FATIGUE DAMAGE DESCRIPTION OF STEELS AT ELEVATED TEMPERATURES

J. Okrajni and G. Junak

Silesian University of Technology

ABSTRACT: The low cycle fatigue life assessment procedure of creep resistant steels has been presented in the paper. The model has been worked out that describe the influence of the loading history on the fatigue life. It has been assumed that there is dependence between the energy P, which express damage in the particular cycle and number of cycles. The verification has been made basing on the low-cycle examinations curried out on two stages.

INTRODUCTION

Increasing requirements, which modern technical devices have meet, require development of many fields of engineering sciences. One, among others, to increase durability and reliability of machine and engineering plant components increases an interest in problems of mechanical behaviour of materials and the component life prediction. Development of durability prediction methods involves progress in fields, e.g. fracture mechanic, low cycle fatigue, thermal fatigue and creep. When the lifetime of a given object is to be predicted, it is first necessary to select the most appropriate method of material testing [1, 2, 3, 4, 5, 6], and then to be able to model complex mechanical systems and their elements using relevant methods in discipline of mechanics of solids. Appropriate criteria are also required with respect to operating conditions and loading history.

The Palmgren-Miner linear cumulative damage expression has been often used to describe fatigue life under mechanical loading [7, 8, 9, 10]. This low is agreed with experiments with different accuracy that depends, among others, on the loading sequence [8, 10]. In the paper the model has been worked out that describe the influence of loading history on the fatigue life. The model is based on the hypothesis of damage accumulation. The low-cycle fatigue investigations of stainless steels have been carried out to verify the model. Tests were accomplished at room and elevated temperature.

DESCRIPTION OF THE MODEL

The hypothesis is based on the assumption that the value of a local accumulated damage, which at the moment of failure reaches a critical value, decides upon fatigue failure. There are many fatigue hypotheses, stating that the value of dissipated or accumulated energy in the material in the fatigue process is a fatigue criterion [1, 3 ÷ 6, 11, 12]. The energy responsible for the failure is defined in a different way. The base for its determination are the characteristics of a fatigue cycle in the form of a hysteresis loop. When analysing the process of local deformation in a low-cycle fatigue, Moskwitin [11] determines the value of energy responsible for the failure for particular fatigue cycles assuming that the material has properties diversified in its volume. Considering the model of material featuring different yield point in particular grains, Moskwitin determines maximum value of dissipated energy for the given total strain range $\Delta\varepsilon = \Delta\varepsilon_p + \Delta\varepsilon_s$ in a fatigue cycle (Fig.1a):

$$P_{\max} = P(\Delta\varepsilon_p) \ , \tag{1}$$

where: P – is a surface of hysteresis loop, $\Delta\varepsilon_p$- plastic strain range.
For an ideal elastoplastic material, value P reaches extremum for elastic strain range $\Delta\varepsilon_s = \frac{\Delta\varepsilon}{2}$.
Then we get:

$$P_{\max} = \Delta\sigma\Delta\varepsilon_s = E\Delta\varepsilon_s{}^2 = \frac{1}{4}E\Delta\varepsilon^2 , \tag{2}$$

where: E-Young modulus.

Equation (2) has been determined for the uniaxial tension and material model consisted of rods with different yield point.

By introducing a critical energy value by W_k we can get:

$$W_k = P_{\max} \cdot N_f \tag{3}$$

and:

$$\Delta\varepsilon = 2\sqrt{\frac{W_k}{E}} \cdot N_f{}^{-\frac{1}{2}} = C \cdot N_f{}^{-\frac{1}{2}} \ , \tag{4}$$

where: C -a material constant, N_f- number of cycles to failure

In case of a material showing cyclic hardening, constant C will depend on hardening factor.

Analysing the fatigue diagrams determined for different materials it is possible to state that dependence (4) describes them well in case of big strain ranges (Fig. 1b). When the number of cycles, up to failure, is higher we observe the bigger discrepancy between theoretical dependence and results of experimental examinations (Fig. 1b).

