A Creep Fatigue Crack Propagation Study of the PM Nickel Based Superalloy UDIMET 720 Li

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ABSTRACT: *In this paper, the fatigue and creep crack growth behaviour was studied at temperatures of 650 and 725ºC in compact tension specimens, and the results were compared. Fatigue tests were carried out with a constant stress ratio (R=0.1) at two different frequencies (5 and 0.25Hz) in order to study the effect of frequency in crack propagation. The results obtained in these tests were converted, based on time, and compared with the creep results. For fatigue, da/dN vs. ΔK curves were used, and for creep, da/dt vs. K_{max} curves, since, for this material, the stress intensity factor has shown to be the most appropriate parameter for the study of crack propagation. The FCGR results have shown that the effect of frequency is predominant over the temperature influence, that is, da/dN has a more significant increase when the frequency is lowered from 5 to 0.25Hz than when the temperature is increased from 650 to 725ºC. An analysis of the cracking mechanisms will be presented in the paper, specially for creep, where mixed load type crack propagation was found (I+II) for loading under mode I only. The main failure mechanism detected in the material was mixed mode transgranular – intergranular. However, in creep intergranular and secondary cracking was predominant when the crack propagated at inclined angles (I+II) with the crack propagation direction of mode I. The crack growth rates, da/dN and da/dt, where mainly related with the stress intensity factor component in mode I.*

1. INTRODUCTION

The nickel base superalloy Udimet 720Li was developed bearing in mind its use in turbine discs and applications in energy production. The combination of the alloying elements, as well as its fabrication process and sintering, were devised with the aim of improving its behaviour in service, where the fatigue-creep interaction is predominant and the temperatures are between 650 and 700ºC.

It is generally accepted [1-2] that this improvement is essentially due to the refinement of the grain size, associated to a higher number of alloying elements and a greater dispersion of the γ' phase.

In the fabrication process, the powder material was isostatically heated, pressed and extruded; a solution treatment was subsequently applied, from which a uniform structure of fine grain was obtained, with an average size of 7μm. The composition of the microstructure (Table 1) is, approximately, 18% of phase (γ'), associated with a small amount of carbo-nitrites. The thermal treatment consisted in four hours of preparation with a temperature between 1080 and 1100ºC, followed by cooling in oil up to 650ºC and maintenance of this temperature for 24 hours and an air cooling. Finally, the material was exposed to a temperature of 760ºC for 16 hours, followed by cooling at room temperature.

TABLE 1: Chemical composition of the sinterized nickel base superalloy Udimet 720Li.

Ni	Cr	Mo	Ti	Al	Co	Zr	W	Fe	B	C
59.3	16.2	3.2	5.1	2.6	14.5	0.035	1.7	0.072	0.022	<0.1

There is a limited amount of work published in the literature presenting fatigue and crack growth data on Udimet 720Li.

The effect of stress ratio on FCGR was analysed in [3]. However, all this data were essentially obtained at temperatures below or up to 600ºC. Byrne and co-workers [4] carried out more extensive work on the FCGR mechanisms, at temperatures between 600 and 650ºC. Additional results obtained at 725ºC were published recently by the authors [5]. Creep crack growth rate data is also available by the authors [5], but no other creep data was found in the literature for temperatures above 650ºC.

This paper presents a summary of the fatigue and creep crack growth rate results mainly obtained at 650ºC. The obtained fatigue and creep crack growth rate data is compared with published data obtained at 650ºC for other nickel based superalloys of the cast and wrought type.

2. EXPERIMENTAL DETAILS AND RESULTS

All the tests were made in CT specimens (26x13mm), in a servohydraulic test machine. The specimens were taken from a turbine disc and tested in a high temperature furnace. The monitorization of the crack growth was made with a pulsed potential drop system.

By using the valid results for each test zone, calibration curves were obtained, as well as da/dN; ΔK cracking diagrams. Results were correlated with a Paris law type relation, $da/dN=C\Delta K^m$; linear regression type correlations were applied to the results. The values of the C constant and the <u>m</u> exponent were determined for all the test situations. The values of da/dN were obtained from the numerical differentiation of the pairs of values a and N obtained in each specimen, according with the finite difference method.

