

FATIGUE CRACK PROPAGATION OF Ni-BASE SUPERALLOYS

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Manuscript received 1 September 2004

Time-dependent Fatigue Crack Propagation (FCP) behaviors of five Ni-base superalloys were investigated at various temperatures under fatigue with various holding times and sustained loading conditions. The new concept of damage zone is defined and employed to evaluate the alloys' resistance to hold-time FCP. A special testing procedure is designed to get the maximum damage zone of the alloys. Udimet 720 and Waspaloy show shorter damage zones than alloys 706 and 718. The fractographical analyses show that the fracture surfaces of the specimens under hold-time fatigue conditions are mixtures with intergranular and transgranular modes. As the extension of holding time per cycle, the portion of intergranular fracture increases. The effects of loading stress intensity, temperature, holding time, alloy chemistry, and alloy microstructure on damage zone and the crack growth behaviors are studied. Hold-time usually increases the alloy's FCP rate, but there are few exemptions. For instance, the steady state hold-time FCP rate of Waspaloy at 760°C is lower than that without hold-time. The beneficial effect of hold-time was attributed to the creep caused stress relaxation during the hold-time.

KEY WORDS Ni-base superalloys, fatigue crack growth, hold-time

1. Introduction

Large civil fixed wing aircraft, and many military aircraft are designed using damage tolerance (DT) approach such as in accordance with Civil Aviation Authority (CAA) and Federal Aviation Authority (FAA) regulatory requirements. Rotary winged aircraft are still designed using safe life (SL) approach. The SL design philosophy provides the estimation of the live for the component or structure in examination and ensures that during the specified life, the probability of premature failure is suitably remote. The DT design philosophy is a derivation of the SL philosophy. It states that when a component or structure enters in service has already flaws or cracks, however uses linear elastic fracture mechanics (LEFM) theory to predict the rate of crack growth. So the crack growth rate must be shown to produce cracks of sufficient size that can be detected by periodic inspection before the crack size results dangerous for the safety of the component or structure^[1]. Therefore, it is critical to study the fatigue crack propagation (FCP) behaviors of Ni-base superalloys.

FCP behavior of nickel-base superalloys has been studied for more than 30 years^[2]. In recent years, many models for the fatigue crack growth have been proposed based on the fracture mechanics. Most of the models^[3-8] have an exponential relationship between da/dN and ΔK . Different exponents have been obtained in different models. Although theoretically the LEFM approach can only be employed in entire elastic condition, it has been confirmed that LEFM is still valid under small yielding area condition

rienced various heat treatments are shown as Fig.1. There are continuous β precipitates along grain boundaries of the specimen under β treatments. On the contrary, for the one under no β treatments, only a few β particles, which are believed to be the leftover during the solution stage, are found at grain boundaries.

Table 1 Chemical compositions (wt%) of tested materials

Alloy	C	Fe	Ni	Cr	Al	Ti	Co	Mo	Nb	W
In718	0.033	17.94	Bal.	18.41	0.56	0.91	-	3.03	4.98	-
In706	0.021	36.84	Bal.	16.07	0.23	1.85	0.028	0.05	3.05	0.001
U720	0.013	0.14	Bal.	16.14	2.48	5.15	14.45	2.85	-	1.18
Waspaloy	0.019	0.38	Bal.	19.55	1.37	2.95	13.51	4.25	0.01	0.06
In783		24.88	28.21	3.24	5.32	0.32	34.39	-	3.11	-

2.2 Characterization of maximum damage zone

In this investigation, a new concept of damage zone was introduced to study the hold-time fatigue crack growth of superalloys. Damage zone was defined as the area surrounding the crack tip where the material's resistance to crack growth was damaged by previous mechanical loading and/or environmental degradation. A special series of tests were conducted to characterize the alloys' damage zones. Single-edge-notched (SEN) plate type of specimens with a gauge section of 3.2mm thickness and 19mm width were employed in the tests. The DC potential drop technique was utilized to monitor crack length during tests. A 3.81-mm-deep notch was introduced at the center of the opposite edge of current outlets by a wire electro-discharge-machine (EDM). Each specimen was pre-cracked at a low ΔK level for 1.25mm crack growth away from the EDM notch. This procedure ensured that the crack growth reached a steady state and was no longer affected by the starter notch geometry. As shown in Fig.2, the specimen was pre-cracked, then was heated to a higher temperature and was subjected to constant stress intensity sustained loading. After a period of sustained loading, it was cooled to the room temperature and the fatigue tests were conducted with the frequency of 1/6Hz. The max K employed in this case was same as that of sustained loading. The max damage zone sizes of the materials were obtained from this test sequence. Also, the effect of temperature and the stress intensity on the damage zone size of material was investigated in this study.

