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Thermo-mechanical fatigue behavior of reduced activation ferrite/martensite stainless steels

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Abstract

The thermo-mechanical cycling fatigue (TMCF) behavior of reduced activation ferrite/martensite stainless steels is examined. The test rig consists of a stiff load frame, which is directly heated by the digitally controlled ohmic heating device. Cylindrical specimens are used with a wall thickness of 0.4 mm. Variable strain rates are applied at TMCF test mode, due to the constant heating rate of 5.8 K/s and variable temperature changes. TMCF results of as received EUROFER 97 in the temperature range between 100 and 500–600 °C show a reduction in life time (a factor of 2) compared to F82H mod. and OPTIFER IV. TMCF-experiments with hold times of 100 and 1000 s show dramatic reduction in life time for all three materials.

1. Introduction

Test blanket modules (TBM's) are subjected during service to alternating thermal and mechanical stresses as a consequence of the pulsed reactor operation of the International Thermonuclear Fusion Reactor (ITER). Of particular concern is the fatigue endurance of TBM's manufactured of reduced activation ferrite/martensite (RAF/M) steels. RAF/M-steels such as the Japanese F82H mod., the German OPTIFER IV and the European EUROFER 97 will be subjected to cyclic strains and stresses produced by these temperature changes.

In order to design such structures, operating under combined mechanical and thermal cycling, fatigue life has to be examined in isothermal fatigue tests for materials data generation and in thermal fatigue for verification of design codes [1–7].

2. Experimental

Three RAF/M steels in the range of 8–9% Cr content are tested in different as received and tempered conditions. Chemical compositions are given in Table 1.

The thermal treatment of the three examined materials has been for F82H mod.: austenitization (38 min at 1040 °C, air cooled), tempering (2 h at 750 °C, air cooled), OPTIFER IV: austenitization (30 min at 1075 °C, air cooled), tempering (2 h at 750 °C, air cooled) and EUROFER 97: austenitization (31 min at 980 °C, air cooled), tempering (90 min at 760 °C, air cooled).

Cylindrical specimens of F82H mod., OPTIFER IV and EUROFER 97, with 77 mm length and 8.8 mm diameter in the cylindrical gauge length of the specimen and with a wall thickness of 0.4 mm, have been used for the thermo-mechanical cycling fatigue (TMCF)-experiments. All materials have been tested in air.

The TMCF test rig (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 described in more detail elsewhere [2].

The temperature cycling of the specimen has been performed between the lower temperature $T_L = T_{min}$ and the higher temperature $T_H = T_{max}$. Temperature rate is kept constant at 5.8 K/s for all thermal conditions and variable strain rates are applied, due to the variable temperature changes. Tests are automatically terminated after reaching a preset current value indicating that a crack covered half of the cross-section of the specimen.

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Table 1
Chemical composition of tested materials in wt% (basemetal: Fe)

Type	C	Cr	Ni	Mo	V	Nb	Si	Mn	Ta	B	W	N
F82H mod., Heat 9741	0.089	8.16	0.019	0.0018	0.16	0.0001	0.11	0.161	0.02	<0.0002	2.17	0.0065
OPTIFER IV, Heat 986779	0.12	9.35	0.007	<0.002	0.26	<0.0006	0.022	0.54	0.07	<0.004	1.03	0.05
EUROFER 97, Heat E83697	0.12	8.93	0.022	0.0015	0.2	0.0022	0.06	0.47	0.14	<0.001	1.07	0.018

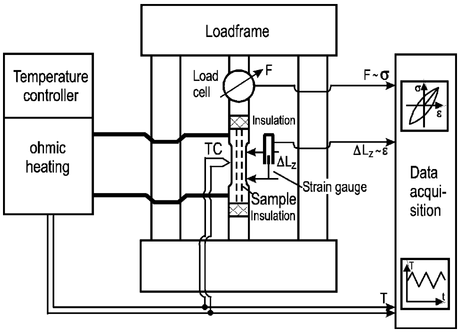

Fig. 1. Schematic of the load frame of the thermal fatigue testing facility.

The sum of the thermal strain ε_{th} and the mechanical strain ε_{me} was kept constant, due to the fact, that $\Delta\varepsilon_{me} = -\Delta\varepsilon_{th}$, the cyclic mechanical strains are out of phase with the selected triangular temperature-time cycles. Thus, at the high temperature of each cycle a compressive stress-level is reached and at the low temperature a tensile stress-level. T_L was 100 °C or 200 °C and T_H was the variable parameter. A value of $R_\varepsilon = -\infty$ could have been realised in the test.

