Investigation of the high temperature fatigue behavior of the nickel-base superalloy Waspaloy™ under biaxial-planar loading

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ABSTRACT. The wrought nickel-base superalloy Waspaloy™ was studied under biaxial-planar cyclic loading at elevated temperature. The total strain and temperature controlled tests were carried out at laboratory atmosphere using a servohydraulic biaxial-planar tension-compression machine (Instron) equipped with a biaxial-orthogonal extensometer and a high frequency heating device. The developed test configuration was verified by thermography and thermocouple measurements at predefined temperature profiles. Based on the measured principal strains in the gauge area, the principal stresses were calculated by the elastic unloading at the load reversal points of hysteresis loops. The cyclic deformation and fatigue behavior under proportional loading were compared to uniaxial tests at the same temperature as well as to literature data. The biaxial fatigue behavior is presented in cyclic deformation curves and finally, the fatigue life is reported.

INTRODUCTION

Typical application fields for nickel-base superalloys are high temperature subjected components such as turbine blades, vanes and turbine disks in power plants and aircraft engines. The loadings are mainly caused by centripetal forces and by pressure differences in the various stages of compression. With restriction to the essential loads which are subjected to the components a biaxial stress state is often present [1]. Further, during service these components are exposed to a thermo-mechanical loading. Currently, the design process using the visco-plastic deformations and mechanisms based on damage models is based on material data of uniaxial tests. Thus the influence of triaxiality on the fatigue behavior is neglected. Due to this discrepancy, there is the endeavor to carry out multi-axial high-temperature fatigue tests [1, 2, 3]. The biaxial-planar material testing represents the connection in the chain between uniaxial and real component testing.

The investigated nickel-base superalloy Waspaloy™ was extensively tested in literature under tensile, compressive, creep and fatigue loading, respectively, at different temperatures. In particular, the fatigue behavior of the alloy was investigated from room temperature up to 800°C with different grain sizes [4] and varying stress ratios [5]. Furthermore, the damage mechanism [4] and the crack propagation were investigated [6]. Clavel observed that Waspaloy deforms at room temperature inhomogeneously at low strain amplitudes by mechanical microtwins, which dissolve by increasing strain ranges as well as with progressing fatigue, so that planar slip bands are visible. At elevated temperature the deformation occurs homogeneous by planar slip bands [6]. Especially for small grain sizes Lerch et al. [4] have also found planar slip bands, which are bowing out between the precipitates and Orowan loops around the precipitates are visible. With increasing grain size the precipitates were sheared by planar slip bands. Dreshfield [5] investigated the fatigue behavior under different stress ratios and observed that the stress ratio has no influence on the fatigue life of Waspaloy. The results of the fatigue lives at 425°C [5] will be used for comparison with our own experiments.

The aim of the present work is to investigate the fatigue behavior of Waspaloy at 400°C at different stress states. To achieve this goal, a biaxial-planar test set-up with induction heating was used which provides a homogeneous temperature field within the gauge area of the cruciform specimen. For the evaluation of the influence of the multiaxiality on the fatigue behavior, uniaxial low cycle fatigue tests and biaxial-planar tests at proportional in-phase and shear loading were carried out.

MATERIAL

The investigated material is the forged nickel-base superalloy Waspaloy™, which was produced by Böhler-Uddeholm AG as rolled sheet material and delivered in the solution annealed state (1040 °C for two hours). A two-step precipitation heat treatment was carried out at 850 °C for four hours as well at 760°C for 16 hours with final cooling in air. Finally the cylindrical specimen for the uniaxial tests and the cruciform specimen were turned and milled as well as mechanically polished to avoid crack initiation caused by poor surface quality. The chemical composition of Waspaloy™ is given in table 1.

A first mechanical characterization was performed by high temperature tensile tests at 550 °C and 650 °C with a strain rate of 10^{-3} s^{-1}. The values averaged for two specimens are presented in table 2.

The measured strength and elongation values of the studied material are corresponding to the minimum requirements of the standard DIN EN 10088-1.

Table 1: Chemical composition of Waspaloy™ in wt. %.

