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LOW CYCLE FATIGUE AND ANALYSIS OF THE CYCLIC STRESS-STRAIN RESPONSE IN SUPERALLOY INCONEL 738LC

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Abstract: *The paper describes the results of fatigue behavior study on cast polycrystalline nickel based superalloy tested at 23 and 800 °C. Cylindrical specimens of Inconel 738LC were cyclically strained under total strain control to fracture and multiple step tests were performed to study the effect of temperature on the internal and effective cyclic stress components. Fatigue life curves were approximated by the Manson-Coffin and Basquin laws. The resulting curves were shifted to lower fatigue lives with increasing temperature. The evolution of the effective and internal stress components and effective elastic modules were derived from the hysteresis loops which were analyzed according to the statistical theory of hysteresis loop. Cyclic stress-strain response at both temperatures and the changes of internal and effective stress components were discussed in relation to microstructural parameters of the superalloy.*

Keywords: ***Low cycle fatigue, Inconel 738LC, hardening/softening curves, cyclic stress-strain curve, fatigue life curve.***

1. Introduction

Nickel based superalloy Inconel 738 LC is cast polycrystalline material precipitation strengthened to achieve excellent high temperature strength and hot corrosion resistance. Designers widely use this material for production of structural parts such as blades and disks for gas turbine engines subjected to repeated elastic-plastic straining in a wide range of temperatures (Donachie, 2002).

In a design of components for high temperature applications the thorough knowledge of fatigue behaviour of IN 738 LC is crucial. The hardening and softening behaviour as well as the cyclic stress-strain curves were studied at temperatures 23 and 900°C (Jianting, 1983, Jianting et al. 1983, Wahi et al. 1997). Nevertheless a more detailed study of the sources of cyclic stress which can be obtained from the analysis of the shape of the hysteresis loops in this type of material has not been performed. Analysis of the loop shape allows determining and splitting total cyclic stress in two components: effective and internal stress (Polák 1991). According to statistical theory of hysteresis loop used already for the study of cyclic plasticity in stainless steels the second derivative of the hysteresis half-loop contains information about the effective stress and the probability density distribution of the critical internal stresses (2x Polák et al. 2001).

The aim of the present work is to describe results obtained in the study of low cycle fatigue behaviour of this material. Effect of temperature on the internal and effective cyclic stress components in repeated loading performed in total strain control was studied at room temperature and at 800 °C.

2. Experimental

Material IN 738 LC in the form of conventionally cast rods having chemical composition 16.22 Cr, 8.78 Co, 2.63 W, 1.71 Mo, 1.77 Ta, 3.37 Ti, 3.35 Al, 0.84 Nb, 0.2 Fe, 0.1 C, 0.04 Zr, 0.008 B, the rest Ni (all in wt. %) was provided by PSB Turbo, Velká Bíteš a.s. Microstructure of the material is dendritic and consists of large γ grains having average size about 3 mm and containing 59% volume fraction of γ′ precipitates with near-cuboidal shape having average diameter of 670 nm (see *Fig. 1*).

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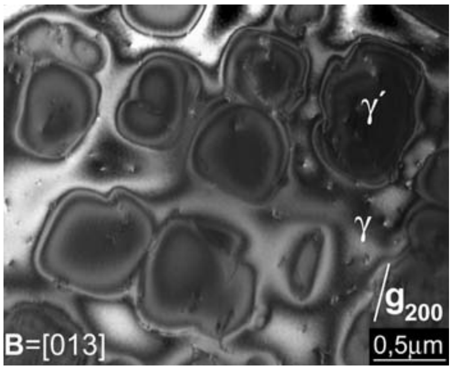


Fig. 1: TEM image of microstructure with 59% volume fraction of the γ′ precipitates.

Cylindrical button-end specimens with diameter 15mm and gauge length 6mm were fatigued in electrohydraulic testing machine MTS 880 in regime of strain control. The total strain amplitude was kept constant, strain rate was $2\text{x}10^{-3}\text{s}^{-1}$ and loading was fully reversed, i.e. symmetrical push-pull cycle was applied. The strain was measured and controlled using a sensitive extensometer with a 12 mm base. The loading was performed in air at two temperatures: 23°C and 800°C.

