LOW CYCLE FATIGUE OF X40CrMoV51 AT HIGH TEMPERATURES

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Load controlled high strain fatigue tests were performed on X40CrMoV51 steel at temperatures around 600°C. The plastic strain was measured as function of the number of cycles. A mean damaging strain amplitude is defined for use in a Manson-Coffin rule. Effects arising from a temperature gradient along the specimen axis and from localized strain (necking) are discussed.

INTRODUCTION

High strain fatigue tests are frequently carried out at constant plastic strain range $\Delta\varepsilon_{pl}$ (rather at constant change in specimen length). For life-time prognosis the results are plotted according to the Manson-Coffin rule (1,2):

$$N_f \cdot \Delta\varepsilon_{pl}^{\,m} = a \qquad (1)$$

a and m are material parameters. N_f means the number of cycles to fracture.

It has been pointed out (3) that experimental scatter can be reduced drastically by using N_{cr} (the number of cycles until the formation of a significant crack) instead of N_f. It is, however, not always easy to determine N_{cr} from changes in load amplitude.

In high strain fatigue tests at constant load amplitude it is usually quite easy to determine N_{cr} from a drastic increase in the changes of length of the specimen. Moreover, N_{cr} does not differ much from N_f. On the other hand, $\Delta\varepsilon_{pl}$ will usually change during the test so that a mean damaging strain range $\overline{\Delta\varepsilon_{pl}}$ must be defined for use in equ.(1).

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Further corrections may be necessary if the strain has a gradient over the length of the specimen. At small strains such gradients may be produced even by slight gradients of temperature. At large strains one may have to consider localisation of strain (necking).

EXPERIMENTAL PROCEDURE

The load controlled push-pull fatique tests were performed on a servohydraulic testing machine at 550°C, 600°C and 650°C. The material was the martensitic steel X40CrMoV 51 (weight% C = 0.38, Si = 0.9, Mn = 0.36, P = 0.016, S = 0.013, Cr = 5.20, Mo = 1.26, V = 0.99, Cu = 0.16, Al = 0.034, Fe = bal.) with standard heat treatment to 40 HRC.

In order to suppress creep deformation a frequency of 2 Hz was chosen. The specimens were heated by a three-zone furnace, the temperature was taken by a thermo-couple. Changes in length of the specimen were measured as a function of the number of cycles N. Elastic strain was subtracted from the signal in an E-module-compensator so that all strains referred to in this paper are plastic strains.

STRAIN DISTRIBUTION AT LOW STRAINS

Contact with the grips gave the specimen a temperature profile as shown in fig 1a. At stresses near the yield point this leads to a considerable non-uniformity of strain as shown in fig. 1b. This curve has been determined point by point from a series of stress-strain curves at the corresponding temperatures. The area under the curve gives the elongation which corresponds to the average strain shown as a dashed line in fig.1b. The specimen will break in the section with maximum strain (n-times the average strain) and this therefore is the strain to be used in equ. (1). In our example n = 1.33 at the beginning of the test and will decrease towards 1 as fatigue proceeds.

DETERMINATION OF N_{cr} AND $\overline{\Delta\varepsilon}$ AT SLOW CHANGES OF PLASTIC STRAIN

Our results usually looked like fig. 2, i.e. the strain changes about almost linearly (and slowly) with the number of cycles N:

$$\Delta\varepsilon = \Delta\varepsilon_o \,(1 + cN) \qquad (2)$$

At a critical number of cycles N_{cr} the changes in length deviate from linearity and increase rapidly until the specimen breaks at N_f.

