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Letter to the Editors

Multiplicative model for out-of-phase thermal fatigue degradation of ferritic–martensitic steel MANET-II

A. Zisman [a], V. Rybin [a], C. Petersen [b,*], R. Schmitt [b]

[a] *Central Research Institute of Structural Materials PROMETEY, Shpalernaya 49, RUS-193015 St. Petersburg, Russian Federation*
[b] *Forschungszentrum Karlsruhe für Technik und Umwelt, Institut für Materialforschung II, Postfach 3640, D-76021 Karlsruhe, Germany*

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Abstract

Hollow specimens of a Cr-steel have been subjected to triangle temperature cycles and different temperatures. Out-of-phase thermal fatigue lifetime is analysed and compared to isothermal fatigue data close to the mean cycle temperature. Segments associated with different temperature ranges and isothermal fatigue lines display in logarithmic scale only a slight slope difference. The thermomechanical fatigue degradation model suggests that the strain-related degradation per cycle is multiplied by a factor reflecting the particular effect of temperature oscillation.

1. Introduction

Accelerated damage relative to that of low-cycle fatigue (LCF) loading has been established on a ferritic–martensitic steel, when subjected to cyclic deformation at temperature changes at similar frequency; no matter which temperature within the cycle being considered as a reference one on comparison with LCF [1–3]. Therefore the LCF data available can hardly be used straightforward in conservative predicting lifetime of test blanket structural materials for the International Thermonuclear Experimental Reactor (ITER), designed for essentially non-stationary thermal conditions. At the same time, out-of-phase thermomechanical fatigue (OTMF) data on candidate materials of test blankets are rather poor and very hard to accumulate. Thus, an approach to fatigue lifetime, integrating known LCF and OTMF data and being efficient enough, is getting a highly actual problem. As a matter of fact, the working area for steels in ITER application (temperature range 150°C to about 400°C and plastic strain range up to 0.3%) is situated in the gap between the LCF and OTMF data available. Therefore the practicable task is selecting a way convincing enough to interpolate those data.

A 'straightforward' way of interpolation by due averaging the material response at LCF conditions over the temperature range in cycle [4] appears to be non-conservative according to the data of Ref. [1–3] and those of Ref. [5]. In other words, some specific degradation due to the temperature oscillation as such should be taken into account apart from the conventional degradation due to cyclic plastic (or/and creep) strain. Our main proposition is that the temperature oscillation actuates microdamage events on the structural scale of material, thus accelerating all the degradation mechanisms arisen from the cyclic inelastic strain. At the same time the microscopic damage mentioned can hardly destruct a macroscopic body until directed macroscopic strain is imposed. This reasoning suggests that the degradation in cycle should be decomposed multiplicatively; the strain-related degradation, referred to a due reference temperature, being multiplied by a factor reflecting the temperature oscillation. The goal of this article is to process data on LCF and OTMF of the ferritic–martensitic steel MANET-II in order to verify the model suggested above and to discuss its application in predicting lifetime of those for test blankets of candidate materials.

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[*] Corresponding author. Tel.: +49-7247 823 267; fax: +49-7247 824 566; e-mail: claus.petersen@imf.fzk.de.

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2. Experimental

Under investigation is a ferritic–martensitic 10.6% Cr-steel MANET-II. Hollow hourglass-shaped and cylindrical specimens have been machined from rods and sheets and then heat treated. Being fixed in the rigid frame, the specimens are ohmically heated and convection cooled in air with triangle temperature cycles at a heating and cooling rate of ±5.8 K/s. The mean temperature in cycle is stress-free. The experiment starts tension going to the minimum temperature and thus providing out-of-phase thermal fatigue conditions. Load and strain are recorded continuously by means of a digital data acquisition system. The net strain measured on the specimens is the sum of the thermal and mechanical strains. Hence the latter is calculated by subtracting the thermal strain from the net strain. The plastic strain range is defined from the hysteresis loop at zero stress, the loop being recorded for the mechanical strain as indicated above. The steel MANET-II is tested at temperature ranges 200–700°C, 100–600°C and 200–600°C; the reference LCF data being obtained at 450°C. For more details on the material composition, state of specimen design and experimental procedure the reader is referred to Refs. [1,2]. The steel MANET-II shows rather complicated OTMF – cyclic hardening behaviour, Figs. 1 and 2. For this reason the plastic strain range $\Delta\varepsilon^{\mathrm{pl}}$ in %, is taken for each specimen at half lifetime, $N_{\mathrm{f}}/2$.

