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# A creep–fatigue crack growth model containing temperature and interactive effects

Hao Liu [a,b], Rui Bao [a,*], Jianyu Zhang [a], Binjun Fei [a]

[a] Institute of Solid Mechanics, Beihang University (BUAA), Beijing 100191, China
[b] School of Applied Science, Taiyuan University of Science and Technology (TYUST), Taiyuan 030024, China

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ABSTRACT

A trinomial superposition model containing a temperature parameter and accounting for creep–fatigue interactive effect for predicting creep–fatigue crack growth rates is proposed in this paper. Items and parameters in the model are investigated via fatigue crack growth experiments with 0 s and 90 s dwell time at different elevated temperatures on a nickel-based powder metallurgy superalloy FGH97. The results indicate a good capability of the proposed model in correlating the crack growth rate with creep–fatigue interactive effect. The model is also validated by available test results of Alloy 718 at 550 °C and 650 °C with various dwell times.



## 1. Introduction

Fatigue crack growth assessment for structural components serving in elevated-temperature environment is one of the most important tasks to ensure the structure integrity. The effect of temperature can shorten crack growth life (CGL) significantly, and the thermal–mechanical coupling effects can introduce complexity in the analysis of crack growth behavior [1–3]. Many efforts have therefore been made on modeling the creep–fatigue crack growth of metals at elevated temperatures [4].

Siverns and Price [5] have pointed out that the process of fatigue crack growth with the creep effect is similar to that in the room temperature condition. The process can be divided into three different stages: crack initiation, stable crack growth and rapid crack growth. For the CGL evaluation that is important for damage tolerance design, the stable crack growth stage is the most relevant, which is governed by cyclic loading and dwell time, as well as the test environment. To calculate the crack growth rate (CGR) in this stage, numerous models have been proposed [6–25], of which the competing model and superposition model are widely accepted and used in engineering.

The competing models [6–11] contain only one item, hence are named as monomial models, which relates to the dominant mechanism, i.e. cycle loading or dwell time, of crack growth process to correlate the CGR. The competing models are suitable for the cases, in which a large difference exists between the cycle-dependent and time-dependent CGRs. The more significant one will be the dominant factor which is selected to describe the CGR. The competing model can be expressed by Eq. (1), in which $\left(\frac{da}{dN}\right)_{\text{cycle}}$ denotes the cycle-dependent crack growth component; $\left(\frac{da}{dN}\right)_{\text{time}}$ represents the time-dependent crack growth component.

$$\left(\frac{da}{dN}\right)_{\text{cycle}}\frac{da}{dN} = \max\left[\left(\frac{da}{dN}\right)_{\text{cycle}}, \left(\frac{da}{dN}\right)_{\text{time}}\right] \tag{1}$$

When the dwell time is not imposed and the loading frequency is not too low, e.g. 0.05–20 Hz [16], the creep effect can be neglected and the monomial model is usually adopted to correlate the CGR. For this case, the Paris law [9] or modified Paris laws [10,11] are suitable. Usually, the modified Paris laws are obtained by replacing the parameter $C$ with a correction factor $C(T)$, i.e. $C$ changes as a function of the test temperature $T$. Jeglie et al. [10] and Mcgowan [11] have presented different $C(T)$ expressions. Furthermore, Mcgowan [11] have found that for different test frequencies the $da/dN$-$\Delta K$ curves are parallel to each other in the double-logarithmic coordinate at a given temperature or different temperatures at a specified test frequency.

When the loading frequency is lower enough, e.g. lower than 0.05 Hz, or a holding time is imposed at the maximum load, creep damage will be significant. Consequently, CGR increases remarkably due to the combined effect of creep and fatigue. Research are therefore focused on the creep crack tip control parameters and creep CGR models, and different control parameters have been

* Corresponding author. Tel.: +86 10 82314957.
*E-mail address:* rbao@buaa.edu.cn (R. Bao).

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**Nomenclature**

| | |
|---|---|
| $a$, $a_0$ | crack length, initial crack length |
| $a_1$, $a_2$, $b_1$, $b_2$, $c_1$, $c_2$ | fitted material related parameters from test data |
| $A$, $m$ | material related parameters describing creep crack growth rate |
| $B$,$W$ | specimen thickness, specimen width |
| $C$, $C_1$, $C_2$, $n$ | material related parameters describing fatigue crack growth rate |
| $C^*$, $C_t$, $(C_t)_r$ | creep fracture parameters |
| $da/dN$ | crack growth rate |
| $D$, $q$ | material related parameters describing creep–fatigue interactive crack growth rate |
| $f$ | loading frequency |
| $K$, $\Delta K$, $K_{max}$ | stress intensity factor (SIF), SIF range, maximum SIF in a load cycle |
| $N$ | number of cycles |
| $p_1$, $p_2$, $p_3$ | material related parameters for interaction factor |
| $R$ | nominal stress intensity factor ratio ($R = K_{min}/K_{max} = P_{min}/P_{max}$) |
| $t$, $t_h$ | time, dwell time |
| $T$ | temperature |
| $\eta$ | creep–fatigue interaction factor |

proposed, such as the stress intensity factor ($K$) [26,27], net section stress ($\sigma_{net}$) [28,29], reference stress ($\sigma_{ref}$) [30,31] and energy rate integral ($C^*$ or $C_t$) of the crack tip strain rate field [32], which are confirmed to be feasible and effective in certain materials. It is recommended by ASTM E1457-00 [33] that the creep control parameters $C_t$ or $C^*$ is suitable when materials show creep-ductility feature, whereas the stress intensity factor $K$ is used when materials show creep–brittle behavior.

