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Multiaxial fatigue behavior of EUROFER 97

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Abstract

Proportional and non-proportional multiaxial fatigue testing of tubular specimens have been performed under purely alternating strain-controlled loading in order to assess the lifetime behavior of the ferritic martensitic steel EUROFER 97 under multiaxial fatigue conditions. Both load paths and the phase shifts were varied. The first test series at room temperature was performed with fixed directions of the principal stresses and strains. A second test series was conducted under alternating tension–torsion loading. In this case no fixed principal axis system is obtained. In fact, rotating principal stresses and strains are included. In a further step, tests were performed at elevated temperatures (500 °C). The results obtained reveal the influence of the phase shift for different temperatures as well as the influence of test execution method (fixed or rotating principal stress system) for the same material.

1. Introduction

First wall materials of a fusion reactor will be exposed to different complex loading conditions. One of these complex loading conditions is represented by multiaxial fatigue. In this paper the cyclic behaviour of EUROFER 97 under different multiaxial loading situations will be described. An overview of the classification of multiaxial fatigue experiments is given in Fig. 1. EUROFER 97 was tested with all different kinds of the chosen loading types. In the case of tension–torsion loading, a portion of the tests was performed at elevated temperature, and the remainder is still in progress.

2. Experimental setup

To perform multiaxial fatigue experiments with a fixed principle axis we used a biaxial test facility, as described in [1,2]. After finishing these experiments we modified the existing facility to perform tests with a rotating principle axis at room temperature as well as at elevated temperature. For this purpose we disassembled the pressure vessel and replaced it with a resistance furnace (Fig. 2). To ensure that the clamping jaws are not heated, the bolts which are welded with the specimens were extended, so that it was possible to mount cooling sleeves. Furthermore, we used a combined tension/torsion extensometer, instead of the axial strain and the radial displacement extensometers, to measure the axial strain ε_{ax} and the shear strain γ simultaneously. For the tests at elevated temperature

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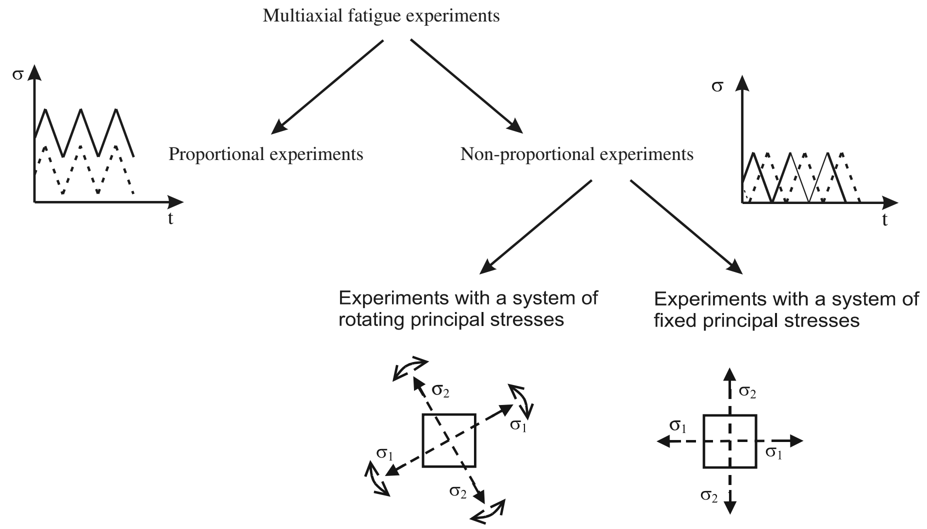

Fig. 1. Classification of multiaxial fatigue experiments.