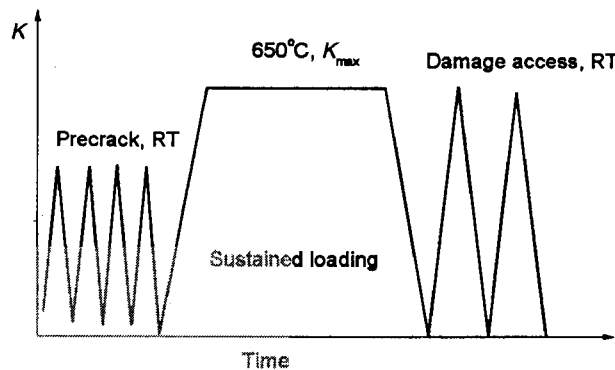


Fig.2 A sketch of the testing procedure to measure the damage zone size.

2.3 Fatigue crack propagation tests

The FCP tests were carried out at 538, 650, 706 and 760°C. The loading cycles included 3 seconds triangle waveform and trapezoid waveform with 3 seconds ramp and different hold-time at max load.

Finally the specimen was broken to calibrate the crack size.

3. Experimental Results

3.1 Damage zone characterization

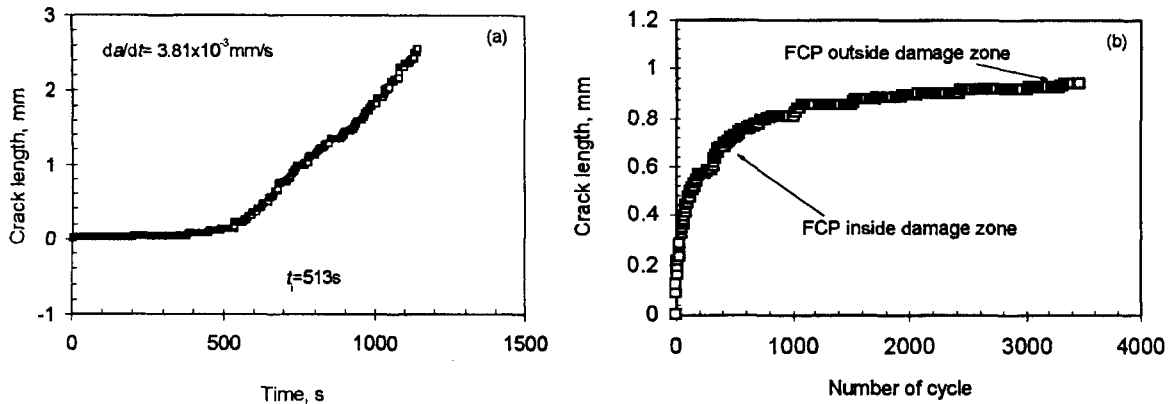


Fig.3 Damage zone characterization of Inconel 783: (a) crack growth during sustained loading at 650°C; (b) crack growth during the following room temperature fatigue test.

Fig.3 shows the typical crack growth behaviors of Inconel 783 during damage zone characterization test. It should be pointed out that the crack growth tests are under constant K control. As shown in Fig.3a, during the high temperature sustained loading, the crack length remains unchanged for 500 seconds, and then the crack starts to grow. The incubation time and da/dt can be measured during this stage. The existence of a damage zone in front of the crack tip was confirmed by the curves. Comparing with the final crack growth rate (Fig.3b), the crack grew much faster in the material closer to the crack tip after sustained loading. The da/dN within damage zone decreases monotonically with the crack length. It is clear that the damage is localized and the material outside the damage zone is not damaged. The size of damage zone formed during sustained loading can be easily measured in Fig.3b.

