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Thermo-mechanical Fatigue of the Nickel–Base Superalloy Nimonic 90

M. Marchionni[1,a], H. Klingelhöffer[2,b,] H. Kühn*[2,c], T. Ranucci[1,d], K.Matzak[2,e]

[1]Consiglio Nazionale delle Ricerche – Istituto per l'Energetica e le interfasi (CNR-IENI), Via Roberto Cozzi 53, 20125 Milano, Italy;
[2] Federal Institute for Materials Research and Testing (BAM), Unter den Eichen 87, 12205 Berlin, Germany
[a] marchionni@ieni.cnr.it, [b] hellmuth.klingelhoeffer@bam.de,
[c] hans-joachim.kuehn@bam.de, [d] ranucci@ieni.cnr.it , [e] kathrin.matzak@bam.de

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Abstract. The thermo-mechanical fatigue (TMF) behaviour of the Nimonic 90 Nickel base superalloy has been investigated within two laboratories. In-phase-tests (IP) where the maximum mechanical strain occurs at the maximum temperature (850°C), and 180°-out-of-phase-tests (180° OP) where the maximum mechanical strain coincides with the minimum temperature (400°C) have been applied. All tests were carried out at varying mechanical strain ranges with a constant strain ratio of R_ε = - 1. A temperature rate of 5 K/s was used throughout the whole cycle without any additional cooling system during decreasing temperature. The fatigue life of 180° OP tests is longer compared to identical IP tests. The stress / mechanical strain hysteresis loops are completely different and some characteristic values are compared to each other. The fracture surfaces observed show that fatigue crack (or cracks) starts on the external surface and propagates inwards. The fractures of 180° OP tests are transgranular showing the presence of fatigue striations, while the fractures of IP tests are mixed transgranular and intergranular with no fatigue striations.

Introduction

Since the seventies, materials subjected to cyclic stresses and temperatures have been studied by isothermal low cycle fatigue testing (LCF) and the results have been produced by considering a reference temperature that corresponds to the maximum value of the thermal cycling. After the introduction of thermo-mechanical fatigue (TMF) as a diagnostic device for the material study [1], the comparison of LCF and TMF testing has determined opposite conclusions. Partly LCF and TMF results were found to be comparable [2, 3]. Partly it was found that the stress history of a thermo-mechanical cycle leads to results completely different from those produced by isothermal testing [4, 5,]. The TMF procedure is particularly recommended for those new materials whose high temperature properties are not known. There is clear evidence that the TMF test procedure does represent material loading of hot components in e.g. power stations and aero engines much better than LCF testing.

In order to customise the TMF testing procedure a European project has recently concluded [6] and a Code of Practice (CoP) has produced [7]. The TMF tests were performed on the Nickel base superalloy Nimonic 90 at defined experimental conditions and the results contributed to the definition of the test procedure. The scope of the present work is to extend the comparison of TMF results performed on Ni90 alloy according to the CoP procedure and to verify the material life in different experimental conditions.

Experimental Testing Technique

At both laboratories TMF tests were performed on a 100 / 250 KN servo-hydraulic testing machine, a 6 / 17.5 kVA induction furnace and a controller for load, strain and temperature variations according to a programme previously defined. Specimens with cylindrical gauge length and 6 mm diameter were used. Test temperature is controlled by K type thermocouple spot-welded outside the gauge length in order to avoid the crack initiation at the welding. The temperature profile in the gauge length is optimized and calibrated before a series of experiments. A thermal strain calibration is performed in the temperature range selected before each TMF test. It is obtained by performing a thermal cycle, repeated at least five times, having the same shape of the TMF cycle in order to determine the mean values of the cycles. In practice the total strain is the sum of the mechanical and the thermal strain previously determined. In such way the specimen thermal strain is compensated during all the thermo-mechanical cycle.

Material and Testing Conditions

The wrought Ni-base superalloy Nimonic 90 with a nominal composition of (wt. %) Ni 59, Cr 19.5, Co 16.5, Al 1.5, Ti 2.5, Mn 0.3, Si 0.3, C 0.07, B 0.003 and Zr 0.006 was used for TMF tests. The alloy has an equiaxed grain structure with an average grain size of 72 µm. Bars of 20 mm diameter were solution heat treated for 8 hrs at 1080°C, water quenched and then aged for a 5 hrs at 850°C to obtain blanks for manufacturing test pieces. The temperature range was from 400 to 850°C with triangular wave-form and a temperature rate of 5 K/s. The mechanical strain cycle was also triangular in phase and 180° out of phase with temperature cycle.

TMF Results and Discussion

The TMF results are described in table 1. Fig. 1 shows the cyclic hardening and softening curves of the TMF tests. At OP tests a little hardening is observed in tension and softening is obtained in compression. This can be explained by the influence of temperature where low temperature encourages hardening and high temperature softening. For IP tests the opposite situation can be seen (Fig. 1). This behaviour is similar to that at isothermal LCF tests (Fig. 2) where the same hardening and softening behaviour is found. The curves of both laboratories fit very well.

