For more than a century, Darmstadt has been a centre of essential expertise in structural durability. Test and measurement equipment, computational methods and design philosophies have been developed here, over the past decades. To illustrate the continuity of activities in this field several institutes and companies have grouped together to present the Symposium on Structural Durability in Darmstadt. The symposium is organised by Center for Engineering Materials State Materials Testing Institute Darmstadt Chair and Institute for Materials Science (MPA-IfW), Institute of Steel Construction and Materials Mechanics (IFSW), System Reliability, Adaptive Structures and Machine Acoustics SAM (SAM), Fraunhofer Institute for Structural Durability and System Reliability (Fraunhofer LBF), Instron GmbH (INSTRON), Hottinger Baldwin Messtechnik GmbH (HBM), Adam Opel AG (OPEL).

The objective of the Symposium on Structural Durability in Darmstadt (SoSDiD) is to present the current state of the art to the national and international fatigue community. Constributions have been gathered from German and international experts as well as from Darmstadt research work in structural durability. The symposium is intended to supply a lively forum for discussing basic questions and current trends, bringing together scientists and engineers working in this field.

In the area of structural durability the main subjects in 2017 will be thermo-mechanical fatigue, environmentally assisted fatigue and random vibration.

ISBN 978-3-939195-55-9

Proceedings of the 5th Symposium on Structural Durability in Darmstadt SoSDiD

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Editors:
M. Vormwald, H. Th. Beier, K. Breidenbach

Printing and Bindery:

typographics GmbH
Röntgenstraße 27a, 64291 Darmstadt
Tel. (0 61 51) 71 96 09, Fax (0 61 51) 71 96 21
ISDN/Leonardo (0 61 51) 354 91-11
E-Mail: print@27a.de

ISBN (Print) ISBN 978-3-939195-55-9

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THERMOMECHANICAL FATIGUE OF LOST FOAM CAST ALUMINIUM-SILICON CYLINDER HEADS - EXPERIMENTS AND SIMULATION

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ABSTRACT

The lifetime of aluminium-silicon cylinder heads is assessed by mechanism-based damage models which use the results of thermomechanical deformation calculation. For this purpose viscoplastic material models are used. For parameter identification uniaxial thermomechanical fatigue (TMF) tests were performed. The specimens for these tests were extracted from the region between the intake and exhaust port of the cylinder heads. In this work cylinder heads were investigated which were manufactured by the Lost Foam casting process. Its high system-dependent porosity shows a significant influence on the lifetime under TMF loading. Therefore, the pores in the specimens were detected by micro-CT before and after TMF testing. Additionally, the fracture surfaces were investigated by SEM. By means of this procedure the characteristic parameter for TMF loading was identified.

KEYWORDS

Cylinder head, Lost Foam, thermomechanical fatigue test, viscoplastic deformation model, parameter identification, characteristic parameter, micro-CT

INTRODUCTION

In automotive cylinder heads thermomechanical loads caused by temperature cycles (engine start-stop especially in PHEV application, full load, partial load) lead to thermomechanical fatigue (TMF). The result is crack initiation within the critical section on the combustion chamber side [1-2]. Additionally, a significant variation of the lifetime of identically loaded sections is observed. The main reason for lifetime variation is the casting process of the cylinder heads. In this work cylinder heads were investigated which were manufactured by the Lost Foam casting process. Its system-dependent porosity shows a significant influence on the lifetime under TMF loading. To reduce the development time of cylinder heads and to define standards for the effective quality control and process optimisation a combined test and computation method is introduced. The aim of this method is the calculation of the lifetime and the lifetime variation of cylinder heads subjected to TMF loading as a function of the variation of characteristic parameters in specimen geometry.

The lifetime of aluminium-silicon cylinder heads is assessed by damage models which use the results of the thermomechanical deformation calculation [3-4]. For identification of the model parameters uniaxial thermomechanical fatigue tests were performed. In this paper the experimental procedure of TMF testing and the procedure of identifying the deformation model parameters are described in detail. The experimental results and the results of the parameter identification are illustrated for a particular ageing state. Moreover, micro-computer tomography scans of the specimens were performed before and after TMF testing. By means of this procedure the characteristic parameter for TMF loading was identified.

