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Crystal plasticity analysis of cylindrical indentation on a Ni-base single crystal superalloy

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ABSTRACT

Crystal plasticity simulations and experiments of cylindrical indentation on Nickel base single crystal superalloy specimens are presented and discussed. The subsurface stress and strain fields presented are similar to those observed in meso-scale dovetail joints in single crystal turbine blades. Load is applied in the [001] primary orientation while the secondary orientation of the single substrate is varied. The secondary orientations $[\bar{1}10]$ and [010] are examined at room temperature. The plastic zone below the indent is analysed in terms of the activated slip systems. The Finite Element predictions are compared to the detailed experimental observation of slip lines on the free lateral surface of the substrate. Results presented are of particular relevance to the understanding of slip localisation in single crystal dovetail contacts and subsequent crystallographic crack nucleation and propagation induced by subsurface shear stresses.

1. Introduction

Nickel Base Single Crystal (NBSX) superalloy turbine blades used in high performance aircraft and rocket engines, are subject to high operating temperatures and high monotonic and cyclic stresses in a highly corrosive environment. Aircraft turbine mission profiles are often characterised by multiple throttle excursions, which shifts attention to fatigue and fracture considerations associated with areas below the blade platform which contain various stress risers in the form of buttresses and attachments. These stress concentration features are prone to contact fatigue damage, and can result in crystallographic initiation and crack growth along octahedral planes (Deluca and Annis, 1995; Arakere and Swanson, 2002). A quantitative description of the fatigue crack nucleation process in a single crystal anisotropic contact is far from complete. Some factors that are considered to play an important role in fatigue crack nucleation are the magnitudes of resolved shear stress on the slip planes and the normal stress on the slip plane with the highest resolved shear stress (Nalla et al., 2002). To better identify crack nucleation mechanisms, an understanding of evolution and localisation of plastic slip in single crystal meso-scale contacts, where the stress state is strongly triaxial, is essential. The anisotropic elastic and plastic properties of single crystal specimens depend on crystal orientation. In metallic single crystals, crack nucleation in regions of stress concentration is typically preceded by cyclic slip localisation. The growth of nucleated cracks is also preceded by plasticity at the crack tip. Thus, both initiation and propagation of cracks are influenced by elastic and plastic anisotropic material properties, and consequently by crystallographic orientation. Fracture toughness of single crystals has also been found to be dependent on both primary and secondary orientation of single crystals (Shrivastava and Ebrahimi, 1997; Gumbsch et al., 1998; Ebrahimi and Kalwani, 1999; Arakere and Swanson, 2001; Arakere and Swanson, 2002; Ranjan and Arakere, 2008).

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Examples of fretting/contact damage is often observed in the regions where the blade-root is attached into the turbine-disk. The material deterioration usually begins with either crystallographic or non-crystallographic damage initiation, and is often followed by crack propagation along crystallographic planes. Thus, an understanding of the fracture process in NBSX alloys is essential in evaluating the fatigue life of turbine-blades. To foster such an understanding, the study of localised plastic deformation (which usually precedes damage initiation) in NBSX superalloys is a necessary step. While there exist many experimental studies addressing the evolution of macro-level-plasticity in this kind of materials, to the authors' knowledge, there are few studies that are aimed at an analysis of sub-surface behaviour. Many instances of material-damage-initiation and micro-crack-propagation are observed to occur in the sub-surface layers of the material. Consequently, the following article presents a tool to aid in the necessary analysis of localised sub-surface fields in NBSX specimens.