3.2 Hold-time fatigue crack propagation

Fig.4 shows the fatigue crack propagation rates of Waspaloy, U720, 706 and 718 as a function of holding time at the maximum stress intensity at 650°C. It is indicated that all of the four alloys have similar growth rates under 3 seconds loading. The crack growth rates of 3+10 seconds and 3+30 seconds show obvious time-dependence for U720, In706 & In718. With the increase in holding time, the growth rates increase linearly for these three alloys. It is clear that alloy 718 shows the strongest time-dependency of FCP. Waspaloy and U720 show better resistance against the hold-time crack growth than alloys 706

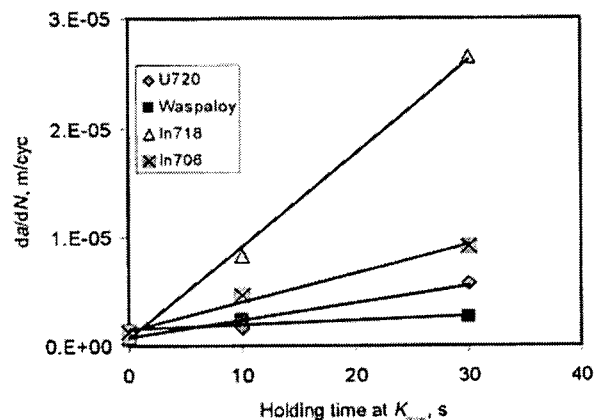


Fig.4 FCP rates of the superalloys as a function of holding time at maximum load.

and 718. The crack growth rates of Waspaloy are cycle dependent with less than 30 seconds holding under 650°C.

Fractography analyses of the fractured surfaces of the specimens were conducted by means of SEM. Typical graphs of U720 are shown in Fig.5. It is clear that the failure mode of pre-crack at room temperature is transgranular and ductile with a small area of quasi-cleavage. Some fatigue striations can be found on the surfaces. The rough surface indicates a high-energy mode of failure with no secondary cracking. The fracture mode of fatigue at 650°C is both intergranular and transgranular with secondary crack, regardless of the difference in holding time. The proportion of intergranular crack increases with the increase of hold time. The large number of small particles is believed to be primary γ' .

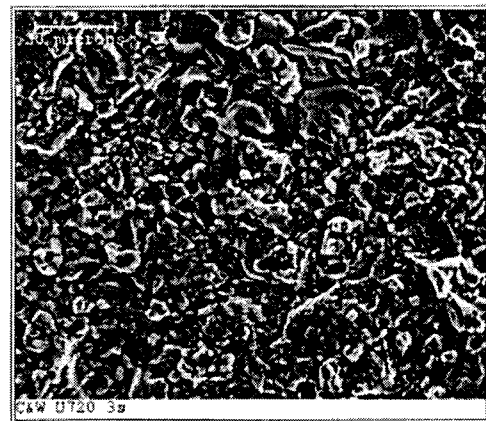
4. Discussions

4.1 Damage zone vs. fatigue crack propagation

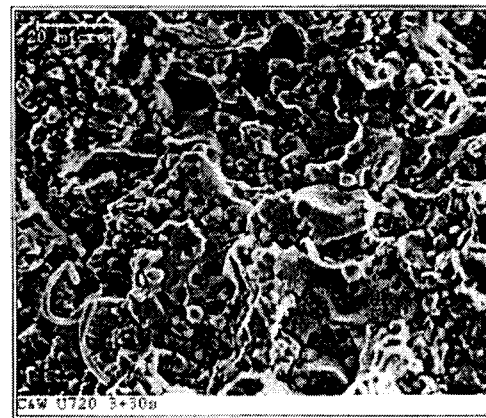
It is well known that during the cycle dependent fatigue, the material in front of the crack tip is damaged only by cyclic loading. However, if the test is conducted in air at high temperature and there is hold-time at max load in fatigue cycle, the time-dependent behaviors must be taken into consideration. Damage by cyclic loading accounts for a very less amount of the total damage of materials. It has been mentioned in the "introduction" section that the time-dependent fatigue crack growth is attributed as the result of SAGBO. During the hold-time at maximum loading, the material in front of the crack tip is damaged by the diffusion of oxygen, and the resistance against cracking is significantly lowered. During the next unloading and loading, the crack will pass through the damage zone and result in fast crack growth. This kind of crack growth is obviously time-dependent. The size of damage zone represents the resistance of materials against the crack growth. Therefore, a new concept, damage zone is defined as: the area in front of the crack tip, where the material is damaged by the oxygen diffusion and the resistance of



(a)



(b)



(c)

Fig.5 SEM fractography of Udimet720 after fatigue crack growth tests: (a) pre-crack, U720; (b) fatigue, 3 seconds, U720; (c) fatigue, 3+30 seconds, U720

material to crack growth is lower than a criterion which can prevent the crack growth during the fatigue cycle. In this paper, the existence of damage zone in front of the crack tip has been confirmed by the special designated test sequence (Fig.3).

