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Influence of phase angle on lifetime, cyclic deformation and damage behavior of Mar-M247 LC under thermo-mechanical fatigue

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ABSTRACT

This study considers the thermo-mechanical fatigue behavior of Mar-M247 LC under 0° (in-phase), +180° (out-of-phase), +90° (clockwise diamond) and −90° (counterclockwise diamond) phase shift between mechanical loading and temperature. Tests were carried out under total strain control with a temperature range of 100–850 °C and a heating and cooling rate of 5 K/s. Mechanical strain amplitudes were 0.3% to 0.6% with a strain ratio of $R_\varepsilon = -1$. Results show that for the strain amplitudes tested, lifetime depends significantly on the phase angle. For a given strain amplitude, lifetime increases in the sequence: in-phase < out-of-phase < clockwise diamond ≈ counterclockwise diamond. Metallographic examination indicates that life reducing damage mechanisms are intergranular creep damage under in-phase loading and accelerated crack propagation at high tensile stress under out-of-phase loading. For both diamond phase loadings pure fatigue damage seems to be dominant. Based on the observed damage mechanisms, the lifetime behavior is discussed.

1. Introduction

In gas turbine blades and vanes start-up, load change and shut down operations may induce thermo-mechanical fatigue (TMF) which determines often their service life. Under elevated temperature conditions, the total TMF damage is composed of fatigue, creep and oxidation damage. Depending on the phase angle between mechanical strain and temperature, the dominant damage mechanism may vary [1,2]. In many investigations on polycrystalline high temperature alloys it was found that TMF-tests with a phase angle of 0° (in-phase, IP) lead to mainly intergranular crack propagation, whereas for a phase angle of 180° (out-of-phase, OP) transgranular crack propagation dominates [1–7]. Intergranular crack propagation in IP tests is usually ascribed to creep damage on grain boundaries because of tensile stress occurring in the high temperature region. Oxidation of grain boundaries may also play a role [7]. However, IP-TMF tests in vacuum showed that grain boundary oxidation is not necessary to induce intergranular damage and crack propagation [8]. Reported detrimental effects in OP tests are cracking of oxide layers under tensile stress at low temperatures [9,10] and generally high tensile stress in the low temperature regime [6]. The different damage mechanisms for IP and OP tests usually lead to different life curves in a strain–life diagram. The slope of the life curves may also differ and crossovers may occur [11,12]. While TMF IP and OP is frequently investigated, fewer studies consider other phase angles e.g. +90°, −90° or −135°, although they may represent the real loading conditions more closely [13]. Results show that for a given mechanical strain amplitude, a variation of phase angle may have a significant influence on lifetime [2,4,6,14]. This study considers lifetime, cyclic deformation and damage behavior of cast nickel-base superalloy Mar-M247 LC under TMF loading with 0°, +90°, +180° and −90° phase shift. The objective is to attain a better understanding about how damage mechanisms vary with phase angle and affect the lifetime.

2. Material

The material investigated was Mar-M247 LC, a γ′-strengthened cast nickel-base alloy typically used for turbine blades and vanes. The chemical composition is given in Table 1. It was supplied by Doncasters Precision Castings (Bochum, Germany) as round bars. The material underwent a hot isostatic pressure (HIP) treatment (1185 ± 15 °C, 4 h ± 10 min, 172.5 ± 5 MPa, in argon) to reduce interdendritic porosity. Subsequently it was solution annealed (1185 ± 15 °C, 2–4 h) and aged (875 °C, 4 h ± 10 min). The secondary dendrite arm spacing is about 32 μm [15]. From the bars, solid round specimens with a cylindrical gauge length of 17 mm and a gauge length diameter of 7 mm were machined.

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Table 1
Chemical composition of Mar-M247 LC, given in wt%.

Ni	W	Co	Cr	Al	Ta	Ti	Mo	C	Fe	Si	Zr	Nb	Mn	V	Cu
Bal.	9.44	9.24	8.19	5.6	3.18	0.67	0.5	0.07	0.04	0.03	0.02	< 0.02	< 0.01	< 0.01	< 0.01

3. Experimental details

The TMF experiments were conducted on a servo-electric fatigue testing machine with a 100 kN load cell. An induction heating system with maximum power of 5 kW was used to heat the specimens. Cooling was achieved by thermal conduction into the water cooled grips and could be additionally forced by three controlled air jets. For temperature measurement, a ribbon type Ni–CrNi thermocouple (type K) was applied in the middle of the gauge length. Total strain was measured with a high temperature capacitive extensometer that was attached to the specimen using alumina rods. The tests were carried out under total strain control following the European Code of Practice [16]. Both temperature and mechanical loading paths were triangle shaped. For all tests, the temperature range was 100–850 °C. Prior to each test, the thermal strain ε^{th} was derived by thermally cycling the specimen at zero load. The total strain–time course for the load cycles was then calculated by adding the desired mechanical strain–time course to the thermal strain–time course ($\varepsilon_t = \varepsilon^{th} + \varepsilon^{me}$). The mechanical strain may be further divided into plastic and elastic parts. Hereinafter, the term “mechanical strain, ε^{me}” denotes always the total mechanical strain. Four phase angles between mechanical loading and temperature were investigated: 0° (in-phase, IP), +180° (out-of-phase, OP), +90° and −90°. The phasing +90° is referred to as clockwise diamond (CD) cycle and −90° as counterclockwise diamond (CCD) cycle because their strain–temperature course forms a diamond that is cycled clockwise or counterclockwise, respectively. Fig. 1 shows the time courses of temperature and mechanical strain for the investigated phase angles. The heating and cooling rate was 5 K/s giving a cycle time of 300 s. IP and OP loading cycles were started at the mean temperature of the cycle $T_m = 475$ °C. CD and CCD loading cycles were started at minimum temperature $T_{min} = 100$ °C. The mechanical loading was fully reversed ($R_\varepsilon = -1$) with mechanical strain amplitudes of $\varepsilon_a{}^{me} = 0.3$, 0.4, 0.5 and 0.6%. The fatigue life N_f was determined using a 10% drop of the stabilized maximum stress as failure criterion. Some specimens fractured completely before a 10% drop of maximum stress was attained. After testing, some specimens were sectioned longitudinally along the gauge length for metallographic examination. An etchant consisting of 97.1% HCl and 2.9% H_2O_2 was used to etch the sections for crack path observation.

