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Is stored energy density the primary meso-scale mechanistic driver for fatigue crack nucleation?

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ABSTRACT

Fatigue crack nucleation in a powder metallurgy produced nickel alloy containing a non-metallic inclusion has been investigated through integrated small-scale bend testing, quantitative characterisation (HR-DIC and HR-EBSD) and computational crystal plasticity which replicated the polycrystal morphology, texture and loading. Multiple crack nucleations occurred at the nickel matrix-inclusion interface and both nucleation and growth were found to be crystallographic with highest slip system activation driving crack direction. Local slip accumulation was found to be a necessary condition for crack nucleation, and that in addition, local stress and density of geometrically necessary dislocations are involved. Fatemi-Socie and dissipated energy were also assessed against the experimental data, showing generally good, but not complete agreement. However, the local stored energy density (of a Griffith-Stroh kind) identified all the crack nucleation sites as those giving the highest magnitudes of stored energy.

1. Introduction

The microstructural and mechanistic origins of the drivers of fatigue crack nucleation remain elusive, and yet the process of crack nucleation may often comprise a significant fraction of overall component life in a range of key industries including those in aerospace, power generation and land transport. In modern aero engines, nickel-based superalloys have been widely used for applications in turbines due to their excellent properties, with high strength, corrosion and temperature resistance. Increasingly, some of these components are produced by powder metallurgy (PM) routes due to their near-net-shape forming, high cost effectiveness, efficiency, and more homogeneous microstructure compared to other conventional forming methods (Reed, 2008). However, it has been found that non-metallic inclusions and agglomerates are unavoidable in these alloy systems resulting from the manufacturing processes, and they significantly degrade mechanical properties and service life of these components. Fatigue failure which is driven by the presence of inclusions shows shorter lifetimes to fracture (Texier et al., 2016a), and as a consequence, their role has been investigated by many researchers (Caton et al., 2004; Pineau and Antolovich, 2016; Naragani et al., 2017), as well as for the effects of grain size distribution (Alexandre et al., 2004), twin and twin boundaries (Texier et al., 2016b), the size and shape of agglomerate (Gabb et al., 2008), which further illustrates the importance of fatigue in the presence of inclusions. However, it still remains a key scientific and technological challenge to establish full mechanistic and physical understanding of microstructure-sensitive crack nucleation at inclusions (Sweeney et al., 2013; Findley and Saxena, 2006; Reed et al., 2008; Sangid, 2013; Miao et al., 2012; McDowell and Dunne, 2010).

Over the past few years, the crystal plasticity finite element (CPFE) method, integrated with experimentally characterized

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microstructures and experiments, has been developed to capture the full-field stress and strain distributions under relevant loading regimes (Dunne et al., 2007a). Remarkably, the fatigue crack nucleation sites under cyclic loading can be accurately predicted (Zhang et al., 2015). In previous work, Korsunsky et al. (2007) analyzed the effects of localized crystal slip within an idealised Ni-base superalloy on crack initiation using microstructure based CPFE modelling. It was suggested that fatigue cracks tend to nucleate at slip localization sites where the dissipation of energy is very high. In (Dunne et al., 2012), geometrically necessary dislocation (GND) distributions at carbide particles in single-crystal Ni were studied with integrated high-resolution electron backscatter detection (HR-EBSD) and CP modelling showing the development of local thermally-driven residual stress and GND density adjacent to the carbide, potentially influencing subsequent fatigue crack nucleation. Musinski et al. (Musinski and McDowell, 2012) studied the influence of microstructure (grain size and γ' precipitate volume fraction) on fatigue life of Ni-base superalloy IN100 when subjected to high temperature, using rate-dependent and microstructure-sensitive CPFE modelling. It was shown that larger notch sizes led to shorter fatigue life. Zhang et al. (2014) studied the full-field elastic strains developed in Ni alloy at an agglomerate resulting from thermal excursions, using combined HR-EBSD and gradient-enhanced CP modelling showing good agreement. Non-metallic inclusions in Ni alloy Rene-95 were considered in (Xie et al., 2004; Jiang et al., 2015a, 2016a; Zhang et al., 2016), and researchers have also examined other alloy systems including aluminium (Hahn and Rosenfield, 1975; Babout et al., 2004a, 2001, 2004b; Chen et al., 2013) and steels (Landron et al., 2010; Fairchild et al., 2000; Lautridou and Pineau, 1981; Murakami et al., 2013).