The stress-strain history at each temperature was recorded with the sampling rate 1 ms, i.e. each hysteresis loop contained more than 2000 data points. Relative strain and relative stress from the tensile and compression parts of hysteresis loops were calculated using maximum and minimum strains in a cycle and the first and the second derivatives of the hysteresis half-loops were determined (Polák 1991). The numerical smoothing procedures were used and the number of neighbour points involved in evaluation of derivatives was optimized.

3. Results and discussion

Cyclic hardening/softening curves i.e. the dependences of the stress amplitude σ_a on the number of cycles N are plotted in *Fig. 2*. At room temperature and for low levels of strain amplitude (see *Fig. 2a*) the saturation until failure is observed. For middle amplitudes the initial hardening is followed by the slow softening which changes into the secondary hardening. For high amplitudes the continuous hardening becomes more pronounced. At elevated temperature (800°C) the material exhibits different behaviour. In cycling with high strain amplitudes superalloy initially cyclically hardens and later slowly softens up to the end of the fatigue life. For low levels of applied strain amplitude the saturated behaviour can be seen (*Fig. 2b*).

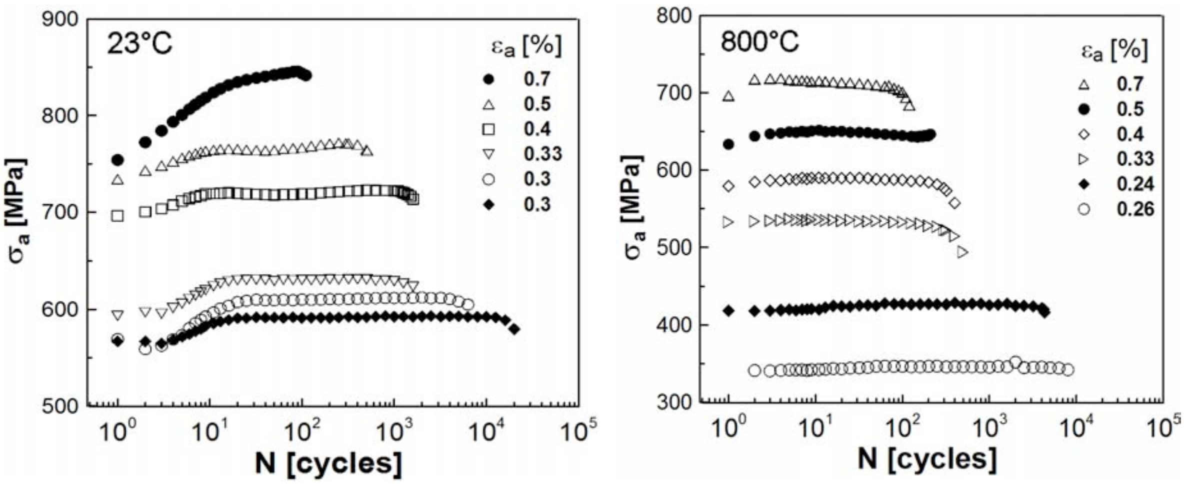


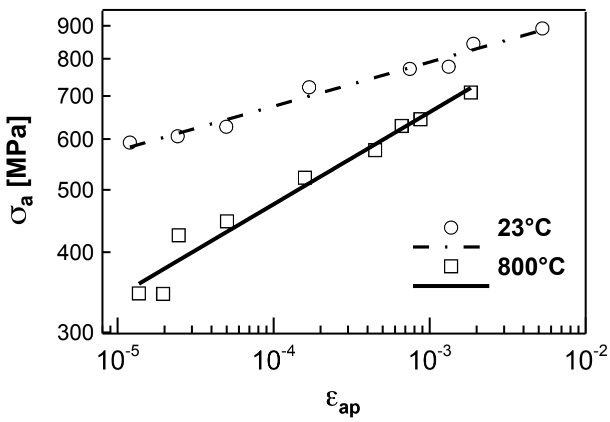
Fig. 2. Cyclic hardening/softening curves at room and at elevated temperatures.

