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Reduced softening of EUROFER 97 under thermomechanical and multiaxial fatigue loading and its impact on the design rules

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ABSTRACT

Within the development of the test blanket module (TBM) for use in the ITER and DEMO fusion power plants, interest increasingly focuses on design rules for components built from EUROFER 97. One of the specific characteristics of EUROFER 97 as a ferritic–martensitic steel is its cyclic softening yielding to lower stresses under strain-controlled fatigue loading and, hence, longer lifetimes. Our thermomechanical and multiaxial fatigue tests, however, revealed lifetimes that were remarkably lower than those expected on the basis of isothermal uniaxial fatigue tests. The reduced cyclic softening observed in these experiments is believed to be one of the reasons of the shorter fatigue lifetimes. When applying the design rules derived for EUROFER 97 from isothermal uniaxial data considering the recommendations in the ASME and RCC-MR codes to our thermomechanical and multiaxial fatigue tests for verification purposes, strong loss of their conservatism was found. The lifetimes observed in some of the multiaxial experiments were even lower than the design lifetimes that had been supposed to be sufficiently conservative. To overcome this problem, new design rules will be proposed, which are based among others on the damage and lifetime prediction model developed lately for EUROFER 97.

1. Introduction

Application of EUROFER 97, a reduced-activation ferritic–martensitic (RAFM) steel, as a structure material for thermomechanically highly loaded blanket and divertor components of future power plants requires reliable design rules. In the majority of lifetime prediction approaches and existing design codes, lifetime of thermomechanically multiaxially loaded structures is assessed on the basis of isothermal lifetime data and prediction rules considering phenomena mainly observed under isothermal uniaxial loading. It is therefore very important to verify the prediction capability of the rules in thermomechanical multiaxial load cases and to modify them for specific phenomena, if necessary.

Within the EFDA Technology Work Programme, TTMS-005 'Rules for Design, Fabrication, and Inspection', structural design criteria for components built from EUROFER 97 will be developed and qualified. Investigations will focus on high-temperature rules, particularly those preventing creep, fatigue, and creep/fatigue interaction, which have not yet been considered and implemented in the current ITER Structural Design Criteria for In-Vessel Components (SDC–IC) [1]. Consequently, the high-temperature rules of the following current design codes well-established for nuclear applications were evaluated: ASME Boiler and Pressure Vessels Code (Code Case N-47) and the French RCC-MR code (RB 3200 and RC 3200). For this purpose, various verification experiments, among others uniaxial themomechanical as well as isothermal multiaxial fatigue tests, were planned and performed. Evaluation is aimed at determining whether the well-established rules provide for a sufficient safety margin when they are applied to EUROFER 97 structures and if so, how large the amount of their conservatism is. In the following sections, the verification tests performed will be described briefly and their results in particular with respect to the design fatigue curves shall be evaluated and discussed. After this, the design fatigue curves will be modified to eliminate the lack of conservatism observed.

2. Thermomechanical fatigue tests

The thermomechanical fatigue tests were performed using cylindrical hollow EUROFER 97 specimens and the thermomechanical fatigue rig described in [2,3]. During the test, the specimen clamped between two stiff rods in a stiff load frame is cooled and heated cyclically between the upper and lower temperatures starting from a mean temperature at which the specimen initially is stress-free. Due to clamping, total strain of the specimen remains constant during the test and equals 0, such that cooling and heating of the specimen induce out-of-phase mechanical strain and stress. The amplitude of the mechanical load induced is varied from test to test by varying the upper temperature of the test.

To evaluate the tests, finite element simulations were performed taking into account the coupled nonlinear deformation

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damage behavior of EUROFER 97 [4]. The mechanical strain range calculated by these simulations exceeds the value measured as an average for the gauge length in the real test. However, this maximum mechanical strain range is still lower than that of the experimentally observed fatigue life predicted on the basis of isothermal fatigue data (see Fig. 1). Accordingly, it may be concluded that thermomechanical cycling of EUROFER 97 produces more fatigue damage than isothermal cycling with the same mechanical strain range. This might be attributed to possible deformation instabilities fostered by progressive strain localization which is observed in the simulation at the middle of the thermomechanical fatigue specimen. It is caused by both temperature gradients in the specimen and the cyclic softening behavior which is characteristic for this type of material [5,6]. Another reason might be the reduced softening noticed when comparing the extreme stress values within a cycle calculated in the simulation with those measured experimentally (see Fig. 2). Particularly, the peak tensile stresses measured after an initial cyclic hardening followed by cyclic softening are higher than those calculated (see Fig. 2). This indicates smaller softening than expected from the deformation model and the isothermal uniaxial deformation behavior, respectively. On

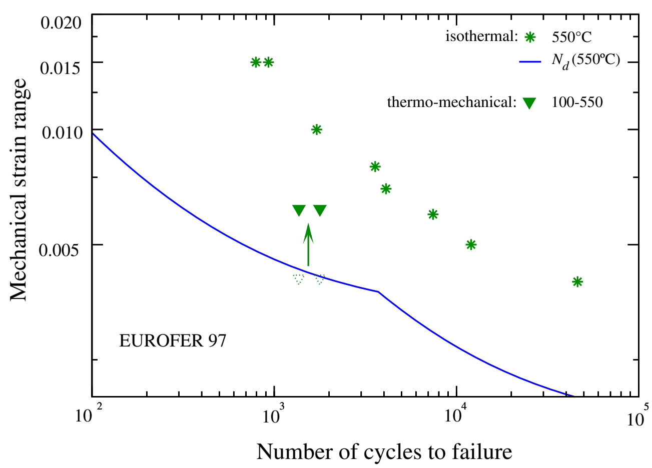

Fig. 1. Maximum mechanical strain range at half the number of cycles to failure calculated for the thermomechanical fatigue tests and plotted versus the number of cycles to failure in comparison to those of isothermal fatigue tests and of the design curve derived from it as well as in comparison to the values measured as an average over the gauge length (open symbols with dashed outline).

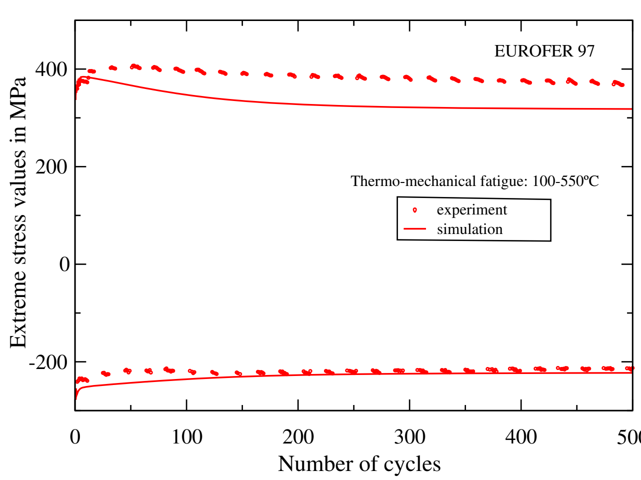

Fig. 2. Extreme stress values within a cycle versus number of cycles for a thermomechanical fatigue test: comparison of the values calculated in the finite element simulation and those measured during the test.

the other hand, it may explain the shorter lifetime obtained experimentally (see Fig. 1). In addition, oxidation might explain the negative influence of thermomechanical loading on lifetime. Oxide layers formed during the high-temperature part of the cycle under compression might crack during the following low-temperature tensile part, thus promoting fatigue crack initiation and accelerating failure. However, even that RAFM steels have due to their high chromium content a reduced oxidation capability particularly at the temperatures considered (up to 550 °C) oxidation may be excluded as a reason for the behavior above only when similar thermomechanical tests performed under vacuum or inert atmosphere verify this behavior.

3. Isothermal multiaxial fatigue tests

Two types of strain-controlled multiaxial fatigue tests were performed on EUROFER 97 tube specimens:

1. Cyclic pull–push tests in axial and circumferential directions of the specimen and, hence, with fixed directions of principal stresses and strains (FPSS) at room temperature. These tests will hereinafter be referred to as FPSS tests.
2. Cyclic pull–push and alternating torsion tests in the axial direction of the specimens, in which the directions of the principal stresses and strains are not fixed under non-proportional loading conditions (phase shift $\neq 0°$ or $180°$) and rotate during a cycle (rotating principal stresses and strains, RPSS). These tests, hereinafter referred to as RPSS tests, were performed at room temperature and 500 °C.

