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An investigation of the failure mechanisms in high temperature materials subjected to isothermal and anisothermal fatigue and creep conditions

C. J. Hyde*, W. Sun and T. H. Hyde

Department of Mechanical, Materials and Manufacturing Engineering, University of Nottingham, Nottingham NG7 2RD, UK

Abstract

Many engineering components are subjected to conditions which have a detrimental effect on the materials from which they are made. Such components are used, for example, within high temperature regions of aeroengines (e.g. turbine discs) and power plant (e.g. steam pipes) and such conditions can include periods of isothermal and/or thermo-mechanical cyclic loading which may cause fatigue, excessive plasticity and creep. The combination of conditions to which the materials are subjected can have a strong influence on the failure mechanisms induced within the material.

This study is concerned with the identification of the failure mechanisms which occur in RR1000 (a Nickel-based superalloy used in aeroengine turbine discs) tested under both isothermal and anisothermal cyclic conditions. The various types of test conditions applied to the specimens (e.g. waveforms which contain high temperature tensile conditions or alternatively low temperature tensile conditions) and the related failure mechanisms (e.g. intergranular, transgranular or mixed cracking), have been identified. Comparisons of the predictions of failure lives with experimental data from tested specimens, subjected to various test conditions, are also presented.

Keywords: Thermo-mechanical fatigue; in-phase; out-of-phase; intergranular cracking; transgranular cracking

1. Introduction

Many components in power generation plant, chemical plant, aeroengines and superplastic forming dies etc, are subjected to combined cyclic mechanical and thermal loading. This combination of loading is known as thermo-mechanical fatigue (*TMF*) and is usually considered, experimentally, as either "In-phase" (*IP*), where φ=0°, or "Out-of-phase" (*OP*), where φ=180°, as shown schematically in Figure 1, where φ represents the phase angle between the mechanical and temperature waveforms. In addition, many of these components may be operating with cracks or crack-like flaws within them. Therefore, it is vitally important that the physically-based materials models used to predict the behaviour of such

* Corresponding author. Tel.: +44 (0)115 951 3735.
E-mail address: christopher.hyde@nottingham.ac.uk.

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materials/components take account of the failure/crack growth mechanisms actually present within materials. Such models, used in the past for the prediction of cyclic plasticity and crack growth, include the unified Chaboche viscoplasticity constitutive model [1, 2], which takes account of various phenomena, such as cyclic plasticity, creep relaxation and cyclic hardening/softening, and the Liu and Murakami creep damage model [3] capable of accurately predicting creep/creep crack growth within materials.

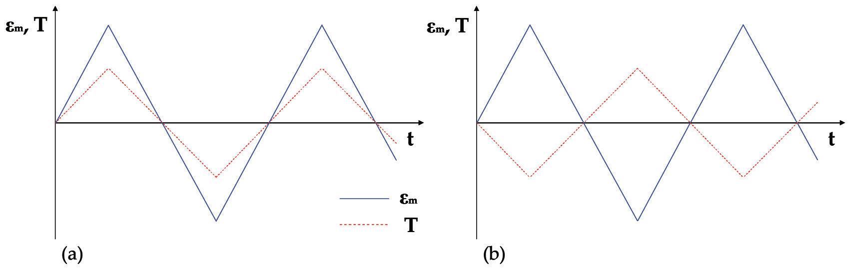

Figure 1. Schematic representations of common anisothermal waveforms (a) *IP* [φ=0°], and (b) *OP* [φ=180°].

This paper is particularly concerned with the identification of the cracking mechanisms present within the fracture surfaces of RR1000 specimens. Testing has been carried out under both isothermal and anisothermal cyclic conditions, on square cross-sectioned, corner notched specimens, in order to ensure a common site for crack initiation and propagation (i.e. the notch tip). The fracture surfaces have been investigated using scanning electron microscopy (*SEM*). Data is also presented to show the relationship between the anisothermal lives of the specimens, with those for the isothermal 'equivalents'. The experimental set-up used for the testing is briefly described.

2. Experimental Testing

The material considered within the present study, is RR1000, a Nickel-based superalloy. Table 1 shows the chemical composition of this material. All testing presented has been performed under either isothermal or anisothermal cyclic plasticity conditions and the failure criterion used was a 10% drop from the stabilised cyclic *ΔP/2* value.

Table 1. Chemical composition (wt%) of RR1000 [4].

