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Finite element analysis of void growth behavior in nickel-based single crystal superalloys

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ABSTRACT

Nonlinear stiffness method (NSM) was established to control the stress triaxiality. Based on the 3-D cell model, the void growth behavior in nickel-based single crystal superalloys (SXs) was analyzed with crystal plasticity theory and NSM. A range of factors were considered including stress triaxiality, initial volume fraction of voids, Lode parameters, crystallographic orientation, slip system activation and elastic anisotropy. The calculation results show that these factors influence the void growth character. The stress triaxiality is the driving force and plays an important role in void growth. At low stress triaxiality, the void deformation mainly exhibits as shape change, and at high stress triaxiality, it mainly exhibits as bulk expansion. The initial volume fraction of void influences the growth rate remarkably. The smaller the volume fraction is, the higher the growth rate is. The Lode parameter has great effect on the void growth and its shape change. The crystallographic orientation and activated slip systems have noticeable influence on the void growth, too. The void growth rate, when $\{1\,1\,1\}\langle 1\,1\,0\rangle$ slip system is activated, is higher than that when $\{1\,1\,1\}\langle 1\,1\,2\rangle$ slip system is activated. The elastic anisotropy plays an important role in void growth. The void grows faster in elastic isotropic matrix than that in elastic anisotropic matrix.

1. Introduction

Nickel-based single crystal superalloys (SXs) have been widely used for high temperature applications such as non-cooled turbine blades and cooled turbine blades due to their good creep resistance. Although single crystal turbine blades have been extensively used, their potentials have not been fully explored. One important reason is the existence of casting defects, especially the casting microporosities and micro-cracks, which greatly degrades the materials and furthermore affects the strength and life of casts [1–3]. As shown in Fig. 1, a typical scanning electron microscopic photo of fracture surfaces indicates that the voids induced by cast defections play an important role during deformation, damage and rupture in SXs. Therefore, the study on the void nucleation, growth and coalescence in SXs is very useful for understanding the damage and rupture mechanism of SXs, especially for the life prediction under practical conditions.

Researchers have studied the damaging mechanism induced by void nucleation, growth and coalescence on polycrystal ductile materials, and then suggested some influential mechanical models, such as Rice–Tracey model [4] and Gurson model [5] etc. Many experiments and calculations have been carried out on the basis of Gurson model [6–9]. Gurson model is a rate-independent constitutive model based on J_2 flow theory. However, single crystal materials, different from polycrystalline materials, have no grain boundary, which improves its high temperature mechanical properties but causes crystallographic orientation-dependent problems, so Gurson model is not applicable for single crystal materials. The research by Oregan et al. [3] shows that mechanical behaviors of casting microporosities analyzed with crystal plasticity theory and J_2 flow theory, respectively, are significantly different. Few researches have been carried out on casting microporosities and micro-cracks of SXs due to experimental difficulties [10], their complex constitutive relation and the problem of numerical instability.

Cell model establishes the connection between the macro- and the micro-mechanical behaviors of materials and is extensively applied in meso-level simulation of casting microporosities [6,11–15]. Therefore, it is of great practical significance to adopt cell model to analyze the evolution of casting defects (voids, inclusions and micro-cracks) of SXs and their effect on the life of SXs.

Wan et al. [16] adopted crystal plasticity theory to carry out finite element analysis of void expansion in SXs based with three-dimensional (3-D) cell model. In his analysis, the effect of different stress triaxiality, Lode parameters, slip system activation and loading orientations were considered to draw some meaningful conclusions: accumulated shear strain plays important role in void growth; larger accumulated shear strain corresponds with higher volume fraction casting microporosities; the activated slip system

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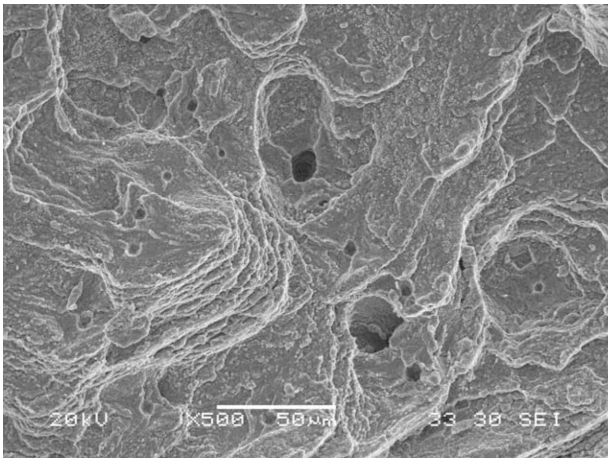

Fig. 1. SEM photos of fracture surface of creep–fatigue tested CMSX-4 specimens at 980 °C in [0 0 1] crystallographic orientation.

greatly affects the void growth; the void growth is closely associated with crystal orientation. However, the anisotropy of SXs not only includes crystallographic orientation-dependent directionality of the activated slip system, but also elastic anisotropy. To investigate the void expansion in SXs, initial void volume fraction, stress triaxiality, Lode parameter, slip system activation, loading orientations as well as elastic anisotropy should be considered.

