Effect of humidity on fatigue crack propagation of aluminum alloys

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Abstract

High specific strength materials are getting more important for saving energy in various kinds of transportation systems. Although high strength materials are sensitive to the environment, aluminum alloys are insensitive to the mild atmosphere. Aluminum alloy makes stable oxide film and has the resistance to the progress of oxidation. Since aluminum alloys do not show the clear fatigue limit, the information on the fatigue crack propagation behavior is essential for designing of the structure and estimating of the life of the structures. We carried out the fatigue tests on Al-Zn-Mg, 7075-T6 and Al-Mg, 5083-O alloys. They have quite different microstructure. The former has the strongest alloy among Al alloys and the strength is performed by the precipitation hardening. The latter has the strongest alloy among solid solution aluminum alloys. The fatigue crack propagation behavior was examined by compact tension specimen in two kinds of different environment. The atmosphere was controlled by dry and wet argon at ambient temperature. The dry argon did not contain water vapor and the humidity was almost 0%. The wet argon was added by water vapor and the humidity was kept more than 90%. The fatigue crack propagation properties for the steady state region, the second stage, were characterized by the Paris law, $da/dN = C(\Delta K)^m$. The exponent, m depends on the environment and is changed by the humidity. There is a relationship between C and m for both alloys. The relationship depends upon the environment alone. The crack propagation rate is usually accelerated by water vapor. The crack propagation test was also conducted in the dry argon with hydrogen gas. Since the fatigue crack propagation does not show any effect of hydrogen gas, the acceleration is due to the hydrogen atoms, which were produced on the fresh fractured surfaces. The chemical reaction on the fresh aluminum surface could produce hydrogen ions in the water on the surfaces. The difference in the oxides film formed on the aluminum surfaces would bring the clear change of the fatigue crack propagation. Besides, the crack closure effect was hardly observed for these alloys. The fractured surfaces in dry argon was typical striation pattern for both alloys. In wet environment, the surface was covered with fine structures for 5083 alloy.

Keywords: *fatigue crack propagation rate, humidity, aluminum alloy, Paris law, hydrogen embrittlement*

I. Introduction

Aluminum alloys with higher strength are focused for energy saving through the reduction of the weight of vehicles and the transportation systems. We are interested in two kinds of high strength aluminum alloys, which are 7075, Al-Zn-Mg and 5083, Al-Mg alloys. The former is precipitation-hardening alloy and the latter is solid solution hardening. Each alloy is the highest in the tensile strength among the respective categories. Fatigue crack propagation behavior of alloys would depend upon the microstructure and the environment. The microstructures of both alloys are quite different. The 7075 alloy contains the second phases and the 5083 is single phase. Fatigue behavior of materials depend upon the environment. An important parameter is humidity, moisture of water, which is ambient atmosphere. We carried out the experiments on both aluminum alloys in the environment, where the humidity and gas were controlled. The fatigue crack propagation behavior was evaluated based on Paris law [1].

II. Experimental procedures

2.1. Materials

The chemical composition of aluminum alloys used for this experiment is shown in Table 1. The specimen for fatigue crack propagation test is the modified compact tension type. The conventional heat treatment T6 was given to 7075, whose tensile strength was 500 MPa. The annealing was done to 5083 with the tensile strength of 300 MPa.

2.2. Fatigue test system

Fatigue crack propagation tests were conducted in the chamber with the controlled atmosphere. The humidity was always checked by the hygrometer. In this experiment, the humidity was selected less than 10 % and more than 90 %. The former is dry condition and the latter wet condition. The test temperature was controlled around 300 K.

Table1. Chemical composition of aluminum alloys. (mass %)

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
5083-O	0.09	0.22	0.02	0.61	4.7	0.05	0.01	0.02	Bal.
7075-T6	0.08	0.18	1.2	0.02	2.4	0.18	6.3	0.01	Bal.

III. Experimental results

3.1. Effect of atmosphere on the fatigue crack propagation rate

The standard experiments were done in the dry argon, where there would be no effect on the fatigue crack propagation. The effect of the humidity on the fatigue crack propagation curves is shown Fig.1.

