Effect of irradiation on mechanical properties of 15Ch2MFA reactor pressure vessel steel

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Abstract: The aim of this study is to investigate the effect of neutron irradiation on mechanical properties of a reactor pressure vessel steel. An experimental characterization of 15Ch2MFA steel used for manufacturing of VVER 440 reactor pressure vessels was carried out by means of tensile and Charpy impact tests. Specimens were irradiated by several neutron fluences before testing. The mechanical tests were modeled by finite element method in order to compute the stress - strain field generated in specimens.

Introduction

The degradation of mechanical properties of reactor pressure vessel (RPV) due to neutron irradiation is still worldwide discussed. It is because of high safety standards applied in nuclear industry.

The main indicator of change in mechanical properties is ductile to brittle transition temperature (DBTT), obtained by Charpy impact tests. Additional information to Charpy impact energy can be obtained by using instrumented Charpy impact pendulum device. Nevertheless, this test does not report direct information about stress - strain field in the instant of fracture. The stress strain field should be obtained indirectly by numerical computation.

Frequently there is a lack of experimental data on irradiated material. In some cases, the only way of obtaining the material parameters is identification procedure using the numerical model. Several simulations of the Charpy specimens by finite element method (FEM) were done in [1-5].

It is well known, that the irradiation cause increase of yield (flow) stress, tensile strength, decrease ductility and changes hardening. Considering that the main irradiation effect is an increase of the yield stress, the whole stress - strain curve of the unirradiated material is frequently shifted to higher stress values, i.e. the strain hardening of unirradiated material does not differ from strain hardening of irradiated material. Which is disputable, since hardening can play an important role.

It is not still well understood influence of strain rate after irradiation. Generally, it is supposed that irradiation has no influence on the hardening due to the high strain rate [6]. In [5] the thermally activated processes were studied by means of tensile test with various crosshead speeds. There were not observed differences of activation parameters in the unirradiated and the irradiated conditions [5], but the investigation was done in limited range of strain rates.

The aim of this study is to determine the stress – strain field generated in the Charpy specimen taking into account the effect of thermally activated deformation.

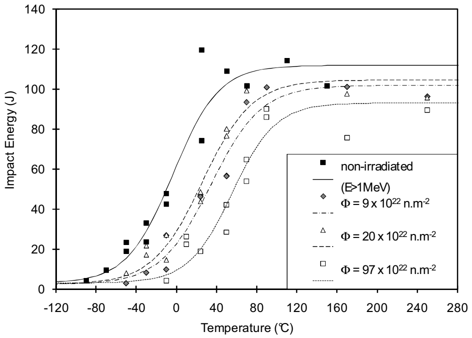

Fig. 1. Transition curve

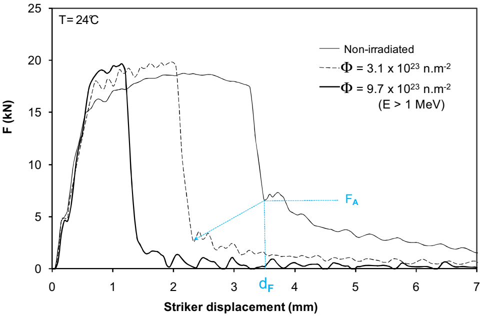

Fig. 2. Charpy impact test record of neutron irradiated and non-irradited specimens at room temperature. (F_A is the force at crack arrest)

Material

The steel chosen for this study was the 15Ch2MFA (15Cr2MoV) tempered bainitic steel [7]. This steel is used for fabrication of pressure vessels of VVER 440-type nuclear reactors. The forged plate of 190 mm thickness was subjected to the thermal treatment of normalizing at 1010°C/12 hours followed by cooling in air, and tempering at 730°C/14 hours followed by furnace cooling. The resulting microstructure corresponds to the tempered bainite. The chemical composition is given in Table 1.

The standard tensile and Charpy V-notch (CVN) specimens were taken at a depth position at one quarter of the plate thickness from the surface (1/4*t* position) in the T (long transverse) and T-S (long transverse - short transverse) orientations.