Co	Cr	Mo	Ti	Al	Ta	W	Fe	Re	Hf
14-19	14.4-15.2	4.25-5.25	3.45-4.15	2.85-3.15	1.35-2.15	≤2	≤1	≤1	0.5-1
Nb	**Si**	**Mn**	**Y**	**V**	**Zr**	**C**	**B**	**Ni**	
<0.5	≤0.2	≤0.15	≤0.1	≤0.1	0.05-0.07	0.012-0.033	0.01-0.025	Balance	

The test machine used to carry out the isothermal and anisothermal cyclic loading tests is an Instron 8862 *TMF* system. This system utilises radio-frequency (*RF*) induction heating in order to achieve rapid heating and can also achieve rapid cooling by use of forced air cooling through the centre of the specimen when testing hollow specimens (not applicable to the work presented within this paper), respectively. Figure 2 shows an *RF* induction coil, test specimen and extensometry in use during a test. The extensometer was placed on the opposite corner to the corner crack. This was to ensure that 'bulk strain' was put into the specimen during testing rather than a portion of the movement of the extensometry being taken up by 'opening' of the crack, which would occur if the extensometry was placed on the same corner as the crack, with each extensometer arm being on opposite sides of the crack. This 'crack-opening' would cause the strain experienced within the 'non-cracked' cross-sectional area of the specimen to be reduced compared with the intended input strain and hence this was avoided. All testing presented within this paper was carried out under strain-control. Temperature control was achieved by using *TC*s on the gauge-section of the specimen (near the opposite corner to the initial notch). Figure 3 shows the corner notched specimen geometry used for all of the testing presented within this paper.

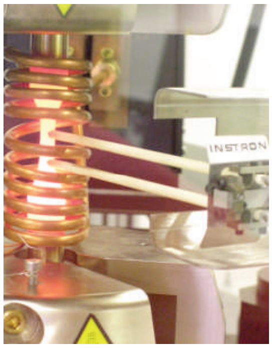

Figure 2. *TMF* test machine set-up showing the *RF* induction heating coil, test specimen and extensometry.

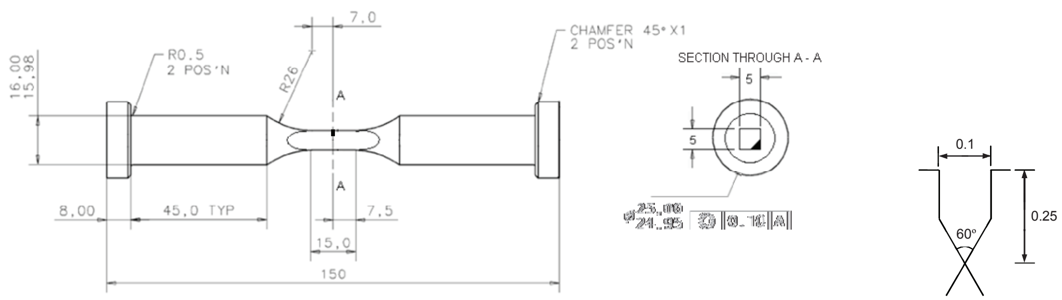

Figure 3. Corner crack specimen (dimensions in mm).

3. Comparison of thermo-mechanical fatigue with corresponding isothermal fatigue lives

Figure 4 presents data which allows a comparison of the lives of specimens tested under isothermal (both high and low temperatures) and anisothermal (both *IP TMF* or *OP TMF*) test conditions. The cyclic load-range for each cycle ($\Delta P=P_{max}-P_{min}$) obtained during the tests are shown plotted against cycle number, N. Parts (a) and (b) of Figure 4 show *TMF* data with the temperature-ranges of T=300-650°C, i.e. ΔT=350°C and T=300-650°C, i.e. ΔT=350°C with the corresponding *IF* data for the minimum and maximum temperatures, respectively. From Figure 4 it can be seen that the maximum cycle temperature *IF* condition is the most detrimental to the life the specimen. This is followed by the *IP* and *OP TMF* conditions, respectively, with the *IF* condition at the minimum cycle temperature giving the largest specimen life. This can be explained by considering the portion of life during which the specimen is subjected to high temperature tensile conditions, as it is under these conditions that the material accumulates the most damage (i.e. creation of voids and crack growth). It can also be seen by comparing the *TMF* data from parts (a) and (b) of Figure 4 that *IP TMF* is more detrimental to the life of the specimen than *OP TMF*, especially at a lower temperature-range.

