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Deformation and damage of RAFM steels under thermo-mechanical loading: A challenge for constitutive equations

J. Aktaa *, M. Klotz, C. Petersen

Forschungszentrum Karlsruhe GmbH, Institute for Materials Research II, P.O. Box 3640, D-76021 Karlsruhe, Germany

Abstract

A coupled deformation damage model recently developed for reduced activation ferritic martensitic (RAFM) steels and implemented in the finite element code ABAQUS was used to simulate thermo-mechanical fatigue tests performed on EUROFER 97 tube specimens. Previous evaluation of these tests showed that thermo-mechanical fatigue loading leads to remarkably reduced lifetime in comparison to isothermal fatigue loading with the same mechanical strain range, but changes in the stress range as well as actual test conditions, e.g. temperature gradients, were not considered. However, by applying the coupled deformation damage model, changes in stresses between isothermal and thermal loadings were taken into account. Results showed a local mechanical strain range that was greater than that obtained experimentally. However, the lifetime due to the calculated fatigue load was still higher than that was found experimentally. Some geometric nonlinear deformation instabilities are suggested, but must be verified.

1. Introduction

Reduced activation ferritic martensitic (RAFM) steels as structural materials of fusion reactors will be subjected to complex thermo-mechanical cyclic loading and high irradiation doses. Correct characterization of their deterioration under these loading conditions is a precondition of a sufficiently reliable lifetime prediction procedure. In the majority of lifetime prediction approaches and in existing design codes as well lifetime assessment of thermo-mechanically loaded structures is made on the base of isothermal lifetime data and prediction rules considering phenomena mainly observed under isothermal loading. Thus, it is very important to verify the prediction capability of the proper rules in thermo-mechanical load cases and if necessary to modify them considering specific phenomena.

Within the adopted lifetime prediction approach a coupled deformation damage model taking into account the complex non-saturating cyclic softening of RAFM steels has been developed and successfully applied to describe the creep-fatigue behavior of F82H mod and EUROFER 97 under isothermal cyclic loading [1]. In this model an internal state variable for damage representing in a phenomenological manner all kinds of material deterioration is introduced and an evolution equation describing

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[*] Corresponding author. Tel.: +49 7247 824946; fax: +49 7247 824980.

E-mail address: aktaa@imf.fzk.de (J. Aktaa).

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its change under creep-fatigue loading is formulated (for more details see [1]). To analyze structures built from RAFM steels the model has been implemented in the finite element code ABAQUS, which is used to simulate thermo-mechanical fatigue (TMF) tests for verification. In the following, the thermo-mechanical fatigue tests considered are briefly described and thereafter the procedure and results of their simulation are presented and discussed.

2. Thermo-mechanical fatigue tests

The thermo-mechanical fatigue tests considered here were performed on EUROFER 97 (9CrWVTa–RAFM steel, see [2] for composition) using cylindrical hollow specimens and the thermo-mechanical fatigue rig as described in [3]. During the test, the specimen, which is clamped between two stiff rods in a stiff load frame, is cooled and heated cyclically between the upper and lower temperatures starting from the mean temperature, at which the specimen initially is stress free. Due to clamping, the total strain of the specimen remains constant during the test and equal to 0 so that cooling and heating of the specimen result in induced out of phase mechanical strain and stress (Fig. 1). The amplitude of induced mechanical load is varied from test to test by varying the upper temperature of the test. In a first evaluation, the mechanical strain range determined for the cycle at the half number of cycles to failure is plotted versus the number of cycles to failure and compared with the corresponding plots obtained from the isothermal fatigue tests (Fig. 2). For the same mechanical strain range, the thermo-mechanical fatigue tests show up to a factor of 20 lower numbers of cycles to failure than the isothermal fatigue tests. Consequently the fatigue lifetimes of thermo-mechanical fatigue tests may lie very close to and even below the design curve constructed from the average curve of isothermal fatigue tests using the criteria of ASME BPVC, Section III, code case N-47 by applying a safety factor of 2 with respect to strain range or a factor of 20 with respect to number of cycles to failure, whichever gives the lower value [4] (Fig. 2). These safety factors are supposed to consider reliably all influencing factors not considered under isothermal fatigue, e.g. those under thermo-mechanical fatigue. In addition, this difference between thermo-mechanical fatigue and isothermal fatigue test results for EUROFER 97 is much higher than the differences published in the literature for other materials [5].

