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Crack Growth of a Polycrystalline Nickel Alloy under TMF Loading

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Abstract

Thermo-mechanical fatigue (TMF) is an important factor for consideration when designing aero engine components due to recent gas turbine development, thus understanding failure mechanisms through crack growth testing is imperative. In the current work, a TMF crack growth testing method has been developed utilising induction heating and direct current potential drop techniques for polycrystalline nickel-based superalloys, such as RR1000. Results have shown that in-phase (IP) testing produces accelerated crack growth rates compared with out-of-phase (OOP) due to increased temperature at peak stress and therefore increased time dependent crack growth. The ordering of the crack growth rates is supported by detailed fractographic analysis which shows intergranular crack growth in IP test specimens, and transgranular crack growth in 90° OOP and 180°OOP tests. Isothermal tests have also been carried out for comparison of crack growth rates at the point of peak stress in the TMF cycles.

1. Introduction

Over the past fifty years aero engines have advanced significantly, incorporating drastic changes in order to satisfy demand for efficient and high performance engines in both the civil and military sectors. Improved efficiency has been obtained through increasing the working temperature within the core of the engine as well as decreasing the weight of the components, using materials with higher temperature capabilities coupled with low density wherever possible. This has led to thinner disc rims combined with higher operating temperatures and harsh thermomechanical conditions that are pushing the current alloys to their limit. In order to derive accurate models which describe material behaviour, experimental replication of in-service operating conditions is desirable to allow for accurate understanding of failure mechanisms. Since transient engine operation between different phases of the flight cycle such as start up, take-off, cruise, landing and engine shut down causes complex interactions between thermal and mechanical loads, particularly in disc sections, isothermal testing no longer offers an accurate representation of engine conditions and thermo-mechanical fatigue (TMF) testing is required.

TMF testing can be carried out under strain or load control, dependent on the application for which specimen testing is providing information. Either method requires the definition of a phase angle (between thermal and mechanical strains or stresses) and loading direction. The current work investigates testing under load controlled conditions where an in-phase (IP) cycle can be defined as having thermal and mechanical stresses that increase/decrease concurrently. In a test with a phase angle of 180°, also known as an out-of-phase (OOP) test, the minimum temperature will be coincident with the peak applied stress, and vice versa.

Thus there are an infinite number of phase angles between these two extremes where the loading direction then becomes relevant as it describes whether the loading history on stress-temperature axes is clockwise (CW) or anti clockwise (ACW).

It is these laboratory results that can be used to assist TMF lifing, a vital aspect of component design. The total life is important but it is essential that TMF crack growth (TMFCG) is characterised, since modern inspection techniques utilise a 'life to first crack approach' [1,2], which requires the input of accurate fatigue crack growth data. Understanding TMF crack growth is particularly important when assessing the behaviour of melt anomalies or handling damage in gas turbine discs, where cracks may nucleate relatively early and the total life is dominated by their subsequent propagation.

The material utilised in the current programme is the polycrystalline nickel-based superalloy RR1000, developed by Rolls-Royce plc. This turbine disc alloy exhibits excellent tensile and fatigue strength and can be used at temperatures in excess of 700°C [3]. Limited investigations have been undertaken in the field of crack propagation under TMF conditions, presumably due to the experimental difficulty, although investigation of the open literature reveals some data relating to Inconel 718, also a polycrystalline nickel alloy [4,5]. In these investigations, alternative techniques were used for heating and crack monitoring, combining convection air heating with DCPD or induction heating with optical measurements. The focus of the current work is to develop an accurate experimental technique for measuring TMFCG and to assess the TMFCG behaviour of RR1000, comparing it to the isothermal response.

2. Experimental Procedure

A square section corner crack specimen design has been used for all of the thermal profiling and testing. The initial thermal profiling of the rig and preliminary isothermal testing was carried out using Waspaloy, 10x10mm and 7x7mm square section test pieces with a notch size of 0.35mm, before moving to RR1000, 5x5mm testpieces with a notch size of 0.22mm. This smaller size has allowed for faster temperature cycles with a uniform 10°C/s heating and cooling rate resulting in a 300-700-300°C cycle being achieved in 80 seconds. The chemical composition of the two alloys can be observed in Table 1.

