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Lifetime, Cyclic Deformation and Damage Behaviour of MAR-M247 LC under Thermo-Mechanical Fatigue Loading with 0°, 180°, -90° and +90° Phase Shift between Strain and Temperature

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Abstract

Thermo-mechanical fatigue tests under 0° (in-phase), +180° (out-of-phase), +90° (clockwise diamond) and -90° (counterclockwise diamond) phase shift between mechanical loading and temperature were conducted on nickel-based superalloy Mar-M247 LC. 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_ε = -1. Results show, that for the strain amplitudes tested, lifetime varies significantly with strain-temperature phase. In-phase loading gives the shortest lives followed by out-of-phase and the diamond-phase loadings which show comparable lifetimes. Metallographic examination indicates that the dominant damage mechanisms are creep damage at higher temperatures and early cracking of oxide layers at lower temperatures. Both mechanisms occur primarily under tensile stress. Hence, the portion of each mechanism varies with the phase angle.

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Keywords: Thermo-mechanical Fatigue; phase shift; lifetime behavior; damage behavior; nickel based superalloy

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1. Introduction

In hot section components of gas turbines and jet engines, start-up, load change and shut down operations may cause thermo-mechanical fatigue (TMF) which is often the life-limiting factor. Under elevated temperature

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conditions, the total TMF damage is composed of fatigue, creep and environmental damage. Depending on strain-temperature phase, the portions of these damage mechanisms may vary [1,2]. In TMF specimen tests, the most common strain-temperature phases investigated are 0° (in-phase) and 180° (out of phase). Fewer studies consider other phase angles e.g. +90°, -90° or -135°, although they may represent the real loading conditions more accurately. Many results show that for a given mechanical strain amplitude, the phase angle has a significant influence on TMF-lifetime [3,4,5]. The slope of life curves in strain-life diagrams may also vary with strain temperature phase, indicating that the contributions of the various damage mechanisms are also dependent on strain range [2,6,7]. This study considers the lifetime, cyclic deformation and damage behaviour of cast nickel-based superalloy Mar-M247 LC under TMF loading with 0°, +180°, +90° and -90° phase shift. The objective is to attain a better understanding about how particular damage mechanisms vary with phase angle and affect the lifetime.

2. Material

The material investigated was Mar-M247 LC, a cast nickel-based superalloy typically used for turbine blades. The chemical composition in wt. % is 9.44 W, 9.24 Co, 8.19 Cr, 5.6 Al, 3.18 Ta, 0.67 Ti, 0.5 Mo, 0.07 C, 0.04 Fe, 0.03 Si, 0.02 Zr, balance Ni. It was supplied by Doncasters Precision Castings (Bochum, Germany) as round bars. A more detailed description of the material can be found in [8]. From the bars, solid round specimens with a cylindrical gauge length of 17 mm and a gauge length diameter of 7 mm were machined.

3. Experimental details

The TMF experiments were conducted on a servo-electric fatigue testing machine with a 100 kN load cell. Induction heating 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 at the center 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 [9]. 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 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 ($\varepsilon_t = \varepsilon^{th} + \varepsilon^{me}$). Four phase angles between mechanical loading and temperature were investigated: 0° (in-phase, IP), +180° (out-of-phase, OP), +90° (clockwise diamond, CD) and -90° (counterclockwise diamond, CCD). Heating and cooling rate was 5 K/s giving a cycle time of 300 s. The mechanical loading was fully reversed (R_ε = -1) with mechanical strain amplitudes of 0.3, 0.4, 0.5 and 0.6 %. The TMF-lives were determined using a 10 % drop of the maximum stress as failure criterion. After testing, some specimens were sectioned longitudinally along the gauge length for metallographic examination.

4. Results

In Fig. 2 the lifetime results are plotted in a mechanical strain amplitude-life diagram. Dependent on the phase angle TMF-lifetime increases in the sequence IP < OP < CD/CCD. The results of CD and CCD tests fall into one common scatter band. The slope of the in-phase strain-life curve is significantly lesser than for the other phase angles. The typical crossover of the IP and OP curve appears at approximately $\varepsilon_{a,t}^{me}$ = 0.3 %. Fig. 2 shows that in IP tests, stress relaxation during cycling leads to a shift of the hysteresis loops towards the compressive region. For $\varepsilon_{a,t}^{me}$ = 0.3 % the shift is more pronounced than for $\varepsilon_{a,t}^{me}$ = 0.4 %. For OP tests at lower strain amplitudes, a gradual hysteresis loop shift towards the tensile region could be observed. In IP and OP tests at $\varepsilon_{a,t}^{me} \geq 0.5$ % and for all CD and CCD tests, a distinctive shift of the hysteresis loops along the stress axis did not occur.

