Materials Science & Engineering A 587 (2013) 79–84

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

The evolution of plasticity for nickel-base single crystal cooled blade with film cooling holes

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ARTICLE INFO

Article history:
Received 6 July 2013
Received in revised form
21 August 2013
Accepted 24 August 2013
Available online 31 August 2013

Keywords:
Crystal plasticity
Single crystal
Cooled blade
Slip system

ABSTRACT

In order to get the information of the stress structure and the activated slip system of nickel-base single crystal cooled turbine blades, the uniaxial tensile specimens with single hole were studied by means of the crystal plasticity finite element method and experimental observations. The results of experiment suggest that cracks developed and formed fracture surfaces along the deformation bands. The computational results show that the activated slip systems along the thickness direction and at free surface are significantly different. The stress fields on the surface form four banded stripes around the hole, on which the initiation and propagation of the cracks are dependent. The experimental observed slip traces are found to be in a good agreement with the predicted slip sector based on the FEM.

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1. Introduction

The turbine blade is amongst the most critical of components in the aeroengine. Single crystal superalloys have been widely used for turbine blade material due to their superior thermal resistance and melt resistance capabilities [1,2]. As the gas temperature plays a significant role in the efficiency of the gas turbine, cooling holes are used on the surface of the blades to enable the blade material to sustain the high temperatures, as shown in Fig. 1. The film cooling holes have remarkable influence on the strength of the cooled blade due to stress concentration, and there are complicated stress and strain around the film cooling hole as the result of the anisotropy of single crystal.

The slip patterns have important consequences on crack initiation and growth. In order to identify crack nucleation mechanisms of cooled blades, it is important to understand the plastic behavior near the cooling hole. Gan investigated the effect of cylindrical voids on stress and strain fields in FCC single crystals based on the anisotropic slip line theory [3]. Flouriot et al. showed that there are strong differences between the crack tip plastic strain fields observed at the free surface and mid-section of the compact tension fracture mechanics specimen [4]. Westbrooke investigated the characteristics of deformation bands in Ni-based superalloy single crystals for three different orientations [5]. Arakere et al. studied the evolution of plasticity in single crystal notched tensile specimens through a three-dimensional elastic anisotropic model [6]. Sabnis et al. noted that the elastic model used is not capable of accounting for nonlinear effects such as latent hardening and lattice rotation afforded by finite strain crystal plasticity simulations [7]. However, to the author's knowledge, researches on the strength of a cooled blade with film cooling holes were rarely reported in public literatures. In experiment, the deformation bands of single crystal have been widely investigated. Shield and Kim observed the intense local deformation bands around the crack tip in the bcc single crystal [8]. Crone and Shield presented detailed observations of the deformation near a notch tip in copper and copper–beryllium single crystal [9]. These observations provide evidence of the main features of the deformation fields predicted by Rice [10] using continuum single crystal plasticity [11].

The main object of this paper is to study the evolution of plasticity of single crystal blades with film cooling and the characteristics of crystal slipping around the hole. The load orientation is fixed along the [001] direction, while the thickness direction of the hole is parallel to the [100] orientation. Both experimental and finite element studies are carried out. The three-dimensional crystal plasticity finite element method (CPFEM) accounting for the effect of lattice rotation and finite deformation is used to analyze the stress fields and slip systems activated around the film cooling hole. Because of the cooling holes are most susceptible for fatigue crack initiation, our investigations can be used for identifying the critical cooling hole in cooled blade design and obtaining a deeper insight into fatigue cracks around the cooling hole. On the other hand, the simulation results are also used to understand the difference in resolved strains between the specimen core and free surface.

In the first section of this paper, the material and experimental work are introduced. The second section shows the crystallographic constitutive relationship used for finite element

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http://dx.doi.org/10.1016/j.msea.2013.08.045

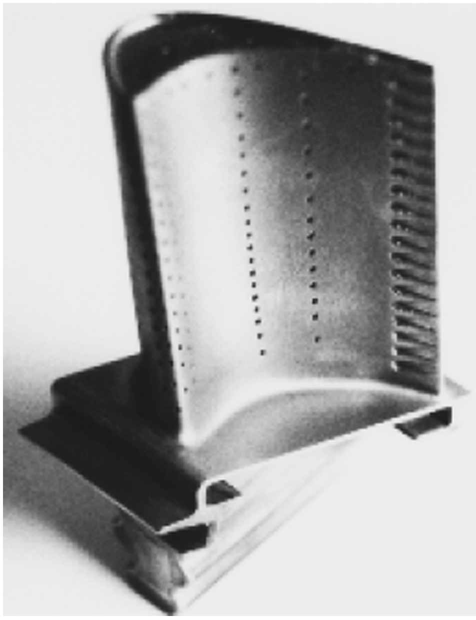

Fig. 1. Cooling blade model.

simulations. Finally, the numerical prediction and the experimental observations are presented and discussed.

