EFFECT OF ENVIRONMENT ON LOW-CYCLE FATIGUE BEHAVIOUR OF CAST NICKEL-BASE SUPERALLOY IN738LC

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ABSTRACT

Low-cycle fatigue tests has been conducted on cast Nickel-base superalloy at 900°C and at the strain rates imposed in vacuum, air and hot corrosion environments. The fatigue life determined in terms of cyclic plastic strain markedly decreases as the environments become severe, i.e. from vacuum through air to NaCl and Na_2SO_4 deposited layer. The strong strain rate effect found in air and hot corrosion environments disappeared when the experiments were conducted in a vacuum of $1{,}3 \cdot 10^{-2}$Pa.

The crack nucleation occurred in selective and favorably oriented grain in vacuum, while for air and hot corrosion environments, the cracks initiated always at hot corroded grain boundaries near the surface or generally at oxide spikes in surface-connected grain boundaries. The crack propagation from these nucleation sites is essentially transgranular for all environments studied.

KEYWORDS

Low-cycle fatigue, nickel-base superalloy, strain rate , stress, fatigue life, total, elastic, plastic strain components, high temperature, environment, crack propagation.

INTRODUCTION

The effects of environments on high-temperature low-cycle fatigue of superalloys are very severe (1-4). In order to clarify the importance of environments vs creep or microstructure instabilities in high temperature fatigue of superalloys as well as the extent to which each factor influences the fatigue life, we studied the low-cycle fatigue of IN738LC at 900°C in vacuum, and compared these results with those from tests in air and NaCl + Na_2SO_4 deposited layer (5). If the influence of the environment is eliminated, any residual strain-rate effect must be due to creep processes or micro structure instabilities.

EXPERIMENTAL PROCEDURES

The experiments were carried out on the cast Nickel-base alloy IN738LC, Table 1 gives their chemical composition

TABLE 1 Chemical Composition of the Alloy

Co	Cr	Al	Ta	W	Mo	Ti	Nb	Zr	B	C	Ni
8.30	15.9	3.40	1.72	2.50	1.60	3.30	0.96	0.07	0.012	0.12	balance

The heat treatment schedules consisted of 2 hours at 1120°C in vacuum or hydrogen followed by cooling to room temperature, then 24 hours at 845°C in argon or vacuum followed by cooling to room temperature.

Some specimens were coated with the mixture of 25% NaCl + 75% Na_2SO_4 by pre-heating to 150°C and then rotating the specimen in a salt-water spray until an even coating of thickness 25 µm was obtained.

L.C.F. tests were carried out by a 25T closed-loop servo-hydraulic system,a vacuum chamber containing the specimen assembly was installed, a vacuum of the order of $1,3 \times 10^{-2}$ Pa could be achieved. The hourglass specimen (Fig.1) was induction heated by an R.F. generator, temperatures were measured and controlled by thermocouples spot welded to each specimen near its minimum diameter. A diametral extensometer was placed on the specimen and all tests were carried out in diametral strain control at 900°C and at strain rate 10^{-2} and $10^{-3}s^{-1}$ with triangular wave form (R = -1).

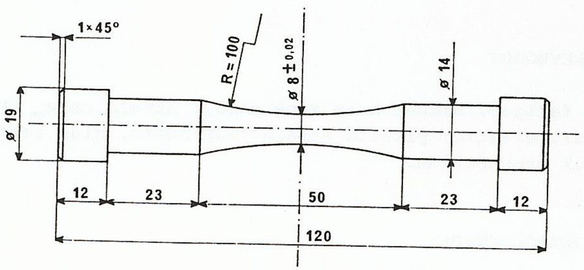

Fig. 1. Low-cycle fatigue test specimen.