The damage zone size of superalloys can be linked with their resistance to time dependent fatigue crack growth. Fig.6 shows the comparison on the damage zone sizes and the hold-time FCP rates of 718, 706, U720 and Waspaloy. The damage zone sizes of 718 and 706 are higher than that of U720 and Waspaloy. Comparing the damage zone sizes with FCP rates, it can be inferred that the hold-time FCP increases as of the damage zone size. Therefore, the damage zone size of the materials can be employed to evaluate the its' resistance to time-dependent FCP. The alloy with smaller damage zone size has better resistance to time-dependent crack growth. The beneficial effect of β phase on the hold-time FCP behavior of Inconel 783 is shown as Fig.7. It was found that β phase prevent the formation of damage zone at 650°C. The crack of the specimen with β phase did not growth after 60 hours holding. There is no damage zone show up during the following damage access stage. The hold-time FCP rate of the one with β phase is much lower than the one without β , although the cycle-dependent FCP rates of the alloy under various heat treatments are similar. β phase improves the resistance of the alloy to SAGBO.

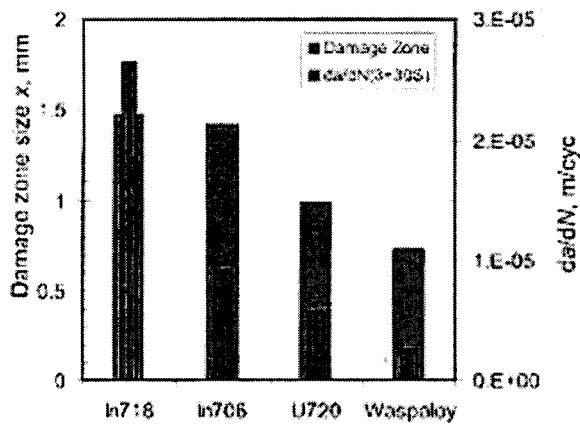


Fig.6 Comparison on the damage zone sizes and hold-time FCP (3+30S) rates of the alloys.

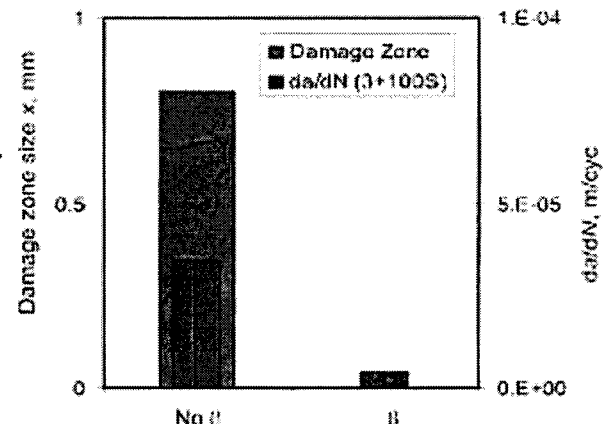


Fig.7 Comparison on the damage zone sizes and hold-time FCP (3+100S) rates of In783 under various heat treatments.

4.2 Damage zone vs. sustained load crack propagation

Fig.8 presents the damage zone size (x) of Inconel 783 alloy as a function of the hold period (t) at different temperatures. Of interest to note in Fig.8a is that at each temperature the damage zone size (x) has a linear relationship with the holding period (t). This suggests that formation of the damage zone reflects a thermally activated process. An Arrhenius equation can be used to correlate damage zone size (x), hold period (t), and temperature (T) as shown in Eq.(1)

$$x = C_0 \cdot t \cdot \exp\left(\frac{-Q}{RT}\right) \tag{1}$$

where C_0 is a constant, and t is the hold period. The slope of parallel lines in Fig.8a gives a Q average

value of 239kJ/mol. The value of Q is 255kJ/mol for the oxidation of nickel-base superalloy at high temperature [19]. The comparable value of Q suggests that the formation of damage zone during hold time is thermally activated. Fig.8b compares the propagation rate of damage zone (dx/dt) and sustained loading crack growth rate (da/dt). The fact that two sets of data, (dx/dt) and (da/dt), are identical indicates that the sustained loading crack growth is indeed a result of oxygen embrittlement in the damage zone.

