ESTIMATION OF SHEAR MODULUS OF NEUTRON IRRADIATED INDUCED PRECIPITATES IN RUSSIAN TYPE OF REACTOR PRESSURE VESSEL STEELS

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Introduction

Neutron irradiation produces nanometre-sized defects in reactor pressure vessel (RPV) steels, which causes deterioration of mechanical behaviour known as neutron embrittlement. This phenomenon can be characterized by irradiation induced change of the yield stress, $\Delta\sigma$. Value of $\Delta\sigma$ depends on the dislocation-precipitate interaction mechanism, which is determined by the type of dislocation and properties of the nanometre-sized defects relative to the matrix: chemical composition, size misfit, coherency to matrix, shear modulus and stacking fault energy. Estimation of the shear modulus of precipitates, G_1, relative to shear modulus of matrix, G_2, has been done in our study for neutron irradiated Russian type (RPV) steels VVER-440 BM 15Kh2MFAA and VVER-440 WM Sv10KhMFT. Both steels were irradiated at temperature of 255 ± 5°C with flux $3x10^{16}$ n/m^2s (E > 0.5MeV) up to fluencies $6.7x10^{23}$, 14.6 $x10^{23}$ and 22.8 $x10^{23}n/m^2$ (15Kh2MFAA) and $8.0x10^{23}$, 17.0 $x10^{23}$ and 27.0 $x10^{23}n/m^2$ (Sv10KhMFT) [1]. The chemical composition of investigated steels is given in the Table1.

Tab. 1 - *Chemical composition of the investigated steels, percentage by mass (Fe balance)*

Material	C	Mn	Si	Cr	Ni	Mo	V	S	P	Cu
15Kh2MFAA	0.16	0.54	0.29	2.70	0.07	0.68	0.28	0.18	0.014	0.09
Sv10KhMFT	0.04	1.25	0.64	1.34	0.06	0.50	0.21	0.13	0.014	0.08

The approach to estimate ratio G_1/G_2 is taken from [2]. At the first step the response of the increase of yield stress caused by the maximal matrix damage (MD), $\Delta\sigma_{MD}$, is determined by the combined analysis of positron annihilation spectroscopy (PAS) data on positron mean life time (MLT) and hardness data, $\Delta\sigma$, for irradiation doses great than the critical dose, Φ_c, after that positron MLT doesn't change. At the second step the ratio G_1/G_2 is found according to Russel-Brown model [3] from the data ($\Delta\sigma-\Delta\sigma_{MD}$) and small angle neutron scattering (SANS) data on the mean radius, r, and volume fraction, c_v, of nanometer-sized defects for irradiation doses great than Φ_c.:

$$\left(\Delta\sigma - \Delta\sigma_{MD}\right) = f_s G_2 \left(\frac{b}{L}\right)\left(1-\left(\frac{E_1}{E_2}\right)^2\right)^{0.75} \qquad (1)$$

where f_s is the Schmidt factor about of 2.5; G_2 the shear modulus of iron matrix about of 49GPa; b the Burger's factor about 0.248nm; $L = 1.77r / (c_v)^{0.5}$ the mean distance between the precipitates

$$\frac{E_1}{E_2} = \frac{E_1^{\infty} \log \frac{r}{r_0}}{E_2^{\infty} \log \frac{R}{r_0}} + \frac{\log \frac{R}{r}}{\log \frac{R}{r_0}} \tag{2}$$

Here $r_0 = 2.5b$, the inner cut-off radius, $R = 1000\, r_0$, the outer cut-off radius used to calculate the energy of dislocation, $\frac{E_1^{\infty}}{E_2^{\infty}} = 0.6$.

Results and discussion

PAS data [4] about positron MLT (Figure 1) and PAS data [5] about the irradiation induced defects concentration (Figure 2) point out that Φ_c can be taken about 14.6 $\times 10^{23}$ and 17.0 $\times 10^{23}$ n/m^2 for investigated 15Kh2MFAA and Sv10KhMFT, respectively. SANS data on r, c_v and data on $\Delta\sigma$ [1] are presented in the Table2. According to our calculation ratio G_1 / G_2 is found 0.97 and 0.92 for investigated 15Kh2MFAA and Sv10KhMFT, respectively. According to the shear modulus of iron matrix $G_2 = 79.3$ GPa, we can conclude that $G_1 = 76.9$ GPa for neutron irradiated VVER-440 BM 15Kh2MFAA steel and $G_1 = 73.0$ GPa for neutron irradiated VVER-440 WM Sv10KhMFT steel.