When the tests were performed under diametral strain controlled conditions, it was necessary to convert the signals of diametral strain into the corresponding axial variations in order to control the hydraulic actuator of the materials testing system. This conversion was achieved by means of a computer module in which signals supplied by the diametral extensometer (diametral strain) and signals of the load cell (load) were transformed into axial deformation signals. This function is expressed analytically by the following relationship:

$$\varepsilon = -\frac{\varepsilon_d}{\nu_p} + \left(1 - \frac{\nu_e}{\nu_p}\right) \cdot \frac{F}{AE} \qquad (1)$$

The previously obtained values E and A were preset in the module, as well as the ν_e value measured at the testing temperature, by stressing the specimen in the elastic range. It was assumed ν_p=0.5.

RESULTS AND DISCUSSION

Cyclic Stress Strain Behaviour

An important feature of the LCF process is the variation of stress response with cycle number and plastic strain. Stress range versus endurance plots of some specimens tested in vacuum are shown in Fig. 2. There is an initial period of

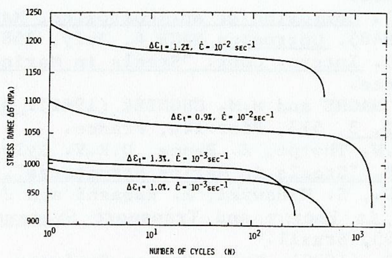

Fig. 2. Cyclic softening behaviour of IN738LC in vacuum at different strain rates.

rapid softening followed by saturation. Finally towards the end of the test, the stress drops off very rapidly for all test specimens. similar to those tested in air and hot corrosion saline environments (5). Cyclic stress-strain curves are given in Fig. 3. The plateau stress range as a function of plastic strain range obeyed an equation of the form:

$$\Delta\sigma = A\Delta\varepsilon_p^n \qquad (2)$$

where the symbols have their usual meaning. It is clear from Fig. 3 that the stress range is reduced as the strain rate decreases over a given plastic strain range.

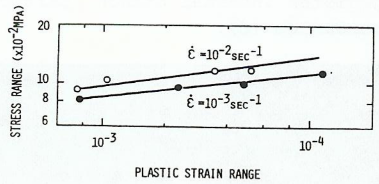

Fig. 3. Cyclic stress/strain behaviour of IN738LC in vacuum at 900°C.

L.C.F. Behaviour

Longitudinal plastic strain range $\Delta\varepsilon_p$ and longitudinal elastic strain range $\Delta\varepsilon_e$ vs. life as shown in Fig. 4. It is evident that, for the test in vacuum, the data determined from an analysis of the hysteresis loop at approximately half life are found to have a linear relationship between the two kinds of strain ranges and cycles to initiation, independent of strain rate. The Coffin-Manson equations representing these data are given by:

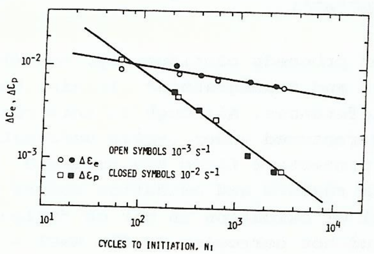

Fig. 4. LCF Behaviour of IN738LC in vacuum at 900°C and at two different strain rates.

$$\Delta\varepsilon_e = 0.015\ N_i^{-0.098} \quad (3)$$

$$\Delta\varepsilon_p = 0.29\ N_i^{-0.75} \quad (4)$$

In contrast with tests in vacuum, for tests in air and saline environments the Coffin-Manson equations are strongly influenced by strain rate; only at a given strain rate is there a linear relationship between the two kinds of strain ranges and cycles to initiation (Fig. 5).

On the other hand, air and NaCl + Na_2SO_4 deposited layer markedly decrease fatigue life determined in terms of cyclic plastic strain, compared with

similar tests in vacuum, and this influence of saline environment on fatigue life is most severe.

