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Experimental Stress Analysis

Evaluation of thermo-mechanical fatigue test based on FEM simulation

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Abstract: Methodology for evaluation of uniaxial thermo-mechanical fatigue test is presented. Classical evaluation provides dependence average strain range of specimen – cycles to failure. Proposed methodology evaluates localized strain range in the place of the specimen's rupture. The principle of this methodology is finite element simulation of real fatigue test and assigning of computed local mechanical strain range to cycles to failure from experiment. This methodology was applied to GGV 30 vermicular grey cast iron.

Keywords: Thermo-mechanical fatigue, Coffin apparatus, FE simulation, GGV 30 cast iron

1. Introduction

Loading with cyclically changing temperature in operating mode heating – cooling is typical for some structures. In the case of relatively high and non-uniform distributed temperatures arises plastic strain. It is consequence of constrain of heated regions due to relatively cool environment and (or) external constrains. Plasticized regions are strained by residual stresses during the cooling. Cycle heating - cooling is reflected in alternating tensile and compressive plastic macrodeformation. It leads to the initiation and propagation of fatigue cracks. This is typical for low-cycle fatigue phenomenon. When the structure is not loaded by external forces, the term thermal fatigue is used. When external loading and (or) constraints are applied, alternating of thermal and mechanical strain is occurred. This phenomenon is called thermo-mechanical fatigue. Research and experiences show [1] that thermo-mechanical fatigue damage of the material can occurs earlier than in the case of comparable mechanical loading at constant temperature. The reason may be that during load with alternating warming and cooling temperature is non-uniformly distributed in the material. Localization of high plastic deformation is in the regions with a high temperature. This local deformation is typically much higher than the deformation in the case of uniform temperature distribution and equivalent mechanical alternating loads. There is an influence with metallurgical processes during alternating temperatures too. Therefore it is necessary to identify thermo-mechanical fatigue process in materials using special tests.

2. Thermo-mechanical fatigue test

The overview of experimental techniques in thermal and thermo-mechanical fatigue research gives [2]. A typical thermo-mechanical fatigue uniaxial test with external constrains is performed on Coffin apparatus. The rod specimen is fixed in the apparatus and cyclically

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heated and cooled until the rupture. This test usually leads to the relationship between the level of mechanical strain range and number of cycles to failure. The typical measure of the strain range is the range of the average relative extension of the test specimen. The principle of the described test is an alternate heating and cooling of the rod specimen fixed between two points.

2.1. Coffin apparatus

There is presented project of thermo-mechanical fatigue testing of GGV 30 vermicular grey cast iron. Real tests were performed in SVUM a.s. company on the Coffin apparatus (Fig. 1). This apparatus consists of two stiff faces connected through connecting rods. The rod specimen is attached to the faces in clamping devices and heated by direct passage of electric current. Cooling of the specimen is accelerated by a fan. Stiffness of the connecting rods k_C is calibrated. Mutual displacement of apparatus faces Δl_C is measured and the reaction force F_R between the faces can be determined. The temperature in the centre of the sample is measured by thermocouple and is also used for heating control. The fatigue test is carried out for temperature cycling between minimum T_{min} and maximum T_{max} temperature in the middle of the sample.

