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Thermal fatigue on MANET II

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Abstract

Out-of-phase thermal fatigue experiments in air are performed in a test facility, which has been designed to allow temperature cycling of the sample by ohmic heating. The test specimens are hollow, hourglass-shaped and cylindrical samples of a ferritic-martensitic stainless steel, MANET II, in the tempered condition. The effects of different thermal cycle ranges and the imposition of several hold time conditions on the mechanical behaviour are investigated. A continuous softening is the characteristic feature observed in all thermal fatigue tests. Larger temperature changes and the application of temperature hold periods produce an accelerated softening process, leading to smaller numbers of cycles to failure. Compared to a prior heat MANET I, the thermal fatigue endurance of MANET II is found to be in the same scatterband.

1. Introduction

Structural components of an ITER – or DEMO – blanket will be subjected during service to alternating thermal and mechanical stresses as a consequence of the high heat loadings and pulsed reactor operation, coolant pressure, magnetic loads and temperature gradients. The material of the structure must be dimensionally stable and retain adequate mechanical properties during exposure to these environmental conditions if the required performance and prolonged endurance of the structure are to be achieved. Of particular concern is the fatigue endurance of the MANET II steel under the cyclic straining produced by the temperature changes. At present thermal fatigue, together with radiation damage, are considered as the phenomena most detrimental to the lifetime of the structure.

A thermal fatigue test facility, described in Refs. [1] and [2], is used to measure the thermal fatigue life of candidate structural materials of the ITER blanket. Recent data sets of out-of-phase thermal fatigue tests on two heats of the ferritic–martensitic stainless steel MANET are reported and compared with respect to heat to heat variability and to sample geometry under various temperature cycle loading conditions.

2. Experimental

Two heats – MANET I and MANET II – of a ferritic–martensitic Cr-steel are under investigation. This steel has the German Steel Denomination Nr. 1.4914.

The MANET I material is in the form of 20 mm diameter rods with Heat Nr. 53645 and the chemical composition: C, 0.13; Cr, 10.6; Ni, 0.87; Mo, 0.77; V, 0.22; Nb, 0.16; Si, 0.37; Mn, 0.82; B, 0.0085; N, 0.02 and Zr, 0.053 wt%. The MANET II material is a 20 mm thick sheet with Heat Nr. 50805 and the chemical composition: C, 0.10; Cr, 10.3; Ni, 0.65; Mo, 0.57; V, 0.19; Nb, 0.14; Si, 0.14; Mn, 0.75; B, 0.0075; N, 0.031 and Zr, 0.028 wt%.

Hollow, hourglass-shaped specimens from MANET I and MANET II, as well as hollow cylindrical specimens from MANET II, are machined from the rods and the sheet. In case of the sheet the specimens are machined perpendicular to the rolling direction and from the centerline of the sheet – and than heat treated under the following conditions:

homogenization:	960°C/2 h/vacuum/air cooled,
austenitization:	1035°C/30 min/vacuum/air cooled and
tempering:	750°C/2 h/vacuum/air cooled.

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The resultant microstructure is a fully tempered martensite. It was shown previously by Armas et al. in Ref. [3] and Alvarez-Armas et al. in Ref. [4] that carbides are precipitated along prior austenite grain and lath boundaries, while smaller carbides are contained in the matrix.

The geometry of the hollow hourglass specimen with a radius of 100 mm has the advantage to concentrate the deformation to a small part in the middle of the specimen. To compare data from this sample with those of the hollow cylindrical sample with a gauge length of 10 mm, the strain measurement system is adjusted to 8 mm in the latter case.

The test specimen is heated ohmically. The load frame of the rig is thermally as well as electrically insulated. Load and strain are recorded continuously by means of a digital data acquisition system. A detailed description is given in Ref. [5].

The net strain measured on the specimen is the sum of the thermal and the mechanical strain. Hence the mechanical strain is calculated by subtracting the thermal strain from the total strain.