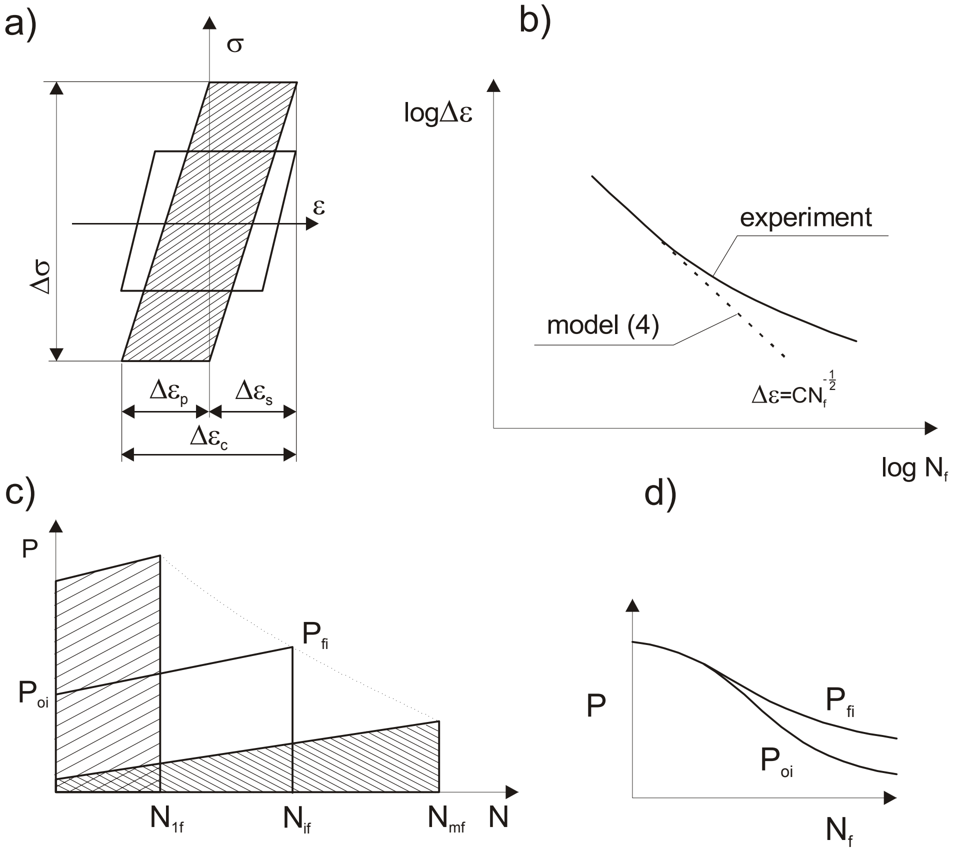


Fig.1: Determination of the maximum value of local dissipated energy in a fatigue cycle: (a); fatigue endurance diagrams: (b); accumulated energy in current cycle as a function of strain range and number of a cycle: (c); accumulated energy in first cycle (P_{oi}) and a last (P_{fi}) cycle as a function of a number of cycles to failure: (d).

It is due, among others, to different mechanisms of cracks formation and their growth in fatigue conditions in case of low-cycle fatigue and in the other part of limited life region of S-N curve. In metal alloys at high values of total strain range, plastic strain in each cycle occur in the whole volume of the material and fatigue life is determined by the process of short cracks formation and growth [10, 13]. In case of low values Δε at the initial stage of fatigue, redevelopment of dislocation systems takes place, then the increase of their density. These phenomena take different intensity in different areas. After some time local areas of high dislocation density are formed in the material in which the process of micro-cracks initiation takes place.