N_{cr} should be used in equ. (1) for the point when failure starts. A simple assumption for the mean strain $\overline{\Delta\varepsilon}$ to be used in equ. (1) is:

$$\overline{\Delta\varepsilon} \approx \Delta\varepsilon_o \;(1 + \frac{c\,N_{cr}}{2}) \qquad (3)$$

This obviously neglects the nonlinear relation between strain and damage which is the reason why m in equ. (1) is usually larger than 1. In order to check the importance of this neglect we apply the Miner-rule (4) to weight each loading cycle according to its contribution to the total damage:

$$\overline{\Delta\varepsilon^m} = \frac{1}{N_{cr}} \sum_{1}^{N_{cr}} (\Delta\varepsilon)^m \tag{4a}$$

$$\overline{\Delta\varepsilon^m} \approx \frac{(\Delta\varepsilon_0)^m}{N_{cr}} \int_0^{N_{cr}} (1 + c\,N)^m \, dN \tag{4b}$$

and hence

$$\overline{\Delta\varepsilon} = \Delta\varepsilon_0 \left[\frac{(1 + cN_{cr})^{m+1} - 1}{c\,N_{cr} \quad (m+1)} \right]^{\frac{1}{m}} \tag{5}$$

This deviates from equ.(3) for $m \neq 1$. The deviation increases for increasing values of m and of $c\,N_{cr}$. Generous upper bounds for m and $c\,N_{cr}$ in our experiment are $m < 1.5$ and $c\,N_{cr} < 2$. With these bounds the values for $\overline{\Delta\varepsilon}$ as calculated from the equs.(3) and (5) differ by only 2% which shows that the mean strain taken from equ.(3) is close enough. This should be true for most experiments of this type.

STRAIN LOCALIZATION AT LARGE STRAINS

In our experiments the constant c in equ.(2) was always positive which indicates a softening of the material. At strains above 0.005 this led to a localization of strain far beyond that caused by the temperature profile in fig. 1. Specimens showed visible necking which was reflected in a deviation from linearity as in fig. 2 but after a much lower number of cycles. This deviation does not indicate the formation of cracks. It could be shown metallographically that deformation in the neck is ductile for many cycles and that cracks appear only a few cycles before fracture.

Therefore equ.(4a) can not be approximated as in equ.(4b) nor is equ.(3) more than a lower bound. A higher (and more realistic) value for $\overline{\Delta\varepsilon}$ can be found by a summation according to equ. (4a) but it depends sensitively on the assumed value of N_{cr}. In fig. 3 the point indicated by an arrow has been corrected in this somewhat arbitrary way.

RESULTS

Fig. 3a shows the results of our test using the values as obtained from experiment. The best straight line through these points is given by

$$N_{cr}\,\Delta\varepsilon^{1.39} = 0.13 \tag{6}$$

Fig. 3b shows our results after the corrections discussed in this paper. The best straight line through these points is given by

$$N_{cr}\,\Delta\varepsilon^{1.25} = 0.41 \qquad (7)$$

The experimental scatter seems to be reduced in fig. 3b and we feel that the values in equ. (7) are better suited for extrapolation than those in equ. (6).

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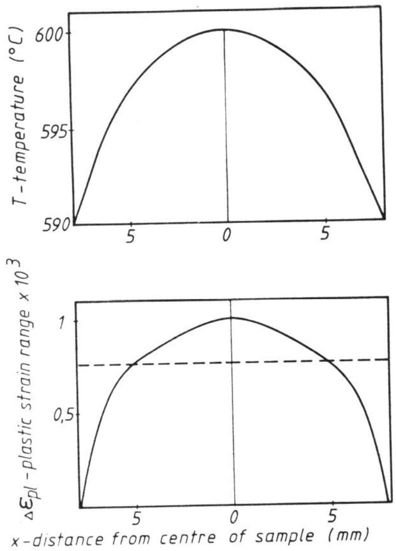

Figure 1 Temperature- and deformation-profile

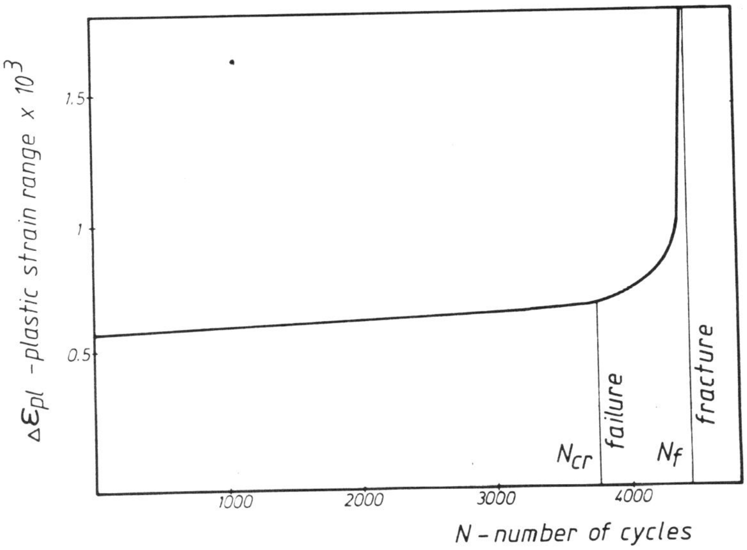

Figure 2 Course of plastic strain range as function of the number of cycles

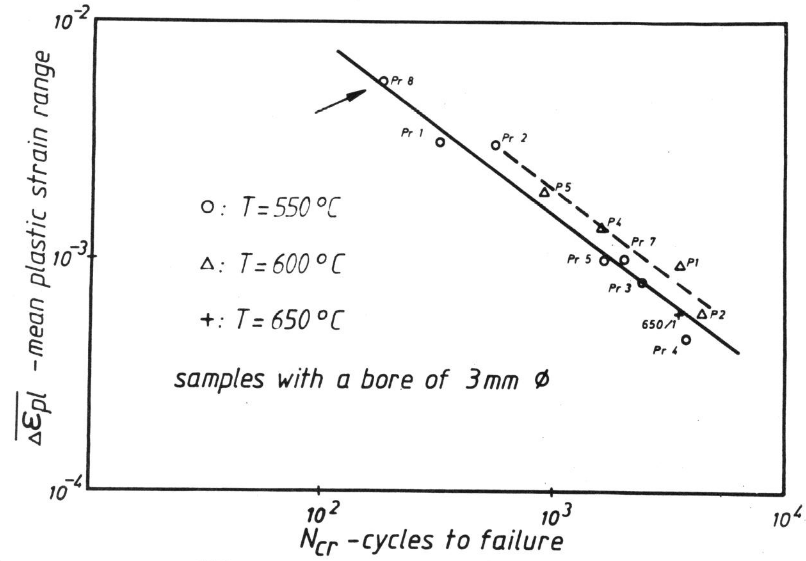

Figure 3 Points ($\overline{\Delta\varepsilon}/N_{cr}$) determined without taking into account the considerations of this paper

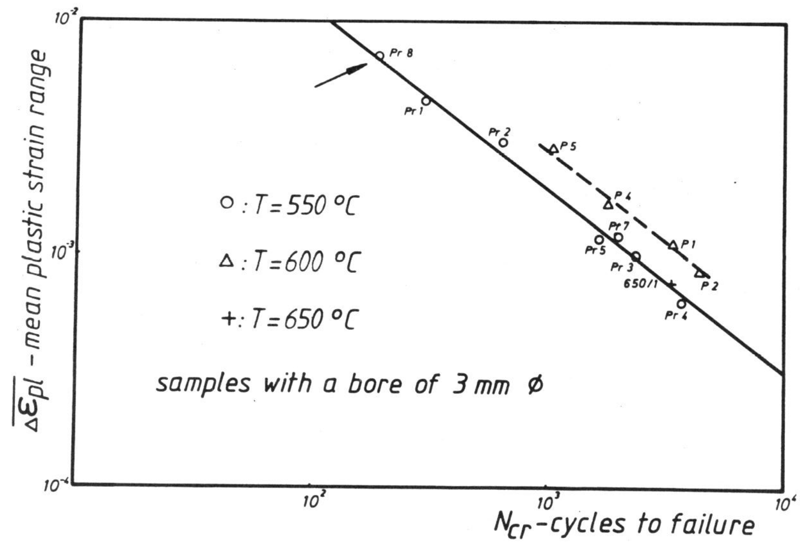

Figure 4 Points ($\overline{\Delta\varepsilon}/N_{cr}$) determined by taking into account the considerations of this paper