THERMOMECHANICAL FATIGUE TEST OF CAST IRON GGG SIMO 4.05 AND ITS NUMERICAL EVALUATION

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Abstract. Evaluation of thermomechanical fatigue (TMF) test of cast iron GGG SiMo 4.05 is presented. A typical uniaxial TMF test is performed on Coffin type apparatus. The rod specimen is fixed in the apparatus and cyclically heated by direct passage of electric current and cooled until the rupture. The mutual approach of specimen's ends is measured during experiment and mechanical strain range of specimen is calculated. In this way, the dependence mechanical strain range – cycles to failure is obtained. This is classical evaluation approach of TMF test performed on Coffin type apparatus. Temperature along the specimen is not constant in the same time. This leads to the fact that the evaluated strain of the specimen is "average". The general usage of such thermomechanical fatigue tests for real structure will be problematical if the temperature field distribution or stiffness doesn't correspond to test conditions. It was proposed methodology that generalizes the results of such thermomechanical fatigue tests. The principle of this methodology is finite element simulation of real fatigue test. Local strain range is determined in the middle of the specimen. This is the typical location of the rupture. Computed local mechanical strain range is assigned to experimentally obtained cycles to failure. Localized lifetime curve is obtained. The proposed methodology allows the evaluation of thermomechanical fatigue test on Coffin type apparatus for more general application.

1 INTRODUCTION

Cyclic heating and cooling is typical for some structures, for example equipment of chemical and energetical industry. If forces generated in material due to constrain are high enough, plastic strain occurs. Alternating tensile and compressive plastic macrodeformation leads to progressive damage and alternatively cracking of structure. The fatigue phenomenon can be categorized as low-cycle fatigue. This type of fatigue with the effects of elevated temperature is usually divided into the following categories:

- thermal (or thermal-stress) fatigue (TF): Structure hasn't external constraints. Thermal stresses arise due to uneven temperature distribution and inhomogeneous thermal properties of structure.
- thermomechanical fatigue (TMF): Structure has external constraints, i.e. action or reaction forces are applied on structure surface.
- isothermal fatigue at elevated temperature (IF): Structure is subjected to alternating external forces only. Elevated temperature remains constant.

Number of cycles to failure in terms of thermomechanical fatigue may be less than during comparable mechanical loading with a constant elevated temperature. The reason may be non-uniform distribution of temperature during cycling. In regions with a large temperature range is localized large plastic strain. This localized strain is typically much larger than the strain in the case of equally distributed temperature and equivalent mechanical load. Other influences are metallurgical processes, oxidation and creep during temperature changes.

Therefore, the material behaviour in terms of thermal and thermomechanical fatigue is examined with special tests. An overview of these tests served [1]. Presented paper focuses on the evaluation of a typical uniaxial TMF test. The rod specimen is clamped between two faces of test apparatus (called a Coffin type after its developer). Therefore it is a test with external constraints. The principle of this test is in cyclic heating and cooling of specimen until the rupture. Heat is generated by direct passage of electric current. Measured is mutual movement of apparatus faces during the temperature cycling. Mechanical strain is determined from these data. Evaluation of this test provides the dependence mechanical strain range - cycles to failure (TMF lifetime curve).

When applying results from above evaluation of TMF test it is necessary to be taken into account that temperature along the specimen is not constant in the same time (see figure 6 and subsection 3.2). This leads to the fact that the evaluated strain of the specimen is "average". The general usage of such thermo-mechanical fatigue tests for real structure is problematical, when the temperature field distribution and stiffness does not correspond to test conditions. It was proposed methodology which generalizes the results of such thermo-mechanical fatigue tests. The principle of this methodology is numerical simulation of real fatigue test. It is possible to find numerical simulation of hight-temperature cycling loading. For example [2] described IF and TMF simulation using viscoplasticity model, but temperature uniformity in gauge section of specimen is considered. Our simulation using finite element method (FEM) takes into account real temperature distribution during TMF test. Local strain range is computed in the middle of the specimen. This is the typical location of the rupture. Computed local mechanical strain range is assigned to experimentally obtained cycles to failure. Localized life-time curve in terms of TMF is obtained.

