends to saturate. Piascik and Gangloff^{1,2)} compared fatigue crack growth rates of 2090 Al–Li alloys in vacuum, water and moist air. In their work constant K_{max} fatigue crack growth tests were carried out in order to eliminate the effect of roughness-induced crack closure. Their results show that the crack growth rates in moist air are about four times larger than those in vacuum. They also reported that the crack growth rates in water are ten times larger than those in vacuum. The extent of crack growth rate increase attained in our experiments is comparable to their results. They performed constant K_{max} tests under constant humidity conditions. The interesting trial which

was made in the present study is to change the humidity cyclically. Using this method we could demonstrate a comparatively small change in the crack growth rate depending on the humidity condition of the laboratory air. The obtained results also show that the change in the crack growth rate is synchronized with the change in the relative humidity.

4. Conclusions

The extent of the increase in fatigue crack growth rates due to the increase in relative humidity of the laboratory air was examined for 8090 Al–Li alloys. The intrinsic fatigue crack growth rate increase as increasing the relative humidity of the laboratory air. But the extent of the increase was considerably small compared to the growth rate difference between the laboratory air and vacuum conditions. The constant ΔK test at a high stress ratio under programmed humidity cycle conditions was effective for detecting the relatively small humidity effect on the fatigue crack growth rate in the present study.

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