Table 1: Chemical composition of Waspaloy and RR1000 (%wt) [6]

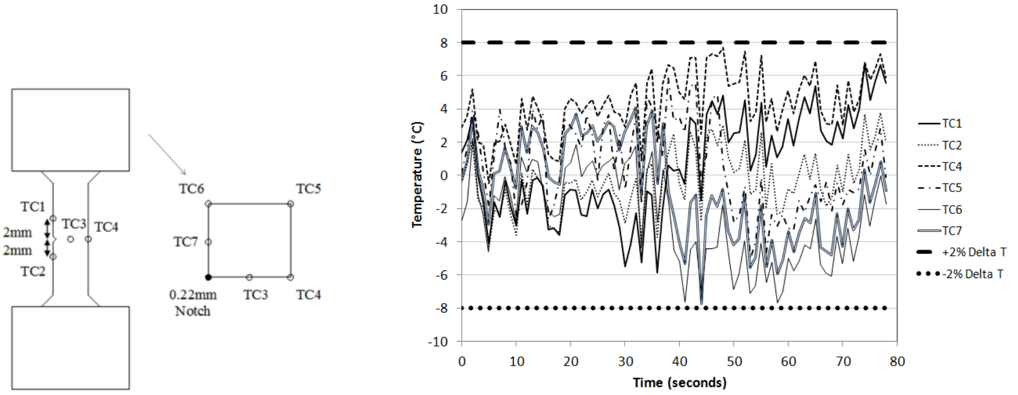
Alloy	Ni	Co	Cr	Mo	Ti	Al	Ta	Zr	Hf	C	B
Waspaloy	Bal	13.5	13.5	4.3	2.95	1.37	-	0.06	0	0.019	0.0063
RR1000	Bal	14.0-19.0	14.35-15.15	4.25-5.25	3.45-4.15	2.85-3.15	1.35-2.15	0.05-0.07	0.5-1.0	0.012-0.033	0.01-0.025

The test machine used for the isothermal and TMF work was an Instron 1362 electric screw testing system. Temperature control was achieved using an induction coil and associated fan cooler to allow for a uniform triangular cycle operating between 300°C and 700°C. The crack was monitored via a direct current potential drop (DCPD) method, so a set of wires were spot welded above and below the notch as well as 5mm above the notch in the centre of the face for referencing. The temperature was recorded and controlled with a spot welded N-type thermocouple 1mm below the notch plane on the centre of the adjacent face. The thermal profiling was carried out using seven sets of thermocouples in various locations to ensure that the temperature remained within the upper and lower bounds set for strain controlled TMF testing in the *Validated Code-of-Practice for Strain-Controlled Thermo-Mechanical Fatigue Testing* (+/-2% ΔT) [7] from test to test.

Pre-cracking is an important stage for any crack propagation test in order to escape any residual effects from the machined notch, hence a perfected method was established for the TMFCG testing in the current work. This procedure has been followed for all of the isothermal and TMF tests allowing a fair comparison, all of which have been carried out under a load ratio of R=0.1 and a maximum stress of 450MPa. The two types of isothermal test waveforms investigated were 1-1-1-1s trapezoidal and a 0.0125Hz sine wave, giving a fast cycle (4 seconds) and a slow cycle (80 seconds) respectively. The specimens were cycled either isothermally or using a TMF cycle until the crack reached about 40% of the gauge width, equating to 2mm, before crack measurements were carried out, and then cycled to failure at room temperature or removed for longitudinal sectioning for further analysis using a Jeol 6100 Scanning Electron Microscope.

3. Results and Discussion

Initial investigations were designed to ensure that the chosen heating technique, induction heating, gave minimal thermal gradients across the specimen, presented in Fig. 1. The direction of the cooling air is shown by the arrow and the positions of the thermocouples are presented in Fig. 1 a). It is clear that the 5x5mm RR1000 test specimen, when cycled between 300°C and 700° over 80 seconds, gave a tolerable thermal response within +/- 2% ΔT, as shown in Fig. 1 b). This provided confidence in the use of induction heating before progressing to crack growth testing.

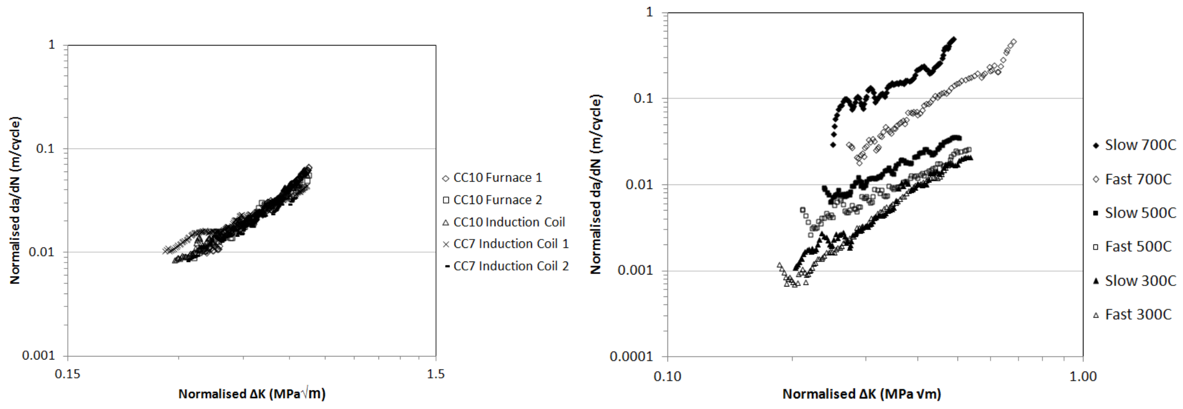


a) b)