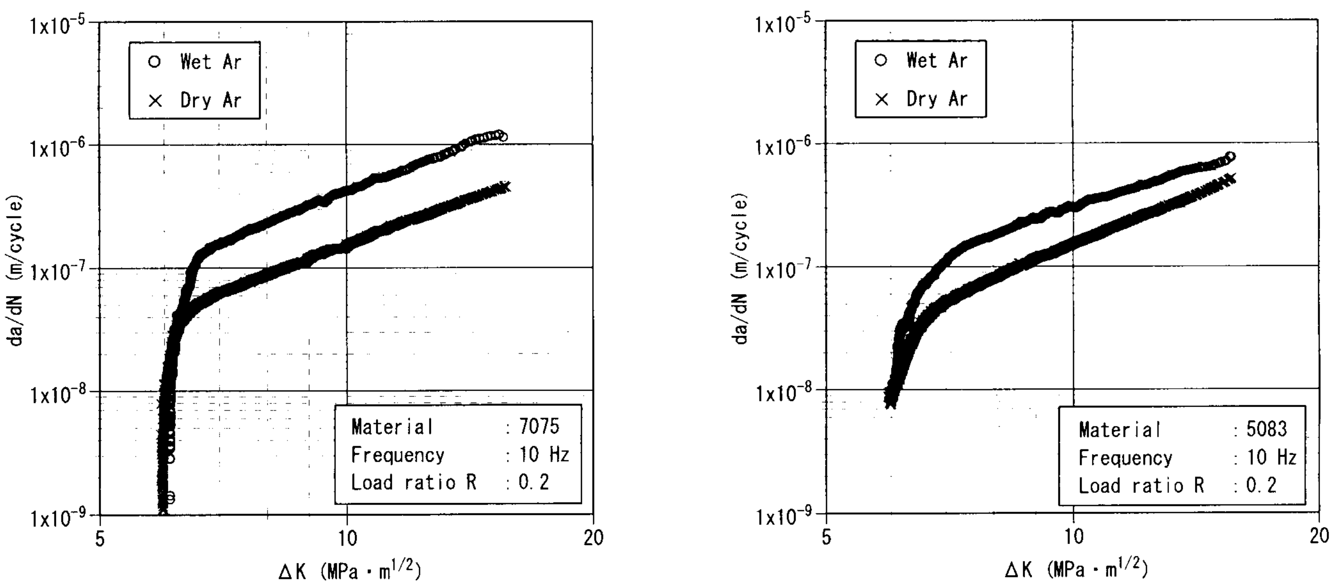


Fig.1. Effect of atmosphere on fatigue crack propagation rate of aluminum alloys.

The effect of the humidity on the fatigue propagation rate was larger for 7075 than for 5083. The effect depends upon the strength of the aluminum alloy. For 5083, the effect was reduced at the higher ΔK region. However, the definite difference was not recognized in the relationship of da/dN vs. ΔK of both alloys. In the inert gas, the fatigue crack propagation behavior would be similar for aluminum alloys regardless of the strength [2]. The mechanism would be controlled by ductile mode, which brings the striation pattern on the fatigued surfaces.

3.2. Effect of test condition on the fatigue propagation rate

The effect of the test condition, load ratio and frequency, was examined in the wet environment for both alloys. The interesting results were observed for both alloys. The effect of the frequency was neither recognized for 7057 nor 5083 alloys. When the reduction of the load ratio, $R = P_{min}/P_{max}$ was reduced, the apparent threshold ΔK was increased. When both alloys were fatigued at the higher load ratio, the crack took the discontinuous propagation behavior. Similar behavior was observed at the lower frequency. The discontinuity in the crack propagation was outstanding in the wet environment [3]. The existence of water vapor would be important for the phenomenon. The behavior is quite different from the results of magnesium alloys, which are chemically reactive to water [4]. The difference would be due to the chemical reaction and chemical product on the fresh surfaces introduced by the fatigue crack propagation [5]. The chemical product is oxide file formed through the chemical reaction of matrix metal and oxygen. The oxides are Al_2O_3 for aluminum alloys and MgO for magnesium alloys. The former is harder and denser than the latter.