Fig. 1 shows the results and correlations da/dN; ΔK for 650ºC at 5 and 0.25Hz. Results show a significant influence of the frequency in the crack speed, which increases from a factor of 2 in the lower zone of the values of ΔK(≅20 MPa.m$^{1/2}$) until a factor of about one order of magnitude for ΔK÷60 MPa.m$^{1/2}$, when the frequency lowers form 5 to 0.25Hz, sinusoidal.

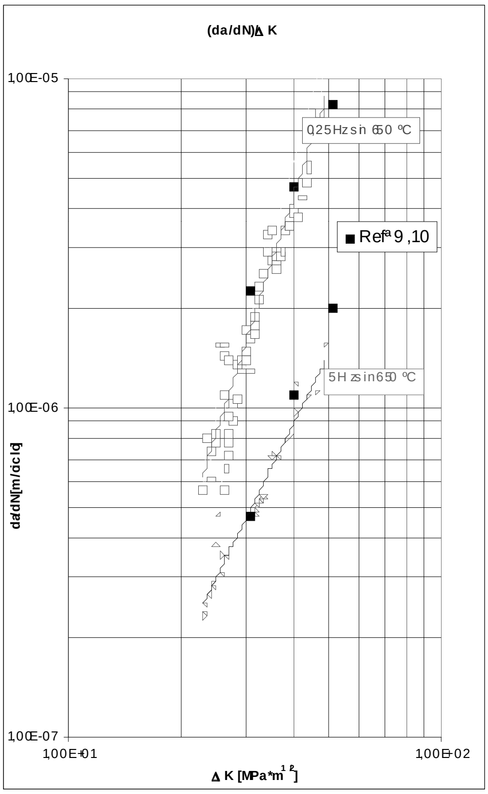
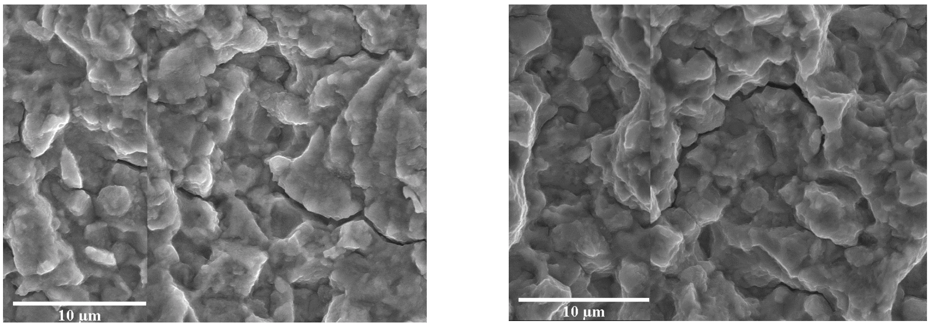


Figure 1: Results and correlations da/dN; ΔK. R=0.1. CT specimens. 650ºC (5 and 0.25Hz). PM nickel base superalloy Udimet 720Li.

The fractographic analysis indicates that the fatigue crack mode of this material, at 650ºC, changes from mixed with transgranular dominance, at 5Hz (Fig. 2a), to mixed with intergranular dominance, at 0.245Hz (Fig. 2b). This change in the behaviour of the material according to frequency is due to an increase in the time of exposure to the maximum load and, consequently, to a higher tensile field, which provokes a greater damage due to the oxidation and creep effect [6, 7].



a) b)

Figure 2: SEM fractographic image of the fracture surface of the material. a) 650ºC, 5Hz.ΔK≅30 MPa.m$^{1/2}$.b) 650ºC, 0.25Hz. ΔK≅30 MPa.m$^{1/2}$.

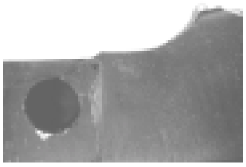


Figure 3: Curved crack in CT specimen. Creep at 650ºC.

In the case of curved cracks in mode I loading, the following reference relation is applicable for the stress intensity factor, K:

$$K_{II}=\cos^3(\theta/2.K_{In}) \qquad (1)$$

where K_{II} is the component of the local stress intensity factor in mode I at the tip of the curved crack with θ angle, and K_{In} the nominal remote stress intensity factor in mode I, given only by the stress intensity factor equation for the CT specimen [8].