3. Processing experimental results

The representation of LCF and OTMF data in total (or mechanical total) strain range versus cyclic lifetime is in common use from simplicity reasons. Similar data are represented in Fig. 3., for MANET-II, $\Delta\varepsilon^{\mathrm{tot}}_{\mathrm{mech}}$ being taken at $N_{\mathrm{f}}/2$. The only conclusion may be made from this graph that OTMF degradation is about an order faster when compared with LCF one at the intermediate temperature in cycle. At the same time, finer analysis is hardly possible as OTMF segments differ in slope both between each other and in relation to the LCF band; all slopes being rather weak herewith. A clearer picture appears, as expected from the physical point of view, when $\Delta\varepsilon^{\mathrm{pl}}$ is employed instead of $\Delta\varepsilon^{\mathrm{tot}}_{\mathrm{mech}}$, Fig. 4; the slope of each OTMF segment being obtained through linear interpolation with the least square methods. The first conclusion from this picture is only little difference in slope both among OTMF segments and between the latter as well as with the LCF band. When neglecting the subtle variation in slope, one may interpret this conclusion as the power m being unique in the degradation law

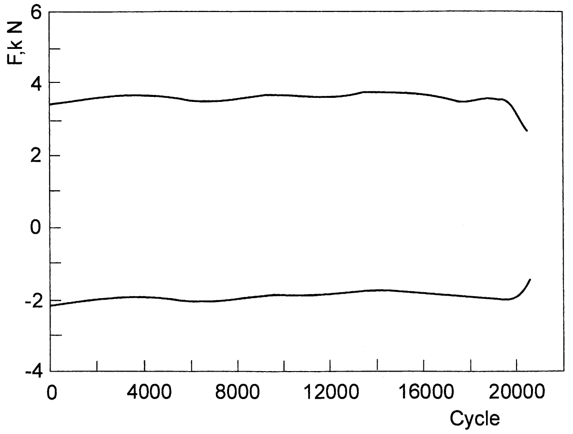

Fig. 1. OTMF cyclic hardening behaviour for steel MANET-II (Max. and min. force, F vs. cycle).

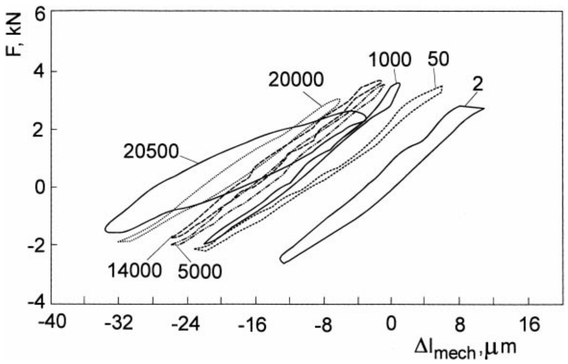

Fig. 2. OTMF cyclic hardening behaviour for steel MANET-II (Hystersis appearence for selected cycles; force, F vs. deflection range, Δl_{mech}).

$$\frac{1}{N_{\mathrm{f}}} = K(\Delta\varepsilon^{\mathrm{pl}})^m \tag{1}$$

for all OTMF segments and the LCF band. The second conclusion from Fig. 4 is that the more the temperature range ΔT increases during cycling, the more the vertical of the respective OTMF segment translation downwards

