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Stres-strain characteristics under mechanical and thermal loading

J. Okrajni*, A. Marek, G. Junak
Department of Mechanics of Materials, Silesian University of Technology,
ul. Krasińskiego 8, 41-403 Katowice, Poland
* Corresponding author: E-mail address: Jerzy.Okrajni@polsl.pl

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Properties

ABSTRACT

Purpose: The main problem addressed in the paper is the description of a deformation process under the conditions of mechanical and thermal interactions.
Design/methodology/approach: The mathematical modelling has been used to describe the stress-strain behaviour of materials. The method of fatigue testing has been adopted to determine experimentally stress-strain characteristics. The method based on the long term own experience in thermo-mechanical investigations and new European Code-of-Practice for Thermo-Mechanical Fatigue Testing.
Findings: An appropriate model description has been developed. Fatigue examinations of the P91 steel that is used in power industry, were carried out. The validation of the model has been performed. So far, experimental verification of the usefulness of the model description to determine the stress-strain characteristics' course for a selected value of the phase shift angle between the temperature and total strain cycles has been made. It has been found that the proposed model reflects the deformation process nature very well in variable temperature, strain and stress conditions. Hence, a conclusion seems to be justified that the approach presented in the paper could constitute the right basis for appropriate constitutive equations, which depict the material behaviour under thermo-mechanical conditions.
Research limitations/implications: The developed description should be useful in problems of fatigue behaviour predictions of materials under different mechanical and thermal loadings in industry practical applications and in research problems connected for instance with fatigue life criteria description and validation.
Originality/value: The new material characteristics have been shown in the work and the own new method of the material fatigue behaviour prediction. The work is addressed to researchers interested in problems of material testing and material behaviour prediction under different loadings that we can meet in the operation practice.
Keywords: Fatigue; Mechanical properties; Metallic alloys; Applied mechanics

1. Introduction

Thermo-mechanical fatigue is one of important phenomena deciding upon the cracking processes in machine components and devices exposed to mechanical and thermal influences in the power, chemical and metallurgic industries, in aviation and transport [1-5] In spite of its fatigue-like nature, this kind of material destruction is also connected with other processes stimulated by the long-term influence of elevated temperature such as ageing, oxidation or creep, and in some cases the interdependence between the fatigue phenomena and the processes mentioned has to be taken into account. In order to identify the properties of materials used under cyclic temperature changes and mechanical load, it is also important to consider the interdependences mentioned as well as characteristics of individual processes consisting of conditions of use in individual elements.

This is because most frequently the application of properties indicated in tensile tests is then impossible. What constitutes a useful and practically applicable characteristics of the thermo-mechanical fatigue in a given material i.e. characteristics of cyclic deformation processes and fatigue life understood as a number of cycles to a specimen fracture in agreed conditions of the fatigue tests. This data is necessary for designers when predicting behaviour and strength of the elements in case of the aforementioned types of materials application, and these are as important as creep and low-cycle fatigue characteristics, which are commonly used in practice when describing materials cracking processes taking place in elevated temperature [5-11].

The thermo-mechanical fatigue tests belong to the most complex mechanical tests. Briefly, it can be said that they consist in simultaneous temperature control and total (geometric) strain - ε. The result of the two control signals is mechanical strain- ε_M being the difference between total strain-ε and thermal strain-ε_T.

$$\varepsilon_M = \varepsilon - \varepsilon_T \qquad (1)$$

Due to the number of parameters deciding upon material behaviour in practical applications [1-4, 12-15], thermo-mechanical fatigue tests can show a large variety. Different sorts of temperature cycles and strain can be used – sinusoidal ones, trapezoidal, cycles with constant strain and temperature rates or rectangular cycles. Dislocations in the strain cycle phase in relation to the temperature cycle are possible. The difference can also concern the values in maximal and minimal test parameters and the cycle period or its individual parts. Due to diversity of tests and their realisation period in laboratory conditions, it is possible to perform only selected types, relating the studies to the most frequent cases of fatigue in machine elements and devices. Among widely-used tests there are those using characterised by constant heating and cooling rates and constant strain rate. However, the strain cycle in the phase can be dislocated compared to the temperature cycle [1, 2].

Taking into account a limited number of tests carried out in laboratory conditions, the problem to be solved is the description of materials characteristics in other cases, based on selected research results. The paper concentrates on the description of deformation characteristics (stress-strain characteristics) in the form of a hysteresis loop, working out their mathematical models based on low-cycle fatigue studies.