In the *Fig. 3a* the cyclic stress-strain curves (CSSCs), i.e. dependences of the stress amplitude on plastic strain amplitude at half-life for both temperatures are plotted together with the lines representing the approximation of the data by the power law:

$$\log \sigma_a = \log K' + n' \log \varepsilon_{ap}. \quad (1)$$

Fatigue life curves in the representation of the stress amplitude σ_a at half life vs. the number of cycles to fracture N_f are shown in *Fig. 3b*. Experimental data can be fitted by the Basquin law:

$$\log 2N_f = (1/b)(\log \sigma_a - \log \sigma_f'). \quad (2)$$



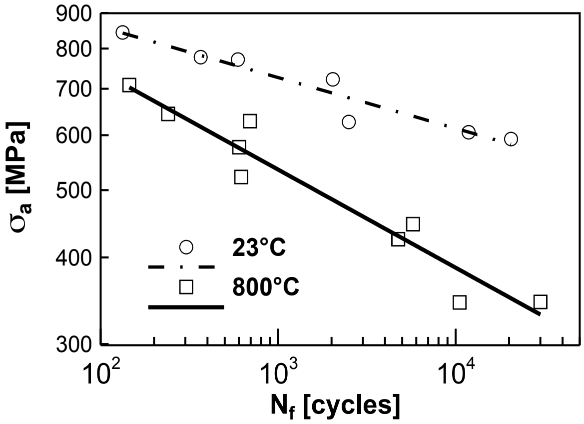


Fig. 3. (a) Cyclic stress-strain curves, (b) Fatigue endurance curves.

Parameters of CSSC and Basquin curves, i.e. fatigue hardening coefficient, K′, fatigue hardening exponent n′, fatigue strength coefficient σ_f' and fatigue strength exponent b were evaluated using regression analysis and are shown in Table 1.

Table 1. Parameters of CSSC and Basquin curves of IN 738 LC.

Temperature	K′	n′	σ_f'	b
23°C	1 270 MPa	0.068	1 330MPa	- 0.079
800°C	1 780 MPa	0.140	1 700 MPa	- 0.152

Two saturated hysteresis loops recorded at both temperatures of cycling with approximately the same amplitude of plastic strain ~1.4x10^{-3} are shown in *Fig. 4*. The shape of respective half-loops was then analyzed and the first and the second derivatives of tensile parts of hysteresis loops (divided by effective modulus E_{eff} or by the half of the square of effective modulus) were plotted vs. relative strain ε_r (lower axis) and/or vs. fictive/effective stress $\varepsilon_r E_{eff}/2$ (upper axis) in *Fig. 5*.

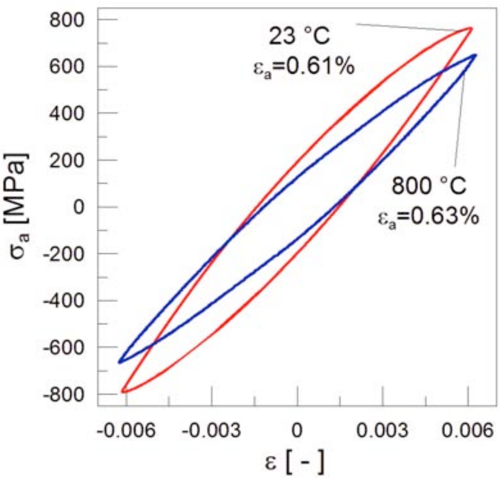


Fig. 4: The saturated hysteresis loops at 23 °C cycled with ε_a = 0.61%, and at 800 °C with ε_a = 0.63%.

