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Microstructurally sensitive crack nucleation around inclusions in powder metallurgy nickel-based superalloys

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ABSTRACT

Nickel-based superalloys are used in high strength, high-value applications, such as gas turbine discs in aero engines. In these applications the integrity of the disc is critical and therefore understanding crack initiation mechanisms is of high importance. With an increasing trend towards powder metallurgy routes for discs, sometimes unwanted non-metallic inclusions are introduced during manufacture. These inclusions vary in size from ~10 μm to 200 μm which is comparable to the grain size of the nickel-based superalloys. Cracks often initiate near these inclusions, and the precise size, shape, location and path of these cracks are microstructurally sensitive. In this study, we focus on crack initiation at the microstructural length scale using a controlled three-point bend test, with the inclusion deliberately located within the tensile fibre of the beam. Electron backscatter diffraction (EBSD) is combined with high spatial resolution digital image correlation (HR-DIC) to explore full field plastic strain distributions, together with finite element modelling, to understand the micro-crack nucleation mechanisms. This full field information and controlled sample geometry enable us to systematically test crack nucleation criteria. We find that a combined stored energy and dislocation density provide promising results. These findings potentially facilitate more reliable and accurate lifing prediction tools to be developed and applied to engineering components.

1. Introduction

Turbine discs are safety critical components in modern aero engines and are typically made from nickel-based superalloys. Powder metallurgy routes are employed for these components as this enables precise microstructure control, which is required to extract optimal performance, typically focussing on high strength and excellent damage tolerance with minimal component weight [1]. Unfortunately, this manufacturing route can introduce non-metallic ceramic inclusions during the powder generation and handling processes which are often between of 10 μm–200 μm and occasionally found with the nickel powder particles. The inclusions are introduced from the refractory crucible materials which are used to produce the alloy, such as the primary vacuum induction melt ingot, the secondary vacuum induction melt ingot, guide tube arrangement for the atomization stream and reactions between the molten stream and the gases in the atomization chamber [2]. Although every effort has been made to filter them, complete removal from the final products is difficult to achieve [1].

Discs are operated in the extreme environment of a gas turbine, often at elevated temperatures (650 °C –800 °C) and undergo severe cyclic loading. The typical failure mode is fatigue [3] and for powder metallurgy (PM) alloys, often fatigue crack initiation begins at these non-metallic inclusions, which reduces component life by 100 times [4,5]. Simple correlations exist that indicate the importance of these inclusions, such as those between size and life debit [2,5–7]. However, a full mechanistic understanding of crack initiation and microstructurally sensitive short crack growth has yet to be achieved [8–13]. This lack of understanding inhibits further development of physically-based models that can be employed to design new materials and enhance component life.

Microstructurally sensitive crack nucleation related to non-metallic inclusions is not limited to PM nickel-based superalloys for aeroengine applications, as these issues are shared with weld steels [14,15] and aluminium alloys [16]. Therefore generation of

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physically based understanding, rather than empirical curve-fitting, enhances our ability to realise microstructure engineering for enhanced fracture resistance [17] across a range of materials systems and component applications. This study focuses on the ceramic inclusion existing in PM nickel-based superalloy. This can be related to prior work which has focussed on oxide (hard and brittle) or carbide (relatively ductile) inclusions [2]. The inclusion in this work is highly porous and hollow structure, which may generate significant differences in the associated damage and fatigue crack initiation mechanisms as compared with the prior work.

This manuscript builds on our prior work in the area of non-metallic inclusions and fatigue crack initiation in nickel-based superalloys [18,19]. Highlights pertinent to the current work include observations that the distribution and evolution of geometrically necessary dislocation (GND) density and large Type III (intragranular) residual stresses, both measured using high angular resolution EBSD, are correlated with microstructure around the non-metallic inclusion during deformation under three-point bending in a low cycle fatigue test [18]. The patterning of stored GND density and residual stresses were found to be developed during the first cycle. The evolution of these patterns under subsequent cycles did not substantively change the structure of these deformation patterns. These observations were limited to cyclic fatigue around an inclusion in one PM alloy within a small region (~20 grains), as a result of the experimental difficulty and time (>100hr microscopy time for 16 observations). Furthermore, this study only focused on residual deformation with a diffraction based technique and so correlations with accumulated plastic slip were impossible. A sister study by Zhang et al. [20] focussed on fatigue crack nucleation near a different non-metallic inclusion in an alternative nickel-based superalloy, this time employing conventional EBSD with high spatial HR-DIC. Zhang noted that there was significant microstructural sensitivity towards the range of accumulated local plastic strains, which was further modelled by Zhang et al. [19] with Crystal Plasticity Finite Element Analysis (CP-FEA). In the latter work, the use of integrated crystal modelling with HR-DIC studies local to the non-metallic inclusions showed that a key defect nucleation mechanism was that of interfacial nickel/oxide decohesion and the interfacial decohesion strength was quantified.