2. Algorithm ofthe procedure

One of the methods commonly applied in the analysis of a deformation process taking place in low-cycle fatigue conditions is an approach which refers to the steady state, which should be approximately characterised by stability of the characteristics in the form of a hysteresis loop for any selected strain range. Such an approach is correct only in some cases. Most often, the characteristics of a state known as the "steady" or "saturated" state depend on the load history and in the case when an assumption is made that a material shows the occurrence of a saturated state, what is left to be solved is the problem of an evaluation of the accuracy of description of the characteristics. Such evaluation is most frequently based on the results of laboratory research. In the case of thermo-mechanical fatigue, the problem becomes much more complex due to the influence of temperature on the cyclic deformation processes, which strengthen or weaken the material, and thus, on the saturated state characteristics. Taking into account the much higher degree of complexity of the description of material behaviour in thermo-mechanical fatigue conditions compared to the low-cycle fatigue at constant temperatures, at the stage of developing the basis for a model approach to the stress-strain characteristics in such conditions, it seems reasonable that an assumption is made about stability of the material characteristics.

A consequence of such an assumption is the possibility of presenting stress as a function of strain and temperature, without the necessity of taking into account the effects connected with the loading history. The method presented in the paper takes advantage of mathematical models of dependences describing the course of hysteresis loop branches, determined for individual constant temperatures of tests. The origin of the coordinates was assumed to be found at the peak of a hysteresis loop, at minimal strain. In such case, the curves showed in Fig. 1 illustrated part of a hysteresis loops at increasing stress and strain.

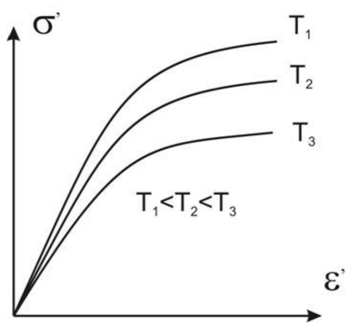

Fig. 1. Characteristics of deformation - a half of hysteresis loop under deformation in isothermal conditions – a part of the cycle at increasing strain.

In Fig. 2 it will be the upper section between points of coordinates (ε_R,σ_R) and (ε_C,σ_C). In the proposed method a mathematical model of the characteristics shown in the figure 2 was adopted, with its general form as follows:

$$\sigma' = f(\varepsilon', T), \quad \varepsilon' \in (0, \Delta\varepsilon) \qquad (2)$$

Performing transformation of the function (2) and taking into account initial conditions for a part of the hysteresis loop illustrating the course of histeresi loop with increasing strain, the following dependency is obtained:

$$\sigma = f[(\varepsilon - \varepsilon_R), T] + \sigma_R \qquad (3)$$

A similar transformation for a part of the cycle with decreasing strain gives:

$$\sigma = -f[|\varepsilon - \varepsilon_C|, T] + \sigma_C \qquad (4)$$

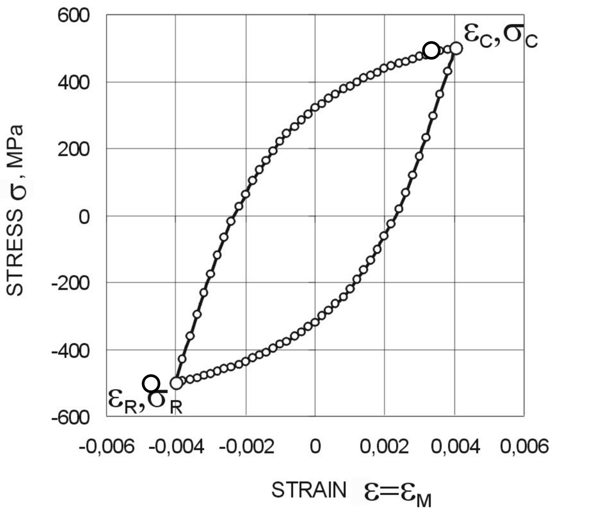

Fig. 2. Characteristics of deformation process - hysteresis loop at cyclic isothermal low-cycle fatigue.

Equations (3) and (4) include the constant values being the coordinates of the hysteresis loop peaks.

Determining the course of dependences between mechanical strain, stress and temperature under thermo-mechanical fatigue becomes a considerably complex issue. The dependences between stress and strain will be influenced by the temperature which is an independent variable in function $f[\varepsilon',T]$ and, at the same time, they will be depended on the values of σ_R and σ_C (Fig. 3).

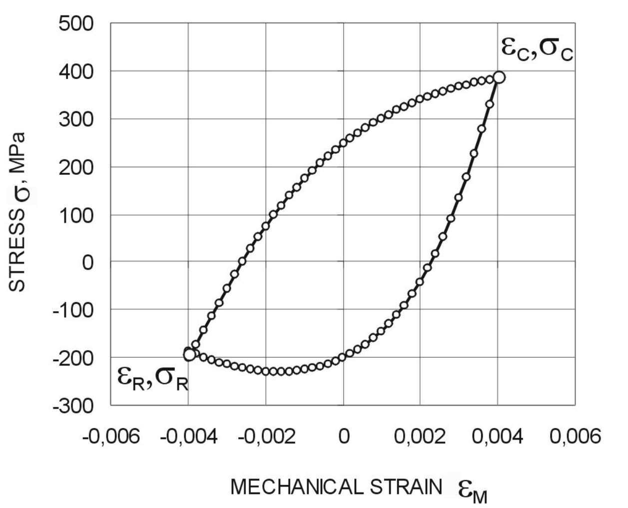

Fig. 3. Characteristics of the deformation process: hysteresis loop under thermo-mechanical fatigue.

