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Influence of irradiation on the ductile fracture of a reactor pressure vessel steel

Petr Haušild [a,*], Miloš Kytka [b], Miroslav Karlík [a], Pavel Pešek [b]

[a] *Department of Materials, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University, Trojanova 13, 120 00 Praha 2, Czech Republic*

[b] *Integrity and Technical Engineering Division, Nuclear Research Institute, Husinec – Řež 130, 250 68 Řež, Czech Republic*

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Abstract

The mechanical properties of 15Ch2MFA steel were characterised by tensile and instrumented Charpy tests. The fracture surfaces of Charpy specimens broken in the ductile-to-brittle transition temperature range contain a certain proportion of ductile fracture correlated to fracture energy. Measured ductile crack lengths show the same dependence on fracture deflection and/or fracture energy for irradiated and non-irradiated specimens. The decrease of upper shelf energy with increasing neutron fluence could be explained by an increasing amount of shear fracture.

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1. Introduction

The instrumented Charpy impact test is widely employed for determining the ductile-to-brittle transition temperature (DBTT) and for characterization of the neutron induced embrittlement of nuclear reactor pressure vessel steels. The resistance to brittle fracture is one of the decisive factors in the complex safety assessments of nuclear power plants. However, the final (brittle) fracture is frequently preceded by ductile tearing in the DBTT range. Ductile crack growth preceding the unstable cleavage fracture changes significantly the stress–strain field ahead of the notch root or the crack tip (stress, strain and constraint, see e.g. Refs. [1,2]). Therefore, premature ductile crack growth can lead to a sudden increase of the stress ahead of the notch root and consequently, it can lead to the cleavage initiation.

Although there has been an extensive research on the micromechanisms of ductile fracture, only a little has been published about the influence of irradiation on ductile crack growth.

Ductile fracture by dimpled rupture (Fig. 1) occurs in low-alloyed steels in three steps: microvoid nucleation on cracked or debonded second phase particles, microvoid growth, and coalescence of microvoids. There exists a number of theoretical descriptions of cavity nucleation and growth, reviews can be found e.g. in Refs. [3–5]. In previous research of fractured impact and/or static loaded Charpy specimens from A508 Cl.3 reactor pressure vessel steel [1,6], the ductile area situated next to the notch root (after extracting of shear fracture near the lateral faces) was found to be closely correlated

* Corresponding author. Tel.: +420 224358514; fax: +420 224358523.
E-mail address: petr.hausild@fjfi.cvut.cz (P. Haušild).

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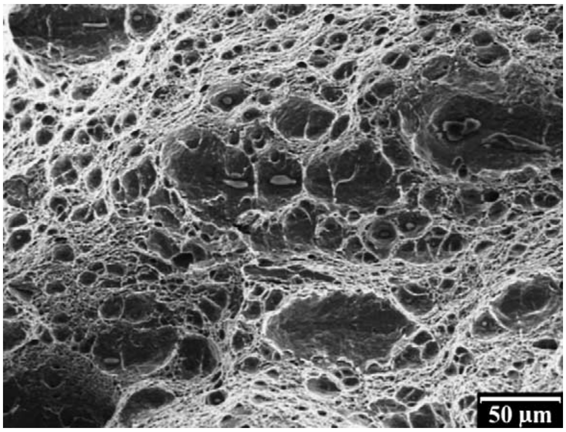

Fig. 1. Ductile fracture of 15Ch2MFA steel (non-irradiated state, SEM). Note the broken MnS inclusions at the bottom of ductile dimples.

with the CVN impact energy even for the areas of surface less than 1 mm^2 (corresponding values of impact energy were lower than 20 J). In the temperature range from −60 °C to 0 °C (DBTT range) and strain rates of 10^{-3} s^{-1} (quasi-static loaded specimens) and 10^3 s^{-1} (impact loaded specimens), the micromechanisms and kinetics of ductile crack growth were found to be the same, independent of temperature and strain rate.

In the presented paper, the influence of neutron irradiation on ductile crack initiation and growth is studied on fracture surfaces of impact loaded Charpy specimens broken in the DBTT range.

