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Microstructure sensitivity of fretting fatigue based on computational crystal plasticity

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ABSTRACT

Three-dimensional finite element simulations are conducted to study the effects of microstructure on the fretting fatigue behavior of duplex Ti–6Al–4V. These fretting simulations involve a rigid cylindrical indenter pressed on the half space of Ti–6Al–4V with different realizations of microstructure. The deformation behaviors of the primary α and α/β lamellar phases at room temperature are described by three-dimensional crystal plasticity constitutive relations. Microstructure attributes considered in this sensitivity study include crystallographic texture, grain size, and grain size distribution. Voronoi tessellation is used to construct the three-dimensional finite element models with various grain size distributions. The plastic strain behaviors and the distribution of the average maximum plastic shear strain among grains are analyzed and contrasted. The relative susceptibility for crack formation, including effects of various microstructure features, is determined using the Fatemi–Socie parameter. The results suggest that both average grain size and especially crystallographic texture have more influence on the plastic deformation and fretting fatigue behavior than grain size distribution for the fretting condition considered.

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1. Introduction

Fretting fatigue is a near-surface phenomenon that occurs over a very small area. Damage, plastic deformation, and microstructure transformation occur within a depth of several grains from the surface. The tangential relative surface displacement between two bodies is also extremely small (several μm). Since the material microstructure is of comparable dimensions, it can significantly influence the mechanical behavior.

Titanium-based alloys are used in critical rotating components in gas turbine engines due to their high specific strength advantage over other materials. Among these alloys, Ti–6Al–4V is one of the most widely used in aerospace structural applications. A wide range of mechanical properties can be achieved by varying the microstructure of dual-phase Ti–6Al–4V through heat treatment and thermomechanical processing. For example, reducing the size of the primary α grains and $\alpha-\beta$ lamellar colonies results in higher yield strength [1].

Conventional plasticity is useful for modeling the macroscopic stress–strain response of Ti–6Al–4V. However, the homogenized approach is incapable of explicitly describing the effects of microstructure on mechanical behavior. Goh et al. [2] and Morrissey et al. [3] developed a microstructure-scale two-dimensional crystal plasticity model of duplex Ti–6Al–4V that employed a planar triple slip idealization. The two-dimensional crystal plasticity model was extended to a full three-dimensional version by Mayeur and McDowell [4]. Both the primary α grains and $\alpha-\beta$ lamellar colonies are captured in this model. Zhang et al. [5] extended the Mayeur–McDowell model to predict the measured macroscopic responses of a duplex heat treated Ti–6Al–4V alloy subjected to a complex cyclic loading histories. The sensitivity of material strength to microstructure was examined and shown to be in good agreement with the experimental observations [5].

Fretting fatigue simulations using the two-dimensional crystal plasticity model showed the impact of microstructure on the fretting deformation behavior [2,6]. The early work showed that differential yielding among grains due primarily to crystallographic orientation in regions of steep cyclic gradients lead to intense concentrations of shear. Plastic strain accumulation is primarily due to ratcheting. Fretting simulations using full three-dimensional crystal plasticity models exhibit similar behaviors but allow the study of realistic microstructures, including the distributions of grain orientations and realistic textures [7–10]. Dick and Cailletaud [11] have also conducted fretting fatigue simulations on Ti–6Al–4V with more realistic modeling of grain shapes using Voronoi polyhedra, although they considered only the primary α phase. Similar effects of microstructure attributes on creep and high strain rate behavior of Ti–6Al–4V have been studied using crystal plasticity by Hasijia et al. [12] and Schoenfeld and Kad [13], respectively.

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In this paper, fully three-dimensional fretting simulations are conducted on duplex Ti–6Al–4V to investigate the sensitivity of three microstructure attributes on fretting behavior: the average grain size, the grain size distribution, and texture. Conclusions on the relative influence of these microstructure parameters are drawn based on the deformation response and analysis using shear strain based fatigue indicator parameters.

2. Materials

Duplex Ti–6Al–4V contains a mixture of primary hcp α phase and secondary α plus bcc β phase arranged in a lamellar structure, as shown in Fig. 1. It is well known that the texture and microstructure morphology have a profound effect on the performance of Ti–6Al–4V. For example, the grain size determines the effective slip distance within the globular α phase, and in turn affects the yield strength [1]. The key first order microstructure attributes of Ti–6Al–4V include average globular (primary) α size, lamellar colony size, volume fraction of the primary α phase, and mean thicknesses of the secondary α and β phases in the lamellar colonies.

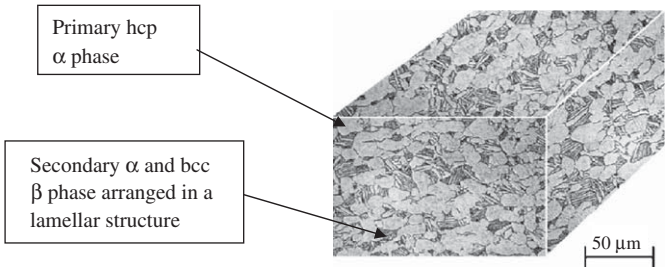

Fig. 1. Microstructure of duplex Ti–6Al–4V.

