Engineering Failure Analysis 93 (2018) 55–63

Contents lists available at ScienceDirect

Engineering Failure Analysis

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

A new critical plane-energy model for multiaxial fatigue life prediction of turbine disc alloys

Shen Xu[a], Shun-Peng Zhu[a,b,*], Yong-Zhen Hao[a], Ding Liao[a], Guian Qian[c]

[a] School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China
[b] Center for System Reliability & Safety, University of Electronic Science and Technology of China, Chengdu 611731, China
[c] State Key Laboratory of Nonlinear Mechanics (LNM), Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

ARTICLE INFO

Keywords:
Multiaxial fatigue
Virtual strain energy
Critical plane
Mean stress
Life prediction

ABSTRACT

For engine components under complex loadings, multiaxial fatigue life prediction is critical for ensuring their structural integrity and reliability. Combining the critical plane method with the virtual strain energy concept, a new multiaxial fatigue damage parameter is proposed to characterize the influence of both shear/normal mean stress and non-proportional hardening on fatigue life. Particularly, no extra material constants are needed for model application. Experimental data of TC4 and GH4169 alloys under various loading paths are utilized to evaluate and validate the proposed damage parameter as well as four other models. Results show that the proposed damage parameter yields a higher accuracy on multiaxial fatigue life prediction than others.

1. Introduction

The integrity of aero engine components in service are mainly threatened by multiaxial fatigue failure due to their various multiaxial loading paths [1–6]. Accordingly, increasing attentions are being paid on developing valid approaches for multiaxial fatigue analysis [7–14]. Among them, most multiaxial fatigue models were presented based on simple combinations of stresses or strains [15,16]. Though a scalar parameter might provide a reasonable life prediction, it cannot explain well the experimental phenomenon that cracks initiate and grow on a specific plane rather than a random one [17]. Based on this, the critical plane-based methods have been introduced for practice, in which the critical plane is normally defined differently for different multiaxial fatigue damage parameters.

In particular, various multiaxial fatigue models have been put forward through combining the critical plane-based method with stress/strain-based parameters [17] as well as strain energy-based damage parameters, which combine the effects of loading histories and both states of stress and strain. Among them, Garud [18] applied the plastic strain energy density for multiaxial fatigue analyses. However, this plastic work is really small in a high cycle fatigue (HCF) regime and is difficult to measure or calculate for model application with sufficient accuracy. According to this, Liu [19] developed two damage parameters on the planes with the maximum amount of axial/shear work component to consider both tensile/shear failure modes, which contains elastic and plastic parts to overcome the limitations of Garud's model, but the need of judging failure mode causes the inconvenience for model application. Then, Chu [20] introduced a similar parameter to combine shear and normal works and replaced the stress range with the maximum stress to account for the effect of mean stress, however, ignored the mean stress effect in the case of non-proportional loading with

* Corresponding author at: School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China.

E-mail address: zspeng2007@uestc.edu.cn (S.-P. Zhu).

https://doi.org/10.1016/j.engfailanal.2018.07.001
Received 25 May 2018; Received in revised form 21 June 2018; Accepted 5 July 2018
Available online 05 July 2018

zero strain amplitude. Thus, a stable and effective multiaxial fatigue criterion is still lacking for engineering practice.

In this regard, through considering the virtual shear strain energy and the normal stress term, this work aims to present a new critical plane-strain energy damage parameter for fatigue lifing of engine components. For the rest of this paper, a short review on several commonly-used multiaxial fatigue damage parameters is briefly presented in Section 2. Section 3 defines the maximum virtual shear strain-energy plane as the critical plane and develops a new multiaxial fatigue damage parameter. In Section 4, experimental data of TC4 and GH4169 alloys under different loading paths are utilized for model validation. Section 5 draws the conclusions.

2. Existing damage parameters for multiaxial fatigue analysis

As aforementioned, various damage parameters have been presented for multiaxial fatigue analysis, including stress-based, strain-based and strain energy-based ones. Particularly, several commonly-used ones are introduced as follows.

i) McDiarmid's criterion

McDiarmid [21] analyzed the same fatigue data used by Findley [22], but came to a slightly different model. He replaced Findley's material parameter k with the quantity $\frac{t_{A,B}}{2\sigma_{uts}}$ to avoid the inconvenience of defining k and developed a stress-based criterion as.

$$\frac{\Delta\tau_{max}}{2t_{A,B}} + \frac{\sigma_{n,max}}{2\sigma_{uts}} = 1 \tag{1}$$

With regard to fatigue life prediction, Eq. (1) can be rewritten according to the Basquin's equation by

$$\frac{\Delta\tau_{max}}{2} + \left(\frac{t_{A,B}}{2\sigma_{uts}}\right)\sigma_{n,max} = \tau_f'(2N_f)^{b_0} \tag{2}$$

where $\Delta\tau_{max}$ is the maximum shear stress range, $\sigma_{n,\ max}$ is the maximum normal stress on the same plane, $t_{A,\ B}$ is the fatigue strength for Case A (acting on the free surface) or Case B (growing into the depth) cracking and σ_{uts} is the ultimate tensile strength. Eq. (2) characterizes both A and B case cracking modes. Case A cracking propagates along the free surface, and Case B cracking results in cracks that penetrate into the material. In the McDiarmid's damage parameter, the critical plane is defined by the plane with maximum shear stress. However, most stress-based models, including models of Findley [22] and Dang Van [23], can only provide acceptable life prediction results in the HCF regime due to the small plastic deformation.

ii) WB and FS criteria

On the basis of the research of Brown and Miller [24], Wang and Brown [25] introduced a maximum shear strain plane and modified the normal strain on the same plane. Furthermore, they considered the mean stress effect on fatigue life and put forward a strain-based criterion, namely the WB damage parameter, which can be expressed by

$$\begin{gathered}\frac{\Delta\gamma_{max}}{2} + S\Delta\varepsilon_n = A'\frac{\sigma_f' - 2\sigma_{n,mean}}{E}(2N_f)^b + B'\varepsilon_f'(2N_f)^c \\ \text{where} \quad A' = 1 + \nu_e + (1-\nu_e)S \\ B' = 1 + \nu_p + (1-\nu_p)S\end{gathered} \tag{3}$$

where $\Delta\gamma_{max}$ is the maximum shear strain range, $\Delta\varepsilon_n$ is the normal strain range on the plane experiencing the maximum shear strain, $\sigma_{n,\ mean}$ is the normal mean stress on the plane, E is the elastic modulus, ν_e and ν_p are the elastic and plastic Poisson's ratios, and S is an additional material constant that accounts for the influence of normal strain on fatigue cracking.

Based on Eq. (3), Fatemi and Socie [26] replaced normal strain term with the normal stress, which leads to the FS damage parameter as

$$\frac{\Delta\gamma_{max}}{2}\left(1 + k\frac{\sigma_{n,max}}{\sigma_y}\right) = \frac{\tau_f'}{G}(2N_f)^{b_0} + \gamma_f'(2N_f)^{c_0} \tag{4}$$

where σ_y is the cyclic yield strength [27], k is an additional material constant defined to reflect the effect of normal stress on crack growth. Though both the WB and FS models evaluate fatigue life for various ductile materials with an acceptable prediction ability, it is inconvenient to determine the value of S or k by fitting axial and torsion data, particularly under limited testing data conditions. In addition, its additional material constants calculated by different ways usually lead to different life predictions.

iii) SWT and MSWT models

Smith, Watson and Topper [28] considered the effect of both the principal strain range and the maximum stress, then introduced an alternate damage model, namely the SWT model.