TABLE 2 : Values of C, m of the Paris law. Creep tests. Udimet 720Li.

		Da/dt=CK$_{In}$^{m}			**Da/dt=CK$_{II}$^{m}**		
Ref.	**T**	**C**	**m**	**r^2**	**C**	**m**	r^2
	ºC	mm/hour			mm/hour		
1892	650	1.45E-4	2.87	0.94	6.5E-9	5.86	0.92
1898	725	1.10E-11	7.15	0.94	6.91E-16	10.9	0.92
1897	725	1.09E-05	3.73	0.97	1.99E-11	7.97	0.97
TOTAL	725	1.80E-06	4.28	0.85	3.73E-08	5.61	0.68

The creep tests performed are indicated in Table 2. At the creep crack tests it was shown that the crack propagated with a curved trajectory, inflecting towards the direction of the applied load (Fig. 3). The direction of the propagation occurred, thus, in mixed mode I+II, where the Mode II component increased as the crack length increased. Apparently, this type of behaviour is peculiar to the nickel base superalloys, and has been very briefly referred to in the literature [4,5], although not in detail.

In Fig. 4, the da/dt; K_{max} data, quoted in [3,4] and obtained for Udimet 720Li, are also plotted. For creep lower da/dt values were obtained in [3,4], which could be due to the testing method, which was constant K testing in [4,8] under a decreasing stress field. For the computation of K_{In} and K_{Ii}, the projected equivalent depth of the crack, a_{ef}, was used in equation (1). a_{ef} is, therefore, the crack depth in the mode I direction of crack growth, normal to the loading axis. The equation for a_{ef} is:

$$a_{ef}=A_{pI}/B \tag{2}$$

where A_{pI} is the projected area of the curved crack (Fig. 3) in the mode I direction. To use the calibration line methodology, the real area, A, of the curved crack should be used. Assuming that a uniform crack front is obtained (no variation of A and <u>a</u> in the thickness direction), the relation between A an A_{pI} is given by

$$A_{pI} = A\cos\theta \tag{3}$$

where θ is the tangent angle to the curved crack in each point. It was found that θ varied $\pm$ 20% along the crack front (through the thickness), and the mean value of θ through the thickness was used in equations (1-3).

Since this approach is approximate, further work is in progress to obtain K or J for the curved cracks, using a 2D or 3D FE approach, which will provide a more adequate solution. Non-uniform crack fronts and tilted cracks could be taken into account in the FE simulations, in the follow-up of previous work for tunnelling cracks [9]. It was verified that, even for K_{max}, the highest crack speed, da/dt, is obtained for a frequency of 5Hz, which means that, in this type of material, the plastic cyclic deformation seems to induce a larger damage within the same time, t.

As previously observed, the fractographic analysis has shown that the failure mode in this material, for fatigue at 650ºC, is essentially mixed, intergranular/transgranular.

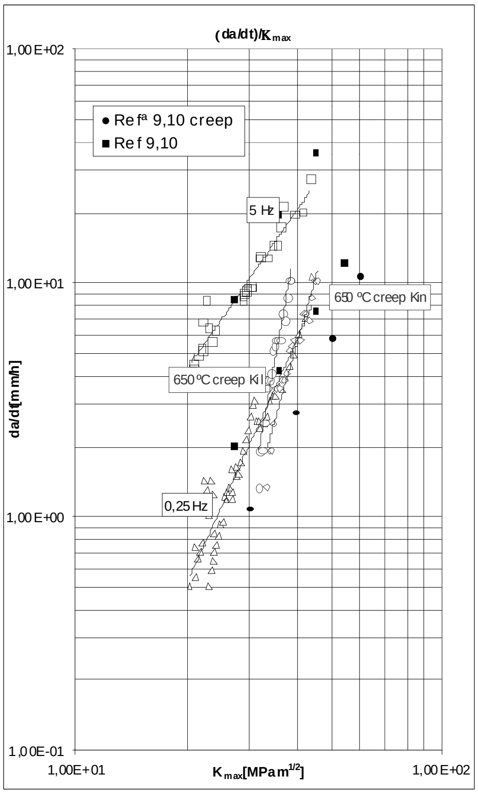


Figure 4: Results and correlations da/dt; K_{max}. Udimet 720Li. Creep at 650ºC.

