The 22nd Conference of Mechanical Engineering Network of Thailand
15-17 October 2008, Thammasat University, Rangsit Campus, Pathum Thani, Thailand

Fatigue Crack Growth Behavior of Magnesium Alloy AZ61 under Corrosive Environment

Montra Permsub[1*], Supachai Surapunt[1], Shaifulazuar Bin Rozali[2], Kohsoku Nagata[3] and Yoshiharu Mutoh[3]

[1] Department of Industrial Engineering, Faculty of Engineering, Thammasat University
Khlong Luang, Pathum Thani 12121, Thailand
*E-mail: montra_permsub@hotmail.com
[2] Department of Materials Science, Nagaoka University of Technology, Nagaoka-shi, Japan
[3]Department of System Safety, Nagaoka University of Technology, Nagaoka-shi, Japan

Abstract

Fatigue crack growth tests of AZ61 magnesium alloy were carried out under low humidity environment without corrosion influence and 3.5% NaCl spray environment to investigate corrosion fatigue crack growth behavior and effect of stress ratio. The crack growth curves arranged by ΔK_{eff} showed the one curve regardless of stress ratio under low humidity. However, those under 3.5% NaCl spray environment did not show the unique curve but the different curves depended on the stress ratio and the kind of test (ΔK-decreasing and ΔK-increasing tests). Influence of corrosion environment on crack growth behavior was observed: lower ΔK_{th} and lower crack growth resistance under corrosion environment.

Keywords: Corrosion fatigue, fatigue crack growth, stress ratio, magnesium alloy

1. Introduction

Magnesium alloy is one of the most attractive structural materials with light weight, which is increasingly applied to electronic products, automotive vehicles, etc. Poor corrosion resistance of magnesium alloys is also known as one of the principal drawback of these alloys for wide applications in various fields. This is due to the high chemical activity of magnesium which in many cases leading to the low corrosion resistance.

The lightweight property of magnesium alloys could reduce the total weight of the automobile up to 20%. This will substantially increase the efficiency of fuel consumption in automobile and at the same time reduce the CO_2 emissions. Therefore, the automobile industry is and will continue to be the most important consumer of magnesium alloys.

Since many mechanically loaded parts such as in automobile are often subjected to prolonged cyclic stresses in corrosive medium, it is very important to understand the corrosion fatigue behavior of magnesium alloys. Many researchers reported the reduction of fatigue strength and life of magnesium alloys under corrosive environment [1- 4]. However, most of research works on corrosion fatigue of magnesium alloys has been limited to the evaluation of fatigue strength using smooth specimen. Detailed corrosion fatigue crack propagation behavior and effects of frequency, stress ratio, etc. have not yet been fully understood.

The aim of present study is to investigate the fatigue crack growth behavior of AZ61 magnesium alloy under corrosive environment with low and high stress ratio. Fatigue crack growth (FCG) test were carried out under two different environments: (a) low humidity environment (relative humidity of 55 at 20°C), and (b) 3.5% NaCl spray environment.

2. Experimental procedure

2.1 Material

The material used in the present study was AZ61 (Mg-6%Al-1%Zn) magnesium alloy. The dimensions of received extruded plate was 3.0 x 70 x 1000 mm. The chemical and mechanical properties are summarized in Table 1 and 2 respectively. The microstructure of AZ61 is shown in Fig.1.The average grain size was about 12 μm.

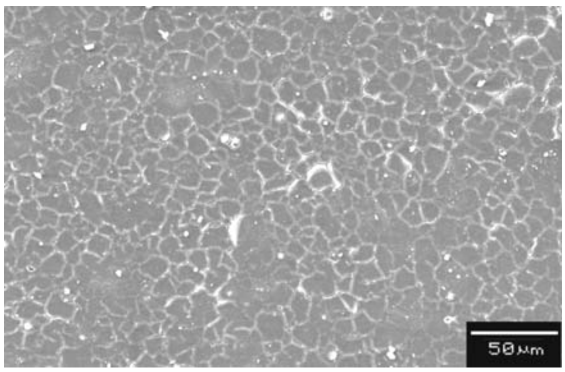

Figure 1. Microstructure of extruded AZ61 magnesium alloy.

