FATIGUE CRACK GROWTH BEHAVIORS IN

ALLOY 718 AT HIGH TEMPERATURE

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Abstract

The fatigue crack growth rates of alloy 718 were studied in detail at 550 and 650℃ to offer the data for design selected and life estimated of turbine disk. In addition, to simulate the takeoff-cruise-descent operation condition of air engine, and to study the effect of creep on fatigue crack growth rate at high temperature, the effect of hold time at peak load on fatigue crack growth rate has been studied also.

Superalloys 718, 625, 706 and Various Derivatives
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Introduction

In resent 20 years , the investigation of low cycle fatigue (LCF)behavior and fatigue crack growth rate (da/dN) for superalloys used to turbine engine have been emphasized(1-5). Particularly, the LCF and its da/dN properties of turbine disk alloys are considered to be a critical factor for material selected and life estimated(6). This is due to some needs of advanced performance, structural integrity, safe reliability and maintainability of air engine, and the designer adopts the fatigue and damage tolerance design technology. Therefore, the requirement of fatigue crack growth behavior of superalloys is more and more urgent.

In this paper according to the requirements of material research and life estimation, the fatigue crack growth rate and effect of hold time on fatigue crack growth rate of alloy 718 were studied at high temperature.

Material and Experimental Procedure

The material used is a disk of alloy 718. the diameter is 500mm, and the chemical composition is listed in Table I. The heat treatment regime is direct ageing, 720℃ 8hrs with 50℃/hr furnace cold up to 620℃ 8hrs air cold. The conventional mechanical properties obtained are listed in Table II.

Table I Chemical Composition of Alloy 718

C	Cr	Mo	Ti	Nb	Ni	Fe
0.035	19.90	3.06	0.99	5.05	52.0	bal.

Table II Conventional Mechanical Properties of Alloy 718

Temp (℃)	UTS (MPa)	YS (MPa)	Elong (%)	AR (%)	E (GPa)
R.T.	1515	1328	14.2	21.7	206.3
650	1232	1087	25.2	55.6	143.8

The specimen of fatigue crack growth rate used is WOL-type one with 10mm thickness as shown in Fig.1. The expression of stress intensity factor (7) is

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

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

P	load (kN)
a	crack length (mm)
B	specimen thickness (mm)
W	specimen width (mm)

The da/dN tests were conducted with tension to tension load control, stress ratio R=0.1, using the frequency f=1Hz triangular wave for continual cycle loading and trapezoid wave form with hold time 15s on upper peak load for hold time tests as shown in fig.2. The fatigue crack growth tests were performed in a servo-hydraulic fatigue testing machine MTS-809 type with a high temperature furnace. The testing temperature is equal to 550 and 650℃, using the pulsed D.C.potential drop method to measure the fatigue crack length.

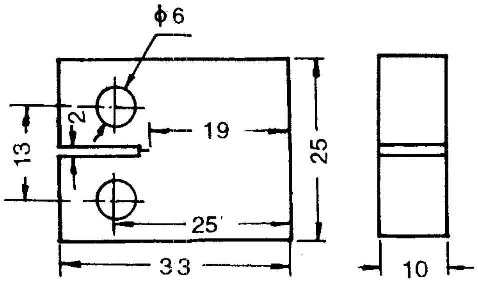

Fig.1 WOL-type da/dN specimen

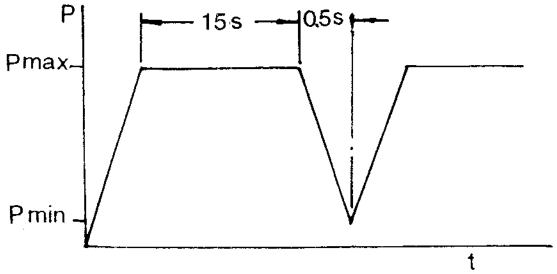

Fig.2 Trapezoid wave form and its parameters

Experimental Results

da/dN-ΔK Curve

The da/dN-ΔK curves of alloy 718 at 550 and 650℃are shown in Fig.3. according to the Paris formula

$$\frac{da}{dN} = C(\Delta K)^n \qquad (2)$$

it is fitted the data in Figure 3. We have got two relationships.