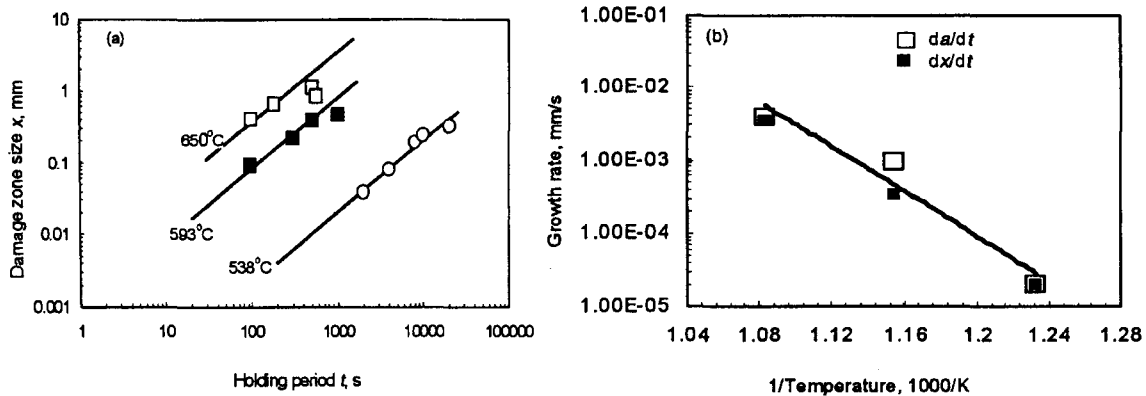


Fig.8 Damage zone measurement: (a) damage zone size (x) as a function of holding period (t) at $K_{max} = 38.5\text{MPa} \cdot \text{m}^{1/2}$; (b) comparison of da/dt and dx/dt .

4.3 Effect of creep on fatigue crack propagation

Fig.9 shows the results of fatigue crack growth tests under constant ΔK control at 760°C. It is interesting that under lower stress intensity factor, the crack growth rates for 3+100 seconds are lower than that for 3 seconds. When K_{max} was increased to 32.5MPa \cdot m^{1/2}, the crack growth rate of 3+100 seconds became higher than that of 3 seconds. The results at 760°C show that under lower ΔK condition, the hold-time plays a beneficial role, instead of harmful one, on the fatigue crack growth behavior of Waspaloy alloy. However, if the stress intensity factor is higher than a critical value, the hold-time shows its harmful effect.

The results of fatigue crack growth test under constant load show similar trend with the ones under constant ΔK control. As shown in Fig.10, at the beginning of the tests, K value was relatively low, and fatigue crack growth rates of the specimen under hold-time fatigue condition were lower than that of the specimen under "pure" fatigue condition. As ΔK increases, fatigue crack growth rates with hold-time become closer to that without holding time. Finally, the fatigue crack growth rates with hold-time are higher than that without holding.

There are two things happen during the hold-time, creep and environmental degradation. It is known that environmental effect is always a harmful one. Oxygen diffuses into the grain boundary in front of the crack tip and decreases the cohesion of the grain boundary and the alloy's resistance to crack growth. Therefore, the beneficial effect of the hold-time should be attributed to the creep effect. The effect of hold-time on fatigue crack growth depends on the competition between beneficial effect of creep and detrimental environment effect.

During the hold-time fatigue crack growth test, the creep behavior of the specimen is not homogeneous because of stress concentration in front of the crack tip. During the first several cycles, there is only primary creep zone in front of the crack tip. As creep develops, steady state creep zone appears which is surrounded by primary creep zone. During the last stage of the test, there is tertiary creep zone shows

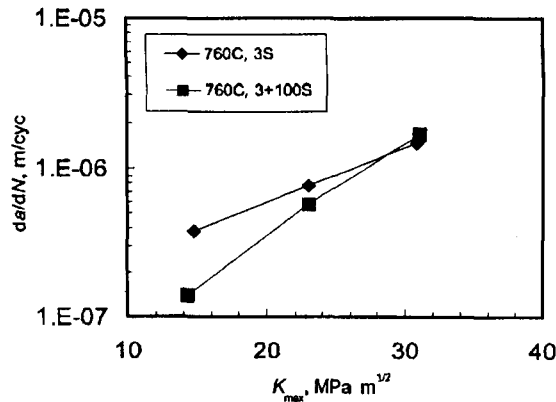


Fig.9 Effect of K on fatigue crack growth of Waspaloy alloy at 760°C under 3 seconds and 3+100 seconds loading (constant K control).

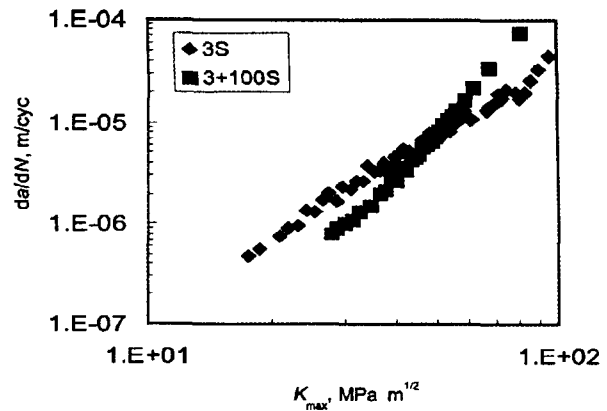


Fig.10 Effect of K on fatigue crack growth of Waspaloy alloy at 760°C under 3 seconds and 3+100 seconds loading (constant load control).

up, which is surrounded by steady state and primary creep zones and there are large amount of creep cavities inside this zone.

Riedel *et al.*^[20, 21] analyzed the creep behavior in front of the crack tip. If a load is applied and then held constant, a creep zone gradually develops in plastic zone. They proposed that the stresses' well within the creep zone could be described by

$$\sigma_{ij} = \left(\frac{C(t)}{A I_r} \right)^{\frac{1}{n+1}} \hat{\sigma}_{ij}(n, \theta) \quad (2)$$

where n is the exponent in the creep equation, A , I_r are numerical constants, $\sigma_{ij}(n, \theta)$ is a variable as a function of n and θ , r is the distance from the crack tip. $C(t)$ is a parameter that characterizes the amplitude of the local stress singularity in the creep zone.

$$C(t) = \frac{K_I^2(1-\nu)^2}{(n+1)Et} \quad (3)$$

where K_I is the first mode stress intensity factor, ν is the Poisson ration, E is the Young's modulus and t is hold-time. $C(t)$ varies with time and is equal to C^* in the limit of long time behavior^[22]. If the remote load is fixed, the stresses in the creep zone relax with time, as creep strain accumulates in the crack tip region. The "effective" stress is lowered by stress relaxation during hold time, which shows that creep plays a beneficial role on fatigue crack growth by stress relaxation.

4.4 Effect of hold-time on fatigue crack propagation of superalloys

Fatigue crack growth behavior can be divided into two categories: cycle-dependent and time-dependent. For cycle-dependent fatigue crack growth, the steady state crack growth rate has been considered to be insensitive to the variations of microstructure and alloy chemistry^[22], although there are some results showing that the resistance of superalloy to fatigue crack growth can be slightly improved by shot peening^[23] composition adjustment^[24] and microstructure control^[25].

If the test is conducted at high temperature in air, fatigue crack growth rate may increase with

hold-time; this kind of behavior is called time-dependent fatigue crack growth. The results of this investigation show that hold-time fatigue crack growth rates of all the five alloys at 650°C increase with hold-time. However, hold-time fatigue crack growth rate of Waspaloy is lower than "pure" fatigue crack growth rate at higher temperature (760°C) and low ΔK . Hold-time shows a beneficial effect on fatigue crack growth of Waspaloy. As discussed above, the beneficial effect of the hold-time was attributed to the creep effect. Therefore, the effect of hold-time on fatigue crack growth depends on the competition between beneficial effect of creep and detrimental environment effect.