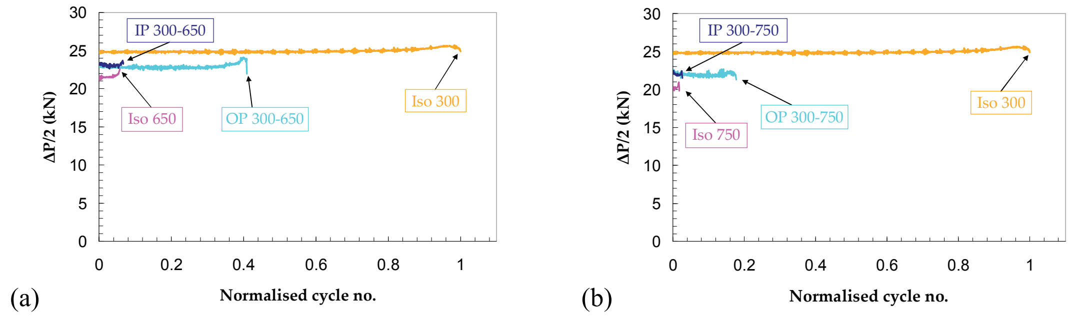

Figure 4. Comparison of *TMF* data with the corresponding *IF* data at the minimum and maximum temperatures incurred during the *TMF* cycle for RR1000 specimens, $\Delta\varepsilon$=0.4% (a) ΔT=350°C and (b) ΔT=450°C.

4. Specimen Fracture Surface Images

This section contains observations of the cracking/failure mechanisms indicated by the fracture surfaces of the pre-notched RR1000 specimens tested under *IF* and *TMF* conditions. As the failure criterion used was a 10% drop from the stabilised cyclic $\Delta P/2$ value, the specimens, in general, have not fully fractured. The specimens were broken open after the test, under a large tensile load at room temperature, revealing the propagating fracture surface from the notch during the test. Parts (a), (b) and (c) of Figure 5 show the fracture surfaces for the *IF* tests performed at 300°C, 650°C and 750°C, respectively. Parts (a) and (b) of Figure 6 show the fracture surfaces for the *IP TMF* tests performed using the temperature ranges of 300-650°C and 300-750°C, respectively and parts (c) and (d) of Figure 6 show the fracture surfaces for the *OP TMF* tests performed using the temperature ranges of 300-650°C and 300-750°C, respectively.

Figure 5(a), obtained for a low temperature *IF* test conditions, clearly shows transgranular cracking, parts (b) and (c) of Figure 5, obtained for high temperature *IF* test conditions, however, clearly show intergranular cracking. It can be seen from parts (a) and (b) of Figure 6, for *IP TMF* conditions, that evidence of intergranular cracking is present. However, parts (c) and (d) of Figure 6, for *OP TMF* test conditions, show that under these conditions there is a mixture of intergranular and transgranular cracking.

Hence, it can be seen that, in general, for specimens which were subjected to tension during periods of high temperature (i.e. high temperature *IF* and *IP TMF*), intergranular cracking is observed, however for specimens which were subjected to tension during periods of low temperature (i.e. low temperature *IF* testing and *OP TMF*), transgranular (or mixed) cracking is observed. Such transitions from intergranular to transgranular cracking with increasing temperature have been attributed to increased oxidation damage at the grain boundaries ahead of the crack tip as temperature is increased [5].

A similar transgranular to intergranular cracking transition with increasing temperature has been observed by Lerch and Jayerman [6], in 1984, for another Nickel-based superalloy, namely, Waspaloy. At temperatures up to and including 500°C, cracks were observed to initiate transgranularly. Above 800°C, however, the cracking mechanism was predominantly intergranular, with a mixture of the two cracking mechanisms being observed between these temperatures. Also, Neu and Sehitoglu [7, 8] have made similar observations for 1070 steel specimens within the temperature-range of 20-700°C. They found that during *IP TMF* testing, cracks generally initiated and propagated intergranularly, whereas under *OP TMF* test conditions, cracks initiated and propagated transgranularly. This behaviour has been confirmed by Kadioglu and Sehitoglu [9] for Mar-M246 and Mar-M247 Nickel-based superalloys within the temperature-range of 500-1038°C; they found that under *IF* conditions, the cracking mechanism was the same as that for *IP TMF*, and is also intergranular. This generally fits very well with the results presented in the present work in terms of grouping the high temperature *IF* with *IP TMF* and low temperature *IF* with *OP TMF* to characterise the way in which the material behaves and fails.

