International Journal of Fatigue 105 (2017) 7–15

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Pre-notched and corroded low cycle fatigue behaviour of a nickel based alloy for disc rotor applications

M. Dowd [a,*], K.M. Perkins [b], D.J. Child [c]

[a] Institute of Structural Materials, Swansea University, Bay Campus, Swansea SA1 8EN, UK
[b] College of Engineering, Swansea University, Bay Campus, Swansea SA1 8EN, UK
[c] Rolls-Royce plc., P.O. Box 31, Derby DE24 8BJ, UK

ARTICLE INFO

Article history:
Received 9 May 2017
Received in revised form 1 August 2017
Accepted 11 August 2017
Available online 16 August 2017

Keywords:
Corrosion
Corrosion fatigue
Environmental assisted fatigue
Pitting corrosion
Superalloys

ABSTRACT

Currently there is doubt surrounding the suitability of chemically-induced stress independent pre-conditioning of specimens to simulate turbine corrosion prior to fatigue testing. The thick oxide scales developed using such techniques can lead to net section loss and typically a lack of grain boundary sulphide attack seen in components that experience stress. An alternative approach to a corrosion-fatigue test scenario is suggested by micro-notching fatigue specimens prior to low salt flux corrosion to form grain boundary sulphide particles within channel-like features akin to stress assisted morphologies. On fatigue testing, a trend was identified where a change of mechanism was observed. The grain boundary oxide likely formed in the wake of freshly precipitated sulphide particles fractures around segments of grains leading to a metal loss that contributes to a significant reduction in fatigue properties.

1. Introduction

As turbine entry temperatures are pushed higher to improve gas turbine efficiency, engine components are forced to accommodate increasingly higher stresses and temperatures. This places significant demands on the high strength nickel alloys used for critical parts; failure of these parts would threaten the safety of an aircraft and its passengers. In light of this, engines are routinely inspected for various forms of damage including handling, foreign object damage and environmental attack. Discs spending increased time at temperature have resulted in instances of corrosion damage detected on components within the declared life. As the turbine disc is a safety critical component, assessment of any surface damage is advantageous to understand the impact on remnant component life. Fig. 1 provides an example of the damage, where a roughly 'V' shaped region of grain loss resides at the surface. In addition, intergranular sulphide particles can be seen penetrating into the alloy. Recent corrosion-fatigue studies on salted specimens [1,2] have shown that a corrosive environment in conjunction with cyclic stress can give rise to similar pit shaped notch features that, depending on salt loading and stress level, reduces fatigue life in comparison to unsalted specimens tested in air.

Historically, the mechanisms of sodium sulphate (Na_2SO_4)-induced hot corrosion in Ni-base superalloys have been categorised as either type-I or type-II hot corrosion depending on the temperature of the system and is closely related to the melting point of the salt contaminant [3]. Type-I hot corrosion is generally observed above 900 °C and is characterised by discrete sulphide particles below a protective chromium oxide. In type-I hot corrosion, the mechanism proceeds as the molten Na_2SO_4 salt deposit causes the separation of alloy from the gas phase and due to low oxygen solubility in Na_2SO_4 [4], an O_2 gradient is established across the deposit. This gradient results in an increase in sulphur activity at the alloy surface, such that sulphur and oxygen is removed from the deposit by the alloy to form sulphides and oxides [5]. Type-II hot corrosion is observed in the temperature region of 650–800 °C and is characterised by a continuous sulphide layer below a dual oxide layer of Ni and Co on top of a mixed Cr, Ti and Al oxide. In type-II hot corrosion, given that Na_2SO_4 melts at 884 °C, the deposit would remain solid at the alloy surface. Hence, in order to propagate the mechanism, liquid formation of the deposit is achieved via the reaction of the SO_3 present in a typical turbine gas stream with transient metal oxides that form at the alloy surface during the early stages of oxidation. This reaction forms metal sulphate (MSO_4), which can dissolve into the Na_2SO_4 deposit to form a eutectic MSO_4-Na_2SO_4 melt [6]. The liquid melt separates the alloy from the gas phase and as the solubility of SO_3 across the deposit is high [4], decreases the oxygen activity of the deposit

* Corresponding author.
E-mail address: m.dowd@swansea.ac.uk (M. Dowd).

http://dx.doi.org/10.1016/j.ijfatigue.2017.08.009
0142-1123/

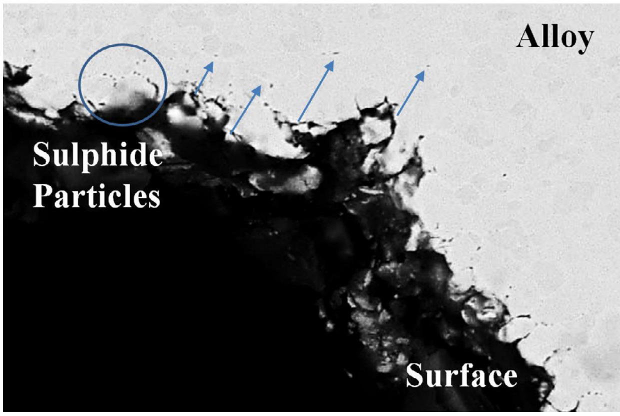

Fig. 1. Corrosion damage, displaying intergranular sulphide particles penetrating into the alloy from the surface (Courtesy of Rolls-Royce plc.).

at the melt/scale interface. The lack of oxide ions present in the deposit leads to solubility of the protective scale into the molten deposit as oxide ions are donated to the deposit by the protective oxides. Following dissolution and subsequent penetration of the protective scale, the molten deposit reaches the alloy surface and high sulphur activity in this region causes the precipitation of a continuous sulphide layer.