A study of literature related to indentation on NBSX superalloys reveals a few interesting applications of indentation experiments. Indentation experiments have been used extensively to measure hardness and mechanical behaviour of materials. Indentation provides a convenient means for investigation and better understanding of the elastic limit and incipient plasticity in crystals. In recent years there has been considerable interest in the study of micro- and nano-scale indentation of anisotropic bulk materials, layered and functionally graded materials, and single crystals, to understand scale-dependent mechanical behaviour. Xu et al. (2009) use experimental indentation to study creep properties of an NBSX material, and use the Crystal Plasticity Finite Element Method (CPFEM) to investigate the effect of varying the primary orientation of the crystal, on the creep surface-morphology (see Xu et al., 2008) in an NBSX material. Eidel (2011) presents an experimental study and a CPFEM investigation of a pyramidal indentation on a CMSX-4 specimen. Brinell-type indentation of CMSX-4 single crystal substrate is considered by Zambaldi et al. (2007) to relate the plastic strain field induced on the indented surface at room temperature and recrystallisation phenomena occurring at higher temperatures. Comparisons between experimental and finite element results are provided regarding the anisotropy of sink-in or pile-up formation on the deformed surface. Arakere et al. (2006) present 2D and 3D numerical techniques to investigate subsurface stresses anisotropic materials, and apply these techniques to simulate cylindrical indentation on a NBSX material. Results from a simulated contact model are also presented as an interesting alternative to using a numerically-intensive conventional finite-element-method -based contact algorithm. Other recent articles on dislocation nucleation and plasticity during indentation of single crystals have been published by Tymiak et al. (2001), Zhu et al. (2004), Deshpande et al. (2004), Balint et al. (2006), Nicola et al. (2007), Kysar et al. (2007) and Casals and Forest (2009).

The mentioned contributions mainly address the deformation of the indented surface, especially the formation of pile-up or sink-in. The configuration studied in the present paper is very different since slip is observed on the lateral surface and not the indented surface so that insight is gained on the plasticity below the indentor, which is possible thanks to the choice of a cylindrical indentation instead of usual Berkovich or Brinell indentation. The case of cylindrical indentation handled in the present contribution corresponds to significantly different mechanical loading conditions and is especially relevant for the behaviour of blade footings. Experimental results of this type in single crystal superalloys are very scarce and their interpretation by means of crystal plasticity finite element simulations is unique. The simulations will explain the experimentally observed strong dependence of the plastic zone size and shape below the indentor depending on the secondary orientation, the primary orientation being kept to [001]. That is why the presented work contains original contributions in this important field of crystal plasticity of Nickel-based superalloys. Accordingly, the paper provides a complementing perspective to indentation compared to existing literature, and which is better suited to the turbine blade footing.

As already stated, the following article aims to address the analysis of sub-surface fields. To this end, numerical simulations were conducted using standard crystal plasticity material models. The details of the material model used in the simulations are discussed in the following sections. The results are then post-processed to generate dominant-slip-maps (as discussed in Sabnis et al., 2012), which are then used to analyse the deformation fields in the NBSX substrate.

Dovetail joints are used to secure compressor and turbine blades to disks in turbine engines. The rotational loads (body forces) of the jet engine turbine blades are reacted at the dovetail joints. The contact locations, their area of contact and contact stress are a complex function of geometry and clearance between the parts. The resulting contact stresses can be quite high, leading to localised yielding. Fretting results from blade vibration, which perturbs both the normal and tangential loads at the contact, resulting in contact fatigue loading. Gas turbine mission profiles are often characterized by multiple throttle excursions associated with maneuvers such as climb, intercept and air-to-air combat. This type of loading shifts attention to fatigue and fracture considerations associated with areas below the blade platform, which contain various stress risers in the form of attachments (Arakere and Swanson, 2001). The gas turbine industry is moving toward a design philosophy that stresses damage tolerance and threshold based designs, which has prompted the study of micromechanics of single crystal contacts, localised plasticity, crack initiation and other events that affect HCF life. Hence the study evolution of plasticity in cylindrical single crystal meso-scale contacts is very much pertinent.

A study of sub-surface plasticity/slip field development in cylindrical single crystal contact that is relevant to meso-scale blade attachment type of contacts is presented in the following sections. A cylindrical indentation experiment on a substrate closely represents the geometry of the section that is in contact with the disk. From a theoretical perspective, two alternative configurations could be considered for the proposed study. The first configuration would use a NBSX cylindrical indent on a hardened-steel substrate. While this configuration represents more closely the setup of a blade attachment, practical considerations concerning the production of an NBSX indent lead to experimentation using the second configuration. The second configuration consists of NBSX substrates upon which indentation tests are conducted. In the study presented here, a hard-