Journal of Achievements in Materials and Manufacturing Engineering

VOLUME 26
ISSUE 2
February
2008

# Low cycle fatigue of steels at high temperature under gradual loading

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Received 03.01.2008; published in revised form 01.02.2008

**Properties**

## ABSTRACT

**Purpose:** The purpose of this paper is description of the creep resistant steels low cycle fatigue life under gradual loading.
**Design/methodology/approach:** The low cycle test at high temperatures have been performed. This kind of fatigue is typical for materials worked at high temperature conditions.
**Findings:** The model has been worked out in the work, which considers an influence of the loading sequence on the fatigue life of steels worked at a high temperature under mechanical loading.
**Research limitations/implications:** The paper presents results of the part of research connected with methods of life prediction of materials worked under mechanical and thermal loading. From many aspects connected with the life criteria the work has been focused on the problem of the influence of the loading sequence on the fatigue life. This problem should be examined with many others when the durability of high temperature component is considered.
**Practical implications:** The results of low-cycle fatigue could be useful in problems of quality assessment of the examined steels and in analysis of the influence of the character of loading on the material behaviour.
**Originality/value:** The paper presents the own new description of the low cycle fatigue life of steels under gradual loading. The own new fatigue life criterion has been proposed.
**Keywords:** Fatigue; Reliability assessment; Residual life analysis; Materials and engineering databases

## 1. Introduction

Fatigue is one of the essential problems that take place in technical objects subjected to influences of cyclic loadings, which determine their durability and performance. It has been a constantly developed domain of scientific research, from the first Wöhler work related to the fatigue of railway carriage axles (1871) [1]. From this time the tremendous progress been to take place in fatigue testing methods as in the methodic of the crack initiation and growth analysis. Currently we have technical possibilities to perform fatigue tests with taking into consideration the complexity of operation conditions. We can consider mechanical and thermal loading. Tests are carried out in corrosion environments. Modern test systems give possibilities to perform experiments under multi-axial loading, which optionally change in time, often as a random loading. Constant progress in material science and material engineering domains widen abilities of the micro structural mechanism analysis of crack initiation and growth processes. At the same time the new materials are working out with a higher durability and fracture resistance. The demands of a technical equipment operation safety, in plants and components after a long exploitation period, prove necessity of new research programs, which should concentrate on criteria and methods of the life prediction and technical state assessment. Generally known and used life criteria assure assessments, which results have a different degree of accuracy consistent within working condition experiments. The accuracy depends on a material grade and history of loading.

The work concentrates on the attempt of the mathematical description of the fatigue life and its experimental validation. The model worked out in the work considers an influence of the loading sequence on the fatigue life of steels worked at a high temperature under mechanical loading. The low cycle fatigue tests have been performed for these steels.

## 2. The purpose of work

Taking into consideration the lack of data related to fatigue life of the Polish creep resistant steels subjected to low cycle fatigue process at high temperatures under gradual mechanical loading, the main objective of the work has been assumed as:

Description of the low cycle fatigue life of the chosen materials worked in the above-mentioned conditions. It has been assumed, that it would be possible to determine, the mathematical description of the fatigue life as depended on the loading sequence and it would be possible to find a physical background of such description. It has also been assumed that fatigue life may be determined by the damage locally accumulated energy. This work is an attempt to justify the theorem:

The fatigue life of steels worked at high temperatures under gradual loading is determined by the locally accumulated damage and this life depends on the sequence of loading. Such fatigue behavior can be described through mathematical models based on a physical backgrounds of the fatigue process.

It would be possible to present only the scheme of the justification in this short paper.

## 3. The scope of the work

The theorem involved a work plan that contained:

- the development of a mathematical description of the relations describing an influence of a loading sequence on a low cycle fatigue life,
- an attempt of an physical interpretation of relations worked out,
- low cycle fatigue tests at room and high temperatures with different loading sequences,
- evaluation of the mathematical model constants,
- comparison of fatigue life calculated from the model with those from experiments.

The experiments have been carried out for selected materials worked in Polish power and chemical industries.

## 4. The mathematical description of the damage accumulation

The proposed description is based on the assumption [2] that the fatigue life depends on the locally accumulated damage, which can be expressed by energy of damage and that energy of damage reaches the critical value at the moment of fracture. In this work the density of energy accumulated in a particular cycle is assigned $P$, the density of energy accumulated after $N$ cycles have denotation $W$, and denotation $W_k$ for the critical value of this energy is used. Assuming $P$ energy density to be constant we obtain after $N$ cycles:

$$W = P \cdot N \tag{1}$$

and after $N_f$ cycles:

$$W_k = P \cdot N_f \tag{2}$$

where $N_f$ is number of cycles to failure.