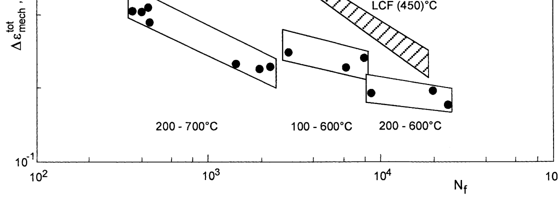

Fig. 3. Comparison of OTMF and LCF data for MANET-II in total mechanical strain range, $\Delta\varepsilon^{\mathrm{tot}}_{\mathrm{mech}}$ at $N_{\mathrm{f}}/2$ vs. number of cycles to failure, N_{f}.

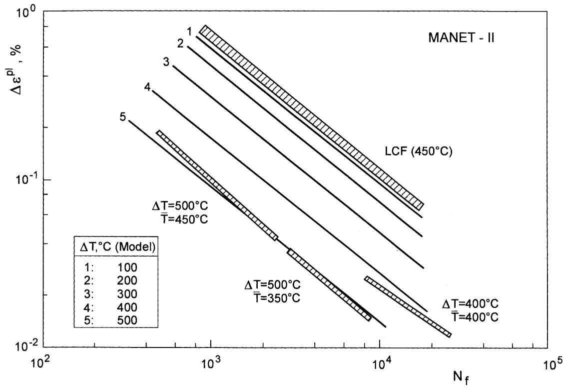

Fig. 4. Comparison of OTMF and LCF data for MANET-II in plastic strain range, $\Delta\varepsilon^{pl}$ at $N_f/2$ vs. number of cycles to failure, N_f

from the LCF band. Somewhat surprising is that segments corresponding to the ranges 200–700°C and 100–600°C are situated almost in line, thus displaying only a weak effect of cyclic mean temperature $\bar{T}$ of 450°C and 350°C, respectively, for the temperature ranges considered. In other words, the factor K in Eq. (1) is strongly dependent on ΔT, but not on $\bar{T}$.

It is worth noting that LCF and OTMF data processed above have been selected to be of close plastic strain rates. The rate in cycle at $N_f/2$ for LCF and OTMF, respectively, was estimated as

$$\begin{aligned}&(\mathrm{a})\quad \dot{\varepsilon}^{pl} = \dot{\varepsilon}^{tot}(\Delta\varepsilon^{pl}/\Delta\varepsilon^{tot}),\\&(\mathrm{b})\quad \dot{\varepsilon}^{pl} = \dot{\varepsilon}^{tot}_{mech}(\Delta\varepsilon^{pl}/\Delta\varepsilon^{tot}_{mech}).\end{aligned}\qquad(2)$$

The variations of $\dot{\varepsilon}^{pl}$ for OTMF and LCF, respectively were $(2\text{–}30)\times10^{-6}\ \mathrm{s}^{-1}$ and $(10\text{–}20)\times10^{-6}\ \mathrm{s}^{-1}$. Despite the reduced number of experimental points under consideration, just such a selection allowed us to indicate regularities represented in Fig. 4.

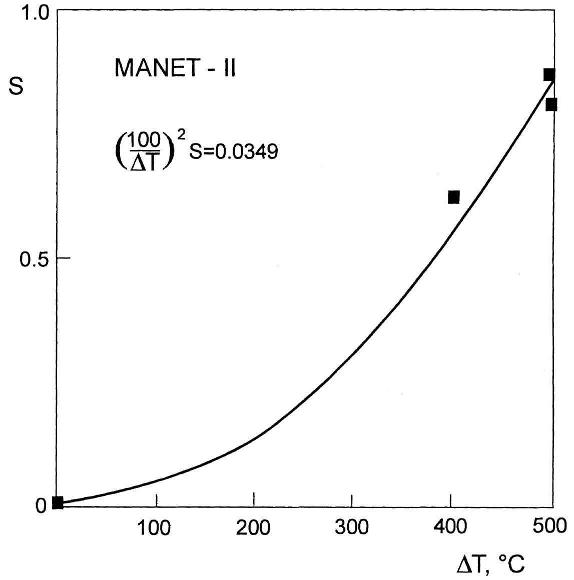

Fig. 5. Shift of thermal fatigue line relative to that of LCF, S vs. the temperature range, ΔT, in cycle for MANET-II steel.