Ni	Cr	Co	Mo	Ti	Al	Zr	Si	C	Mn	B	S	P
59,8	18,5	11,6	5,1	3,0	1,8	0,12	0,6	0,02	0,04	<0,01	<0,01	0,02

Table 2: Results of the high temperature tensile tests at different temperatures.

Temperature [°C]	Yield strenght [MPa]	Ultimate tensile strenght [MPa]	Elongation at rupture [%]
550	849	1205	16,5
650	854	1194	18,6

Main advantages of Waspaloy™ for biaxial-planar testing is the small grain size in the range of 13 to 30 µm or according ASTM between 10 and 12, cf. figure 1a. Moreover, no texture is present, as shown by electron back scatter diffraction (EBSD), see the pole figure in figure 1b. Due to the heat treatment, coherent and spherical γ'-precipitates are formed, which are homogeneously distributed with a size of about 80 nm, see figure 1c.

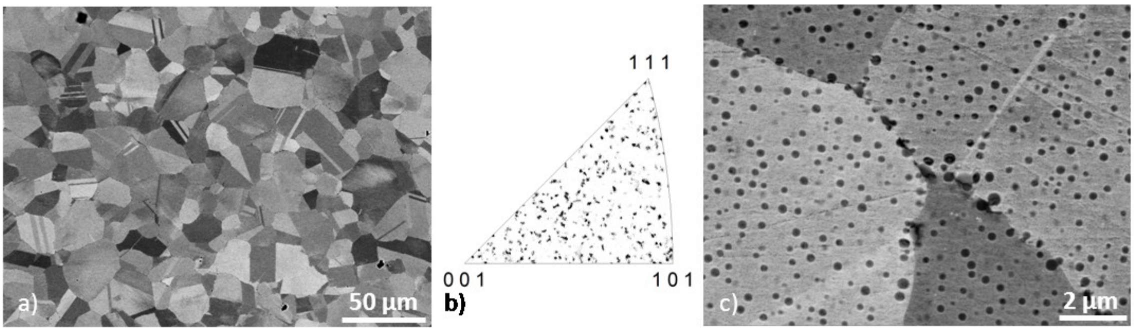


Figure 1: a) SEM image of the microstructure, b) inverse pole figure, which shows no preferred grain orientation, c) SEM image of the monomodal distribution of spherical γ'-precipitates.

EXPERIMENTAL DETAILS

The tests were carried out on a servohydraulic biaxial-planar tension-compression testing machine (Instron) with four cylinders of 250 kN load capacity. The biaxial-planar test rig is equipped with a high frequency generator and an associated external oscillator, on which the cylindrical induction coil is attached. In the test configuration the coil is placed in front of the cruciform specimen, whereby the sample is inductively heated. On the opposite surface of the cruciform specimen, the thermocouple type K for temperature control and the tempered biaxial orthogonal extensometer with a gage length of 13 mm for strain control were applied. The alignment and clamping of the cruciform specimen is ensured by water cooled chuck jaws. In figure 2 the experimental configuration for the fatigue tests is shown.

The geometry of the cruciform specimen has been the typical design for low cycle fatigue testing according to Pascoe and Villiers [7], which was furthermore optimized by Scholz et al. [8] for thermo-mechanical fatigue. The used cruciform specimen has a circular planar gauge area with a diameter of 15 mm, which is reduced to a thickness of 1.6 mm, as shown in figure 3a.