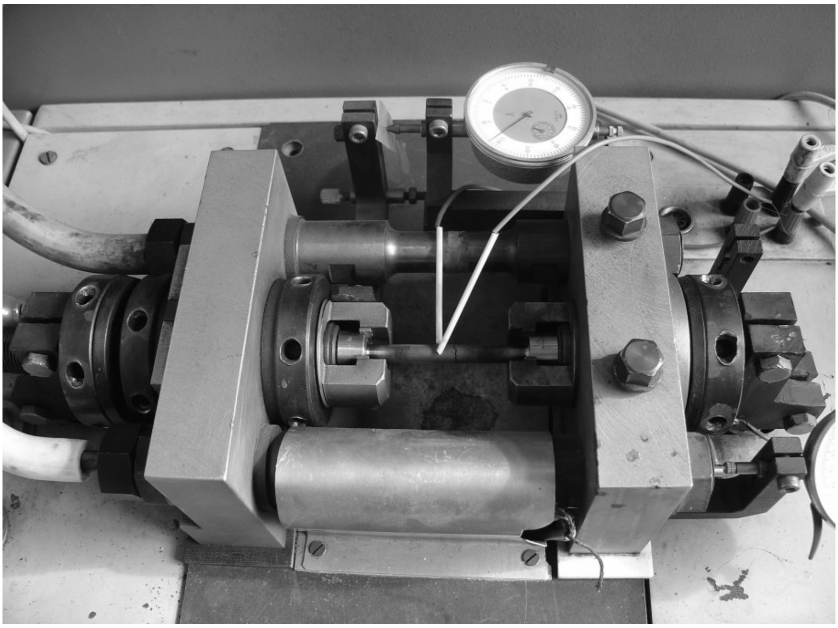

Fig. 1. Coffin apparatus for thermo-mechanical fatigue test

Eleven specimens were tested. Their geometry is shown in Fig 2. Minimum temperature was the same for all specimens – T_{min} = 100°C. Maximum temperatures T_{max} ranged from 500°C to 700°C. Typical temperature cycling is in Fig. 3. 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 $T_{\max}$

Steps 4 to 7 are repeated until the rupture of the specimen.

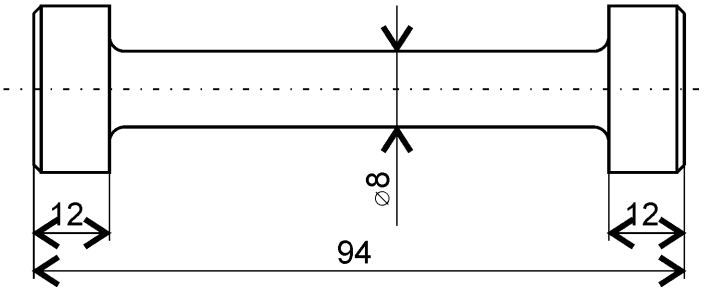

Fig. 2. Geometry of specimen for thermo-mechanical fatigue test

During the test the following parameters are measured:

1. free thermal expansion Δl_T of specimen (one end of the specimen is free)
2. relative approach of apparatus faces Δl_C (both ends of the sample are clamped)

Measurement of Δl_C is performed in selected cycles of heating - cooling at the beginning and proposed end of specimen fatigue life.

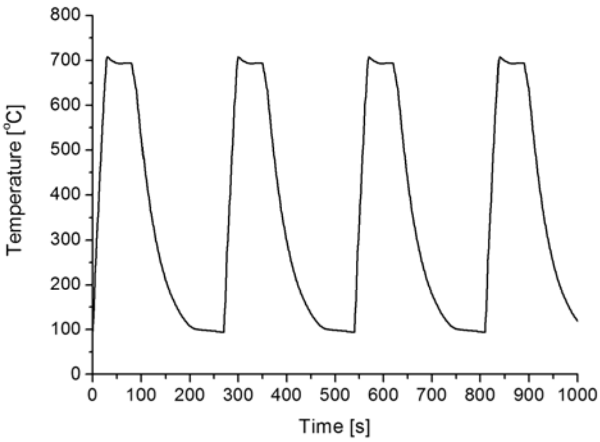

Fig. 3. Typical temperature cycling (temperature in the middle of the specimen, $T_{\max}$ = 700°C)

2.2. Classical evaluation

Strain correction is proposed with regard to the localization of strain in regions with high temperature. Defined reference length l_0 is less than the total length of the sample with respect to the clamp. This length is defined as l_0 = 67 mm. Mechanical strain with correction at time t is defined as

$$\varepsilon(t) = \frac{\Delta l(t)}{l_0} \tag{1}$$

where $\Delta l(t)$ is a mechanical extension of the sample. Mechanical strain range with correction $\bar{\varepsilon}$ is determined as the difference of maximum and minimum values of strain in the interval of one cycle

$$\bar{\varepsilon} = \varepsilon_{\max} - \varepsilon_{\min} = \frac{\Delta l_{\max} - \Delta l_{\min}}{l_0} \tag{2}$$

