International Journal of Fatigue 90 (2016) 12–22

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

A modified strain energy density exhaustion model for creep–fatigue life prediction

Run-Zi Wang [a], Xian-Cheng Zhang [a,*], Shan-Tung Tu [a,*], Shun-Peng Zhu [b], Cheng-Cheng Zhang [c]

[a] *Key Laboratory of Pressure Systems and Safety, Ministry of Education, School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai 200237, PR China*
[b] *School of Mechatronics Engineering, University of Electronic Science and Technology of China, Chengdu 611731, PR China*
[c] *AVIC Commercial Aircraft Engine Co. LTD, Shanghai Engineering Research Center for Commercial Aircraft Engine, Shanghai 201108, PR China*

ARTICLE INFO

Article history:
Received 5 January 2016
Received in revised form 26 February 2016
Accepted 1 March 2016
Available online 7 March 2016

Keywords:
Creep–fatigue
Strain energy density exhaustion
Life prediction model
Mean stress

ABSTRACT

The accumulated creep–fatigue damage is expected to be an important failure mechanism for lots of high-temperature components. The aim of this paper is to propose a modified strain energy density exhaustion model to predict the tension-hold-only creep–fatigue life. This model exhibits high accuracy due to the reasonable evaluation of creep damage. The proposed model elaborates the determinations of mean stress, stress relaxation rate and creep damage. A few existing experimental data sets of Grade 91 steel, Alloy 617 and 304 stainless steel are used to verify the prediction capacity of the present model under different temperatures and loading conditions. Results show that most of the experimental data falls into a range within a scatter band of ±1.5 on life.

1. Introduction

Hot-section components in aero-engine, gas turbine and coal-fired power plant applications operate under cyclic loading at high temperatures, which are often identified as life-limited components. These components are not only subjected to normal working stress, but also subjected to additional stresses including cyclic stress and thermal stress due to the variations of temperature and loading along with time. In such a case, the time-dependent damage of high-temperature components is often generated due to the combined creep–fatigue deformation [1–7]. For instance, the frequent start-ups and shut-downs produce the fatigue damage, which would lead to fatigue failure accompanied with surface cracks. While the creep damage may occur during dwell time and creep failure is generally manifested as creep voids at grain boundaries by cavitation damage. However, during creep–fatigue interactions, the creep damage occurs within the material while fatigue crack damage is observed at surface. The interaction and linking of these two damage mechanisms lead to an accelerated failure and the failure path would become mixed (trans-plus intergranular) [8–10].

A fundamental understanding of the combined creep–fatigue deformation is of great importance to the design, life prediction and long-term operation of hot-section components at elevated temperature. It is often simulated in the laboratory by high-temperature low-cycle fatigue (HTLCF) tests with incorporation of hold time at a given peak constant strain, as schematically shown in Fig. 1. Generally, the creep–fatigue tests conducted in strain controlled conditions can well describe the actual working situations of high-temperature components, such as turbine blades, where a rapid start-up phase is followed by a steady running period. In the past decades, considerable efforts have been devoted to characterizing the creep–fatigue behavior of materials used at high temperature. The creep–fatigue endurance depends on various factors including temperature and loading waveform (e.g., strain rate, hold time and strain range). Using the traditional models for pure fatigue life prediction, the effects of loading frequency and hold time on creep–fatigue life cannot be effectively described [11,12]. Hence, it is difficult to accurately predict the creep–fatigue life due to complex damage mechanism and no unified model has been developed over the past half-century.

Manson and Halford [8] reviewed the methods now in use, or contemplated for use under creep–fatigue conditions. Most of these methods were developed on the basis of generalization of Manson-Coffin equation [11,12], such as strain-range partitioning

---

* Corresponding authors at: Key Laboratory of Pressure Systems and Safety, Ministry of Education, School of Mechanical and Power Engineering, East China University of Science and Technology, Meilong Road 130, Xuhui District, Shanghai 200237, PR China. Tel.: +86 21 64253513.

E-mail addresses: xczhang@ecust.edu.cn (X.-C. Zhang), sttu@ecust.edu.cn (S.-T. Tu).

