International Journal of Fatigue 75 (2015) 89–99

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Influence of oxidation on fatigue crack initiation and propagation in turbine disc alloy N18

R. Jiang [a,*], S. Everitt [a,b], N. Gao [a], K. Soady [a], J.W. Brooks [c], P.A.S. Reed [a]

[a] Materials Research Group, Engineering and the Environment, University of Southampton, Highfield, Southampton, Hampshire SO17 1BJ, UK
[b] QinetiQ, Boscombe Down, Salisbury, Wiltshire SP4 0JF, UK
[c] University of Birmingham, Edgbaston, Birmingham, West Midlands B15 2TT, UK

ARTICLE INFO

Article history:
Received 15 October 2014
Received in revised form 6 February 2015
Accepted 13 February 2015
Available online 21 February 2015

Keywords:
Ni-based superalloy
Stress assisted oxidation
Fatigue crack
Creep
Apparent activation energy

ABSTRACT

Fatigue crack initiation and propagation behaviour in subsolvus heat treated turbine disc alloy N18 has been assessed in air and vacuum at 650 and 725 °C under three-point loading. Fatigue crack initiation processes have been evaluated using single edge U-notch specimens under a 1-1-1-1 trapezoidal loading waveform along with interrupted tests at 650 °C to allow intermittent observations of the notch surface. The results show apparent grain boundary (GB) oxidation can occur under an oxygen partial pressure of 10^{-2}–10^{-3} Pa. Cracks mainly initiate from grain boundaries or γ/γ' interfaces due to the formation and subsequent cracking of Cr-rich and/or Co-rich oxides, and occasionally initiate from surface pores. Fatigue life in these tests appears to be dominated by this crack initiation process and is significantly reduced by increasing temperature and/or application of an oxidizing environment. Crack growth tests conducted under 1-1-1-1 and 1-20-1-1 loading waveforms indicate that oxidation significantly degrades the crack growth resistance of N18 and is associated with more intergranular fracture surface features. Additional oxidation effects on propagation caused by higher temperature or prolonging dwell time appear limited, whereas a prolonged dwell period seems to instead promote additional creep process, which further enhance crack growth, especially at higher temperature.

1. Introduction

Aeroengine turbine discs operate at elevated temperatures under dynamic loads in an aggressive service environment over significant periods of time, this requires disc materials to possess high strength at elevated temperatures, good fatigue and creep performance under these service conditions, along with excellent oxidation and corrosion resistance. Powder metallurgy (PM) Ni-based superalloys have been widely used for aeroengine turbine disc application due to their exceptional combined mechanical properties at elevated temperatures in combination with good oxidation/corrosion resistance [1–3]. However, oxidation accelerated fatigue failure (shorter fatigue life or faster crack growth rate) is usually observed when assessing the fatigue performance of disc alloys at elevated temperatures, especially when a dwell period is applied at the peak load [4–10]. Such a phenomenon is usually associated with intergranular fracture resulting from the interaction between GB oxidation/embrittlement effects and mechanical fatigue processes [8,11–16]. The varying extent of intergranular fracture features observed is the consequence of the competitive effects of oxidation and cyclic fatigue processes in the advancing crack. Generally, intergranular features are dominant on the fracture surface when oxidation makes a significant contribution to the crack tip failure process, whereas transgranular fracture features dominate when the effect of oxidation is absent or is weak [4,17,18]. In some cases, a transition from intergranular features to transgranular features can be observed on the fracture surface as the stress intensity factor range (ΔK) increases, indicating the point where the mechanically-driven crack propagation process outstrips the crack tip oxidation process [18].

Extensive studies have shown that the poorer fatigue performance of disc alloys in an oxidizing environment is closely related to oxidation enhanced crack initiation and/or propagation which are associated with stress assisted oxygen diffusion and resultant oxidation [6,10,11,16,19]. It is generally considered that enhanced crack initiation is mainly caused by GB oxide cracking due to the brittle nature of the formed oxides. The additional stress concentration arising from volume expansion/contraction because of the formation of these oxides may facilitate the cracking process [19]. In addition, the reduced GB sliding and migration ability caused by the absorption of oxygen or other embrittlement agents

* Corresponding author. Tel.: +44 (0)23 80599450; fax: +44 (0)23 80593016.
E-mail address: Rong.Jiang@soton.ac.uk (R. Jiang).

http://dx.doi.org/10.1016/j.ijfatigue.2015.02.007
0142-1123/

(released by chemical reactions because of the involvement of oxygen) may lead to the build-up of local stress at these regions, which further results in crack initiation [20]. The enhanced crack propagation associated with intergranular fracture is usually ascribed to decohesion/reduction in cohesion strength of GBs ahead of the crack tip due to dynamic embrittlement [14,15] or GB oxide/matrix-oxide interface cracking caused by stress assisted grain boundary oxidation (SAGBO) [8,11–13].