The specimens were enclosed and neutron-irradiated in the same capsules as standard surveillance specimens. The chains contained the set of activation monitors (including fast as well as thermal neutrons) and also fission monitors. Each capsule contained two rings of copper wire to evaluate the azimuthal fluence. The capsules were irradiated in emptied surveillance channels in the VVER 440-type nuclear reactor. The mean irradiation temperature was estimated after evaluation of the melting temperature monitors to 275 °C.

Tensile tests were carried out on the INSTRON 1342/8500+ hydraulic testing machine at room temperature at constant crosshead speed of 0.5 mm min^{-1}. Results of tensile tests are reported in [8]. Charpy tests were carried out on an instrumented impact pendulum device Tinius-Olsen 74 (sampling frequency was 1 MHz) with nominal impact energy 358.5 J and nominal impact velocity 5.1 m s^{-1} at various temperatures ranging from -190 °C to +240 °C.

Table 1. Chemical composition of 15Ch2MFA steel (wt%).

C	Mn	Si	P	S	Cu	Cr	Ni	Mo	Co	V	As
0.18	0.50	0.31	0.014	0.016	0.10	2.80	0.07	0.65	0.009	0.009	0.009

The results of the instrumented Charpy tests of neutron-irradiated and non-irradiated specimens are shown in Fig. 1. Neutron irradiation caused a shift of DBTT of about 65 °C after neutron fluence $\Phi \cong 10^{24}$ n m^{-2}. Neutron irradiation caused a slight decrease of the upper shelf energy from about 110 J in the non-irradiated state to about 95 J after neutron fluence $\Phi \cong 10^{24}$ n m^{-2}. The influence of irradiation on an instrumented test record is illustrated in Fig. 2. The maximum reaction force increases with increasing neutron fluence. Conversely, the fracture displacement d_F (striker displacement at brittle fracture initiation) and the force F_A at the crack arrest decrease.

Numerical modeling

The finite element method was used in order to compute the stress-strain distribution in the Charpy V-notch specimen. For numerical modeling, the methodology developed by Rossoll et al. [1] was adopted. 23 000 linear elements with selective integration were employed in the finite element analysis (Marc® 2007). The mesh size (Fig. 3) in the notch root region was about 10 µm. The striker was modelled by a rigid surface contact element. A friction coefficient of 0.1 was assumed for contact surfaces. Loading of the specimen was made by imposing a fixed displacement to the striker. The computations were performed in the framework of finite strains, with an updated-Lagrangian formulation. 3D quasi-static formulation was used. Due to the symmetry only one quarter of the specimen was modeled. The mesh consisted of 8 layers in the thickness direction with decreasing node distance to the outer surface to account for a gradient of stress and strain.

It was shown by Rossol [1] that the inertial effect is damped by viscoplasticity ahead of the notch and vanishes rapidly so that the quasi-static computation is sufficient for the fracture time which occurred in the DBTT range. On the other hand, 3D modelling is required. Heating of specimen caused by impact test is confined to notch root, and practically does not affect the stress - strain field [1]. In the Ref. [9], the static flow stress of the matrix was represented piecewise linear in the uniform strain range, and as a Hollomon stress-strain law at higher strains. Viscous effects due to high strain rates during the Charpy test were modeled using Cowper Symonds formula.

In our work, the following constitutive equations were used for actual flow stress:

$$\sigma\left(\varepsilon_{pl},\dot{\varepsilon}_{pl}\right)=K\left(\varepsilon_{pl}\right)^{n}\frac{\ln\left(\dot{\varepsilon}_{pl}/\dot{\varepsilon}_{0}\right)}{A}, \tag{1}$$

Where first term corresponds to strain hardening and second to the strain rate dependency of yield stress, n is strain hardening parameter, K constant, ε_{pl} plastic strain, $\sigma\left(\varepsilon_{pl},\dot{\varepsilon}_{pl}\right)$ dynamic flow stress, $\dot{\varepsilon}_{pl}$ plastic strain rate, $\dot{\varepsilon}_{0}$ normalization parameter, A activation volume dependent parameter.