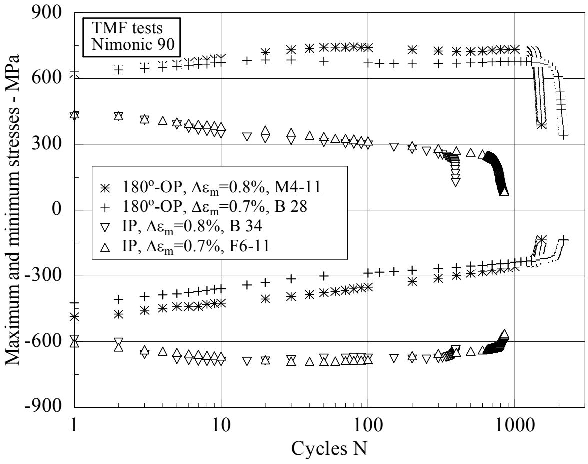

Figure 1: Cyclic hardening and softening curves of the material Nimonic 90 for TMF tests, 400-850°C

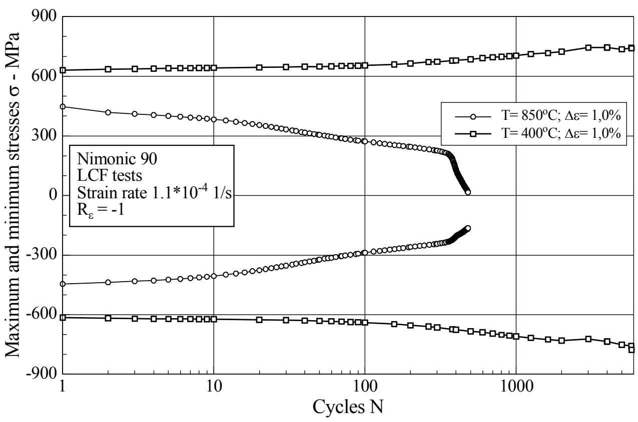

Figure 2: Cyclic hardening and softening curves of Nimonic 90 alloy for LCF tests at 400 and 850°C

The high stress levels in tension for OP tests are due to the minimum temperature within the TMF cycle while they are low in compression at the maximum temperature. This behaviour is well known as the temperature dependent strength. For IP tests the opposite stress values are found. The shape of hysteresis loops for IP and OP tests are quite different. The OP hysteresis loop has significant higher tensile stresses of an approx. factor of 2-3 compared to the compression stresses. Generally the tensile stresses support crack growth. The IP hysteresis loop shows low tensile and high compression stresses.

Tested by	Test no	TMF, LCF Cycle	Temp, [°C]	$\Delta\varepsilon_m$ [%]	$\Delta\varepsilon_{in}$ at N/2 [%]	σ_{max} at N/2 [MPa]	σ_{min} at N/2 [MPa]	N_{10}
BAM	L3-5	IP	400-850	0.6	-	258	- 631	1350
BAM	F6-11	IP	400-850	0.7	0.219	271	- 650	755
BAM	J4-11	IP	400-850	0.7	0.256	238	- 621	813
BAM	L5-11	IP	400-850	0.7	0.229	273	- 609	944
BAM	F6-21	IP	400-850	0.7	0.113	272	- 677	690
CNR	L5-21	IP	400-850	0.7	0.144	255	- 644	805
CNR	J4-21	IP	400-850	0.7	0.138	263	- 645	805
CNR	B34	IP	400-850	0.8	0.23	275	- 668	396
BAM	L3-3	IP	400-850	1.0	-	344	- 777	184
CNR	B27	IP	400-850	1.2	0.509	432	- 795	64
CNR	B28	OP-180°	400-850	0.7	0.19	669	- 235	1970
CNR	K3-21	OP-180°	400-850	0.8	0.236	753	- 285	1530
CNR	G4-21	OP-180°	400-850	0.8	0.238	756	- 293	1355
CNR	M4-21	OP-180°	400-850	0.8	0.285	687	- 270	1505
BAM	H4-11	OP-180°	400-850	0.8	0.323	644	- 284	1380
BAM	M4-11	OP-180°	400-850	0.8	0.288	729	- 275	1422
BAM	K3-11	OP-180°	400-850	0.8	0.308	678	- 279	1361
CNR	B31	OP-180°	400-850	0.9	0.3	769	- 289	1065
BAM	X2-22	OP-180°	400-850	1.0	-	732	- 274	546
CNR	B15	OP-180°	400-850	1.2	0.525	854	- 411	320
BAM	X2-18	OP-180°	400-850	1.4	-	870	- 418	221
BAM	A	Isothermal	850	1.0	0.671	245	- 261	378
BAM	B	Isothermal	400	1.0	0.178	744	- 722	5793
BAM	C	Isothermal	850	1.2	0.856	244	- 260	197
BAM	D	Isothermal	400	1.2	0.342	769	- 801	2449