2. Materials and experimental details

The DD6 nickel-base single crystal superalloy is the second generation single crystal superalloy developed by Chinese research institution and has been used commercially in the turbine blade. Refer to Table 1 for its chemical composition. The alloy contains 1.6 wt% rhenium which is lower than that in the second generation single crystal superalloys such as PWA1484, CMSX-4 and René N5 [12], and thus has a competitive advantage of lower cost. It has a high volume fraction of coherent intermetallic γ' precipitates dispersed throughout the nickel matrix γ phase [13], although this material contains two phases, the property of plastic deformation is analogous to a single phase FCC crystal.

Fig. 2 shows the geometry definition of the single-hole tensile specimens used in the study. The crystallographic orientations are determined by Laue back-reflection X-ray procedures, and the misorientations are less than 5° in the casting direction. It should be pointed out that during the manufacture of a single crystal blade, the airfoil stacking line is between 0° and 10° relative to the [001] primary orientation. The hole was formed by electric spark machining and the surfaces of the specimens were carefully polished to remove the damage.

The specimens used in this paper were 60 mm long, with a gage length of 20 mm. Tensile testing was carried out at ambient temperature in an Instron 8871 model servohydraulic machine. The strain rate was $10^{-5}\,s^{-1}$. The specimen was loaded to small strain levels in order to analyze the evolution of slip traces around the hole before and after yielding.

3. Constitutive modeling and material parameters

Crystallographic constitutive model is developed based on the theory of Taylor and his co-workers [14–16]. In the crystal plastic model, the total deformation gradient F is decomposed into elastic

Table 1
The chemical composition (wt%) of DD6.

Cr	Co	W	Al	Ta	Re	Mo	Ni
3.8	8.5	7.0	5.2	6.0	1.6	1.5	balance

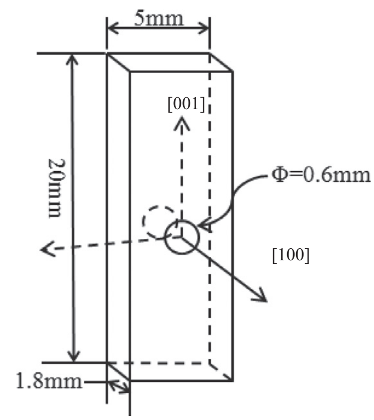

Fig. 2. Dimensions of specimen.

and plastic components.

$$F = F^e F^p$$

As the crystal deforms and rotates, lattice vectors stretch and rotate. The slip directions $m^{(\alpha)}$ is given in the deformed configuration by

$$m^{*(\alpha)} = F^e m^{(\alpha)}$$

The slip plane normal vector is given by

$$n^{*(\alpha)} = \left((F^e)^{-1}\right)^T n^{(\alpha)}$$

The velocity gradient in the current state is given by standard formula:

$$L = \dot{F}F^{-1} = \dot{F}^*(F^*)^{-1} + F^*\dot{F}^p(F^p)^{-1}(F^*)^{-1}$$

where L can be also be expressed as

$$L = D + W$$

D and W are the symmetric rate of the stretching and spin tensors, respectively.

Since plastic deformation occurs by dislocation slip, the following equation can also be obtained

$$L^p = \sum_{\alpha=1}^{N} P^{(\alpha)}\dot{\gamma}^{(\alpha)}$$

where $\dot{\gamma}^{(\alpha)}$ is the slipping rate of the α slip systems, the Schmidt tensor $P^{(\alpha)}$ is defined as

$$P^{(\alpha)} = \frac{1}{2}(m^{*(\alpha)} \otimes n^{*(\alpha)} + n^{*(\alpha)} \otimes m^{*(\alpha)})$$

Further, we denote by σ the Cauchy stress tensor, by τ the weighted Cauchy stress tensor

$$\tau = (\det F)\sigma$$

and by

$$T = F^e \tau F^{e-1}$$

The second Piola–Kirchhoff stress tensor relative to the intermediate configuration.

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