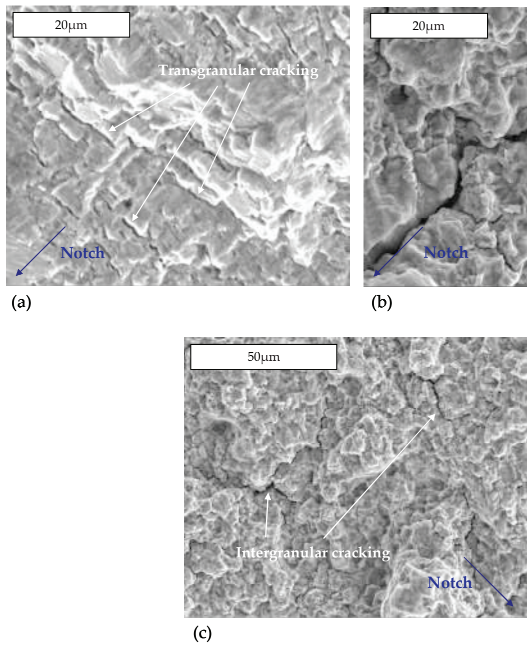

Figure 5. High magnification *SEM* images of the cracking on the fracture surfaces of RR1000 specimens with 0.25mm starter notches, tested under *IF* conditions (a) 300˚C, (b) 650˚C, and 750˚C.

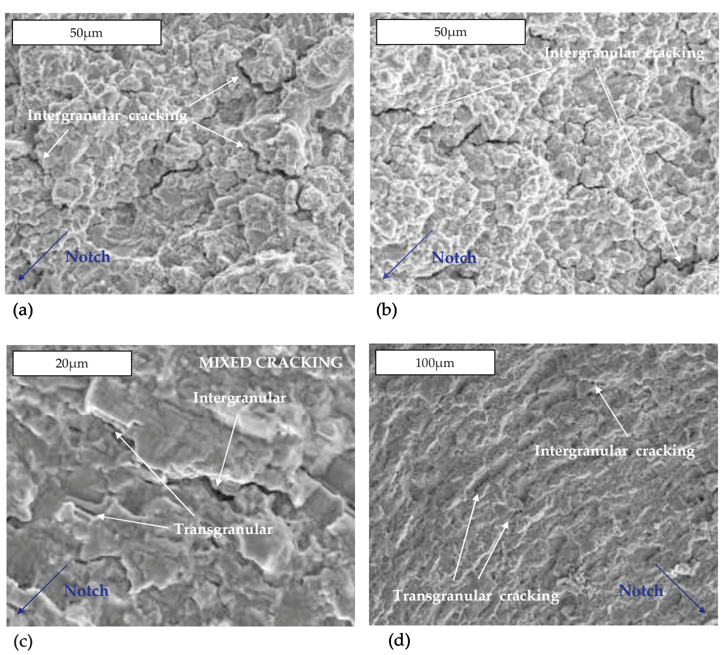

Figure 6. High magnification *SEM* images of the cracking on the fracture surfaces of RR1000 specimens with 0.25mm starter notches, tested under *TMF* conditions (a) *IP* 300-650°C, (b) *IP* 300-750°C, (c) *OP* 300-650°C, and (d) *OP* 300-750°C.

5. Discussion and Future Work

Various *IF* and *TMF* testing conditions have been applied to uniaxial specimens in order to establish the effect that they have on the life of specimens made from RR1000. Many of the observations made are as would be expected, such as the life of the specimens reducing as a function of increasing temperature. The *TMF* lives obtained for the RR1000 specimens have been compared with the 'equivalent' *IF* lives, showing that the higher the portion of life during which the specimen is subjected to high temperature tensile conditions, the lower is the resulting specimen life (i.e. high temperature isothermal conditions are the most detrimental to the life of the material and low temperature isothermal conditions are the least detrimental; the *IP* and *OP TMF* conditions are between the two isothermal extremes of the temperature conditions with the *OP* test conditions resulting in a longer specimen life than the *IP* test conditions, as the temperatures are lower when tensile conditions are experienced). This is considered to result from the fact that the creation of voids and the growth of cracks generally occur under tensile conditions and this effect is found to increase as the temperature increases.

The cracking mechanisms under which the specimens failed have also been investigated. Generally it has been found that for situations under which the specimen is subjected to tension at higher temperatures (i.e. high temperature *IF* and *IP TMF* conditions), intergranular cracking is observed and that for the conditions under which the specimen is under tension at lower temperatures (i.e. lower temperature *IF* and *OP TMF* conditions), transgranular cracking is observed. However, under *OP TMF* conditions, a mixture of intergranular and transgranular cracking is present, producing an exception to this simple characterisation of the cracking behaviour into two groups.

Future work will include more detailed investigations on the process of crack initiation and propagation behaviour, which are the fundamental issues for predicting the failure of material and components under thermo-mechanical fatigue conditions.

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