EXPERIMENTAL PROCEDURE

Uniaxial thermomechanical fatigue tests were performed under control of the mechanical strain in a servo-hydraulic test rig. The heating of the specimen was conducted by a 10 kW high-frequency generator. Heat was generated within the material by an induction coil which was fitted to the specimen geometry. A flattened thermocouple (type K) with 0.1 mm thickness was used for temperature measurement. For strain measurement a high-temperature extensometer with a gauge length of 12 mm was used (Fig. 1, left).

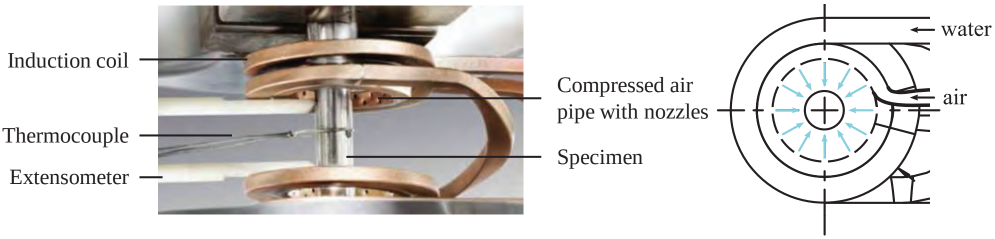

Fig. 1: TMF test setup (left); outer water-cooled pipe and inner compressed air pipe with nozzles for air transportation to the specimen (right)

In this work a precipitation-hardened aluminium-silicon cast alloy was used. To consider the influence of the Lost Foam casting process on the lifetime under TMF loading the specimens were extracted from the region between the intake and exhaust port of the cylinder heads (Fig. 2). Thus, the specimens have small dimensions: the specimen length is 80 mm, the mount diameter 10 mm and the test diameter 7 mm. In order to be able to perform TMF tests with these specimens the induction coil consists of two pipes: An outer water-cooled pipe and an inner compressed air pipe with nozzles for air transportation to the specimen (Fig. 1, right).

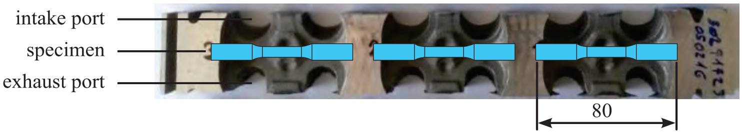

Fig. 2: Specimen extraction

Six tests were performed in a temperature range between 50°C und 250°C with heating and cooling rates of 5°C/s using a triangle shaped signal. The strain ranges $\Delta\varepsilon_{mech,1}$, $\Delta\varepsilon_{mech,2}$ and $\Delta\varepsilon_{mech,3}$ were applied according to the engine service conditions. All strains are scaled to $\Delta\varepsilon_{mech,2}$: $\Delta\varepsilon_{mech,1} = 1.2\ \Delta\varepsilon_{mech,2}$ and $\Delta\varepsilon_{mech,3} = 0.8\ \Delta\varepsilon_{mech,2}$. A hold time of 60 s was applied at the highest temperature of 250°C. The TMF tests were carried out with a phase shift of 180° between the temperature and strain signal (out-of-phase - OP).

MODELLING

Material model

For modelling the thermomechanical deformation behaviour the material model “Two-layer viscoplasticity” (TLV) was used because it considers the elastic, plastic and viscous material properties and additionally is implemented in the FE software Abaqus [1, 5-6]. In this work the uniaxial material equations are solved in Matlab by the explicit Euler integration method [7]. The elastic properties of the material are described by Hooke’s law, written here in rate formulation,

$$\dot{\sigma} = E\,\dot{\varepsilon}_{el} = E_{pl}\left(\dot{\varepsilon}_{mech} - \dot{\varepsilon}_{pl}\right) + E_v\left(\dot{\varepsilon}_{mech} - \dot{\varepsilon}_v\right) \text{ with } E = E_{pl} + E_v \tag{1}$$

where σ is the stress, E the Young’s modulus, ε_{el} the elastic strain, ε_{mech} the mechanical strain, ε_{pl} the plastic strain and ε_v the viscous strain. E_{pl} is the Young’s modulus in the elastic-plastic network and E_v is the Young’s modulus in the elastic-viscous network. The flow function f is used to determine whether a stress state leads to elastic or plastic deformation of the material. It is defined as follows,

$$f = \left|\sigma_{pl} - \alpha\right| - R_e \tag{2}$$

where σ_{pl} is the stress in the elastic-plastic network, α the back stress and R_e the initial yield stress. The material shows an elastic behaviour for $f < 0$ and a plastic behaviour for $f = 0$. In the case of $f = 0$, the plastic strain rate is calculated as product of the rate of the equivalent plastic strain p and the plastic flow direction $df/d\sigma$. The described relation is defined as plastic flow rule:

$$\dot{\varepsilon}_{pl} = \dot{p}\,\frac{df}{d\sigma} = \dot{p}\,\frac{\sigma_{pl} - \alpha}{R_e} \tag{3}$$