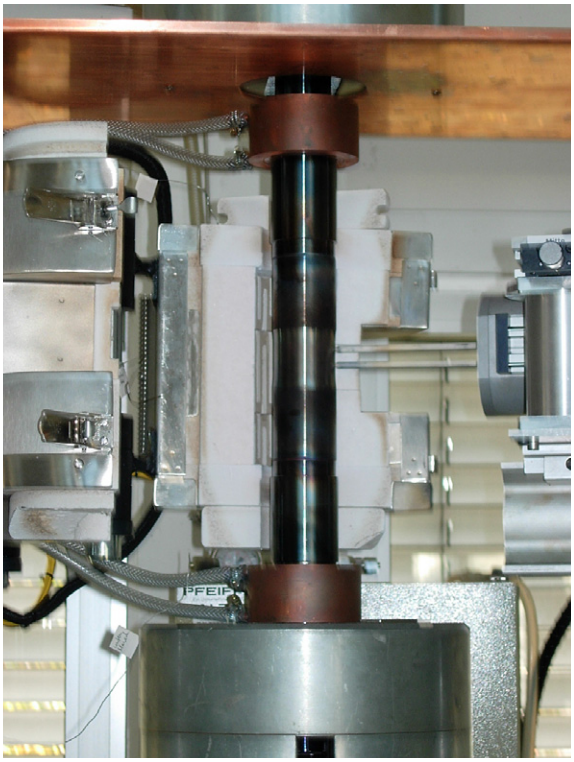

Fig. 2. Modified biaxial test facility for tension/torsion tests.

reported here the temperature was held constant at 500 °C during the entire experiment.

The specimens used had a waisted tubular geometry which was nearly the same as in [1]. Only minor revisions, related to the diameters in the gauge zone were made due to the semi-finished parts being available. The advantages of this geometry, described in [1] were thereby fully preserved.

3. Multiaxial tests with fixed principal axis

An equivalent loading parameter has to be defined to compare the results of experiments at different phase shifts. For this purpose the equivalent plastic strain range $\Delta\varepsilon_{pl}^{eq}$ which is defined as

$$\Delta\varepsilon_{pl}^{eq} = \sqrt{\frac{2}{3}}\left(\max_{t_0}\max_{t}\|\tilde{\varepsilon}_{pl}(t) - \tilde{\varepsilon}_{pl}(t_0)\|\right) \tag{1}$$

was introduced [1]. Therewith it is possible to compare experiments with different phase shifts.

Multiaxial fatigue tests were performed at different phase shifts and different loading amplitudes. The direct adjustment of the equivalent plastic strain range was not possible. We were only able to control the total strain for the axial and the circumferential direction separately. For all experiments we defined the nominal amplitude in the axial direction equal to the nominal amplitude in circumferential direction. The correlation between the adjusted nominal amplitudes and the $\Delta\varepsilon_{pl}^{eq}$ values obtained for the cycle after reaching half the number of cycles to failure is shown in Fig. 3. For an increasing phase shift the equivalent plastic strain range decreases at the same nominal amplitude value.

The lifetimes observed are plotted in Fig. 4 in comparison to those obtained from uniaxial tests. The number of cycles to failure N_f, for the multiaxial tests, is defined by the number of cycles at which a crack penetrating the wall is observed [1]. The uniaxial tests

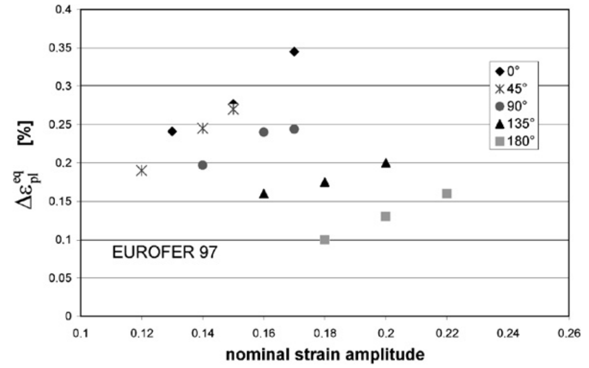

Fig. 3. Correlation of the nominal values and the equivalent plastic strain range for various phase shifts.

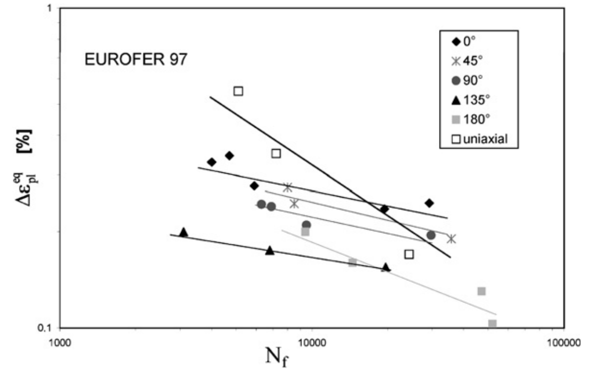

Fig. 4. Correlation of non-proportional life with the equivalent plastic strain range for various phase shifts.

were performed with cylindrical solid specimens. Due to this fact it was not possible to estimate N_f in the same manner for the two types of test. To assure a comparability between the number of cycles to failure in the uniaxial and in the multiaxial tests, N_f in the uniaxial tests is not determined by the common 30% load drop of the stationary phase. In fact, we used only a 3% load drop, because in the multiaxial case at N_f no pronounced load drop is observed.

It can be seen that for different phase shifts, the number of cycles to failure varies clearly at the same equivalent plastic strain range. Furthermore it can be recognized, that a decreasing phase shift tends to result in a higher life at the same equivalent load.

This behaviour can be explained by the different pronounced hardening for the different phase shifts. At the same equivalent strain the equivalent stress varies, depending on the phase shift. For a quantitative consideration, the equivalent stress range Δs^{eq} was determined for each experiment. Its determination is analogous to the equivalent plastic strain range $\Delta\varepsilon_{pl}^{eq}$ mentioned above, i.e. the value for the

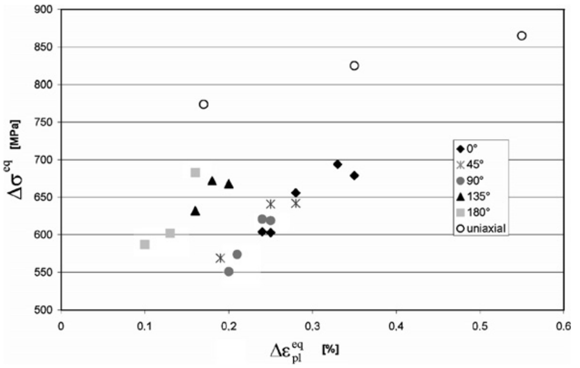

Fig. 5. Correlation of the equivalent plastic strain range and the equivalent stress range for various phase shifts.

cycle at half the number of cycles to failure is used. The results showed us, that for an increasing phase shift the stress range also increases, at the same equivalent strain range. Due to this higher stress level at the same strain level, a reduced fatigue life can be expected. Fig. 5 shows this issue very clear. In the uniaxial case the equivalent stresses are higher than in the multiaxial case. This fact should lead to reduced fatigue lifetimes at the same plastic strain range. In Fig. 4 it is shown, that only one result fulfills this prognostication. The other two results show a higher lifetime than the corresponding multiaxial tests. The reason for this behaviour is not yet identified. The transition from the uniaxial to the multiaxial loading leads probably to effects we have not considered. It seems that in the uniaxial case the dependence of lifetime on the stress/strain level is much more pronounced than in the multiaxial case. Further investigations on this are necessary.

4. Multiaxial tests with rotating principal axis

To identify differences between the different multiaxial loading procedures (fixed and rotating principle axis), experiments with a rotating principal axis were performed at room temperature. To investigate the influence of temperature, tests at elevated temperature (500 °C) were also performed. So far only tests with a phase shift of 0° were performed. The equivalent plastic strain range $\Delta\varepsilon_{pl}^{eq}$ was calculated in the same manner using Eq. (1). The adjustment of $\Delta\varepsilon_{pl}^{eq}$ is analogous to the manner described in Section 3 for multiaxial tests with fixed principal axis. The correlation between the adjusted nominal amplitudes and the obtained $\Delta\varepsilon_{pl}^{eq}$ for the phase shift of 0° is shown in Fig. 6. For elevated temperature the resulting equivalent plastic strain ranges are

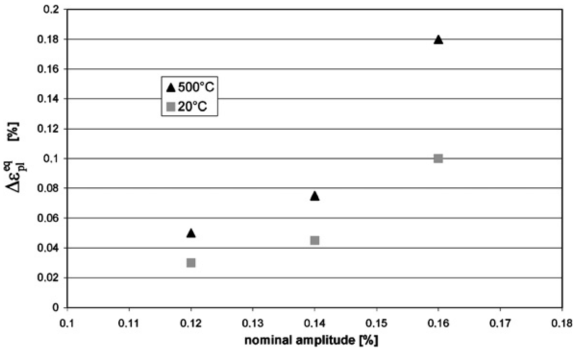

Fig. 6. Correlation of the nominal amplitude values and the equivalent plastic strain range obtained for a phase shift of 0° at different temperatures.

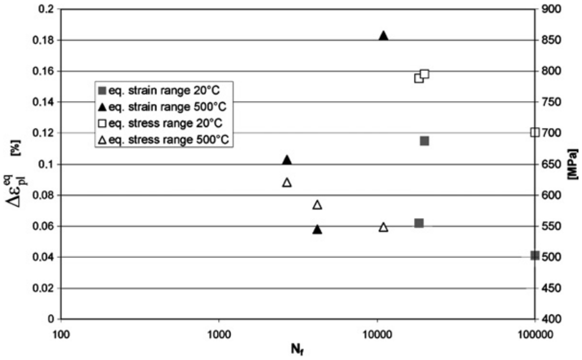

Fig. 7. Correlation of lifetime with the equivalent plastic strain range and the equivalent stress range for a phase shift of 0°.

higher than they for room temperature cases, at the same adjusted nominal strain amplitudes.

The determination of the number of cycles to failure is more complicated here than in [1]. In this case, it is not possible to determine the wall penetration exactly, because the specimen is unpressurised. So we have to define the number of cycles to failure from the load drop. The number of cycles to failure is defined as a 10% load drop of the equivalent stress, relating to the equivalent stress at half the number of cycles to rupture. The experimentally observed lifetimes are illustrated in Fig. 7. A big difference in lifetime is observed between room temperature and elevated temperature at the same equivalent strain. Surprisingly the experiments with the highest strain ranges (for room temperature as well as for elevated temperature) do not have the lowest lifetime. This leads to the conclusion that for these processes the plastic strain is not the only critical parameter. So we also calculated the equivalent stress range $\Delta\sigma^{eq}$ for the cycle at half the number of cycles to rupture, for each test and added the results in Fig. 7. The stresses show the expected results. Higher lifetimes correlate with lower stresses. But the most interesting result is that higher nominal strain amplitudes and thus higher plastic strain ranges do not necessarily lead to higher stress ranges. The cyclic softening of this material is, at least for this setup, apparently so strongly pronounced that higher nominal strains could lead to lower stress and therewith to higher lifetimes. By further investigations this observation will be verified.

5. Conclusions

Investigations with a fixed principal axis reveal a clear influence of the phase shift on lifetime. In fact a decreasing phase shift tends to result in a higher life at the same equivalent load. This can be explained by the different hardening behaviour due to the different phase shifts.

The experiments with the rotating principal axis are still at the beginning. Since so far only tests with 0° phase shift have been performed, it is not possible to draw conclusions about the influence of phase shift for this setup. The temperature has, as expected, a big influence on $\Delta\varepsilon_{pl}^{eq}$ at the same nominal amplitude as well as on the lifetime at the same $\Delta\varepsilon_{pl}^{eq}$. At elevated temperature the number of cycles to failure decreases dramatically. For this multiaxial loading case, the cyclic softening of EUROFER seems so strong, that it is questionable whether the equivalent plastic strain range is the only characteristic value determining failure.

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