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A multiaxial high-cycle fatigue life evaluation model for notched structural components

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ABSTRACT

A model for multiaxial high-cycle fatigue life evaluation of notched structural components is proposed, which considers the impact of the stress field on fatigue life by utilizing the Theory of Critical Distances (TCD) and Finite Element Method (FEM). The maximum shear stress range plane is defined as the critical plane, and the damage parameters are the maximum effective shear stress amplitude and the maximum effective normal stress, which are obtained by averaging the stress in the hemisphere volume around the maximum stress point. To validate the accuracy of the model, multiaxial fatigue tests are carried out for both smooth and notched specimens of Aluminum–Silicon alloy. The results indicate that the evaluated life and experimental life have a good agreement.

1. Introduction

Vehicle engine design tends to lightweight and high specific volume power, and component parts are under increasing harsher conditions. As a result, many engine components simultaneously bear a significant mechanical and thermal load. Fatigue failure is one of the main causes of damage. Fatigue properties of materials are one of the most important factors affecting the reliability of the structural components. Aluminum–Silicon (Al–Si) alloys are widely used for complex components such as pistons and cylinder heads owing to the following advantages: good casting properties, small linear expansion coefficient, light weight and excellent wear resistance, etc. Some researchers have already studied failure mechanisms and life evaluation of Al–Si alloys under thermal–mechanical fatigue loading [1–4]. Actually, the failure in non-high temperature zones of piston and cylinder head, such as the piston pin boss and the cylinder head top ceiling, is mainly due to high-cycle mechanical fatigue under high frequency and low stress levels. Furthermore, the stress of these zones may be multiaxial and unevenly distributed due to complex loadings and notch features, which affect the fatigue strength. Therefore, it is necessary to study multiaxial high-cycle mechanical fatigue properties for notched structural components of Al–Si alloys. Currently, local stress and strain approaches and the Theory of Critical Distances (TCD) are common approaches for multiaxial high-cycle fatigue life evaluation for notched structural components.

Local stress and strain approaches estimate the fatigue life by the local maximum stress/strain at notch root utilizing the criteria such as equivalent stress criteria, critical plane criteria and energy criteria. Equivalent stress criteria reduce a multiaxial stress state to a uniaxial equivalent stress state and relate the fatigue life to uniaxial fatigue properties [5,6]. Based on the initiation and propagation mechanisms of fatigue crack, critical plane criteria are generally considered as more effective methods owing to the clear physical meaning. Findely [7], Matake [8] and McDiarmid [9] have made many advancements in this field. Energy criteria estimate the fatigue life by the strain energy density. Garud [10] and Glinka and Plumtree [11] have published significant contributions to this method. In fact, fatigue behavior of a notch is not uniquely defined by the local maximum stress but also depends on other factors determined by notch geometry and local stress distribution [12]. Therefore, evaluating fatigue life through the local maximum stress at notch root is often overly conservative [13].

The TCD postulates that the failure in notched structural components can be estimated accurately by using information from the linear-elastic stress field in the vicinity of stress raiser apices through an appropriate effective stress [14]. The theory was first proposed by Neuber [15] and Peterson [16], and has recently been reformulated on the basis of the concepts of Linear Elastic Fracture Mechanics by Taylor et al. [17–23]. For now, the TCD for multiaxial fatigue is not as mature as that for uniaxial fatigue. The stress state

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and distribution of notch under multiaxial loading are more complex than those under uniaxial loading. Therefore, it is more difficult to determine the appropriate focus path [18] and effective stress to be used in the TCD. Developing concise and applicable models for multiaxial fatigue life evaluation of notched structural components seems to be necessary.

In this paper, a multiaxial high-cycle fatigue life evaluation model is proposed on the basis of the critical plane criterion through the investigation of multiaxial fatigue properties under proportional and non-proportional loadings. The impact of the stress field on fatigue life is taken into account by the Volume Method (VM) of the TCD, and the effective stress at notch root is calculated by Finite Element Method (FEM). To validate the accuracy of the model, fatigue tests under axial–torsion cyclic loading have been carried out on both smooth and notched specimens of Al–Si alloy, respectively. The group method is employed for fatigue tests at each stress level due to the scatter data.

2. Multiaxial fatigue life evaluation model for notched structural components

2.1. Multiaxial fatigue life evaluation model for smooth components

Multiaxial fatigue refers to the damage under multiaxial cyclic loading, which means that at least two stress components vary over time periodically. The loading is non-proportional if any cyclic loading results in the rotation of principal axes in time, while it is proportional if the principal directions of cyclic loading remain fixed [24].

