EFFECT OF TEMPERATURE AND HOLD TIME ON LOW-CYCLE FATIGUE OF STEEL 13 CRMO 44

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ABSTRACT

Low-cycle fatigue tests of steel 13 CrMo 44 have been performed under strain controlled conditions at room temperature and at elevated temperature in air. Effect of strain rates (frequencies) and hold times on the fatigue life has been ascertained. Cyclic stress-strain response and stress-relaxation behavior were studied. Finally the applicability of the predictive methods for fatigue life at high temperature proposed by other investigators has been discussed. In order to clarify the micromechanisms of fatigue at high temperature, microstructural features were also examined.

KEYWORDS

Cyclic stress-strain response, stress-relaxation, high temperature fatigue, frequencies, hold time, predictive method

MATERIAL AND TEST PROCEDURE

Test specimens of round type were machined from 20 mm thick plates of the low alloyed steel 13 CrMo 44. The experiments were conducted on a servo-hydraulic push-pull machine equipped with a multi-zone radiant heater. Total longitudinal strain control with the commonly used triangular waveshape was chosen for loading. The fatigue tests were carried out with strain rates between 8×10^{-3} sec^{-1} and 1.6×10^{-4} sec^{-1} at room temperature and 560 °C in air. Hold periods from 1 minute up to 60 minutes per cycle were introduced in tension at a strain rate of 4×10^{-3} sec^{-1}. The total strain range applied in tests was between 1 % and 4 %.

RESULTS

The effects of temperature, strain rate and hold time on the fatigue behaviour were investigated and the results are given in Fig. 1 and Fig. 2. The criterion used for fatigue failure was the critical number of cycles N_{cr} instead of N_f, number of cycles to fracture. N_{cr} is defined as the number of cycles leading to the damage state which noticeably weakens the specimen (Lachmann, 1978; Rie, 1973, 1979). Other authors have adopted a similar approach in order to characterize the fatigue life. Fig. 1 shows that the results can be well described by the analogous Manson-Coffin equation

$$N_{cr}^{\alpha}\Delta\varepsilon_a = C \qquad (1)$$

where α and C are constants and $\Delta\varepsilon_a$ is total strain range.

It can be seen that the fatigue life decreases with increasing temperature. Furthermore it was found that at high temperature the fatigue life decreases with decreasing strain rate. The curves in Fig. 1 have a constant slope for different strain rates at high temperature. The effect of hold time was investigated and the results are given in Fig. 2. The existence of such an effect has been reported previously (Conway, 1973; Krempel, 1971; Rie, 1974). Fig. 2 shows the effect of different hold times on the fatigue life of 13 CrMo 44 steel at 560 °C. The fatigue life decreases with increasing hold periods. It is evident that the value of α increases with increasing hold time. It can be concluded that the increase in hold time at constant temperature has a comparable effect on fatigue life as temperature increase when tested without hold time.

Economical and safe design of structures in low-cycle fatigue region recquires the knowledge of the cyclic deformation behaviour of the material. The results obtained in monotonic and cyclic tests at room temperature and 560 °C are given in Fig. 3. Hold time leads to the increase of cyclic strain hardening. The cyclic crack stress strain curve is obtained by plotting the $\Delta\sigma_{cr}$ at N_{cr} versus strain range $\Delta\varepsilon_a$. It can be described by equation

$$\Delta\sigma_{cr}/2 = K' (\Delta\varepsilon_a/2)^{n'} \qquad (2)$$

where K' is the cyclic strength coefficient. The cyclic strain hardening exponent n' was found to be 0.180 and 0.123 at room temperature and 560 °C respectively.

DISCUSSION

In the absence of time dependent effects the fatigue life can be predicted by equation (1) with the fatigue exponent $\alpha \approx 0.5$. This equation has been found to be applicable for most of the common structural materials at room temperature (Coffin, 1974) as shown in Fig. 1. The temperature increase can lead to the increase of the value $\alpha > 0.5$ depending on the material and test temperature. A similar correlation has been reported by other investigators (Berling, 1969; Coffin, 1973; Williams, 1973). The increase of the exponent α was often referred to an additional creep damage. An oxidation was also considered to be the cause.
In continuous cycling nevertheless microstructural investigations after fatigue tests revealed no evidence of any creep damage even at the lowest strain rates applied. Crack propagation is essentially transgranular and no failure has been found in the interior of the specimens. The cracks are filled with oxides (Fig. 4). The oxide layer tends to increase with decreasing strain rates. The time dependency of damage processes at high temperature has been considered (among others) by introducing the frequency term in equation (1). This modified relationship (Coffin, 1969) is expressed by equation

$$(N_{cr} f^{k-1})^{\beta} \Delta\varepsilon_a = C_2 \qquad (3)$$

where f is frequency and k, β, C_2 are constants.

The equation (3) is achieved by assuming that the degrading effect of temperature and strain rate arises from the interaction between environment and cyclic strain. Therefore it is envisaged that the enhanced crack initiation through oxide layer and accelerated crack growth by selective oxidation at the crack tip leads to the additional reduction of fatigue life with decreasing strain rates. It is obvious that the results shown in Fig. 5 can be well described by equation (3). The estimated values of the constant k = 0.86, β = 0.70 and C_2 = 1.26 are in good agreement with those reported by Coffin (1973). This agreement together with the results of the microstructural investigations is consistent with the environment controlled fatigue regime defined by Coffin (1969). Nevertheless the application of the frequency modified life concept in predicting hold time behaviour from short time data could not be proved valid in the case of long hold periods. The estimation of the fatigue life using constants obtained by the frequency modified fatigue life concept leads to an overestimation of life compared with the experimental results. This seems to suggest that an additional damage has occured during the hold period. Hold time leads to greater reduction of fatigue life with decreasing strain range (Fig. 2). On the other hand total testing time for constant strain range increases with increasing hold time. The relative plastic strain increase caused by the stress relaxation is related with the strain range and hold time as shown in Fig. 6. The results in Fig. 2 and Fig. 6 suggest that the increased relative plastic strain caused by the stress relaxation has lead to the additional life reduction. Scanning electron microscopic examination of the longitudinal section confirmed this view. Typical creep damage was revealed. Wedge cracks and cavitations are clearly visible in Fig. 7. This creep damage is responsible for the varying value of α in the tests with 10 and 30 minutes hold period. On the contrary no grain boundary voids and cavitation could be found in specimens tested with 1 minute hold time. The life reduction in this case is considered to be caused mainly by the interaction of environment and cyclic strain. The influence of creep damage can then be ignored.

CONCLUSIONS

Low-cycle fatigue tests conducted at 560 °C on 13 CrMo 44 lead to the following conclusions:

1. For continuous cycling and for the test with relatively short hold time ($<$10 min) fatigue life is influenced mainly by the interaction between environment and cyclic strain.
2. With increasing hold time ($>$10 min) creep becomes an important factor additionally to the environment effect.
3. Microstructural analysis allowed the additional life reduction to be related to creep damage when tested with long hold periods.
4. Life prediction approach based on the frequency modified concept (equation 3) was found to be applicable only for restricted regimes. Thus creep effect should deserve more attention.
5. For the use of the Method of Universal Slopes (Manson, 1967) modified for estimates of fatigue life at high temperature the environmental effect should be taken into account additionally (Fig. 8). Even creep effect seems not to be considered sufficiently for tests with long hold periods.

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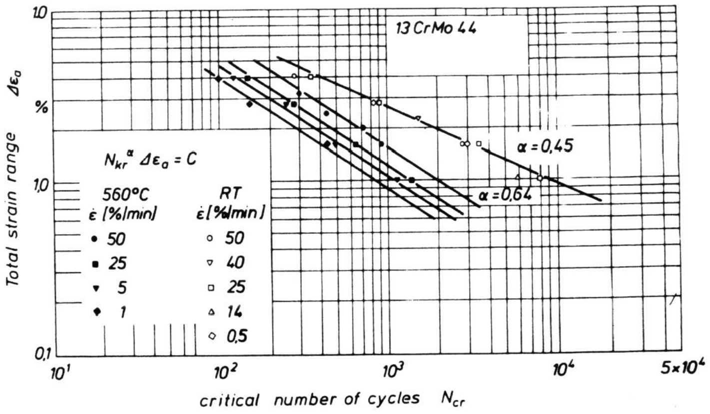

Fig. 1. Total strain range versus critical number of cycles. 13 CrMo 44 at various temperatures and strain rates.

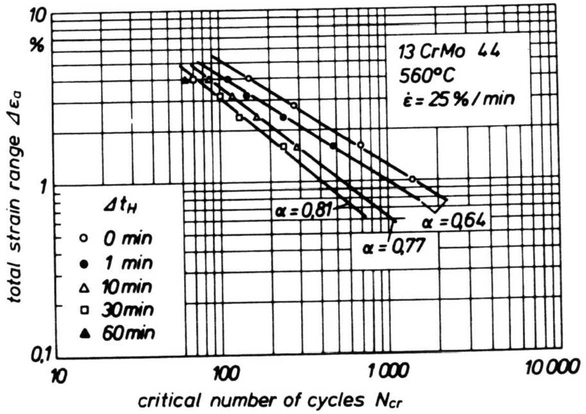

Fig. 2. Total strain range versus critical number of cycles. 13 CrMo 44 at 560 °C with various hold periods.

