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Using of SPT method for estimation of mechanical properties changes of RPV steels after irradiation in the Halden reactor

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Abstract: The paper deals with experimentally estimation and comparison of the mechanical properties changes of RPV steels before and after irradiation of samples in Halden reactor in Norway coming from Unit #3 and #4 of NPP Mochovce (still under construction). Altogether 180 SPT and 30 mini-tensile samples in two sets were prepared for irradiation, obtained from weld metal material (Sv10ChMFT) and base material (15Ch2MFA). In general, a good agreement between results obtained by SPT technique and using mini-tensile specimens was found. Both, base and weld metals of RPVs were found to be bainitic. After that, the first set of samples was irradiated in Halden reactor at temperature T_{irr} = 270 - 280°C with intention to use two fluence values: $\sim 1.0 \times 10^{24}$ n/m^2 and $\sim 2.0 \times 10^{24}$ n/m^2 (> 1 MeV), respectively. Specimens after 1st irradiation were successfully tested and preliminary results show small increase of the strength characteristics (R_e, R_m) if compare to "zero condition" testing results. FATTs, evaluated by the temperature dependence of the SPT energy, exhibit transition behaviour and shift towards higher temperatures.

Keywords: small punch test; RPV steels; Halden reactor

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1. Introduction

The reactor pressure vessel (RPV) is the most crucial component of every nuclear power plant (NPP) and continuous evaluation of its mechanical properties is necessary for safe operation. During the standard operation of NPP, RPV is subjected to various types of degradation processes. The wall of the RPV around the reactor core is exposed to high doses of neutron flux and the steel becomes brittle [1]. The neutron radiation causes changes of mechanical properties; in the first place, it is the shift of the ductile-brittle transition temperature towards higher values. Changes of tensile properties and fracture toughness are considerable too. Standard tests require collection of large-dimension samples coming from the precious materials, usually obtained after exposure to radiation. Since samples for SPT testing are quite small, high activity of irradiated materials is no longer an issue. The SPT technique therefore represents a very useful and effective method applied for characterization of mechanical properties such as ultimate tensile strength (R_m), yield stress (R_e) and fracture appearance transition temperature (FATT) [2, 3].

The main aim of the actual VUJE – Halden project includes irradiation and testing of materials from RPVs of unit #3 and unit #4 of NPP Mochovce. These two units are still under construction and the expected start of the operation will be soon. The results of the project are therefore highly relevant for the assessment of the safe operation of both units.

2. Materials and Methods

The principle of SPT testing procedure which has been applied in VUJE is the penetration of a disk shape specimen by a hemispheric rod and recording of loads and deflections during the test. The specimen has 8.00 mm in diameter and 0.50 mm in thickness. The receiving die bore diameter is d= 4 mm, and a punch tip radius r = 1.0 mm. The chamfer edge of the receiving die is recommended to be with radius R=0.2 mm. Polynomial function, as a result of compliance correction measurements, was introduced into system. The testing is performed on a standard tension test machine, equipped with load and crosshead feed gauges and a data recorder for the registration of load-deflection curves. Using relatively simple testing system and with one type of specimen only, it is possible to estimate yield stress and ultimate tensile strength, and fracture appearance transition temperature (FATT) based on the results of temperature dependence of small punch energy determined from the area under the load – deflection curve. The SPT testing procedure is accepted by the Nuclear Regulatory Authority of the Slovak Republic [4] and currently, it is under the process of standardization into the form of both EN and ASTM standards [5].

Altogether 180 SPT and 30 mini-tensile samples in two sets were prepared for irradiation as it is shown in Table 1. Prepared sets consist of two types of bainitic RPV steels: weld material (Sv10ChMFT) and base material

(15Ch2MFA) from two units (#3 and #4) of Mochovce NPP. After irradiation in the Halden reactor, the samples were tested in hot labs of IFE in Kjeller, Norway. Testing and evaluation of samples after their irradiation bring knowledge about irradiation behaviour of these reactor structural steels before putting the units into operation.

Table 1. List of prepared samples.

Material / Marking	**Number of specimens for irradiation 1**		**Number of specimens for irradiation 2**		**Total number of specimens**	
	SPT	Mini tensile	SPT	Mini tensile	SPT	Mini tensile
Weld metal RPV - MO3	22	4	22	3	44	7
Base material RPV - MO3	23	4	23	4	46	8
Weld metal RPV - MO4	22	3	22	4	44	7
Base material RPV - MO4	23	4	23	4	46	8
Total	**90**	**15**	**90**	**15**	**180**	**30**

