LOW CYCLE FATIGUE AND FATIGUE CRACK

GROWTH BEHAVIORS OF ALLOY IN718

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Abstract

The low cycle fatigue (LCF) behavior and fatigue crack growth rates (da/dN) of alloy IN718 were studied in detail at 360,550 and 650 ℃, including the cycle stress-strain behavior, Massing effect, the LCF lives expressed by plastic strain energy and fatigue crack growth rates. In addition, the effect of hold time on da/dN was also discussed. The experimental results show that the da/dN is increased with the temperature increased. The effect of hold time on da/dN is very significant at 650℃, while it is a little below 550℃.

Superalloys 718, 625 and Various Derivatives
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Introduction

In resent years, the investigation of LCF behavior and fatigue crack growth rates for superalloy have been emphasized(1-5). Particulally, the LCF and da/dN properties of turbine disk alloys are considered to be a critical factor for material selected and life estimated(6). In addition, the experience shows that fatigue cracks appear easily at slot bottom in the I-st stage turbine disk of some aero-engines. However, after the crack initiation the crack growth is very slow. Therefore, the turbine disk with fatigue crack still have enough residual strength and can safely operate for a long time(7).

In this paper, the LCF behaviors and fatigue crack growth rates of alloy 718 were studied in detail at 360, 550, and 650°C to offer the data for design selected and life estimated of disk.

Material and Experimental Procedure

The chemical composition of alloy 718 is listed in TableI. The heat treatment regime is 960°C one hr air cold and 720°C 8 hrs furnace cold up to 620°C 8 hrs air cold. The conventional mechanical properties obtained are listet in Table II.

Table I Chemical Composition of Alloy 718

C	Mn	S	P	Si	Cr	Al	Ti
0.047	<0.1	0.002	<0.005	<0.16	19.20	0.53	1.10

Pb	Bi	Mg	Cu	Nb	Ag	Mo	Ni
0.0007	0.0005	0.0012	0.069	5.09	<0.001	2.86	bal.

Table II Conventional Mechanical Properties of Alloy 718

Temp. (°C)	U.T.S. (Mpa)	Y.S. (Mpa)	Elong. (%)	A.R. (%)	Stress-Rupture at 686 Mpa (hr) Smooth Spec.	Notched Spec.
R.T.	1402	1190	21	43	-	-
650	1128	981	18	34	> 657	126

The LCF specimen used is axial loading smooth specimen with 6mm diameter. The da/dN specimen used is WOL-type specimen with 10mm thick and the expression of stress intensity factor(8) is

$$K=\frac{P}{B\sqrt{W}}F\left(\frac{a}{W}\right) \tag{1}$$

where $F(a/w)= 30.96(a/w)^{1/2} - 195.8(a/w)^{3/2} + 730.6(a/w)^{5/2} - 1186.3(a/w)^{7/2} +754.6(a/w)^{9/2}$

P load (kN)

a crack length (mm)
B specimen thickness (mm)
W specimen width (mm)

The fatigue tests were performed in a servo-hydraulic fatigue testing machine with a high temperature furnace, and were run at 360, 550 and 650℃. For LCF tests the total strain control was used with strain ratio R=-1 and a frequency 0.33Hz using triangular wave form. The da/dN tests were conducted with load control and stress ratio, R=0.1 using DC potential method to measure the fatigue crack length.

Experimental Results and Discussion

High Temperature LCF Behaviors

The experimental results at 360,550 and 650℃ are listed in Tab. III. According to Manson-Coffin equation

$$\frac{\Delta\varepsilon_t}{2}=\frac{\sigma_f'}{E}(2N_f)^b+\varepsilon_f'(2N_f)^c \tag{2}$$