2 TMF EXPERIMENTS

2.1 Testing device and procedure

Tests of TMF were carried out on Coffin type apparatus (figure 1) in the company SVUM a.s. with own participation. This apparatus consists of two solid faces (A) connected through connecting rods (B). Stiffness of the connecting rods k_C is calibrated. The rod specimen (C) is attached to the faces in clamping devices (D) and heated by direct passage of electric current. Cooling of the specimen is accelerated by a fan. The fatigue test is carried out for temperature cycling between minimum T_{min} and maximum T_{max} temperature in the middle of the specimen.

Each of the thermo-mechanical fatigue tests consists of the following steps:

1. clamping the specimen at one end, other end is free
2. heating to a temperature T_{max} (free thermal dilatation of the specimen)
3. clamping the sample at the other end at the temperature T_{max}
4. holding time at the temperature T_{max}
5. cooling the sample to a temperature T_{min}
6. holding time at the temperature T_{min}
7. heating to a temperature T_{max}
8. Steps 4 to 7 are repeated until the rupture of the specimen.

This type of test provides out-of-phase waveform. Between the mechanical strain and temperature waveforms is phase angle 180°. Following parameters are measured:

- free thermal expansion of specimen Δl_T (during step 2)
- mutual approach of apparatus faces Δl_C (during steps 4 to 7)
- temperature. Record of temperature in the centre of the specimen is also used for heating control.

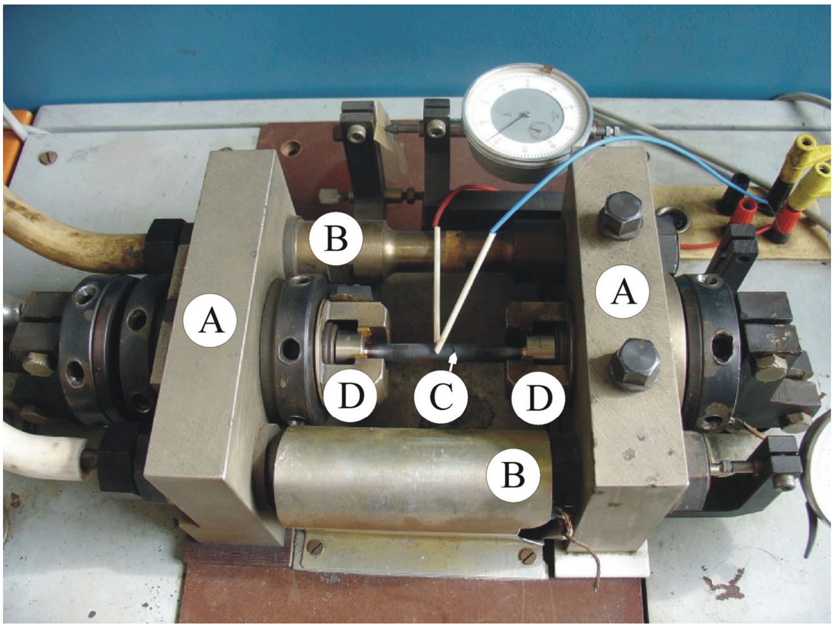

Figure 1. Apparatus for thermomechanical fatigue testing.

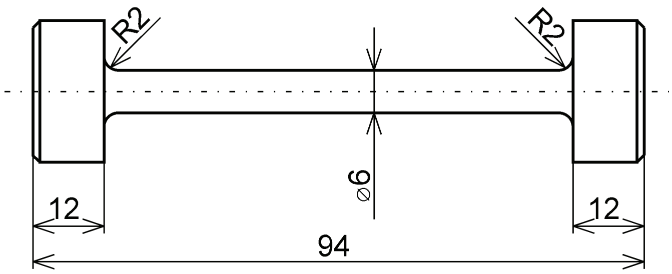

Figure 2. Geometry of the specimen for TMF test.