The irradiation condition requirements were proposed with respect to the irradiation conditions of the surveillance samples program designed by VUJE for Slovak nuclear power plants. The irradiation temperature should be T_{irr} = 270 - 280°C. Melting monitors, placed into special thermometric case, were used to provide information about irradiation temperature. They were made of eutectic alloys with specific chemical compositions (usually contain Pb, Ag, and Sb) correspond to exact melting temperature. After all, the melting (i.e. reaching melting temperature of alloy) was evaluated by visual control. By the melting monitors the irradiation temperature of the first capsule was identified above 282.6 °C and below 292°C. The neutron fluence is planned to two different levels: $F_1 = 1.0 \times 10^{24}$ n/m^2 – comparable to one campaign of irradiation in the power reactor – marked as "Irradiation 1" (tested in June 2017); and $F_2 = 2.0 \times 10^{24}$ n/m^2 – comparable to three campaigns of irradiation in the power reactor – marked as "Irradiation 2" (to be tested in May 2018).

The properties of the experimental materials in the initial state were also described in [6]. Table 2 summarizes chemical compositions of used experimental materials. Both, base and weld metals of RPVs are bainitic steels. Typical microstructures are shown in Figure 1a, b.

Table 2. Chemical composition of used materials.

Material	**Element content [mass. %]**										
	C	**Mn**	**Si**	**P**	**S**	**Cr**	**Ni**	**Mo**	**V**	**Cu**	**Co**
BM3	0.160	0.54	0.32	0.010	0.010	2.87	0.09	0.69	0.30	0.045	0.005
WM3	0.042	1.10	0.55	0.010	0.011	1.36	---	0.55	0.20	0.060	0.003
BM4	0.150	0.52	0.29	0.009	0.013	2.69	0.03	0.67	0.31	0.043	0.005
WM4	0.032	1.04	0.63	0.009	0.010	1.35	---	0.55	0.20	0.050	0.005

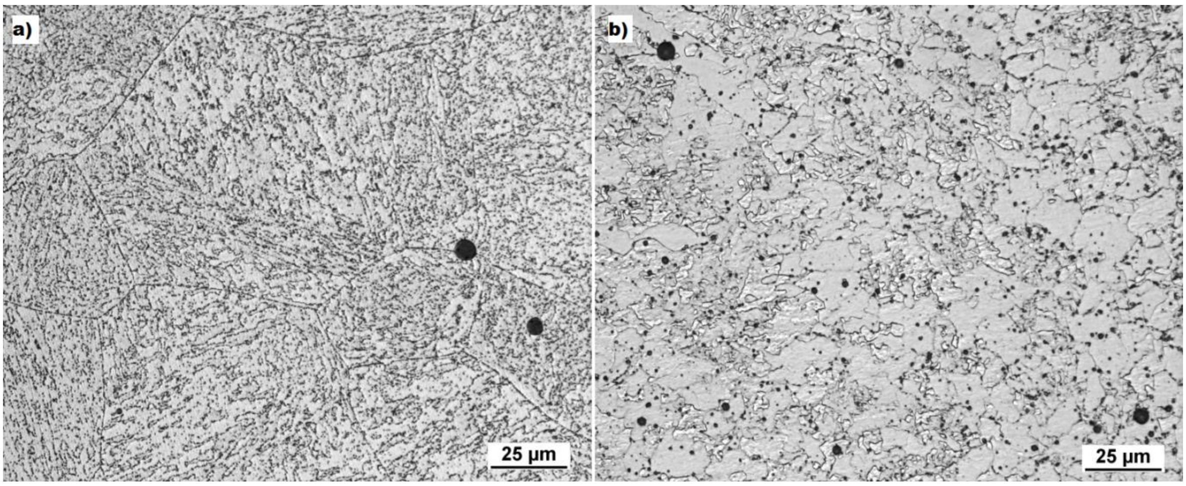

Figure 1. Microstructure of (**a**) base metal and (**b**) weld metal.

3. Results and Discussion

3.1. Tensile properties

Testing results of SPT and mini-tensile specimens before and after 1st irradiation in the Halden reactor are summarized in Table 3. The table shows the yield stress (R_e) and the ultimate strength (R_m) for each material. For determine Rm and Re, linear correlation functions $R_e(Rp_{02}) = \beta.F_e/h^2$ and $R_m = \beta.F_m/(h.u_m)$ were used, where β stands for empirical coefficient, h is initial specimen thickness, and u_m corresponds to displacement. Tensile properties were tested at the room temperature. The values R_e and R_m in Table 3 are the average values of three measurements. Graphical representations of the results given in Table 3 are in Figures 2a-d being chosen as the most convenient to emphasize trend in mechanical properties values.

Table 3. Mechanical properties before and after 1st irradiation.

