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VERMICULAR GREY CASTING GGV 30 THERMAL FATIGUE EVALUATION USING COFFIN'S TEST AND FEA

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Summary: *This paper presents the alternative methodology of standard Coffin's thermal fatigue test evaluation with respect to the strain localization in regions with high temperature. FE calculation is assumed to provide us with relevant information about material state of real structures under mostly thermal loading in the process of thermal fatigue life assessment. Thus, the same calculation using the same material model and data was suggested as a tool determining local straining of specimen during Coffin's test. This idea was utilized to evaluate low cycle thermal fatigue curve of vermicular grey casting GGV 30 and compared with the standard one, evaluated using adjusted length of specimen.*

1. Introduction

Methodology of so-called Coffin's thermal fatigue test evaluation with respect to the utilization in FE calculations is introduced in this paper. Cyclic thermal loading caused by periodic heating and cooling occurs typically in many structures in real life. It was shown that fatigue processes under such circumstances are not necessarily the same as during mechanical loading in conditions of elevated temperature (Manson, 1966). Special test based on periodical heating (using direct electric current passage through it) and cooling of specimen bar fixed at its end points until fracture is reached is being commonly used for many years. Series of such tests supply us with the fatigue curve (strain range-number of cycles) dependency enabling to estimate limit number of cycles of structures under conditions of low-cycle fatigue. General advantage of this procedure is its simplicity and low costs. Usual evaluation methods use either average strain in the bar or employ some empiric formulas to estimate strain at point of fracture.

The idea of methodology presented in this paper is based on localized total strain range determination using FE simulation of the test. Presented methodology was applied on evaluation of thermal fatigue properties of vermicular grey cast iron GGV 30. These results are considered to be suitable to predict fatigue life of thermally loaded structures, as parts of combustion engines, using finite element analysis.

The process of material straining in conditions of thermal loading is very complex. It includes both thermal expansion as source of internal forces in constrained bodies and gradual/severe change of material properties (elasticity, plasticity, strength) with increasing

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and decreasing temperature/phase conversions of material. Using of material models of such complexity is not possible in usual cases. Therefore, employing of the same "simple" material model during thermal fatigue test evaluation as well as in the procedure of computational prediction of fatigue life of real structure may help to reach reasonable results from engineering point of view.

2. Experiments

Coffin's thermal fatigue test is based on cyclic heating and cooling of the specimen fixed between two rigid plates (Fig. 1, pos. 1, 2) connected with massive rods (4) with stiffness k_{MC}, so that the tension/compression force in specimen can be determined using measured (6) relative displacement of fixing plates Δl_{MC} as $F_R = k_{MC}\Delta l_{MC}$. Specimen (3) is heated periodically by direct electric current passage through it. The temperature at the center of specimen is measured by thermocouple (5). It was utilized to verify temperature fields obtained by thermovision and to provide feedback control oh heating process.

