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# Environment and time dependent effects on the fatigue response of an advanced nickel based superalloy

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ABSTRACT

The fatigue behaviour of the nickel based superalloy RR1000 is characterised using double edge notch specimens incorporating shot peening. Evaluations were conducted at two test temperatures, 300 °C and 650 °C, employing baseline and dwell waveforms. The effects of air and vacuum environments plus prior exposure at 650 °C were also assessed. It is demonstrated that surface oxidation does not control performance at the test conditions of interest. Rather, the modification to stabilized peak and mean stresses resulting from either thermal relaxation of peened stresses or a time dependent shake down of stress under mechanical loading governs ultimate behaviour.



## 1. Introduction

To meet the demand for reduced acquisition and life cycle costs in civil aviation, modern gas turbine engines are expected to achieve increasingly higher levels of fuel economy, reduced $NO_x$ emissions and noise, and with reduced module weight. These challenges inevitably necessitate higher overall pressure ratios, and higher compressor discharge and turbine entry temperatures. As such, disc rotors in the high pressure compressor (HPC) and turbine (HPT) must accommodate higher temperatures and stresses. This places significant demands on the high strength nickel alloys that are used for these critical components, particularly as loss of integrity can threaten the safety of the aircraft and passengers.

Prolonged exposure of nickel based components to oxidising environments could potentially influence fatigue crack initiation and growth mechanisms through surface and crack tip embrittlement, respectively, as well as microstructural modification [1–3]. In addition, high temperature exposure and stress excursions from service operation could regulate surface residual stresses introduced during processing. The combined effects of competitive fatigue–creep–environment mechanisms require a detailed fundamental understanding in order to predict component performance.

The present paper will describe a programme of fatigue experiments on the advanced nickel based superalloy RR1000. A peened, double edge notch specimen design, with a $K_t$ factor of 1.9, was employed to simulate nominal stress raising features. Crack initiation was monitored in these test pieces using a pulsed DC potential drop (DCPD) technique for experiments conducted in atmospheric and high vacuum environments. In recognition of the complex thermal–mechanical cycle imposed on disc rim features during normal gas turbine operations, additional tests were conducted where specimens were exposed at relatively high temperature but subsequently cycled at lower temperature conditions.

Detailed fractography will be presented to support our conclusions on the effects of environment, surface residual stress and surface finish on crack initiation in this specimen design.

## 2. Experimental methods

Laboratory scale fatigue specimens were machined from a RR1000 disc rotor forging that had been processed and heat treated to a standard proprietary condition. Details concerning the chemical composition, typical microstructures and basic mechanical properties of polycrystalline RR1000 have been previously reported [4–7]. The current material contained approximately 47% of precipitation phases (a combination of primary, secondary and tertiary $\gamma$') within a FCC $\gamma$ matrix. Primary gamma prime and to a lesser extent MC carbides control the grain size of the alloy, in this case to an average size of ASTM 13-10 (approximately 10 μm).

A double edge notch specimen design, Fig. 1, was employed for low cycle fatigue testing. Each semi-circular notch provides an average, elastic stress concentration factor of $K_t$ = 1.9 along the notch root, representative of moderate stress raising component features. The notches were machined using an end milling tech-

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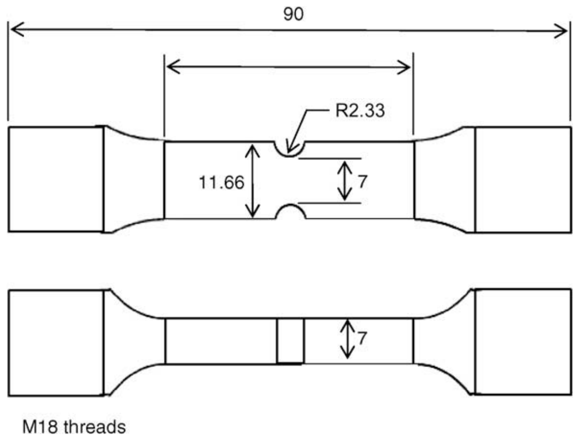


**Fig. 1.** Double edge notch specimen geometry (dimensions in mm).

nique with all edges deburred. Unless specified, the notches in all specimens were subsequently etched (to simulate component inspection preparation) and shot peened.

Three distinct waveforms were employed under load control during the study. "Baseline" cyclic loading applied a trapezoidal, 15 cycle per minute waveform consisting of 1 s linear rise and fall ramps with 1 s holds at peak and minimum stress (designated 1/1/1/1). The "on load dwell" cycle comprised similar rise, fall and off-load periods but incorporated a hold at peak stress for 10 s (1/10/1/1). In contrast, "off-load dwell" applied the 10 s dwell at the minimum stress level (1/1/1/10). These waveforms are represented schematically in Fig. 2. An applied stress ratio of 0.01 was employed throughout this series of tests.