The kinematic hardening is described by the evolution equation by Armstrong and Frederick which is a linear differential equation of first order:

$$\dot{\alpha} = C_\infty \, \dot{\varepsilon}_{pl} - \gamma \, \dot{p} \, \alpha \tag{4}$$

C_∞ and γ are the parameters of kinematic hardening. The viscosity of the material is described by the following equation:

$$\dot{v} = A(\sigma_v)^n \tag{5}$$

This relation is derived by the power law of Chaboche. A and n are the viscosity parameters. σ_v is the stress within the elastic-viscous network and v is the equivalent viscous strain. To simulate the thermomechanical deformation behaviour it is necessary to consider the temperature dependence of the model parameters.

Parameter identification

To save computing time in the FE calculation of the thermomechanical deformation behaviour of cylinder heads only two cycles are calculated (Fig. 3, left). In order to identify the parameters of the material model (Chapter “material model”) the second calculated cycle is fitted to a stress-strain hysteresis loop of a performed uniaxial thermomechanical fatigue test. A linear relation between the parameters and the temperature is assumed for E, R_e, C_∞ and A. The parameters γ and n are assumed to be constant.
There is a positive mean stress in OP TMF tests. It is not possible to consider the evolution of the mean stress during the simulation calculating only two cycles. Hence, a shift of the experimental stress-strain hysteresis is necessary. By this procedure the shape and area of the hysteresis loop are determined by the model (Fig. 3, left).

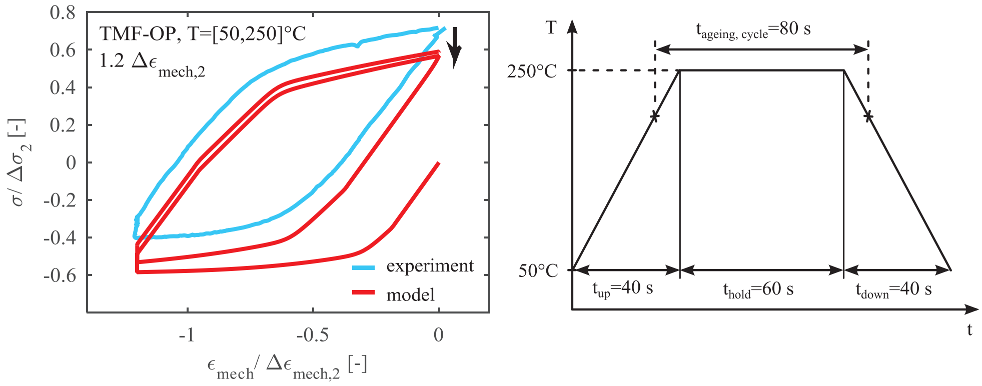

Fig. 3: Two calculated stress-strain hystereses and one experimental hysteresis which is shifted to the second calculated hysteresis (left); temperature profile for one TMF cycle (right)

Aluminium-silicon cast alloys undergo an ageing effect which strongly reduces the strength of the material. Ageing tests show that at elevated temperatures the strength declines quickly reaching a saturated level after about 50 hours [6]. To consider the ageing of the material within the simulation the parameter identification has to be performed with a stress-strain hysteresis loop from a TMF test which was exposed to the maximum temperature for about 50 hours. The ageing time at maximum temperature t_{ageing} is calculated by the product of the cycle number N and the ageing time per cycle $t_{ageing,cycle}$ which is assumed to be the sum of the hold time t_{hold} of 60 s and 20 s for ascending and descending temperature (Fig. 3, right).