The thermo-mechanical fatigue tests are analyzed in a first step from the mechanical point of view in order to identify whether the highly reduced lifetime is an effect related to the test conditions or to the material or to both. When doing so it is recognized that the mechanical strain range determined and

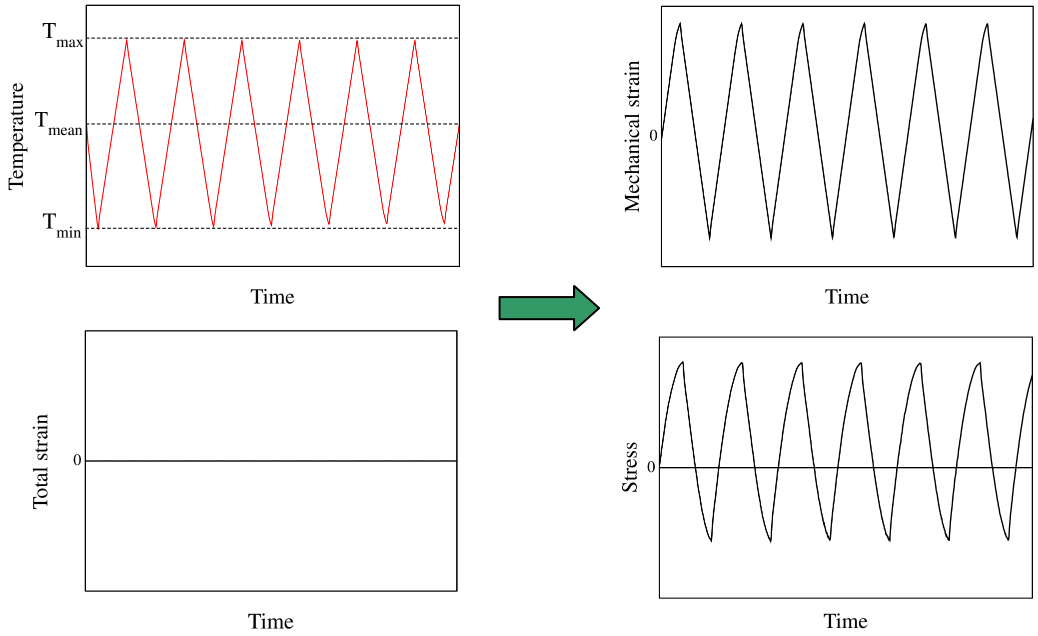

Fig. 1. Test conditions of thermo-mechanical fatigue experiments and the resulting mechanical loads.

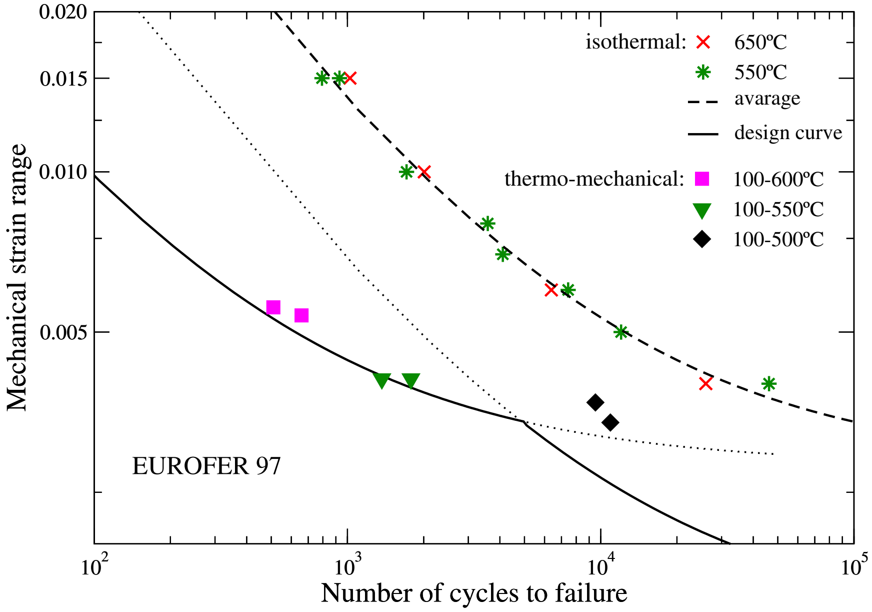

Fig. 2. Results of thermo-mechanical fatigue tests in comparison to those of isothermal fatigue tests and the design curve derived from mechanical strain range at the half number of cycles to failure versus number of cycles to failure.