When cooling the specimen (both ends are fixed), stress and mechanical strain arises. If the Coffin apparatus was perfectly rigid, it would be a mechanical extension at the time Δl(t) due to cooling equal to the difference of maximum thermal dilatation at maximum temperature in the centre of the sample Δl_{Tmax} and thermal expansion at the time Δl_T(t). There is approach of apparatus faces, mechanical extension is specified as

$$\Delta l(t) = \Delta l_{T\max} - \Delta l_T(t) - \Delta l_C(t) \tag{3}$$

The approach of faces is zero at the beginning of first cycle (clamping of both ends), 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

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

$$\Delta l_{\min} = \Delta l_{T\max} - \Delta l_{T\max} - \Delta l_{C\min} = -\Delta l_{C\min} \tag{5}$$

Mechanical extension range $\Delta \bar{l}$ is given by

$$\begin{aligned}\Delta \bar{l} &= \Delta l_{\max} - \Delta l_{\min} = \Delta l_{T\max} - \Delta l_{T\min} - \left(\Delta l_{C\max} - \Delta l_{C\min}\right) \\ &= \Delta l_{T\max} - \Delta l_{T\min} - \Delta \bar{l}_C\end{aligned} \tag{6}$$

where $\Delta \bar{l}_C$ is the faces approach range in one cycle. Mechanical strain range with correction $\bar{\varepsilon}$ can be expressed with measured values as

$$\bar{\varepsilon} = \varepsilon_{\max} - \varepsilon_{\min} = \frac{\Delta l_{T\max} - \Delta l_{T\min} - \Delta \bar{l}_C}{l_0} \tag{7}$$

Based on the known stiffness of the test apparatus k_C and the relative displacement of faces $\Delta l_C(t)$ can be determined the reaction

$$F_R(t) = k_C \Delta l_C(t) \tag{8}$$

and tensile stress

$$\sigma(t) = \frac{F_R(t)}{A} = \frac{k_C}{A}\Delta l_C(t) \tag{9}$$

where A is specimen's cross section. Stress range $\bar{\sigma}$ is

$$\bar{\sigma} = \frac{k_C}{A}\Delta \bar{l}_C \tag{10}$$

2.3. Results

The Table 1 shows the measured values at the start of cycling for 11 test samples used for determination of the thermo-mechanical fatigue life-time curve: “average” mechanical strain range $\bar{\varepsilon}$ - cycles to failure N (Fig. 4).

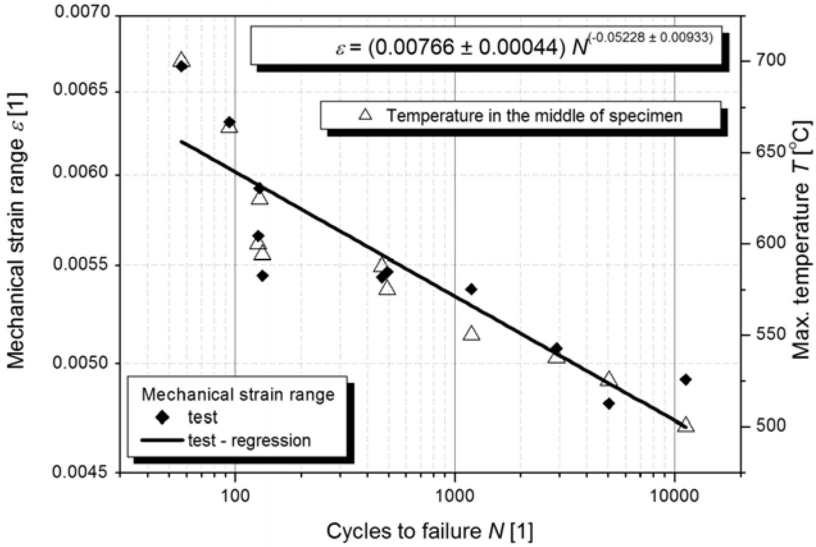

Fig. 4. Life-time curve of GGV 30 vermicular grey cast iron – "average" curve (classical evaluation)

Table 1. Results of thermo-mechanical fatigue test of GGV 30 cast iron

Spec. No.	T_{max} [°C]	$\Delta l_{T\max}$ - $\Delta l_{T\min}$ [mm]	$\Delta \bar{l}_C$ [mm]	$\bar{\varepsilon}$ [%]	$\bar{\sigma}$ [MPa]	N [1]
1	500	0.345	0.0145	0.4922	183.2	11 244*
2	525	0.340	0.0171	0.4809	216.0	5 047
3	537.5	0.357	0.0164	0.5073	207.2	2 913
4	550	0.378	0.0172	0.5373	217.3	1 191
5	575	0.390	0.0231	0.5464	291.8	493
6	587.5	0.386	0.0210	0.5436	265.3	466
7	594	0.388	0.0224	0.5445	283.0	133
8	600	0.400	0.0202	0.5656	255.2	127
9	624.5	0.420	0.0222	0.5925	280.5	129
10	664	0.446	0.0218	0.6318	275.4	94
11	700	0.465	0.0175	0.6665	221.1	57

* The specimen 11 didn't broke.