RESULTS

TMF tests

In Fig. 4 the cyclic hardening/ softening curves for all OP TMF tests performed (left) and the stress-strain hysteresis loops of a TMF test with a mechanical strain range of $\Delta\varepsilon_{mech,1}$ = 1.2 $\Delta\varepsilon_{mech,2}$ (right) are shown. All stresses are scaled to the stress range $\Delta\sigma_2$ at half number of cycles to failure for the TMF test with a mechanical strain range of $\Delta\varepsilon_{mech,2}$. Each TMF test shows a positive mean stress due to out-of-phase loading. The maximum and minimum stresses of each cycle decrease with increasing cycle number due to ageing and cyclic softening effects. The lifetime (cycle number at a stress drop of 20%) is almost identical for the same applied strain ranges. Only the TMF tests with an applied mechanical strain range of $\Delta\varepsilon_{mech,2}$ show a significant lifetime difference. The relaxation during the hold time is constant over the cycle number. During the first cycle dynamic relaxation due to the increasing applied temperature is observed (Fig. 4, right).

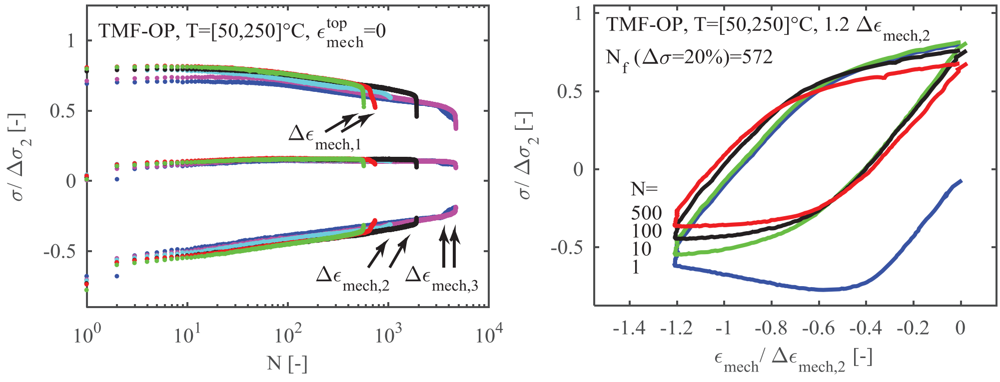

Fig. 4: Cyclic hardening/ softening curves for all performed OP TMF tests (left); stress-strain hysteresis loops of a TMF test with a mechanical strain range of $\Delta\varepsilon_{mech,1}$ = 1.2 $\Delta\varepsilon_{mech,2}$ (right)

TMF simulation

In Fig. 5 (left) the experimental stress-strain hysteresis loop of a TMF test with a mechanical strain range of 1.2 $\Delta\varepsilon_{mech,2}$ is shown. The model was fitted to the experimental hysteresis. The shape and area of the hysteresis loop as well as the stress range and the stress relaxation are exactly reproduced by the model. The identified parameters were used for the calculation of another TMF test with a smaller mechanical strain range (Fig. 5, right). The shape and area of the hysteresis loop as well as the stress relaxation are well reproduced by the model. The calculated stress range is negligibly larger than the experimental stress range. The described procedure is shown for illustration for the ageing time of 6.4 hours (286 cycles). To span a field of several ageing temperatures for the application in cylinder heads more TMF tests with different maximum temperatures are necessary.

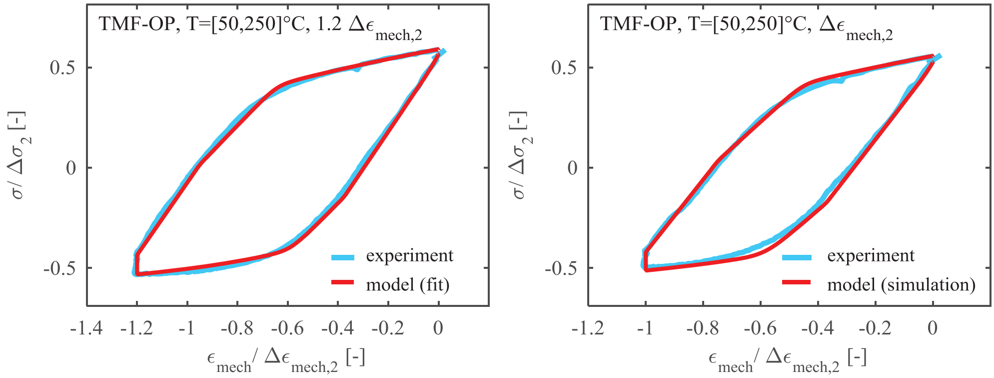

Fig. 5: Experimental and fitted stress-strain hystereses of a TMF test with a mechanical strain range of 1.2 $\Delta\varepsilon_{mech,2}$ (left); experimental and calculated stress-strain hystereses of a TMF test with a mechanical strain range of $\Delta\varepsilon_{mech,2}$ at the same ageing state (right)

