

TMF Life Prediction of High Temperature Components Made of Cast Iron HiSiMo: Part I: Uniaxial Tests and Fatigue Life Model

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ABSTRACT

HiSiMo cast irons are frequently used as material for high temperature components in engines as e.g. exhaust manifolds and turbo chargers. These components must withstand severe cyclic mechanical and thermal loads throughout their service life. The combination of thermal transients with mechanical load cycles results in a complex evolution of damage, leading to thermomechanical fatigue (TMF) of the material and, after a certain number of loading cycles, to failure of the component. In this paper (Part I), the low-cycle fatigue (LCF) and TMF properties of HiSiMo are investigated in uniaxial tests and the damage mechanisms are addressed. On the basis of the experimental results a fatigue life model is developed which is based on elastic, plastic and creep fracture mechanics results of short cracks, so that time and temperature dependent effects on damage are taken into account. The model can be used to estimate the fatigue life of components by means of finite-element calculations (Part II of the paper).

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INTRODUCTION

High temperature components in combustion engines and exhaust systems must withstand severe cyclic mechanical and thermal loads throughout their service life. Inhomogeneous temperature distributions and the interaction with neighboring components constrain the thermal expansion and contraction of the material, resulting in high local stresses and inelastic strains. The thermal transients with associated mechanical load cycles results in a complex evolution of damage, leading to thermomechanical fatigue (TMF) of the material and, after a certain number of loading cycles, to failure of the component.

Ferritic cast iron materials are preferred materials used for exhaust manifolds because of low costs, high heat conductivity and low coefficient of thermal expansion compared to austenitic materials. However, high temperature strength as well as creep and scaling/oxidation resistance are significantly lower, so that the range of application is typically below 800 °C and is limited further upwards due to austenitization.

Traditionally numerous expensive and time-consuming bench tests are necessary to identify the appropriate design that ensures the integrity of the component throughout the whole product life. Hence, there is a demand for material models that are applicable to ferritic cast iron materials and allow the estimation of the components lifetime. With these models, the components could be optimized via computer simulations and the number of bench tests could be reduced.

Reliable lifetime models for TMF problems are rare. Simple phenomenological lifetime models, as e.g. the Manson-Coffin relation, the Smith-Watson-Topper parameter or the Ostergren parameter, cannot reproduce the dependency of damage on the stress-temperature history appropriately. The well-known Sehitoglu model [1] incorporates damage accumulation due to fatigue, oxidation and creep. However it uses a purely phenomenological model for fatigue. Hence lifetime models are needed that refer to the actual damage mechanism, namely the growth of TMF cracks, and that are able to reproduce the dependency of crack growth rates on cycle times, strain amplitudes, mean stress and temperature.

In this paper a mechanism-based model for TMF life estimation of the ferritic cast iron HiSiMo is described, that uses fracture mechanics results to describe crack growth. The material properties included in the model are determined on the basis of experimental results obtained in uniaxial tests. In Part II of the paper, the model is extended to multiaxial loading conditions and applied together with a time and temperature dependent plasticity model to predict the fatigue life of an exhaust manifold.

EXPERIMENTAL

In this section, the investigated material, the testing conditions for materials characterization and the results of the tests are presented.

Material

In this paper the ferritic cast iron HiSiMo, which contains 3.7 % Si and 0.6 % Mo, is investigated. The material was supplied in the form of directly cast round specimen with a circular cross section of 7 mm in the gauge length. The specimen are tested in the as-cast condition without surface machining in order to keep the fine-grained surface layer, which is also present in critical areas of the components.

Figure 1 depicts a metallographic section on an edge near region with cast skin. The graphite nodules are well formed and correspond to a morphology of type VI-7 according to the European standard EN ISO 945. The cast skin shows no graphite depletion or voids.