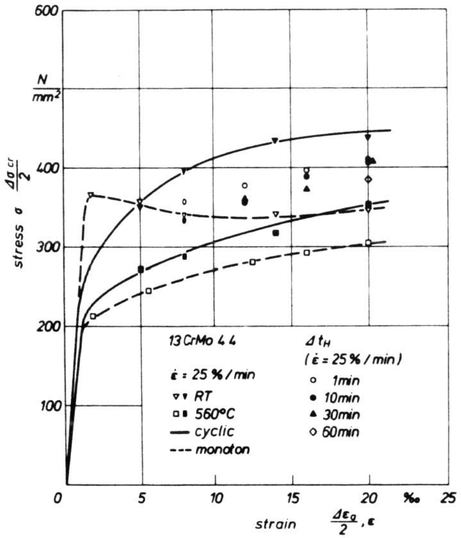

Fig. 3. Monotonic and cyclic crack stress strain curve for 13 CrMo 44

Fig. 4. Longitudinal section of 13 CrMo 44 specimen showing fatigue crack growing from probe surface. (560 °C; air; $\Delta\varepsilon_a$ = 2,8 %; $\dot{\varepsilon}$ = 1 % min^{-1}; N_{cr} = 150 cycles)

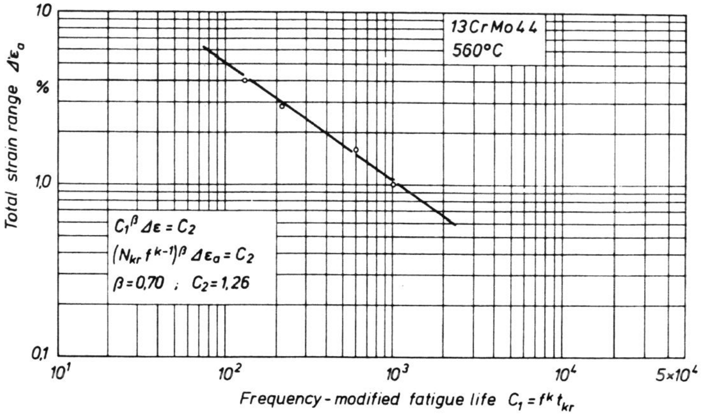

Fig. 5. Total strain range versus frequency-modified fatigue life estimated with N_{cr}.

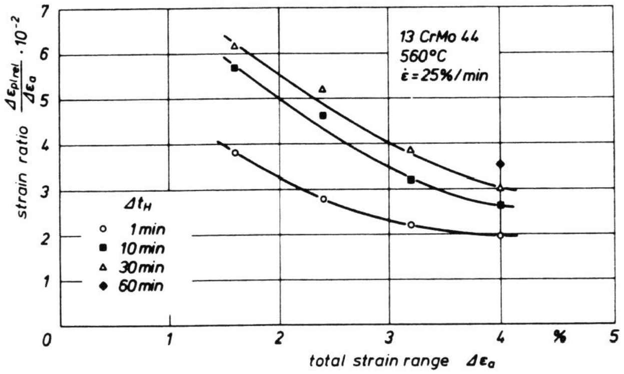

Fig. 6. Strain ratio versus total strain range for 13 CrMo 44 cycled with various hold times showing different plastic strain caused by stress relaxation.

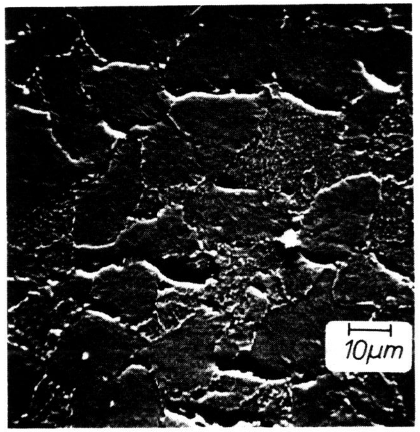

Fig. 7. Scanning electron microscopic view of longitudinal section of 13 CrMo 44 showing "creep damage" (voids, cavitation).

($560\ ^{\circ}C$; air; $\Delta t_H = 30$ min; $\Delta\varepsilon_a = 1{,}5\ \%$; $\dot{\varepsilon} = 25\ \%\ \mathrm{min}^{-1}$).

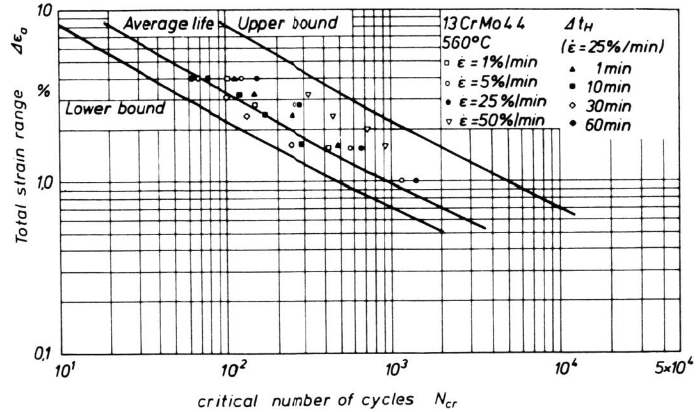

Fig. 8. Total strain range versus critical number of cycles for 13 CrMo 44.