Material	Initial state				After 1st irradiation			
	SPT		Standard		SPT		standard	
	R_e [MPa]	R_m [MPa]	R_e [MPa]	R_m [MPa]	R_e [MPa]	R_m [MPa]	R_e [MPa]	R_m [MPa]
BM3	470	569	478	601	527	598	557	654
WM3	485	620	490	606	504	629	519	620
BM4	457	600	495	547	526	675	539	653
WM4	509	609	467	590	511	636	507	612

From the Table 3 and Figures 2a-d it is possible to specify trend of base and weld metals in terms of mechanical properties values (Rm, Re). It was found that irradiation leads to a slight increase in strength characteristics, especially in case of base materials, and results obtained by SPT and standard method correlate with each other very well.

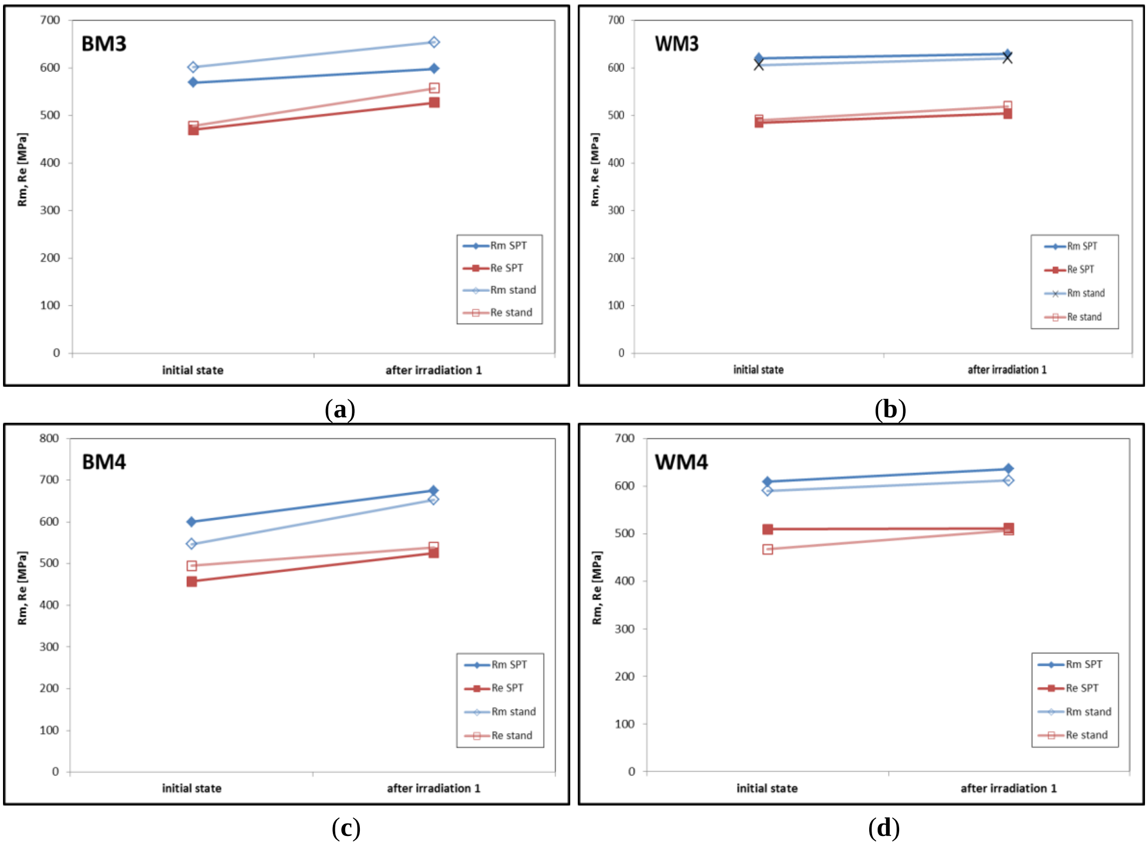

Figure 2. Tensile properties of RPV materials before and after irradiation; (**a**) base metal EMO 3, (**b**) weld metal EMO 3, (**c**) base metal EMO 4, (**d**) weld metal EMO 4.

3.2. Transition temperature and fracture properties

The values of the transition temperatures (FATT) evaluated by the temperature dependence of the SPT energy are listed in Table 4. Energies are obtained from SPT tests at various test temperatures for all evaluated materials. The SPT energy is calculated from a single load-deflection curve needed to deform and crack the SPT sample. By doing this for several different temperatures, the TT_SPT was constructed. This curve consists of two fits, the first one describes the brittle and transition regime (lower energy plateau corresponds to or is extrapolated to a temperature of 50 K), and the second one the ductile regime. Exponential and power functions are used. The intersection of the two curves (upper energy plateau) marks the maximum of the fitted energy, E_{max}. The SPT transition temperature is then defined as temperature where $DBTT_{SPT} = (SP_{max} + SP_{min})/2$. For comparison of the SPT results, TT_{KCV50} and TT_{FATT} values from standard Charpy-V tests in the initial state are given, where TT_{KCV50} stands for transition temperature determined by Charpy-V test for 50 J/cm^2, TT_{FATT} is transition temperature determined by Charpy-V test for 50% of brittle fracture, and TT_{SPT} represents transition temperature determined by SPT.