Under multiaxial cyclic loading, the crack substantially generates along the maximum shear stress plane and then propagates under the action of the normal stress. According to this physical phenomenon, Findley [7] proposed a shear-mode critical plane criterion through bending-torsion fatigue tests in the 1950s. The critical plane is the maximum linear combination plane of the shear stress amplitude, $\Delta\tau/2$, and the maximum normal stress, $\sigma_{n,\max}$. Fatigue failure is expected to occur on the plane [25]:

$$(\Delta\tau/2 + k\sigma_{n,\max})_{\max} = t_{eq} \tag{1}$$

where k is a material parameter determined experimentally, and t_{eq} is related to the torsion fatigue strength of the material.

At present, a common method for multiaxial fatigue tests is applying the axial–torsion cyclic loading to the cylindrical specimen. Extensive research works have shown that the fatigue life under non-proportional loading is usually lower than that under proportional loading [26–28], and the fatigue life decreases with the increase of phase differences of axial–torsion cyclic loading [29,30]. The reason is that the continuous rotation of principal stress axes under non-proportional loading leads to additional hardening of the material [31]. Additionally, if the applied von Mises stress amplitude, $\Delta\sigma_{eq}/2$, is the same, the shear stress amplitude on the maximum shear stress range plane varies a little while the maximum normal stress gradually increases with increasing the phase difference of axial–torsion cyclic loading. Fig. 1 shows the stress curve on the plane under in-phase and 90° out-of-phase of axial–torsion loading when $\Delta\sigma_{eq}/2$ is 160 Mpa. Consequently, it is more reasonable to define the maximum shear stress range plane as the critical plane, since the fatigue crack initiates along such a plane, and the $\sigma_{n,\max}$ on this plane reflects the fact that the fatigue life is reduced under non-proportional loading.

For the convenience of application in engineering, a tension-mode criterion is proposed, in which the maximum shear stress range plane is defined as the critical plane. The damage parameter is a combination of the maximum shear stress amplitude, $\Delta\tau_{\max}/2$, and the $\sigma_{n,\max}$ on the plane, by means of the von Mises criterion:

$$\sqrt{3(\Delta\tau_{\max}/2)^2 + k\sigma_{n,\max}^2} = f_{eq} \tag{2}$$

where f_{eq} is related to the tension fatigue strength of the material and can easily be acquired by experiments.

The *S–N* curve model in the high-cycle fatigue regime is described by the Basquin equation and then a new multiaxial high-cycle fatigue life evaluation model is proposed. The model is suitable for both proportional and non-proportional loadings:

$$\sqrt{3(\Delta\tau_{\max}/2)^2 + k\sigma_{n,\max}^2} = \sigma_f'(2N_f)^b \tag{3}$$

where σ_f' and b are the tension fatigue property parameters of the material, and N_f is the fatigue life.

2.2. The impact of the stress field on fatigue life

The calculation of the effective stress for the TCD includes the Point Method (PM), the Line Method (LM), the Area Method (AM) and the Volume Method (VM) [18]. The effective stress of PM is the stress of a single point at a critical distance ahead of the notch tip. The effective stress of LM, AM and VM is the average stress on a line, area and volume within a critical distance ahead of the notch tip, respectively. Fatigue failure occurs when the effective stress range at notch root reaches the fatigue limit of the material.

The critical distance is related to the parameter L [12,32], which is the material characteristic length, and can be calculated as follows [12]:

$$L = (1/\pi)(\Delta K_{th}/\Delta\sigma_0)^2 \tag{4}$$

where ΔK_{th} is the threshold value of stress intensity factor, and $\Delta\sigma_0$ is the fatigue limit of the material.

The above methods of the TCD are mostly derived for notched structural components under uniaxial loading, but the complexity of the structure and loading for multiaxial fatigue usually leads to more difficulties in determining the appropriate focus path when utilizing the PM, LM and AM. For the convenience of application, the VM is here employed to calculate the effective stress at notch root. The maximum shear stress range plane at the maximum stress point is defined as the critical plane. The hemisphere volume with critical radius 1.54L ahead of the point is selected as fatigue process zone, where the radius value is taken from the literature [18]. The stress tensor at any point within the volume is converted into the shear stress and the normal stress the critical plane. Then, the effective stress can be acquired by the averaged values as follows:

$$\tau_R = \frac{1}{V}\int f(\tau)dv \tag{5}$$

$$\sigma_{n,\mathrm{FI}} = \frac{1}{V}\int f(\sigma_n)dv \tag{6}$$

where V is the volume of fatigue process zone, τ_{FI} and $\sigma_{n,\mathrm{FI}}$ are the effective shear stress and the effective normal stress, respectively, $f(\tau)$ and $f(\sigma_n)$ are the shear stress and the normal stress in the critical plane, respectively.

Stress field distributions can be simulated by FEM [12,33]. The finite element stress, σ_i^e, represents the stress in the space which the finite element belongs to. If the mesh of the structure is refined enough, the finite element stress distribution can accurately represent the stress distribution of the notched component. Therefore, Eqs. (5) and (6) can also be formulated based on the FEM results as follows: