LOW CYCLE AND THERMOMECHANICAL FATIGUE BEHAVIOUR OF AN ADVANCED ODS NICKEL BASE SUPERALLOY

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ABSTRACT

The influence of thermomechanical cycling on isothermal low cycle fatigue behaviour of an advanced oxide dispersion strengthened nickel base superalloy for gas turbine vanes application has been studied. The results show that thermomechanical cycle between 550°C and 1050°C is more damaging than isothermal low cycle fatigue at 850°C. Anisotropy introduced by alloy fabrication process determines a fatigue resistance in longitudinal transverse direction lower than that in longitudinal direction. Finally the fatigue mechanisms are analysed by scanning electron microscopy observations of fracture surfaces.

KEYWORDS

Gas turbine, vanes, ODS superalloy, thermomechanical fatigue, low cycle fatigue.

INTRODUCTION

In service conditions gas turbine components are subjected to cyclic stress or strain variations due to start-up and stop-down. Vanes and blades are undergone to the highest concentration of creep and fatigue damage that, in extreem service conditions, can determine an unexpected failure of the component. Besides the creep life prediction, the studies of fatigue design are very important for a correct component design. Untill few years ago the isothermal low cycle fatigue tests have been the most common procedure to characterize the fatigue behaviour of alloys for gas turbine components [1, 2, 3].

Recently the evolution of the materials for vanes and blades has required a more accurate design procedure that takes into account the complex loading and temperature variations in the components. The thermomechanical fatigue testing [4, 5, 6], in which the cycle shape models the in-service conditions as close as possible, has shown to be an useful tool for component life time prediction, in addition to creep and low cycle fatigue characterization.

In this paper the mechanical behaviour of an advanced ODS nickel base superalloy type MA760 is studied. In particular the thermomechanical fatigue (TMF) behaviour in the temperature range 550 - 1050°C is compared with the isothermal low cycle fatigue (LCF) behaviour at 850°C.

MATERIAL AND EXPERIMENTAL CONDITIONS

The material investigated is an oxide dispersion strengthened nickel base superalloy (MA 760) produced by mechanical alloying. The Table 1 shows the alloy chemical composition.

Table 1. Chemical composition of MA 760 alloy in wt %.

C	Si	Fe	Cr	Al	Mo	Ni
0.043	0.04	1.02	19.70	5.97	1.92	bal

S	Zr	N	O	B(ppm)	W	Y_2O_3
0.03	0.14	0.284	0.54	110	3.50	1.03

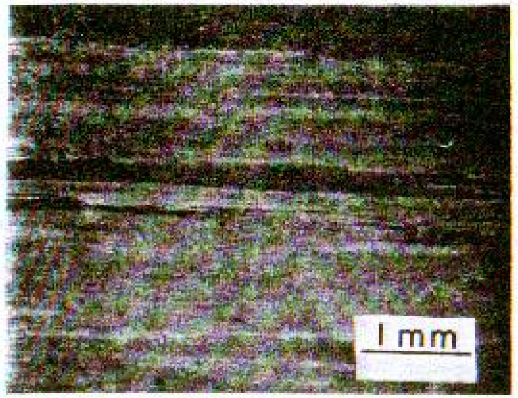

Fig. 1 Aspect of MA 760 alloy elongated grains.

Table 2. Diamond cycle for TMF tests on MA 760.

Time [s]	Temperature [°C]	Strain [%]
0	550	0
10	550	$-\varepsilon_m$
110	1050	0
160	800	$+\varepsilon_m$
210	550	0

Owing to the production route [7], that includes hot extrusion and hot rolling, the mechanically alloyed materials present a strong anisotropy as can be observed in the metallography of MA760 alloy shown in Fig. 1.
The material has been supplied by Inco Alloys Ltd (UK) in bars with a large cross section (LCS) of 32mm x 96mm and with a small cross section (SCS) of 20mm x 60mm. The specimens tested in L direction were cut from SCS bar, while the specimens tested in LT direction from LCS bar. All the specimens were cylidrical with a gauge length of 20mm and a diameter of 7mm.

The samples have been heated by induction coil and the temperature has been controlled by thermocouples spot-welded onto the specimens outside the gauge length to avoid a crack initiation in correspondence of the welding.
LCF tests have been performed at 850°C in longitudinal strain controlled conditions in tension and compression with a triangular wave form (R= -1) and a strain rate of 5.10^{-3}s-1.
TMF tests have been carried out in the temperature range of 550°C and 1050°C with a diamond cycle of 210 seconds as shown in Table 2.
In all LCF and TMF tests the hysteresis loop and the stress response have been recorded at intervals.

EXPERIMENTAL RESULTS AND DISCUSSION

The LCF results are presented in Figs. 2 and 3 in which the elastic and plastic strain components are plotted versus the number of cycles to failure N. In the diagram a reduction of fatigue life of the alloy tested in LT direction is observed. The fatigue parameters determined according to Coffin-Manson [8] and Basquin [9] laws are reported in Table 3.

Table 3. Fatigue parameters for MA 760 alloy.

Material	A	α	B	β
L	0.0125	0.0105	0.201	0.649
LT	0.009	0.0737	0.072	0.547

In the Table A and s are the Basquin coefficients, B and bare the Coffin-Manson coefficients represented by the following equations.

$$\Delta\varepsilon_e = A \cdot N^{-\alpha} \qquad (1)$$

$$\Delta\varepsilon_p = B \cdot N^{-\beta} \qquad (2)$$

The comparison of LCF and TMF results is shown in Fig. 4. The thermomechanical cycle

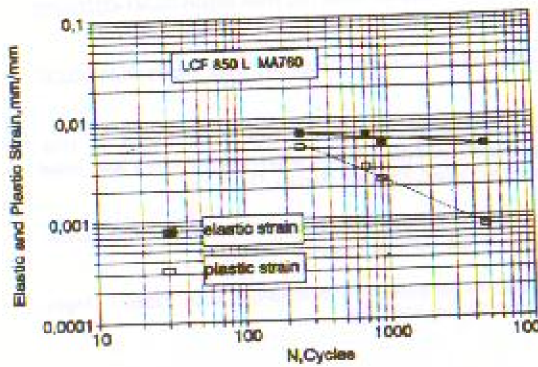

Fig. 2 Elastic and plastic strain components vs N in the alloy tested in L direction.

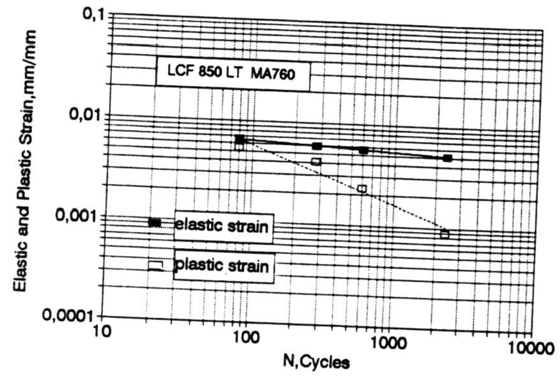

Fig. 3 Elastic and plastic strain components vs N in the alloy tested in LT direction .

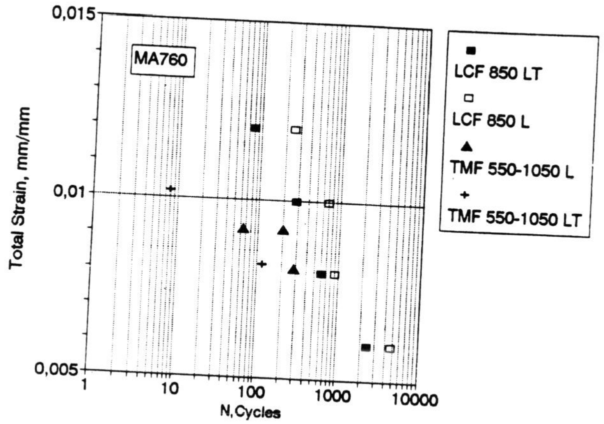

Fig. 4 Comparison of LCF and TMF endurances of MA 760 tested in L and LT directions.

determines a reduction of fatigue life more apparent at higher strains. According to LCF results the material tested by TMF in LT direction shows a lower fatigue endurance that confirms a reduced mechanical resistance of the alloy in LT direction.
Beyond the LCF life prediction procedure a comparison of LCF and TMF results is not easily to be performed. Even if some authors have tried to do this [10, 11, 12], the TMF data do not compare fairly with isothermal data, depending upon testing temperature, cycle shape, material resistance to oxidation and microstructural stability. The application of Coffin-Manson law (that requires the presence of a plastic component evaluated in correspondence of stress zero value) is not often easy, owing to the peculiar form of hysteresis loop obtained in TMF tests. In the case of diamond cycle the hysteresis loop is not simmetrical and the plastic strain component (evaluated in correspondence of stress equal to zero) does not correspond to the maximum value observed in the cycle (Fig. 5). The reduction of TMF life can be ascribed to