http://dx.doi.org/10.1016/j.ijfatigue.2016.03.005
0142-1123/

Nomenclature

σ_{max}	maximum stress in one cycle
σ_{min}	minimum stress in one cycle
σ_m	mean stress in one cycle
$\Delta\sigma_{r,\mathrm{tension}}$	stress relaxation range at tensile hold period in one cycle
$\Delta\sigma_{r,\mathrm{compression}}$	stress relaxation range at compressive hold period in one cycle
D_f	accumulated fatigue damage
D_c	accumulated creep damage
d_c	creep damage per cycle
t_h	tensile hold time in one cycle
$t_R(\sigma,T)$	creep-rupture time at given stress level and temperature
k, α	material- and temperature-dependent coefficients in creep-rupture equation
σ_0	initial stress of the hold time at half-life cycle
B'', b	constants in Feltham's stress relaxation model
d_f	fatigue damage per cycle
N_0	number of pure fatigue cycles using the same total strain range in the creep–fatigue tests
N_{c-f}	predicted creep–fatigue cycles
$\dot{\varepsilon}_{in}$	instantaneous inelastic strain rate
$\varepsilon_f(\dot{\varepsilon}_{in},T)$	creep ductility equation at a given instantaneous inelastic strain rate and temperature
E	Young's module at half-life cycle
β, d	material- and temperature-dependent coefficients in creep ductility equation
ε_L	lower shelf ductility
ε_U	upper shelf ductility
$\dot{\varepsilon}_{crit}$	critical strain rate corresponding to a point of inflection in energy-strain rate curve
γ	slope of the curve at the critical point
$\dot{w}_{in}$	instantaneous inelastic strain energy density rate
$w_{f,crit}(T)$	critical failure strain energy density under the condition free from the creep damage at a certain temperature
φ, n_1	material- and temperature-dependent coefficients in the energy-based ductility exhaustion model
Ω, θ	constants in Gittus's stress relaxation model
σ_{cc}	stress level for crack closure
σ_{lim}	stress level for plastic deformation
$w_f(\dot{w}_{in},T)$	function of failure strain energy density at a given instantaneous inelastic strain energy density rate and temperature
$d_{c,new}$	creep damage per cycle in the present model
w_{in}	inelastic strain energy density at a given time during the hold period
$w_{in,new}$	inelastic strain energy density considering mean stress effect at a given time during the hold period
$\dot{w}_{in,new}$	instantaneous inelastic strain energy density rate considering mean stress effect at a given time
$\Delta\varepsilon_t$	total strain range
A, B	material-dependent constants in Jeong et al.'s stress relaxation formula
$\Delta\varepsilon_p$	plastic strain range at half-life cycle
$\dot{\sigma}$	stress relaxation rate during the hold period
M, N	constants in the creep damage in the present model
$w_f(\dot{w}_{in,new},T)$	failure strain energy density criterion for mechanistic cavity growth at a given instantaneous inelastic strain energy density rate and temperature
B_1	temperature-dependent regression coefficient in the power-law relationship for mechanistic cavity growth
R	universal gas constant
Q	activation energy
$\overline{D}_f$, $\overline{D}_c$	the point of interaction in the bilinear interaction diagram
n	power exponent in the simplified continuous envelope
F_r	life reduction ratio

(SRP) [13], frequency-modified life (FML) equation [14], and damage function approach [15]. On the other hand, linear damage summation (LDS) methods including time fraction (TF) model [16] and ductility exhaustion (DE) model [17–19] have also been widely used in the past twenty years. Moreover, energy criteria combined with traditional LDS method were also considered by Takahashi [20–22], Skelton [23,24], Payten and Dean [25] and Splinder and Payten [26]. Although the above-mentioned models have been proved to be successful in specific conditions, they cannot be used for different materials under different experimental conditions.

The present paper attempts to propose an energy-based model to predict strain-controlled creep–fatigue life. Only the tension-hold is considered in this model. The proposed model contains three main aspects for modification of traditional LDS method and is validated by three different materials, namely Grade 91 steel, Alloy 617 and 304 stainless steel (SS) under different loading conditions.

2. Existing life prediction models based on LDS

Three classic creep–fatigue life prediction models based on LDS are briefly reviewed in this section, since these models provide important insights to develop the present model. Accumulated fatigue damage D_f and accumulated creep damage D_c are calculated separately in LDS approach. The failure of materials occurs when the summation of accumulated fatigue and creep damage reaches a critical value. Generally, this critical value is set to be unity in the previous models.

2.1. TF model

In TF model [16], the creep damage per cycle, which is related to stress level and creep-rupture time from creep tests, is given by

$$d_c=\int_0^{t_h}\frac{dt}{t_R(\sigma,T)} \tag{1}$$

where d_c is the creep damage per cycle, t_h is the tensile hold time in one cycle and $t_R(\sigma,T)$ is the creep-rupture time at a given stress level, σ, and temperature, T. In order to identify $t_R(\sigma,T)$, the uniaxial tensile creep tests at given temperatures under different stress levels are necessary. Generally, the power-law relationship between t_R and σ is used [20], i.e.,

$$t_R(\sigma,T)=k\cdot\sigma^{-\alpha} \tag{2}$$

where k and α are material- and temperature-dependent coefficients. To calculate the creep damage per cycle, the stress relaxation along with hold time is often determined by using the model proposed by Feltham [27], i.e.,

$$\sigma=\sigma_0\cdot\left[1-B''\cdot\ln(bt+1)\right] \tag{3}$$

where σ_0 is the initial stress of the hold time at half-life cycle, B'' and b are constants, and t refers to time from the start of hold period. Substituting Eqs. (2) and (3) into Eq. (1), the creep damage per cycle can be determined.

On the other hand, the fatigue damage per cycle, d_f, is calculated as a reciprocal of fatigue life without hold time, namely