2.2 Specimen

Fatigue crack growth (FCG) tests were conducted on 3 mm thick compact tension (CT) specimens. Details of the specimen geometrical configuration are illustrated in Fig. 2 and are in accordance with ASTM specification E-647-95a [5]. Prior to fatigue crack growth tests, all of the specimens were polished using 600, 800, 1000, 1200, 1500 grit silicon carbide papers and 6, 3 μm diamonds abrasive, rinsed with ethanol in an ultrasonic oscillator and air dried. The final polished surface was mirror-like surface, which makes clear observation of crack during FCG test. The fatigue crack propagation direction was perpendicular to the extruded direction.

Table 1. Chemical composition of the AZ61 magnesium alloy used (mass%)

Al	Zn	Fe	Ni	Cu	Si	Mn	Mg
5.95	0.26	0.64	0.005	0.009	0.0008	0.0007	Bal.

Table 2. Mechanical properties of the AZ61 magnesium alloy used

	Yield stress $\sigma_{0.2}$ (MPa)	Tensile strength σ_B (MPa)	Elongation (%)	Young's modulus E (GPa)
AZ61	200	290	18	43

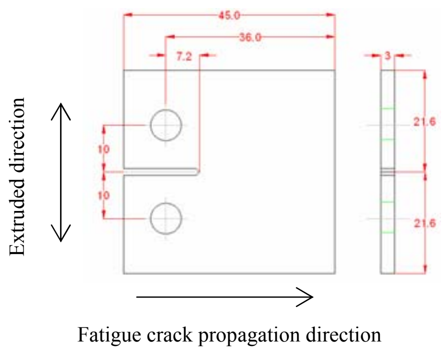

Figure 2. Dimensions of the CT specimen used in this study.

2.3 Test procedure

The specimens were pre-cracked to a length of 9.8 mm in air prior to FCG rate tests. FCG rate tests were carried out using servo-hydraulic fatigue machine with a sinusoidal loading waveform. ΔP control mode for ΔK-decreasing and ΔK-increasing tests were conducted to obtained a complete curve of FCG by using one specimen for each load ratios ($R = P_{min}/P_{max}$) under a frequency of 5 Hz.

FCG data were obtained from two environments; (1) in a laboratory room under a controlled atmosphere at a temperature of 20°C and relative humidity of 55%, and (2) in 3.5% NaCl fogging environment (salt spray) in accordance with ASTM specification B-117-02. The schematic diagram of experimental set up is shown in Fig. 3. The compressed air supplied to the nozzle for atomizing the salt solution was maintained at 0.1 MPa/m^2 and the quantity of collected salt solution is between 1.0 to 2.0 ml per hour. The concentration of sodium chloride used in this study was 3.5% and approximately equal to the concentration of artificial sea water. The pH of the solution was maintained at a range from 6.5 to 7.2.

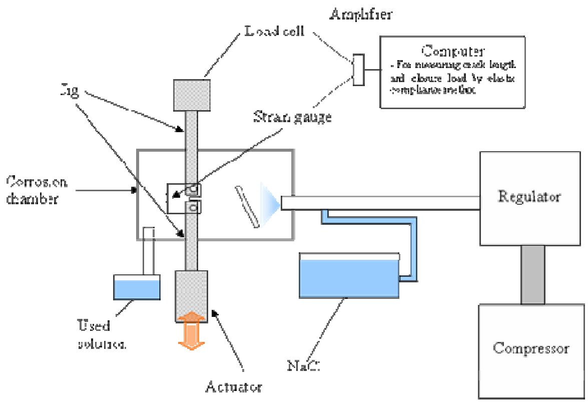

Figure 3. Schematic diagram of experimental setup

Fatigue crack lengths on both sides of the polished specimen surfaces were measured to an accuracy of 1 μm by using computer controlled compliance technique and also monitored by traveling optical microscope. The crack length measured by the compliance technique was equal to that measured by traveling microscope under air environment. So, surly the crack length measurement by compliance technique was applied to the tests under 3.5% NaCl spray environment. The crack length measured by traveling microscope was evaluated by using Equation (1).

$$a = a_0 + \frac{d_1 + d_2}{2}, \qquad (1)$$

where a_0 : initial crack length (= 7.2 mm), d_1, d_2: crack extension length on each side of the specimen.