It should be pointed out that the effect of hold-time on fatigue crack growth might not be the same during different stages of the test. Fig.11 shows the crack propagation behaviors of Waspaloy at the beginning of fatigue crack growth tests with and without hold-time. At the beginning of the test without hold-time, there is an incubation time within which no crack growth occurs, then followed by a transition area. Finally, the steady state crack growth was obtained. The crack growth behavior of the alloy at the early stage of the test with 100 seconds holding is totally different compares with the one without hold-time. There is no incubation time under the test with hold-time. At the beginning, the crack propagates very fast and gradually slows down to the steady state. Therefore, the effect of hold-time is harmful and then gradually changes to beneficial. According to the previous analyses, at the beginning of the test, environmental effect dominates the whole hold-time effect and makes it harmful on the fatigue crack growth. However, the development of beneficial creep effect in front of the crack tip gradually overcomes the harmful environmental effect, which makes the total effect of hold-time becomes beneficial.

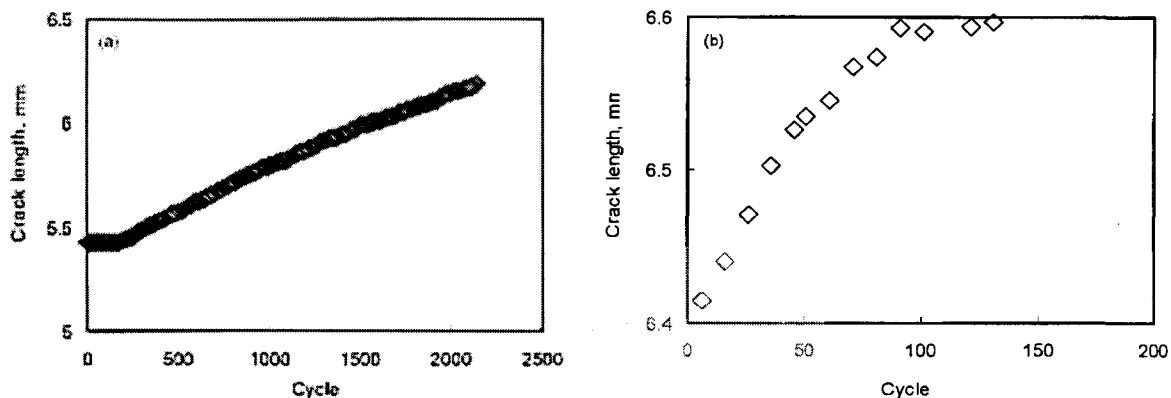


Fig.11 Crack propagation behaviors of Waspaloy at the beginning of fatigue crack growth tests with and without hold-time: (a) 760°C, 3 seconds, constant K control, $K_{\max} = 16.5 \text{ MPa} \cdot \text{m}^{1/2}$, $R = 0.1$; (b) 760°C, 3+100 seconds, constant K control, $K_{\max} = 16.5 \text{ MPa} \cdot \text{m}^{1/2}$, $R = 0.1$.

5. Conclusions

Time-dependent FCP behaviors of five Ni-base superalloys, including alloys 718, 706, 783, U720 and Waspaloy, have been investigated at various temperatures under fatigue with various holding times and sustained loading conditions. A new parameter, damage zone, to investigate the crack growth behavior during hold-time fatigue was defined and confirmed a special designed test. Several conclusions were drawn in this investigation:

- (1) In the cycle dependent regime of fatigue crack propagation, crack propagation rates of the al-

loys is not sensitive to the alloy chemistry, microstructure and loading frequency.

(2) In the time dependent regime of fatigue crack propagation, environmental degradation plays the key role of time-dependency of crack propagation rates. The concept of damage zone size, proposed in this paper can be measured and employed to evaluate the alloy's resistance to time dependent FCP. The alloy with the smallest damage zone size shows the best resistance to hold-time FCP.

(3) Microstructure plays important role in time dependent FCP. For instance, β -NiAl precipitates along the grain boundaries in Inconel 783 alloy.

(4) During the steady-stage hold-time FCP of Waspaloy, stress relaxation caused by creep lowers the stress concentration in front of the crack tip, and fatigue crack growth rates of the alloy. Therefore, creep plays a beneficial role during this stage of hold-time FCP. However, creep damage leads to cavity nucleation and growth at the grain boundaries, which accelerate fatigue crack propagation of the alloy in the final stage.

(5) The time dependent fatigue crack propagation of Ni-base superalloys is very completed. The effect of hold-time on fatigue crack growth depends on the competition between beneficial stress relaxation effect and harmful creep damage plus environmental effect.

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