Fig. 5 is a fractography of the creep crack at 650ºC. The failure is now intergranular, with a great number of empty voids (cavities), some of them interconnected by coalescence. The slippering between grain boundaries is reduced, as a consequence of the smaller plasticity of the material and the reduced time of loading. The roughness of the fracture surface is quite high, due to the intergranular character of the failure. The main mechanism of the creep damage, in this case, is the coalescence of the microcavities.

The present data for Udimet 720Li at 650ºC was compared with da/dt and da/dN data for other Ni base superalloys. The plots da/dt and da/dN against frequency are shown in Figs. 6a) and 6b). For da/dt under fatigue loading, the present results are only marginally higher than the results obtained for the other alloys (Fig. 6a)). Under creep (Fig. 6a)), there is a sudden increase in daq/dt due to the change of failure mode to a basic intergranular fracture (Fig. 5). The obtained results da/dN against are in good agreement with those obtained in the other Ni base superalloys of similar composition (Rene 95 and Waspalloy) but, for Udimet 720Li, da/dN is slightly higher than for Inconel 718, which is a Ni-Fe cast and wrought alloy. Within the range of frequencies analysesd, a unique straight line may be fitted to the entire set of da/dN against frequency data (Fig. 6b)), indicating a similar cracking mechanism of mixed mode at this temperature.

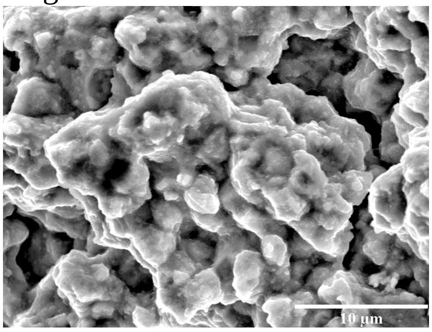
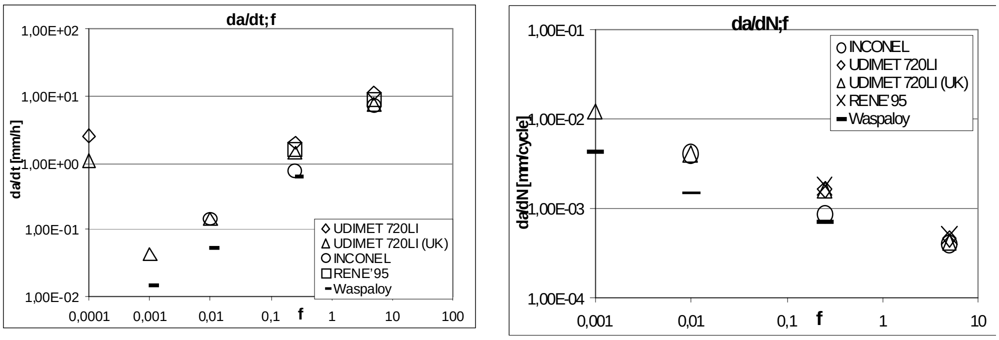


Figure 5 : SEM fractographic image of the fracture surface of Udimet 720Li. 650ºC, creep/K_{max}≅30 MPa.$m^{1/2}$.



a) b)

Figure 6 : a) da/dt (log) against the frequency logf. ΔK=30MPa.$m^{1/2}$.
b) da/dN against the frequency logf. ΔK=30MPa.$m^{1/2}$

3. CONCLUSIONS

- The fatigue failure mode detected and observed at the SEM was essentially mixed, transgranular/intergranular, even at room temperature.
- The creep crack growth was in mixed mode (I+II), with a curved crack propagating in loading conditions typical of the mode I.
- The conversion of the fatigue results to da/dt has shown that the crack speed is higher for higher frequencies, that is to say, the plastic cyclic deformation contributes for a higher crack speed of the material.
- CGR on Udimet 720Li at 650ºC was foud to be slightly higher than Inconel 718, but very close to other similar grades Ni base superalloys

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