Table 1: TMF results of Nimonic 90 alloy

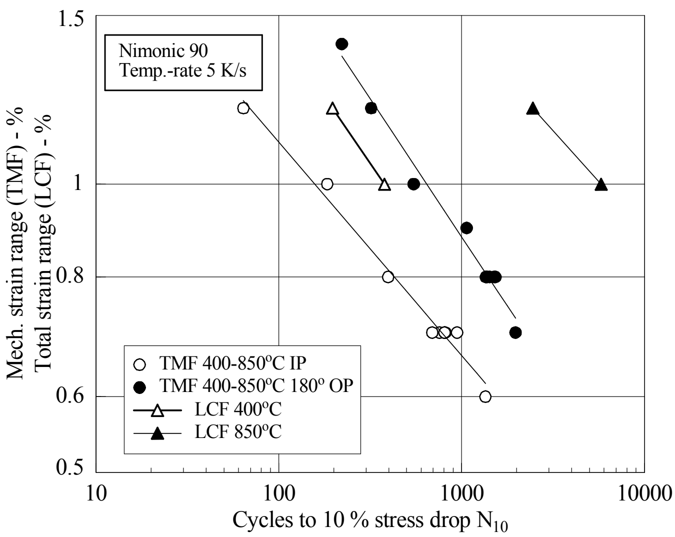

Figure 3: TMF and LCF life of Nimonic 90 alloy

In Fig. 3 the TMF life curves show that the IP condition reduces significantly the fatigue life. The reduction of TMF life for IP cycle could be ascribed to the tensile strain at the maximum temperature that is more damaging than in the 180° OP where at maximum temperature there is a compressive stress. The reason for that shall be shown in fractography investigations. The TMF tests have been conducted in both laboratories and they present a very low scatter. The slope of the curve for OP tests is found higher than the IP test curve. Four isothermal LCF tests have been performed at the lowest and the highest temperature used within the TMF tests for comparison. The isothermal LCF tests at 850°C show a fatigue life between IP and 180° OP curves. Whereas the isothermal 400°C tests lead to much longer fatigue life than the 180° OP tests.

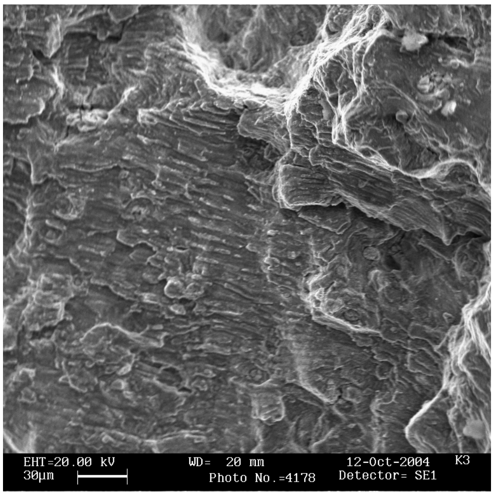

Figure 4: 180°OP test; transgranular crack growth, fatigue striations

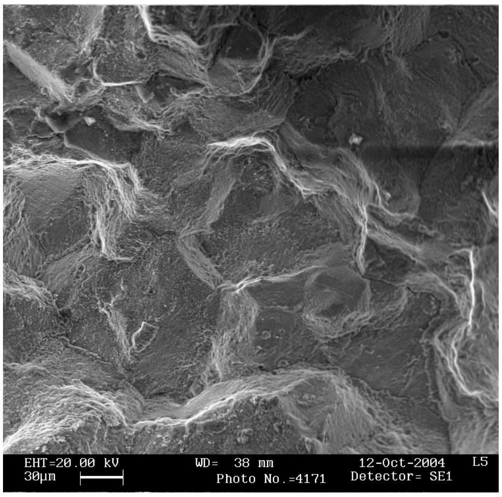

Figure 5: IP test; intergranular crack growth

Some of the fractured specimens have been investigated in order to evaluate the fatigue damage. In general cracks are initiated on the specimen surface and propagate towards the internal in the transgranular mode. OP tests with $\Delta\varepsilon_m = 0.8$ % show multiple crack initiations. In the transgranular crack propagation area few crack striations can be observed (Fig. 4). Figure 5 shows the intergranular crack propagation zone of an IP test with 0.7 % mechanical strain. The grain structure can be clearly seen. The high temperature in the tension phase of the IP test is damaging the grain boundaries more then when it is applied in the compression phase like at OP tests.

Conclusions

Thermo-mechanical fatigue tests have been conducted in two different laboratories on the Nimonic 90 Nickel-base superalloy. In phase and 180° out of phase tests have been applied in the temperature range of 400-850°C with a temperature rate of 5 K/s. It was found that the TMF test results of both laboratories can be compared very well. The use of the European Code of Practice is a good tool to improve the comparability of test results obtained in different laboratories. The IP life time was the most detrimental which was due to the change of the fracture mode from transgranular to intergranular which was obtained in fractography investigations. A comparison of TMF and LCF tests complete the reflections. The most detrimental TMF IP test has reached a similar fatigue life compared to an isothermal LCF test at the highest temperature used in the TMF test.

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