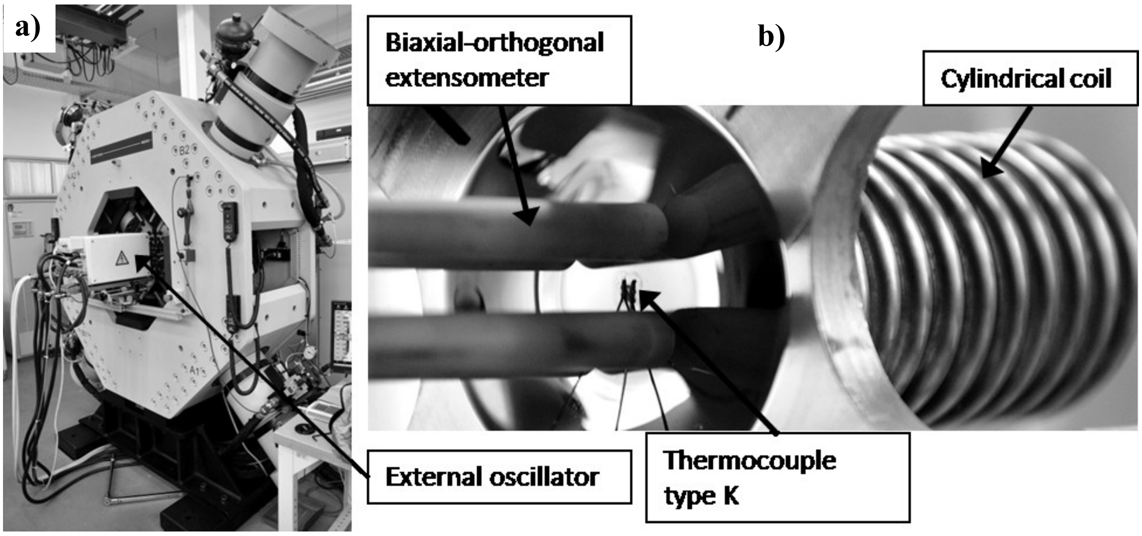


Figure 2: a) Biaxial-planar tension-compression machine with external oscillator and cylindrical coil. b) Applied extensometer and thermocouple as well as the aligned cylindrical induction coil on the back side of the cruciform specimen.

The usual way to calculate the principal stresses for biaxial-planar testing is the simplifying assumption of an effective cross-sectional area, which depends on the present stress states, whereby a previous simulation is required. In this study the calculation of the stresses was done using elastic unloading after load reversal. At this the linear unloading part of the hysteresis loop, a linear regression was made and the elastic part of the total strain was determined by extrapolation to the abscissa axis. Finally, the Hooke's law for plane stress state was used to calculate the stress in both axes. Therefore, only the Young's modulus and the Poisson's ratio at the specific temperature are necessary. The equivalent stresses and strains were calculated by using the yield criterion according to von Mises. A detailed description of the partial unloading method is given by the authors' group elsewhere [9, 10].

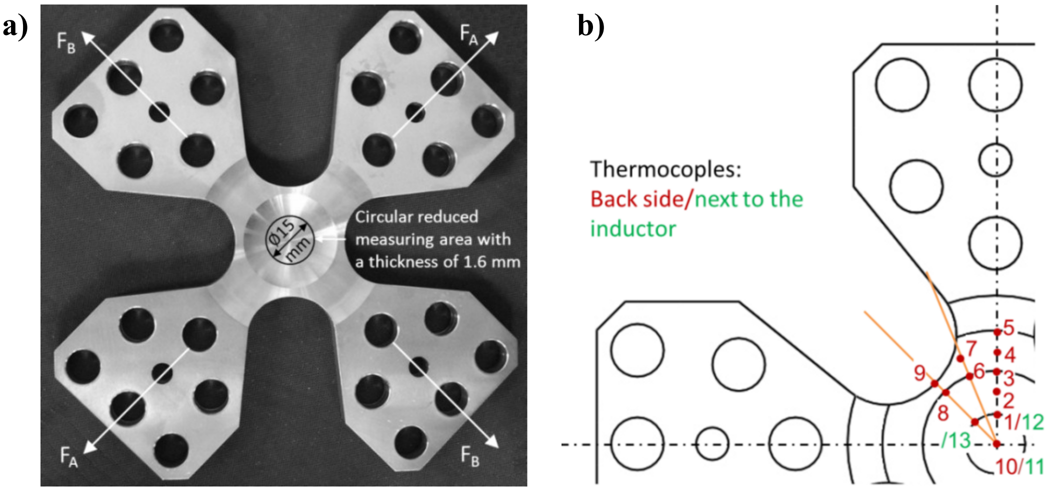


Figure 3: a) Specimen geometry and b) position of the thermocouples attached by welding.

The adaption of the biaxial-planar test rig for high temperature fatigue was done by a cruciform specimen with 13 thermocouples welded on it and a thermography camera. The exact position of the thermocouples on the cruciform specimen is shown in figure 3b. Predefined temperature profiles were used to evaluate the sample behavior as well as temperature field within the specimen at different temperatures and heating rates. Based on this temperature ramp signals with isothermal holding times, the suitability for isothermal low cycle fatigue and future thermo-mechanical fatigue was demonstrated.