4. OTMF degradation model and interpolation procedure

In accordance with conclusions made in the above section the OTMF degradation in cycle can be represented as

$$\Delta P = C(\bar{T},\Delta T)\Delta P^{\mathrm{LCF}}(\bar{T},\Delta\varepsilon^{pl}),\qquad(3)$$

where ΔP^{LCF} is the LCF degradation at temperature $\bar{T}$, $C\geqslant 1$ the factor accelerating the degradation rate due to temperature oscillations, and $\bar{T}$ some reference temperature within the temperature cycle. For experimental data considered above $\bar{T}$ has been taken close to the mean temperature in cycle. However, this choice may appear wrong under other conditions, in particular when changing out-of-phase to in-phase scheme or when introducing the hold time in the temperature cycle. The problem of $\bar{T}$ selection in the general case is out of scope of the present paper and needs further investigations. Taking in mind the relationship (1), let us rewrite Eq. (3) as

$$\Delta P = C(\bar{T},\Delta T)K^{\mathrm{LCF}}(\bar{T})(\Delta\varepsilon^{pl})^m,\qquad(4)$$

where C equals unit if $\Delta T = 0$ at any $\bar{T}$. Then the fatigue graph shift S, owing to the temperature oscillation may be represented as

$$S = \log\frac{(\Delta\varepsilon^{pl})^{\mathrm{LCF}}}{(\Delta\varepsilon^{pl})^{\mathrm{TMF}}}\Bigg|_{N_f,\bar{T}} = \frac{1}{m}\log\, C(\bar{T},\Delta T),\qquad(5)$$

being zero in LCF case when $\Delta T = 0$ and $C = 1$.

When interpolating the shift S, its value at each temperature range investigated is defined between the middle point of the respective OTMF segment and the lower border of the LCF band, while at $\Delta T = 0$ it is supposed $S = 0$ as a definition. These points as well as quadratic interpolation line are represented in Fig. 5 for MANET-II steel. Based on this interpolation, the model lines of OTMF are drawn in Fig. 4 for ΔT equal to 100°C, 200°C, 300°C, 400°C and 500°C.

5. Summary and discussion

Appearance of LCF and OTMF data of MANET-II steel, when represented in logarithmic axes in the plastic strain range in cycle versus lifetime, allows one to employ a simple multiplicative model for OTMF degradation. According to this model, the strain-related LCF degradation at the mean temperature in cycle is multiplied by a factor reflecting the effect of temperature oscillation. On this basis an interpolation has been carried out between available LCF and OTMF data, thus predicting OTMF lifetime of this steel within ranges of plastic strain and temperature just expected under ITER conditions. The latter ranges still are not covered by the thermal fatigue experiments performed on rigidly constrained specimens [1,2]. To get lacking experimental points in order to improve the lifetime prediction accuracy, it is necessary to impose active strain variation for temperature ranges in cycle less than 400°C.

The question of special importance is the selection of a reference temperature in OTMF loading to be used in comparison with LCF data. In this study a temperature close to the mean cyclic temperature has been taken as reference only for the following qualitative reasons. On the one hand, the higher the temperature, the shorter is the LCF lifetime in general. In this sense the maximum temperature in cycle would be reference one. On the other hand, under OTMF-conditions the maximum tensile stress corresponds to the minimum temperature during cycling. Such a reasoning suggests that for inphase thermal fatigue, the maximum temperature of the cycle should be taken as a reference temperature. This problem being not a focus of the present article, needs special investigation. Another point to be reflected within the model proposed, is the effect of hold time during cycling. Further investigation is needed to conclude whether this effect may be merely embodied in the LCF term of the product in Eq. (4).

Acknowledgements

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