The test conditions are: Triangle temperature cycles with constant heating and cooling rates $\dot{T} = \pm 5.8$ K/s in a range of a fixed lower temperature T_L (200°C) and a variable higher temperature T_H (550–700°C). In addition to the pure triangular temperature cycling tests, tests with constant temperature hold periods of 100 s are performed. The hold time is at the high temperature T_H: HTH, at the low temperature T_L: HTL, or at both temperatures: HTHL.

3. Experimental results

Due to the fact, that the thermal fatigue testing device is of a design which does not enable to control either stress or strain, quantities like the stress range $\Delta\sigma$, the total mechanical strain range $\Delta\epsilon_{t,m}$ and the plastic mechanical strain $\Delta\epsilon_{p,m}$ change with the number of cycles. Hence only the measured values at $N_f/2$ are taken when comparing test results.

The small thermal elongation of the ferritic–martensitic steels causes total mechanical strain ranges of both heats between 0.2% and 0.8% during triangular thermal fatigue experiments. From the data sets of thermally cycled hourglass samples of MANET I and MANET II the total mechanical strain ranges $\Delta\epsilon_{t,m}$ at $N_f/2$ are plotted versus the number of cycles to failure N_f in Fig. 1. By increasing ΔT, $\Delta\epsilon_{t,m}$ at $N_f/2$ increases and leads to smaller N_f values. This effect is mainly driven by the ΔT influence on the plastic mechanical strain $\Delta\epsilon_{p,m}$ at $N_f/2$, which is plotted versus N_f for MANET I and MANET II in Fig. 2. The $\Delta\epsilon_{p,m}$ values at $N_f/2$ range from 0.02% up to 0.5%. With increasing ΔT the amount of plastic mechanical strain range increases due to the growing compressional creep contribution at the high-temperature end of the cycle.

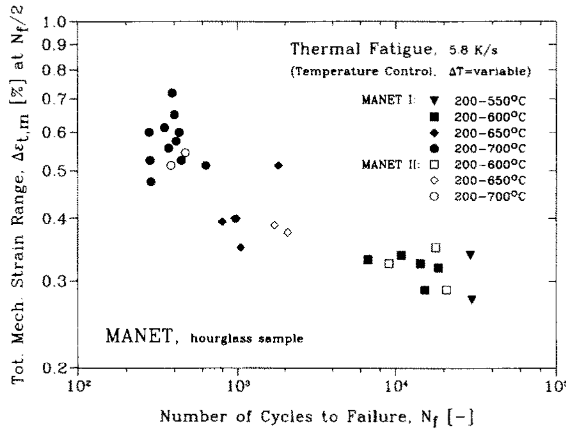

Fig. 1. Comparison of thermal fatigue data of the ferritic–martensitic steels MANET I and MANET II in a $\Delta\epsilon_{t,m}$ at $N_f/2$ versus N_f diagram.

Fig. 3 compares the total stress ranges $\Delta\sigma_t$ at $N_f/2$ of MANET I and MANET II, obtained during thermal fatigue. The $\Delta\sigma_t$ values at $N_f/2$ of MANET I increase up to a maximum value of about 670 Mpa with increasing ΔT and $\Delta\epsilon_{t,m}$ at $N_f/2$. The MANET II values reach only $\Delta\sigma_t$ values at $N_f/2$ of about 610 Mpa under the same conditions.

To avoid the strain concentration in the middle of an hourglass sample, also cylindrical samples have been machined and tested under the same thermal cyclic test conditions as the hourglass sample.

The data sets of thermally cycled hourglass and cylindrical samples of MANET II are compared in Fig. 4, where total mechanical strain ranges $\Delta\epsilon_{t,m}$ at $N_f/2$

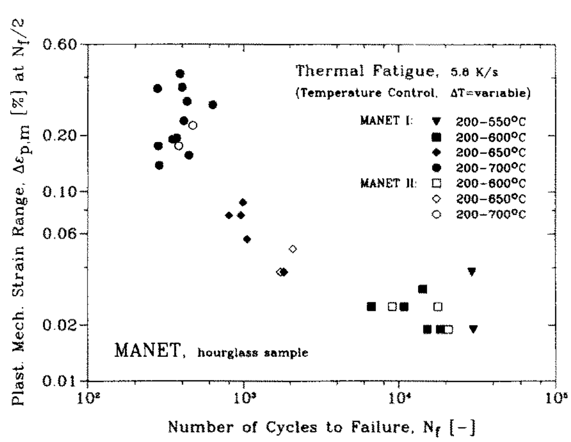

Fig. 2. Comparison of thermal fatigue data of the ferritic–martensitic steels MANET I and MANET II in a $\Delta\epsilon_{p,m}$ at $N_f/2$ versus N_f diagram.

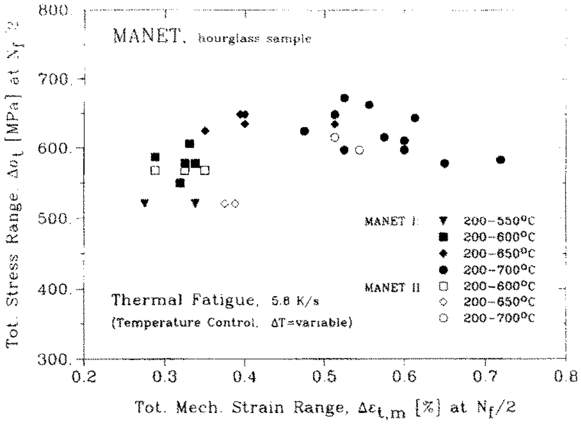

Fig. 3. Comparison of thermal fatigue data of the ferritic-martensitic steels MANET I and MANET II in a $\Delta\sigma_t$ at $N_f/2$ versus $\Delta\epsilon_{t,m}$ at $N_f/2$ diagram.

are plotted versus the number of cycles to failure N_f. The differences between the two sample geometries are negligible. The two sets of results lead to the same conclusion, i.e. that with increasing ΔT, $\Delta\epsilon_{t,m}$ at $N_f/2$ increases and results in smaller N_f values. Also the plastic mechanical strain $\Delta\epsilon_{p,m}$ at $N_f/2$, which is plotted for cylindrical and hourglass samples of MANET II in Fig. 5, shows evidence for the small differences between both data sets.

Fig. 6 compares the total stress ranges $\Delta\sigma_t$ at $N_f/2$ of cylindrical and of hourglass samples of MANET II, obtained during thermal fatigue. The $\Delta\sigma_t$ values at $N_f/2$ of both kinds of samples are found in a broader but similar scatterband.

The influence of hold times during thermal fatigue of MANET II can be seen from Fig. 7. This plot shows

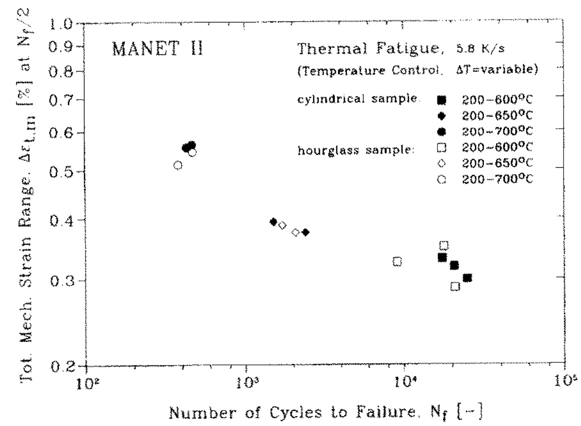

Fig. 4. Comparison of thermal fatigue data of cylindrical and hourglass samples of MANET II in a $\Delta\epsilon_{t,m}$ at $N_f/2$ versus N_f diagram.

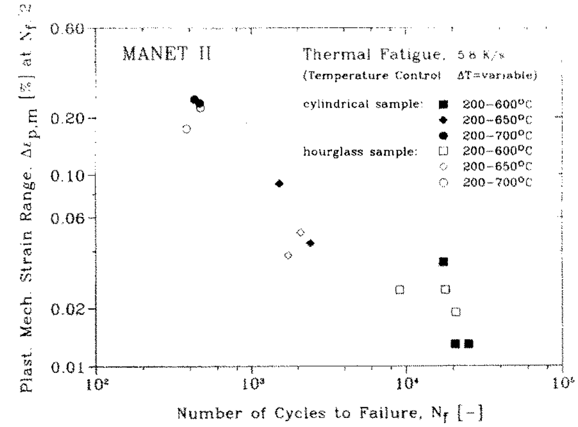

Fig. 5. Comparison of thermal fatigue data of cylindrical and hourglass samples of MANET II in a $\Delta\epsilon_{p,m}$ at $N_f/2$ versus N_f diagram.