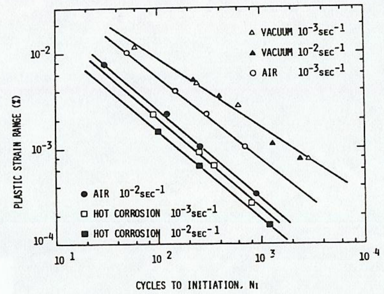

Fig. 5. The effect of environments on LCF behaviour of IN738LC at 900°C.

Scanning observations showed that some tests in vacuum, crack propagation appeared to be transgranular (Fig. 6). There were no pronounced and visible oxide or corrosion products in the fracture surface as seen in Fig. 6 and 7.

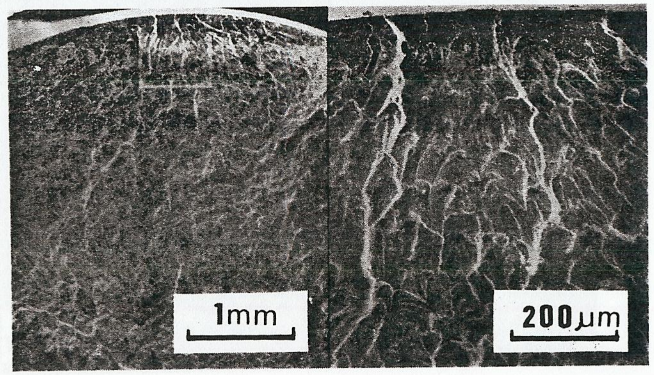

Fig. 6. Scanning electron micrograph of a fracture showing fatigue crack nucleation and propagation in vacuum (N_i=2900 cycles, $\Delta\varepsilon_p$=0.078, $\dot{\varepsilon}=10^{-3}s^{-1}$).

For tests in air, crack nucleation essentially occurred along oxidized boundaries. On the other hand, for tests in hot corrosion environment, nucleation of fatigue cracks always occurred by surface ridging (Fig. 8). In contrast with tests in vacuum there are some oxide and corrosion products (Fig. 8 and 9) in the fracture surfaces of specimens tested in air and hot corrosion saline environments. After a relatively short period of intergranular crack propagation the cracks of specimens tested in air and hot corrosion environments frequently became transgranular (Fig. 8-9).

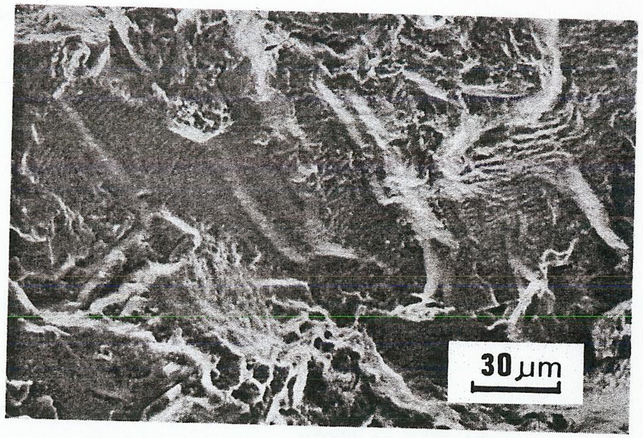

Fig. 7. Scanning electron micrograph of a fracture showing transgranular propagation of fatigue crack in vacuum (N_i = 2400 cycles, $\Delta\varepsilon_p$=0.075%, $\dot{\varepsilon}=10^{-2}s^{-1}$).

Fig. 8. Scanning electron micrograph of a fracture showing nucleation of fatigue crack by surface ridging (N_i=1200 cycles, $\Delta\varepsilon_p$=0.016%, $\dot{\varepsilon}=10^{-2}s^{-1}$).

From the above mentioned results, it can be seen that because of the action of oxidation and corrosion, fatigue crack nucleation in vacuum occurred less easily than in air, while nucleation in air was less likely to occur than in presence of salt deposited layer.