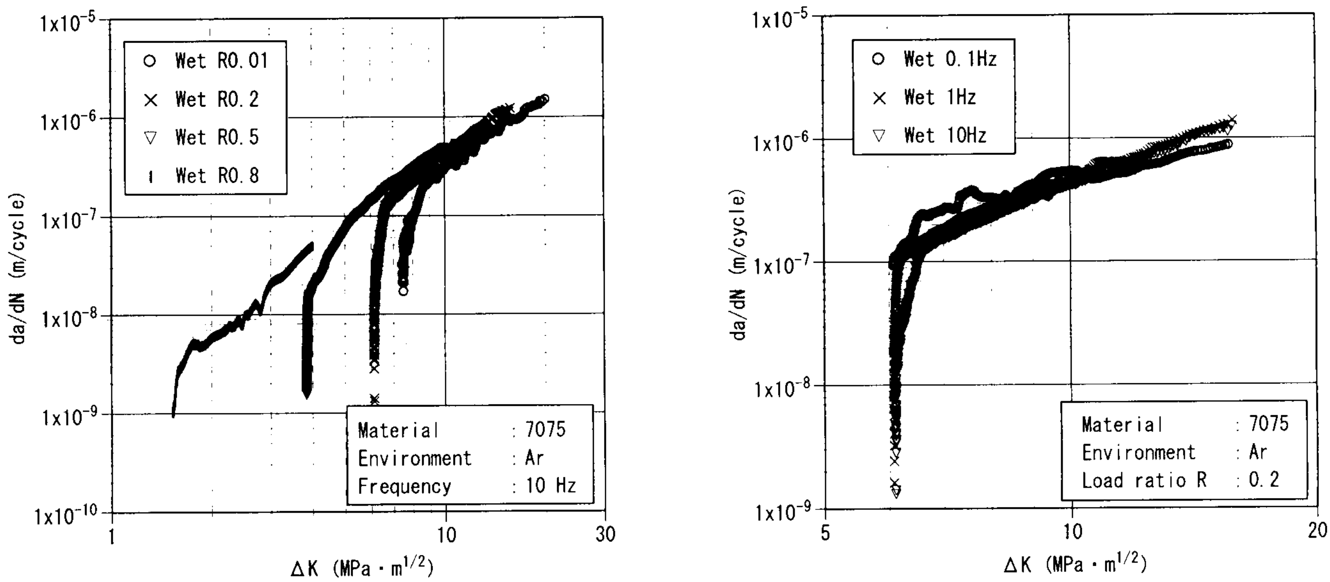


Fig.2. Effect of load ratio and frequency on fatigue crack propagation rate of 7075 alloy in wet argon atmosphere.

