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# Tensile and low cycle fatigue properties of different ferritic/martensitic steels after the fast reactor irradiation 'ARBOR 1'

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A B S T R A C T

In the irradiation project 'Associated Reactor Irradiation in BOR 60', named 'ARBOR 1', tensile and low cycle fatigue specimens of reduced activation ferritic/martensitic steels have been irradiated in a fast neutron flux (>0.1 MeV) of 1.8 $10^{15}$ n/cm$^2$ s and with direct sodium cooling at a temperature <340 °C to 15 and ~30 dpa. With increasing irradiation damage the tensile behaviour of, e.g. EUROFER 97, leads to hardening in combination with a dramatic reduction in uniform strain, but with a considerable total strain. The low cycle fatigue behaviour of all examined ferritic/martensitic steels, like EUROFER 97, F82H mod. and ODS-EUROFER 97 with 0.5% $Y_2O_3$, show at total strains below 1% an increase of number of cycles to failure, due to irradiation hardening.



## 1. Introduction

Structural materials will be exposed in an energy generating fusion reactor to very high levels of irradiation damage of about 100 dpa. A simulation facility – like IFMIF – is not available in the nearer future, to study the materials behaviour under fusion relevant irradiation conditions, e.g. specific He/dpa-ratio. Therefore these irradiation damage conditions can be realised in fast reactors only. Due to the fact that fast reactor irradiation facilities in Europe are not available anymore, a cooperation between Forschungszentrum Karlsruhe (FZK) and State Scientific Centre of Russian Federation Research Institute of Atomic Reactors (SSC RF RIAR) had been implemented. The performed irradiation project 'Associated Reactor Irradiation in BOR 60' is named 'ARBOR 1' (arbor is Latin for tree).

The BOR 60 experimental fast reactor of SSC RF RIAR – nowadays widely used as irradiation facility for material science purposes – offers different irradiation positions in the reactor core of 450 mm in height and 550 mm in diameter. Into the selected cell D-23 direct temperature measurement by thermocouple is possible during irradiation [1].

The ARBOR 1 irradiation device is described in detail in [2] and was instrumented with neutron monitors as well as temperature detectors. The calculation of the damage dose values for ferritic steel specimens was conducted using the SPECTER code [3].

The ARBOR 1 irradiation included 150 mini-tensile/Low Cycle Fatigue (LCF) specimens and 150 mini-impact (KLST) specimens of nine different RAFM steels. They had been irradiated in a fast neutron flux (>0.1 MeV) of 1.8 × $10^{15}$ n/cm$^2$ at temperatures between 331 °C and 338 °C up to ~30 dpa. For Post Irradiation Examinations (PIE) had been unloaded 50% of the specimens. The other 50% of both specimens types were reloaded into the ARBOR 2 rig for further irradiation in BOR 60 to reach a maximum irradiation damage of 70 dpa [4].

The mechanical PIE is performed under the ISTC Partner Contract Nr. # 2781p. The impact properties have been published in [5], recently. Therefore tensile and LCF testing results are reported here as the second part of the mechanical PIE of the ARBOR 1 irradiation.

## 2. Experimental details

Tensile and LCF specimens of different materials were utilised to investigate the tensile and LCF properties after irradiation. The description of the specimens of EUROFER 97, F82H mod., OPTIFER IVc, EUROFER 97 with different boron contents and ODS-EUROFER 97 with 0.5% $Y_2O_3$ has been reported together with their chemical composition already in [2].

Tensile and LCF tests are performed with an electro-mechanical testing machine INSTRON 1362 DOLI, equipped with a three-zone furnace and a high-temperature extensometer of MAYTEC which is installed in the hot cell of the SSC RF RIAR material science laboratory [6,7].

In the ARBOR 1 mechanical PIE, small size cylindrical specimens of 8 mm gauge length and 2 mm diameter are tested under static (tensile) loading at different temperatures (250, 300 and 350 °C) with a strain rate of 3 × $10^{-3}$ $s^{-1}$. From the load–displacement curves strength and strain data quantities like the 0.2% offset yield

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stress ($R_{p0.2}$), ultimate tensile stress ($R_m$), uniform strain ($A_g$) and total strain ($A$) are calculated.

The dynamic (LCF) loading was performed at a constant temperature of 330 °C with different total strain ranges between 0.8% and 1.2%. LCF behaviour is shown as total strain range ($\Delta\varepsilon_{tot}$) vs. number of cycles to failure ($N_f$) and compared to literature results from NRG.

## 3. Results and discussion

Since the most considerable changes due to irradiation are found in the ($R_{p0,2}$)- and ($A_g$)-values from tensile data of EUROFER 97, only these quantities are depicted. For comparison, results from other recently published irradiation campaigns are included. But these results were generated on different specimen shapes and under different tensile testing conditions. Tensile tests have been performed on four different kinds of specimens types utilised in the different irradiations. NRG irradiated cylindrical specimens of 20 mm gauge length and 4 mm diameter and performed the tests with a strain rate of $5 \times 10^{-4}$ s$^{-1}$[8]. In the SPICE irradiation cylindrical specimens of 18 mm gauge length and 3 mm diameter were tensile tested under vacuum with a strain rate of $10^{-4}$ s$^{-1}$ [9]. In the 15 dpa WTZ 01/577 irradiation cylindrical specimens of 15 mm gauge length and 3 mm diameter were tensile tested with a strain rate of $3 \times 10^{-3}$ s$^{-1}$ [10].

So the 2.5 dpa damage (SIWAS-04) has the lowest increase of around 300 MPa in Yield Stress and the 30.2 dpa damage (ARBOR 1) the highest increase of around 460 MPa in Yield Stress that is nearly a duplication of the unirradiated quantity. The effect of the irradiation damage on the Uniform Strain is also considerable – mostly $A_g$-values below 0.5% are reached – but does not depend so much of the damage dose as the stress values [11].

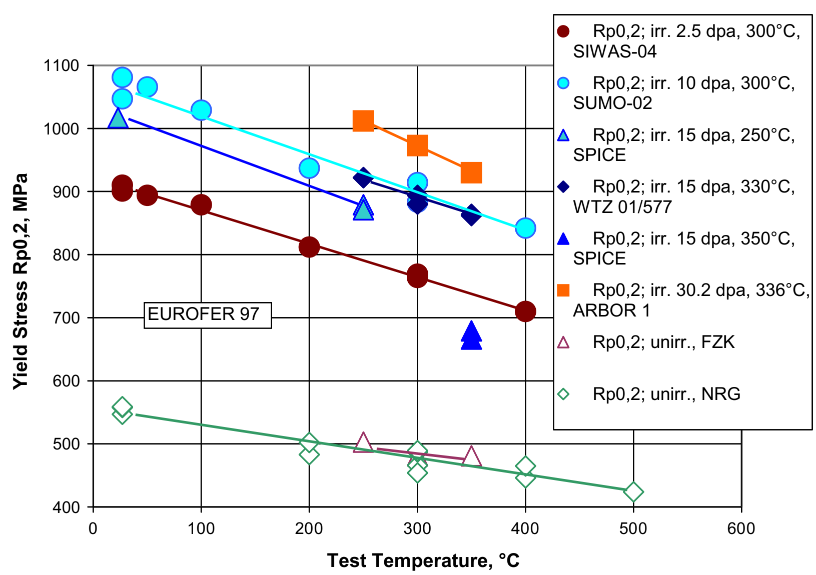


**Fig. 1.** Yield stress ($R_{p0.2}$) behaviour of 30,2 dpa irradiated EUROFER 97 as a function of test temperature compared to other irradiated and unirradiated data (the temperature in the legend indicates the irradiation temperature).

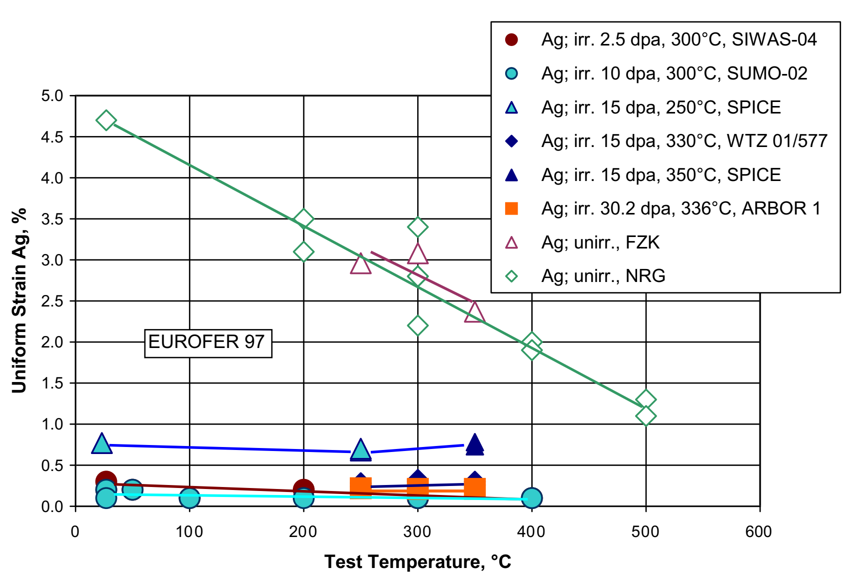


**Fig. 2.** Uniform strain ($A_g$) behaviour of 30.2 dpa irradiated EUROFER 97 as a function of test temperature compared to other irradiated and unirradiated data (the temperature in the legend indicates the irradiation temperature).

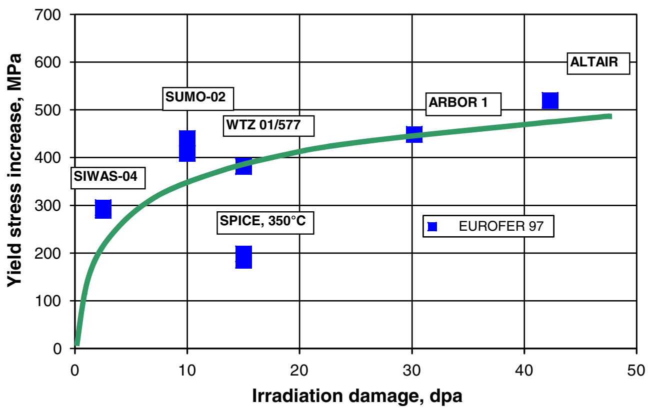


**Fig. 3.** Yield stress increase due to irradiation damage compared to data of other irradiations (test temperatures close to irradiation temperatures).

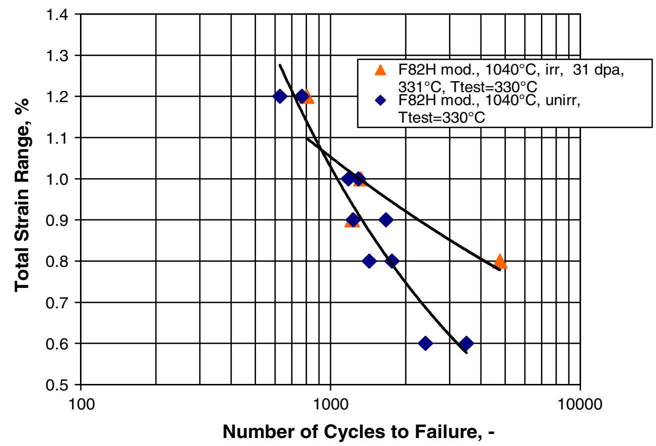


**Fig. 5.** Effect of irradiation on the LCF behaviour of F82H mod.

Even if one takes into account the slightly different tensile testing conditions, with increasing irradiation damage a continuous increase of the yield stress, $R_{p0.2}$, (Fig. 1) and a dramatic decrease in uniform strain, $A_g$, (Fig. 2) was measured.

More detailed tensile results of F82H mod., OPTIFER IVc, EUROFER 97 with different boron contents and ODS-EUROFER 97 will be published soon [12].

In Fig. 3 the yield stress increase is plotted in dependence of the irradiation damage for irradiations performed around 300 °C [13]. It follows nearly the rate proposed by Whapman and Makin [14], but it does not reach saturation at 42 dpa. Only the yield stress increase of specimens irradiated at 350 °C to 15 dpa damage (SPICE), that is not included in the fit, is much lower and demonstrates the strong influence of irradiation temperatures in this temperature range between 300 and 350 °C.

The comparison of irradiated and unirradiated cyclically loaded specimens of EUROFER 97, shown in Fig. 4, leads after LCF testing to an ambiguous behaviour. Even if specimen sizes and raw materials for specimens preparation are different the findings are similar. The ARBOR 1 results of the 31 dpa irradiation damage at 331 °C and – taken for comparison – NRG results of a 2 dpa irradiation damage at 300 °C [8] can be described by two effects. The first one occurs at high total strain ranges, $\Delta\varepsilon_{tot} > 1\%$ where the material is loaded remarkably over the yield stress point. Therefore in the second cycle no additional strain hardening takes place and thus the numbers of cycles to failure are smaller than under unirradiated conditions. Furthermore this effect increases with increasing irradiation damage.

The second effect occurs at low total strain ranges, $\Delta\varepsilon_{tot} > 1\%$ where the numbers of cycles to failure of irradiated specimens are increasing. Analysing the hysteresis loops, very narrow loops are recorded with little plastic strain contribution only. This is due to the irradiation induced damage, which raised the yield stress point above the elastic strain range with increasing irradiation damage.

Also for the 31 dpa irradiated F82H mod. (Fig. 5) a similar tendency was found in LCF testing, but the increase in numbers of cycles to failure for lower total stain ranges is not as high as for EUROFER 97.

As ODS-EUROFER 97 with 0.5 % $Y_2O_3$ had also been included in the ARBOR 1 irradiation, the results of LCF testing of these specimens after irradiation to 31 dpa damage at 331 °C seems really encouraging. In Fig. 6 the LCF behaviour after irradiation is compared to that of unirradiated specimens. Even if the material reaches in the unirradiated state at higher total strain ranges, $\Delta\varepsilon_{tot} > 1\%$, the lowest numbers of cycles to failure, compared to EUROFER 97 and F82H mod., the increase of numbers of cycles to failure in the lower total strain ranges, $\Delta\varepsilon_{tot} > 1\%$, is remarkable. At low total strain ranges a higher number of cycles to failure could be achieved on irradiated ODS-EUROFER 97 with 0.5% $Y_2O_3$, than for F82H mod. The above mentioned influence of irradiation on LCF behaviour was found also on this material.

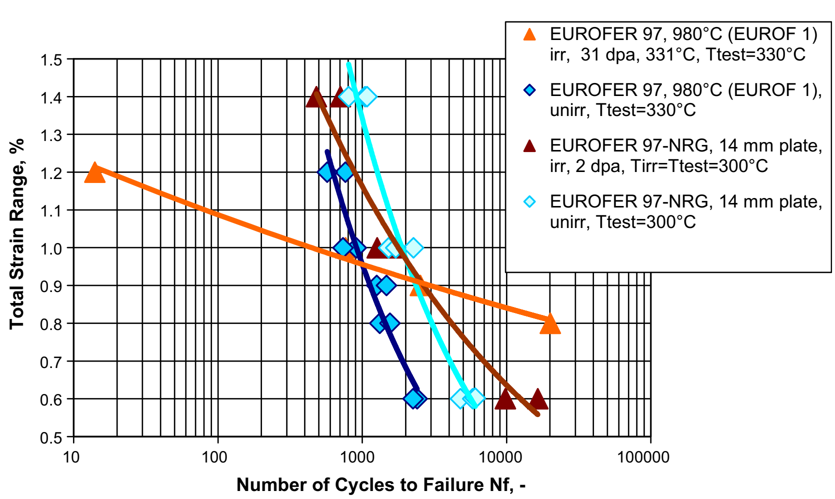


**Fig. 4.** Effect of irradiation on the LCF behaviour of EUROFER 97.

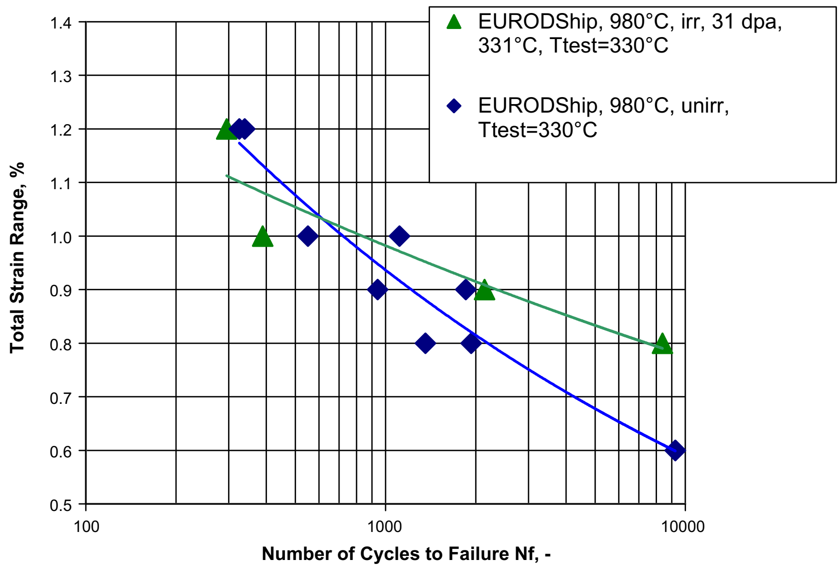


**Fig. 6.** Effect of irradiation on the LCF behaviour of ODS-EUROFER with 0.5% $Y_2O_3$.

## 4. Conclusions

Tensile hardening does not show saturation at 42 dpa irradiation damage and 330 °C. A model describing radiation hardening is working well for tensile properties.

Reduced activation steels reach in the lower total strain ranges, $\Delta\varepsilon_{tot} > 1\%$, at 30 dpa irradiation damage and 330 °C after LCF loading, a higher number of cycles to failure than the unirradiated materials.

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