The fatigue process is largely one of crack propagation. Under cyclic plastic deformation, protective films are unlikely to reform at an exposed crack tip because of the mechanical action of stress and of the chemical action of

NaCl on the scales in hot corrosion environment. The former ruptures the scales mechanically, and the latter continually disrupts any protective oxide scales that form, allowing Na_2So_4 to contact the underlying metal surface, while Na_2So_4 promotes internal attack, particularly in regions adjacent to the grain boundaries (6).

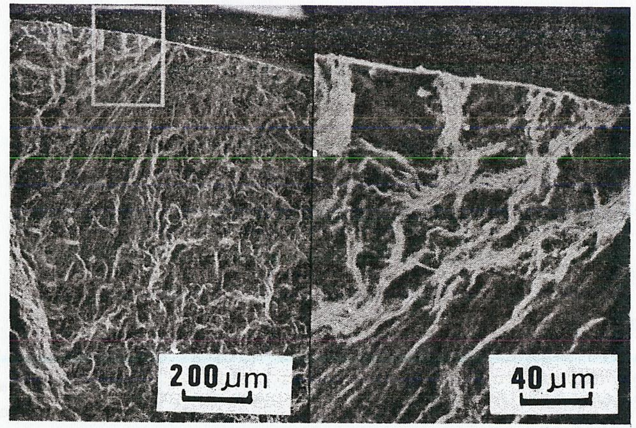

Fig. 9. Scanning electron micrograph showing oxide in fracture surface (N_i=700 cycles, $\Delta\varepsilon_p$=0.104%, $\dot{\varepsilon}=10^{-3}s^{-1}$).

Therefore hot corrosion proceeds continuously, and propagation of fatigue cracks is uninterrupted and transgranular. In air, however, crack propagation shows distinct differences. Although in this case brittle protective oxide films (Cr_2O_3) are ruptured under cyclic deformation, oxidation proceeds slowly and then protective films are reformed. With fatigue, this process of straining, film rupture and oxidation occurs repeatedly. It is quite evident that the effect of oxidation in air on fatigue crack propagation is less severe than that of hot corrosion in 25% NaCl + 75% Na_2SO_4 mixture deposits. Thus hot corrosion saline environment resulted in a marked decrease in fatigue lifetimes represented on the basis of plastic strain (Fig. 5), compared with similar tests in air.

Since vacuum eliminates environmental effects, there is no embrittled zone at a crack tip; each increment of crack advance will be substantially smaller for the unaffected plastic zone of the vacuum experiments, than for the embrittled oxidized or hot-corroded crack tip developed in the presence of air or 25% NaCl + 75% Na_2SO_4 deposited layer. This accounts for the substantial difference in fatigue life determined in terms of cyclic plastic deformation between tests in vacuum and air or saline environments.

From Fig. 5 it can be seen that vacuum can eliminate the effect of strain rate, while in air and in presence of salt there is a marked strain rate effect, i.e. when strain rate is decreased, the fatigue life is increased.

CONCLUSIONS

1. The high-temperature LCF properties ($\Delta\varepsilon_e$ and $\Delta\varepsilon_p$) of IN738LC can be represented by the Coffin-Manson equation at a given strin rate, regardless of vacuum, air or deposited layer of $NaCl/Na_2So_4$.

2. A comparison of the experimental results of experiments conducted in air, hot corrosion saline environment and vacuum on IN738LC at 900°C at two different strain rates shows not only a substantial increase in fatigue life, but also the disappearance of the effect of strain rate in a vacuum of $1.3x10^{-2}$Pa.

3. Hot corrosion saline environment resulted in a marked decrease in LCF properties, compared with similar tests in air, and this decrease was greater at lower values of strain rate.

4. For tests in vacuum, crack nucleation always occurred in favorably oriented grain, and for similar tests in air, crack nucleation, essentially occurred along oxidized grain boundaries, while for tests in hot corrosion saline environment, cracks always initiated by surface ridging at selective grain boundaries. All three undergo transgranular propagation.

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