In Fig. 3 stress-temperature hysteresis loops at half of the lifetime for IP, OP, CD and CCD tests with $\varepsilon_{a,t}^{me}$ = 0.5 % are displayed respectively. In the IP case, the highest tensile stress coincides with the highest temperature and the highest compressive stress with the lowest temperature. For the OP test the reverse holds true.

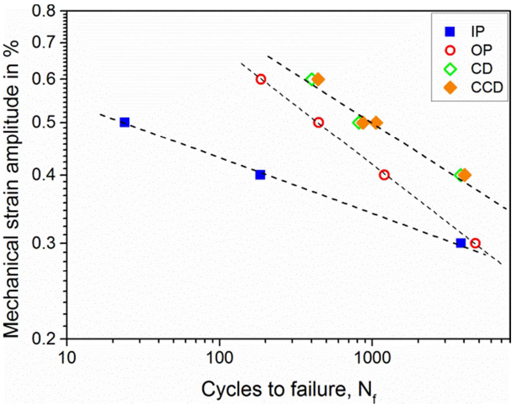

Fig. 1. Comparison of TMF-lifetime under IP, OP, CD and CCD conditions

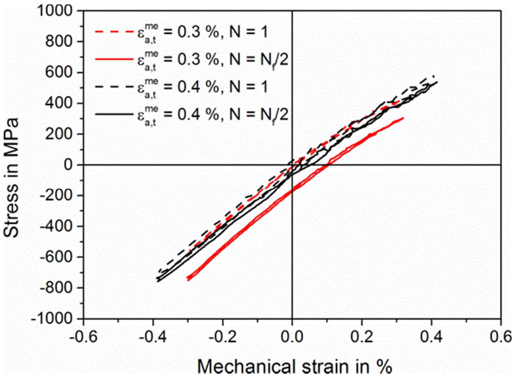

Fig. 2. Hysteresis loop shift in IP and OP tests at lower mechanical strain amplitudes

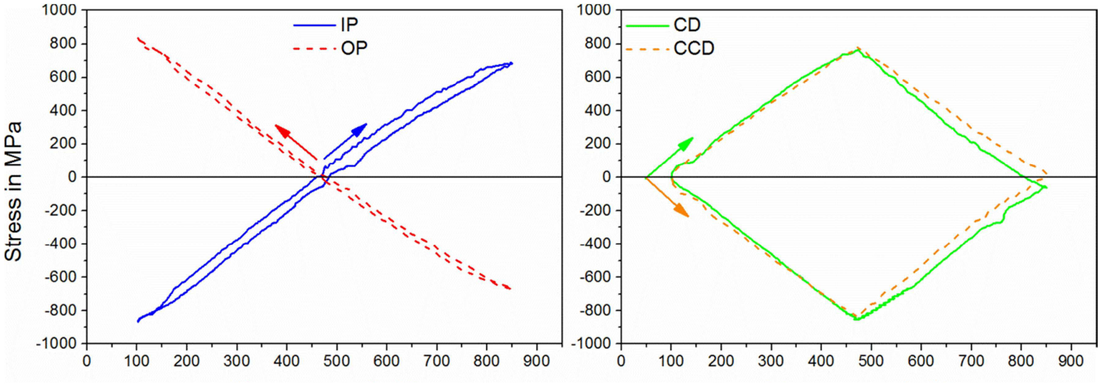

Fig. 3. Influence of the phase angle on stress-temperature hysteresis loops, the arrows indicate the loading direction

For both CD and CCD tests, the highest stress appears around the mean temperature, whereas at the highest and lowest temperatures the stress is minor. The metallographic examination showed that under IP loading, crack initiation and propagation is typically intergranular, while for OP, CD and CCD loading, it is predominantly transgranular.

5. Discussion

The results reveal that dependent on the TMF-phase angle, the dominant damage mechanisms vary and affect thereby the lifetime. For IP tests, tensile stresses at high temperatures lead to creep damage on grain boundaries favouring intergranular crack propagation and reducing the lifetime. For OP tests, stress at high temperatures is compressive and does not cause intergranular damage. In CD and CCD tests, only minor stress is induced at the highest temperatures and no significant creep damage occurs. Thus, for OP, CD and CCD testing, crack propagation is fatigue induced and mainly transgranular. Compared with CD/CCD tests, the shorter lives under OP loading may be a result of the positive mean stress inherent to OP tests. Furthermore, in OP tests, high tensile stresses appear at low temperatures when the surface oxide layer has the lowest ductility. This may lead to early surface crack initiation. The mechanism has also been stated in other studies [10,11]. Hence, life reducing damage mechanisms appear to be intergranular creep damage at high temperatures and early cracking of the surface oxide layer at low temperatures. Both operate mainly under tensile loading: the former predominantly in IP tests, the latter in OP tests. In diamond-phase tests, the highest tensile loading occurs at mean temperature, thus neither of the aforementioned damage mechanisms plays a significant role. Accordingly, only pure fatigue damage takes place and lifetimes are longer than for IP and OP conditions.