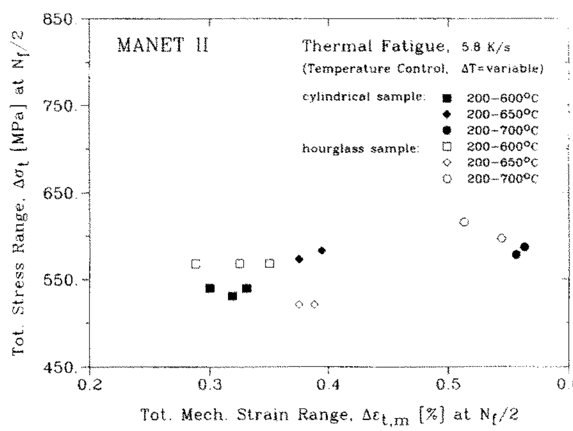

Fig. 6. Comparison of thermal fatigue data of cylindrical and hourglass samples of MANET II in a $\Delta\sigma_t$ at $N_f/2$ versus $\Delta\epsilon_{t,m}$ at $N_f/2$ diagram.

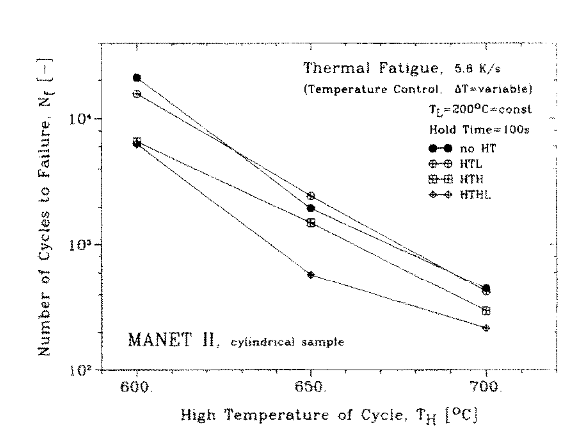

Fig. 7. Number of cycles to failure versus the high temperature T_H of the thermal cycle for the ferritic-martensitic steel MANET II.

the number of cycles to failure N_f as a function of the temperature at the high-temperature end of the cycles, T_H. Three different thermal cycling conditions ΔT are selected, corresponding to $T_H = 600$, 650 and 700°C. From the figure it is evident that, for each ΔT examined, the numbers of cycles to failure are reduced when applying a hold time of $t_H = 100$ s. The reduction in N_f becomes larger in the sequence HTL, HTH and HTHL. On the other hand this effect becomes weaker for higher T_H and ΔT, respectively.

4. Conclusions

A test method for performing uniaxial out-of-phase thermal fatigue tests on metals is presented. The test facility consists of an ohmic heating system built in a rigid load frame. The hollow hourglass or cylindrical shaped, tubular specimens of the two heats, MANET I and MANET II of the ferritic–martensitic stainless steel are subjected to constant linear heating and cooling rates in a temperature range of a fixed low temperature (200°C) and a variable high temperature (550 to 700°C) in air atmosphere. Total mechanical strain ranges between 0.2 and 0.8% are achieved, and evaluated by measuring the total strain and subtracting the thermal strain from it.

Increasing ΔT values give rise to an increase of the total mechanical and plastic mechanical strain range at $N_f/2$, corresponding with decreasing numbers of cycles to failure as well as with an increase of the total stress range at $N_f/2$ with increasing total mechanical strain range at $N_f/2$.

The thermal fatigue life of the examined ferritic–martensitic steel MANET II is mostly found to be shortened when hold times of 100 s at the high-temperature end of the cycle are applied.

Acknowledgements

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