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Fracture toughness characterization in the lower transition of neutron irradiated Eurofer97 steel

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ABSTRACT

This research investigated the evolution of tensile, hardness, and fracture properties of Eurofer97 tempered martensitic steel following neutron irradiation. The irradiation-hardening was measured with Vickers hardness tests on broken parts of sub-sized compact tension specimens as well as with tensile tests deformed at room temperature. The fracture toughness was measured with pre-cracked sub-sized 0.18T compact tension specimens. Two specimen sets were irradiated up to a nominal dose of about 0.35 dpa at two different temperatures, 423 and 623 K, in the experimental reactor at AEKI-KFKI in Budapest. The median fracture toughness–temperature curve $K(T)$ was characterized in the lower to middle transition region for each irradiation condition using the master-curve method. The irradiation-induced temperature shifts of $K(T)$ were determined by calculating the reference temperature T_0 at which the median toughness is 100 MPa m$^{1/2}$. A significantly larger shift was determined for Eurofer97 irradiated at 423 K than at 623 K. Indeed, an upper shift of 98 K was found for the 423 K irradiation while only 50 K was measured for the 623 K. On the one hand, that observation reflects the difference in the irradiation-hardening following those two irradiation temperatures. On the other hand, when compared with other published data, the ΔT_0 shift at 623 K irradiation was found to be greater than expected for the corresponding irradiation-hardening. Thus, it was suggested that non-hardening embrittlement mechanisms start to operate around 623 K.

1. Introduction

Reduced activation ferritic–martensitic (RAFM) steels are leading candidates as structural materials for the future fusion reactors due to their good physical and mechanical properties, swelling resistance in 573–823 K operating temperature window, and ability to meet low activation waste requirements [1]. Eurofer97 is a RAFM steel chosen as a reference structural material for the test blanket modules (TBMs) that will be tested in ITER [2].

A typical consequence of high energy neutron irradiations in fusion reactor is the degradation of mechanical properties such as irradiation-induced hardening leading to embrittlement and loss of fracture toughness [3,4]. Although the fracture toughness database for unirradiated Eurofer97 is quite large [5,6], the development of a high quality database on the effects of irradiation on the constitutive and fracture properties of irradiated material for different irradiation temperatures and doses remains an important objective. Thus, considerable efforts have been devoted on characterization of post-irradiation mechanical and micro-structural properties of Eurofer97. We emphasize that the embrittlement effects observed at irradiation temperatures lower than 673–723 K stem from irradiation-induced hardening [7], whereas at higher irradiation temperatures where irradiation-induced softening occurs, the fracture properties degradations are associated with non-hardening embrittlement (NHE) contributions [8].

The goal of this paper is to present new results of mechanical characterization of Eurofer97 after two irradiations in experimental reactor at AEKI-KFKI in Budapest to 2.5 × 10^{20} n/cm^2 (0.33 dpa) at 423 K and to 2.8 × 10^{20} n/cm^2 (0.37 dpa) at 623 K. In particular, irradiation-induced hardening and embrittlement, measured by a shift of the reference temperature T_0 of the master-curve method, are reported.

2. Material and experimental procedures

2.1. Material

The material used in this research was the reduced activation Eurofer97 steel, heat E83697, 25 mm-thick plate, produced by Böhler AG. The chemical composition (wt%) was Fe–8.9Cr–0.12C–0.46Mn–1.07W–0.2V–0.15Ta. The heat-treatment was 0.5 h at 1253 K for 0.5 h and tempering at 1033 K for 1.5 h. This steel was fully martensitic after quenching.

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2.2. Mechanical testing

The static fracture toughness data reported here were obtained with fatigue pre-cracked compact tension $C(T)$ specimens. Sub-sized $0.18T$ $C(T)$ specimens were used with thickness (crack front) (B) equal to 4.5 mm with width (W) equal to $2B$ and the crack length a to specimen width W ratio (a/W) was about 0.5. The fracture toughness tests were performed over the temperature range (153–273 K). Temperature control was provided by a PID controller equipped with a regulated N_2 gas flow.

The results of the fracture toughness tests were evaluated using the ASTM E1921 standard in terms of K_{Jc}, an elastic–plastic equivalent stress intensity factor derived from the value of the J_c integral at the onset of cleavage fracture, J_c [9].

$$K_{Jc} = \sqrt{J_c E'} \quad (1)$$

where E' is the plane strain Young's modulus.

