Creep-fatigue interaction model for crack growth of nickel-based superalloys with high temperature dwell time

Hongqin Yang [1,*], Rui Bao [2], Jiazhen Zhang [1]

[1] Beijing Aeronautical Science & Technology Research Institute of COMAC, Beijing 100083, PR China
[2] Institute of Solid Mechanics, Beihang University (BUAA), Beijing 100191, PR China
* Corresponding author: yanghongqin@comac.cc

Abstract A three-term crack growth model was developed by adding a creep-fatigue interaction term to the traditional linear superposition law. It is based on the hypothesis that the maximal creep-fatigue interaction occurs when creep and fatigue crack growth rates are comparable. Thereby a novel exponential form of interaction intensity factor was proposed. In order to verify the model, the creep-fatigue crack growth behaviour of a nickel-based powder metallurgy superalloy (FGH97) was experimentally investigated. Creep-fatigue crack growth rates were obtained at 750 °C with various dwell times. Comparison of the crack growth rates between fitted and measured values at 0s, 90s, 450s and 1500s dwell times show great agreement. Encouragingly, excellent predictive ability of the model was verified by the experiment at 25s dwell time. Furthermore, to test the applicability of the interaction law on other materials, experimental data of two additional superalloys from references, namely Alloy 718 and Hastelloy® X, were used to fit the model. The results are also satisfactory.

Keywords Crack growth rate modelling, high temperature, dwell time, nickel-based superalloys

1. Introduction

As for the quantitative description of creep-fatigue crack growth rate, several models have been developed. Tong et al. [1] proposed single term models, in which creep damage is taken into account by modifying the coefficient of the basic fatigue model. Other researchers [2] have used an alternative approach. They assumed that creep-fatigue behaviour is governed by competing mechanisms of creep and fatigue crack growth, and whichever gives a higher growth rate dominates the entire crack growth process. A more universal model is based on simple linear superposition of creep crack growth and fatigue crack growth [3]. However, such methods tend to overlook the effect of creep-fatigue interaction, which cannot be ignored by many materials.

For this reason, a three term model considering the interaction effect separately was referred in [4], expressed in the form of linear superposition of fatigue crack growth rate, creep crack growth rate and their interactions. However, the quantitative relationship between the creep-fatigue interaction and the loading condition for certain materials is still an open question. The work of Grover and Saxena [5] indicated that the intensity of the creep-fatigue interaction is directly related to the relative sizes of the creep zone and cyclic plastic zone.

Recently, the authors [6] presented an exponential formed interaction intensity factor to help describing the interaction effect. The accuracy of the model proposed was experimentally confirmed by a nickel-based superalloy FGH97. The study presented here is a continuation of that work and applicability of the model on other materials was verified.

2. Creep-fatigue interaction model

The simple linear superposition equation, as shown in Eq. (1), is preferentially considered to model the creep-fatigue crack growth rate[3].

$$\frac{\mathrm{d}a}{\mathrm{d}N} = (\frac{\mathrm{d}a}{\mathrm{d}N})_{\mathrm{fatigue}} + (\frac{\mathrm{d}a}{\mathrm{d}N})_{\mathrm{creep}} \tag{1}$$

where $(\mathrm{d}a/\mathrm{d}N)_{\mathrm{fatigue}}$ denotes the fatigue crack growth rate, including the effect of environment (oxidation for example). It can be achieved by Eq. (2) according to the Paris law. $(\mathrm{d}a/\mathrm{d}N)_{\mathrm{creep}}$ represents the creep crack growth rate. Selecting K as the creep crack growth dominant parameter due to its practicability, $(\mathrm{d}a/\mathrm{d}N)_{\mathrm{creep}}$ is thereby expressed by Eq. (3).

$$(\frac{\mathrm{d}a}{\mathrm{d}N})_{\mathrm{fatigue}} = C(\Delta K)^{n} \tag{2}$$

$$(\frac{\mathrm{d}a}{\mathrm{d}N})_{\mathrm{creep}} = A(K_{\mathrm{max}})^{m} t_{\mathrm{h}} \tag{3}$$

where $K_{\mathrm{max}} = \Delta K / (1 - R)$, C, n, A and m are material related parameters.

