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Thermal fatigue behavior of low activation ferrite–martensite steels

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Abstract

Components like test blankets of the thermonuclear fusion reactor ITER or like DEMO-blankets are subjected during service to alternating thermal and mechanical stresses as a consequence of the pulsed reactor operation. Of particular concern is the fatigue endurance of reduced activation ferrite-martensite steels like the Japanese F82H mod. and the German OPTIFER IV, compared to martensitic steel for the next European torus (MANET II), as reference material, under cyclic strains and stresses produced by typical temperature changes. Into self developed thermal cycling fatigue test rigs variable strain rates are applied to these materials, due to the constant heating rate and variable temperature changes. Thermal fatigue behavior of ferrite-martensite MANET II, including dwell times, will be reported. On the other hand F82H mod. as well as OPTIFER IV samples are thermal cyclically tested in different as received conditions and the the results are compared to those of MANET II samples after the three-step reference annealing.

1. Introduction

Structural components like test blankets for the thermonuclear fusion reactor ITER and DEMO-blankets are subjected during service to alternating thermal and mechanical stresses as a consequence of the high heat fluxes and pulsed reactor operation, as well as coolant pressure, neutron irradiation, magnetic loads and temperature gradients. The material of the structure must be dimensionally stable and retain adequate mechanical properties during exposure to the environmental conditions, if the required performance and prolonged endurance of the structure are to be achieved. Of particular concern is the fatigue endurance of ferrite–martensite steels under cyclic strains and stresses produced by the temperature changes. Along with radiation damage, this is currently considered as the most detrimental lifetime phenomenon for the above structure [1,2].

In order to design such structures operating under combined mechanical and thermal cycling, fatigue life has to be estimated with reasonable accuracy. Currently, fatigue life prediction analysis is based on isothermal fatigue data obtained at a chosen (often maximum operational) temperature. It has been shown that in some cases this approach is non-conservative. The generation of test data by thermal fatigue experiments, simulating more accurately the service conditions, has thus become necessary. Nevertheless, these experiments are very expensive; they are neither standardized nor applied in design codes. Therefore, thermal fatigue resistance still has to be predicted from isothermal fatigue data [3,4].

Of particular concern is the fatigue endurance of low activation ferrite–martensite (LAM) steels like the Japanese F82H mod. and the German OPTIFER IV compared with the conventional ferrite–martensite MANET II (martensitic steel for the next european torus), as reference material, under cyclic strains and stresses produced by these temperature changes. These steels had been selected by the EC Fusion Materials Long Term Programme as prime candidate materials for applications as a first wall of the blanket structure.

2. Experimental

The examined alloys are two LAM steels and one conventional 9–10% Cr stainless steel, tested in different

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Table 1
Chemical composition of tested materials in wt%

Type	C	Cr	Ni	Mo	V	Nb	Si	Mn	Ta	B	W	N
F82H mod., heat 9741	0.09	7.68	–	–	0.15	0.01	–	0.16	0.03	–	2.2	0.007
OPTIFIER IV, heat 986489	0.1	8.5	–	–	0.23	–	–	0.6	0.1	0.003	1.2	0.06
MANET II, heat 50805	0.10	10.3	0.65	0.57	0.19	0.14	0.14	0.75	–	0.08	–	0.03

as-received and tempered conditions. Chemical compositions are given in Table 1. F82H mod. as well as OPTIFER IV samples are thermal fatigue tested in as received conditions and the ferrite–martensite MANET II samples after the three-step reference annealing for comparison:

F82H mod.: Austenitization (38 min at 1040°C, air cooled), tempering (1 h at 750°C, air cooled)
OPTIFER IV: Hot forged
MANET II: Homogenization (2 h at 960°C, air cooled), austenitization (30 min at 1075°C, air cooled), tempering (2 h at 750°C, air cooled)

Cylindrical hollow samples of F82H mod., OPTIFER IV and MANET II, respectively, have been used for the thermal cycle fatigue (TCF) experiments. All tests have been conducted in air.