$$\frac{da}{dN} = 2.23 \times 10^{-8} (\Delta K)^{2.66} \qquad (550℃) \qquad (3)$$

$$\frac{da}{dN} = 2.69 \times 10^{-7} (\Delta K)^{2.17} \qquad (650℃) \qquad (4)$$

Where $\Delta K = K_{max}(1-R)$, K_{max} is the maximum stress intensity factor, R is stress ratio.
From Fig.3 it is obviously seen that these curves appear an opposite direction "S". Therefore, when we use the Paris formula to fit the data on these curves from beginning to ending, it must be to take place some error. Thus in order to describe these curves better, we have adopted an expression in reference(8)

$$\frac{da}{dN} = e^B \left(\frac{\Delta K}{K_{th}}\right)^P \ln\left(\frac{\Delta K}{K_{th}}\right)^Q \ln\left(\frac{K_c}{\Delta K}\right)^R \qquad (5)$$

where K_{th} threshold stress intensity factor (MPa $\sqrt{m}$)
Kc plane stsess fracture toughness (MPa $\sqrt{m}$)
B, P, Q, R constants

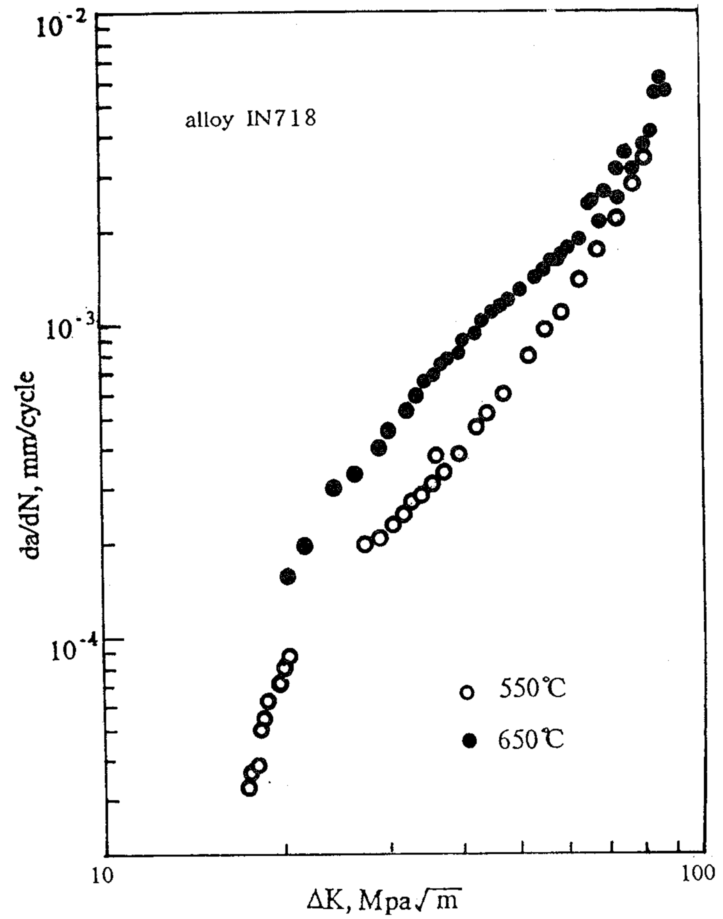

Fig.3 da/dN-ΔK curves of alloy 718 at 550 and 650℃

By means of eguation (5) to fit the data in Fig.3, it can be obtained the da/dN-ΔK relationship as follows

$$\frac{da}{dN} = e^{-8.13}\left(\frac{\Delta K}{17}\right)^{0.4}\ln\left(\frac{\Delta K}{17}\right)^{0.46}\ln\left(\frac{105}{\Delta K}\right)^{-1.18} \qquad (550℃) \qquad (6)$$

$$\frac{da}{dN} = e^{-7.68}\left(\frac{\Delta K}{15}\right)^{0.53}\ln\left(\frac{\Delta K}{15}\right)^{0.94}\ln\left(\frac{94}{\Delta K}\right)^{0.37} \qquad (650℃) \qquad (7)$$

The comparison of da/dN calculated results from equation (2) and (5) are listed in Table III.