The observed shifts of hysteresis loops in IP and OP tests at lower strain amplitudes are a consequence of stress relaxation effects in the high temperature regime. In IP tests, the relaxation effects lead to a decrease of maximum stress, while for OP tests, maximum stress is increased. The shift continues up to the point when the yield stress at minimum temperature is reached and the plastic strain due to stress relaxation is reversed by low temperature dislocation glide. For higher strain amplitudes, the yield stress at minimum temperature is reached earlier, thus, the shift is less pronounced or does not occur at all (Fig. 2). Hence, an increase of strain amplitude in IP tests results in a relatively high increase of tensile stress and therefore in a high increase of the dominant creep damage. In OP tests however, an increase of strain amplitude gives only a moderate increase of maximum stress and damage to the oxide layers. This is the reason why in Fig. 1, the slope of the IP life curve is considerably shallower than the slope of the OP life curve. Under CD and CCD conditions the stress level is not shifted because both maximum and minimum strain occurs at the mean temperature. So, there is no asymmetry in the effective deformation mechanisms. Accordingly the slope of the CD/CCD life curve in Fig. 1 lies between that for the IP and OP curve.

6. Conclusions

TMF tests with IP, OP, CD and CCD phasing and a temperature range of 100 – 850 °C were conducted on Mar-M247 LC. It was found that the phase angle has a significant influence on deformation and damage behaviour and thereby on lifetime. For mechanical strain amplitudes between 0.3 and 0.6 %, lifetime increases in the sequence IP < OP < CD/CCD. Identified damage mechanisms are intergranular creep damage at high temperatures, which is pronounced under IP loading, and early cracking of the brittle oxide layer at low temperatures, which occurs mainly in OP tests. Both mechanisms are induced by tensile stress. Since for CD/CCD tests, tensile stresses at highest and lowest temperatures are minor, neither of the identified damage mechanisms is pronounced and their lifetimes are longer than IP and OP lifetimes. The different slopes of the IP and OP life curve in a strain-life diagram could be attributed to stress relaxation effects occurring at lower strain amplitudes and altering the portions of creep and oxide layer damage.

References

[1] R.W. Neu, H. Sehitoglu, Thermo-Mechanical Fatigue, Oxidation and Creep: Part I. Damage Mechanisms, Metallurgical Transaction A 20a (1989) 1755 – 1767.

[2] D.A. Boismier, H. Sehitoglu, Thermo-Mechanical Fatigue of MAR-M247: Part 1 – Experiments, Journal of Engineering Materials and Technology 112 (1990) 68 – 79.

[3] S. Kraft, R. Zauter, H. Mughrabi, Aspects of High-Temperature Low-Cycle Thermomechanical Fatigue of a Single Crystal Nickel-Base Superalloy, Fatigue & Fracture of Engineering Materials & Structures 16 (1993) 237 – 253.

[4] T. Egly, K.-H. Lang, D. Löhe, Influence of phase shift and strain path on the thermomechanical fatigue behavior of CMSX-4 specimens, International Journal of Fatigue 30 (2008) 249 – 256.

[5] S. Guth, A. Korinth, K.-H. Lang, Lifetime, Cyclic Deformation and Damage Behaviour of NiCr22C012Mo9 under TMF-Loadings with various Phasing of Strain and Temperature, Seventh International Conference on Low Cycle Fatigue, Aachen, 2013, pp. 171 – 176.

[6] K. Kuwabara, A. Nitta, T. Kitamura, in: D.A. Woodford (Ed.), Thermal-Mechanical Fatigue Life Predictions in High-Temperature Component Materials for Power Plant, Proceedings of ASME International Conference on Advances in Life Prediction Methods, 1983, pp. 131 – 141.

[7] H. Sehitoglu, in: M.R. Mitchell, R.W. Landgraf (Eds.), Thermo-Mechanical Fatigue Life Prediciton Methods, Advances in Fatigue Lifetime Predictive Techniques, ASTM STP 1122, 1992, pp. 47 – 76.

[8] D. Gelmedin, K.-H. Lang, J. C. Newman jr., Prediciton of Fatigue Lives of MAR-M247 LC Based on the Crack Closure Concept, Advanced Engineering Materials 14 (2012), 848 – 852.

[9] Directorate-General Joint Research Center: EUR22281EN - Validated Code-of-Practice for Strain-Controlled Thermo-Mechanical Fatigue Testing , 2006.

[10] D.A. Boismier, H. Sehitoglu, Thermo-Mechanical Fatigue of Mar-M247: Part 2 - Life Prediction, Journal of Engineering Materials and Technology 112 (1990) 80 – 89.

[11] Hong, H.; Kang, J.; Choi, B.; Kim, I.; Yoo, Y. & Jo, C. A comparative study on thermomechanical and low cycle fatigue failures of a single crystal nickel-based superalloy, International Journal of Fatigue 33 (2011) 1592 – 1599.