In order to take the creep-fatigue interaction into account, a three-term crack growth model was developed by adding a third-term to the traditional linear superposition equation, see Eq. (4).

$$\frac{\mathrm{d}a}{\mathrm{d}N} = (\frac{\mathrm{d}a}{\mathrm{d}N})_{\mathrm{fatigue}} + (\frac{\mathrm{d}a}{\mathrm{d}N})_{\mathrm{creep}} + (\frac{\mathrm{d}a}{\mathrm{d}N})_{\mathrm{interaction}} \tag{4}$$

where $(\mathrm{d}a/\mathrm{d}N)_{\mathrm{interaction}}$ denotes the influence of creep and fatigue interaction on the crack growth rate, and the expression should be discussed.

As Grover and Saxena [5] indicated, at short t_{h}, the creep zone size is small relative to the cyclic plastic zone size during all the crack growth period since the creep zone grows very slowly, resulting in fatigue dominating cracking. At long t_{h}, the creep zone grows larger than cyclic plastic zone size, and the crack growth rate becomes time dependent. In between, the cracking will rely on both creep and cyclic plastic damage. The most significant interaction occurs when creep and cyclic plastic damage size are comparable. Also provided in their study is that the ratio of the creep and cyclic plastic zone sizes is dependent on the dwell time t_{h}, load ratio R and the material related parameters. This implies that the creep fatigue interaction should also depend on these parameters.
Based on these, a factor, η, was proposed to characterize the intensity of the creep and fatigue interaction, as shown in Eq.(5).

$$h = \exp(-\ p_1(\ln f + p_2 \mathrm{D}K + p_3)^2) \tag{5}$$

where, p_1, p_2 and p_3 are material related parameters, $f = (T+t_h)^{-1}$ is the frequency of the load waveform and T is the load period of the baseline triangular waveform. It can be seen that there are two extreme cases. On one extreme, η approaches zero, indicating that there is almost no interaction between creep and fatigue. For the other extreme case in which η approaches 1, it implies that the interaction reaches the most significant.

Accordingly, taking $D(\Delta K)^q$ as the basic term, $(da/dN)_{\text{interaction}}$ can thereby be expressed as following:

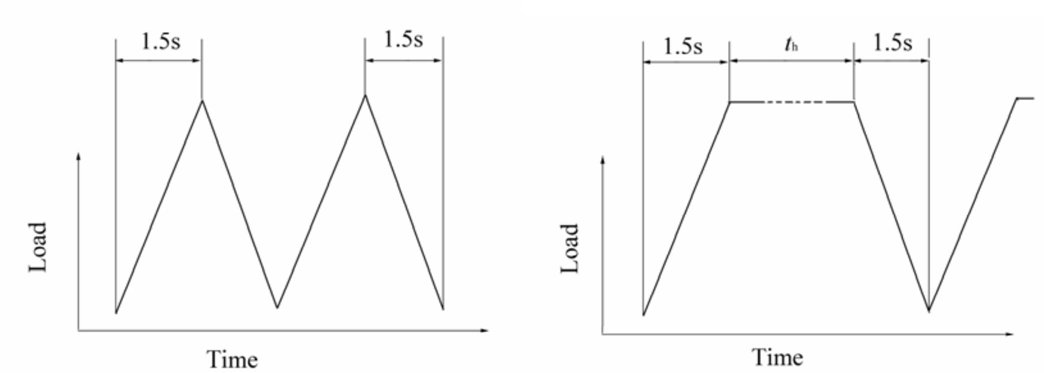
$$\left(\frac{da}{dN}\right)_{\text{interaction}} = D(\Delta K)^q \cdot \eta \tag{6}$$

where $K_{\max} = \Delta K / (1 - R)$, D and q are material related parameters.