Table III The Comparison of da/dN Calculated Results from Equation(2)and(5)

ΔK	550℃			650℃		
MPa $\sqrt{m}$	eq.(2)	eq.(5)	δ%	eq.(2)	eq.(5)	δ%
20	6.44×10^{-5}	7.50×10^{-5}	14	1.77×10^{-4}	1.42×10^{-4}	25
30	1.89×10^{-4}	2.18×10^{-5}	13	4.27×10^{-4}	4.50×10^{-4}	5
40	4.07×10^{-4}	4.03×10^{-4}	1	7.97×10^{-4}	8.09×10^{-4}	1.5
50	7.37×10^{-4}	6.68×10^{-4}	10	1.29×10^{-3}	1.23×10^{-3}	5
60	1.20×10^{-3}	1.08×10^{-3}	11	1.91×10^{-3}	1.76×10^{-3}	8.5
70	1.80×10^{-3}	1.77×10^{-3}	2	2.68×10^{-3}	2.47×10^{-3}	8.5
80	2.57×10^{-3}	3.11×10^{-3}	17	3.58×10^{-3}	3.58×10^{-3}	1

The Effect of Hold Time on da/dN

In order to simulate the takeoff-cruise-descent operation condition of air-engine and to study the influence of creep on low cycle fatigue crack growth rate, the effect of hold time at peak load on fatigue crack growth rates was studied at 650℃. The results obtained is shown in Fig.4. It is seen that the crack growth rate with hold time is increased in the large stress intensity factor range but in the lower stress intensity factor range it is decreased. It may be two mechanism in this condition, that is advanced and retarded action mechanism. At the intersection point of two curves with and without hold time, the action of two mechanisms is just the same.

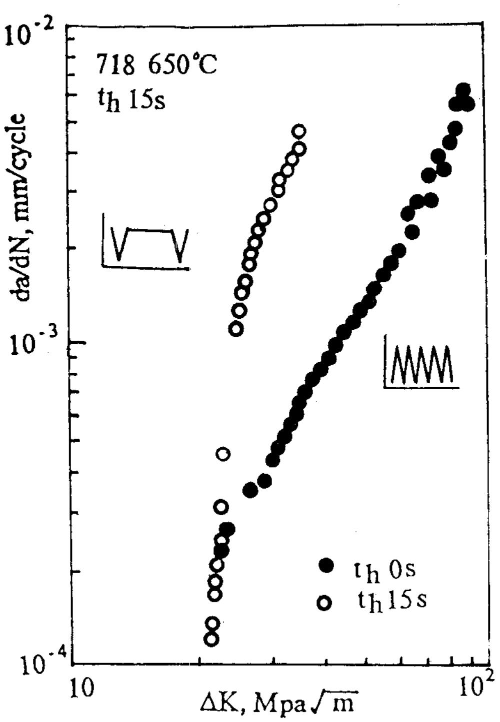

Fig.4 The crack growth behavior with and without hold time at 650℃ for alloy 718

DISCUSSION

The crack Growth Model With Hold Time In order to predict the crack growth rate with hold time, some scholars have studied a lot of models and mechanisms under the interaction of fatigue and creep. Saxena(9)have considered that the fatigue crack growth rate with stress dependent may be represented by

$$\frac{da}{dt} = b(\frac{K^2}{t})^p \tag{8}$$

Where b and p are material constants, t is hold time at upon peak load, K is stress intensity factor at crack tip. If the crack propagating at hold time, the total crack growth rate can be calculated by superposed principle.

$$(\frac{da}{dN})_{total} = (\frac{da}{dN})_f + \int_0^{t_h} (\frac{da}{dt})dt \tag{9}$$

Where t_h is hold time, $(da/dN)_f$ is pure fatigue crack growth rate without hold time, da/dt is creep crack growth rate. Put equation (8) into (9), it can be obtained the total crack growth rate:

$$(\frac{da}{dN})_{total} = (\frac{da}{dN})_f + \int_0^{t_h} b(\frac{K^2}{t})dt \tag{10}$$

If $(da/dN)_f$ is represented by Paris equation, $da/dN=c(\Delta K)^n$, then

$$(\frac{da}{dN})_{total} = C(\Delta K)^n + A'(\Delta K)^{2P} t_h^{(1-P)} \tag{11}$$

where $A' = \frac{b}{1-P}\frac{1}{(1-R)^{2P}}$.