Strain hardening was identified from tensile tests of irradiated and non-irradiated specimens [9]. After irradiation, the yield stress and the tensile strength are increased, the strain hardening rate is decreased (Fig. 4), but remains practically unchanged with increasing Φ.

Extrapolation to strains larger than the uniform strain has been carried out with a Hollomon formulation (Eq. 1) taking into account the deformation preceding the onset of necking (maximum in tensile curve in Fig. 4). For first 2% of deformation, linear extrapolation has been used as in Ref. [1]. Parameters are listed in Table 2.

Table 2. Constitutive parameters for extrapolation of tensile curves.

Φ [x10^{23} n.m^{-2}]	K [mPa]	n	yield stress [MPa]
0	870	0.086	565
0.9	833	0.046	670
3.3	843	0.043	680
7.1	859	0.040	700
9.5	880	0.042	720

At the notch root of Charpy specimen, high strain rates occur during deformation (up to ~10^{-3} s^{-1}) [1], which leads to higher stresses comparing with statically loaded specimens. Influence of strain rate was taken into account by strain rate dependency of yield stress, which was assumed as thermally activated process (Eq. 1).

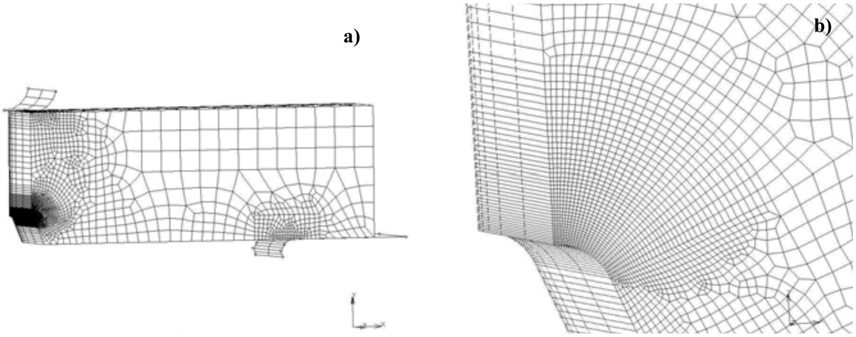

Fig. 3. a) One quarter of Charpy specimen with 3-D mesh used for computation. b) Detail of the notch.

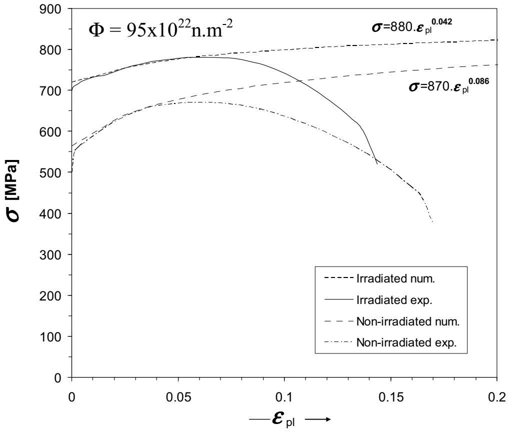

Fig. 4. Extrapolation of stress-strain curve for non-irradiated and irradiated ($\Phi = 95\text{x}10^{22}\text{n.m}^{-2}$) material.

Identification

The results of numerical modeling of Charpy impact test are compared with experimental data in Fig. 5. At the beginning, the identification was done for non-irradiated material (Fig. 5a). The minimum strain rate has been fixed to value 10^{-5} s^{-1}, which we supposed to be enough small to neglect the rate effect. The global response in neutron-irradiated specimen (Fig. 5b) is slightly overestimated, which is in agreement with [9]. Subsequently we made again identification for irradiated material and find out *A* for different neutron fluences. The obtained results are listed in Table 3. From the table is obvious, that the activation volume is increasing with increasing neutron fluence.

Table 3. Identified activation parameters for Charpy specimen.