3. Numerical simulation of thermo-mechanical fatigue test

When applying results from classical evaluation of thermo-mechanical fatigue test it is necessary to be taken into account that 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 thermo-mechanical fatigue tests for real structure is problematical, when the temperature field distribution or stiffness not corresponds to test conditions. It was proposed methodology that generalizes the results of such thermo-mechanical 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 life-time curve is obtained.

3.1. FE model

Simulation of each fatigue test was performed in two steps. The specimen was clamped at one end (to avoid the displacement) and the corresponding temperature field was generated. After the first heating to T_{max} it was imposed coupling between nodes at the other end and a reference point. It was connected through a spring connector to the rigid frame. Connector stiffness corresponds to the stiffness of the apparatus connecting rods k_C. Then the sample was cyclically loaded by temperature field. 10 cycles to obtained stabilized stress-strain cycle there were simulated.

3.2. Temperature field

The temperature field was generated in dependence on time and axial coordinate of the specimen. The temperature field was interpolated through the temperature distribution inside of one cycle scanned by thermo-camera. For each sample it was defined user procedure that contains the interpolation data for the temperature distribution. Measurement of the temperature fields was carried out by VZLU Praha a.s. company. Data were symmetrized and in sequence of discrete times interpolated.

3.3. Material model

The material was modeled as elasto-plastic with linear kinematic hardening. It is the simplest model that can be used to describe the cyclic plasticity. This model requires a data as curve with the linearized dependence stress σ – plastic strain ε_{pl} of stabilized half-cycle at different temperatures. For the material GGV 30 were not available cyclic deformation tests at various temperatures, but only static tensile tests. Therefore cyclic curves were calibrated as equivalents of reduced or increased static curves. There were computed cases with stress values converted to q times of original values. The q factor was chosen from sequence {0.70, 0.75, 0.80, 0.85, 0.90, 0.95, 1.00, 1.10}.

3.4. Calibration calculations

Calibration calculation means simulation for specimens for which the cyclic load curve was measured. Cyclic load curve is stable relationship between stress and mechanical strain during one period. Cyclic load curves were shifted by minimum value of mechanical strain in the period to easy compare each other (Fig. 5). These calculations were performed for models with different materials. The materials were derived from the static curves multiplied by factor q. Cyclic load curves were calculated for selected specimens and compared with measured curves. The appropriate value of factor q was estimated as the value for which the difference between calculated and measured dependence is minimal. The value $q = 0.8$ has been chosen.

3.5. Determination of localized lifetime curve

FE simulation for each specimen with material based on calibrated GGV 30 cyclic stress-strain curve was performed. Local cycling load curve in the middle of specimens were evaluated (Fig. 6). It is relation between stress and local mechanical strain in the middle of the specimen. The local mechanical strain range is possible to obtain. The dependence of local mechanical strain range on cycles to failure is modified thermo-mechanical fatigue life-time curve. Comparison of both "average" and local life-time curves is in Fig. 7. Two specimens – 10 (T_{max} = 664 °C) and 11 (T_{max} = 700 °C) – are problematical. From simulations results relative low mechanical strain range, but cycles to failure are also low. Possible explanation for this phenomenon is significant decrease of yield stress in large region of specimen. It isn't necessary high local strain in the middle of specimen for total mechanical extension. Low cycles to failure are probably related to high temperature. Further research is required to explain this problem.