Fig. 5 shows the first and the second derivatives for two temperatures (23°C and 800°C) and their evolution with the number of cycles. The initial drop of the second derivative corresponds to the relaxation of the plastic strain under decreasing effective stress. At relative strain where the second derivative reaches its first minimum the effective modulus E_{eff} and the effective stress can be evaluated.

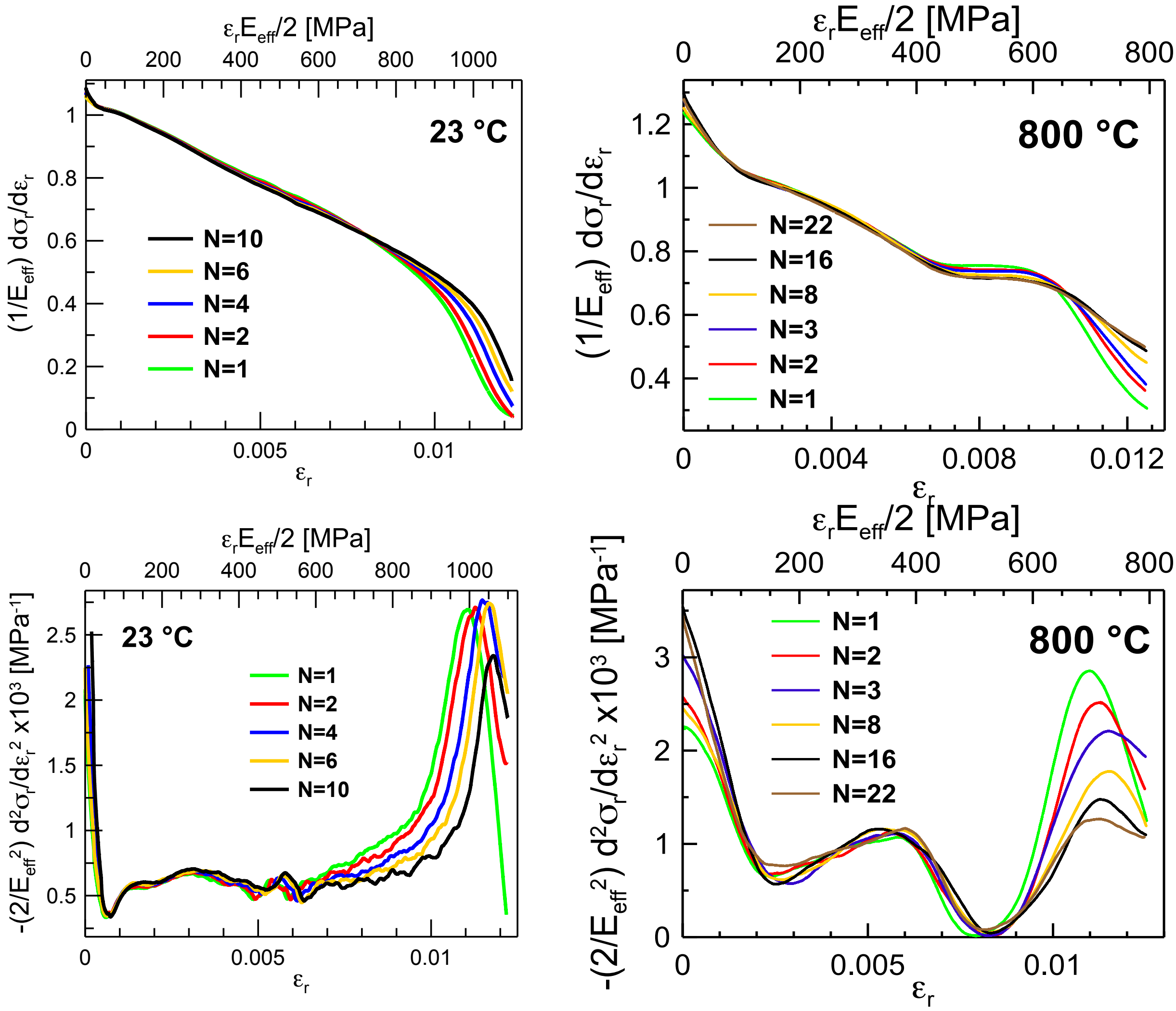


Fig. 5. The first and the second derivatives of the tensile half-loops (from Fig. 4) in relative coordinates cycled at 23°C (E_{eff} =180 GPa) and 800°C (E_{eff} = 127 GPa).