The TCF test rig, schematically shown in Fig. 1, consists of a stiff load frame for mechanical clamping of the sample, which is directly heated by the digitally controlled ohmic heating device. Cylindrical specimens of 77 mm length and of 8.8 mm diameter in the cylindrical gauge length of the specimen with a wall thickness of 0.4 mm have been used. Variable temperature changes, with constant heating and cooling rates of ±5.8 K/s, are applied during TCF test mode, which result in variable strain rates.

In respect with extensometry a TCF test includes complications to strain measurement not normally encountered with isothermal LCF tests. Since both temperature and mechanical strain cycling are taking place, mechanical strain can be obtained by subtracting the thermal strain from the net strain.

Due to the fact that all these ferrite-martensite steels show cyclic softening from the very early cycles, the values for total mechanical strain range, plastic mechanical strain range and total stress range had been

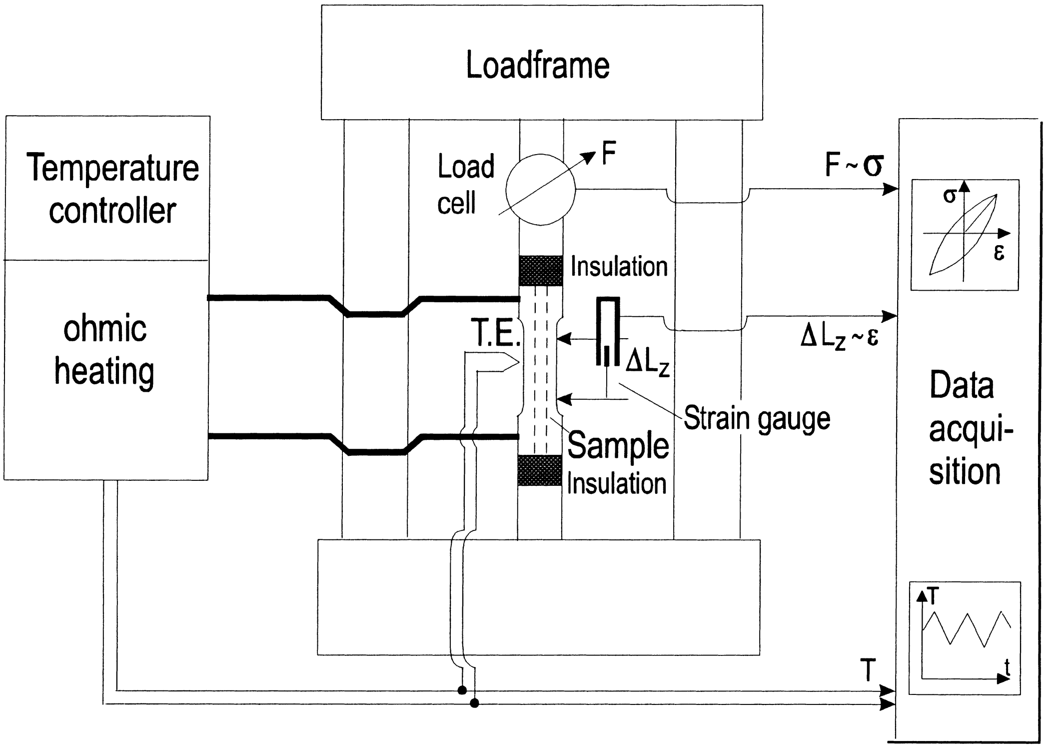

Fig. 1. Scheme of the thermal fatigue test facility.

