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INFLUENCE OF TEMPERATURE ON FATIGUE CRACK PROPAGATION IN TiAl ALLOYS*

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Experimental investigations of fracture toughness for a TiAl-based γ-alloy were performed at different temperatures. The temperature effect on fatigue crack growth behavior is evaluated, the formula describing its rate in range to II (stable propagation) was derived, as well as specific values of equation constants were obtained on the basis of experimental results. Tests were conducted in vacuum at 25, 750, and 850°C. The experimental results demonstrate that temperature exerts great influence on fatigue crack growth rates. With an increase in temperature up to 750°C, the growth rate of such cracks increases, after reaching this temperature, the brittle-ductile transition of a TiAl-based alloy is taking place. A similar relationship is also observed for conventional alloys.

Keywords: fatigue crack growth, TiAl alloy, temperature.

Introduction. Significant interest in TiAl alloys for high-temperature structural applications is determined by some of their advantages over conventional metallic systems [1–3]. TiAl-based alloys are promising structural intermetallic materials, which may be considered as potential high-temperature materials. γ-TiAl alloys are highly competitive materials for heat-resistant structural parts of aerospace, aviation, and automotive engines. The effect of temperature can be of great significance for γ-alloys as these materials undergo the brittle–ductile transition at about 700°C [4]. Fatigue fracture at high temperatures was predominantly intergranular, probably, due to a higher slip activity, inducing crack initiation in these ranges [5]. An increase in temperature enhances the fatigue crack growth resistance only in inert environment. The fatigue resistance does not significantly degrade with temperature, at least up to 800°C. While the fatigue crack growth resistance is almost unaffected under 500°C, it grows above 500°C, and mainly at high crack growth rates, which results in flatter slope of the da/dN curve [6]. Therefore, it is essential to study the influence of temperature on fatigue crack propagation in γ-TiAl alloys.

Based on the experimental data of Mabru et al. [7], the present study is aimed at investigating the fatigue crack propagation patern in range II. The influence of temperature on fatigue crack growth rate is investigated at three different temperatures in vacuum. Then the propagation behavior is analyzed according to the data obtained in the experiment. Then the modified formula for the fatigue crack propagation pattern is derived to describe the influence of temperature on its behavior.

1. Experimental Methods. The experimental results were taken from Mabru et al. [7] and the material used in the experiment is γ-TiAl alloy with duplex microstructure. Fatigue crack propagation experiments were performed on CT specimens. The experimental data are shown in Fig. 1.

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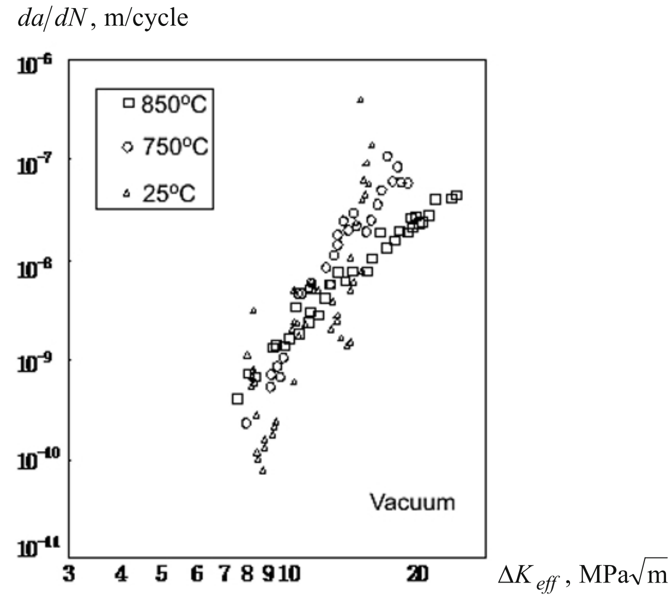

Fig. 1. Influence of temperature on the crack propagation pattern.

Figure 1 presents crack propagation rate curves obtained in vacuum for a lamellar TiAl alloy at different temperatures and the stress ratio $R = 0.1$. In these tests, the three temperatures, which are 25, 750, and 850°C, respectively, are chosen to characterize their influence on fatigue crack propagation. The threshold values (ΔK_{th}) are similar for all temperatures.