Φ [x10^{23} n.m^{-2}]	*A*	$\dot{\varepsilon}_0$ [s^{-1}]
0	58	6.47E-31
0.9	85	1.22E-42
2	90	8.19E-45
9.7	100	3.72E-49

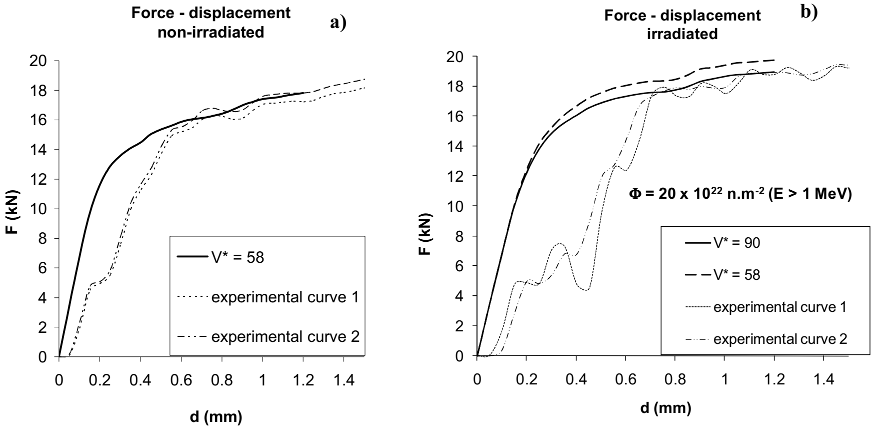

Fig. 5. Experimental and numerical global response for a) non-irradiated and b) irradiated Charpy specimen.

Identified dependencies of the yield stress on strain rate are shown in Fig. 6. I t can be seen, that increase of the yield stress with strain rate is more important in non-irradiated state than in irradiated. Moreover, the increase of the yield stress with strain rate is less important with increasing neutron fluence.

The Fig. 7 shows the stress distribution ahead of the notch root in Charpy specimen (for striker displacement 0.5mm). Neutron irradiation significantly changes the stress distribution ahead of the notch root. The stress level ahead of the notch root (peak value) significantly increases by the neutron irradiation and the location of the stress maximum is slightly shifted far from the notch.

The stress level computed using activation volume identified in non-irradiated state is higher (more conservative) than with activation volume identified in neutron-irradiated state.

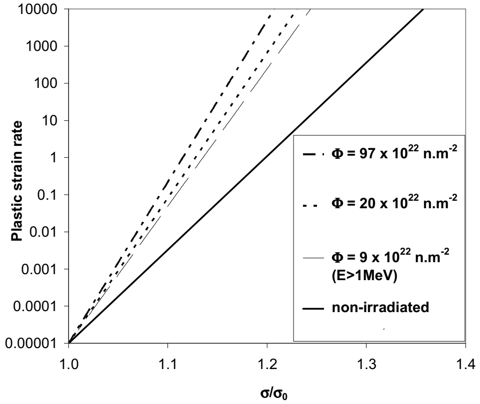

Fig. 6. Plastic strain rate dependence on normalize stress.

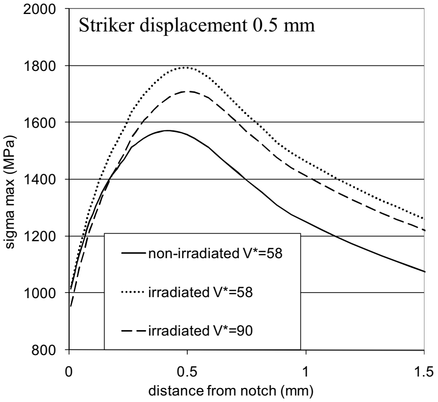

Fig. 7. Stress distribution in the Charpy specimen for striker displacement 0.5mm and neutron fluence.

Summary

Experimental characterization of irradiated 15Ch2MFA steel was carried out by means of tensile and Charpy impact tests.

Numerical modeling was performed using finite element method in order to compute the stress – strain field generated in the Charpy specimen.

Stress – strain relation incorporating strain hardening and yield stress dependency on strain rate based on thermal activation was used.

The activation volume was determined for non-irradiated state and for several different irradiation conditions and it was found to increase with increasing fluency.

It was showed, that maximum of stress distribution next to the notch in Charpy specimen is shifted and increase with irradiation. Using of activation volume identified for non-irradiated material can therefore lead to an overestimation of stress peak value in irradiated material.

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