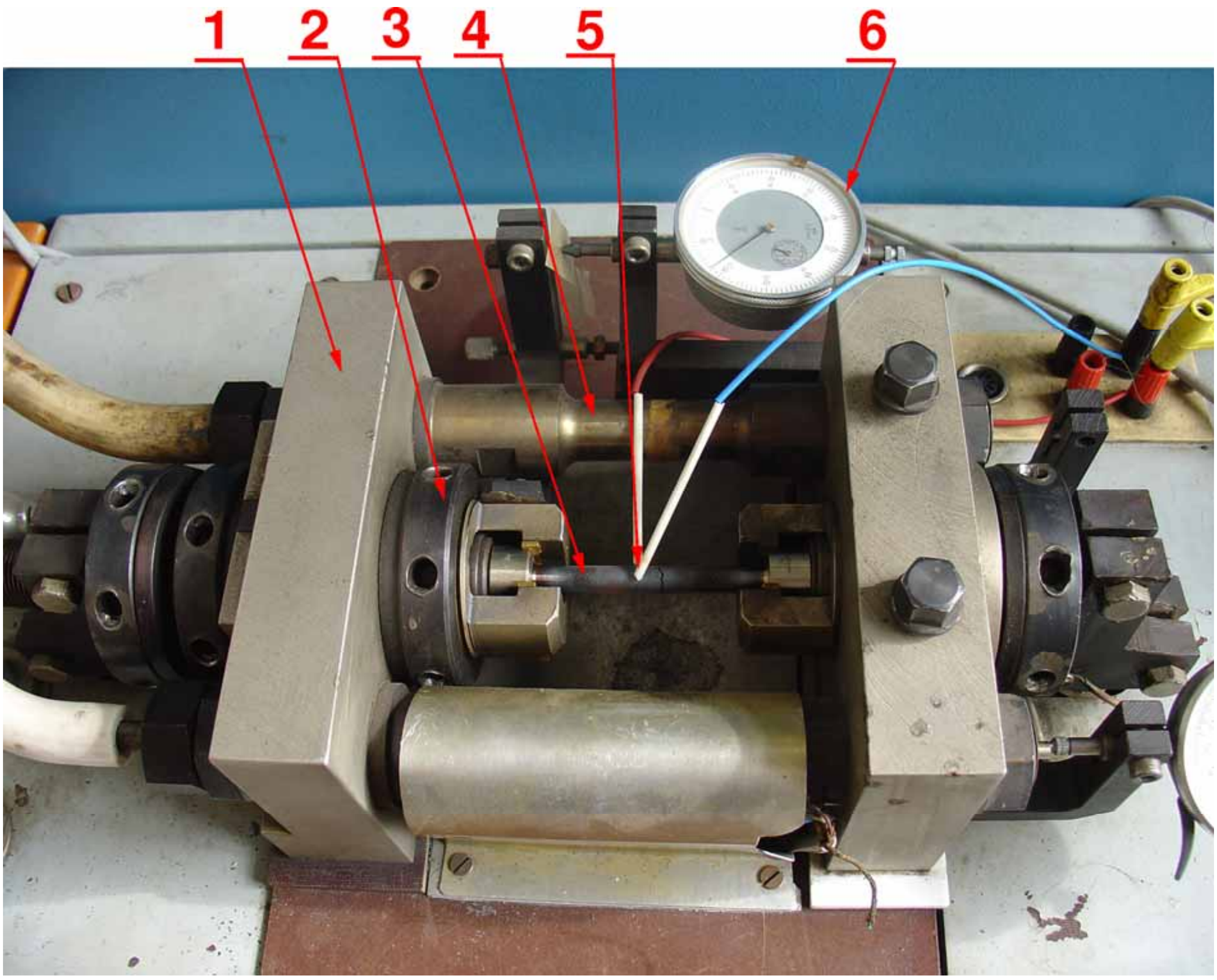


Fig. 1: Manson-Coffins experimental set-up.

During single test the temperature oscilates between $T_{\min}$ and $T_{\max}$ at the specimen centre. (in our case (Kneifl & Čipera, 2006) $T_{\min} = 100^o\,\mathrm{C}$ was common for all tests while $500^o\,\mathrm{C} < T_{\max} < 700^o\,\mathrm{C}$.

At the beginning of test the specimen is inserted between free (not connected with rods) plates and heated to reach maximum temperature $T_{\max}$. As the plates are free, the specimen dilatation Δl_T caused only by thermal expansion determines their distance. Then the connection between plates is reestablished and cooling period starts. Tensile stress in specimen overcomes yield point and plastic deformation occurs in specimen. Then, heating-cooling cycles periodically repeat until the specimen break. There are two quantities measured during the test by default:

- Free temperature dilatation. Measured is $\Delta l_{T\max}$ between $T_{\min}$ and $T_{\max}$.
- Relative approximation of the plates. Measured is the range of approximation $\overline{\Delta l_{MC}}$ in scope of single loading cycle at the beginning of the test and, approximately, at the middle and at the end of specimen life.

Adjusted strain (strain with correction) can be expressed as

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

using adjusted length l_0 of specimen anticipating fact, that the processes affecting thermal fatigue are conditioned by temperature and straining, so that only central part of specimen is took into account. Adjusted strain range can be expressed as

$$\overline{\varepsilon_{corr}} = \varepsilon_{corr,\max} - \varepsilon_{corr,\min} = \frac{\Delta l_{T\max} - \overline{\Delta l_{MC}}}{l_0} \tag{2}$$

Stress is given by

$$\sigma(t) = \frac{F_R(t)}{A} = \frac{k_{MC}}{A}\Delta l_{MC}(t) \tag{3}$$

from which the stress range is

$$\overline{\sigma} = \frac{k_{MC}}{A}\overline{\Delta l_{MC}} \tag{4}$$

Dependence between corrected strain range $\overline{\varepsilon_{corr}}$ and cycles until break N under temperature $T_{\max}$ is the basic low cycle thermal fatigue material characteristics.

Additionally, the dependence $\varepsilon_{corr} - \sigma$ during heating – cooling cycle was measured for subset of specimens to calibrate material and verify numerical model.