This paper established a new method to control the stress triaxiality – nonlinear stiffness method, and with this new method it analyzed the void expansion in SXs based on crystal plasticity theory and 3-D cell model. All the factors were considered including stress triaxiality, the initial volume of voids, Lode parameters, crystal orientation, slip system activation and elastic anisotropy.

2. 3-D cell model

Casting defects (voids, inclusions and micro-cracks) in SXs are randomly shaped and distributed. The randomness affects the mechanical behavior and damage of SXs. To facilitate theoretical analysis, the simplified model with hypothesized periodically distributed spherical cavities was used. In 3-D case, taking imposed load and geometrical symmetry into account, it is only necessary to analyze 1/8 3-D cell model, as is shown in Fig. 2. Along x_1, x_2 and x_3 of the rectangular coordinates, the initial side lengths of

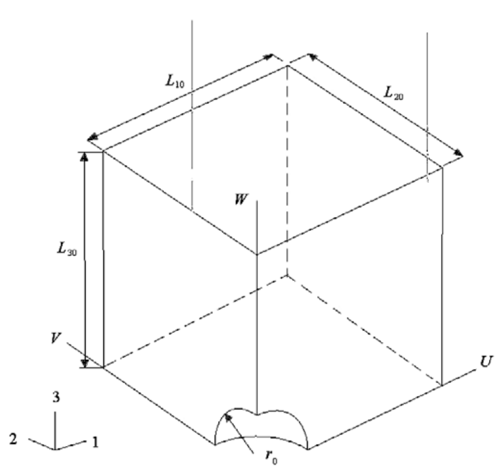

Fig. 2. 3-D cell model: a spherical void contained within a cubic cell.

the model are L_{10}, L_{20} and L_{30}, and the initial radius of the cavity is r_0. When the strain loads are imposed, the three boundaries are kept plane, in case that there is no superposition among the deformed parts of the model. Therefore, there is no shear stress on each loading surface, and their displacements are represented as uniform normal displacements U, V and W, respectively. During the deformation process, the instantaneous side lengths of the cell model are

$$L_1 = L_{10} + U, \quad L_2 = L_{20} + V, \quad L_3 = L_{30} + W \tag{1}$$

the macro-strain of the cell model is

$$E_1 = \ln\left(\frac{L_1}{L_{10}}\right), \quad E_2 = \ln\left(\frac{L_2}{L_{20}}\right), \quad E_3 = \ln\left(\frac{L_3}{L_{30}}\right) \tag{2}$$

the macro-equivalent strain is

$$E_e = \frac{\sqrt{2}}{3}\sqrt{(E_1 - E_2)^2 + (E_2 - E_3)^2 + (E_3 - E_1)^2} \tag{3}$$

and the macro-stress is defined as

$$\Sigma_1 = \frac{1}{L_2 L_3}\int_0^{L_2}\int_0^{L_3}[\sigma_{11}]_{x_1=L_1}dx_2 dx_3 \tag{4}$$

$$\Sigma_2 = \frac{1}{L_1 L_3}\int_0^{L_3}\int_0^{L_1}[\sigma_{22}]_{x_2=L_2}dx_3 dx_1 \tag{5}$$

$$\Sigma_3 = \frac{1}{L_1 L_2}\int_0^{L_1}\int_0^{L_2}[\sigma_{33}]_{x_3=L_3}dx_1 dx_2 \tag{6}$$

σ_{11}, σ_{22} and σ_{33} stand for local normal stresses in matrix. Because the displacements on each boundary surfaces of the cell model are uniform, the stress on them is necessarily non-uniform. In finite element calculation, when the total addition of node force on each surface is divided by instantaneous cross section area, the result is instantaneous average stress on each surface, i.e. the macro-stresses of the cell model are calculated as

$$\Sigma_1 = \frac{F_1}{L_2 L_3}, \quad \Sigma_2 = \frac{F_2}{L_1 L_3}, \quad \Sigma_3 = \frac{F_3}{L_2 L_1} \tag{7}$$

In which F_1, F_2 and F_3 are the total addition of node force on each surface.

The macro-equivalent stress and the average stress are

$$\Sigma_e = \frac{1}{\sqrt{2}}\sqrt{(\Sigma_1 - \Sigma_2)^2 + (\Sigma_2 - \Sigma_3)^2 + (\Sigma_3 - \Sigma_1)^2} \tag{8}$$

$$\Sigma_h = \frac{1}{3}(\Sigma_1 + \Sigma_2 + \Sigma_3) \tag{9}$$

The triaxial stress state parameter of the cell model, i.e., stress triaxiality, is

$$T = \frac{\Sigma_h}{\Sigma_e} \tag{10}$$

The volume fraction of the void is calculated by the simplified volume formula of ellipsoidal volume calculation formula. The initial volume fraction of the void f_0 is calculated as follows

$$f_0 = \frac{\frac{1}{6}\pi r_0^3}{L_{10}L_{20}L_{30}} \tag{11}$$

For convenience, the deformed void shape is exactly assumed ellipsoidal, so the instantaneous volume fraction can be calculated as

$$f = \frac{\frac{1}{6}\pi abc}{L_1 L_2 L_3} \tag{12}$$