The experiments were carried out in vacuum to minimize interference with other factors, like environment.

As is seen in Fig. 1, at the onset of crack growth, the three curves are close. The behavior of the curves at 750°C is almost the same as that at room temperature, whereas the curve at 850°C is slightly lower than those at 25 and 750°C as ΔK_{eff} is increased.

2. Modification of the Fatigue Crack Propagation Rate Formula at Different Temperatures. The complete formula of the fatigue crack growth rate covers the near-threshold, central stable propagation and rapid propagation ranges (I, II, and III, respectively).

2.1. Several Formulas of the Fatigue Crack Growth Rate.

2.1.1. The Paris [8] Formula. In 1963, Paris presented the formula for calculating crack propagation patterns under constant amplitude loading:

$$\frac{da}{dN} = C(\Delta K)^m, \tag{1}$$

where ΔK is the stress intensity factor range, $\Delta K = \Delta K_{\max} - \Delta K_{\min}$, and C and m are the material constants. The formula is generally applied to various materials, but suitable only for describing the behavior in range II.

2.1.2. The Forman [9] Formula. The Paris formula does not reflect the influence of average stress on the crack propagation rate and does not show the effects of accelerated crack propagation when the stress intensity factor ΔK approaches the critical value K_c. Considering the above factors, Forman proposed another formula of the crack growth rate

$$\frac{da}{dN} = \frac{C(\Delta K)^m}{(1-R)K_c - \Delta K}, \tag{2}$$

where K_c is the critical value of stress intensity factor, R is stress ratio, and C and m are the material constants.

This equation mainly describes the medium-rate crack propagation behavior of range II and the rapid crack propagation of range III.

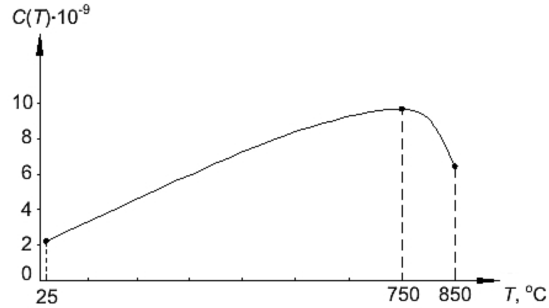

Fig. 2. Influence of temperature on the fatigue crack growth rate for range II.

2.1.3. The Zheng–Hirt [10] Formula. Zheng and Hirt designed a reasonable model of the fatigue crack propagation rate, termed the passivation cracking model of the crack tip

$$\frac{da}{dN} = B(\Delta K - \Delta K_{th})^2, \tag{3}$$

where B represents the fatigue crack growth factor, and ΔK_{th} is the threshold value. It can be applied to describe the propagation range II and near-threshold range I. The formula is simple and easy for engineering applications.

2.2. Modified Formula of the Fatigue Crack Growth Rate. Based on formulas of the fatigue crack propagation rate (1), (2), and (3), the modified formula can be derived to demostrate the influence of temperature on fatigue crack propagation of range II. According to the above formulas and the data in Fig. 1, the modified formula for range II at different temperatures can be presented as

$$\frac{da}{dN} = C(T)(\Delta K_{eff})^m, \tag{4}$$

where ΔK_{eff} is the variable range of the effective stress intensity factor, m equals 3.52, $C(T)$ is the temperature-dependent coefficient, T is the temperature. According to Fig. 1, $C(T)$ will be $2.92 \cdot 10^{-9}$, $9.35 \cdot 10^{-9}$, and $6.18 \cdot 10^{-9}$ when T equals 25, 750, and 850℃, respectively.

The results can be used to plot the graph demostrating the influence of temperature on the fatigue crack growth rate of range II (Fig. 2).

As can be seen in Fig. 1, the crack propagation rate is growing with time. Meanwhile, as Eq. (4) and Fig. 2 show, within range II at temperatures of 25 and 850℃, the $C(T)$ values are slightly lower than those at 750℃, which indicates that the fatigue crack growth rate is fastest at a certain temperature in range II.