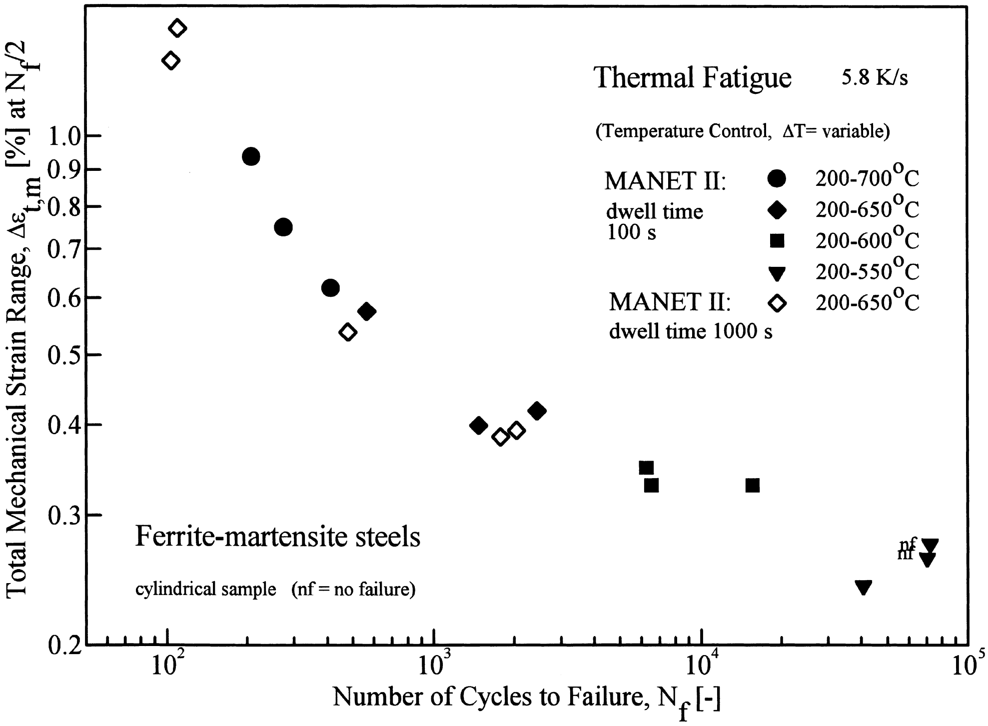

Fig. 2. Comparison of total mechanical strain range of thermal fatigue behavior between MANET II with 100s and 1000s dwell time.

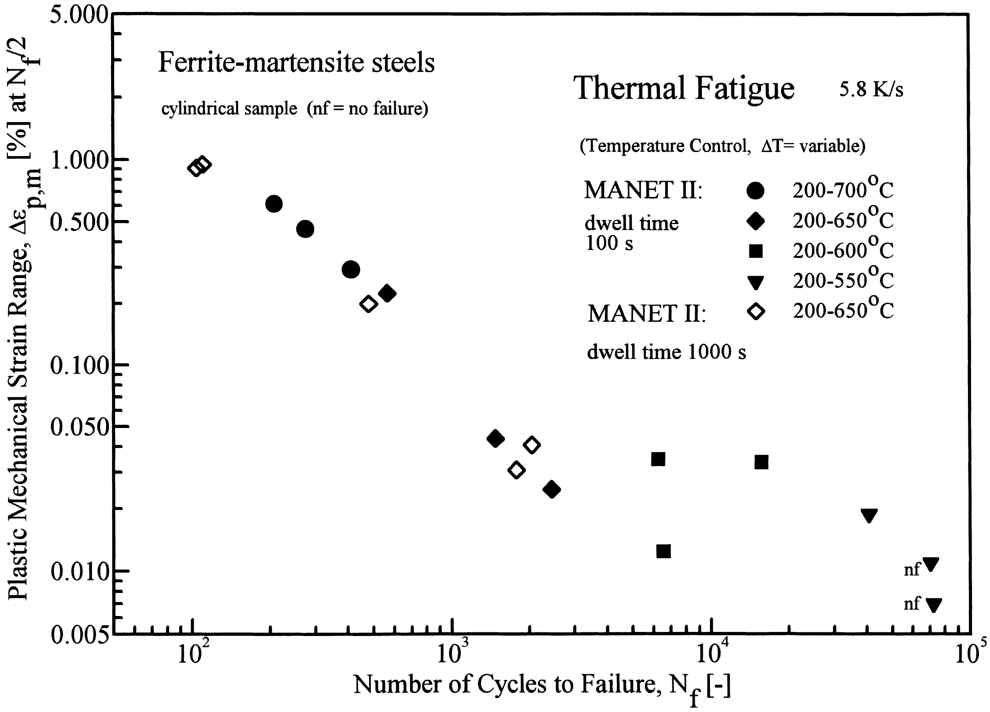

Fig. 3. Comparison of plastic mechanical strain range of thermal fatigue behavior between MANET II with 100s and 1000s dwell time.

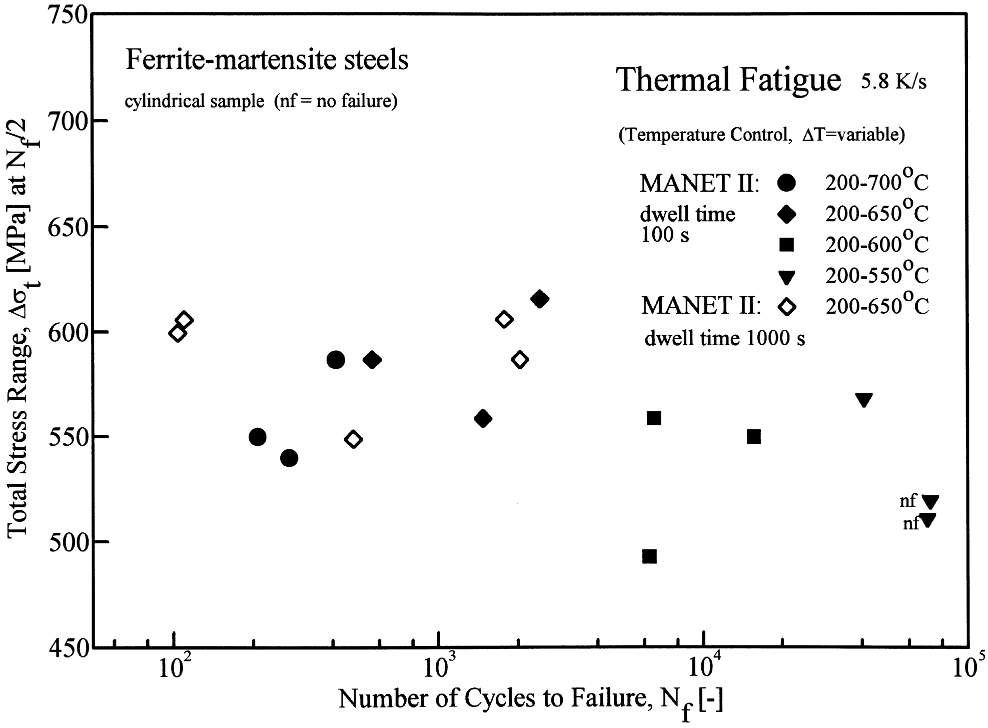

Fig. 4. Comparison of total stress range of thermal fatigue behavior between MANET II with 100s and 1000s dwell time.