Table III The LCF Experimental Results of Alloy 718

Temp. (℃)	$\Delta\varepsilon_t/2$ (%)	$\Delta\varepsilon_e/2$ (%)	$\Delta\varepsilon_p/2$ (%)	$\Delta\sigma/2$ (Mpa)	N_f (cycle)
360	0.425	0.415	0.010	802	34270
	0.500	0.425	0.070	827	7228
	0.630	0.500	0.130	975	3111
	0.785	0.500	0.285	973	1113
	0.93	0.535	0.400	1035	845
	1.175	0.500	0.670	974	497
	1.390	0.570	0.820	1102	301
	2.155	0.610	1.545	1180	81
550	0.425	0.400	0.025	766	18180
	0.505	0.400	0.105	762	4250
	0.645	0.465	0.180	879	1526
	0.805	0.445	0.360	842	913
	0.970	0.445	0.525	844	611
	1.160	0.550	0.610	1047	273
	1.400	0.525	0.875	999	208
	2.160	0.590	1.570	1116	63
650	0.434	0.380	0.054	667	8486
	0.503	0.480	0.095	709	2581
	0.648	0.443	0.205	775	1220
	0.795	0.465	0.330	811	473
	0.895	0.475	0.420	829	240
	1.075	0.680	0.495	1015	175
	1.395	0.54	0.855	946	82
	2.915	0.645	2.270	1126	19
	4.065	0.690	3.375	1203	6

It can be fitted the data in the Tab. III and obtained the exponents and coefficients in equation (2) as shown in Tab. IV

Table IV The Exponents and Coefficients of LCF for Alloy 718

Temp. (°C)	σ'_f (Mpa)	b	ε'_f (%)	c	K' (Mpa)	n'
360	1630	-0.0651	156	-0.8248	1530	0.0742
550	1546	-0.0729	73.1	-o.7408	1524	0.0912
650	1476	-0.0840	18.4	-0.6047	1950	0.1457

From Tab. III and Tab. IV it can be seen that the low cycle fatigue life of alloy 718 is decreased with temperature increased,the cyclic fracture stress σ'_f and fracture ductility ε'_f are reduced from1630 Mpa and 156 % at 360℃ to 1476 Mpa and 18.4 % at 650℃, respectively. In addition, the intersections of elastic and plastic line so called transitional fatigue life N_T are also decreased with the temperature increased. They are $1.1x10^3$, $8x10^2$ and $4x10^2$ corresponding to 360, 550 and 650℃.

The cyclic stress-strain behavior of material is an important part of low cycle fatigue research. The cyclic stress-strain curve of alloy 718 is shown in Fig. 1. The stable stress amplitude vs. cycles curves at strain control for different total strain range are shown in Fig. 2. It is obviously from Fig. 1 and Fig. 2 that alloy 718 belong to cyclic softening material. This result is agreement with the result of reference (9).

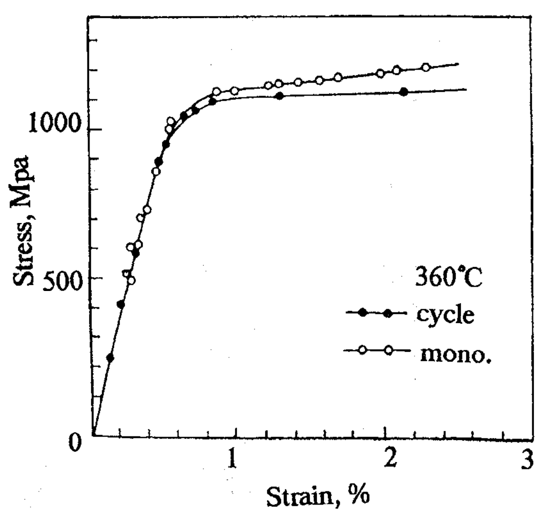

Fig. 1 The cyclic and monotonic σ-ε curves at 360℃

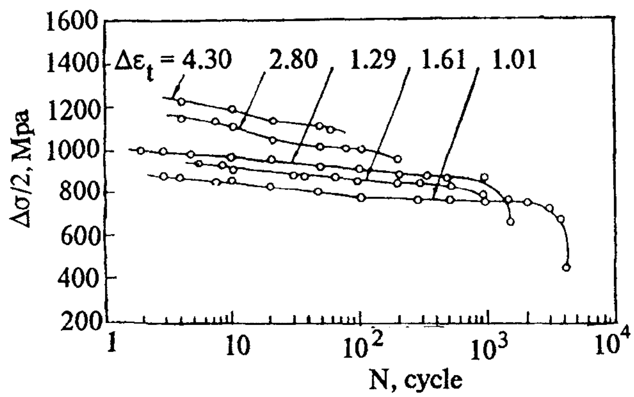

Fig. 2 Δσ/2-N curves at 550℃

<u>Massing Effect</u>

The Massing effect is phenomenon of a material subjected at cyclic plastic deformation. If the material has this character, the cyclic stress-strain curve