The biaxial-planar tests as well as the uniaxial low cycle fatigue tests were carried out under total strain control as a triangular wave shape signal and isothermal temperature control at 400 °C with a constant strain rate of $1*10^{-3}$ s^{-1}. At first the uniaxial tests were performed at 0.45, 0.6 and 0.8 % total strain amplitudes. Proportional biaxial-planar low cycle fatigue tests were carried out under symmetric push-pull loading at two different equivalent total strain amplitudes of 0.5 and 0.7 %, so a strain ratio $\varphi = \frac{\varepsilon_{tot}^{B}}{\varepsilon_{tot}^{A}} = 1$ was realized. Furthermore, the fatigue behavior under shear loading was investigated at equivalent total strain amplitude of 0.8 %, so that the phase offset between both axes was 180° and the strain ratio φ was -1.

RESULTS AND DISCUSSION

The temperature ramp signal at a temperature change from 350 to 400 °C and a heating rate of 3.3 K/s is given by the four thermocouples in the center of the cruciform specimen, see figure 4. Furthermore, the temperature differences to the setpoint were calculated for the visualization of the deviation.

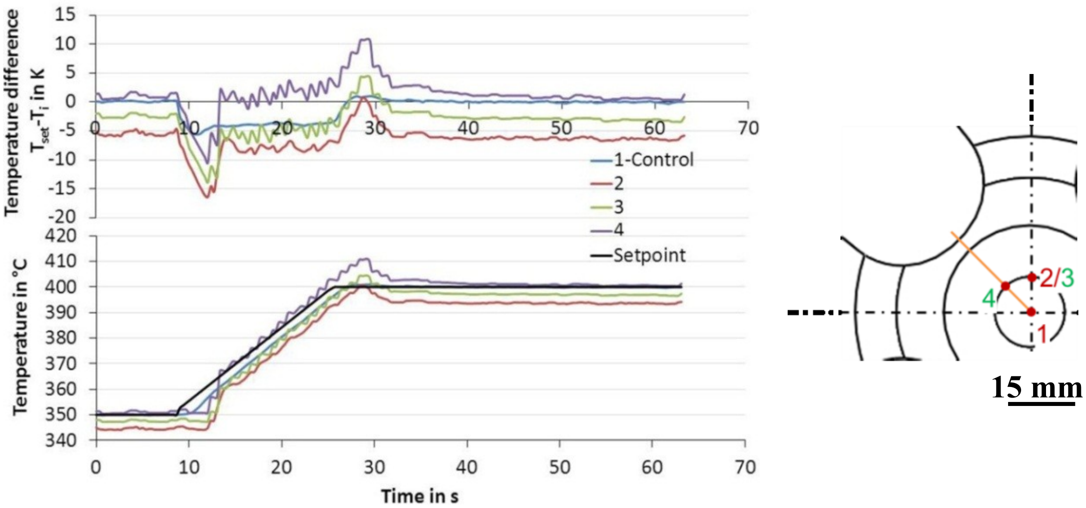
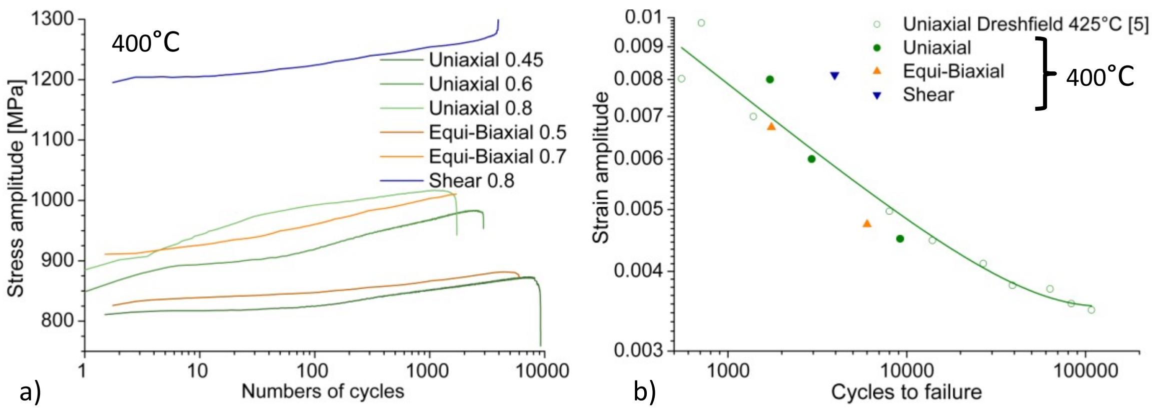