3. Crack growth experiment on FGH97

The material in this study is a nickel based PM superalloy, named FGH97, taken from a turbine disk. It was strengthened by the formation of γ' precipitates based on Ni_3Al and received both the solid-solution-strengthening and age-hardening treatment. The nominal chemical composition is as follows (wt%): C 0.02-0.06, Cr 8.0-10, Mo 3.5-4.2, W 5.2-5.9, Al 4.8-5.3, Ti 1.6-2.0, Co 15.0-16.5, Nb 2.4-2.8, Hf 0.1-0.4, Mg $\leq$ 0.02, Zr $\leq$ 0.015, B $\leq$ 0.015, Ce $\leq$ 0.010 and the balance nickel[7]. Compact tension (CT) specimens were employed, where width W = 50 mm and initial crack length a_0 = 22.5 mm. More details can be found in Ref.[6].

The baseline loading cycle is a triangular wave of load ratio R = 0.05. Different dwell time t_h = 90s, 450s and 1500s at the maximum load are superimposed to the baseline loading cycle to obtain a trapezoidal creep-fatigue loading condition, see Fig. 1. The baseline triangular fatigue loading cycle can be reasonably regarded as t_h = 0s reasonably. A typical service temperature of 750°C was conducted.



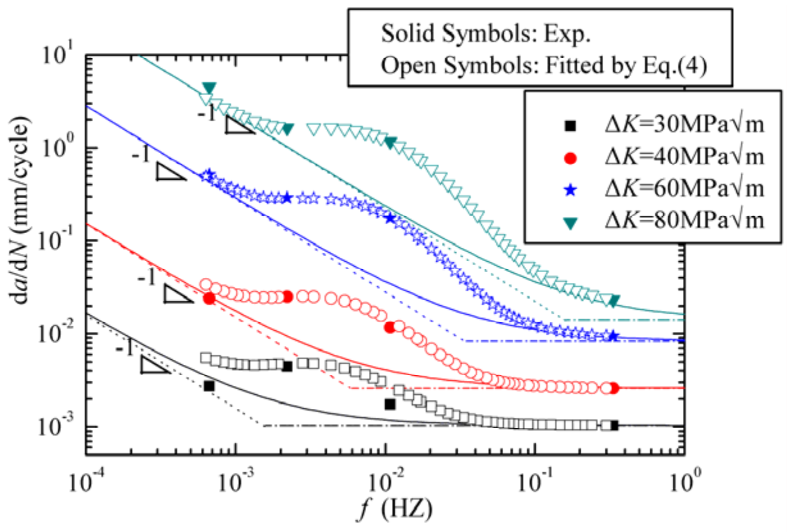
(a) (b)

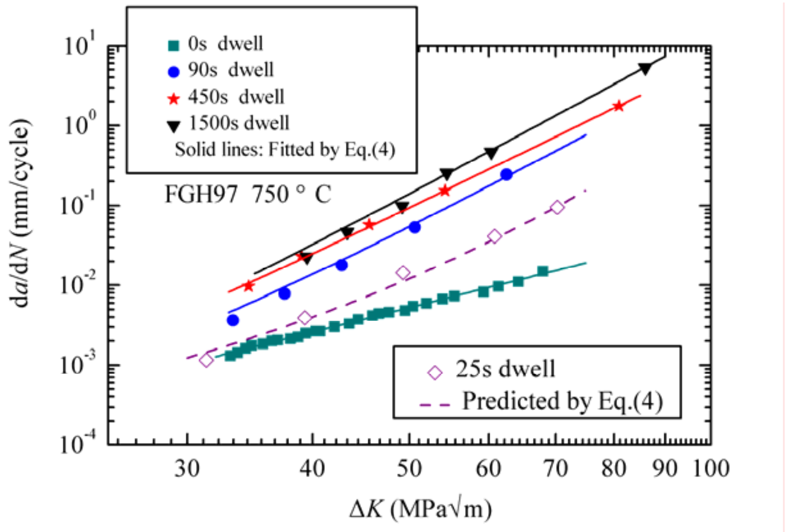
Figure 1. Schematic of loading waveforms (a) Triangular; (b) Trapezoidal