$$\Delta\varepsilon_t = \frac{\Delta\sigma}{E} + 2\left(\frac{\Delta\sigma}{2K}\right)^{1/n'} \tag{3}$$

can be represented by the trace line magnified one time of the hysteresis loop. Therefore the Massing effect is very useful for local stress strain method to estimate the structural fatigue life. The hysteresis loops of alloy 718 at 360 and 550°C under different total strain range are shown in Fig. 3. This figure shows that the loading part trace of these hysteresis loops are good superposed and indicates that this alloy has Massing character.

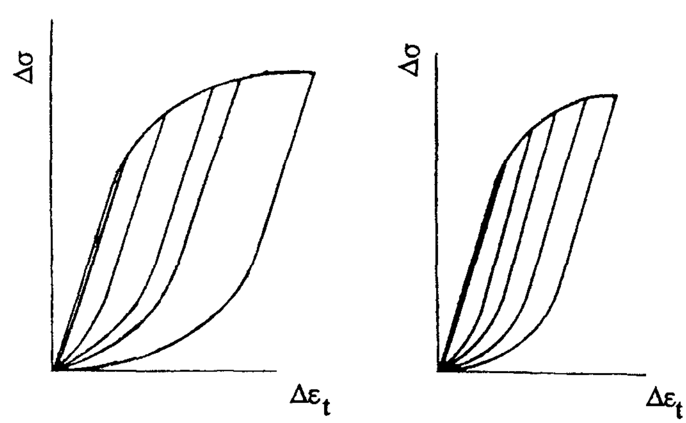

Fig. 3 The hysteresis loops at 350 and 550℃

The LCF Represented by Plastic Strain Energy

The low cycle fatigue damage of material is mainly due to cycle plastic strain energy exhaustion. Let ΔW represent exhausted plastic strain energy, then the increment of plastic strain energy

$$dW=\sigma\, d\varepsilon_p \tag{4}$$

and

$$\Delta W=2\int_0^{\Delta\varepsilon_p}\Delta\sigma\, d\varepsilon_p \tag{5}$$

because

$$\Delta\sigma=K'\Delta\varepsilon_p^{n'} \tag{6}$$

then

$$\begin{aligned}\Delta W&=\frac{2K'}{n'+1}(\Delta\varepsilon_p)^{n'+1}\\&=\frac{2}{n'+1}(\Delta\varepsilon_p)[K'(\Delta\varepsilon_p)^{n'}]\\&=\frac{2}{n'+1}\left(\frac{\Delta\sigma}{2}\right)(\Delta\varepsilon_p)\end{aligned} \tag{7}$$

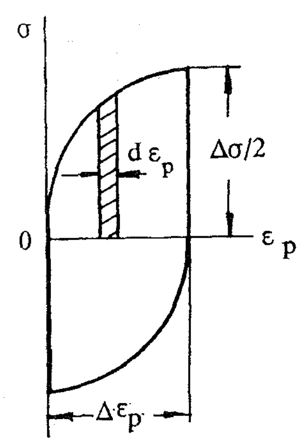

Fig. 4 Plastic strain loop

According to equation

$$\Delta W=C\, N_f^{\gamma} \tag{8}$$

it can be obtained the LCF expressions of plastic strain energy for alloy 718, as follows:

$$\Delta W = 5508\ N_f^{-0.902} \quad (360^\circ C) \tag{9}$$

$$\Delta W = 2253\ N_f^{-0.802} \quad (550^\circ C) \tag{10}$$

$$\Delta W = 572\ N_f^{-0.670} \quad (650^\circ C) \tag{11}$$

The relationship between ΔW and N_f appears a linear relation on the double logistic coordinate as shown in Fig. 5.