Table 4. SPT and standard results of transition temperature evaluation for RPV materials.

Material	**Initial state**			**After 1st irradiation**
	SPT	standard		SPT
	TT_{SPT} [°C]	TT_{FATT} [°C]	TT_{KCV50} [°C]	TT_{SPT} [°C]
BM3	- 20.2	- 24.7	- 39.6	+ 12.1
WM3	- 18.0	- 16.0	- 23.2	+ 31.5
BM4	- 2.9	- 59.4	- 86.0	+ 15.6
WM4	+ 14.9	+ 13.2	- 12.4	+ 19.9

The obtained temperature dependences of the SPT energy for all tested materials are illustrated in Figures 3a-d.

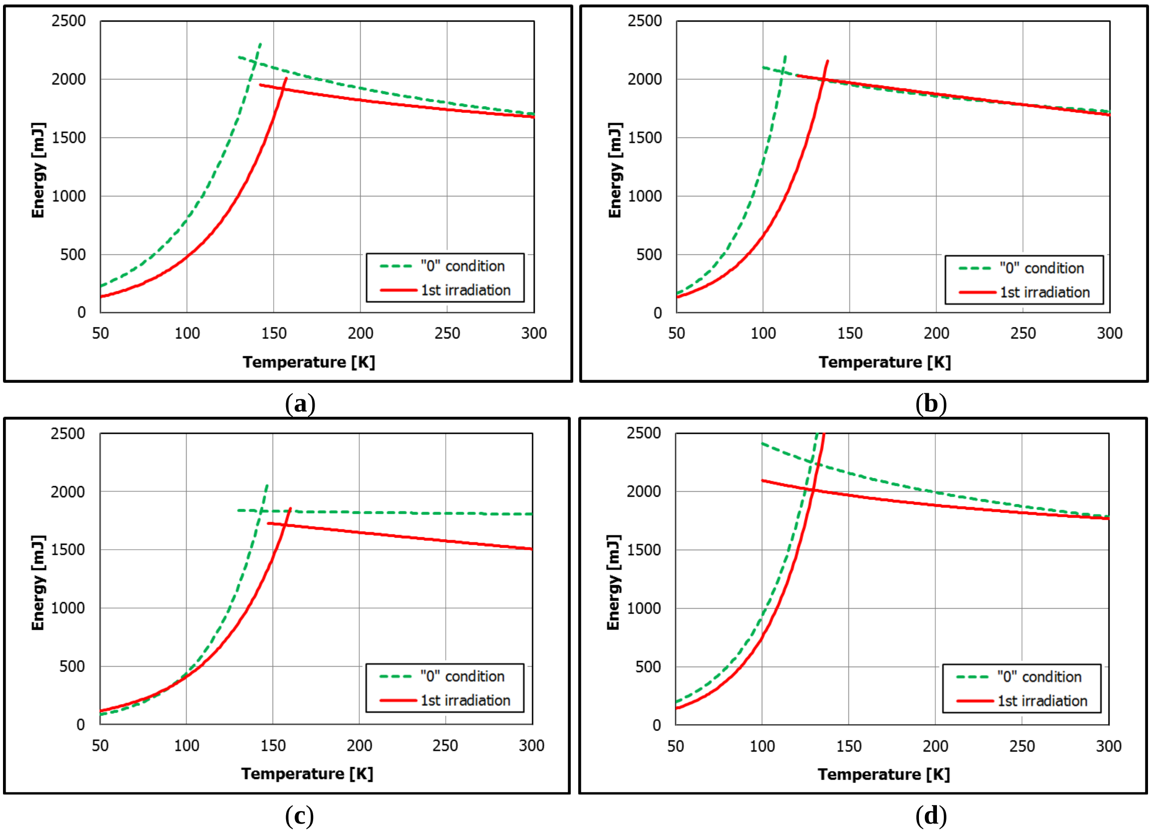

Figure 3. Temperature dependence of the SPT energy for RPV before and after 1st irradiation; (**a**) BM3, (**b**) WM3, (**c**) BM4, (**d**) WM4.

4. Conclusions

The results can be summarised as follows:

- All SPT specimens, as well as mini-tensile specimens after 1st irradiation in the Halden reactor, were successfully tested and obtained values evaluated.
- A small increase in the strength characteristics of all materials after their irradiation in the Halden reactor was observed.
- Good agreement between the results obtained by SPT technique and using mini-tensile specimens was confirmed.
- Neutron irradiation was found to shift of TT_{FATT} towards higher temperatures for base and weld metal.
- The presented results are only preliminary, after the evaluation of the second capsule they will be completed and the current VUJE - Halden project will be finalized.

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