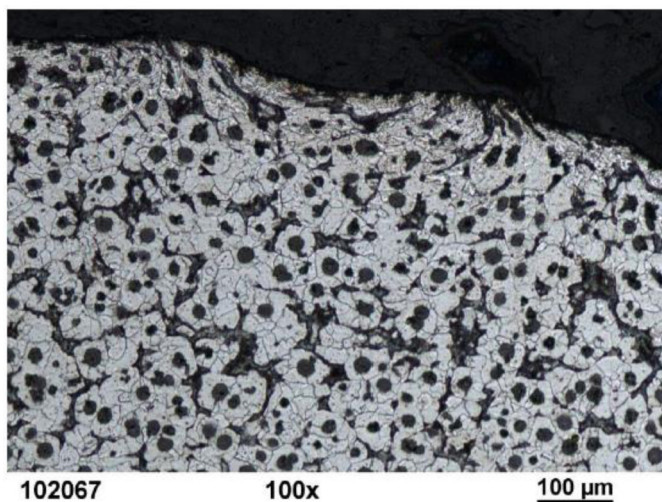


Figure 1. Micrograph of edge near region with cast skin

Setup and Procedure

The experiments were performed with a universal servo-hydraulic testing machine of Instron Ltd. The elongation in the gauge length was measured with a Maytec extensometer, which comes into contact with the specimen with ceramic rods. The gauge length was 10 mm. The specimens are heated inductively. The temperature of the specimen is measured with three NiCr-Ni thermo-couples in the gauge length to monitor

the homogeneity of the temperature distribution. Strain and temperature histories are controlled with self-made software programmed in LabView.

Strain-controlled isothermal complex low-cycle fatigue (CLCF) [1] tests were conducted at 20, 200, 400, 500, 600, 700 and 800 °C. The CLCF tests are composed of a non-periodical part and a periodical part. In the nonperiodical part, strain rates and hold times in tension and compression are used (Figure 2). In the periodical part of the CLCF test, the specimen is cycled to failure with a constant strain rate. With this complex loading program strain rate effects, stress relaxation and the hardening properties of the material can be investigated in a single experiment.

The isothermal CLCF tests are supplemented by TMF tests. In-phase as well as out-of-phase mechanical strain-controlled TMF tests were performed. The minimum temperature was 200 °C in each case, the maximum temperatures were 600 in one test series and 720 °C in the second test series. The tests were performed according to the TMF standard ISO 12111. The cycle periods of the TMF tests were typically a factor 20 to 50 longer than those of the CLCF tests.

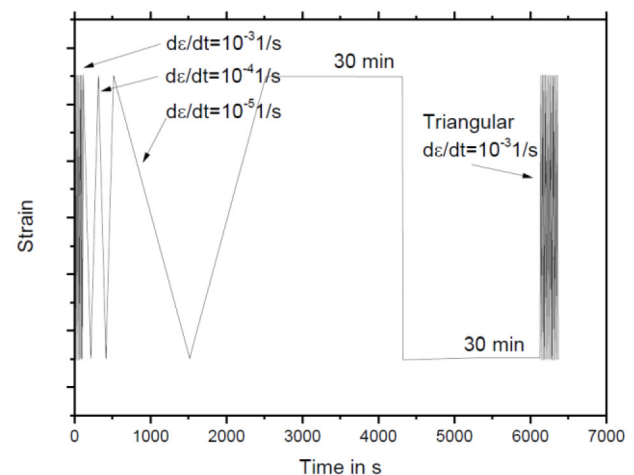


Figure 2. Strain history in CLCF test

Experimental Results

Measured stress over time relations of the non-periodic part of selected CLCF tests are shown in Figure 3. Starting at a temperature of 500 °C significant time dependent material behavior (rate dependency and stress relaxation) is observed and becomes more pronounced with increasing temperature. The material strength drops significantly in the temperature range from 400 to 700 °C. Selected TMF test results are shown in Figure 4. The same scale for the stresses is used in these figures.

The fatigue lives of all tests are shown in Figure 5. The cycles to failure N_f in the fatigue tests are determined at a drop of 5 % of the maximum tensile force. By trend, tests at comparable mechanical strain amplitude show a decreasing fatigue life with increasing temperature in the strain life diagram. However, tests at 400 °C and the TMF tests show longer fatigue lives.

which becomes very clear in the plot showing the plastic strain range over life. At 400 °C the material also shows the least ductility in tensile tests.

Fractography by means of scanning electron microscopy (SEM) of the fractured specimens tested at 400 °C reveals that partially cleavage fracture occurs (Figure 6). This can explain the low fatigue lives already at low plastic strain amplitudes. Due to highly oxidized fracture surfaces in the TMF tests, no statement regarding brittle fracture mechanisms is possible to explain the relatively low fatigue lives of those tests. At temperatures below and above 400 °C, the fracture mechanism is predominantly ductile. Exemplarily, a SEM image of a fracture surface of a specimen tested at 500 °C is shown in Figure 7.