When the magnitude of damages caused by fatigue loads and creep effects are roughly equal, both contributions to crack propagation from the two aspects should be considered; consequently the superposition model is often adopted to describe the creep–fatigue CGR. Available superposition models can be classified as binomial and trinomial models; the former contains two items, i.e. fatigue-related CGR and creep-related CGR, and the latter contains the creep–fatigue interaction item apart from the other two items, therefore it comprises three items.

The basic form of binomial superposition models [12–18] is shown in the following equation:

$$\frac{da}{dN} = \left(\frac{da}{dN}\right)_{\text{fatigue}} + \left(\frac{da}{dN}\right)_{\text{creep}} \tag{2}$$

where $\left(\frac{da}{dN}\right)_{\text{fatigue}}$ denotes the pure fatigue crack growth component, including the effect of oxidation from environment. If $\Delta K$ is used as a control parameter, it can be calculated by the Paris law or modified Paris laws. $\left(\frac{da}{dN}\right)_{\text{creep}}$ represents the pure creep crack growth component, selecting $K$, $C_t$ or $C^*$ as the crack tip control parameter, the creep component can be expressed in different forms based on the material test results. Utilizing Eq. (2), researchers [12–18] have succeeded in describing the CGRs of different materials at elevated temperature.

However, many experiments show that the interaction effect of fatigue and creep on CGR cannot be neglected [4]. This means that test measured CGRs are much higher than predicted values obtained using the binomial superposition model. For that, trinomial superposition models [19–24], expressed by Eq. (3), have been proposed, by which the complex creep and fatigue interaction effects are considered.

$$\frac{da}{dN} = \left(\frac{da}{dN}\right)_{\text{fatigue}} + \left(\frac{da}{dN}\right)_{\text{creep}} + \left(\frac{da}{dN}\right)_{\text{interaction}} \tag{3}$$

where $\left(\frac{da}{dN}\right)_{\text{interaction}}$ denotes CGR due to the creep–fatigue interaction. Researchers introduced different forms of interaction item for different materials at elevated temperature. Tu et al. [4] have summarized lots of existing trinomial superposition models for predicting of CGR under creep fatigue condition.

Yang and Bao [21] have also presented a trinomial expression to correlate the creep–fatigue CGR based on an experimental investigation of crack growth in a nickel based superalloy FGH97. Their test results showed good agreements with five kinds of different dwell times at 750 °C. However, the effect of temperature on fatigue, creep and their interaction is not included in the model.

This paper presents a follow-on study of Yang and Bao's work on the trinomial superposition interaction model to investigate the temperature effect on creep–fatigue CGR at elevated temperature.

## 2. A trinomial model containing temperature parameter for creep–fatigue crack growth rate

Based on the load-line displacement discussion, Yang and Bao [21,25] argued that alloy FGH97 should be classified as a creep–brittle material and parameter $K$ was selected to correlate the CGR. They have then proposed a trinomial model, Eq. (4), to correlate the CGR of FGH97 at elevated temperature.

$$\frac{da}{dN} = C(\Delta K)^n + A(K_{max})^m t_h + D(\Delta K)^q \eta \tag{4}$$

where $D(\Delta K)^q \eta$ represents the CGR component caused by the interaction mechanism of creep and fatigue. The interaction factor, $\eta$, reflects the degree of the creep–fatigue interaction, which is expressed by the following equation:

$$\eta = \exp\left(-p_1(\ln f + p_2 \Delta K + p_3)^2\right) \tag{5}$$

where $p_1$, $p_2$ and $p_3$ are material related parameters. This equation can describe and have successfully predicated the CGRs of creep–fatigue of FGH97 with different dwell times at 750 °C [21]. However, this model cannot predict the creep–fatigue crack growth rates at another temperature. To widen the applicability of this model, a temperature parameter should be added.

Since temperature can change the material properties, such as causing degradation of the elastic modulus and strength, elevated temperature can accelerate the crack growth rate. All the three items in Eq. (4) will be influenced by the temperature parameter $T$; these are further discussed in the following for each item of Eq. (4).

The first item correlates the cycle-dependent CGR, using the Paris law. Taking logarithm on both sides of the Paris law, Eq. (6) can be obtained, which indicates a linear relationship between $\lg(da/dN)$ and $\lg(\Delta K)$, and the slope is fitted as coefficient $n$.

$$\lg\left(\left(\frac{da}{dN}\right)_{\text{fatigue}}\right) = \lg(C) + n\lg(\Delta K) \tag{6}$$

According to Mcgowan's work [11] that the $da/dN$-$\Delta K$ curves at different temperatures are parallel to each other in double-logarithmic coordinate, it is assumed that parameter $n$ remains unchanged for CGRs under different elevated temperatures. This