EFFECTS OF TRACE Zr ON FATIGUE CRACK GROWTH RATE OF HIGH DAMPING Zn-Al ALLOY①

Zhou Shanchu, Luo Binghui
Department of Materials Science and Engineering,
Central South University of Technology, Changsha 410083

ABSTRACT The fatigue crack growth rate of a high damping Zn-Al eutectoid alloy containing trace Zr and a Zn-Al eutectoid alloy has been measured. The Paris expression of both alloys has been obtained from the experimental results. The experimental results show that the lower fatigue crack growth rate of the alloy containing Zr is related to its higher internal friction value.

Key words Zr Zn-Al alloy fatigue crack growth rate internal friction

1 INTRODUCTION

Having been quenched and aged, Zn-Al alloys, especially those having eutectoid reaction, such as the Zn-22% Al alloy, possess very good damping capacity[1-3]. These alloys can effectively abate vibrations and noises in a variety of machines and equipments. In consideration of the machinery parts which are made of the high damping Zn-Al alloys and used under vibration, and the load exerting on the parts under cyclic loading, the main losing efficacy form of the parts may be fatigue damage or fatigue fracture; besides, the fatigue crack growth rate is one of the basic parameters of fatigue ultimate design. However, the reports of research on the fatigue capacity of the Zn-Al alloys and the reports about the effects of the alloying elements on the fatigue property of the Zn-Al alloys are very seldom seen. The purposes of the present paper are to study the effects of trace Zr on the fatigue crack growth rate of the Zn-Al eutectoid alloy and to find the corresponding Paris expression of the alloy, and to try to discover the relationship of fatigue crack growth rate, $\mathrm{d}a/\mathrm{d}N$, with the alloy's internal friction value, Q^{-1}. If the relationship of the $\mathrm{d}a/\mathrm{d}N$ with the Q^{-1} has been found, the basic law will possess great reference significance to the alloying design and the fatigue design of the Zn-Al alloys and another type of high damping multiple-phase alloys.

2 EXPERIMENTAL

The experimental alloys were Zn-22% Al and Zn-22% Al-0.18% Zr. The starting materials used were 99.95% purity Al, 99.99% purity Zn and Al-Zn master alloy.

For the preparation of specimens, about 500 g metals were melted in a crucible furnace. 90 mm × 50 mm × 20 mm ingots were homogenized at 653 K for 8 h, then hot rolled to 3.5 mm thickness. The blanks were water-quenched after heating at 653 K for 1 h. The sheet billets were warm-rolled to 1 mm, and then the specimens were cut from the sheets. The specimens were aged at 423 K for 24 h. The measurements of mechanical properties and the damping capacity were carried out immediately after aging.

The tensile test and the internal friction test

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were carried out following the state-specified standards GB228- 87 and GB/T13665- 92 respectively. The experimental results are shown in Table 1.

Table 1 Mechanical properties and internal friction values of studied alloys (25 ℃)

	$\sigma_{0.2}$/MPa	σ_b/MPa	δ_5/%	$Q^{-1}/10^{-2}$
Zn-22%Al	212	279	55	3.43
Zn-22%Al -0.18%Zr	190	257	64	3.85

The fatigue crack growth rates were measured using non-standard specimens, whose scheme is shown in Fig. 1. The edge-notch (pre-crack), whose width and length are 1.5mm and 3.0mm respectively, has been worked with wire cuting method. The tests were carried out on an Instron 8032 dynamic testing system. The extensometer gauge (gauge length l_0= 25mm) has been used in the course of fatigue test. The fatigue loading conditions for the two kinds of alloy specimens are all the same: tension-tension loading, maximum stress σ_{max}= 100MPa, minimum stress σ_{min}= 50MPa, stress amplitude $\Delta\sigma$ = 50MPa, stress ratio R= 1/2; sine wave, frequency f = 1Hz; testing temperature is ambient temperature. The cycle-index, N_i, and the strain peak, S_i, and other data have been typed automatically by testing system at specified intervals during the course of fatigue test. For every specimen, the test was stopped when the tester could see obvious extensive crack with the naked eye.