By definition, the net strain ε_{net}, at $T = T_{min}$ was set to zero and therefore,

$$\varepsilon_{net} = \varepsilon_{me} + \varepsilon_{th} = \varepsilon_{in,me} + \varepsilon_{el,me} + \varepsilon_{th} = 0 \tag{1}$$

or

$$\varepsilon_{me} = \varepsilon_{in,me} + \varepsilon_{el,me} = -\varepsilon_{th}, \tag{2}$$

but in the real TMF-experiment the condition $\varepsilon_{net} = 0$ was difficult to obtain, therefore a negligeble amount of net strain was detected.

From Eq. (2), the mechanical and also the sum of the inelastic and elastic strain generated by the total suppression of thermal strains were determined. During all performed experiments, temperature T, thermal strain ε_{th}, net strain ε_{net}, mechanical strain ε_{me}, inelastic mechanical strain $\varepsilon_{in,me}$, elastic mechanical strain $\varepsilon_{el,me}$ and nominal stress σ, are measured or calculated as a function of time. This is plotted qualitatively for the 1st and the 2nd cycle in Fig. 2.

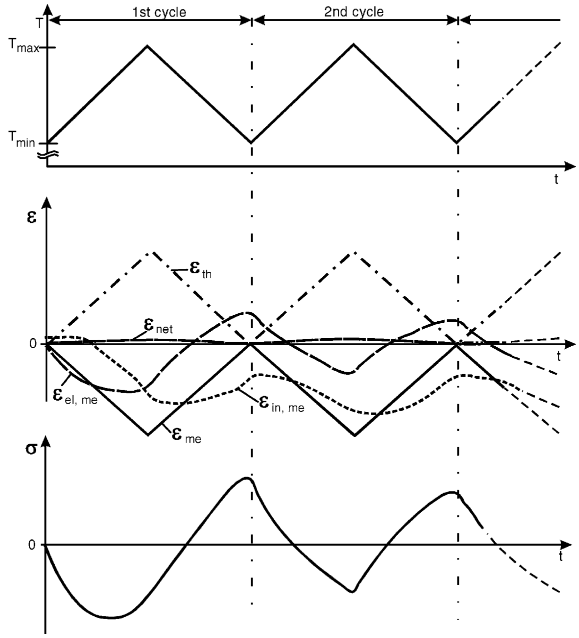

Fig. 2. Time dependence of the measured quantities for the 1st and 2nd cycle.

Due to the fact that hold time tests also have been performed, our hold time definition will be introduced: HTH, hold time at the higher temperature T_H, HTL, hold time at the lower temperature T_L and HTHL, hold time at both temperatures. Hold times of 100 and 1000 s have been realised.

3. Results and discussion

3.1. Tests without hold time

F82H mod., EUROFER 97 and OPTIFER IV were thermally cycled in the temperature range between 100 and 500–600 °C. For each temperature range two tests

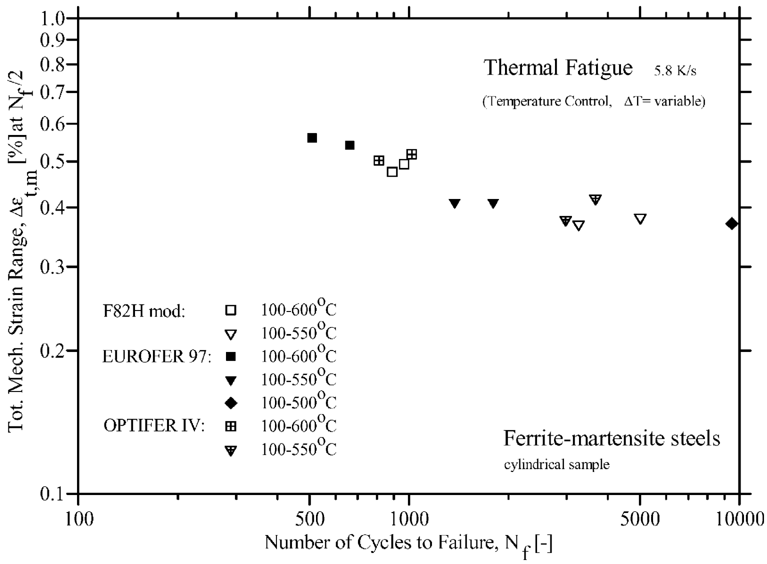

Fig. 3. Comparison of total mechanical strain range $\Delta\varepsilon_{t,m}$ of thermal fatigue behaviour between F82H mod., EUROFER 97 and OPTIFER IV.