Figure 4: Sample behavior of the cruciform specimen for a temperature ramp signal demonstrated by 4 thermocouples, which are placed in the gauge area.

In general, all thermocouples in the gauge area of the cruciform specimen follow the reference signal, so that only small deviations result. In the anisothermal part of the temperature ramp signal, the deviations are between +3 and -6 K within the gauge area. However, the controlled thermocouple (1) met the reference temperature within the specification of ± 5 K valid for thermo-mechanical fatigue [11], although the control parameters are adjusted to the isothermal case. Furthermore the heating as well as cooling rate can be reduced for even smaller deviations. During the isothermal temperature control, the deviations are smaller, so that the temperature difference between the thermocouples in the gauge area of 5 K is kept.

The results of the thermocouple measurements are confirmed by thermography images, which show the highest temperature and a uniform temperature distribution in the gauge area. Therefore, the formation of the circular temperature field within the cruciform specimen is characteristic for the cylindrical inductor. This ensures that the central region is the most stressed region during the fatigue testing. Thus, the requirements for high temperature low cycle fatigue testing are met.

Figure 5a shows the cyclic deformation curves for the biaxial as well as uniaxial tests. Furthermore, in figure 5b the lifetimes are given and compared to literature data of Dreshfield [5], who investigated the low cycle fatigue behavior of a low carbon Waspaloy™ at 425 °C. For the uniaxial tests, the fatigue lives were determined at a load decrease of 5 %. The fatigue lives for the biaxial tests were determined from the decrease of the stiffness of the specimens to identify the numbers of cycles to failure.



a) b)

Figure 5: a) Cyclic deformation curves of the different uniaxial and biaxial tests. b) Lifetimes for all performed tests compared to data of the literature.

Basically, the cyclic deformation curves are characterized by an initial cyclic hardening. This region is followed by a part with decreasing hardening rate as well as steady state part. Finally, a secondary hardening can be observed until initiation of a macro crack. The courses of the uniaxial and equi-biaxial cyclic deformation curves are in a good agreement to each other. The shear test leads to the highest stress amplitudes being up to 250 MPa higher than the uniaxial reference test with the same strain amplitude.

In figure 6b, the lifetimes of the uniaxial tests lie within the scatter of two to the literature data [5], so that a good agreement exists.

The equi-biaxial tests arranged within the usual scatter in the course of uniaxial fatigue tests. This good agreement between uniaxial and equi-biaxial tests shows that the strain energy of distortion criterion according to von Mises is valid for this case.

Besides the significantly higher stress amplitude for the shear test, also a 2.5 times longer fatigue life was measured. Concerning this higher lifetime for the shear stress state, there is already some literature [3, 12] which also reports such an effect and attributes it to crack initiation and propagation. Nevertheless, further tests are necessary to confirm this result.

For all biaxial tests, the specimens show a crack initiation and crack propagation in the gauge area of the sample.

CONCLUSIONS

The test rig is suitable for biaxial-planar fatigue tests at high temperatures. The temperature measurements show that the presented set up meets the specifications for uniaxial tests according to [11]. The cylindrical coil leads to a circular temperature field with a homogeneous temperature distribution in the gauge area.

The fatigue lives of the uniaxial tests are consistent with the literature data within the typical scatter. Also the fatigue lives of the equi-biaxial test are close to the uniaxial values. The cyclic deformation curves and fatigue lives of the uniaxial and equi-biaxial tests are consistent to each other using the strain energy of distortion criterion.

The shear test shows a large deviation to the uniaxial reference case with stress amplitudes being 250 MPa higher. Also the fatigue life for the shear test is significantly higher using strain energy of distortion criterion. To verify these effects more biaxial-planar tests and deformation simulations are necessary.

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