Stress intensity factor range ΔK of the CT specimens was calculated as [5]:

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} \frac{(2+\alpha)}{(1-\alpha)^{\frac{3}{2}}} \times (0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4), \qquad (2)$$

where ΔP : the load range (= P_{max}- P_{min}), B : specimen thickness, W: specimen width, α : a/W

The threshold stress intensity factor range, ΔK_{th} is corresponding to ΔK at which no crack growth was observed for 10^6 cycles. During FCG test, crack closure point was evaluated by using elastic compliance method.

The effective stress intensity factor range, ΔK_{eff} was defined as:

$$\Delta K_{eff} = K_{max} - K_{cl} = U \times \Delta K, \qquad (3)$$

Where, K_{max} is the stress intensity factor calculated from the maximum load and K_{cl} is the stress intensity value at crack closure load, $P_{closure}$. U is the effective stress intensity range ratio or the crack closure ratio.

Crack closure ratio U can be expressed as;

$$U = \Delta K_{eff} / \Delta K, \qquad (4)$$

Fracture surface observations were carried out under scanning electron microscope (SEM). The corrosion product was analyzed by using an energy dispersive spectroscopy (EDS).

3. Results and discussion

3.1 Crack growth behavior under low humidity

From the fatigue crack growth tests under low humidity condition (without corrosion influence), relationship between fatigue crack growth rate, d*a*/d*N* and stress intensity factor range, ΔK is shown in Fig. 4. As commonly known for metallic materials (any text book), fatigue crack growth rates became higher with increasing stress ratio, *R*. ΔK_{th} values for $R = 0.1$ and 0.7 were about 1.2 and 0.7 MPa.m$^{1/2}$, respectively.

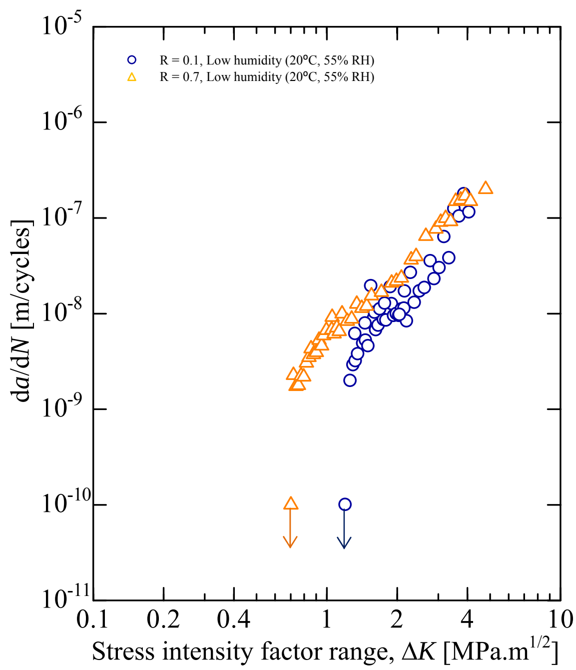

Figure 4. The FCG curve, d*a*/d*N* vs ΔK, for magnesium alloy AZ61 under low humidity environment (relative humidity of 55 at 20°C).

From the crack closure measurements, relationship between closure ratio, U and stress intensity factor range, ΔK is shown in Fig.5. As can be seen from the figure, the crack closure behavior was more significant in lower ΔK region for $R = 0.1$, while no crack closure behavior was observed for $R = 0.7$.

Based on these crack closure measurements, the fatigue crack growth curves were rearranged by using a parameter "effective stress intensity factor range, ΔK_{eff}", as shown in Fig. 6. As can be seen from the figure, the fatigue crack growth curves for $R = 0.1$ and 0.7 were almost on the same curve regardless of stress rates, which was not different from the behavior of other metallic materials.