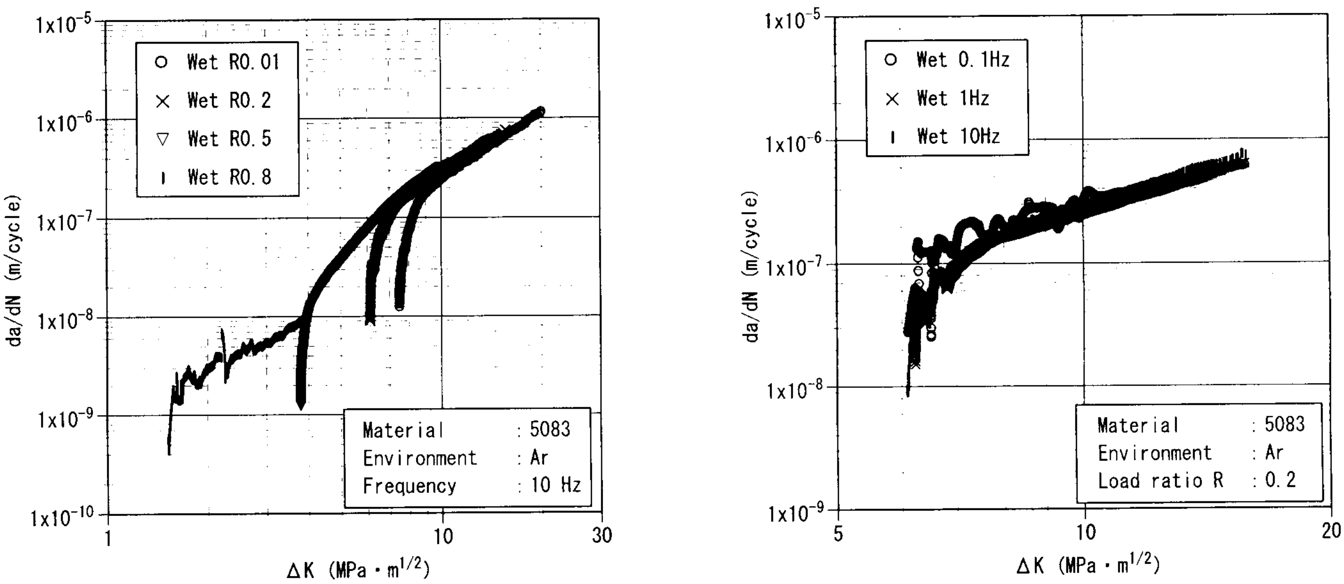
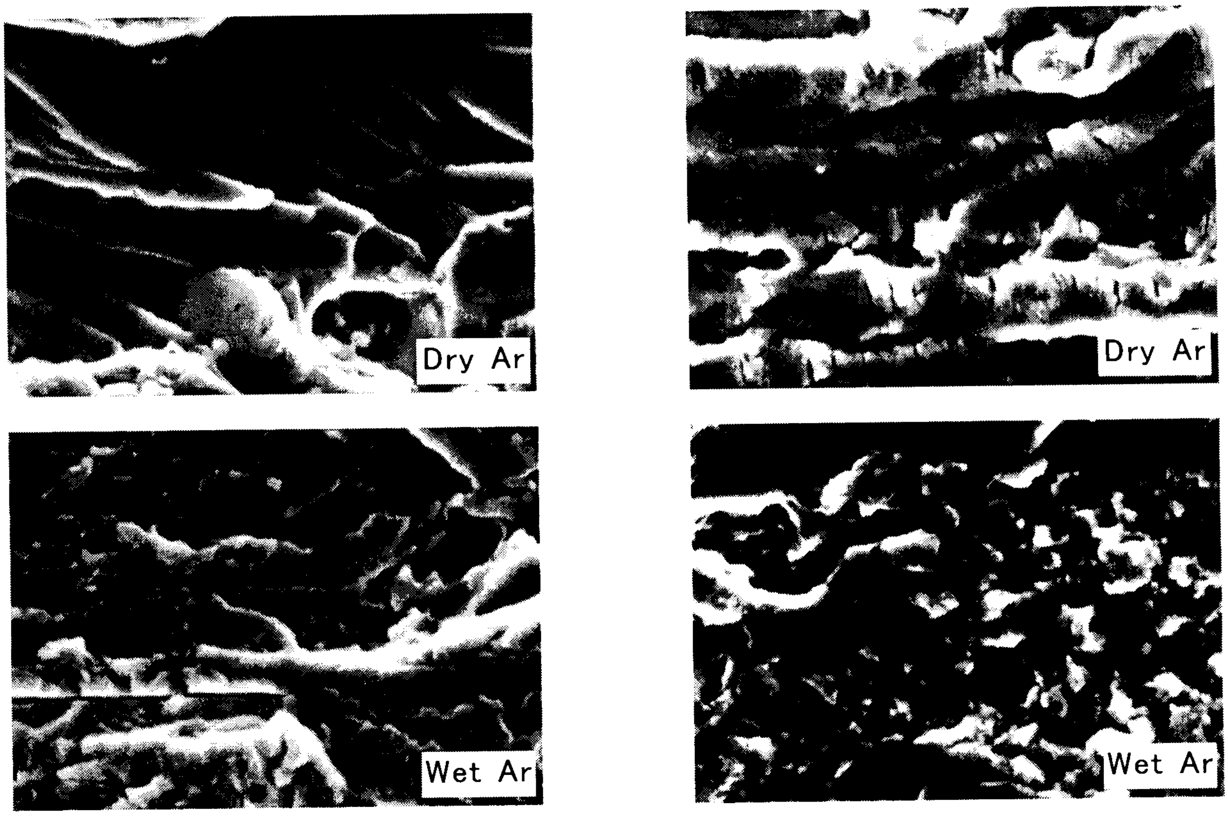


Fig.3. Effect of load ratio and frequency on fatigue crack propagation rate of 5083 alloy in wet argon atmosphere.

3.3. Observation of fractured surfaces

The fracture surfaces were observed to examine the difference of the fracture mechanism. The typical photos are shown for both alloys in Fig.4. The quite difference was observed between the wet and the dry environment for both alloys. In dry argon atmosphere, the fatigue crack propagates in the striation pattern for both alloys. The 7075 alloy with the higher strength shows the perpendicular cracking. However, in the wet environment, the chemical products were observed on the fatigue fractured surfaces. The fragmentation of the oxide is more remarkable for 7075 than 5085 alloy. The difference would result in the higher fatigue crack propagation rate. The brittleness of the oxide film would make the easy path for the penetration of hydrogen atoms.



Δ K=10 (MPa·m$^{1/2}$), 10Hz, R=0.2 [7075] 10μm Δ K=10 (MPa·m$^{1/2}$), 10Hz, R=0.2 [5083]

Fig.4. SEM micrograph of fatigue fractured surfaces of aluminum alloys in dry and wet argon atmosphere.