In order to clarify the creep-fatigue interaction, the da/dN vs. f data of the present alloy at four specified ΔK in log-log scale is plotted in Figure 2(a). For pure fatigue loading, according to Eq. (2), the crack growth rate showing no influence by f, therefore, ln(da/dN) vs. ln(f) curves should be parallel to the abscissa f at specified ΔK. And for pure creep crack growth, according to Eq. (3), the da/dN is proportional to t_h at certain stress level, hence, the gradients for ln(da/dN) vs. ln(f) curves should be -1. Thereby, the solid lines in Figure 2(a), calculated by Eq. (1), denote the simple linear superposition of the fatigue and creep components. The experimental data at four specified ΔK are also provided in the figure by various symbols.

It can clearly be seen from that, first, the t_h effect on da/dN is nonlinear in the log-log scale. With the t_h increases, the effect is initially increased and then decreased, especially at low ΔK stage. Second, the experimental data in the medium ΔK and t_h are much greater than the solid lines. Comparisons between the fitted and experimental crack growth rates are presented in Figure 2(b). The results show good agreements at all four dwell times, ignoring slight deviation in the quite low ΔK and ln(f) stage. Thereby, interaction intensity factor η, as expressed in Eq.(5), can depict this interaction satisfactory.

Comparisons between the fitted and experimental crack growth rates are presented in Figure 2(b). The results show good agreements at 0s, 90s, 450s and 1500s. Furthermore, to verify the predictive capability of the model, additional crack growth rate for t_h = 25s is computed by Eq. (4) and are compared with the experimental data, also shown in Figure 2(b). Excellent correlation between the predicted and observed growth rates was obtained. It appears that the model can provide accurate descriptions of the influence of t_h and ΔK on the crack growth behaviour at 750°C.