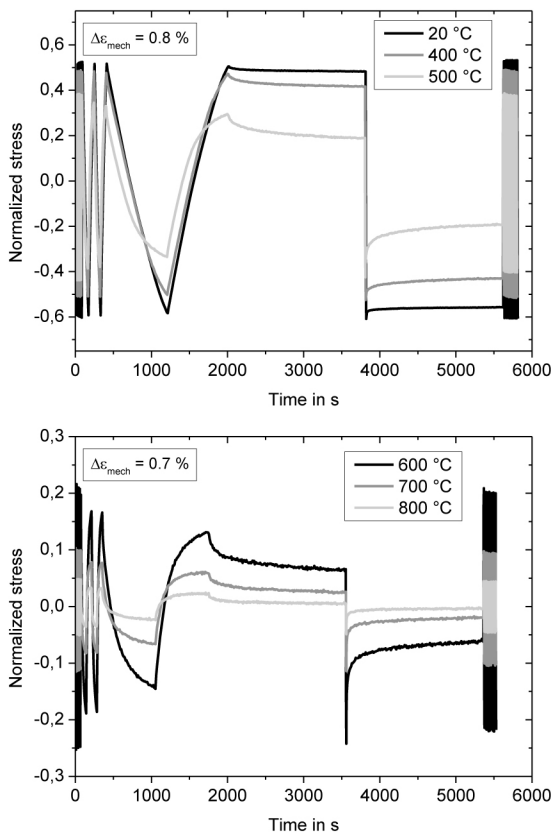


Figure 3. Exemplary stress response at low (top) and high temperatures (bottom). Note: different ordinate scales.

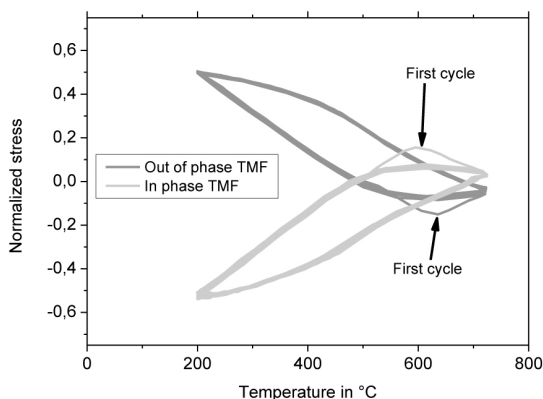


Figure 4.

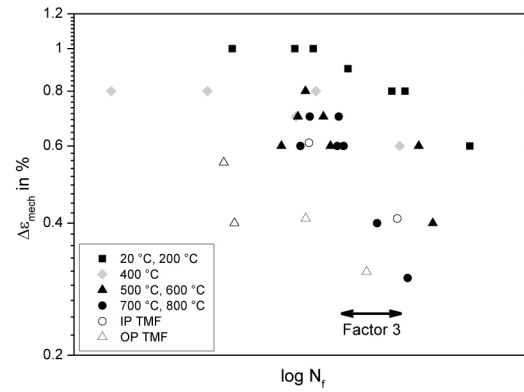


Figure 4. (cont.) Exemplary stress response of the first 10 cycles of IP and OP TMF experiments with the same temperature range and mechanical strain range.

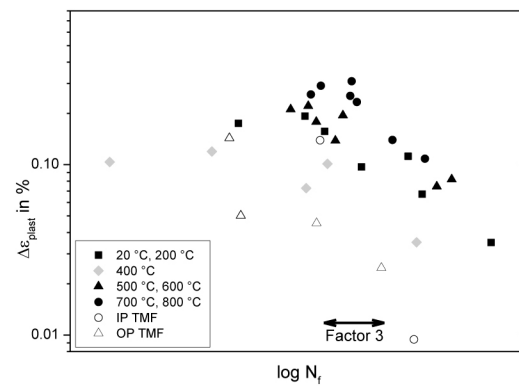


Figure 5. Strain-life (top) and Manson-Coffin (bottom) plot of all CLCF and TMF tests.



Figure 6. SEM image of fracture surface of specimen tested at 400 °C showing regions cleavage fracture (river patterns).