IV. Discussion

4.1. Paris parameters, m and C for the second stage

In this experiment, Paris law, $da/dN = C(\Delta K)^m$, was applied to evaluate the effect of the environment on the fatigue crack propagation behavior. The fatigue crack propagation behavior experimentally obeyed the above equation, where the parameter C and m are constant in the second region [6]. The constant, $m \approx 2$ is deduced by the energy criterion at the crack tip subjected to small scale yielding. In this experiment, we observed the values of C and m for both alloys under all experimental conditions. The results are shown in Fig.5, where the relationships between C and m are recognized. The relationships are divided into two groups, dry and wet condition. Humidity, water vapor accelerates the fatigue crack propagation of aluminum alloys through the increase in C and m at the second stage.

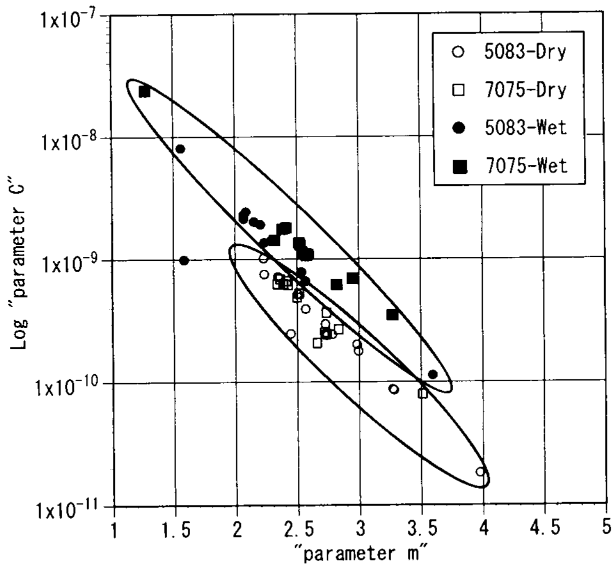


Fig.5. Paris parameters, C and m for 7075 and 5083 alloys.

4.2. Effect of humidity and hydrogen embrittlement

The following chemical reaction can take place on the fresh aluminum alloy surfaces in water.

$$2Al \rightarrow 2Al^{+3} + 6e \quad (1)$$

$$6H_2O \rightarrow 6H^{+1} + 6OH^{-1} \quad (2)$$

$$2Al^{+3} + 6OH^{-1} \rightarrow 2Al_2O_3 + 3H_2 \quad (3)$$

While aluminum oxide was formed, hydrogen ions were resolved in the water on the aluminum surfaces. The ions can easily penetrate into the aluminum matrix because of the extraordinarily small size. The hydrogen ions in the water on the aluminum surfaces should run through the aluminum oxide film formed on the fresh aluminum surface. The difference in the properties of the oxides is observed in the fatigue crack propagation behavior in wet environment. In Fig.1, the propagation rate of 7075 alloy is higher then of 5083 alloy. The oxide film of 5083 alloy is more dense and less brittle than of 7075 alloy. The hydrogen ions can easily diffuse in the aluminum alloys and make the matrix brittle and so hydrogen embitterment takes place. The acceleration of fatigue crack propagation in wet environment is due to the existent of hydrogen ions and the easiness of diffusion of the ions in the oxide film.

4.3. Effect of microstructure on fatigue crack propagation.

There is not found clear difference of the microstructures of the alloys in the parameters, C and m as shown Fig.5. The stable fatigue crack propagation at the second stage is independent of the microstructure, unless the materials are brittle [7]. Aluminum alloy in the mild environment never becomes brittle, because the fatigue crack propagation is actually controlled by the ductile striation mechanism. However, the properties of the oxide film formed on the fresh surfaces would depend upon the difference of the alloy composition. The heterogeneous structure, the 7075 alloy would make local cell on the surface and then the rough and thick film would be expected. The difference would also bring the closure effect. In this experiment, the effect was not observed definitely. But it was recognized slightly for the 5083 alloy.

V. Conclusion

We carried out the fatigue crack propagation tests for 7075 and 5083 aluminum alloys in dry and wet environment. The fatigue crack was accelerated in wet atmosphere, though the fatigue crack propagation rate was similar for both alloys in dry argon atmosphere. The crack acceleration was induced by hydrogen embrittlement. The hydrogen was ions which were in the water on the fresh aluminum surfaces. The hydrogen ions can easily penetrate the oxide film and the aluminum matrix. The difference of the properties of the oxide film formed on the aluminum surfaces was observed in the fatigue crack propagation behavior of the aluminum alloys. The fatigue fractured surfaces in wet atmosphere showed quite different features from that in inert atmosphere.

VI. References

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