In components, sulphide particles may be seen at the grain boundaries ahead of corrosion features which demonstrates similarities to a transitional-type hot corrosion morphology [7] where at type-II temperatures, the sulphides of Cr and Ti appear as interconnecting sulphide networks at the grain boundaries. Earlier work suggests that the nucleation of grain boundary sulphides under type-II conditions arises from the decomposition of the melt such that it is no longer present at the metal surface as a continuous layer [8]. With the progress of time, this discontinuity renders the surface scale in contact with the ambient atmosphere allowing the introduction of sulphide particles to the grain boundaries from the sulphide layer via sulphidation-oxidation processes [8]. As shown in a hot corrosion assessment of RR1000 [1], the change in corrosion morphology from a continuous sulphide layer to grain boundary sulphide particles can be achieved under type-II conditions by significantly reducing the deposit flux.

Currently there is a lack of research considering the effect of transitional type hot corrosion on the remnant fatigue resistance of Ni-disc alloys. The majority of the published work addresses the impact of a classical type-II hot corrosion mechanism on fatigue life [9,10], where the methodology involves pre-pitting specimens prior to fatigue, a commonly used technique across numerous alloy systems. Whilst pre-pitting provides an ability to rank disc alloys based on their resistance to corrosive attack, subsequently fatigue testing pre-pitted specimens assumes that corrosion acts independently of stress. The resultant corrosion morphology achieved post-test displays thick oxide scales and evidence of pit coalescence leading to net section loss or broad front attack. In addition, the lack of diffused sulphur along the grain boundaries ahead of the advancing oxide front in areas of high stress concentration highlights the limitations of pre-pitting experiments in replicating service corrosion in the laboratory and suggests that the deposit flux is in excess of what is required to generate representative corrosion morphology. In this research, cylindrical round bar specimens are pre-notched to simulate the stress concentrating effect of the observed corrosion damage and subsequently corroded with a low flux of salt to simulate the transitional type hot corrosion morphology. The specimens are then subjected to a series of fatigue testing in an air environment to investigate the impact of representative corrosion features on cyclic life.

2. Experimental program

The pre-notched and corroding process the specimens undergo is described schematically in Fig. 2. Here, a micro-notch geometry is machined into the test specimen prior to low salt flux corrosion to precipitate grain boundary sulphide particles akin to stress assisted corrosion morphologies. Subsequent investigations into the effect of stress level on the low cycle fatigue response of corroded material can then be performed whilst considering the stress raising potential of the pit shaped notch features typically formed during corrosion-fatigue.

2.1. Material and specimens

The alloy used in this study is RR1000, a γ' precipitation-hardened Ni-based disc alloy developed by Rolls-Royce plc. for jet engine disc rotor applications. It has a nominal composition (in wt.%) of 18.5Co-15Cr-5Mo-3.6Ti-3Al-2Ta-0.5Hf-0.03C-0.02B-0.06Zr, balance Ni [11]. Material for this work was taken from forged and fully heat-treated material. A sub-γ' solvus heat treatment was used to generate a Fine Grain (FG) variant of RR1000 with a grain size between 5 and 10 μm.

Fatigue testing was performed using 11-off pre-notched (5-off of which were pre-corroded) FG RR1000 specimens which were compared to 15-off plain and un-corroded FG RR1000 specimens. The specimen design used was a cylindrical round bar of Ø4.5 mm and 12 mm gauge length. Prior to pre-notching and corrosion the specimen surfaces were machined to a specification of Ra < 0.25 μm and all specimens were subsequently shot peened at Metal Improvements Company (Derby, UK) to a specification of 6–8 Almen intensity and 200% coverage using 110H steel cast shot media.

2.2. Pre-notching and corroding

For the 11-off pre-notched specimens, three fully circumferential notches were machined to a depth of 40 μm, with a root radius of 50 μm into the gauge section. The machining process involved rotating the test specimen at 600 rpm perpendicularly against a fixed carbide cutting tool with the desired notch profile preformed on the tip. During turning, high pressure coolant was applied to eliminate the likelihood of brittle ‘white layer’ formation [12] commonly associated with rapid heating/quenching during the machining of Ni-alloys [13]. The notches were spaced 3 mm apart (see Fig. 3(a)) to ensure that each notch was a separate stress concentrating entity, i.e. when stress is applied; a nominal surface stress level is measured at the midpoint between two adjacent notches. Prior analysis via an axis-symmetric finite element (FE) model constructed during this research was used to verify that the design of the notches resulted in a constant stress concentration factor, $K_t = \sim 2.7$, and to verify that adjacent notch stress fields are independent. Fig. 3(a) illustrates the specimen design and Fig. 3(b) shows a digital microscope surface reconstruction of a selected notch from a machined specimen. This method allowed fatigue failure at one notch location, leaving the remaining intact notches for post-test mechanistic investigation. Prior to corrosion, the notched specimens were submerged in a neutral cleaning agent and placed in an ultrasonic bath to lightly remove loose machining debris and any residual coolant that may have remained.

Prior to fatigue testing, 5-off pre-notched specimens were salted using a micro-pipette technique, using a fully-saturated solution containing 98% Na_2SO_4 – 2% NaCl mixture dissolved in diluted methanol. These specimens were pre-heated to 100 °C on a hotplate and the solution was applied to the specimen gauge with a fine tip micro-pipette to allow access to the small notch features. The specimens were corroded under stress free conditions