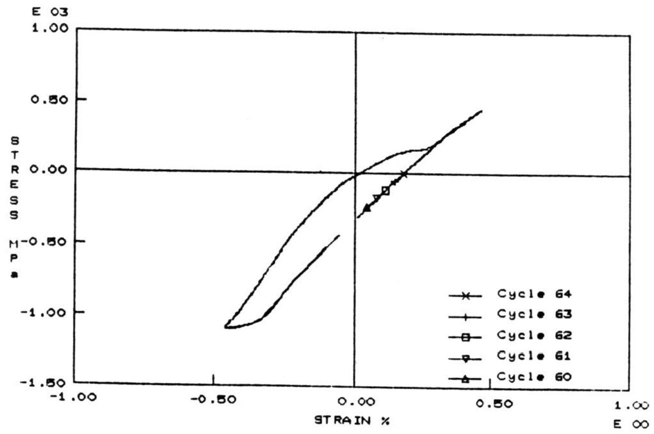

Fig. 5 Example of TMF hysteresis loop: $\Delta\varepsilon_t$=0.92 %, N=64.

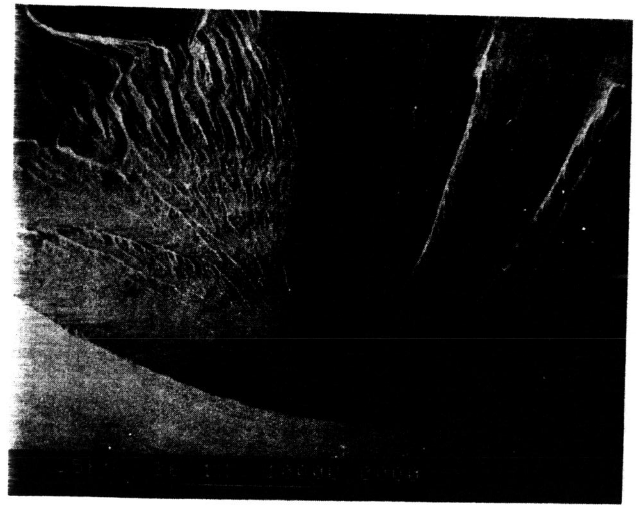

Fig. 6 Crack initiation and propagation in LCF test (L direction): $\Delta\varepsilon_t$=0.6%, N=4700.

the longer cycle time that produces more time dependent effects and to the maximum cycle temperature that enhances oxidation phenomena.
The analysis of fracture surfaces show that the damage mechanisms in LCF and in TMF are similar. After a crack incubation which time is as long as the strain is low, the crack initiates on the external surface and propagates towards the internal in transgranular mode.

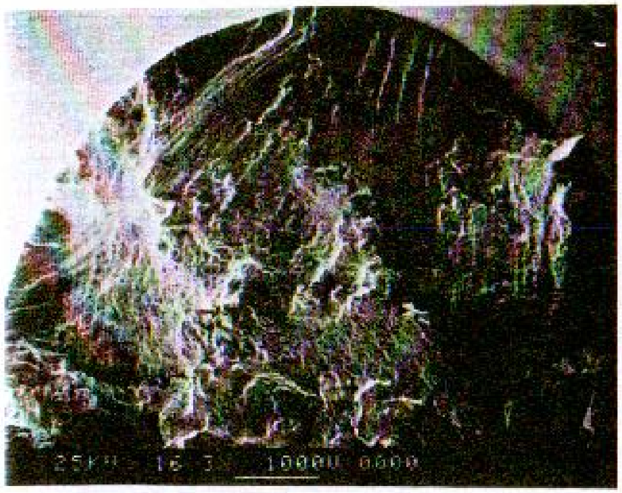

Fig. 7 Crack initiation and propagation in TMF test (L direction): $\Delta\varepsilon_m$=0.81%, N=280.

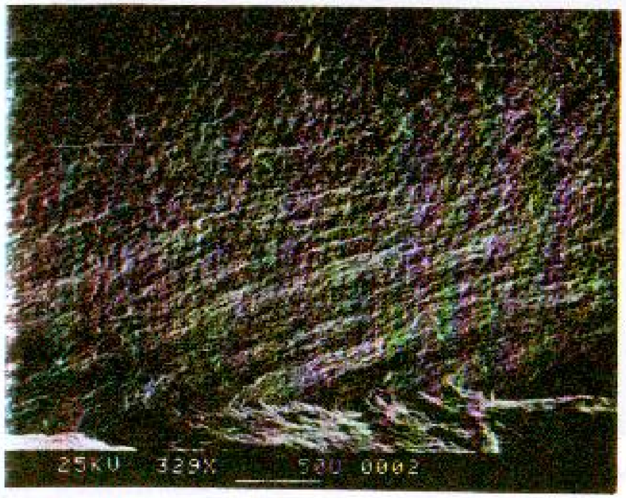

Fig. 8 Example of fatigue striations in the same specimen of Fig. 6.

