Materials Science & Engineering A 699 (2017) 128–144

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Characterisation of strain localisation processes during fatigue crack initiation and early crack propagation by SEM-DIC in an advanced disc alloy

R. Jiang*, F. Pierron, S. Octaviani, P.A.S. Reed

Materials Research Group, Faculty of Engineering and the Environment, University of Southampton, Highfield, Southampton SO17 1BJ, UK

ARTICLE INFO

Keywords:
Ni-based superalloys
Strain localisation
Digital image correlation
Fatigue cracking
Transverse strain

ABSTRACT

Fatigue failure processes in metallic materials are closely related to the evolution of strain localisation under cyclic loading. Characterisation of this strain localisation is important in understanding the mechanisms of fatigue crack initiation and propagation, and provides critical validation data to develop appropriate crystal plasticity models for prediction of these processes. In this study, strain localisation during fatigue crack initiation and early crack propagation in an advanced Ni-based superalloy for turbine disc application has been characterised at the grain level with a sub-micron resolution by digital image correlation on SEM images using secondary γ' themselves as the speckle pattern. The obtained full-field strains have been analysed in global coordinates associated with the applied loading direction and in terms of the local coordinates associated with individual slip bands. Deformation arising from in-plane *and* out-of-plane dislocation slip can be identified by a combination of shear strain $\boldsymbol{\varepsilon}_{xy}$ and transverse strain $\boldsymbol{\varepsilon}_{yy}$ in the local slip band coordinates in combination with EBSD analysis. Cracks preferentially initiate from slip/strain bands adjacent and parallel to twin boundaries and then propagate along the slip/strain bands, leading to the onset of significant transverse strain $\boldsymbol{\varepsilon}_{yy}$ in the local band coordinates as a consequence of crack opening. Crack propagation is closely related to strain accumulation at the crack tip which is determined by the grain orientation and grain size. Transverse strain $\boldsymbol{\varepsilon}_{yy}$ in local slip band coordinates together with the inclination angle between dislocation slip direction on an activated {111} plane and the slip trace of this {111} plane at the specimen surface is proposed to be a cracking indicator/fracture criterion.

1. Introduction

Powder metallurgy (PM) Ni-based superalloys have been widely used for high pressure disc rotor applications in aeroengines due to their excellent combined properties, i.e. high strength at elevated temperatures, good resistance to fatigue, creep, oxidation and corrosion [1–3]. Among all the properties of PM Ni-base superalloys for disc applications, fatigue resistance is one of the most important, often limiting the overall service life. It is generally accepted that fatigue crack initiation and short crack growth processes are important to optimise as they contribute to the majority of fatigue life of a turbine disc during service. This is due to the high overall component stresses which results in a relatively small extent of fatigue crack propagation prior to fast fracture and thereby limits the fatigue life dependency to the fatigue crack initiation and short crack growth regime [4–8]. In the course of service, disc alloys are subjected to complex loading conditions across the disc section at a temperature range of 400–750 °C, which usually results in intragranular fatigue crack initiation at the disc bore where the material is subjected to lower temperatures but higher stresses [8–11] and intergranular fatigue crack initiation at the disc rim due to stress/strain assisted grain boundary oxidation at higher temperatures [12–15]. Extensive studies have shown that fatigue crack initiation is usually found at slip bands/crystallographical facets [8,11,16], pores [4,17] and especially twin boundaries (TBs) [8,16,18] at the relatively lower temperatures in the disc bore region. This is closely related to the intrinsic deformation behaviour of the disc alloys with insignificant/limited environmental damage. Once a crack initiates, it is observed to propagate along a crystallography facet or grain boundary (GB) in the early stages of crack growth, with a strong interaction with microstructural features. This is also affected by the loading conditions and the development of the plastic zone/accumulated strain at the crack tip [4,5,10,16,19].

Significant efforts have been made by many researchers to understand the mechanisms of these fatigue cracking processes under a wide range of different loading conditions via experimental studies [4,6,8,10,11,16] and to predict the crack initiation and propagation in disc alloy/components using crystal plasticity finite element (CPFE) models [20–25]. To understand these fatigue failure mechanisms and to

* Corresponding author.
E-mail address: Rong.Jiang@soton.ac.uk (R. Jiang).

http://dx.doi.org/10.1016/j.msea.2017.05.091
Received 28 February 2017; Received in revised form 22 May 2017; Accepted 23 May 2017
Available online 24 May 2017

develop and validate these CPFE models, one missing requirement has been the quantitative assessment of the actual localised strains at the grain level and their dependency on grain orientation and the neighbouring grains/microstructures under the relevant in-service temperatures and loading conditions [21,22,25,26]. However, quantitative measurement of full-field strain distribution at a grain level is still quite challenging. For instance, accumulated inelastic strain at the crack tip has been used as a fracture criterion in a CPFE model to predict crack propagation in disc alloy RR1000 based on Karabela's study [21], but the experimental validation of the accumulated inelastic strain at a grain level at the crack tip is still not in place, which limits the further development of these CPFE models.