The reference temperature (T_0) was determined in accordance with ASTM E1921-03 standard [9] (master-curve method). However, slight modifications of the master-curve shape were considered in this work as proposed by Mueller et al. [5]. As demonstrated in [5], the modified-master curve for Eurofer97 reads:

$$K_{med,Jc} = 12 + 88\exp(0.019(T - T_o)) \quad (2)$$

This modified master curve allows determining T_o (at which the median toughness of $1T$ $C(T)$ specimens is 100 MPa $m^{1/2}$) with data obtained in the very low part of the transition and with sub-sized specimens. The crack front length adjustments, from $0.18T$ to $1T$ size, were done as per ASTM standard as:

$$K_{B_2} = K_{\min} + [K_{B_1} - K_{\min}]\left(\frac{B_1}{B_2}\right)^{1/4} \quad (3)$$

Note that in this study we considered a $K_{Jc,limit}$ calculated with an M factor equal to 80 instead of 30 as recommended in the ASTM-E1921 standard. The justification for this modification is given in [5].

$$K_{Jc\_limit} = \sqrt{\frac{E' b \sigma_y}{M}} \quad (4)$$

Tensile tests have been conducted at room temperature on irradiated small flat specimens. The tensile tests were carried out with a screw-driven Zwick 010 machine at an imposed nominal strain-rate of $1.5 \times 10^{-3}\ s^{-1}$. The elongation of specimens was deduced from the displacement of the machine crosshead, measured using a linear variable differential transformer with compliance correction. The stresses and strains reported hereafter are expressed in engineering units.

Hardness tests up to HV_{10} were performed on both as-received and irradiated Eurofer97 samples using a hardness tester equipped with a Vickers indenter tip. The indentations on the irradiated specimens were done on the $0.18T$ $C(T)$ actual specimens.

2.3. Neutron irradiation conditions

Two different irradiations of subsized $0.18T$ $C(T)$ fatigue pre-cracked fracture toughness and small flat tensile specimens were performed in the BAGIRA rig of the experimental reactor at AEKI-KFKI in Budapest, Hungary. The first irradiation, up to a fluence of 2.5×10^{20} n/cm^2 ($E > 1.0$ MeV; about 0.33 ± 0.05 dpa), was carried out at a temperature of about 423 K. The second irradiation, up to a similar fluence of 2.8×10^{20} n/cm^2 ($E > 1.0$ MeV; about 0.37 ± 0.04 dpa), was performed at a higher temperature of 623 K. After the irradiations, the specimens were transported to the hot cells of the Paul Scherrer Institute hot-laboratory for performing mechanical tests.

2.4. Finite element (FE) model

Significant loss of the uniform tensile elongation after irradiation at 423 K did not allow direct evaluation of true stress true strain curve beyond ≈0.5% plastic strain. Finite element (FE) modeling was performed, using ABAQUS 6.10-3, in order to estimate the average flow stress of Eurofer97 irradiated at 423 K to 0.33 dpa.

In general, for the stress analysis problems, ABAQUS uses incremental J_2 plastic flow theory and the Newton's method as a numerical technique for solving the nonlinear equilibrium equations.

Required inputs to the ABAQUS code include the Young's modulus (E), Poisson's ratio (ν), and the flow stress as a function of the effective plastic strain after the yield.

Fig. 1 shows a three dimensional (3D) elastic–plastic FE model of small flat tensile specimen used in this study. The specimen instance was meshed with 26796 linear hexahedral elements of the type 8-node linear brick, reduced integration. The contact between the specimen and the two pins simulated as analytical rigid bodies was assumed frictionless.

The required $\sigma(\varepsilon)$ curve of irradiated material was obtained by iteratively modifying trial $\sigma(\varepsilon)$ input function until the model output reproduced the experimental engineering stress–strain $s(e)$ curve (or in other words the load–displacement curve); this work followed previous tests conducted by Yamamoto et al. [10].

3. Results and discussion

3.1. Tensile properties

Fig. 2 represents tensile data of Eurofer97 irradiated at 423 K and 623 K to 0.33 dpa and 0.37 dpa, respectively. As a consequence of neutron irradiation, a strong increase of yield stress ($\Delta\sigma_y$ = 235 - MPa) and a loss of the uniform elongation (Δe_u = 5.9%) were observed for irradiation at 423 K. Less pronounced effect is shown for T_{irr} = 623 K, where the engineering stress–strain curve is very close to the unirradiated one, with $\Delta\sigma_y$ = 35 MPa and Δe_u = 0.8%.

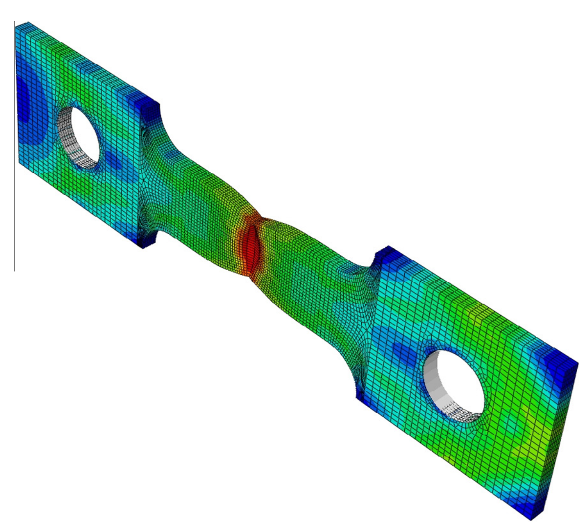

Fig. 1. 3D finite element model of the flat tensile specimen.