Fig. 1: a) Thermocouple locations with cooling direction shown by arrow, b) the scatter from the target temperature for an 80 second TMF cycle (300-700-300°C)

As previously discussed the initial phase of the investigation comprised of validating the use of induction heating since minimal previous work has been found in the open literature using this particular setup. Moverare et al. [4] made use of induction heating with an optical means of crack monitoring, whilst Jacobsson et al. [5] took a convection air heater approach and potential drop (PD) for monitoring the crack. Quartz lamp heating has also been utilised in previous work [8] but induction heating is a common method used by a large range of authors [4,9] and so too is DCPD for crack monitoring [5,10]. However, little evidence of widespread use for TMF crack growth testing is available, mainly due to concerns regarding potential crack tip heating and disruption of PD readings [5]. Despite this, the capability of achieving fast cycles makes it an attractive heating technique, and similarly, DCPD offers a simple yet effective technique for crack monitoring, giving desired crack sensitivity and accuracy [10]. With this in mind, the preliminary work sought to establish the effectiveness and consistency of the technique in comparison with previously generated crack growth data conducted in a radiant furnace, for which growth data in Waspaloy was available. The aim of the simple isothermal tests were to compare radiant furnace results using DCPD with the induction coil/DCPD setup, before moving onto smaller specimens to determine whether crack growth rates were affected by specimen size. The results of these tests can be observed in Fig. 2 a) where it is clear that not only is there minimal scatter between the crack growth rates of the radiant furnace and induction coil, but also between the 10x10mm and 7x7mm specimens.

Isothermal RR1000 tests were then carried out to provide baseline crack growth data. These were performed at 300°C, 500°C and 700°C to provide a direct comparison with the temperature at which peak stress was achieved in various phase angle TMF tests, i.e. OOP180° (300°C), OOP90° (500°C) and IP (700°C) respectively. Fig. 2 b) shows the two waveforms used at each temperature, the fast 1-1-1-1 trapezoidal and the slow 0.0125Hz sinewave, to establish whether the cycle length had any effect on crack growth rates, and in the case of the 0.0125Hz sinewave, to replicate the length of the TMF cycle. As expected, the 0.0125Hz sine waveform at 700°C showed faster growth rates than the trapezoidal waveform, since it spent more time at the higher stresses, introducing creep and environmental damage at the crack tip. The 500°C tests produced a similar response in that the slow (0.0125Hz) cycle resulted in accelerated crack growth compared with the fast (0.25Hz) cycle, although the effect was less pronounced. The 300°C tests showed a consistent crack growth rate in both waveforms since the effects of creep and environmental damage at this temperature are negligible. The overall trend observed is as expected, the higher the temperature, the faster the growth rate.



a) b)

Fig. 2: Isothermal Paris curves for a) various heating techniques and specimen sizes for Waspaloy and b) different temperatures and cycle lengths for RR1000

With the baseline isothermal data collated, the results of the TMF tests shown in Fig. 3 can be rationalised. The IP test is positioned between the two isothermal Paris curves at 700°C since it was subject to higher stresses at or near to peak temperature, for longer than the 1-1-1-1 trapezoidal but shorter than the slow cycle isothermal test, which suggests that the cycle length is a dominant factor due to time dependent damage mechanisms. A similar trend to the IP results was found in the 90°OOP but less pronounced, suggesting again that cycle length was an important factor resulting in the introduction of time dependent damage. The 180°OOP test shows a faster crack growth rate than the 300°C isothermal tests suggesting that oxidation of the crack tip at high temperatures may play a significant role in accelerating growth rates. The same trend was observed and documented by a number of authors in that the IP tests resulted in intergranular fast crack growth rates compared to transgranular slow crack growth in the OOP tests [11,12].