The oxidation accelerated fatigue failure caused by stress assisted oxygen diffusion and oxidation along grain boundaries is a complex process. It is reported that this process is mainly dependent on oxygen partial pressure, temperature and local stress/strain level, as well as composition and microstructure of investigated alloys [5,6,18,21–23]. For instance, a transitional oxygen partial pressure that is independent of loading conditions but is sensitive to Cr content is observed in fatigue crack growth data of disc alloy Inconel 718 [6]. Above this transitional pressure, a significantly accelerated crack growth occurs, which is believed to be caused by the formation of Ni oxide rather than the dense Cr_2O_3 ahead of the crack tip. Additionally, considerable research on disc alloys, such as U720Li [5] and LSHR alloy [18], has shown that higher temperature and longer dwell at the peak load (which are associated with higher diffusivity and longer diffusion time respectively) are inclined to promote crack growth due to the synergistic oxidation-fatigue effect in an oxidizing environment. This effect is much more significant in the fine grained variants of these disc alloys which are able to provide more grain boundaries acting as short-circuit diffusion paths [5,18,23]. It is relatively complex to quantitatively evaluate unambiguously the simple effect of alloy composition on crack growth. This is due to the varying microstructure, grain boundary character and mechanical properties caused by not only the varying composition, but differing mechanical processing and heat treatment approaches, although some efforts have been made [4,22,24].

N18 is a PM disc superalloy, developed for the SNECMA M88 engine used in the RAFALE aircraft [1]. It is designed for long-term use at 650 °C and limited use at 700 °C. A trade-off between good fatigue crack growth and oxidation resistance as well as excellent creep and strength retention at high temperature was made during alloy design, along with some modification of grain size to optimise this balance, principally adopting sub-solvus heat treatments due to its high γ' solvus temperatures (~1190 °C) [1,25–28]. A great deal of research has illustrated that N18 has good phase stability up to 700 °C and possesses high strength and creep resistance associated with a good damage tolerance capability up to 650 °C [1,25]. It is also reported that N18 has better fatigue crack growth resistance compared with fine grained Inconel 718 and Astroloy under the same testing conditions [1]. However, most of these studies have been conducted at 650 °C or even lower temperature, where the role of oxidation may be less significant in assisting fatigue failure processes. To enable a better understanding of the interaction between oxidation and fatigue performance (i.e. fatigue crack initiation and propagation) in this alloy, assessment of the fatigue performance of N18 at temperatures close to its limit-use temperatures are necessary. Therefore, in this study, the fatigue crack initiation and propagation behaviour in N18 alloy has been assessed in air and vacuum across a temperature range of 650–725 °C to elucidate the role of oxidation in the fatigue failure process.

2. Materials and experimental procedures

2.1. Materials

The N18 alloy used in this study was extracted from a hot isostatically pressed (HIP) and forged, heat treated “pancake” (disc precursor) provided by QinetiQ. Its composition (in wt.%) and heat treatment schedules are presented in Tables 1 and 2 respectively. The microstructures of N18 alloy are shown in Fig. 1, and the measured γ grain size and the sizes of primary, secondary and tertiary γ' are shown in Table 3. In addition, pores were rarely observed during microstructural evaluation and it is believed that this low porosity is due to the HIP process undergone by the alloy. The detailed experimental procedures used for this microstructural evaluation were reported previously in Ref. [18].

2.2. U-notch fatigue test

Fatigue tests were conducted on polished U-notch specimens under three-point bend loading on an Instron 8501 servo-hydraulic testing machine with an ESH Ltd. high temperature vacuum chamber attached. The test geometry was chosen to assess crack initiation processes and the fatigue performance of N18 in the presence of a stress concentration. As shown in Fig. 2(a), the dimension of the U-notch specimen is 8 mm × 8 mm × 50 mm, and the radius and the depth of the notch are 2 mm and 1.25 mm respectively. The notch type was chosen to provide an elastic stress concentration of around 2, i.e. representative of that seen in the fir tree root fixings used to secure blades to turbine discs. The surface of the notch was ground and then was polished using dental felts and 1 μm diamond polishing paste. Tests were carried out in air and vacuum (1.0×10^{-3}–5.0×10^{-2} Pa) at 650 and 725 °C under a 1-1-1-1 loading waveform with a load ratio of 0.1. The temperature of the specimen was monitored and controlled to an indicated ±1 °C using a Eurotherm 815 thermocontroller and R-type (platinum + 13%rhodium/platinum) thermocouple which was spot welded to the specimen within the hot zone. The span between the two upper rollers is 40 mm. The load was applied to produce a maximum nominal elastic stress (σ_{max}) of 1020 MPa in the uncracked ligament, defined as the net section bending stress at the plane of the notch root calculated using simple beam theory. The stress distribution across the notch at the maximum and minimum applied loads at 650 °C in a quarter of the specimen, calculated in Abaqus by simulating the load roller with an appropriate pressure load and simulating the support roller with a restricted displacement in the vertical direction of the specimen (assuming the contacted region with rollers as elastic to avoid non-convergence in the model), is shown in Fig. 2(c) and (d). The corresponding strains achieved at the notch root are 1.11% and 0.29% respectively according to the finite element simulation. After testing, a JEOL JSM 6500F field emission gun (FEG) scanning electron microscope (SEM) was employed to examine the morphology of fracture surface and the notch root surface.

To further investigate fatigue crack initiation processes, two more interrupted tests were conducted at 650 °C in air and vacuum. After each interruption, the specimen was taken out and observed in the SEM, and then the test resumed until apparent cracks appeared at the notch root. Energy dispersive X-ray

Table 1
Composition of N18 alloy (in wt.%).

Cr	Co	Mo	Ti	Al	C	B	Hf	Zr	Ni
11.1	15.4	6.44	4.28	4.28	0.022	0.008	0.50	0.019	Bal.

Table 2
Heat treatment of N18 alloy.

Subsolvus heat treatment	Aging heat treatment
1165 °C/4 h → Air cool	→ 700 °C/24 h → Air cool → 800 °C/4 h → Air cool