2.2 Principle of test evaluation

When cooling the specimen (both ends are fixed), stress and mechanical strain arises. If the apparatus was perfectly rigid, it would be a mechanical extension in time $\Delta l(t)$ due to cooling equal to the difference of maximum thermal dilatation at maximum temperature in the centre of the sample $\Delta l_{T\max}$ and thermal expansion in time $\Delta l_T(t)$. In fact Coffin type apparatus isn't rigid. There is an approach of apparatus faces $\Delta l_C(t)$ due to cooling. Mechanical extension is specified as

$$\Delta l(t) = \Delta l_{T\max} - \Delta l_T(t) - \Delta l_C(t) \tag{1}$$

Mechanical strain ε of the sample in time t is defined as

$$\varepsilon(t) = \frac{\Delta l(t)}{l_0} = \frac{\Delta l_{T\max} - \Delta l_T(t) - \Delta l_C(t)}{l_0} \tag{2}$$

Defined reference length l_0 is less than the total length of the specimen. This length is defined as $l_0 = 67$ mm. Correction is proposed with regard to clamped heads of specimen. The approach of faces is zero at the beginning of first cycle, positive at minimum temperatures and negative at subsequent maximum temperatures due to plastic deformation. It is possible to express the maximum and minimum value of mechanical extension in the interval of one cycle as

$$\Delta l_{\max} = \Delta l_{T\max} - \Delta l_{T\min} - \Delta l_{C\max} \tag{3}$$

$$\Delta l_{\min} = \Delta l_{T\max} - \Delta l_{T\max} - \Delta l_{C\min} = -\Delta l_{C\min} \tag{4}$$

Mechanical extension range $\Delta(\Delta l)$ is given by

$$\Delta(\Delta l) = \Delta l_{\max} - \Delta l_{\min} = \Delta l_{T\max} - \Delta l_{T\min} - \Delta(\Delta l_C) \tag{5}$$

where $\Delta(\Delta l_C)$ is the apparatus faces approach range in one cycle.
Mechanical strain range $\Delta\varepsilon$ can be expressed as

$$\Delta\varepsilon = \frac{\Delta(\Delta l)}{l_0} = \frac{\Delta l_{T\max} - \Delta l_{T\min} - \Delta(\Delta l_C)}{l_0} \tag{6}$$

Based on the known stiffness of the test apparatus k_C and the mutual approach of apparatus faces Δl_C can be determined tensile stress

$$\sigma = \frac{k_C}{A}\Delta l_C \tag{7}$$

and stress range

$$\Delta\sigma = \frac{k_C}{A}\Delta(\Delta l_C) \tag{8}$$

where A is specimen's cross section.
It is possible to obtain dependence mechanical strain range – cycles to failure (TMF lifetime curve) based on above described evaluation of mechanical strain range. If the temperature is not constant along the specimen, the "average" strain range is evaluated. Therefore, the use of this lifetime curve is suitable only for structures with a similar temperature distribution and stiffness.

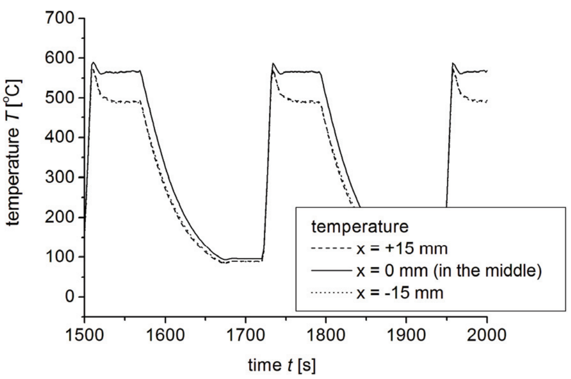

Figure 3. Time course of measured temperatures (part of the record, specimen with required $T_{\max}$ = 570 °C).

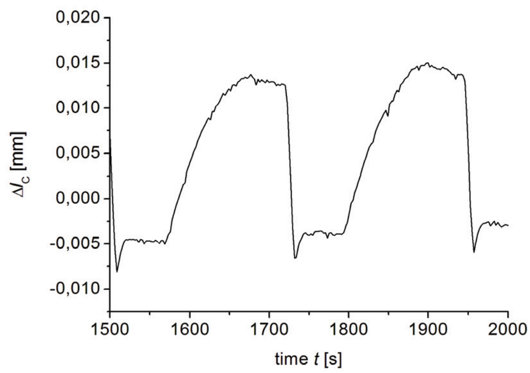

Figure 4. Time course of mutual approach of apparatus faces Δl_C (part of the record, specimen with required $T_{\max}$ = 570 °C).