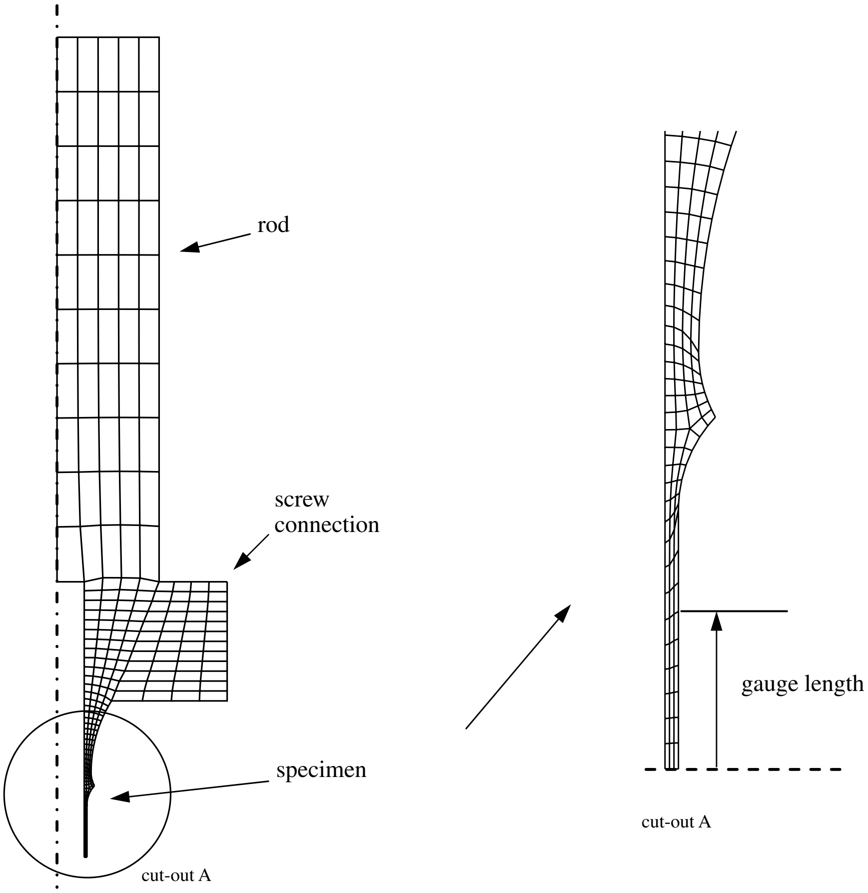

Fig. 3. Finite element mesh of the thermo-mechanical fatigue rig.

plotted in Fig. 2 for thermo-mechanical fatigue tests is actually that measured for the gauge length of the specimen, at which the temperature drops from its middle, where the temperature is controlled equal to the nominal value, to its ends. Depending on the nominal temperature, the temperature variation from the middle to the ends of the gauge length may amount to several tens of °C, so that the mechanical strain range at the middle of the gauge length, where the specimen fails, might be much higher than that measured for the total gauge length. In addition, this difference is expected to increase from cycle to cycle due to the cyclic softening behavior of EUROFER 97. This consideration gave us reason to perform finite element simulations to estimate the mechanical strain range at the middle of the gauge length.

3. Finite element simulations of thermo-mechanical fatigue tests

The finite element simulations of thermo-mechanical fatigue tests have been performed using the finite element code ABAQUS, in which the coupled non-linear deformation damage model developed for RAFM steels [1] had been implemented via the user material interface UMAT. The finite element computations using such a nonlinear material model were expected to be computationally time consuming, so we limited our simulations considering the thermo-mechanical fatigue test to the test conditions of 100–550 °C (lower–upper temperatures).

The axis symmetric finite element model used consists of the specimen and screw connections to the rods (the rig whose length is kept constant during the test). Due to symmetry, only half of this rig needs to be considered (Fig. 3). The specimen building the lowest part of the model on Fig. 3 is a tube with an inner diameter of 8 mm and a wall thickness within the gauge length of 0.4 mm. The gauge length whose half is modeled is 10 mm.

Initially, a non-homogeneous temperature field is applied to the finite element model corresponding to the field measured during the test when achieving the nominal mean temperature at the middle of the specimen. Thereafter, the model is loaded by fixing its total length and varying the non-homogeneous temperature field cyclically according to the temperature measurements performed in the real test. When applying the temperature field, the temperature change across the cross section of the specimens is neglected.

Fig. 4 shows the deformed shape of the specimen and the equivalent inelastic strain and damage fields

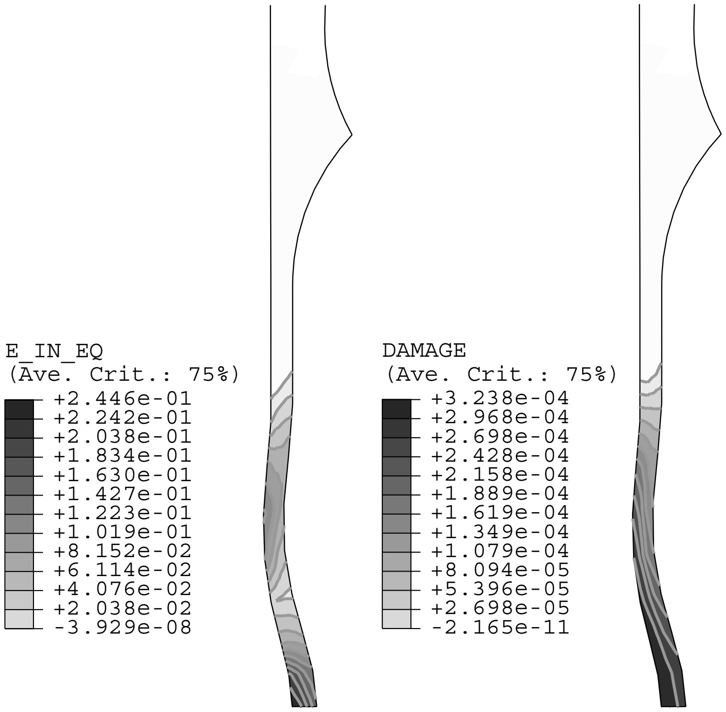

Fig. 4. Shape of deformed specimen, equivalent inelastic strain and damage fields calculated after 500 thermal cycles.

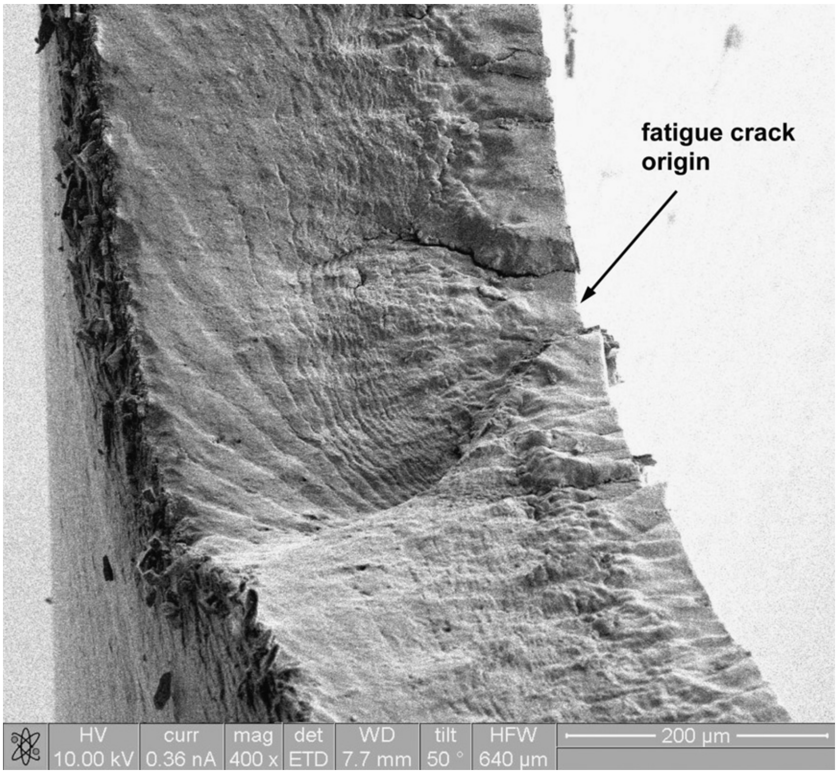

Fig. 5. Scanning electron microscopy image showing fatigue crack origin on fracture surface obtained in one of the thermo-mechanical fatigue tests considered.

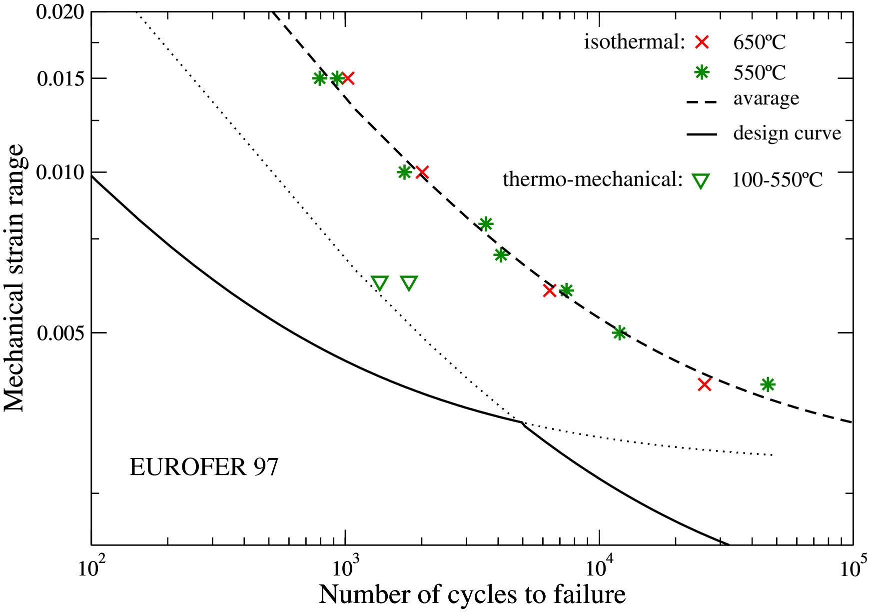

Fig. 6. Maximum mechanical strain range at the half number of cycles to failure calculated using finite element simulations versus number of cycles to failure for thermo-mechanical fatigue tests in comparison to those of isothermal fatigue tests and the design curve derived therefrom.

calculated after 500 cycles. It can be recognized, that the specimen is seriously deformed within the strain gauge and visibly buckles. The maximum inelastic strain and the maximum damage as well are located at the inner side of the specimen mid-section (Fig. 4). This location corresponds very well with the fatigue crack initiation position determined by scanning electron microscopy (SEM) investigations of fracture surface obtained (Fig. 5). At this location, the mechanical strain range calculated for the 500th cycle is 0.0062 and is thus higher than the value measured as an average for the gauge length in the real test (cf. Fig. 2). However, this maximum mechanical strain range is still lower than that corresponding to the experimentally observed fatigue life predicted on the base of isothermal fatigue data (Fig. 6). In addition, the damage values calculated verify that the simulation would yield higher number of cycles to failure than that observed experimentally. In other words, the finite element simulations could explain a part of the reduction in fatigue life but not as much as observed in the thermo-mechanical fatigue tests considered here.

4. Discussion

On the basis of the finite element results, one may conclude that thermo-mechanical cycling of EUROFER 97 yields more fatigue damage than isothermal cycling with the same mechanical strain range. Before doing so, we would point out that the progressive strain localization calculated at the middle of the thermo-mechanical fatigue specimen (Fig. 4), caused by both temperature gradients in the specimen and cyclic softening behavior of the material, leads to speculation that the lifetime observed might be influenced by deformation instabilities which would yield locally higher fatigue loads. These deformation instabilities and the resulting higher local fatigue loads cannot be correctly modeled by the geometric linear simulations performed here. However, geometric nonlinear simulations, which would be the next recommended investigation step, need a specific implementation of the coupled deformation damage model with respect to finite deformations. Possibly modification of the coupled deformation damage model, which was developed and verified for strain magnitudes less than 2%, might also be necessary. In addition the role of deformation instabilities on lifetime observed in the thermo-mechanical fatigue tests can be investigated experimentally by performing thermo-mechanical fatigue tests with the same test conditions using specimens of different geometries and different buckling behavior, respectively. If these tests show lifetimes independent on specimen geometry, the deformation instabilities can be eliminated as an explanation for the unexpected low lifetime observed in the thermo-mechanical fatigue tests considered.

5. Conclusions

Simulations of thermo-mechanical fatigue tests using the finite element method in combination with an advanced coupled deformation damage model result in a local mechanical strain range greater than that assumed experimentally on the base of strain gauge measurements. However, the lifetime due to the calculated local fatigue load is still higher than the lifetime observed experimentally with the corresponding high fatigue load derived from isothermal fatigue experiments. On the basis of strain localization observed in the finite element simulations, geometric nonlinear deformation instabilities are expected, which would yield even higher local fatigue load and thus explain the very low fatigue lifetime observed experimentally. To verify this assumption, geometrically nonlinear simulations, which require development of additional tools, as well as thermo-mechanical fatigue tests with specimens of different geometries are recommended.

Acknowledgments

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References

[1] J. Aktaa, R. Schmitt, Fus. Eng. Des. 81 (2006) 2221.
[2] R. Lindau, M. Schirra, Fus. Eng. Des. 58&59 (2001) 781.
[3] C. Petersen, J. Nucl. Mater. 258–263 (1998) 1285.
[4] ASME Boiler and Pressure Vessel Code, Section III, Code Case N-47, 1974.
[5] D.A. Miller, R.H. Priest, in: R.P. Skelton (Ed.), High Temperature Fatigue: Properties and Prediction, Elsevier Applied Science, 1987, p. 113.