Figs. 6 and 7 show two examples of crack initiation respectively after LCF and TMF testing. The alloy tested in L direction exhibits the presence of fatigue striations either in LCF (Fig. 8) or in TMF (Fig. 9). In the last case the striations spacing is sensibly larger due to the longer cycle time and the fatigue striations are less visible for the presence of a thick oxidation layer.

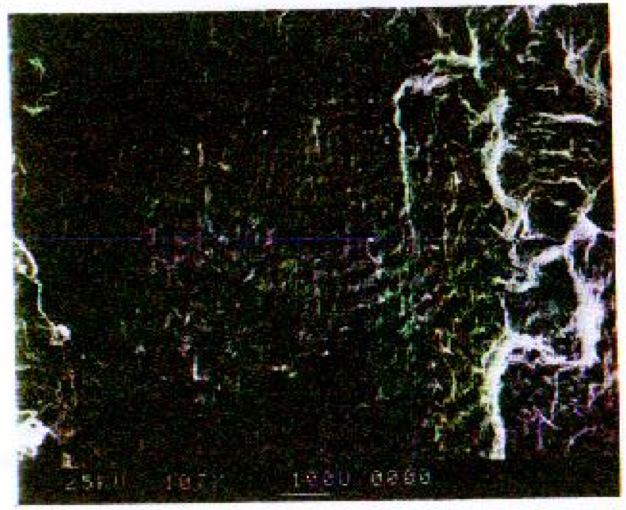

Fig. 9 Example of fatigue striations in the same specimen of Fig. 7.

The alloy tested in LT direction shows a brittle fracture after either LCF or TMF. In the first case, even if crack initiation is similar to that observed in L direction, fatigue striations are not apparent and the fracture propagates in steps through elongated grains (Fig. 10). Large secondary cracks are often observed.
When the alloy is tested by TMF in LT direction the morphology of fracture surfaces is not substantially different from that observed after LCF tests. Crack initiation is external and propagation is transgranular without fatigue striations. Secondary cracks along grain boundaries are often observed.

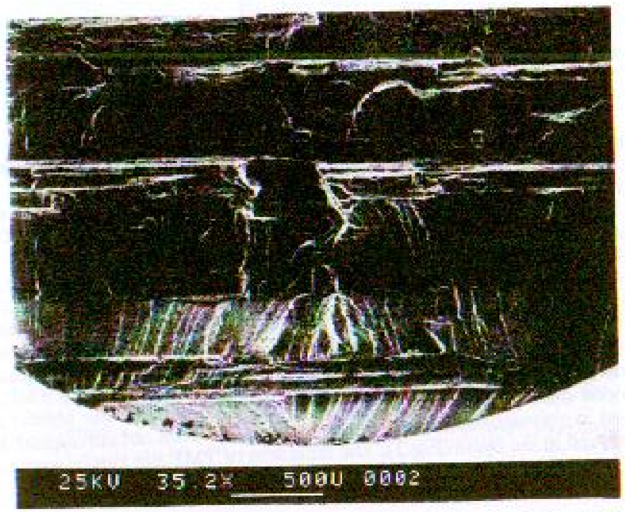

Fig. 10 Crack initiation and propagation in LCF test (LT direction): $\Delta\varepsilon_t$=0.6%, N=2350.

CONCLUSIONS

LCF and TMF tests performed on MA760 alloy in L and LT directions have shown:

- the alloy tested in LT direction presents a shorter fatigue life and a higher brittleness both after LCF and TMF testing;
- TMF life shorter than LCF life can be ascribed to longer TMF cycle (20 times than LCF cycle) and to the highest temperature overtaken during cycling in respect to isothermal LCF cycle that accelerates oxidation phenomena;
- fracture surfaces of LCF and TMF specimens show surface crack initiation and transgranular crack propagation towards the internal;
- in the specimens tested in L direction the LCF and TMF fractures present fatigue striations not observed in the specimens tested in LT direction.

ACKNOWLEDGMENTS

The authors thank gratefully Mr. D. Valenti and Mr. G. Carcano for fractures examination and metallography.
The work has been performed in the framework of the European programme COST 501 2nd Round.

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