3. Modeling of Coffin's test

FE model of Coffin's test was assessed using ABAQUS 6.7 code. Axisymmetric model (Fig. 2) of test specimen was fixed at left (2) and supported with spring (substituting the stiffness of experimental equipment) at right (5, 6) end.

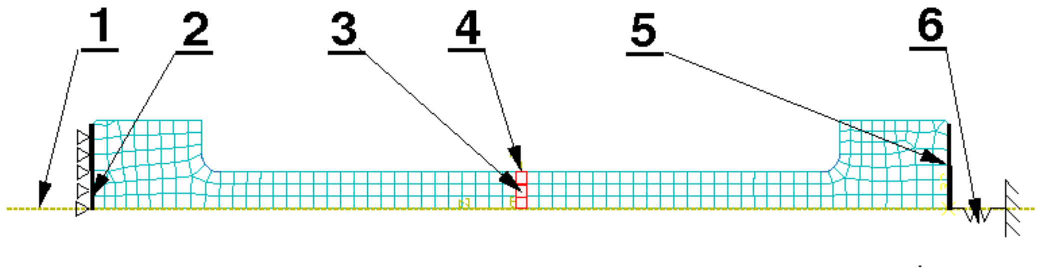
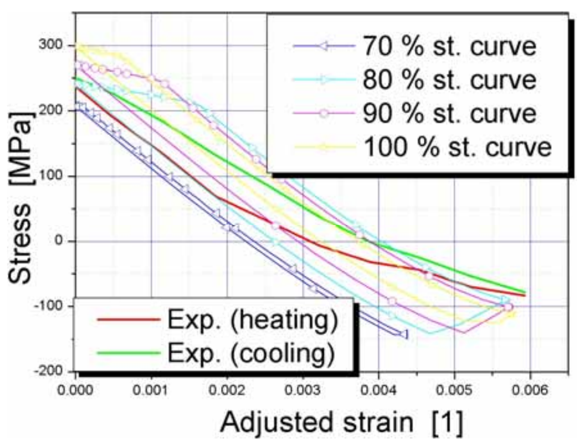


Fig. 2: FE model of specimen.

Model was loaded with real temperature field measured using thermovision (Andrýsek & Cagáň, 2006) and processed by user subroutine provided each node with temperature depending on it's horizontal coordinate and time. Each model was loaded with 12 cycles heating - cooling to obtain stabilized loading curve. Automated procedure (in Python and Abaqus API) was developed to evaluate the same loading curve $\sigma = \sigma(\varepsilon_{corr})$ that had been previously evaluated from measured data.

Elastic-plastic material model with cyclic plasticity simulation capability was utilized. The model is based on Von Mises's plasticity condition and linear kinematic hardening. This material model is very simple, and it's capability to describe cyclic plastic straining of material is limited. With respect to incompleteness of available GGV 30 material data, it's utilization was found acceptable. Because of lack of material data, calibrated static tensile curves at elevated temperatures were used instead of cyclic deformation curves. As the material input consists of Young elasticity modulus E and plastic strain – stress ($\varepsilon_{pl} - \sigma$)



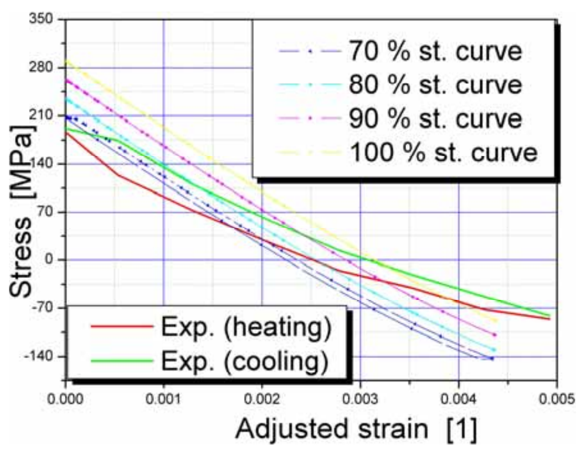


Fig. 3: Experimental and FE loading curves for specimen 10 (the best correspondence) and specimen 2 (the worst correspondence).

dependence approximated to be linear (given by two points: yield point[$\varepsilon_{pl} = 0;\ R_e$] and strength point [$\varepsilon_{pl} = \max;\ R_m$]), calibration coefficient q, was introduced to modify static curves to be in correspondence with cyclic behaviors. Approximate cyclic curve for given temperature follows from the static one by simple scaling as linear, defined by points [$\varepsilon_{pl} = 0;\ qR_e$] and [$\varepsilon_{pl} = \max;\ qR_m$]. The calibration criterion is based on correspondence between measured and computed loading curves $\varepsilon_{corr} - \sigma$.