Fig. 1 Fatigue testing specimen (mm)

The fatigue crack length at different cycle-indices, N_i, for every specimen has been calculated from the corresponding strain peak, S_i. Because of fitting the extensometer gauge on the specimen during the course of fatigue test, and according to Fig. 2, the relationship of the fatigue crack length a_i perpendicular to force-axis with the absolute elongation, Δl_i, is

$$\frac{1/2(l_0+\Delta l_i)}{(3+a_i)} = \mathrm{tg}76.5°$$

Fig. 2 Fatigue crack size scheme (mm)

Because $\Delta l = l_0 \cdot S_i$, l_0= 25 mm, tg76.5° = 4.167, after processing, the following expression can be obtained.

$$a_i = 3S_i \tag{1}$$

According to Eq. (1), the fatigue crack length, a_i, at N_i cycles can be calculated from the corresponding strain peak, S_i. By comparison of the calculaled a_i with the measured a_i, the reliablity of Eq. (1) has been confirmed.

3 RESULTS AND DISCUSSION

3.1 *a-N* curve

The experimental results are given in Table 2. The main data in Table 2 are N_i and a_i. Every a_i is the average value obtained from measuring crack length of five specimens. The *a-N* curve shown in Fig. 3 can be obtained from N_i and a_i.

The $(\mathrm{d}a/\mathrm{d}N)_i$ in Table 2 had been obtained by means of graphic method. The foundation of the method is that the slope of any point of the curve is equal to $(\mathrm{d}a/\mathrm{d}N)_i$. The range of stress-intensity factor, ΔK_i, i. e. a difference between the maximum stress-intensity factor, K_{max}, and the minmum stress-intensity factor, K_{min}, has been calculated by means of the following relation.

$$\Delta K_i = \Delta\sigma\sqrt{a_i}\cdot Y \tag{2}$$

Table 2 Experimental results of fatigue tests

number	material	N_i / 10^2	a_i / mm	$\frac{\mathrm{d}a}{\mathrm{d}N}$ / 10^{-5}	ΔK_i
A		1	0.55	2.86	80.0
B		2	0.67	2.86	81.2
C		3	0.69	2.86	82.5
D		5	0.73	2.86	34.8
E		7	0.77	2.86	37.1
F	M1	8	0.82	6.00	89.9
G		9	0.90	10.41	94.2
H		10	1.03	21.25	100.7
I		11	1.42	30.71	118.3
J		12	1.81	52.50	133.5
K		13	3.01	150	172.2
L		14	4.21	–	203.7
a		1	0.31	1.82	58.7
b		2	0.37	1.82	60.4
c		3	0.38	1.82	61.2
d		5	0.40	1.82	62.8
e		7	0.45	1.82	66.6
f		8	0.48	1.82	68.8
g	M2	9	0.50	1.82	70.2
h		10	0.55	10.0	73.6
i		11	0.68	11.36	81.9
j		12	0.8	23.57	88.8
k		13	1.15	36	106.4
l		14	1.60	47.5	125.6
m		15	2.13	–	–
n		16	2.75	–	–

M1 and M2 represent Zn-22% Al and Zn-22% Al-0.18% Zr respectively.

Fig. 3 *a*-*N* curve

where $\Delta\sigma = 50\,\mathrm{MPa}$, $Y = 1.12\sqrt{\pi}$ for the double edge-notched specimen.

3.2 Fatigue crack growth rate and Paris expression for experimental alloys

The fatigue crack propagation occurs under the condition of yielding in a small range due to the maximum cyclic stress ($\sigma_{max} = 100\,\mathrm{MPa}$) remarkably below the yielding strength ($\sigma_{0.2} \gg 100\,\mathrm{MPa}$) of the tested material. For this reason, the fatigue crack growth rate (the growth rate of the second stage in fatigue crack propagation process) can be described with Paris expression[4]:

$$\mathrm{d}a/\mathrm{d}N = C\,\Delta K^n \tag{3}$$

Taking logarithm for both sides of Eq. (3), the following expression can be obtained:

$$\lg(\mathrm{d}a/\mathrm{d}N) = \lg C + n\lg\Delta K \tag{4}$$

Eq. (4) is a straight line equation, where n and C can be obtained by means of linear regression:

$$n = \left[N\sum_{i=1}^{N}\lg\Delta K_i\cdot\lg(\mathrm{d}a/\mathrm{d}N)_i - \sum_{i=1}^{N}\lg\Delta K_i\cdot\sum_{i=1}^{N}\lg(\mathrm{d}a/\mathrm{d}N)_i\right] / \left[\sum_{i=1}^{N}(\lg\Delta K_i)^2 - \left(\sum_{i=1}^{N}\lg\Delta K_i\right)^2\right] \tag{5}$$

$$\lg C = \frac{\sum_{i=1}^{N}\lg(\mathrm{d}a/\mathrm{d}N)_i - n\sum_{i=1}^{N}\lg\Delta K_i}{N} \tag{6}$$

where N is the number of data pair $(\mathrm{d}a/\mathrm{d}N)_i$ and ΔK_i for regression processing, and $\lg\Delta K_i$, $\lg(\mathrm{d}a/\mathrm{d}N)_i$ can be calculated from Table 2.

Having selected data of *C*, *F*, *G*, *H*, *I*,

J and c, f, g, h, i, j from Table 2 and replacing $(da/dN)_i$ and $\lg \Delta K_i$ of Eqs. (5) and (6) with these data respectively, the value of n and C can be found, so the Paris expression of the two alloys has been obtained as below:

for Zn-22% Al:

$n = 5.685$, $C = 5.495 \times 10^{-16}$

$$da/dN = 5.495 \times 10^{-16} \Delta K^{5.685} \qquad (7)$$

for Zn-22% Al-0.18% Zr:

$n = 7.984$, $C = 6.095 \times 10^{-20}$

$$da/dN = 6.095 \times 10^{-20} \Delta K^{7.984} \qquad (8)$$

On the basis of Eqs. (7) and (8), it may be seen that the fatigue crack growth rate of Zn-22% Al-0.18% Zr is less than that of Zn-22% Al; this point can be seen from Table 2 and Fig. 3, too.

3.3 Relationship of fatigue crack growth rate with internal friction value

As seen from Table 1, the internal friction value, Q^{-1}, of the Zn-Al alloy containing Zr is higher than that of the Zn-Al alloy not containing Zr. Having compared Eq. (7) to Eq. (8), the authors found that the fatigue crack growth rate, da/dN, of the Zn-Al alloy containing Zr is less than that of the Zn-Al alloy not containing Zr. Whether or not the Q^{-1} has relation with the da/dN?

It is stated that the Zn-Al alloy having eutectoid reaction belongs to multiple-phase type high damping alloy. The principal damping mechanism of this type of alloys is as follows[3]. Under the action of cycled loading, macroscopic elastic deformation occurs, viscous flow will occur at the phase boundaries or microscopic plastic deformation will occur in certain phase of the alloy. As a result, energy has been consumed, i. e. internal friction has been produced. On the other hand, the authors think, under the action of cycled loading they will sprout and extend fatigue cracks, this process needs consuming energy. In other words, there occur two courses consuming energy in the alloys under cycled loading: both the phase boundaries viscous flow (resulting in internal friction) and the fatigue crack propagation have need for energy. From the point of view of energy conservation, it is evident the bigger the Q^{-1}, the smaller the da/dN; the smaller the Q^{-1}, the bigger the da/dN.

Ref. [5] indicates that the as-cast grains and as-aged grains of Zn-22% Al alloy can be fined by adding trace Zr, as a result the area of the grain boundaries increases, which will result in strengthening grain boundary viscous flow, thus increasing the internal friction value, Q^{-1}. This point had been confirmed by data in Table 1. But increasing internal friction value, Q^{-1}, must decrease the energy needed for fatigue crack propagation, thus the fatigue crack growth rate, da/dN, becomes small. Therefore, as compared to the Zn-Al eutectoid alloy with lower internal friction value, Q^{-1}, the Zn-Al eutectoid alloy containing Zr with higher internal friction value, Q^{-1}, possesses lower fatigue crack growth rate, da/dN. From the above analyses, it is clear that trace Zr can not only increase the Zn-Al alloy's damping capacity, but improve its fatigue capacity.

4 CONCLUSIONS

(1) Adding trace Zr to Zn-Al eutectoid alloy can decrease the fatigue crack growth rate of the alloy.

(2) Lower fatigue crack growth rate of high damping Zn-Al alloy containing Zr may be related to the damping capacity, i. e. internal friction value, which has been increased by trace Zr.

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