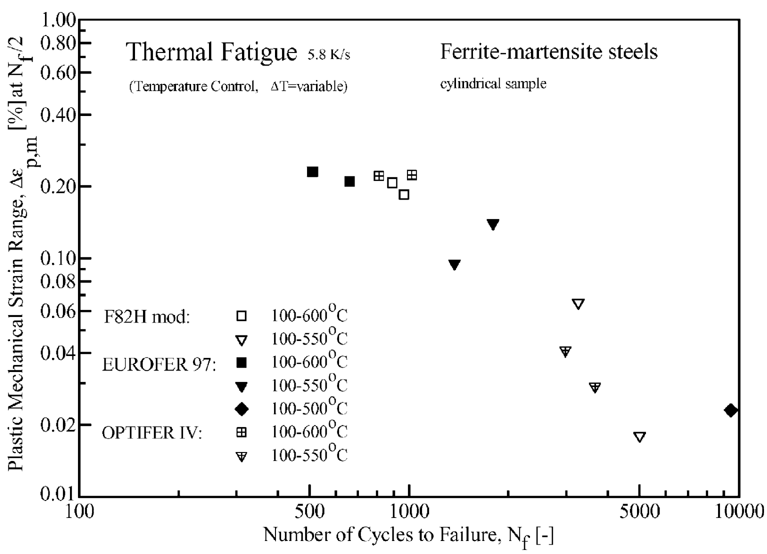

Fig. 4. Comparison of plastic mechanical strain range $\Delta\varepsilon_{p,m}$ of thermal fatigue behaviour between F82H mod., EUROFER 97 and OPTIFER IV.

were performed. The reproducibility remains with in a tolerable scatter. The comparisons can be derived from the following figures – Fig. 3: total mechanical strain range $\varepsilon_{t,m}$ vs. number of cycles to failure N_f, and Fig. 4: plastic mechanical strain range $\Delta\varepsilon_{p,m}$ vs. number of cycles to failure N_f.

In the case of total mechanical strain range $\Delta\varepsilon_{t,m}$ vs. number of cycles to failure N_f, F82H mod. and OPTIFER IV show, in the temperature range of 100–550 °C at a $\Delta\varepsilon_{t,m}$ of about 0.4%, N_f-values between 3000 and 5000 cycles whereas EUROFER 97, at a similar $\Delta\varepsilon_{t,m}$, remains at around 1400 to 1800, that is a factor of 2.5 lower in life time. In the temperature range of 100–600 °C at a $\Delta\varepsilon_{t,m}$ of about 0.5%, F82H mod. and OPTIFER IV show N_f-values around 900 cycles whereas EUROFER 97 at a slightly higher $\Delta\varepsilon_{t,m}$ of 0.55% remains at around 600 that is still a factor of 1.5 lower in life time.

The small difference in $\Delta\varepsilon_{t,m}$ for the different materials is a sign of non-sensitivity.

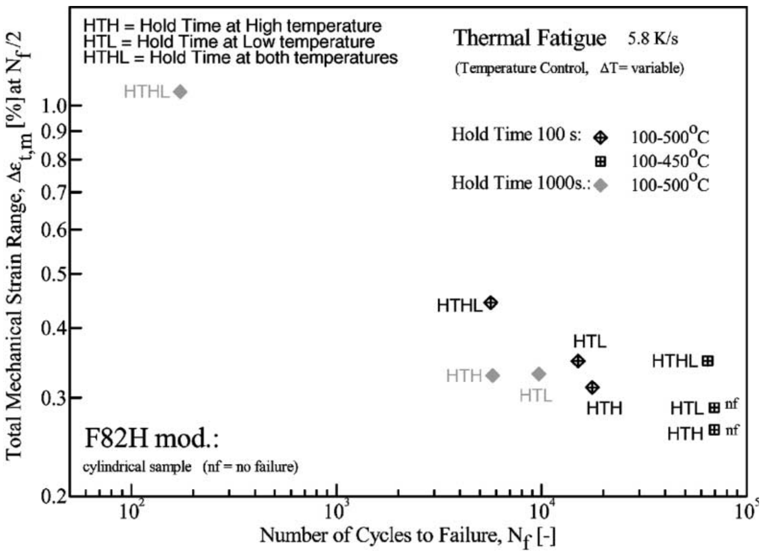

Fig. 5. Comparison of total mechanical strain range $\Delta\varepsilon_{t,m}$ of thermal fatigue behaviour of F82H mod. with 100 and 1000 s hold times in temperature ranges starting from 100 °C.