Based on comparison of measured and computed data (Fig. 3), scale $q = 0.8$ of static tensile test was determined.

Local strain range at the center of specimen $\overline{\varepsilon_{loc}}$ was finally determined using FEA for all tested specimens and associated with their limit numbers of cycles N. Line $N - \overline{\varepsilon_{loc}}$ at graph in Fig. 4 represents local thermal fatigue curve. Original curve based on adjusted strain range is plotted at the same graph. There are two doubtable specimens – specimen 1 and specimen 12. Both of them were cycled under high temperatures $T_{\max}$=700 °C and $T_{\max}$= 664 °C. FEA results into low range of mechanical strain, but lifetime is low as well (57 and 94 cycles until break). This phenomenon could be partially explained by the high temperature in significant part of specimens. Integral dilatation is caused by relatively small strain in relatively long piece of the specimen. Low lifetime probably corresponds with the temperature, that should be verified by further research.

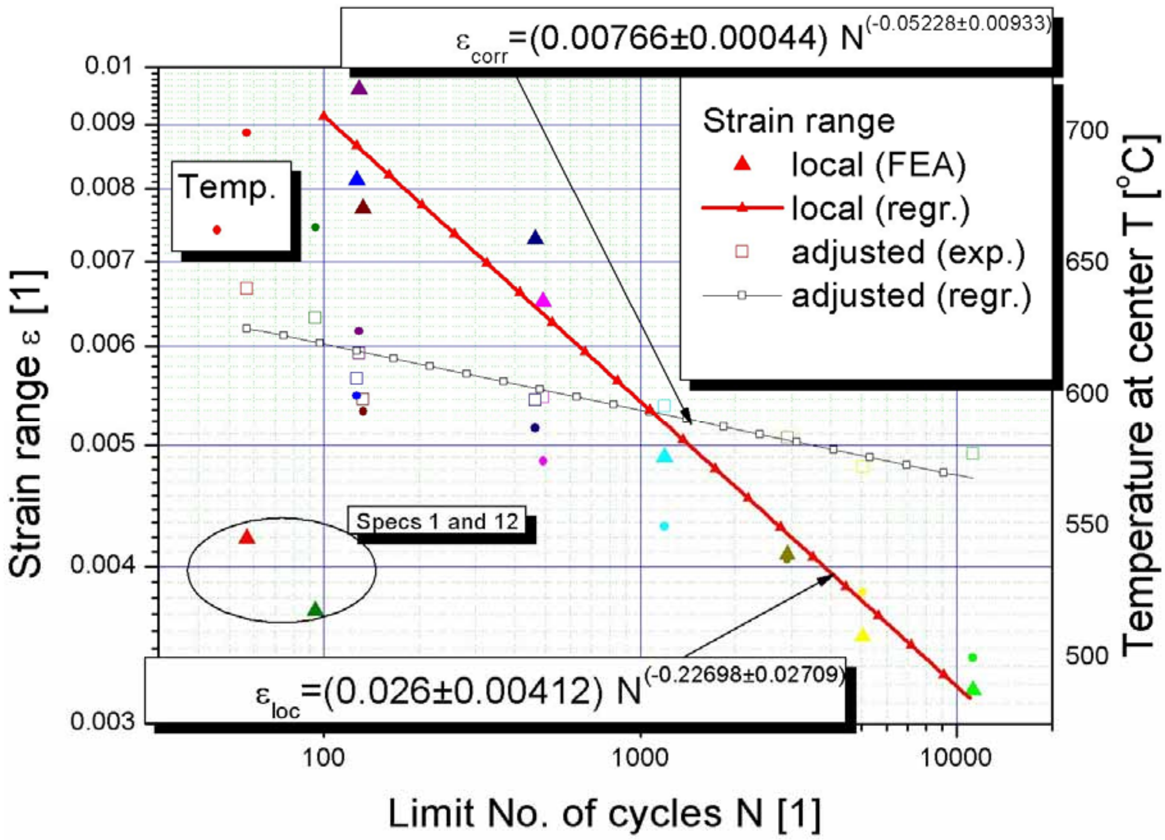


Fig. 4: Local and adjusted fatigue curves.

4. Conclusions

Local fatigue curve for GGV 30 based on local strain range instead of adjusted strain range is plotted in Fig. 3 as well as adjusted fatigue curve (determined fully from experiment). Strain ranges according to localized and adjusted curve differ significantly in slopes. Utilization of presented results in evaluation of limit number of start-stop cycles of C28 engine cylinder head is planed in near future.

Acknowledgement

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