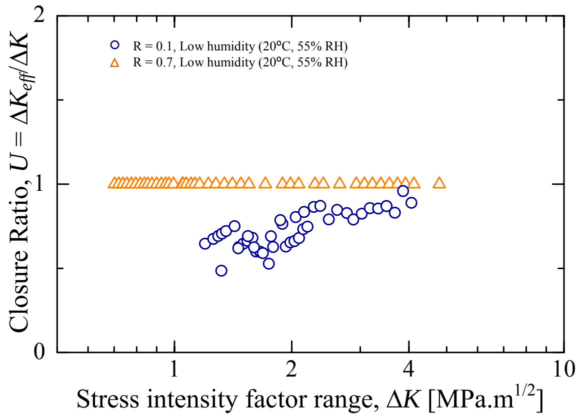

Figure 5. Relationship between crack closure ratio and ΔK for magnesium alloy AZ61 under low humidity environment (relative humidity of 55 at 20°C).

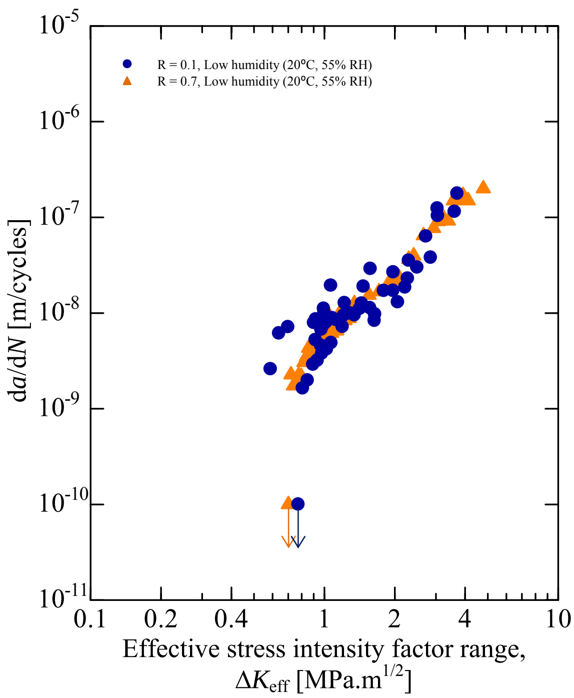

Figure 6. The FCG curve, d*a*/d*N* vs ΔK_{eff}, for magnesium alloy AZ61 under low humidity environment (relative humidity of 55 at 20°C).

3.2 Crack growth behavior under 3.5% NaCl spray environment

From the fatigue crack growth tests under 3.5% NaCl spray environment, relationship between d*a*/d*N* and ΔK is shown in Fig. 7. As can be seen from the figure, two separated curves were obtained for each stress ratio, which were corresponding to test condition: one was for ΔK-decreasing test and the other was for ΔK-increasing test, as indicated in Fig. 7. ΔK_{th} values were about 1.4 and 1.0 MPa.m$^{1/2}$ $R = 0.1$ and 0.7, respectively, which were higher than those under low humidity condition.

From the crack closure measurements, relationship between U and ΔK is shown in Fig.8. As can be seen from the figure, two separated curves were also found in this relationship. Especially, for the case of ΔK-increasing test under R = 0.1, the crack was almost closed, which seemed to be unusual compared to commonly-known behavior of metallic materials without corrosion influence.

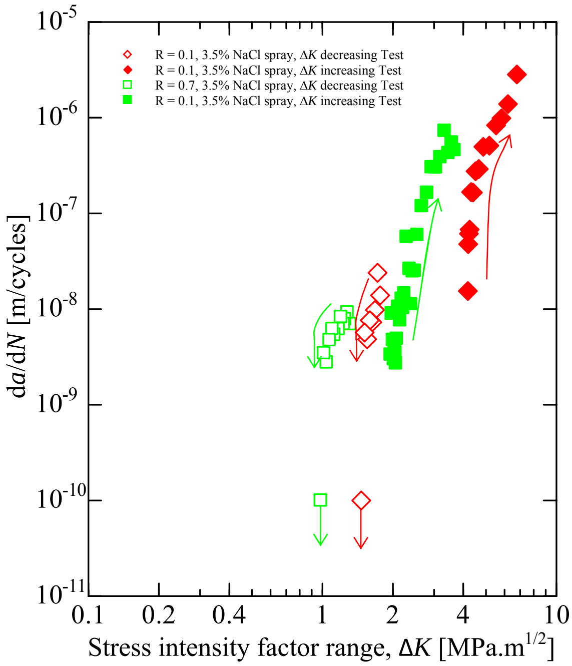

Figure 7. The FCG curve, da/dN vs ΔK, for magnesium alloy AZ61 under 3.5% NaCl spray environment.