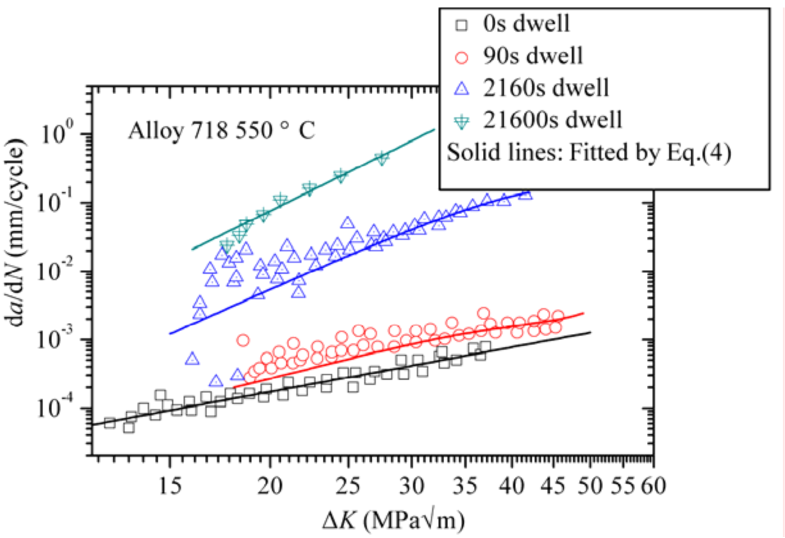
(a) da/dN versus f (b) da/dN versus ΔK

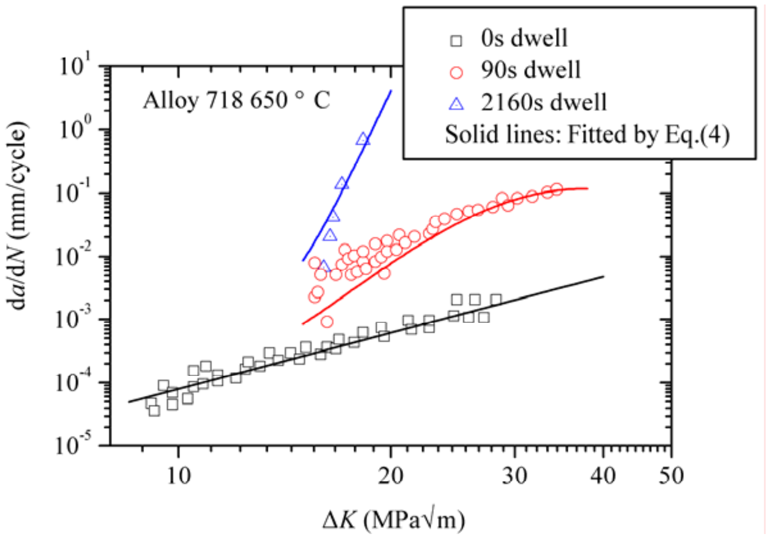
Figure 2. Comparisons between the fitted and experimental da/dN of FGH97 at 750 °C

4. Applicability on Alloy 718 and Hastelloy® X

In order to verify the applicability of the model on other materials, two additional nickel-based superalloys from the references, namely Alloy 718 and Hastelloy® X, were analysed. Alloy 718 is a wrought polycrystalline nickel based superalloy with a large amount of Fe and Cr. The crack growth experiments [8] were conducted on Kb-type specimens with rectangular cross sections of 4.3×10.2 mm. Hastelloy® X alloy is a solid-solution strengthened nickel-based superalloy that combines exceptional oxidation resistance, good fabricability, and excellent high-temperature strength. And the experiments [9] were conducted on CT specimen with thickness of 3.2 mm, height of 61.0 mm and width of 63.5 mm. Here, two temperatures with three or four dwell times were involved for each material. Details of the experiments can be found in references [8] and [9], respectively.

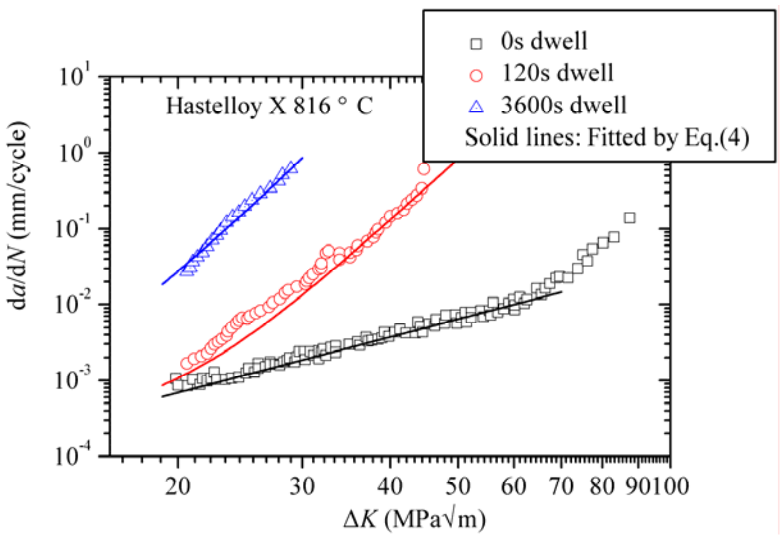
Figure 3 and Figure 4 present the comparisons between the fitted and experimental da/dN of Alloy 718 and Hastelloy® X, respectively. Where, the solid lines in the figures were fitted by Eq. (4). Encouragingly, the results show excellent correspondences for these two alloys.