It was intended from the outset that the investigation would concentrate on just two specific stress/temperature combinations. The temperatures, 300 °C and 650 °C, were selected to represent extremes of a typical rotor disc thermal flight cycle. Prior knowledge of RR1000 elevated temperature fatigue performance and an initial series of scoping tests then helped to define the specific stress levels necessary to induce baseline fatigue failures in

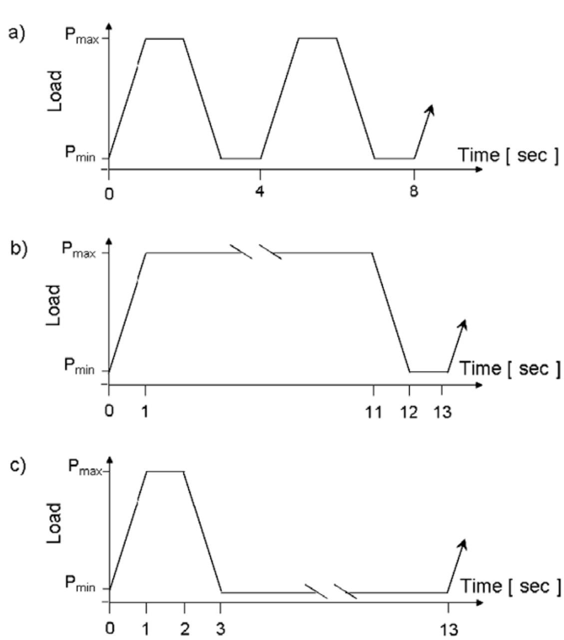


**Fig. 2.** Schematic representations of loading waveforms. (a) "Cyclic" (1/1/1/1), (b) "on load dwell" (1/10/1/1) and (c) "off-load dwell" (1/1/1/10).

**Table 1**
Summary of fatigue testing.

| Test temperature (°C) | Test conditions (waveform, environment ± exposure) |
|---|---|
| 300 | 1/1/1/1, Air, no exposure<br>1/1/1/1, Air, post 100 h/650 °C exposure in air<br>1/1/1/1, Air, post 100 h/650 °C exposure in vacuum |
| 650 | All tests used non-exposed specimens:<br>1/1/1/1, Air<br>1/10/1/1, Air<br>1/1/1/10, Air<br>1/1/1/1, Vacuum |

approximately 30,000 cycles in laboratory air at either temperature. These stress levels are deemed proprietary data, however, this will not detract from the trends in performance and mechanistic studies described in the present paper.

Prior to fatigue testing, selected specimens were exposed for 100 h in air at 650 °C as an arbitrary simulation of surface oxidation. Other specimens were subjected to the same exposure conditions but under a high vacuum ($10^{-5}$ mbar). In both cases, exposed specimens were allowed to cool to laboratory temperature prior to loading.

Fatigue tests were repeated (usually a minimum of three per condition) employing the various forms of loading waveform in either laboratory air or vacuum ($10^{-5}$ mbar) environments. A summary of the fatigue test conditions is given in Table 1.

Pulsed DC potential drop measurements were taken at regular pre-determined intervals across each specimen notch in order to define an initiation life, $N_i$, for each test in addition to the total life to failure, $N_f$, as defined by complete specimen rupture. All fractured specimens were inspected using optical and scanning electron microscopy to identify the number and location of crack initiation sites and confirm the dominant mechanisms controlling crack growth.

## 3. Results

The fatigue response of RR1000 DEN specimens to various combinations of test temperature, environment, waveform and pre-exposure is summarised by the two cumulative frequency plots in Figs. 3 and 4.

Concentrating on behaviour at the test temperature of 300 °C, Fig. 3, given that all the specimens were subjected to identical applied loads, a moderate but consistent knock down on total fatigue life (by approximately 50%) was induced by pre-exposure at 650 °C

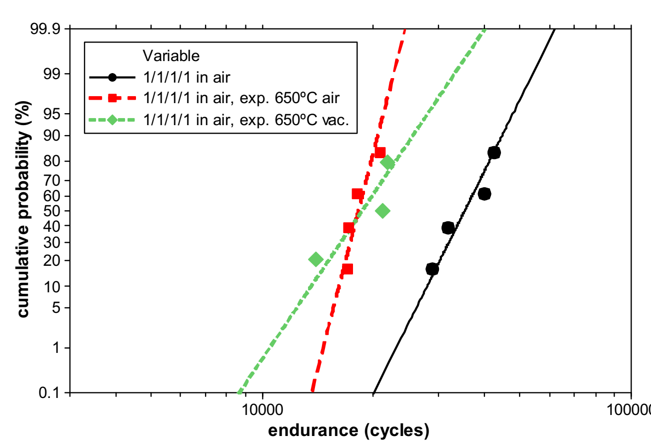


**Fig. 3.** Endurance data for RR1000 under baseline fatigue loading (1/1/1/1) at 300 °C.