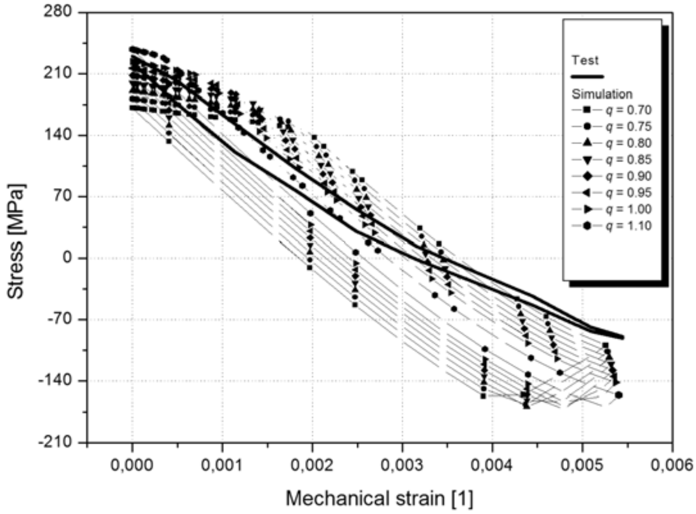

Fig. 5. Cyclic load curves obtained from experiment and calibration computations – example for specimen 7

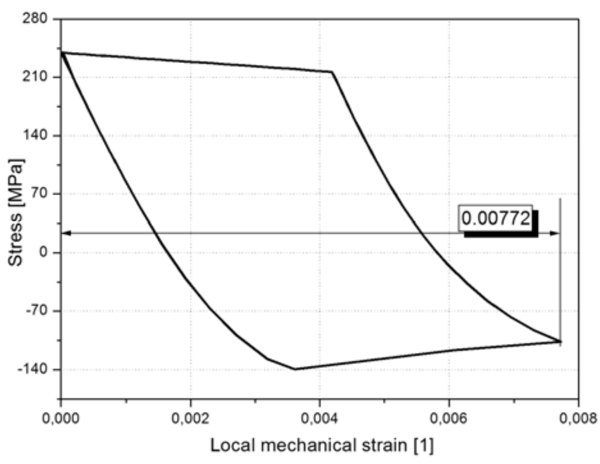

Fig. 6. Local cycling load curve – example for specimen 7

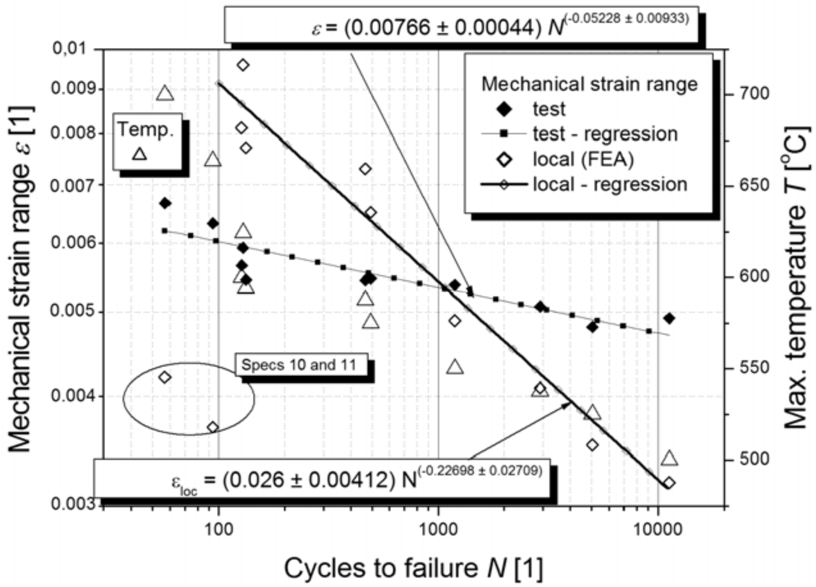

Fig. 7. Life-time curves of GGV 30 vermicular grey cast iron – "average" and localized curves

4. Conclusions

It was proposed methodology for evaluation of the thermo-mechanical fatigue test with regard to the local mechanical deformation in the most exposed region in the specimen. This methodology is based on finite element simulation of fatigue test. Simulation provides a localized mechanical strain range in the middle of the specimen (in place of rupture) which is associated with the experimentally obtained cycles to failure. It is expected that usage of such localized life-time curve is much more general than curve from classical evaluation. The next step is application to suitable real structure and comparison of both life-time predictions from strain range.

Acknowledgements

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