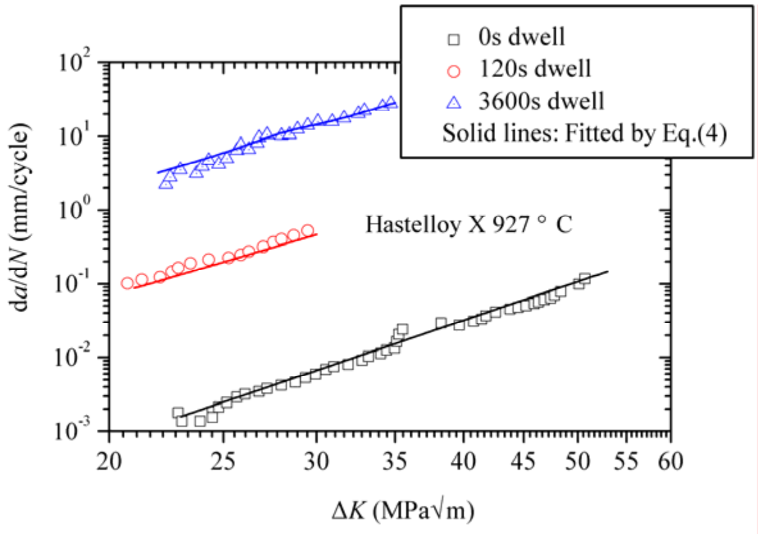




(a) 550 °C (b) 650 °C

Figure 3. Comparisons between the fitted and experimental d*a*/d*N* of Alloy 718





(a) 816 °C (b) 927 °C

Figure 4. Comparisons between the fitted and experimental da/dN of Hastelloy® X

5. Summary

Key results and conclusions drawn from this investigation are summarized below: (1) The exponential form of interaction factor, η, could successfully characterize the intensity of the creep and fatigue interaction. (2) The established three-term crack growth model is capable of accurately representing and predicting the creep-fatigue crack growth behavior of FGH97. (3) The applicability of the three-term model on the nickel-based superalloys Alloy 718 and Hastelloy® X is satisfactory.

References

[1] J. Tong, S. Dalby, et al, Creep, fatigue and oxidation in crack growth in advanced nickel base superalloys. Int J Fatigue, 23(2001), 897-902.

[2] R. Ohtani, T. Kitamura, et al, High-temperature low cycle fatigue crack propagation and life laws of smooth specimens derived from the crack propagation laws, in: H.D. Solomon, G.R. Halford, et al (Eds.), Low Cycle Fatigue, ASTM STP 942, Philadelphia, 1988, pp. 1163-1180.

[3] F. Djavanroodi, Creep-fatigue crack growth interaction in nickel base supper alloy. American Journal of Applied Science, 5(2008), 454-460.

[4] F. Z. Xuan, S. D. Tu, et al., Time-dependent fatigue fracture theory and residual life assessment techniques for defective structures. Chinese Journal of Advances in Mechanics, 35(2005), 391-403.

[5] P. S. Grover, A. Saxena, Modelling the effect of creep-fatigue interaction on crack growth. Fatigue Frac Eng M, 22(1999), 111-122.

[6] H.Q. Yang, R. Bao, et al., Creep-fatigue crack growth behaviour of a nickel-based powder metallurgy superalloy under high temperature. Eng Fail Anal, 18(2011), 1058-1066.

[7] Y. Zhang, Y. W. Zhang, et al, Heat treatment processes and microstructure and properties research on P/M superalloy FGH97. Journal of Aeronautical materials, 28(2008), 5-9.

[8] M. HÖrnqvist, T. Månsson, et al., High temperature fatigue crack growth in Alloy 718-Effect of tensile hold times. Procedia Engineering, 10(2011), 147-152.

[9] Y. L. Lu, P. K. Liaw, et al., Tensile-hold effects on high-temperature fatigue-crack growth in nickel-based Hastelloy X alloy. Mat Sci Eng A, 433(2006), 114-120.