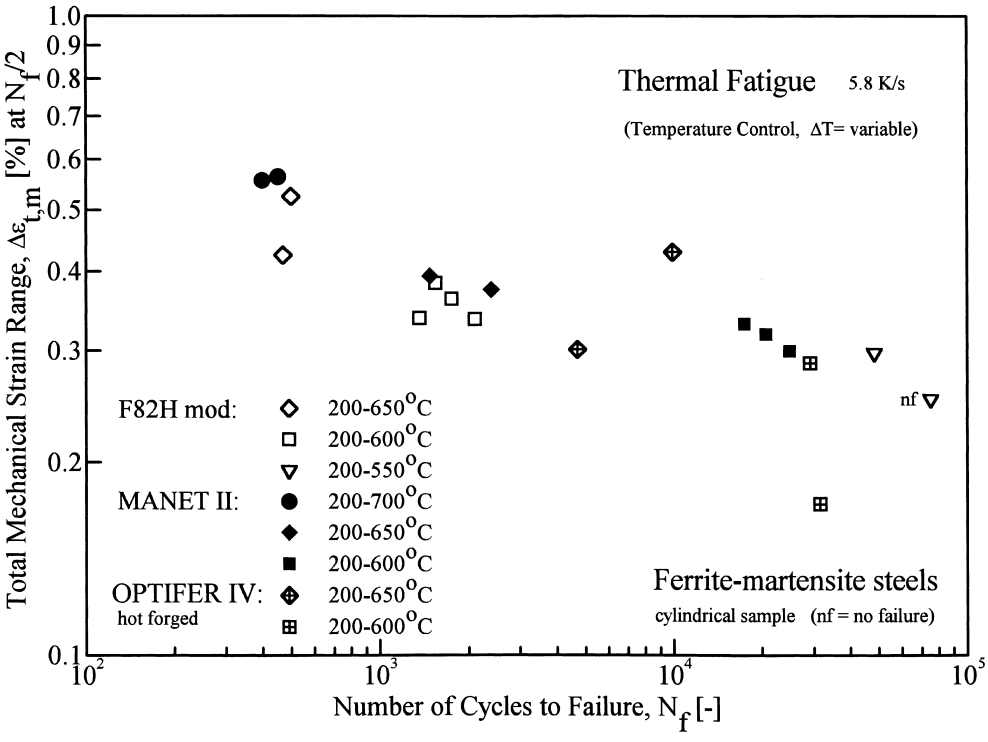

Fig. 5. Comparison of total mechanical strain range of thermal fatigue behavior between F82H mod., OPTIFER IV and MANET II.

defined from the half value of number of cycles to failure.

3. Results

Since MANET II is still the reference material for first wall structures, the influence of two different dwell times on thermal fatigue behavior had been examined. The comparison between 100s and 1000s dwell time on thermal fatigue behavior of MANET II is made in Fig. 2 in respect to total mechanical strain range vs. number of cycles to failure at comparable temperature changes. Where MANET II-data with 1000s dwell time, compared to those with 100s dwell time, at a temperature change of e.g. 200–650°C, show with increasing total mechanical strain ranges a drastic reduction in number of cycles to failure of about one order of magnitude. This is much more pronounced if the dwell times are applied on both – minimum and maximum – temperature of the cycle.

A similar behavior was found in respect to plastic strain range comparing both test conditions. The longer the dwell time was applied, the higher values of plastic strain had been reached and the shorter the number of cycles to failure had been measured. This is shown in Fig. 3.

The third comparison of thermally fatigued MANET II samples of both test conditions, shown in Fig. 4, in respect to total stress range results in a broad scatter for both dwell times and shorter life values for the longer dwell time.

The comparison of the thermal fatigue behavior of F82H mod. and OPTIFER IV with MANET II in respect to total strain range vs. number of cycles to failure is depicted in Fig. 5. Where the tempered F82H mod. shows at a temperature change of e.g. 200–600°C at increased total mechanical strain ranges a drastic reduction in number of cycles to failure of about one order of magnitude compared to MANET II. Whereas the hot forged OPTIFER IV under the same test conditions reacts at decreased or similar total mechanical strain ranges with a slight increase in number of cycles to failure. It should be mentioned that OPTIFER IV regularly will be employed in the tempered condition. Therefore this comparison has to be taken as a preliminary result, because tests of this material in the tempered condition are running.

The comparison of the three materials at a temperature change of e.g. 200–650°C results in respect to plastic strain range for the tempered F82H mod. in much higher and for the hot forged OPTIFER IV in slightly lower values than for MANET II. Therefore the number of cycles to failure is smaller for tempered F82H