These two prior studies highlight two sides of experimental characterisation: Jiang et al. [18] focus on the stored energy problem, associated with residual stress and local hardening due to GND density; whereas Zhang et al. [20] focus on plastic slip, and therefore energy dissipation due to plastic work near the inclusion. Both of these processes are microstructurally sensitive.

In the present work, we combine experimental micromechanical characterisation with HR-EBSD, at the initial and final states, together with HR-DIC captured periodically during mechanical testing, to enable us to assess microstructural evolution during cyclic loading. The nickel-based superalloy near the inclusion has been found to crack, and we used knowledge of the stored GND density (from EBSD) and accumulated plastic strain (from HR-DIC) to test a previously postulated crack nucleation criterion [18]. This experimental study is supplemented with a geometrically faithful finite element model to illustrate the relative importance of inclusion/matrix shape on crack nucleation.

2. Methodology

A 3 mm × 3 mm × 12 mm cuboid nickel-based superalloy FGH96, provided by AVIC-BIAM, was carefully cut to contain the inclusion within the tensile fibre of the bend specimen, as indicated in Fig. 1 (a). Prior to testing, the sample was annealed at 750 °C for 7 h to stress relieve the microstructure and reduce any stored energy. The sample was metallographically prepared using silicon carbide papers down to P4000 grit and subsequently polished with a 0.05 μm colloidal silica slurry for 40 min to remove the residual mechanical damage introduced during sample preparation process, making it suitable for EBSD characterisation and our study.

To capture the initial microstructure around the non-metallic inclusion, a 165 μm × 125 μm EBSD map with 0.25 μm step size at x1000 magnification was obtained using a Bruker e^{-}FlashHR detector and Quantax ESprit 2.0 system. A 25 keV accelerating voltage and 16 nA probing current were applied in a Zeiss Auriga SEM. The measured local microstructure near the non-metallic inclusion is revealed by the IPF map (plotted with respect to the loading direction) in Fig. 1(b). The inclusion is shown as a black unindexed area at the centre of the map. The surrounding nickel-based superalloy matrix is a typical polycrystalline microstructure, including a large fraction of annealing twins. The sample was made using a powder metallurgy route and therefore, as expected, there is no significant texture in this area. The average grain size is approximately 6 μm.

2.1. Mechanical test

Mechanical testing was performed using interrupted cyclic three point bending, with the rig illustrated in Fig. 1 (a). The test was run in displacement control, prescribing the position of the

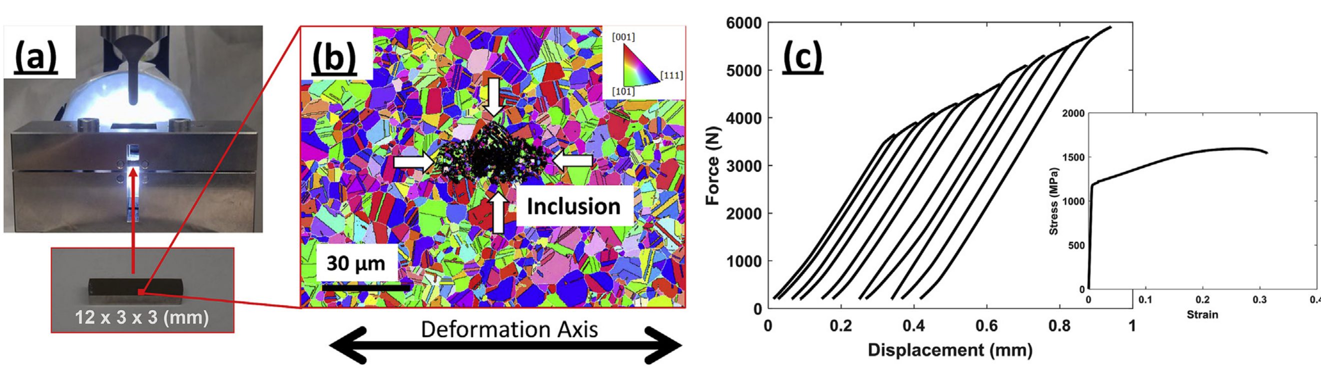

Fig. 1. (a) The experimental three-point bending test set up. The vertical force was applied from the top, and the dimension of the specimen is 12 mm × 3 mm × 3 mm, shown in the insert. The sample was machined to contain the inclusion within the tensile fibre of the bend specimen, indicated with the red box in the insert; (b) the EBSD measured inverse pole figure (IPF) map with respect to the deformation axis (the horizontal one). The inclusion is shown as the unindexed region at the centre of the map, highlighted with white arrows; (c) the measured applied force and cross head displacement curves. The inset showing the macroscopically measured true stress-strain curve of FGH96 alloy under a uniaxial tensile test. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)