What appears as a result is the problem of determining the coordinates (ε_R,σ_R) and (ε_C,σ_C). The influence of temperature on the values of σ_R and σ_C can be considered in equations (3) and (4) by introducing additional functions $\varphi(\varepsilon,T)$ or $\varphi'(\varepsilon,T)$, taking into account the effect of the material memorizing the value of initial deformation and strain. In this way, for the part of hysteresis loop corresponding to increasing strain, the following equation is obtained:

$$\sigma_R = \sigma_{R0} + \varphi(\varepsilon,T) \tag{5}$$

In the case of the part of the loop which corresponds to decreasing strain, the following dependence is assumed:

$$\sigma_C = \sigma_{C0} + \varphi'(\varepsilon,T) \tag{6}$$

Functions $\varphi(\varepsilon,T)$ and $\varphi'(\varepsilon,T)$ should be understood in this case as functions correcting the values of σ_R and σ_C with reference to their initial values σ_{R0} and σ_{C0} due to the current temperature, variable during the deformation process. For the mechanical strain cycle characterized by the value of stress ratio equal –1, the functions $\varphi(\varepsilon,T)$ and $\varphi'(\varepsilon,T)$ can be formulated in general:

$$\varphi(\varepsilon,T) = \frac{1}{2}\{f[(\varepsilon-\varepsilon_R),T_R] - f[(\varepsilon-\varepsilon_R),T]\} \tag{7}$$

$$\varphi'(\varepsilon,T) = -\frac{1}{2}\{f[|\varepsilon-\varepsilon_C|,T_C] - f[|\varepsilon-\varepsilon_C|,T]\} \tag{8}$$

Under thermo-mechanical fatigue σ_R and σ_C will vary continuously, according to the dependences (5) – (8).

3. Validation

Function $f(\varepsilon',T)$ can be assumed in a different form, since it is a mathematical approximation of experimentally determined deformation characteristics in steady state conditions, at fatigue in a range of low-cycle fatigue at constant temperatures. In the case of the first approximation, the following form has been proposed:

$$f(\varepsilon',T) = (A - CT)\arctan(D\varepsilon'), \tag{9}$$

where A, C and D are constants determined based on the experiments.

Constants A, C and D were determined, inter alia, for steel P91. Due to the simple form of function (9), the dependence can be easily used to analyze the course of the deformation process. Strain $\varepsilon' = \varepsilon - \varepsilon_R$ should be then substituted for the hysteresis loop branch at growing strain and $\varepsilon' = |\varepsilon - \varepsilon_R|$ for the hysteresis loop branch at a decreasing strain.

The study also encompasses verification of the model developed by referring the characteristics determined based on the model, the latter having been based on the low-cycle fatigue tests' results, to he results obtained in thermo-mechanical fatigue tests. The tests were carried out for the P91 steel applied in the power industry. Figure 4 illustrates stress-strain characteristics, based on the model, for the test with cycles consistent in phase. It also shows the results in the form of experimental points from the test, in the range from the hysteresis loop stabilisation until failure.

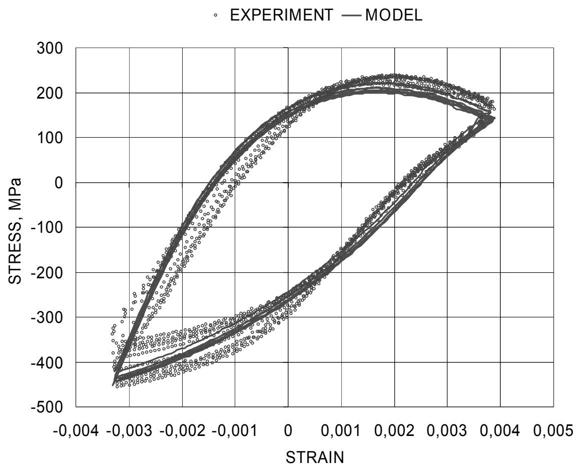

Fig. 4. Results of experimental verification: hysteresis loops determined based on the model – red colour; points representing the research results – blue colour.

4. Conclusions

A conclusion seems to be justified that the approach presented in the paper could constitute the right basis for appropriate constructive equations, which depict the material behaviour under thermo-mechanical conditions.

Although the proposed approach reflects, in a way satisfactory to engineering applications, the course of characteristics in both quantitative and qualitative terms, the problems that remain unsolved are approximation of the low-cycle research results by means of function $f(\varepsilon',T)$ and physical interpretation of this function.

This time it seems to be important to discuss about the TMF problems together with the discussion concerning the fracture of component under mechanical and thermal loading [5, 6, 12-14] that is one of the main phenomena deciding for instance on power industry component durability. Despite the long term experience in thermo-mechanical testing [1-4,12-15] regarding to many aspects of this type of a material damage it is still one of the main, but not enough well known and described, problem of component durability under mechanical and thermal loadings.

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