When the temperature is between 25 and 750℃, the material constant m remains invariant, while $C(T)$ grows with temperature in range II. As is seen, the fatigue crack propagation rate grows with temperature. However, when the temperature is between 750 and 850℃, $C(T)$ exhibited a decrease, instead of an increase. As is seen, the fatigue crack propagation rate decreases with temperature.

In range III, growth rates increase rapidly when the temperatures are 25 and 750℃, and the respective curves are close. The curve at 25℃ is higher than that at 750℃ when ΔK_{eff} increases. Although the growth rate at 850℃ increases, the curve becomes flatter and is apparently lower than the curves at 25 and 750℃. It also can be seen that the curves are very close before entering range III. Therefore, temperature exerts a significant effect on the fatigue crack propagation rate according to the modified formula.

3. Discussion. Based on the Paris equation, which is applicable only to the medium-rate propagation range II, the modified formula is derived. The formula of the temperature effect on the fatigue crack growth rate in the near-threshold range I and the rapid propagation range III was not yet derived. If the formulas for ranges I and III were available, the temperature effect on the fatigue crack propagation rate would be more pronounced, as well as additional information may be gained. Numerous experiments should be performed, and it is still necessary to examine and derive the formula of the whole process as regards the temperature effect on the fatigue crack growth rate.

The three basic elements of crack propagation are the elastic modulus E, the threshold value ΔK_{eff}, and the fracture toughness K_c, which are the basic parameters of crack propagation resistance. The variable range of the stress intensity factor K_c is the driving force of fatigue crack propagation. So the question, which factors are affected, should be identified accurately in the case of temperature variation. According to Fig. 1, the three curves at different temperatures began to deviate at different starting points, so the threshold value ΔK_{eff} may vary. The questions are how temperature affects the threshold value ΔK_{eff} and what is the magnitude of ΔK_{eff} at each temperature.

It also can be seen that the three curves are close in the near-threshold (I) and medium-rate (II) propagation ranges. When entering the rapid propagation range, the curve at 850℃ is apparently different from those at 25 and 750℃. Generally, the ductile–brittle transition temperature is between 700–750℃. So it may be suggested that 750℃ is approximately the ductile–brittle transition temperature of TiAl alloys. This conclusion may explain the reason why the rate of fatigue crack growth at 850℃ is less than that at 750℃. When temperature rises, the material creep occurs, and the crack propagation resistance enhances, so the crack propagation rate drops down.

It can also be seen that the fatigue crack growth curve at 25℃ comes to an end earlier than that at 750℃, and finally this occurs to the curve at 850℃ (Fig.1). That is, if the temperature is higher, the fracture of TiAl alloys occurs earlier. It may be suggested that if the temperature is higher, material molecules are more active, which, of course, needs further substantiation. Further experimental verification would be required to clarify whether the facts mentioned above are correct and whether there is a fast-slow transition temperature like the ductile-brittle temperature. The influence of temperature on high crack growth rates is related to the variation of toughness as a function of temperature. Moreover, different authors agree that the toughening mechanisms are still active under cyclic loading, but solely under high crack propagation rate conditions [11, 12].

This paper examines only three temperatures, namely 25, 750, and 850℃. The curves of temperature effect on fatigue crack propagation are few. Several sets of experiments should be performed to get more data to demostrate the temperature effect on fatigue crack growth rates.

Conclusions. Fatigue crack growth patterns of TiAl alloys were investigated under three different temperatures, namely 25, 750, and 850℃ in vacuum to elucidate the effect of temperature. It turned out that, in range II, the fatigue crack growth rate increases when the temperature is between 25 and 750℃, and the rate decreases when the temperature is between 750 and 850℃. Therefore, when the temperature rises to a certain extent, the acceleration of fatigue crack growth rates starts to decrease. This suggests that the fatigue crack propagation mechanism is the same as the mechanism active in conventional alloys. Therefore, this characteristic of alloys influenced by temperature can be used for practical purposes.

The shortcoming of this paper is the limitation of the modified formula, which can characterize only range II. Also, the new formula to represent the whole process influenced by temperature has failed to be derived.

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