2.3 TMF test program

The test program of thermo-mechanical fatigue was designed for nine specimens. Minimum temperature was the same for all specimens (T_{min} = 100 °C). Range of maximum temperatures T_{max} was set from 510 to 800 °C (T_{max} = 510; 540; 570; 600; 625; 675; 700; 750; 800 °C). The temperature of the specimen during cycling was measured by thermocouple in the centre of the sample and at distances ±15 mm from the centre in the axial direction. A typical time course of measured temperatures is shown in figure 3. During heating to required maximum temperature overshoot appeared. A similar phenomenon appeared at the minimum cooling temperature. Maximum difference between required and real value was 4.3 % for T_{max} and -7 % for T_{min}. During the tests there was recorded mutual approach of apparatus faces Δl_C (figure 4). For the samples with a temperature T_{max} = 625 °C and above was observed ratcheting. Ratcheting is defined as the accumulation of strain during asymmetrical stress cycling in a material.
The TMF lifetime curve evaluated using procedure in subsection 2.2 is displayed in figure 10.

3 NUMERICAL SIMULATION OF TMF TEST

In the case that temperature isn't constant along the specimen in the same time, evaluated mechanical strain range is "average". It doesn't correspond to real mechanical strain range in region of rupture. Therefore numerical simulation using FEM is used for local strain assessment.

3.1 FEM model

Software Abaqus 6.9 was used for the FEM simulation. Test specimen is modeled as a rotationally symmetrical body. The model mesh consists of 247 eight-nodal quads elements for axially symmetric analysis from the software Abaqus library (CAX8R designation). Simulation of each fatigue test is performed in two steps. In the first step the sample is clamped at one end (the boundary condition prevented displacements). The temperature field corresponding to the initial heating from the initial temperature to maximum temperature T_{max} is generated. At the beginning of the second step at a temperature T_{max} is established coupling between a node at the other end and a reference point, which is associated with a spring connector to rigid frame. Connector stiffness corresponds to the stiffness of the apparatus connecting rods k_C. The sample is cyclically loaded by thermal field in accordance with real test. 10 cycles were simulated to obtain stabilised stress-strain cycle (without modelling of ratcheting). Results from the last cycle are used for evaluation of the fatigue test.

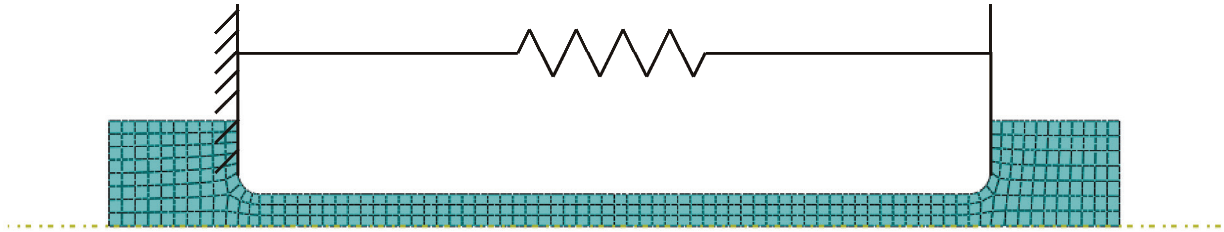

Figure 5. FEM model of specimen in Coffin type apparatus.

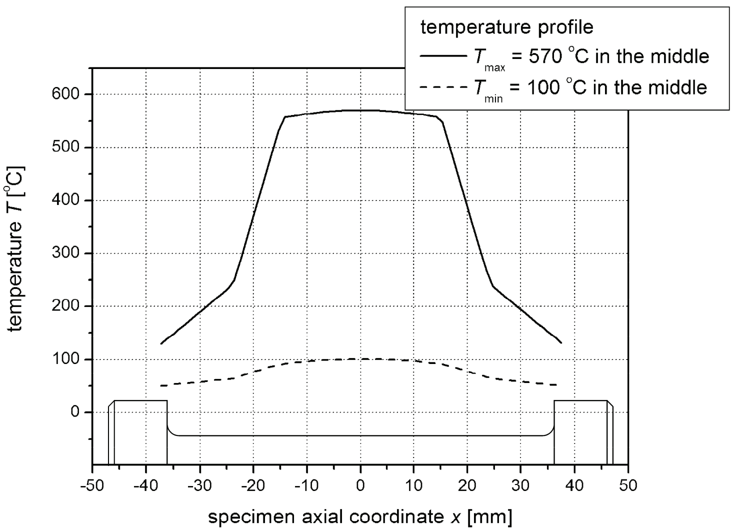

Figure 6. Axial temperature course (specimen with required T_{max} = 570 °C).