The tests were conducted using the setups described in [4], where additional experimental details and an extensive discussion of the tests results can be found. Here, the results concerning the lifetimes observed and their evaluation with respect to the design fatigue curves shall be presented. In Fig. 3, the equivalent total strain range is plotted versus the number of cycles to failure for the multiaxial tests performed. The equivalent total strain ranges were calculated using the criteria formulated for EUROFER 97 according to the rules of the ASME and RCC-MR codes [4]. For comparison, the corresponding design curves indicating the numbers of permissible cycles as determined in [4] for EUROFER 97 are plotted as well. The scatter of the data is mainly caused by the fact that the tests were performed with different phase shifts between the loadings in the two different loading directions [4]. It can be seen that

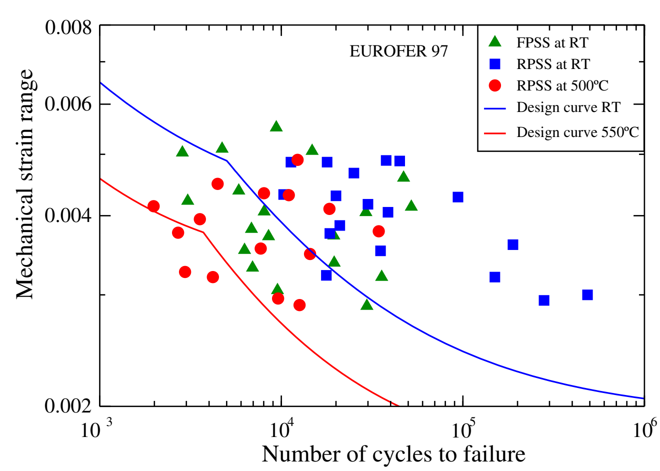

Fig. 3. Equivalent total (mechanical) strain range versus number of cycles to failure for the multiaxial tests performed in comparison to the corresponding design curves identified for EUROFER 97.

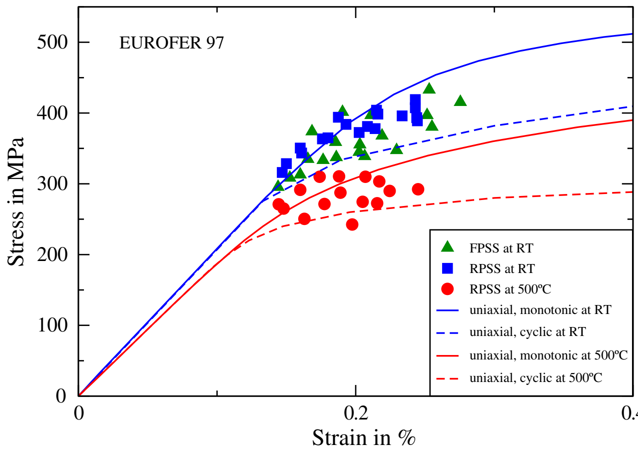

Fig. 4. Stress amplitude (half of the equivalent stress range) versus strain amplitude (half of the equivalent strain range) at half the number of cycles to failure for the multiaxial tests performed and the uniaxial tests in comparison.

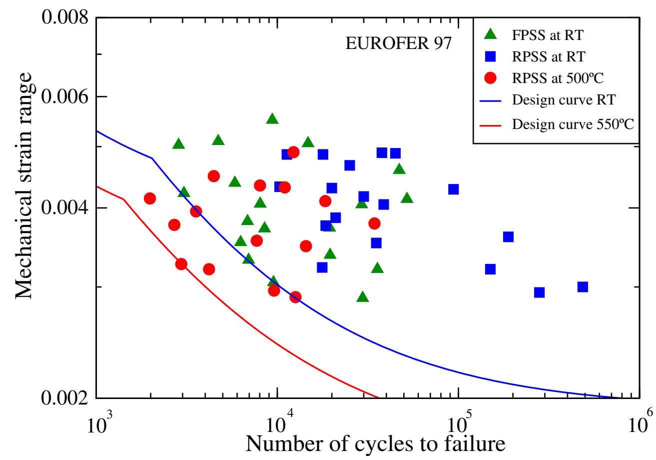

Fig. 5. Equivalent total (mechanical) strain range versus number of cycles to failure for the multiaxial tests performed in comparison to the corresponding improved design curves for EUROFER 97.

for the same mechanical strain range, the number of cycles to failure in case of multiaxial loading is even lower than the number of permissible cycles. This particularly holds for one RPSS test and some FPSS tests at room temperature as well as for some RPSS tests at 500 °C. Hence, the design curves are not sufficiently conservative in spite of high safety factors included. Consequently, conventional design rules considering fatigue and creep–fatigue interaction cannot be applied directly to EUROFER 97.