2. Experimental details

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

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 VVER440-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}. 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. The measurement of ductile crack length (situated next to the notch root) was carried out on the photographs acquired by a standard CCD camera. The final fracture of the CVN specimens occurred in the DBTT range by cleavage. The cleavage facets reflect the light more than the ductile dimples, which makes possible to distinguish the ductile dimpled zones on the fracture surface (Fig. 2). The

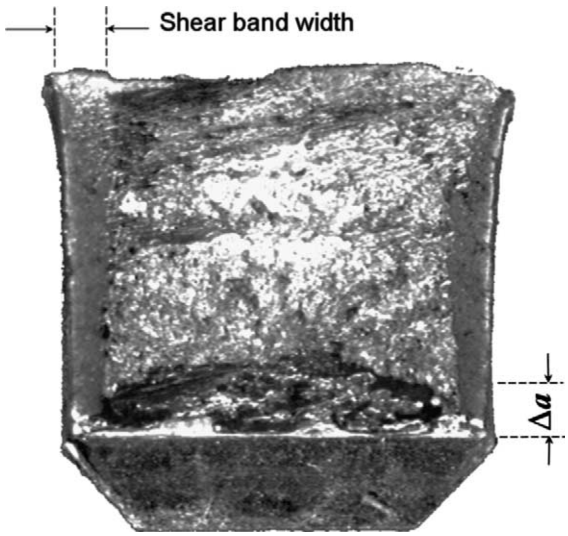

Fig. 2. Fracture surface of an impact loaded CVN specimen broken in the DBTT range. Length of the ductile crack initiated from the notch (dimpled rupture) denoted Δ*a*, shear bands (shear lips) situated at the lateral faces of the specimen.

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

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

ductile crack length was measured as the mean value of crack extensions at nine equally spaced points centred about the specimen centreline (ASTM E1820-99). For non-irradiated specimens, the methodology was confirmed by measurement of ductile crack length in the scanning electron microscope (SEM) Jeol JSM 840.

3. Results and discussion

3.1. Tensile tests

The results of tensile tests of neutron-irradiated and non-irradiated specimens at room temperature are listed in Table 2 and shown in Fig. 3. After irradiation, the yield stress and the tensile strength are increased. The elongation after irradiation is firstly decreased (12.5% after neutron fluence $\Phi_n = 3.3 \times 10^{23}\ \text{nm}^{-2}$ comparing to 17.8% at the non-irradiated state) but increases slightly with increasing neutron fluence (14.5% after neutron fluence $\Phi_n = 9.5 \times 10^{23}\ \text{nm}^{-2}$). This result was not expected since the elongation generally tends to decrease as yield strength increases with increasing neutron fluence.

Table 2
Results of tensile tests of 15Ch2MFA steel before and after neutron irradiation (average value from two tests)

Φ_n (nm^{-2}), $E > 1$ MeV	Yield stress (MPa)	Tensile strength (MPa)	A (%)
0	560	670	17.8
3.3×10^{23}	665	745	12.5
7.1×10^{23}	700	770	13.2
9.5×10^{23}	710	785	14.5

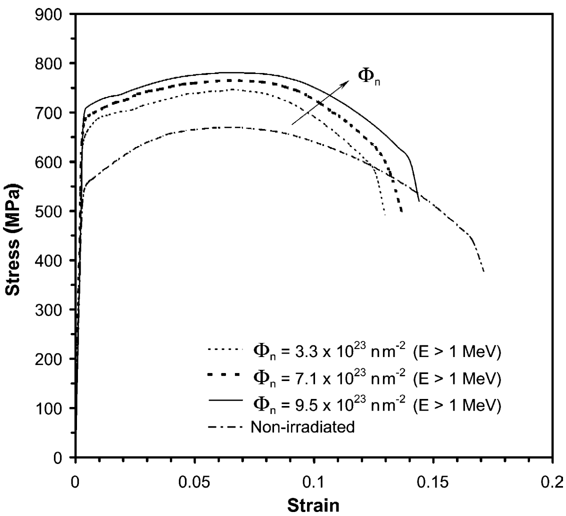

Fig. 3. Results of tensile test of neutron-irradiated and non-irradiated specimens.

The influence of irradiation on hardening can be seen from the fit of the stress–strain curve by the Ramberg–Osgood relationship [8]:

$$\varepsilon = \frac{\sigma}{E} + 0.002\left(\frac{\sigma}{\sigma_{0.2}}\right)^n, \quad (1)$$

where E is the Young modulus, $\sigma_{0.2}$ is an equivalent yield stress at 0.2% elongation, and n a parameter defining the sharpness of the knee of the stress–strain curve.

The values of fitted parameters are listed in Table 3. The hardening exponent n is increased from 12 in the non-irradiated state to 24 after neutron irradiation but remains unchanged after further irradiation dose. Lower hardening rate after irradiation is probably induced by an easier glide after the first dislocation glide through the nanoscale defects generated by neutron damage [9].