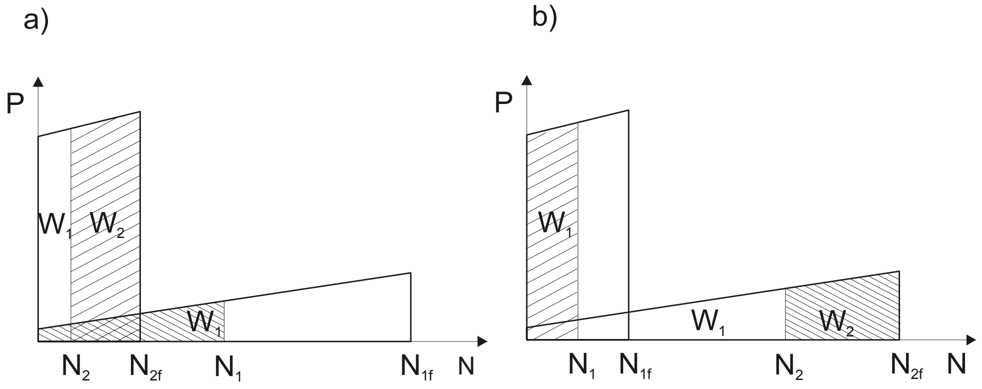
The process of fatigue failure as a macroscopic one has been described in paper [14].

Three stages have been distinguished:

- a crack initiation,
- formation and growth of short cracks,
- growth of a predominant crack formed by joining short cracks.

In case of high loads the second stage dominates. In case of a fatigue at low values of total strain range, the fatigue life is determined by the length of the first fatigue stage. There will therefore be different mechanisms responsible for accumulating local defects at high and low load values. For high loads, it is possible to assume that the process of damage cumulating is in particular cycles of the same character and the fatigue life is determined by the length of the second fatigue stage. This energy is controlled by density and distribution of dislocations, formed at the initial stage of the process. The value of accumulated damage, expressed by energy P, will not show significant changes in the whole fatigue period. For low values of loads P will change in the function of cycle number and strain range (Fig.1c, 1d).

There is a possibility of finding correlation between the function of damage energy and phenomena taking place in the structure of material dislocation. This is the subject of present examinations. At the moment the problem is presented as a model. It has been assumed that there is dependence between P and number of load cycles (fig.1c, 2).



$$\frac{N_1}{N_{1f}}+\frac{N_2}{N_{2f}} \quad \rangle \quad \frac{N_1}{N_{1f}}+\frac{N_2}{N_{2f}}$$

Fig.2. Energy of accumulated damage W_1,W_2 as a function of a loading sequence: low to high (a), high to low (b)

Linear dependence has been taken into consideration for technical application:

$$P=\frac{P_{oi}-P_{fi}}{N_{if}}N+P_{oi}\ , \tag{5}$$

where:

P_{oi}, P_{fi} -energy accumulated accordingly in the first and last fatigue cycle,
N_{if} -number of cycles up to failure at a given strain range $\Delta\varepsilon_i$

The value of accumulated energy after a period of time equal number of cycles N_{if} has been described as a dependence:

$$W_k=\int_0^{N_{if}} P_i\cdot dN=\text{const.} \tag{6}$$

Such a dependence corresponds the fatigue tested at constant $\Delta\varepsilon_i$ value in the whole life period. When $\Delta\varepsilon_i$ changes during the fatigue process, the value of accumulated energy will be added up at particular stages of the process. For a given stage this value is determined on the basis of a dependence:

$$W_i=\int_{N_{ip}}^{N_{ik}} P_i\cdot dN\ , \tag{7}$$

where:

N_{ip}, N_{ik} -number of cycles accordingly at the beginning and the end of a given stage.

Number of fatigue cycles at a given fatigue stage is calculated from the dependence:

$$N_i = N_{ik} - N_{ip} \tag{8}$$

It has been assumed that the failure will take place when total accumulated energy at particular stages of the process reaches a critical value:

$$\sum_{i=1}^{n} W_i = W_k \tag{9}$$

The way of summing up the energy is presented in Fig.2. The example is related to the fatigue occurring at two stages. It has been assumed that the range of deformation changes from low to high value (Fig.2a) or from high to low value (Fig.2b).

The model allows to describe the phenomenon of life diversification in relation to the load sequence, which was described by Miller [10].

THE VERIFICATION PROCEDURE

This paper verifies the model basing on examinations carried out in two stages, according to procedure A and B. Two grades of steels have been tested, i.e. austenitic steel H23N18 and ferritic steel H25T.