To identify physical reasons why the multiaxial fatigue tests produced lifetimes that were much shorter than those expected on the basis of uniaxial data, the cyclic hardening curves (half of equivalent stress range versus half of equivalent strain range, both of the cycle at half the number of cycles to failure) from the multiaxial fatigue tests were plotted and compared with those determined from uniaxial fatigue tests and with the monotonic hardening curves from uniaxial tensile tests (see Fig. 4). It is obvious from Fig. 4 that the FPSS loading mode seems to induce more cyclic softening than the RPSS loading mode. Both multiaxial loading modes, however, do not yield that pronounced cyclic softening observed under uniaxial loading, which indicates that either the deformation mechanisms or their activities might be different under multiaxial loading. The short fatigue lifetimes observed in the multiaxial fatigue tests now may be at least partly attributed to the reduced cyclic softening and the resulting higher stresses compared to the uniaxial tests. In addition, the damage mechanisms under multiaxial loading might be different. Presently, this cannot be excluded due to the lack of proper fractographic observations.

4. Discussion

Based on these findings, the design fatigue curves for EUROFER 97 have been modified taking into account the cyclic softening and its dependence on the loading mode. Again, the basis of these curves, namely, the isothermal low cycle fatigue data of EUROFER 97 (mechanical strain range $\Delta\varepsilon$ vs. number of cycles to failure N_f), was considered. From these data, the relation between the mechanical strain range $\Delta\varepsilon$ and the hypothetical number of cycles to failure N_f^* which would be observed in the absence of softening was derived. To determine N_f^*, the damage model already developed for EUROFER 97 under low cycle fatigue loading conditions was considered [7]. According to this model and the resulting relation between N_f and stress and inelastic strain ranges, the value of N_f^* for a given isothermal uniaxial low cycle fatigue test can be determined as

$$N_f \propto (\Delta\sigma)^{-r}(\Delta\varepsilon^{\text{in}})^{-1} \Rightarrow N_f^* = N_f\left(\frac{\Delta\sigma_{N_f/2}}{\Delta\sigma_{\text{1st cycle}}}\right)^r \frac{\Delta\varepsilon^{\text{in}}_{N_f/2}}{\Delta\varepsilon^{\text{in}}_{\text{1st cycle}}}$$

where r is the stress sensitivity exponent which is a temperature-dependent parameter. $\Delta\sigma_{\text{1st cycle}}$ and $\Delta\sigma_{N_f/2}$ are the stress ranges of the first cycle and the cycle at half number of cycles to failure, respectively, and $\Delta\varepsilon^{\text{in}}_{\text{1st cycle}}$ and $\Delta\varepsilon^{\text{in}}_{N_f/2}$ denote the inelastic strain ranges of these cycles. When calculating N_f^* using the relation above, no significant change of the damage mechanisms in the absence of softening is assumed. From the relation between $\Delta\varepsilon$ and N_f^* obtained, modified design fatigue curves (mechanical strain range $\Delta\varepsilon$ vs. number of permissible cycles N_d) were then deduced by applying appropriate factors (factor of 2 to $\Delta\varepsilon$ or a factor of 20 to N_f^*, whichever is the more conservative at each point). When comparing the permissible numbers of cycles determined by the new fatigue design curves with the numbers of cycles to failure observed in the most critical verification tests, i.e. the multiaxial tests reported in the previous section, reliability of these new fatigue design curves is found to be improved. Almost all verification tests yield longer fatigue lifetimes than those obtained from the new fatigue design curves for components under fatigue loading (see Fig. 5).

5. Conclusions

The reduced cyclic softening of EUROFER 97 under thermomechanical and isothermal multiaxial fatigue loadings has been identified to be at least one reason of the much shorter lifetimes observed under these loading modes in comparison to the isothermal uniaxial references. In many cases, lifetimes are even shorter than those allowed by the design fatigue curves. Consequently, the fatigue design curves derived from uniaxial fatigue data are not sufficiently conservative. Therefore, new fatigue design curves taking into account the influence of reduced cyclic softening on lifetime were derived, which cover reliably the lifetimes observed in all experiments performed so far. However, since the lifetime observed in a few multiaxial fatigue tests is very close to that allowed by the new fatigue design curves further verifications might be necessary. In addition, fractographic observations might give a deeper insight and more hints for further modifications.

Acknowledgments

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