Due to highly anisotropic nature of crystallographic slip of hcp crystals, along with the low symmetry of the hcp structure, the orientation distributions of grains strongly affect the mechanical behavior of the bulk material [14]. Textures created via thermo-mechanical processing of Ti–6Al–4V are generally grouped into three distinct categories: basal, transverse, and basal/transverse textures [13]. Many commercial Ti–6Al–4V alloys have random texture, i.e., grain orientations are randomly distributed. The measured basal plane pole figures for these simulated textures are shown in Fig. 2 [7]. In Fig. 2, RD and TD denote the reference rolling and transverse directions, respectively.

The present study will focus on investigating the effects of three microstructure attributes: average grain size d, grain size distribution, and texture. Other important microstructure attributes are assumed unchanged. These include maintaining the volume fraction of primary α phase at 60% and the lath thicknesses of secondary α and β phases at 1.5 and 0.5 μm, respectively. Table 1 summarizes the microstructure attributes of three groups of Ti–6Al–4V considered in the simulations corresponding to three studied microstructure attributes. It should be noted that, owing to lack of detailed stereological information on lamellar colony size, the average primary α size and lamellar colony size are assumed to be identical.

3. Crystal plasticity model

Relation of the crystal plasticity model for duplex Ti–6Al–4V to dislocation mechanisms is described in detail in Mayeur and McDowell [4]. The model outlined here is intended for isothermal conditions, specifically room temperature.

For the primary α phase, four families of slip systems are included in the model: three $\langle 1\,1\,\bar{2}\,0\rangle(0\,0\,0\,1)$ basal, three $\langle 1\,1\,\bar{2}\,0\rangle\{1\,0\,\bar{1}\,0\}$ prismatic, six $\langle 1\,1\,\bar{2}\,0\rangle\{1\,0\,\bar{1}\,1\}$ first order pyramidal and twelve $\langle 1\,1\,\bar{2}\,3\rangle\{1\,0\,\bar{1}\,1\}$ second order pyramidal slip systems.

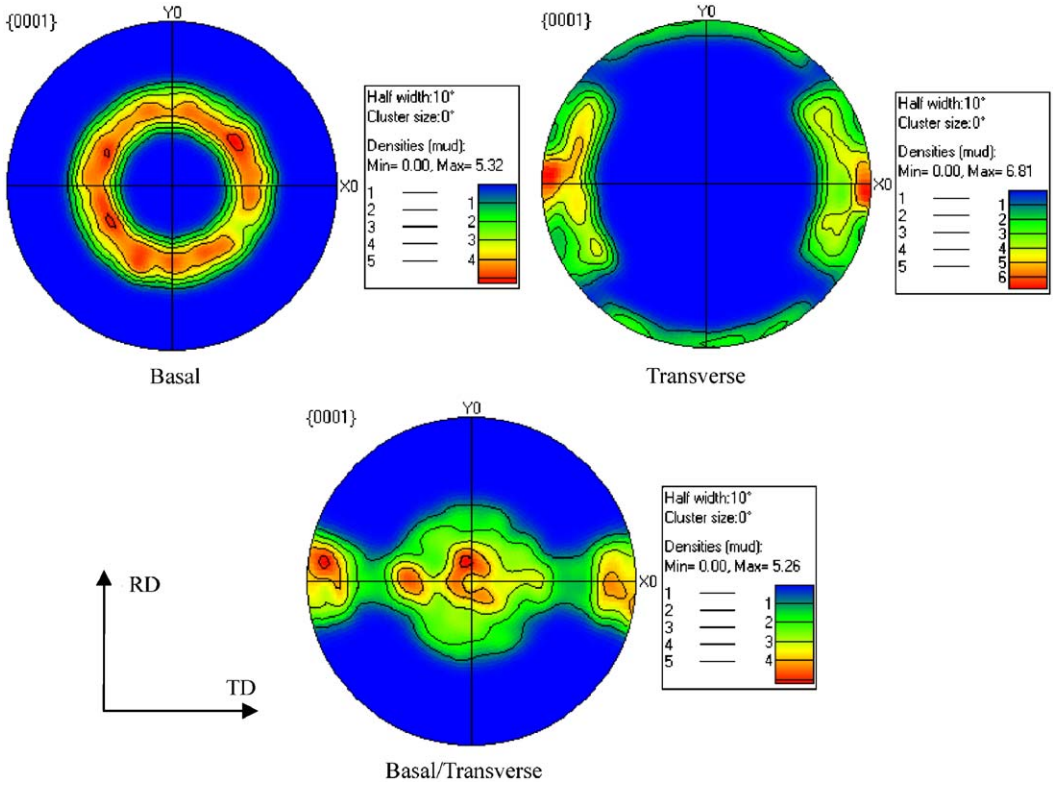

Fig. 2. Basal plane pole figures of representative textures [7].

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