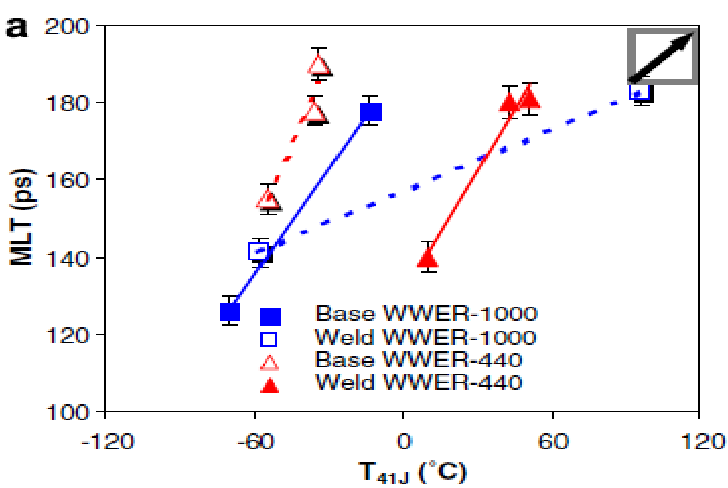

Fig. 1: *Change of the MLT parameter with ductile-to-brittle transition temperature T_{41j}*

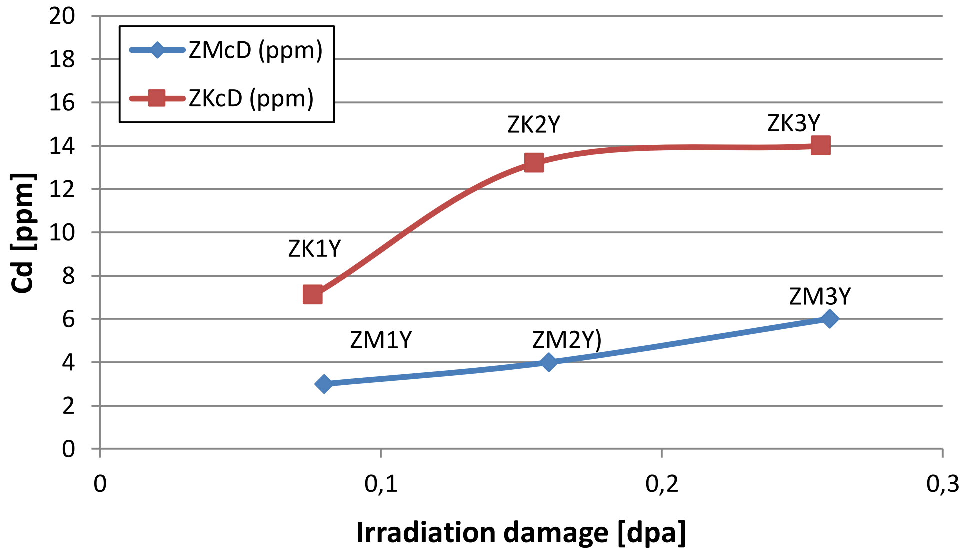

Fig. 2: *The irradiation induced defects concentration Cd at WWER-440 RPV-steel specimens from base (ZM) and weld (ZK) metals after 1,2 and 3 years residence in reactor irradiation chambers in NPP Bohunice (Slovakia)*

Tab. 2 - *SANS and hardness data [1] about microstructure of investigated steels*

Material	Fluence, 10^{23} m^{-2} (E > 0.5 MeV)	R [nm]	c_v [%]	$\Delta\sigma$ [MPa]
15Kh2MFAA	6.7	1	0.043	81
15Kh2MFAA	14.6	1	0.067	160
15Kh2MFAA	22.8	1	0.099	175
Sv10KhMFT	8.0	1	0.048	94
Sv10KhMFT	17.0	1	0.080	141
Sv10KhMFT	27.0	1	0.128	175

The ratios G_1/G_2 about 0.97 and 0.92 for base and weld Russian type of steels in our study are found close to ratios G_1/G_2 about 0.940 and 0.938, which were determined for low and high copper content (0.04 and 0.16wt%Cu) Western type of steels A533B in [2].

The key point of approach [2], used in our study, is an assumption that matrix damage impact into the change of yield stress of RPV steels is dominant one for irradiation doses less than critical dose $\Phi_{c.}$ This statement is need for special agreement with parameterization results of semi-mechanistic analytical model of the radiation embrittlement discussed in [4,6].

Conclusion

1. The ratios of shear modulus of nanodefects in iron matrix to shear modulus iron matrix in Russian type RPV steels can be found according to Russel-Brown model from the combined PAS, SANS and hardness data.
2. Shear modulus of precipitates are 76.9 GPa and 73.0 GPa in neutron irradiated VVER-440 BM 15Kh2MFAA and VVER-440 WM Sv10KhMFT Russian type of steels, respectively.

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References

[1] J. Boehmert, H.-W. Viehrig, A.Ulbricht, Correlation between radiation-induced changes of microstructural parameters and mechanical properties, FZR-380, Juni 2003, Annual Report 2002, Institute of Safety Research, p. 98-103

[2] T. Takeuchi et al., Effects of chemical composition and dose on microstructure evolution and hardening of neutron-irradiated reactor pressure vessel steels, JNM **402** (2011) 93-101

[3] K. G. Russel, L. M. Brown, A dispersion strengthening model based on differing elastic moduli applied to the iron-copper system, Acta Metallurgia, **20** (1972) 969-974

[4] A. Zeman, L. Debarberis, L. Kupcha, *et al*., Study of radiation-induced degradation of RPV steels and model alloys by positron annihilation and Moessbauer spectroscopy, JNM **360** (2007) 272-281

[5] V. Slugen, A. Kryukov, Microstructural study of WWER reactor pressure vessel steels, Nuclear Engineering and Design **263** (2013) 308-312

[6] L. Debarberis, B. Acosta, A. Zeman, *et al*., Effect of irradiation temperature in PWR RPV materials and its inclusion in semi-mechanistic model, Scripta Materialia **53** (2005) 769-773