Microstructure investigations

After TMF testing all fracture surfaces were investigated by scanning electron microscopy (SEM). All fracture surfaces show striations, and crack weals are detected near freely solidified surfaces (Fig. 6, left). This observation indicates that material defects caused by the Lost Foam production process are crucial for crack initiation. Hence, micro-CT scans with a resolution of 10 µm were performed before and after all TMF tests. The CT scan before TMF testing was performed across the entire gauge length of the specimens to consider all material defects. The scan after TMF testing was put into the scan before TMF testing. By comparison of the fracture surfaces scanned by SEM and CT it was possible to detect the crack initiating pore in the CT scan and to determine the morphology of that pore (Fig. 6, right).

At all investigated specimens the crack initiating pores have a small distance to the specimen surface and a small sphericity. The sphericity is defined as the ratio of the surface of a sphere with the same volume to the surface of the regarded pore. The product of the surface distance and the sphericity of the crack initiating pore has one of the smallest values compared to all pores across the gauge length. Therefore this parameter can be considered to be a characteristic quantity. The focus of future work must be to correlate this characteristic parameter with the experimentally observed lifetime.

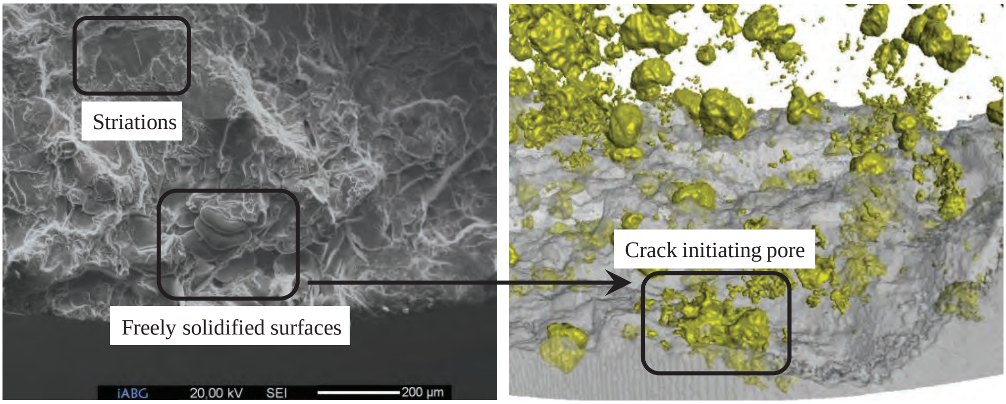

Fig. 6: Fracture surface by SEM (left); pores detected by micro-CT (right)

CONCLUSION AND OUTLOOK

In this work, TMF tests on an aluminium-silicon cast alloy were performed between 50°C und 250°C with specific mechanical strain ranges. The specimens for these tests were extracted from the combustion chamber side of the cylinder heads to consider the influence of the Lost Foam casting process. Additionally, the deformation behaviour was modelled with a viscoplastic material model for a particular ageing state. The parameters were identified by adapting the model to TMF test data. The thermomechanical deformation behaviour was simulated using these identified temperature-dependent parameters. The shape and area of the hysteresis loop as well as the stress relaxation were well reproduced by the model. Moreover, crack initiating material defects were detected by SEM. By means of micro-CT scans before and after TMF testing a characteristic parameter for Lost Foam cast cylinder heads under TMF loading was defined and quantified.

During the next steps further uniaxial TMF tests under identical loading conditions have to be performed to identify a quantitative correlation between the characteristic parameter and lifetime under TMF loading. Subsequently, a suitable extreme value distribution function has to be determined for the variation of the characteristic parameter. The maximum value of the characteristic parameter inside a given number of cylinder heads has to be predicted by extrapolation using the volume ratio between the specimen and the cylinder head volume. Furthermore additional TMF tests with other maximum temperatures are necessary to cover more ageing states for model parameter identification. Thus, the deformation calculation of the cylinder heads can be performed. Additionally, the relation between the characteristic parameter and the lifetime has to be implemented into the lifetime model. Thus, the lifetime as well as the variation of lifetime of cylinder heads subjected to thermomechanical loading can be assessed as a function of the variation of characteristic parameters in specimen geometry.

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