Although X-ray and neutron diffraction have been well established to measure the elastic strains in materials, this averages out the information in the whole activated volume [27–30]. Recently, electron backscatter diffraction (EBSD) has been developed to characterise the residual elastic strain with a high spatial resolution based on the shift of the zone axis of Kikuchi pattern in the materials/specimen due to the improvement of angular resolution during sampling of the Kikuchi pattern [23,31–36]. Meanwhile, the geometrically necessary dislocation (GND) distribution can also be calculated based on the lattice curvature [32,35,36]. This technique appears to be valuable to capture the small levels of residual elastic strains, especially in the single crystal material, in which the reference Kikuchi pattern can be chosen from far field strain-free regions and is applicable to whole sampling area. In terms of polycrystalline alloys however, this incurs a problem of choosing the reference Kikuchi pattern due to the misorientation between different grains. The chosen reference Kikuchi pattern within the sampling area in the polycrystalline alloys is essentially in an unknown strain state (although normally the reference pattern is chosen from the least deformed region) [35–37]. As a consequence of the "reference pattern problem", the measured residual elastic strain only represents the *relative* deformation within the same grain in polycrystalline materials. In addition, this technique is unable to capture a larger plastic strain field. Although the global strain is usually small in fatigue testing, the localised strain at certain microstructural features, e.g. GBs and TBs, can be much higher than the global strain [9,38,39]. Therefore, other complementary techniques are needed to characterise the localised strain evolution during the fatigue cracking process.

Digital image correlation (DIC) is a well-established and robust tool used to measure full-field *in-plane* strain by correlating a random speckle pattern in images taken before and after deformation [26,38–46]. A displacement field is initially obtained via this image correlation process, and then a strain field can be derived through numerical differentiation. Generally, the images used for DIC are captured by an optical camera, which means that it is not possible to achieve sub-micron resolution at a grain level in polycrystalline disc alloys with grain sizes between 10 and 50 μm [39,41,44,45,47]. By using scanning electron microscopy (SEM) to take the images for DIC, the pixel resolution can be significantly improved, thus allowing the characterisation of strain distribution at the grain scale, although the process of SEM imaging itself may cause additional error/noise (i.e. time varying distortion due to image drift at high magnification and spatial distortion at low magnification) due to beam rastering when taking an image [26,38,43,48–51]. Even though in SEM the pixel resolution of the images used for DIC is compatible with the grain size, the obtained strain resolution is still inherently limited by speckle size [47]. As a general rule, a DIC subset needs to contain at least three speckles, therefore, very fine speckles need to be produced for SEM-DIC. In recent publications, Di Gioacchino et al. [26,43] applied nanometer size gold particles on a stainless steel surface via a remodelling process, and achieved a strain spatial resolution at the sub-micron scale in an ex-situ tensile test. They showed that the strain localisation exists in the form of bands (similar to slip bands) within grains under monotonic tensile loads. This concentrated strain in bands was shown to be consistent with the slip traces of the {111} < 110 > slip systems expected based on a combined analysis with EBSD. Stinville et al. [9,38,52] also achieved a similar strain resolution at sub-micron scale in a Ni-based superalloy using secondary γ' as a natural speckle under tension and compression loading, and found that strain localised at the slip bands adjacent and parallel to TBs. However, all these studies using SEM-DIC to investigate strain localisation were mainly conducted under monotonic loads, few studies have been carried out under cyclic loading which may involve the slip reversal associated with back and forth dislocation movement [53]. This is clearly different from the deformation seen under purely monotonic loading. In addition, the interpretation of the axial, transverse and shear strain levels in these studies under monotonic loading was performed only in the global coordinates associated with the loading direction, which cannot directly link the obtained bands of concentrated strain to the crystallography of the investigated materials and dislocation slip behaviour, although the slip traces of {111} < 110 > slip systems and Schmid factor (SF) analysis were carried out based on the EBSD investigation of grain orientation.

In the present study, strain localisation at the grain level with a sub-micron resolution during fatigue crack initiation and early crack propagation regimes in an advanced disc alloy, i.e. Low Solvus, High Refractory (LSHR) alloy, has been investigated by SEM-DIC using secondary γ' as the speckles at room temperature. The strain development/increment at each interruption throughout an interrupted fatigue test has been captured. Annealing twins are a pertinent microstructural feature in PM Ni-based superalloys. Our previous studies and studies by other groups have shown that cracks mainly initiate at TB or in slip bands adjacent and parallel to TB in large twin-containing grains with high SF [8,16,38]. Strain accumulation at/nearby TBs under cyclic load is therefore of particular interest to the present study. The obtained strain field has been analysed in both the global coordinates associated with the loading direction and the *local* coordinates associated with individual slip band to provide insights of the damage arising and evolving from dislocation slip under cyclic loading. Applicability of the transverse strain in the local slip band coordinates along with the inclination angle between dislocation slip direction on {111} plane and slip trace (i.e. intersection line of {111} slip plane on the specimen surface) as a cracking indicator has been discussed.

2. Materials and experimental procedures

2.1. Materials

The LSHR alloy used in this study was provided by NASA. Composition (in wt%) of the LSHR alloy is 12.5Cr, 20.7Co, 2.7Mo, 3.5Ti, 3.5Al, 0.03C, 0.03B, 4.3W, 0.05Zr, 1.6Ta, 1.5Nb, Ni bal. Specimens used for short crack fatigue tests were extracted from a turbine disc which was fabricated by canning atomized LSHR alloy powder followed by hot isostatically pressing, extruding and isothermally forging. The extracted specimens were supersolvus heat treated at 1171 °C for 1 h followed by a cooling of 72 °C/min to dissolve primary γ' and to yield coarse grained microstructures. Subsequently the specimens were aged at 855 °C for 4 h and then 755 °C for 8 h to modify the precipitation of secondary γ'. The obtained microstructural features of the LSHR alloy are summarised in Table 1 as reported in our previous study [3].

Table 1
Grain size and γ' size in the LSHR alloy.

Materials	Grain size range (μm)	Average grain size (μm)	Primary γ' (μm)	Secondary γ' (nm)
LSHR	10–140	36.1 ± 18.1	N/A	153 ± 29