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Multiaxial fatigue life prediction for powder metallurgy superalloy FGH96 based on stress gradient effect

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ABSTRACT

Both proportional and non-proportional axial-torsion fatigue tests were conducted on powder metallurgy (PM) superalloy FGH96 tubular specimens and round bar specimens at 650 °C. The alloy is widely used to manufacture the aero-engine turbine disk by a process of hot isostatic pressing (HIP). The different stress distributions of thin-walled tubular specimen and the round bar specimen under axial-torsion cyclic loading are discussed. A multiaxial equivalent stress gradient factor is defined based on the tensile stress gradient and the shear stress gradient. A modified Zhong-Wang-Wei (ZWW) model considering the effect of the stress gradient is proposed for multiaxial fatigue of FGH96. Comparing to six multiaxial fatigue models, including the maximum effective strain model, the maximum shear strain model, the Fatemi-Socie (FS) model, the Smith-Watson-Topper (SWT) model, the Itoh model and the ZWW model, the predicted multiaxial fatigue lives of FGH96 by the modified ZWW model based on the effect of the stress gradient agreed better with the experimental results.

1. Introduction

PM techniques are widely used to manufacture turbine disks and other hot section components in advanced turbine engines and power generation industries because of their high yield strength, high creep resistance and excellent damage tolerance properties at elevated temperature [1–3]. FGH96 alloy is a typical PM superalloy mark in China [4]. The components (e.g. the turbine disk) made from FGH96 working at elevated temperature are frequently subjected to complex multiaxial loadings. Even under uniaxial loading, the positions in the structures/components which have geometrical discontinuities like notches will be in a state of multiaxial stress/strain [5–10]. Thus researching on the multiaxial fatigue of FGH96 alloy is obviously important for practical application.

Many experimental studies of multiaxial fatigue have been completed and a significant number of life prediction models have been proposed to assess the multiaxial fatigue lives of the materials. These approaches can be classified into four main categories, namely classical equivalent criteria, critical plane criteria, energy criteria and equivalently non-proportional strain criteria. In the early years, researchers often took the equivalent fatigue damage parameters as the basic damage parameters for multiaxial fatigue based on Von Mises criteria or Tresca criteria [11]. These approaches usually provide acceptable result for materials under proportional loadings, but the predicted lives are usually non-conservative for non-proportional loadings [12–14]. Subsequently, the critical plane approach was proposed. This theory postulates that cracks initiate on certain planes (namely critical planes), and the normal stress/strain parameters to those planes assist in the fatigue crack growth process. Brown-Miller [l5], Kandil [16], Fatemi–Socie [11] and Wang-Brown [17] make a great contribution to this significant category. Many researchers also deeply study on this approach and many improved models are proposed [18–27]. Another category about multiaxial fatigue life prediction is the energy criteria, which introduced the strain energy as a fatigue damage parameter. Different energy parameters were chosen to assess the multiaxial fatigue life of materials by Guard [28], Ellyin [29,30], Socie [31], Glinka [32], Palin-luc [33], Pan [34], Farahani [35], Liu [36], Walat [37], Ince [38] and Babaei [39]. In addition, it has been reported that the principal stress/strain axes and the maximum shear plane of the materials or structures rotate during one non-proportional loading cycle. So the slip bands are going to change, which can prevent stable dislocation to form. Then the non-proportional additional hardening would be exhibited finally [40–44]. It comes to a conclusion that the additional non-proportional hardening not only depends on the loading path and history, but also micro characteristics of materials (such as dislocation substructures, slip system and stacking fault energy) [7,42,45]. The

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Nomenclature

A_0	original cross section
b	fatigue strength exponent
b_0	torsion fatigue strength exponent
c	fatigue ductility exponent
c_0	torsion fatigue ductility exponent
E	elasticity modulus
EL	percentage elongation after fracture
G	shear modulus
k	normalization factor
K'	cyclic strength coefficient
n'	cyclic strain hardening exponent
N_f	number of loading cycles to failure
P	applied load
r_m	midsection radius
r_0	midsection radius
T	test temperature
W_a	torque amplitude
α	non-proportional cyclic hardening factor
γ_f'	torsion fatigue ductility coefficient
δ	wall thickness
$\Delta\varepsilon$	total strain range
$\Delta\varepsilon_e$	elastic strain range
$\Delta\varepsilon_p$	plastic strain range
$\varepsilon_{e,a}$	elastic strain amplitude
$\varepsilon_{p,a}$	plastic strain amplitude
ε_{eq}	equivalent strain
ε_f'	fatigue ductility coefficient
ν_e	elastic Poisson's ratio
ν_p	plastic Poisson's ratio
ν_{eff}	effective Poisson's ratio
σ_a	tensile stress amplitude
σ_f'	fatigue strength coefficient
σ_u	ultimate tensile strength
σ_y	yield stress
τ_a	shear stress amplitude
τ_f'	torsion fatigue strength coefficient
Φ	non-proportionality
ψ	percentage reduction of area

non-proportionality parameter is used by many researchers to describe the effect of the non-proportional additional hardening caused by the loading path and history. Meanwhile, the non-proportional cyclic hardening coefficient is applied to characterize the material sensitivity to the non-proportional additional hardening [45–47]. The equivalently non-proportional strain can be defined by combining the basic strain parameter with these two parameters and this approach has become an important category in the studies of multiaxial fatigue [48–51].