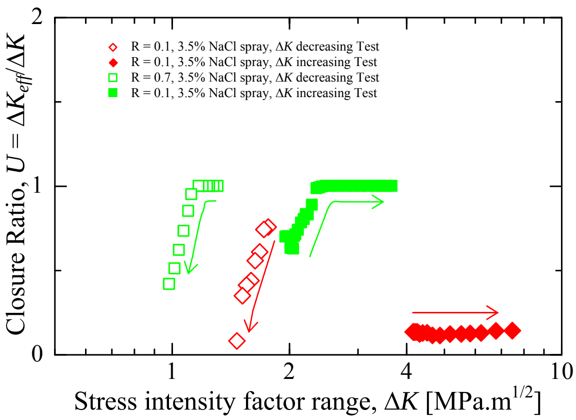

Figure 8. Relationship between crack closure ratio and ΔK of magnesium alloy AZ61 under 3.5% NaCl spray environment.

Based on these crack closure measurements, the crack growth curves were rearranged by using ΔK_{eff}, as shown in Fig. 9. The crack growth curves for ΔK-decreasing and ΔK-increasing tests under R = 0.7 as well as for ΔK-decreasing test under R = 0.1 were come to one curve, while wide scatter was found. The ΔK_{th} values were 0.4 and 0.12 MPa.m$^{1/2}$ for R = 0.7 and 0.1, respectively, which were lower than those under low humidity condition. The crack growth curve for ΔK-increasing test under R = 0.1 was apart from other cases.

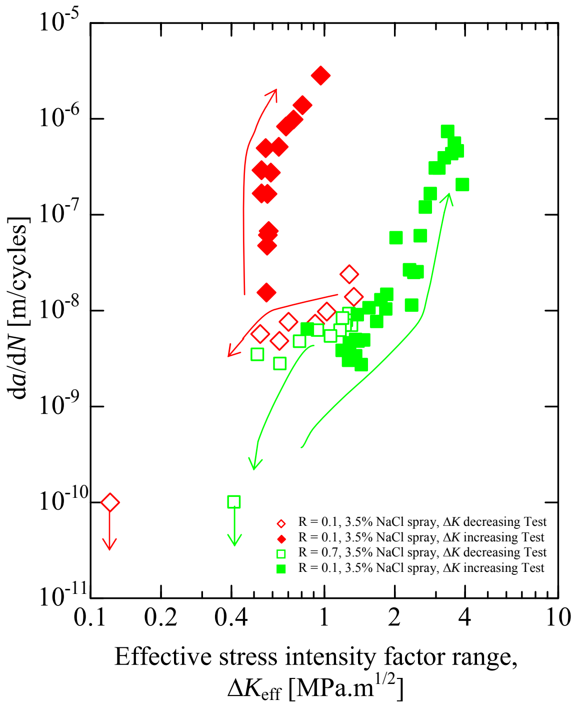

Figure 9. The FCG curve, da/dN vs ΔK_{eff}, for magnesium alloy AZ61 under 3.5% NaCl spray environment.

To investigate this unique crack growth behavior in detail, fracture surfaces were observed by using a scanning electron microscope. Fatigue crack growth regions of fracture surfaces under low humidity are shown in Fig. 10. As can be seen from the figure, wavy-slip-marked surfaces were visible for both R = 0.1 and 0.7, which indicated typical fatigue crack growth surface of ductile metallic materials. Fatigue crack growth regions for ΔK-decreasing test under 3.5% NaCl spray environment are shown in Fig. 11. As can be seen from the figure, fracture surfaces for both R = 0.1 and 0.7 were fully corroded. The fracture surface under R = 0.7 showed more flat and plate-like fracture surface.