Assuming that fracture occurs in local areas, where density $P$ reaches maximum value we can determine the total strain range:

$$\Delta\varepsilon_c = 2\sqrt{\frac{W_k}{E}} \cdot N_f^{-\frac{1}{2}} = C \cdot N_f^{-\frac{1}{2}} \tag{3}$$

Energy density $W_k$ depends on material constants describing the hardening process in case of material cyclic hardening.

When we assume lower values of strain ranges then we observe the bigger discrepancy between experiments and this theoretical description. Such effect can be caused due to the diversification between mechanism of fatigue processes under high and low value of strain range [3-6].

The nature of these processes depends mainly on the phenomena that occur in the dislocation structure of metal. In this work we concentrate on the mathematical formulation without a solid physical description. It is justifiable the assumption, that the rate of damage depends on the strain range.

It has been assumed, that it is possible to describe the density of damage energy $P$ as a function of a total strain range and a number of cycle:

$$P = P(\Delta\varepsilon_c, N) \tag{4}$$

Energy density $P$ increases with number of cycles (Fig.1) from initial value $P_o$ to final $P_{f.}$ values $P_o$ and $P_f$ growth with strain range.

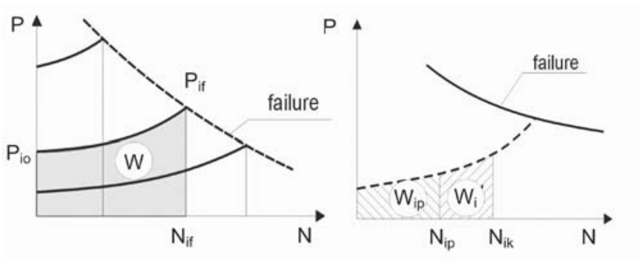


Fig.1. The scheme of $P$ value changes in function of $N$ – (a) and the assumed relationship between $W_i$ and numbers of cycles at the a beginning of fatigue stage - $N_{ip}$ and the end of stage - $N_{ik}$ – (b)

Each curve in Fig. 1a represents a separate value of $\Delta\varepsilon_c$. It has been assumed that $P_f$ growth relatively to $P_o$ with strain range. Such assumption needs proper kind of function (4).

When total strain range is constant in time from beginning of fatigue to the end - failure, energy density of locally accumulated damage can be expressed as

$$W = \int_1^{N_f} P(\Delta\varepsilon_c, N)\,dN \tag{5}$$

where $N_f$ is a number of cycles to failure determined for constant $\Delta\varepsilon_c$.

An assumption has been made that an accumulated damage in whole period of fatigue life is constant, i.e.:

$$\int_1^{N_{1f}} P(\Delta\varepsilon_{c1}, N)dN = \int_1^{N_{2f}} P(\Delta\varepsilon_{c2}, N)dN = \int_1^{N_{jf}} P(\Delta\varepsilon_{cj}, N)dN = W_k \tag{6}$$

In equation (6) $\Delta\varepsilon_{cj}$, $N_{jf}$ are an arbitrarily chosen couple of mutually dependent values of constant total strain range and number of cycle to failure.

$W_k$ is the critical value of density of energy accumulated in area of fracture. When total strain range changes we have to summarize energy densities $W_i$ calculated for an each fatigue stage. Assuming the total strain range at „i" stage equals $\Delta\varepsilon_{ci}$ we can calculate accumulated energy density on this stage:

$$W_i = \int_{N_{ip}}^{N_{ik}} P(\Delta\varepsilon_{ci}, N)dN, \tag{7}$$

where $N_{ip}$ and $N_{ik}$ are numbers of cycles at the beginning and end of a stage.

It has been assumed that the function $P = P(\Delta\varepsilon_c, N)$ would be determined from classic LCF test performed with constant total strain range. The scheme of the method of defining an initial number of cycles for „i" stage is shown in Fig. 1b. A fracture occurs, when the accumulated damage energy reaches a critical value

$$\sum_{i=1}^{n} W_i = W_k \tag{8}$$

This critical value is identified with potential energy release in the moment of tensile specimen fracture.

## 5. Materials

Tests have been carried out for steel H23N18 (EN DIN - X8CrNi25-21) and H25T (EN DIN – X18CrN28) used for power industry and chemical equipment working at temperatures above 600$^o$C.

## 6. The scheme of experiment

The experimental part presented in the paper contained two kinds of tests:

1. Low cycle fatigue with constant total strain range from the beginning to the end of tests. Sine type of cycle with frequency 0,05 to 0,15 Hz was used.
2. Low cycle fatigue with two stages of loading and two procedures:

- A - the first part of test was performed with constant total strain range $\Delta\varepsilon_c$=0,006; the second with total strain range $\Delta\varepsilon_c$=0,014,
- B - the first part of test was performed with constant total strain range $\Delta\varepsilon_c$=0,014; the second with total strain range $\Delta\varepsilon_c$=0,006.