Two peaks of the second derivative are characteristic for a two-phase alloy. They correspond to the subsequent plastic deformation of γ and γ′ phases within a cycle and approximate the probability density function of the critical internal stresses of both components.

The analysis of the hysteresis loop shape obtained in room temperature cyclic straining reveals only poorly defined first maximum. This first peak is more pronounced for elevated temperature. The second peak is well developed for both temperatures and its position at room temperature changes with increasing number of applied cycles, i.e. it is moving to higher fictive stresses, which corresponds to the cyclic hardening. It is in agreement with cyclic hardening/softening curves (see *Fig. 2*)

The effective stresses of γ and γ′ phases at different temperatures can be estimated only approximately and the resulting values are displayed in *Table 2*.

Tab. 2. Effective stresses for both phases (γ and γ′) of In 738 LC tested at two temperatures.

Temperature	23°C	800°C
σ_{eff} (γ)	≈ 100 MPa	170 MPa
σ_{eff} (γ′)	≈ 550 MPa	540 MPa

The effective stress in γ and γ′ phases was found precisely enough only in cycling at 800°C. The effective stress in γ′ phase is high which is in agreement with the difficult movement of dislocations in an ordered structure.

The effective stress of the γ phase is low but increased when the cycling temperature increased to 800 °C. This can be the result of continuous annihilation of dislocations in soft γ phase at elevated temperature and resulting in a drop of dislocation density. In order to achieve the same strain rate the dislocation velocity is high and thus the effective stress increases.

The effective stress of the γ′ phase could be precisely found only at temperature 800 °C but approximate estimate at the room temperature shows that this quantity is nearly temperature independent.

The cyclic hardening observed at room temperature is connected with the continuous increase of the dislocation density in the channels and results in the shift of the second peak of the probability density distribution of the internal critical stresses. In high temperature straining the continuous recovery of the γ phase leads to stabilized stress response.

4. Conclusions

The results of fatigue tests performed on cast Inconel 738LC in regime of controlled total strain in symmetrical strain cycling at temperatures 23°C and 800 °C can be summarized as follows:

High amplitude cyclic straining at 23°C is characterized by hardening that is followed by saturation, at 800 °C a weak softening is shown. Low amplitude cycling at temperature 800°C results in nearly stabilized stress response.

The cyclic stress-strain curve and fatigue life curve in the form of Basquin curve exhibits strong temperature dependence.

Analysis of hysteresis half-loops according to the statistical theory of hysteresis loop allows the estimation of contribution of effective stress and of the distribution of the critical internal stresses.

High stress response of the Inconel 738LC superalloy at high temperature is due to high effective stress in the γ′ phase.

Acknowledgement

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References

Donachie M.J. & Donachie S.J. (2002): *Superalloys: A Technical Guide*. (ASM International, Materials Park).

Jianting G. & Ranucci D. (1983): *Int. J. Fatigue*, Vol. 5, p. 95.

Jianting G., Ranucci D. & Picco E. (1983): *Mater. Sci. Eng.*, Vol. 58, p. 127

Polák J. (1991): *Cyclic Plasticity and Low Cycle Fatigue Life of Metals*. Elsevier, Amsterdam

Wahi R.P., Auerswald J., Mukherji D., Dudka A., Fecht H.-J. & Chen W. (1997): *Int. J. Fatigue* Vol. 19, p. 89

Polák J., Fardoun F. & Degallaix S.: *Mater. Sci. Engng* Vol. A297 (2001), p. 144.

Polák J., Fardoun F. & Degallaix S.: *Mater. Sci. Engng* Vol. A297 (2001), p. 154.