Fatigue crack nucleation from non-metallic inclusions in nickel superalloys has been studied by Zhang et al., using high spatial resolution Digital Image Correlation (HR-DIC) and HR-EBSD together with CPFE modelling (Zhang et al., 2015, 2016). In their Ni-agglomerate system, defect nucleation was found to occur by Ni matrix-agglomerate decohesion or by oxide-particle agglomerate fracture, as opposed to slip-driven, crystallographic crack nucleation. Strong slip localization was found to occur at the agglomerates, together with residual stresses and high GND densities, but the primary driver for Ni-agglomerate decohesion was found to be the interfacial normal stress. A study by Jiang et al. (2016a, 2015a). focused on crack nucleation near a ceramic inclusion in an alternative Ni alloy (FGH96) system. The distribution and evolution of GND density and residual stress near inclusions were characterized by HR-EBSD, and the microstructure-sensitive slip accumulation during cyclic loading assessed using HR-DIC. Jiang et al. noted that the geometry of the inclusion played a significant role in local heterogeneous slip and stress distributions, but also that local accumulation of GNDs is potentially important in micro-crack formation. Inclusion-driven fatigue crack nucleation has also been studied by Pollock et al. (Texier et al., 2016b), in which three different microstructures of Nickel-based superalloy Inconel 718 containing non-metallic inclusions have been investigated subjected to the same strain level, utilizing EBSD characterisation. Their study addressed twins, twin boundary densities, grain size distribution and pre-cracked non-metallic inclusions in fatigue. Naragani and Sangid et al. used high energy synchrotron x-rays to track the evolution of microstructure and mechanical state at microlevel under cyclic uniaxial loading in a PM processed Ni alloy (Naragani et al., 2017). Their work indicated the importance of strain gradients in crack nucleation, and addressed debonding at the interface between inclusion and matrix. These collective studies indicate the potential importance of microstructure-sensitive stress, slip localization (which may be in the form of persistent slip banding), GND and statistically stored dislocation (SSD) density in the nucleation of cracks, such that all of these quantities may be necessary drivers, but that no single quantity is sufficient in its own right to explain fully the nucleation process.

An (elastic) stored energy criterion (Wan et al., 2014; Chen et al., 2017) has been proposed which attempts to unify the contributions to fatigue crack nucleation from local slip accumulation, stress and dislocation density which has as its basis the idea that a local energy density, over a quantified microstructural length scale defined by dislocation density, is necessary and sufficient to drive crack nucleation. It has features in common with both Griffith fracture energy and the Stroh dislocation-based nucleation argument such that the local stored energy must exceed that associated with the energy Gc of the new crack surfaces created. Wan et al. (2014) showed that the location of fatigue crack nucleation in eight microstructurally differing bcc ferritic steel samples could be successfully obtained using the stored energy density. Chen et al. (2017) showed that the stored energy also successfully identified fatigue crack nucleation in a succession of single and oligocrystal fatigued bend test samples, and that secondary fatigue cracking could also be predicted. Wan et al. (2016) used the same approach to predict fatigue life in polycrystalline Ni alloy RS5.

The work presented in this paper addresses crystallographic slip driven fatigue crack nucleation which has been observed in a rather different Ni-agglomerate system (FGH96) described in (Jiang et al., 2016a) in which the agglomerate, or inclusion, is ceramic based and for which Ni matrix – inclusion decohesion does not occur. This allows a fully integrated quantitative experimental characterisation and CPFE modelling study to seek the mechanistic basis of slip-driven fatigue crack nucleation. Concurrent CPFE modelling, together with detailed HR-EBSD for GND measurement and HR-DIC for total strain measurement local to fatigue crack nucleation sites are presented for cyclic bend tests to generate, identify and quantify microcracks, their nucleation sites, and their drivers. An assessment is carried out of the key quantities (micro-texture, slip, stress, GND density, and stored energy density) with respect to the experimental fatigue crack nucleation sites. The materials and methods employed are described first in the next section, including full quantitative characterisation of the agglomerate and Ni alloy considered, the mechanical testing, and the crystal plasticity modelling approach adopted. This is followed by the full presentation of results obtained from the experiments and modelling, in turn leading to discussion of these results and conclusions.

2. Methodology

2.1. Experimental methodology

A rectangular-section beam with dimensions of 3 mm × 3 mm × 12 mm was cut from bar stock to contain the ceramic inclusion and then deformed under three-point bending, as illustrated schematically in Fig. 1(a). This sample was provided by AVIC-BIAM and