The other procedures of gradual loading were curried out as well. All kinds of tests have been done at room and at 600$^o$C temperatures.

## 7. Results

Low cycle fatigue tests made it possible to determine a fatigue life as a function of total strain range. The relationships has been described between $\Delta\varepsilon_c$ and $N_f$ in Manson Coffin expression that was used [7,8]. The Fig. 2 represents fatigue diagrams determined for different types of materials, and different temperatures.

The example of low cycle fatigue characteristics, determined in tests with two stages of loading, is shown in the Fig. 3.

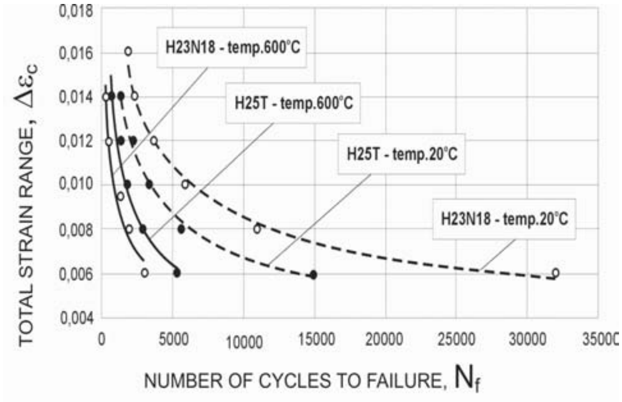


Fig. 2. Fatigue diagrams determined at 20$^o$C and 600$^o$C for H23N18 and H25T steels

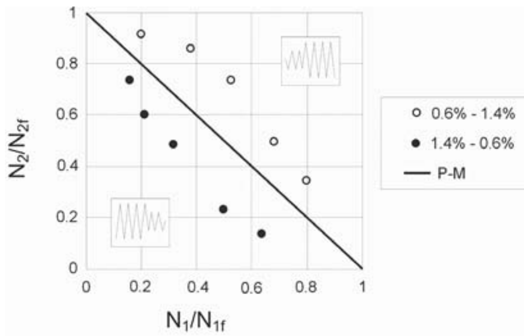


Fig. 3. Fatigue damage diagrams based on Palmgren-Miner theory; steel H23N18 at 20$^o$C

## 8. Validation method

The predicted critical value of the damage energy density has been calculated first. This value has been assumed as a potential energy release in the moment of tensile test specimen fracture. This assumption involve:

$$W_k = 0{,}5\frac{\sigma_t^2}{E} \tag{9}$$

where: $\sigma_t$ – true tensile stress, E – Young modulus.

The formula of energy P density has been suggested as

$$P = c \cdot \Delta\varepsilon_c^{\ d} + a \cdot e^{b \cdot N} \tag{10}$$

P is the function of fatigue test parameters, which in the work is represented by $\Delta\varepsilon_c$, and number of cycles N. Letters c, d, a, b mark temperature dependent material constants. In case of one stage fatigue we can determine $W_k$ in function of P from the equations (5) and (6):

$$W_k = \int_1^{N_f} \left(c \cdot \Delta\varepsilon_c^{\ d} + a \cdot e^{b \cdot N}\right) dN = c \cdot \Delta\varepsilon_c^{\ d} \cdot N_f + \frac{a}{b} \cdot e^{b \cdot N_f} - c \cdot \Delta\varepsilon_c^{\ d} - \frac{a}{b} \cdot e^b \qquad (11)$$

The boundaries of function P validity has been assumed as $\Delta\varepsilon_{min}$=0,006 and $\Delta\varepsilon_{max}$=0,014. First it has been taken for each material and temperature four pairs of $\Delta\varepsilon_c$ and $N_f$ from data obtained in the first kind of tests – for instance from curves on the Fig. 2. It has been defined system of four equations this way. Resolving this system, constants c, d, a, b have been determined. Diagram in Fig. 4 shows the example of influence of a cycle number on an energy P($\Delta\varepsilon_c$, N) value.

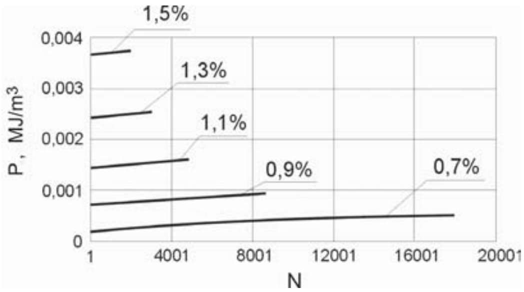


Fig. 4. Energy density P as the function of number of cycles; steel H23N18 at 20°C, for different values $\Delta\varepsilon_c$

## 9. Discussion

The presented work discusses one of many actually important problems that is the part of wide research area of materials and components under mechanical and thermal loading [10-15].