Fatigue crack growth regions of fracture surfaces for the ΔK-increasing tests under 3.5% NaCl spray environment are shown in Fig. 12. As can be seen from the figure, fracture surface under R = 0.1 indicated corroded surface, while that under R = 0.7 indicated the similar fracture surface to that under low humidity condition. These significant difference of corrosion behavior between two stress ratios may induce the different crack growth curve for ΔK-increasing test under R = 0.1 compared to other crack growth curves for ΔK-decreasing and ΔK-increasing tests under R = 0.7. From the results of EDS analysis, it was suggested that the corrode surface would be covered with condensed NaCl and MgO_2 products.

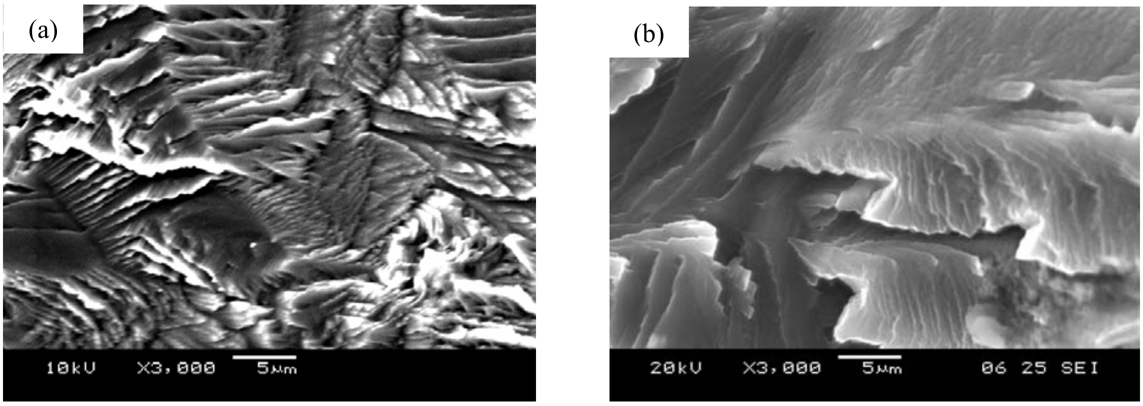

Figure 10. Fractographs of magnesium alloy AZ61 under low humidity environment (a) R = 0.1, ΔK = 1.71 (ΔK_{eff}= 0.98) MPa.m$^{1/2}$ and (b) R = 0.7, ΔK = 1.19 (ΔK_{eff}= 1.19) MPa.m$^{1/2}$

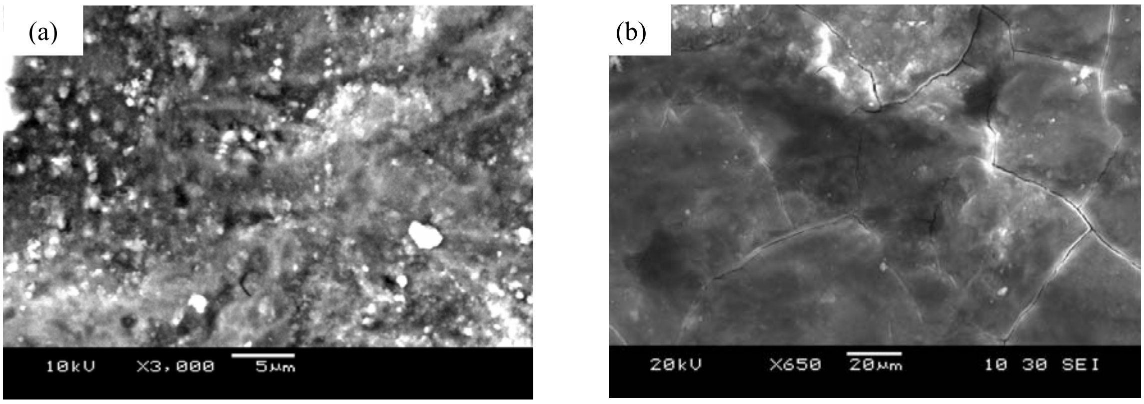

Figure 11. Fractographs for ΔK-decreasing test of magnesium alloy AZ61 under 3.5% NaCl spray environment (a) R = 0.1, ΔK = 1.68 (ΔK_{eff}= 1.02) MPa.m$^{1/2}$ and (b) R = 0.7, ΔK = 1.28 (ΔK_{eff}= 1.28) MPa.m$^{1/2}$