3.2. Charpy tests

The results of the instrumented Charpy tests of neutron-irradiated and non-irradiated specimens are shown in Fig. 4. Neutron irradiation caused a shift of DBTT of about 65 °C after neutron fluence $\Phi_n \simeq 10^{24}\ \text{nm}^{-2}$ (similar results have been reported in e.g. [10,11]). Neutron irradiation caused a slight decrease of the upper shelf

Table 3
Ramberg–Osgood parameters of 15Ch2MFA steel before and after neutron irradiation

Φ_n (nm^{-2}), $E > 1$ MeV	$\sigma_{0.2}$ (MPa)	n
0	520	11.8
3.3×10^{23}	650	23.7
7.1×10^{23}	665	24.1
9.5×10^{23}	680	23.9

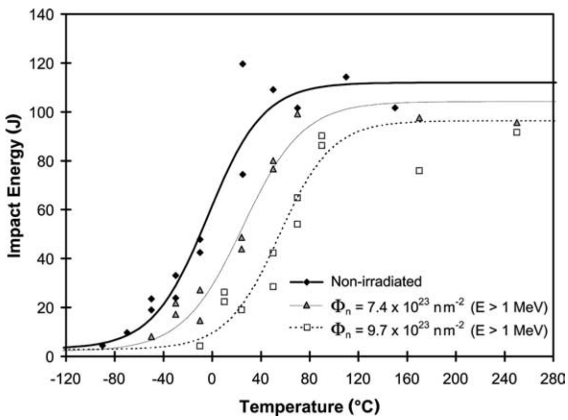

Fig. 4. Transition curve of neutron-irradiated and non-irradiated specimens (Charpy impact tests).

energy from about 110 J in the non-irradiated state to about 95 J after neutron fluence $\Phi_n \simeq 10^{24}\ \mathrm{nm}^{-2}$. The influence of irradiation is illustrated in Fig. 5 on an instrumented test record (tests performed at 25 °C).

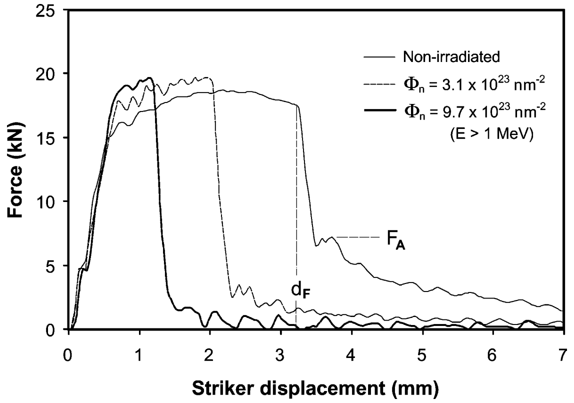

Fig. 5. Instrumented Charpy impact tests data record (filtered signal) of neutron-irradiated and non-irradiated specimens (25 °C). d_F denotes the fracture displacement (striker displacement at brittle fracture initiation) and F_A the force at the crack arrest.

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.

Measured ductile crack lengths Δa are shown in Fig. 6 as a function of the energy absorbed until unstable crack initiation (Fig. 6(a)) and as a function of fracture displacement d_F (Fig. 6(b)). The measured values exhibit a quasi-linear dependence of ductile crack length on the fracture energy; practically the same curves are obtained for neutron-irradiated ad non-irradiated specimens. No significant acceleration in ductile crack initiation or growth with increasing neutron fluence can be noticed in Fig. 6.

Measured shear band widths are shown in Fig. 7 as a function of impact (dial) energy and/or fracture displacement. The measured values exhibit a quasi-linear dependence of the shear band width on the fracture energy and/or fracture displacement. The slope of the dependence of the shear band width on the fracture energy (and/or fracture displacement) increases with increasing neutron fluence. The increasing amount of shear fracture on the fracture surface could eventually contribute to the decrease of the upper shelf energy. In non-irradiated specimens broken completely in a ductile manner, the

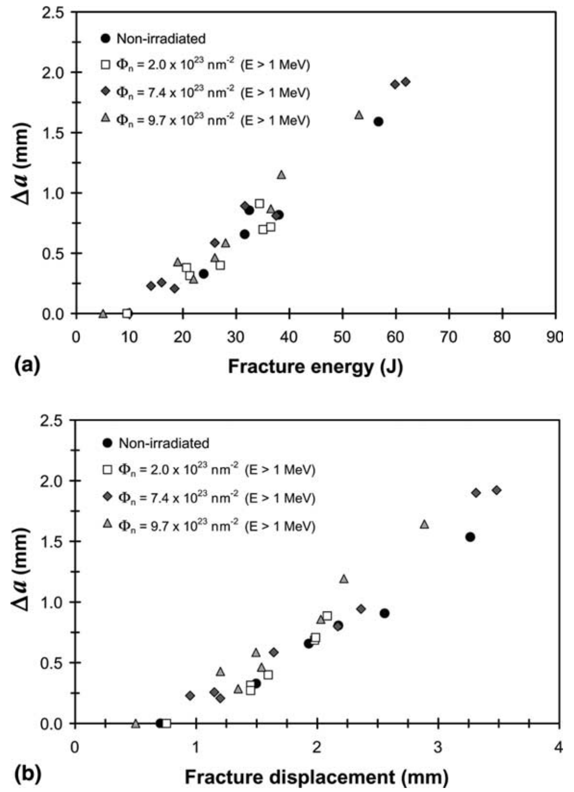

Fig. 6. Measured ductile crack extensions, Δa as a function of energy absorbed until unstable crack initiation (a) and fracture displacement (b).