One of possible functions P($\Delta\varepsilon_c$,N) has been used to describe the course of damage energy density on this stage of investigation. This function has been determined and has to be restricted to $\Delta\varepsilon_c$ range with lower bound 0,006 and upper bound 0,016 i.e. range of the fatigue tests. The discussion of investigation results has to be constrained to this interval as well.

We can observe that the proposed description of fatigue life well exemplifies the character of material behaviour. But description holds true with experiments on different degree, which depends on material grade and temperature. The better accordance has been gained in case of H25T steel.

Sum of energy density for given test as well as appointed $W_k$ value of critical energy from static tensile test were compared.

We can observe the good accordance of the $\sum_{i=1}^{n} W_i / W_k$ value with the theoretically predicted value 1. The mean value, calculated for "2 stages" gradual loading, was 0,980289 with standard deviation 0,143648. For "3 stages" gradual loading the mean value equalled 0,99002 with standard deviation 0,138663 [10]. The advantage of proposed description may be the possibility to search for the physical interpretation of the fatigue damage process. The potential energy release can be used as the fatigue criterion. The value of this energy we assumed as constant and independent on fatigue process history. In fatigue process this energy releases gradually in each cycle. In case of tensile test the potential energy releases in the one cycle at the moment of fracture. Some conclusions related to the presented in the paper hypothesis have been formulated.

The value of accumulated damage in current cycle, expressed by energy density P, don't show significant changes in the whole fatigue period in case of high values of strain ranges. P essentially changes in the function of cycle number for low values of loads.

Results show that it is possible to determine fatigue life in case of sequence loading using the damage cumulative expression. But it is necessary to take into consideration that cumulated energy density P in each cycle depends on the strain range and number of the cycles.

The total locally released potential energy density of fatigue damage in presented work we can compare with critical energy density $W_k$ that may be treated as a constant.

## References

[1] A. Wöhler, Tests to determine the forces acting on railway carriage axles and the capacity of resistance of the axles, Engineering 11 (1971) 199.
[2] W.W. Moskwitin, Cycle durability of construction, Publication Nauka, Novosybirsk, 1981.
[3] B. Tomkins, Fatigue failure and the integrity of structures, Course of Metal Fatigue, University of Sheffield. 1991.
[4] K.J. Miller, K.P. Zachariach, Cumulative damage laws for fatigue crack initiation and stage propagation, Journal of Strain Analysis 12/4 (1977).
[5] K.J. Miller, An introductory lecture on fatigue of metals, Course of Metal Fatigue, University of Sheffield. 1991.
[6] M.F. Ibrachim, K.J. Miller, Determination of fatigue crack initiation life, Fatigue of Engineering Materials and structures 4 (1980).
[7] S.S. Manson, Creep-fatigue analysis by strain range portioning, NACA TM X-67838, 1971.
[8] L.F. Coffin, Fatigue at high temperatures-prediction and interpretation, Institution of Mechanical Engineers, 188, London, 1974.
[9] M.A. Miner, Cumulative damage in fatigue, Journal of Applied Mechanics, 67, A-159 (1945)
[10] G. Junak, Low-cycle fatigue of creep resistant steels under gradual loading. Library of Silesian University of Technology, Gliwice 2003 (in Polish)
[11] J. Okrajni, A. Marek, G. Junak, Description of the deformation process under thermo-mechanical fatigue, Journal of Achievements in Materials and Manufacturing Engineering 21 (2007) 15-24.
[12] D. Renowicz, M. Cieśla, Crack initiation in steels parts working in boilers and steam pipelines, Journal of Achievements in Materials and Manufacturing Engineering 21/2 2007 49-52.
[13] J. Dobrzański, The classification method and the technical condition evaluation of the critical elements' material of power boilers in creep service made from the 12Cr–1Mo–V, Journal of Materials Processing Technology 164-165 (2005) 785-794.
[14] J. Dobrzański, A. Zieliński, M. Sroka, Structure, properties and method of state evaluation of low-alloyed steel T23 (HCM2S) worked in creep conditions, Proceedings of the 11th International Scientific Conference on the Contemporary Achievements in Mechanics, Manufacturing and Materials Science CAM3S'2005, Gliwice-Zakopane, 2005, 171-180, (CD-ROM).
[15] D. Renowicz, A. Hernas, M. Ciesla, K. Mutwil, Degradation of the cast steel parts working in power plant pipelines, Journal of Achievements in Materials and Manufacturing Engineering 18 (2006) 219-222.