3.2 Temperature field

The temperature field is generated by user subroutine in dependence on time and axial coordinate of the specimen. The temperature fields are obtained by interpolation through measured values during experiments. Only dependence on longitudinal axis is taken into account. These data were specified on the basis of similar research of cast iron GGV 30 [3]. Data were symmetrized and in sequence of discrete times interpolated: in the central part of the specimen with 2nd order polynom, in the peripheral parts with straight lines. Figure 6 shows the selected temperature course in the longitudinal axis of the specimen.

3.3 Material model

The material was modeled as elasto-plastic. Plastic behaviour with regard to cyclic loading is described with Chaboche model of kinematic hardening [4]. Used material model is based on the von Mises plasticity

$$F(\boldsymbol{\sigma},\boldsymbol{\alpha},\sigma_Y) = f(\boldsymbol{\sigma}-\boldsymbol{\alpha}) - \sigma_Y = \sqrt{\frac{3}{2}(\mathbf{S}-\mathbf{a}):(\mathbf{S}-\mathbf{a})} - \sigma_Y \tag{9}$$

where $\boldsymbol{\sigma}$ is stress tensor, $\boldsymbol{\alpha}$ is kinematic tensor (tensor of shift of plasticity surface centre), σ_Y is yield stress (radius of plasticity surface), $\mathbf{S}$ is deviator of stress tensor and $\mathbf{a}$ is deviator of kinematic tensor. Plasticity rule expressing the increment of plastic strain tensor $d\boldsymbol{\varepsilon}_P$ is possible to write in form

$$d\boldsymbol{\varepsilon}_P = d\lambda \frac{\partial F}{\partial \boldsymbol{\sigma}} \tag{10}$$

where $d\lambda$ is scalar coefficient corresponding to increase of accumulated plastic strain $d\varepsilon_P$ defined as

$$d\varepsilon_P = \sqrt{\frac{2}{3} d\boldsymbol{\varepsilon}_P : d\boldsymbol{\varepsilon}_P} \tag{11}$$

According to the Chaboche kinematic tensor is composed from M parts

$$\mathbf{a} = \sum_{i=1}^{M} \mathbf{a}_i \tag{12}$$

each part is defined as

$$d\mathbf{a}_i = \frac{2}{3} C_i d\varepsilon_P - \gamma_i \mathbf{a}_i d\varepsilon_P \tag{13}$$

C_i and γ_i are material constants dependent on temperature. In the case of cyclic uniaxial load can be derived dependence between the stress amplitude σ_a and plastic strain amplitude ε_{aP}

$$\sigma_a = \sigma_Y + \sum_{i=1}^{M} \frac{C_i}{\gamma_i} \tanh(\gamma_i \varepsilon_{aP}) \tag{14}$$

This relationship describes the connection of hysteresis loops vertices (cyclic stress-strain curve). In the case of simulated fatigue tests were considered in equation (14) based on experience three kinematic parts, in the third part was considered only linear hardening

$$\sigma_a = \sigma_Y + \frac{C_1}{\gamma_1}\tanh(\gamma_1 \varepsilon_{aP}) + \frac{C_2}{\gamma_2}\tanh(\gamma_2 \varepsilon_{aP}) + C_3 \varepsilon_{aP} \tag{15}$$

This model takes into account six parameters (σ_Y, C_1, C_2, C_3, γ_1, γ_2). Parameter γ_3, which affects the rate of ratcheting, was not considered in the primary research.

3.4 Identification of material parameters

3.4.1 Elastic parameters and static stress-strain curve

Elastic material behaviour is described with temperature dependence of Young's modulus and coefficient of thermal expansion. The value of Poisson's ratio ν is assumed constant. Young's modulus E was setup from static test with strain measurement using extensometer on specimens for constant temperature 20; 100; 200; 300; 400; 500; 600; 700 °C. Modulus for temperature 800 °C was setup from dynamic test. Longitudinal thermal expansion α (the same symbol is used for components of kinematic tensor also) of the material was determined by dilatometer in helium atmosphere in the range from temperature 20 °C to 875 °C and linearized.