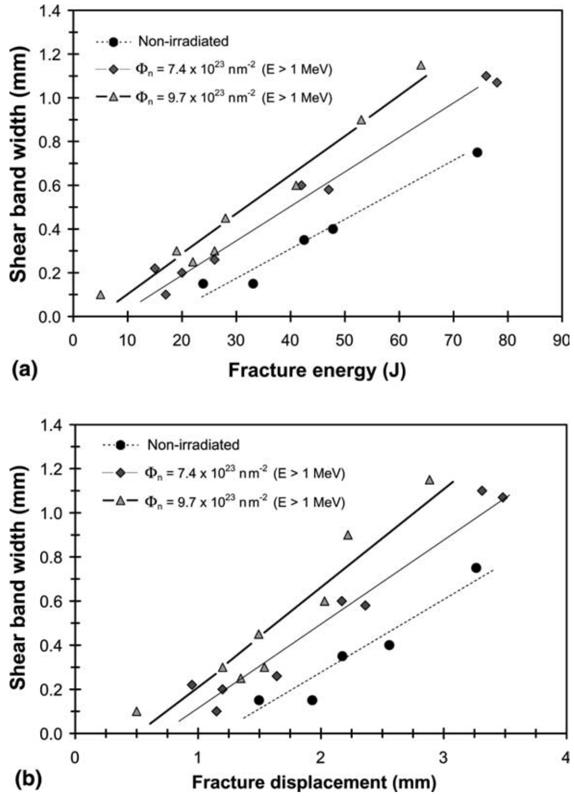

Fig. 7. Measured shear band width as a function of impact (dial) energy (a) and fracture displacement (b).

amount of shear fracture was about 20%. In specimens irradiated by neutron fluence $\Phi_n \simeq 10^{24}\,nm^{-2}$, the amount of shear fracture increased to about 30%. This corresponds quite well to an observed decrease of the upper shelf energy of about 15 J. Nevertheless, it should be noted that non-irradiated and neutron-irradiated specimens with the same impact energy (and/or fracture displacement) belong to different test temperatures.

4. Conclusions

The mechanical properties of non-irradiated and irradiated 15Ch2MFA pressure vessel steels were characterised by means of tensile and instrumented Charpy tests. After irradiation, the yield stress and the tensile strength are increased, but the strain hardening is decreased. The elongation is significantly decreased after irradiation, but slightly increases with increasing neutron fluence.

The instrumented Charpy test revealed a shift of DBTT of about 65 °C after neutron fluence $\Phi_n \simeq 10^{24}\,nm^{-2}$. The results of measurements of ductile crack situated in the zone next to the V-notch of Charpy specimens displayed a high degree of correlation existing between the fracture energy and the ductile crack length. No significant acceleration in ductile crack initiation or growth was observed in the irradiated specimens in comparison with the non-irradiated material. The micromechanisms and kinetics of ductile crack growth are therefore the same (up to given neutron fluences), independent on neutron fluence.

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References

[1] P. Haušild, I. Nedbal, C. Berdin, C. Prioul, Mater. Sci. Eng. A 335 (2002) 164.
[2] A. Rossoll, C. Berdin, C. Prioul, Int. J. Fracture 115 (2002) 205.
[3] S.H. Goods, L.M. Brown, Acta Metall. 27 (1979) 71.
[4] P.F. Thomason, Ductile Fracture of Metals, Pergamon, Oxford, 1990.
[5] H. Riedel, Fracture mechanisms, in: R.W. Cahn, P. Haasen, E.J. Kramer (Eds.), Materials Science and Technology, vol. 6, Wiley, New York, 1992, p. 565.
[6] P. Haušild, I. Nedbal, Kovove Mater. 41 (2003) 270.
[7] J. Koutský, J. Kočík, Radiation Damage of Structural Materials, Materials Science Monographs, vol. 79, Elsevier Science, Amsterdam, 1994.
[8] W. Ramberg, W. Osgood, Description of stress strain curves by three parameters, Technical Note No. 902, National Advisory Committee for Aeronautics, Washington DC, 1943.
[9] G.R. Odette, G.E. Lucas, JOM 53 (7) (2001) 18.
[10] J. Böhmert, F. Bergner, M. Grosse, H.-W. Viehrig, Nucl. Eng. Des. 159 (1995) 131.
[11] J. Böhmert, H.-W. Viehrig, A. Ulbricht, J. Nucl. Mater. 297 (2001) 251.