The schematic illustration of equation(9) is shown in Fig.5.

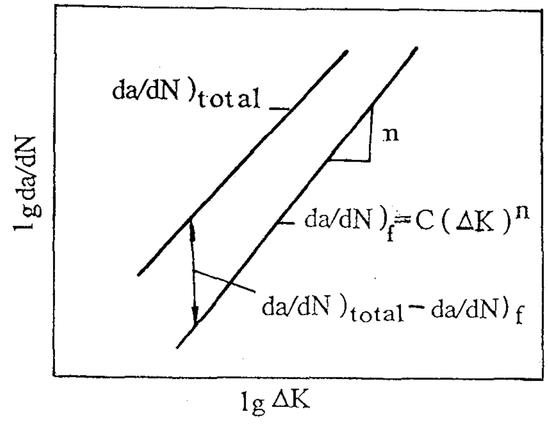

Fig.5 The calculated method of crack growth model with hold time

Saxena(9、10) have successfully processed the data of alloy 718 at 538℃ with hold time bs. 60s using equation(11) and obtained a good results. Therefore, the data of alloy 718 at 650℃ with hold time 15s were reduced by this equation and obtained a result as follows

$$(\frac{da}{dN})_{total} = 2.69 \times 10^{-7}(\Delta K)^{-7} + 6.8 \times 10^{-8}(\Delta K)^{3.69} t_h^{-0.8} \tag{12}$$

However in equation (12) the exponent of t_h is negative. The meaning is that the more t_h , the smaller $t_h{}^{1-p}$. In other words, the value of (da/dN) total will be decreased with the t_h increased. The result may be not conformed with actual condition.

In order to process the experimental data of these paper better, we have adopted an expression of moment creep crack growth:

$$\frac{da}{dt} = AK^m \tag{13}$$

Where A and m are material constants, K is stress intensity factor at crack tip. Put equation(13)into equation(9), we can obtain

$$\begin{aligned}(\frac{da}{dN})_{total} &= (\frac{da}{dN})_f + \int_0^{t_h} AK^m dt \\ &= C(\Delta K)^n + A''(\Delta K)^m t_h \end{aligned} \tag{14}$$

Where $A''=A(1-R)^m$, R is stress ratio. The schematic illustration of equation(14) is shown in Fig.6. The crack growth data for alloy 718 with hold time 15s at 650℃ were fitted by equation(14) and obtained the result as follows:

$$(\frac{da}{dN})_{total} = 2.69 \times 10^{-7}(\Delta K)^{2.17} + 4.59 \times 10^{-10}(\Delta K)^{3.69} t_h \tag{15}$$

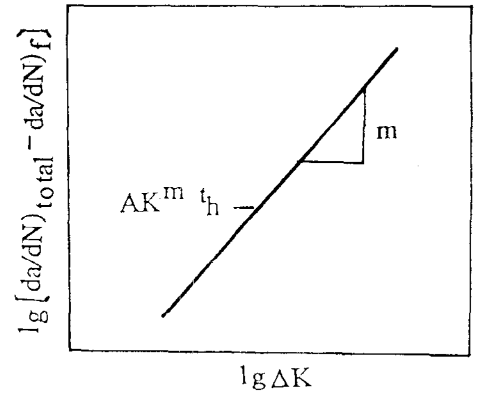

Fig.6 The calculated method of crack growth model (14) with hold time

The above mentioned result show that the total crack growth rate is increased with the hold time t_h increased. This equation(14) may fit the crack growth data with longer hold time at 650℃.

It is noted that the first term on right of equation (14) is continual cycle fatigue crack growth rate, and often adopt Paris formula. However, this formula is mainly used for the second stage of fatigue crack growth. Therefore, some data at the beginning or ending of crack growth are not inclusive, especial the data in the first stage of da/dN-ΔK curve.

CONCLUSIONS

The fatigue crack growth behaviors of alloy 718 and the effect of hold time on fatigue crack growth rate were investigated at 550 and 650℃. The results show that:

The crack growth rate with hold time will be greatly increased at the creep temperature range of material.

It was presented a corrective Saxena's crack growth model with hold time to apply the crack growth rule at 650℃ condition.

$$(\frac{da}{dN})_{total} = C(\Delta K)^n + A''(\Delta K)^m t_h$$

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