Procedure A - first defined part of cycles carried out at total strain range $\Delta\varepsilon$= 0,6%, second part carried out at $\Delta\varepsilon$= 1,4% up to failure.

Procedure B – first defined part of cycles carried out at total strain range $\Delta\varepsilon$=1,4%, second part carried out at $\Delta\varepsilon$=0,6%, up to failure.

Examination was carried out at room temperature and at temperature 873 K. Fig.3. shows result of low-cycle fatigue tests. On this figures have been shown theoretical diagrams according to Palmgren - Miner expression, the experimentally determined points and curves determined according to proposed hypothesis. The correlation coefficients have been computed to describe discrepancies between theoretical formulation and experiments. Values of these coefficients are shown on the Fig. 3.

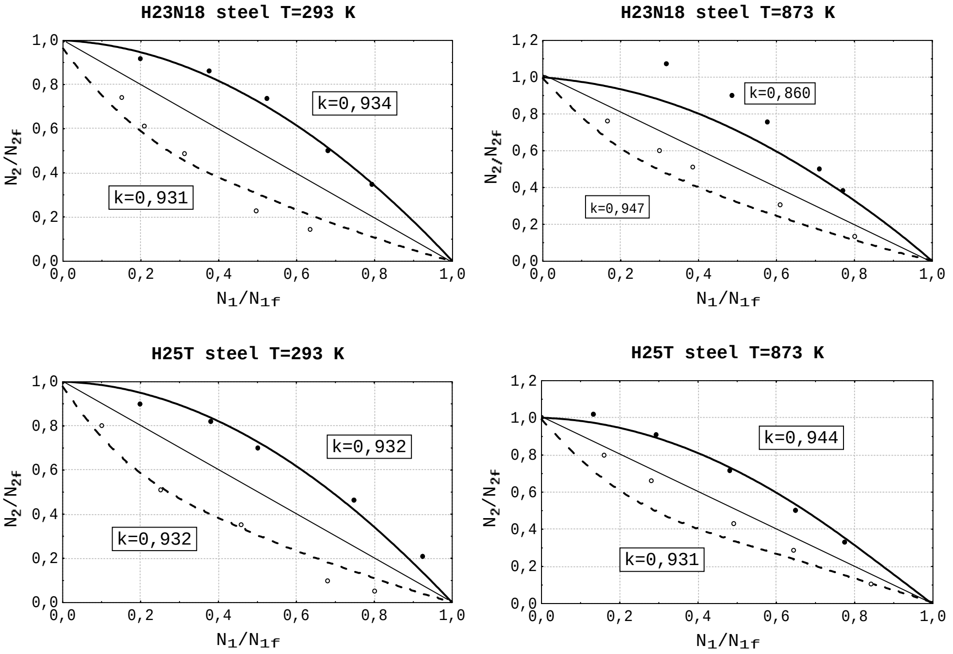


Fig.3. Divergence from the Palmgren-Miner theory, experiment and proposed hypothesis. The straight line represents Palmgren-Miner law. Points represents experiments.

● - low to high strain range change,

○ - high to low strain range change.

Lines —— and - - - represent the model approach.

CONCLUSIONS

Results of experiments and their description gave possibilities to formulate some conclusions related to the presented in the paper hypothesis.

1. In case of a fatigue at low total strain range, the fatigue life is determined by the length of the first fatigue stage. There will therefore be different mechanisms responsible for accumulating local defects at high and low load values. For high loads, it is possible to assume that the process of damage cumulating is in particular cycles of the same character and the fatigue life is determined by the length of the second fatigue stage.
2. The value of accumulated damage in current cycle, expressed by energy P, will not show significant changes in the whole fatigue period in case

of high values of strain ranges. For low values of loads P will change in the function of cycle number.

3. Diagrams and correlation coefficients on the Fig. 3 show that it is possible to determine fatigue life in case of sequence loading using the damage cumulative expression. But it is necessary do take into consideration that cumulated energy in each cycle depends on the strain range and number of the cycle.
4. The total locally accumulated energy W_k we can treat as constant irrespective of the total strain range and this energy can be used as the fatigue life criterion.

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