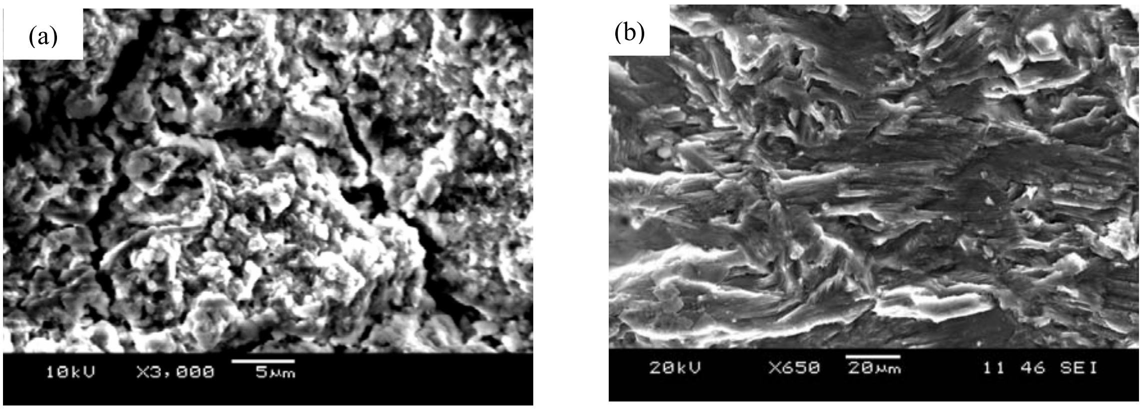

Figure 12. Fractographs for ΔK-increasing test of magnesium alloy AZ61, under 3.5% NaCl spray environment (a) R = 0.1, ΔK = 4.20 (ΔK_{eff}= 0.57) MPa.m$^{1/2}$ and (b) R = 0.7, ΔK = 2.15 (ΔK_{eff}= 1.68) MPa.m$^{1/2}$

4. Conclusion

(1) Fatigue crack growth behavior of magnesium AZ61 under low humidity was influenced by crack closure behavior and the unique crack growth curve regardless of stress ratio could be obtained if the curve was arranged by ΔK_{eff}.

(2) Fatigue crack growth behavior under 3.5% NaCl spray environment was influenced by crack closure behavior as well as corrosion behavior. The unique crack growth curve was obtained for ΔK-decreasing tests under R = 0.1 and 0.7 and ΔK-increasing test under R = 0.7 of the curves were arranged by ΔK_{eff}.

(3) Even if the curve was arranged by ΔK_{eff}, the curve for ΔK-increasing test under R = 0.1 indicated the different curve compared to the other curves. In this

condition, corrosion products and condensed NaCl were almost full between crack surfaces, which induced very high closure point and active corrosion behavior.

References

1. Mayer HR, Stanzl-Tschegg S. Environmental influences at very high frequency. In: Proceedings of the international conference on fatigue in the very high cycle regime; 2001. p. 267–74.
2. Hilpert M, Wagner L. Corrosion fatigue behavior of the high-strength magnesium alloy AZ80. J Mater Eng Perform 2000;9(4):402–7.
3. Unigovski Y, Eliezer A, Abramov E, Snir Y, Gutman EM. Corrosion fatigue of extruded magnesium alloys. Mater Sci Eng A 2003;360:132–9.
4. Sajuri ZB, Miyashita Y, Mutoh Y. Effect of humidity and temperature on the fatigue behavior of an extruded AZ61 magnesium alloy. Fatigue Fract Eng Mater Struct 2005;28:373–9.
5. ASTM standard E-647-95a, Annual Book of ASTM standard, Vol.3 (1) (1998) 562-575.
6. ASTM standard B-117-02, Annual Book of ASTM standard, Vol.3 (2) (2002) 1-11.
7. Kainer, K.U., 2000. Magnesium Alloys and their Application. pp. 1-7