Given the complexity of cyclic tests (determination of the cyclic stress-strain curve) were made only static tests (determination of static stress-strain curve) for constant temperatures 20; 300; 400; 500; 550; 600; 650; 700; 750; 800 °C. Yield stress σ_Y is identified as a stress after its unloading remains permanent strain 0.002.

Cyclic stress-strain curves were estimated as the calibrated static stress-strain curves. Estimation is based on multiplication of stress by coefficient q

$$\sigma_a = q\,\sigma \tag{16}$$

where σ_a is stress on cyclic stress-strain curve and σ on static stress-strain curve for the same value of plastic strain $\varepsilon_P = \varepsilon_{aP}$. Constants of Chaboche model were determined from the measured static stress-strain curves for constant temperatures with calibration coefficients q = 0.7; 0.8; 0.9; 1.0; 1.1; 1.2 using nonlinear regression (Levenberg-Marquardt method). Value q = 1.0 means that static and cyclic curves are the same, $q > 1$ indicated cyclic hardening and $q < 1$ cyclic softening of the material. In the figure 7 is an example of cyclic stress-strain curve estimation from static stress-strain curve for temperature 20 °C.

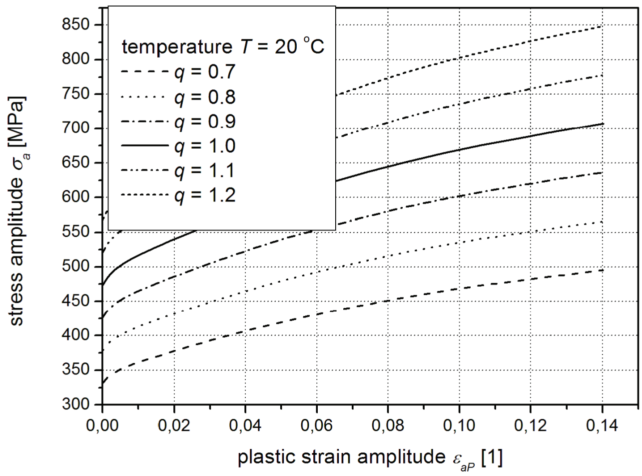

Figure 7. Estimation of cyclic stress-strain curve from static stress-strain curve for different values of calibration coefficient q (temperature 20 °C).

3.4.2 Calibration of cyclic stress-strain curves

Calibration of cyclic stress-strain curve is based on comparison of cyclic load curves. These curves represent stable relationships between stress σ and mechanical strain ε during one period of temperature cycling. Compared are cyclic load curves obtained

- experimentally from experiments described in section 2
- numerically by FEM simulation. Simulated were all TMF test with material parameters obtained from estimation of cyclic stress-strain curve using equation (16). Calibration coefficient q with values 0.7; 0.8; 0.9; 1.0; 1.1; 1.2. was used.

Both types of cyclic load curves were evaluated using procedures described in subsection 2.2. “Optimal” value of coefficient q is this one which provides a similar shape and size for both experimentally and numerically obtained cyclic load curves. Figure 8 shows the example of cyclic load curves determined from experiment and numerical simulations (specimen with required $T_{\max}$ = 570 °C). Relative stress and mechanical strain are introduced. They are defined as ratio of current stress or strain value and maximal stress or strain value for particular specimen from “classical” experimental evaluation. In terms of "thinness" are better calibrations for $q > 1$. Value q = 1.1 was chosen for further simulations.

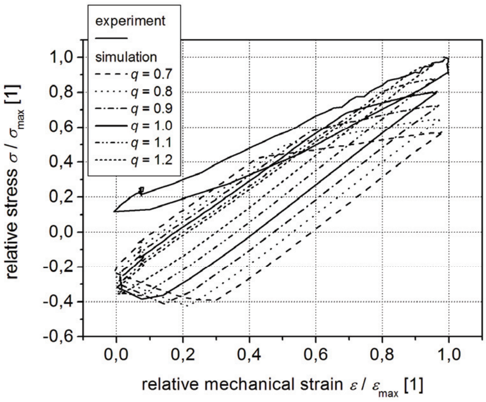

Figure 8. Comparison of experimentally and numerically obtained cyclic load curves (specimen with required $T_{\max}$ = 570 °C).