A slightly different picture can be taken from the behaviour of plastic mechanical strain range $\Delta\varepsilon_{p,m}$ for the different materials under different temperature ranges. In the case of the plastic mechanical strain range $\Delta\varepsilon_{p,m}$ vs. number of cycles to failure N_f, F82H mod. and OPTIFER IV show in the temperature range of 100–550 °C a broad scatter mainly for F82H mod. with $\Delta\varepsilon_{p,m}$-values between 0.02% and 0.06%. The N_f-values remain the same (between 3000 and 5000 cycles) whereas OPTIFER IV and EUROFER 97 at different $\Delta\varepsilon_{p,m}$-values of 0.035% and 0.15%, respectively, give a smaller scatter in strain. The N_f-values remain at around 1400–1800 for EUROFER 97. In the temperature range of 100–600 °C at a $\Delta\varepsilon_{p,m}$ of about 0.21%, F82H mod. and OPTIFER IV show N_f-values around 900 cycles whereas EUROFER 97 at similar $\Delta\varepsilon_{p,m}$ of 0.21% remains at around 600 that is still a factor of 1.5 lower in life time of cause (Fig. 4).

The total stress range $\Delta\sigma_t$ of all three materials and both examined temperature ranges was nearly independent of material and temperature range.

3.2. Tests with hold times

Results of thermal fatigue tests with hold times 100 and 1000 s are up to now only available from F82H mod. material. A first set covers the temperature ranges of 100–450 °C (100 s only) and 100–500 °C (100 and 1000 s). Normally for 100 s the results of HTL – and HTH – tests of 100–450 °C and 100–500 °C have a smaller scatter of $\Delta\varepsilon_{t,m}$ around 0.3% and of N_f around 16 000 cycles. In the case of a 100–500 °C temperature range, the N_f-values without hold times lie around 10 000 cycles (Fig. 5). So the hold times at the low temperature or at the high temperature lead to a slight increase in life time. But at the HTHL condition a reduction in life time down to 6000 cycles (i.e. a factor of 1.6) was found for 100 s hold time with increasing $\Delta\varepsilon_{t,m}$ up to 0.45%. At increasing hold time of 1000 s even the HTL- and HTH-values are found to be less than 1000 cycles, but the HTHL-condition shortens the N_f-values down to 200 cycles at a very high $\Delta\varepsilon_{t,m}$-value of around 1.1% strain. This is a reduction in life of about two orders of magnitude.

Also in thermal fatigue experiments with hold times starting from 200 °C as the lower temperature, a dramatic effect of a hold time of 1000 s at both temperatures, i.e. the HTHL-condition, on the shortening of the life time was found (Fig. 6).

For 100 s the results of HTL- and HTH-tests of 200–550 °C show a smaller scatter of $\Delta\varepsilon_{t,m}$ around 0.3% but a broader scatter with respect to N_f. Here are found N_f-values for HTL of around 25 000 cycles, for HTH of around 8000 cycles and for HTHL of around 3500 cycles.

For 1000 s the results of HTL- and HTH-tests of 200–550 °C have a smaller scatter of $\Delta\varepsilon_{t,m}$ around 0.3% but a broader scatter in respect to N_f. Here N_f - values for HTL are found of around 12 000 cycles, for HTH of around 4000 cycles and for HTHL of around 300 cycles at a $\Delta\varepsilon_{t,m}$ of around 0.8%.

In the data set for the temperature range from 200 to 600 °C this tendency is similar.

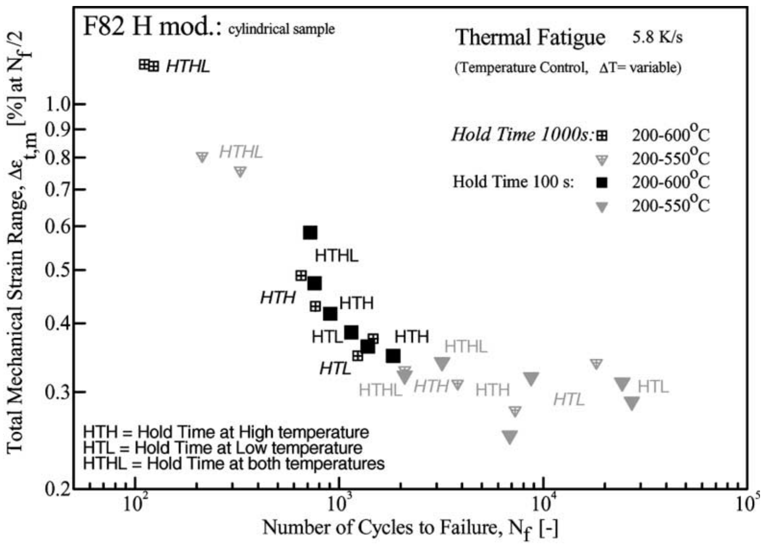

Fig. 6. Comparison of total mechanical strain range $\Delta\varepsilon_{t,m}$ of thermal fatigue behaviour of F82H mod. with 100 and 1000 s hold times in temperature ranges starting from 200 °C.

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