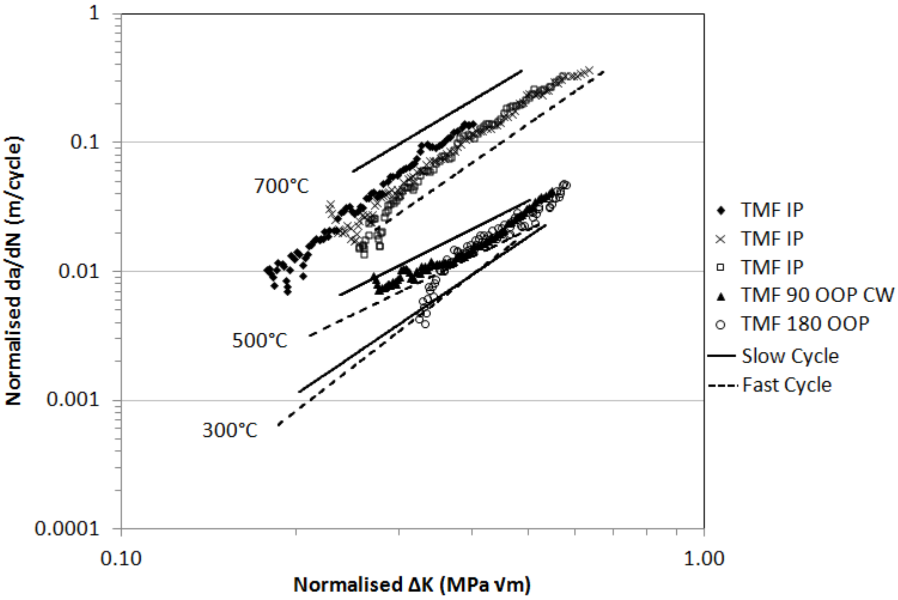
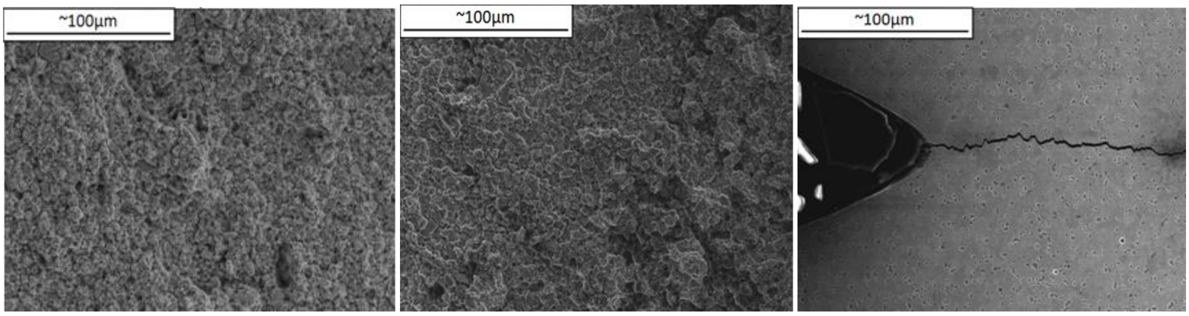


Fig. 3: Isothermal and TMF Paris curve comparison

Fig. 4 shows a selection of fracture surface images relating to the data previously discussed. Fig. 4 a) shows the slow cycle at 700°C whilst Fig. b) and c) shows IP. Consistent trends are found in the test data in that intergranular failure dominates in these test pieces, and is most significant in the slow cycle followed by the IP specimen and then the fast cycle. The propensity for intergranular crack growth is a result of the specimen being exposed to the maximum stress for a longer period of time in the slow cycle than the fast cycle and constantly being exposed at 700°C, as opposed to the IP test where this varies between 300°C and 700°C. For this reason an interaction occurs between fatigue, creep and environmental damage mechanisms causing heavily dominated intergranular cracking. The 90°OOP and 180°OOP showed much flatter fracture surfaces representative of a transgranular type failure mechanism which shows a reduced crack growth rate in comparison to the isothermal 700°C and IP TMF tests. The two are very similar in terms of severity which is also shown by the comparable Paris curves with the 90°OOP giving only a slightly faster growth rate.



a) b) c)

Fig. 4: Fracture surfaces of a) slow cycle 700°C, b) IP, and c) sectioned IP

4. Conclusions

TMF crack propagation testing is key to providing accurate crack growth data for in service conditions so that accurate predictions can be made using high performance crack growth models. The current work has seen the development of such a technique for a polycrystalline nickel alloy from which the following conclusions can be drawn,

- Induction heating and DC Potential Drop techniques are compatible for isothermal and TMF testing.
- Cycle time has a significant effect on crack growth rates in higher temperature isothermal tests.
- 180°OOP growth rates are faster than in both isothermal 300°C tests presumably due to increased oxidation at the crack tip, due to the thermal cycles of the TMF test.
- IP testing produces accelerated crack growth rates compared with OOP due to increased temperature at peak stress and therefore increased time dependent crack growth.
- The ordering of crack growth rates is supported by detailed fractographic analysis which shows intergranular crack growth in IP test specimens, and transgranular crack growth in 90°OOP and 180°OOP tests.

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