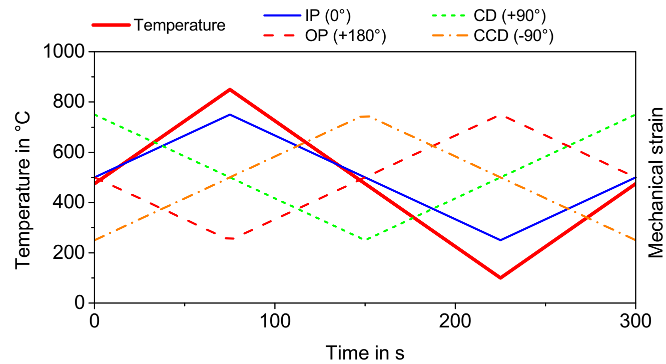

Fig. 1. Temperature and mechanical strain courses for the phase angles investigated.

4. Results

4.1. Lifetime behavior

In Fig. 2 the lifetime results are plotted in a mechanical strain amplitude-life diagram. For the strain amplitudes tested, the phase angle has a significant effect on TMF lifetime. The sequence of fatigue life dependent on the phase angle is IP < OP < CD ≈ CCD. The slope of the IP life curve is significantly lesser than the slope of the OP life curve. Accordingly, the factor between IP and OP life, which is about 20 at $\varepsilon_a{}^{me} = 0.5\%$, decreases rapidly with decreasing strain amplitude. A crossover of the IP and OP curve appears at approximately $\varepsilon_a{}^{me} = 0.3\%$. The slope of the CD/CCD life curve is between that of the IP and the OP curve.

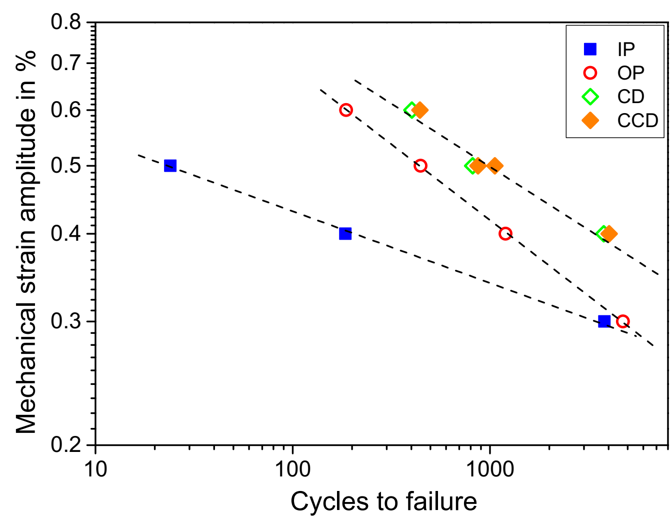

Fig. 2. Comparison of TMF-lifetime under IP, OP, CD and CCD conditions.

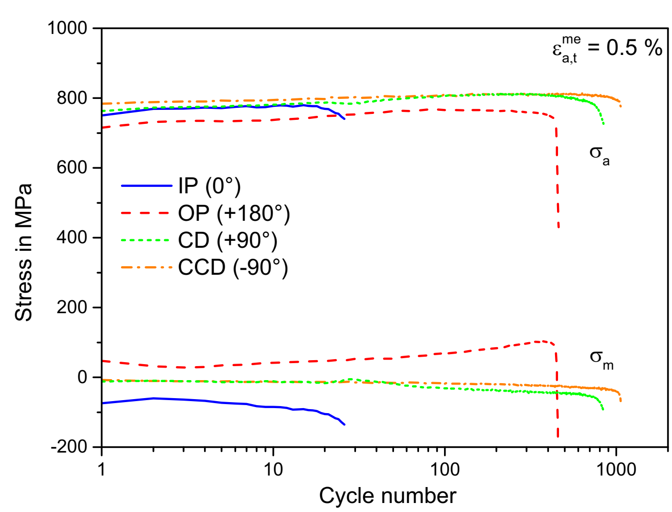

Fig. 3. Development of stress amplitude σ_a and mean stress σ_m during IP, OP, CD and CCD testing.