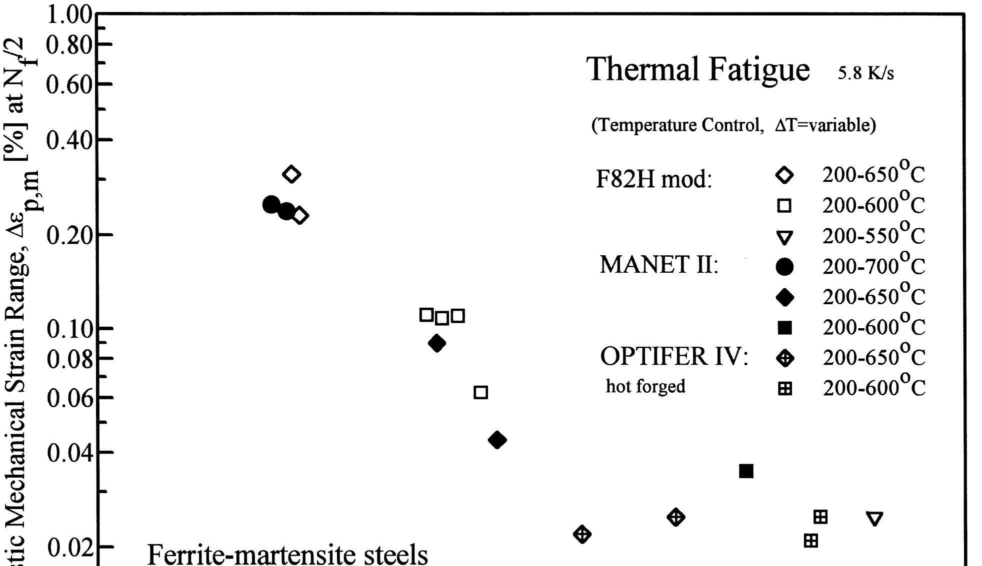

Fig. 6. Comparison of plastic mechanical strain range of thermal fatigue behavior between F82H mod., OPTIFER IV and MANET II.

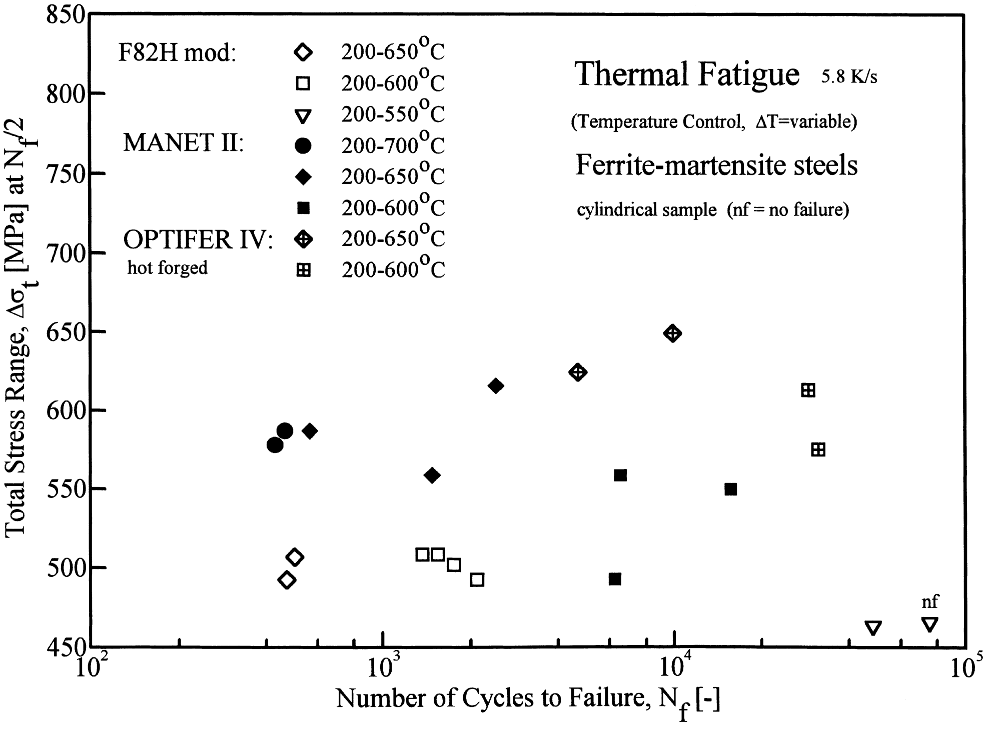

Fig. 7. Comparison of total stress range of thermal fatigue behavior between F82H mod., OPTIFER IV and MANET II.

mod. and higher for OPTIFER IV. This is shown in Fig. 6.

The third comparison of thermally fatigued samples of the three materials is made in respect to total stress range and results for the tempered F82H mod. samples in much lower and for the hot forged OPTIFER IV in slightly higher values than for MANET II. This is shown in Fig. 7

4. Conclusions

Variable temperature changes are applied to mechanically clamped samples of first wall structural materials in air atmosphere by using thermal cycling fatigue test rigs. Increasing dwell times during thermal fatigue of ferrite–martensite MANET II, reduce the number of cycles to failure drastically.

The comparison of MANET II with F82H mod. as well as OPTIFER IV, thermal cyclically tested in different as received conditions, results for the tempered F82H mod. into a reduction of numbers of cycles to failure at comparable range of temperature changes and for the hot forged OPTIFER IV into a slight increase of cyclic life.

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