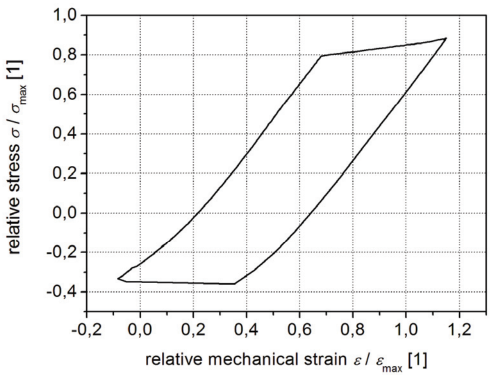

Figure 9. Local cyclic load curve (specimen with required $T_{\max}$ = 570 °C).

3.5 Local lifetime curve

Local cyclic load curve was evaluated from computed values of stress and mechanical strain for each specimen. It is relation between stress and local mechanical strain in the middle of the specimen (figure 9). Relative values with the same definition as by figure 8 are introduced. The local mechanical strain range in the middle of the specimen is possible to obtain. Computed local mechanical strain range is assigned to experimentally obtained cycles to failure. The dependence of local mechanical strain range on cycles to failure is modified lifetime curve in terms of TMF. Comparison of lifetime curve from "classical" evaluation (subsection 2.2) and local lifetime curves for calibration coefficient $q = 1.1$ is in figure 10. Relative mechanical strain range is introduced. It is defined as ratio of current strain range and maximal strain range from numerical evaluation.

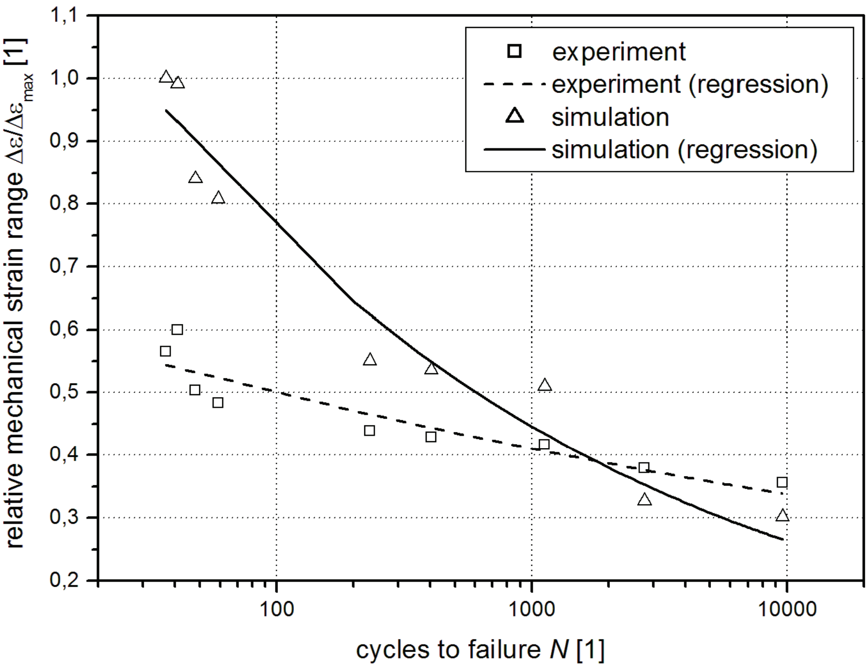

Figure 10. TMF lifetime curves obtained from "classical" evaluation ("average" strain range is used) and evaluation of numerical simulation (local strain range is used).

4 CONCLUSION

Methodology of TMF test evaluation was designed and used for determination of cast iron GGG SiMo 4.05 TMF lifetime curve. Nonuniform temperature distribution along the specimen and local values of strain in the exposed region are taken into account. This allows the evaluation of TMF test on Coffin type apparatus for more general application.

TMF tests are numerically simulated and local strain values are computed. FEM numerical simulation is based on use of the elasto-plastic material model. Chaboche model of kinematic hardening capable of cyclic properties simulation is used. Material model parameters have been identified from cyclic stress-strain curves. Procedure was designed to estimate cyclic stress-strain curves with static stress-strain curves using.

The next step in this research is realization of TMF experiments on specimens with greater value of cross-section and therefore greater stiffness. Temperature range will be the same as in the above described experiments. Because of different specimen stiffness will be evaluated another strain ranges. It is possible to obtain relation between cycles to failure, strain range and temperature range. Further research will also focus on the simulation of ratcheting and the corresponding calibration of this material model.

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