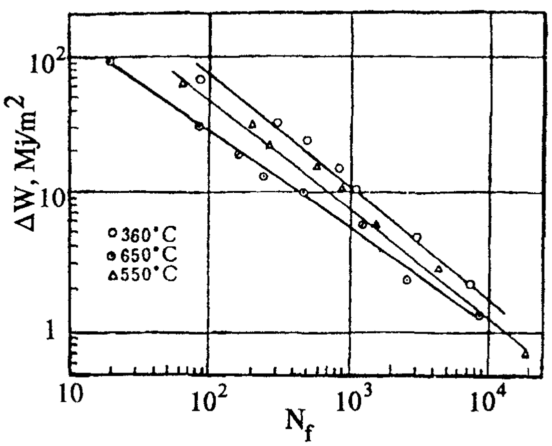

Fig. 5 ΔW-N_f curves

<u>da/dN - ΔK Curves</u>

The da/dN-ΔK curves of alloy 718 at 360, 550 and 650℃ are shown in Fig. 6. Their expressions for Paris' formula are as follows:

$$da/dN = 2.8694 \times 10^{-9} (\Delta K)^{3.1309} \quad (360^\circ C) \tag{12}$$

$$da/dN = 5.4246 \times 10^{-9} (\Delta K)^{3.0313} \quad (550^\circ C) \tag{13}$$

$$da/dN = 1.3131 \times 10^{-7} (\Delta K)^{2.4968} \quad (650^\circ C) \tag{14}$$

Where $\Delta K = K_{max}\,(1\text{-}R)$, K_{max} is the maximum stress intensity factor, R is stress ratio. It is noted that the da/dN is increased with the temperature increased, especially the da/dN at 650℃ is much higher than that of 550℃, while the experimental results at 360℃ and 550℃ are approximate. It can consider that the temperature at 550℃ may be the critical temperature value of fatigue crack growth for alloy 718.

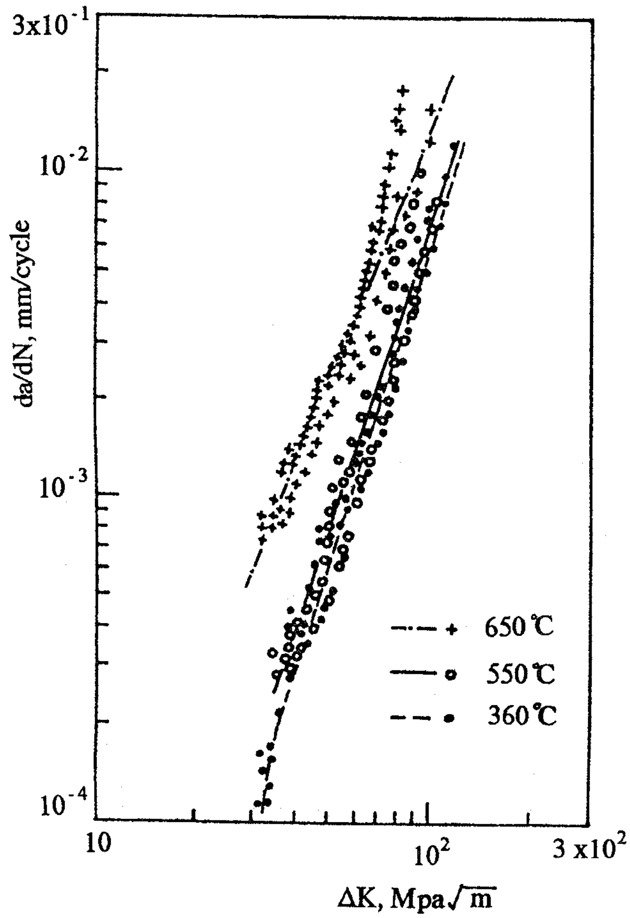

Fig. 6 da/dN-ΔK curves at 360, 550 and 650℃

The Effect of Hold Time on da/dN

In order to simulate the takeoff-cruise-descent operation condition of aero-engine, the effect of hold time at peak load on fatigue crack growth rates was studied at 650℃. Saxena (10) have considered that the fatigue crack growth rate with stress dependent may be represented by

$$\frac{da}{dt}=b\left(\frac{K^2}{t}\right)^p \tag{15}$$

Where b and p are material constant, t is hold time at peak load. If the crack propagation at the hold time, the total crack growth rates can be calculated by superposed principle.