Although numerous multiaxial fatigue damage parameters have been developed during the past decades, most of them are limited to specific load cases and material, and this problem would become even more complex when the stress gradient exist [52–54]. In this paper, a multiaxial stress gradient factor is defined by combining the tensile stress gradient and shear stress gradient, and then which is introduced into a modified model to correlate the multiaxial fatigue of FGH96 alloy. The proportional and non-proportional axial-torsion fatigue tests are conducted to reveal the fatigue behaviors of PM superalloy FGH96. The experimental data are evaluated by six existent multiaxial fatigue models [12,13,39,47,55,56], which are compared to the modified Zhong-Wang-Wei (ZWW) model proposed in this paper.

2. Multiaxial fatigue model

2.1. The equivalent multiaxial fatigue model considering the non-proportional additional hardening

As mentioned above, the non-proportional additional hardening has been considered in many studies of multiaxial fatigue. Combining one suitable multiaxial fatigue damage parameter (e.g. a strain parameter $\bar{\varepsilon}_a$), the general form, which can characterize the effect of non-proportional additional hardening, is expressed by [44]:

$$\varepsilon_{eq} = (1 + \alpha\Phi)\bar{\varepsilon}_a \tag{1}$$

where α is the non-proportional cyclic hardening factor, which can characterize the material sensitivity to the non-proportional additional hardening or the microstructure of the material. Φ is the non-proportionality, which can take into account the effect of the non-proportional additional hardening caused by the loading path and loading history.

2.2. The Zhong-Wang-Wei multiaxial fatigue model

A life prediction model for multiaxial fatigue under proportional and non-proportional loading paths based on the π-plane projection proposed by Zhong-Wang-Wei (ZWW model) was first mentioned in Ref. [56]. This model chooses the largest polar coordinate strain parameter, $\varepsilon_{\pi,\max}$ on the π-plane as the basic multiaxial fatigue damage parameter. The equivalent strain, ε_{eq} is given as:

$$\varepsilon_{eq} = k(1 + \alpha\Phi)\varepsilon_{\pi,\max} \tag{2}$$

The parameter k is the normalization factor and the expression is:

$$k = 1/\frac{\sqrt{6}}{3}(1 + \nu_{eff}) \tag{3}$$

where ν_{eff} is the effective Poisson's ratio, which is given by:

$$\nu_{eff} = \frac{\nu_e\varepsilon_{a,e} + \nu_p\varepsilon_{a,p}}{\varepsilon_a} = \frac{\nu_e\varepsilon_{a,e} + \nu_p\varepsilon_{a,p}}{\varepsilon_{a,e} + \varepsilon_{a,p}} \tag{4}$$

where ν_e and ν_p are the elastic and the plastic Poisson's ratio, respectively. $\varepsilon_{a,e}$ and $\varepsilon_{a,p}$ are the elastic and plastic strain amplitude, respectively. ε_a is the strain amplitude, which is determined by the Ramberg-Osgood relation:

$$\varepsilon_a = \varepsilon_{a,e} + \varepsilon_{a,p} = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{1/n'} \tag{5}$$

where σ_a is the stress amplitude, K' is the cyclic strength coefficient, n' is the cyclic strain hardening exponent.

The non-proportional additional hardening factor α can be derived from the mechanical properties of the material according to Refs. [12,47]. For different materials of face-centered cubic structure (FCC) and body-centered cubic structure (BCC), the parameter can be calculated respectively as:

$$\begin{cases} \alpha = \frac{\sigma_b - \sigma_y}{\sigma_b} & \text{for FCC material} \\ \alpha = 2\frac{\sigma_b - \sigma_y}{\sigma_b} & \text{for BCC material} \end{cases} \tag{6}$$

where σ_u is the ultimate strength, σ_y is the yield stress.

The non-proportionality, Φ is given as [56,57]:

$$\Phi = (I'/I_0)^h \tag{7}$$

where I' is the moment of inertia of the loading path, I_0 is the moment of inertia of minimum circumcircle of the loading path, h is the non-proportionality exponent which determined by the loading path and loading history.

As all parameters are determined, the multiaxial fatigue life prediction model can be given as: