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ScienceDirect
Journal of Nuclear Materials 367–370 (2007) 86–91
journal of nuclear materials
www.elsevier.com/locate/jnucmat

In situ fatigue of the Eurofer 97 steel

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Abstract

In order to investigate the fatigue behavior during irradiation of the EUROFER 97 steel, similar to that which would occur in a fusion reactor, a series of six *in situ* experiments was conducted using a specially designed proton irradiation system. All tests were performed at a total strain range of 0.8%, at 150 and 250 °C. In two experiments, to check the influence of the dislocation structure, the specimens were first fatigued prior to the irradiation and then only fatigued under beam. In one case, when the specimen reached the predicted number of cycles to failure, the beam was turned off and the test continued without a beam. Unexpectedly, the specimen recovered and attained almost the same number of cycles as without the beam irradiation. Secondary experiments were conducted for measuring the irradiation hardening under static stresses, as well as for measuring the flow stress under irradiation.

1. Introduction

First-wall materials used in fusion machines will be stressed and locally deformed under simultaneous irradiation with energetic neutrons. This particular condition has not been studied very often, due to the complicated and expensive experimental facilities required (see [1] for a short review). Most results available describe the evolution in terms of structure and mechanical properties of the *as irradiated* material, after it has been irradiated to the goal level. The properties of post-irradiation tested material, in some cases, may be very different from properties and structure of an *in situ* tested material, for the following reasons. Firstly, under simultaneous deformation, the irradiation takes place in a microstructure in evolution which may, depending on the mechanical conditions imposed, be very different from the *as received* condition. Secondly, enhanced diffusion of point defects and solute atoms may take place and secondary damaging mechanisms, detrimental to the mechanical properties, may occur. Finally, the moving dislocations interact with the irradiation induced defects. The irradiation substructure during *in situ* irradiations can be expected to be different. Consequently, depending on the level of plasticity in the material, irradiation hardening takes place at a smaller rate or disappears completely [2,3]. For all these reasons, it is obvious that the *in situ* condition deserves attention in future programs. The effects on the materials are not simply predictable; in some cases, as for Cu–Cr–Zr alloys [4], the *in situ* condition seems to be beneficial for the fatigue endurance. In the case of F82H, it was

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doi:10.1016/j.jnucmat.2007.03.162

clearly detrimental since the *in situ* fatigue life was reduced compared to a post-irradiation tested specimen [1]. In this work, we describe the results obtained for Eurofer 97, a material similar to F82H but containing a lower level of W.

2. Experimental details

2.1. Material

The chemical composition in wt.% of Eurofer 97, Heat Nr 83697, was Cr:8.93, V:0.2, W:1.07, N:0.018, C:0.12 and Ta:0.14. The material was delivered in the form of 25 mm plates. The final heat treatment applied was: austenitizing at 980 °C for 31 min, followed by air cooling and tempering at 760 °C for 90 min, and subsequent air cooling.

2.2. Irradiation conditions, specimens

The irradiation was carried out with 590 MeV protons, which have been shown in the past to be, at low doses, an adequate simulation for 14 MeV neutrons. The proton beam had a Gaussian distribution, adjusted to a size of $4\sigma_x = 6$ mm and $4\sigma_y = 3$ mm, where σ_x and σ_y are the beam standard deviations in x and y directions. The beam was then wobbled with an amplitude of 2.7 mm along the gauge length, with a frequency of about 3 Hz, to achieve a constant dose distribution. The beam intensity was 12–14 μA. Correspondingly, the proton flux was $4.074–4.75 \times 10^{14}$ p/cm^2 s and the mean current density 65–76 μA/cm^2. Medium energy protons produce heat. For this reason, the tubular in-beam specimen, having a cross section of 2.5×3.4 mm and a gauge length of 5 mm, was cooled by a flow of pressurized helium [2]. A classical plain cylindrical specimen having a diameter of 2.7 mm and a gauge length of 6 mm was tested in a conventional testing machine, for comparison purposes. The 590 MeV protons also generate helium and hydrogen in the alloy. The calculated values for this ferritic steels were 195 and 956 appm/dpa [5,6], respectively.

The irradiation parameters relevant to the experiments are given in Table 1. The indicated dpa dose is the result of a dosimetry analysis.

2.3. Mechanical tests

The fatigue test was conducted under strain control, following an $R = -1$ symmetrical signal. All experiments were conducted at a total strain amplitude of 0.8 % (half-strain amplitude 0.4%). The test frequency of the specimens tested in the *in situ* device was chosen to be 0.005 Hz ($T = 200$ s) for the in-beam test and 0.01667 Hz ($T = 60$ s) for the tests without a beam. The test frequency chosen for testing the plain specimens was 0.125 Hz ($T = 8$ s). Below 300 °C, the test frequency is not expected to influence the mechanical behavior; therefore, to save time, the test frequency was

Table 1
The mechanical tests and irradiation parameters for 590 MeV proton irradiation

	I29I02	I29I03	I29I05	I29I06	N29I04	N29I01	N29F24	N29F25
Irradiation temperature T_{irr} (°C)	150	250	250	150	–	–	–	–
Deformation temperature T_{def} (°C)	120	219	221	125	150	250	120	220
$\Delta\varepsilon_{tot}$ (%)	0.80	0.80	0.80	0.80	0.80	0.79	0.82	0.82
Cycle length T (s)	200	200	200	200	60	60	8	8
$\dot{\varepsilon}$ (s^{-1})	8×10^{-5}	8×10^{-5}	8×10^{-5}	8×10^{-5}	2.67×10^{-4}	2.67×10^{-4}	2×10^{-3}	2×10^{-3}
Accumulated current (beam current integration) D (A s)	3.742	3.042	2.667	2.809	No irradiation	No irradiation	No irradiation	No irradiation
Accumulated dose (dosimetry analysis) D (dpa)	0.21	0.17	0.15	0.16	No irradiation	No irradiation	No irradiation	No irradiation
N_a (–)	1499	1259	1505	2643	2881	2904	11614	5815

Specimen N29I04 and N29I01 have been tested without a beam, but in a helium atmosphere, in the *in situ* device. Predicted helium production ratio: 195 appm/dpa [5]. Damage ratio: $\dot{D}/\dot{\varepsilon} = 1.5 \times 10^{-2}$ dpa. Dose rate: $\dot{D} = 1.2 \times 10^{-6}$ dpa/s. I29I05 and I29I06 received a pre-deformation of 250 and 300 cycles, respectively. The unit for beam current dose is Ampère second [A s].