$$\left.\frac{da}{dN}\right)_{total}=\left.\frac{da}{dN}\right)_{t=0}+\int_0^{t_h}\left(\frac{da}{dt}\right)dt \tag{16}$$

Where t_h is hold time, $da/dN)_{t=0}$ is fatigue crack growth rates without hold time. Put equation (15) into (16), it can obtain the total crack growth rates:

$$\frac{da}{dN}\Big)_{total} = \frac{da}{dN}\Big)_{t=0} + \int_0^{t_h} b\left(\frac{K^2}{t}\right)^p dt$$

$$= C_0(\Delta K)^n + A'(\Delta K)^{2p}\, t_h^{(1-p)} \qquad (17)$$

Where $A' = \frac{b}{1-p}\frac{1}{(1-R)^{2p}}$

The da/dN-ΔK curves with hold time 10 s and without hold time are shown in Fig. 7. From Fig. 7 we can see that the crack growth rate with hold time is much higher than that of without hold time. The fatigue crack growth rate expression for equation (17) is as follows:

$$da/dN = 1.3131x10^{-7}\,(\Delta K)^{2.4968} + 4.7276\ x10^{-7}\,(\Delta K)^{2.7824}\, t_h^{-0.3912} \qquad (18)$$

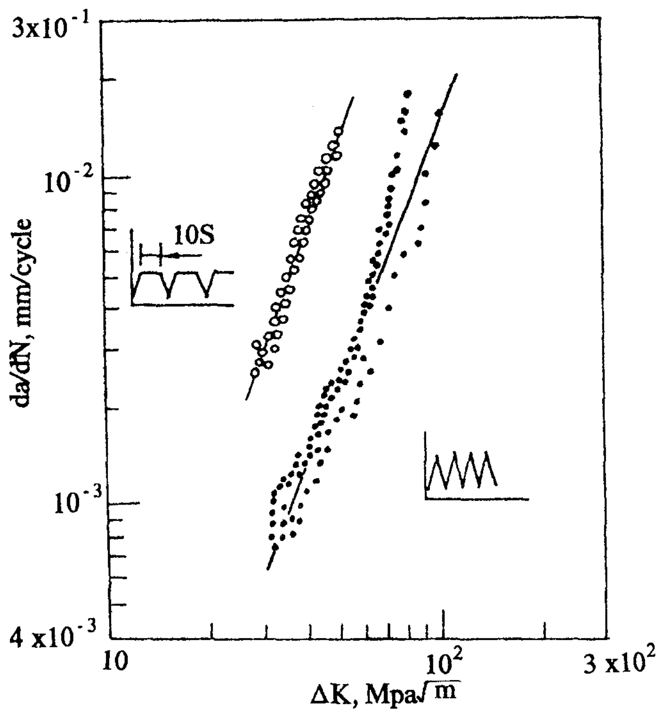

Fig. 7 The effect of hold time on da/dN at 650°C

Conclusions

Through a large number of LCF and fatigue crack propagation experiments for alloy 718, the following conclusions have been obtained:

1. This alloy appears cyclic softening at various temperature.

2. This alloy have Massing character at tested temperature.

3. The reason of LCF life decreased with the temperature increased for alloy 718 is mainly due to the tensile strength and ductility decreased.

4. The relationship between plastic strain energy and fatigue life of alloy 718 is linear relations on double logistic coordinate.

5. From 360°C to 550°C, the change of da/dN of alloy 718 is slight, but da/dN at 650°C is much higher than that at 550°C.

6. The effect of hold time on da/dN is obvious at 650°C, and the da/dN can be calculated by equation (18).

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