Comparison of irradiated 15Kh2MFA material mechanical properties using conventional testing methods and innovative approach of small punch testing (SPT) and automated ball indentation (ABIT)

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Abstract. Article describes two innovative testing methods – Small Punch Testing (SPT) and Automated Ball Indentation Test (ABIT) – which are based on the determination and evaluation of material properties from miniaturized testing specimens. These methods are very promising due to minimum material needed for testing and also in case of testing highly irradiated materials of components that are not included in standard surveillance programs. The test results were obtained for reactor pressure vessel (RPV) base material 15Ch2MFA in both states - initial unirradiated and irradiated. Subsequently results were compared with standard tensile tests to prove applicability of these testing methods for the evaluation of degradation of irradiated structural materials of nuclear power plants.

1 Introduction

Current trend of the extension of the nuclear power plant (NPP) components operational lifetime requires precise information of the structural materials degradation for the assurance of safe and reliable long-term operation. Special attention should be paid to the verification of integrity and strength of materials of hardly replaceable components of the nuclear power plant's primary circuit such as reactor pressure vessel and internals.

Evaluation of the mechanical properties in the present conventional way is usually based on the relatively high consumption of the testing materials, whose availability is often very limited and in several cases archive materials are not available completely. Several years ago, UJV Rez, Integrity and Technical Engineering Division started to pay considerable attention to the employment of perspective semi-destructive testing techniques in the process of irradiated NPP structural materials degradation evaluation – small punch tests and automated ball indentation testing. These methods are valuable for the determination of mechanical properties without affecting the overall integrity of evaluated component and their semi-destructive approach in connection with the small volume of material necessary for the testing. This approach allows focusing on the locations of the operated component which are subject to higher stresses, neutron flux or thermal ageing.

2 Testing methods – fundamentals

Small punch test method is based on the testing of thin clamped specimens using hemispherical punch or ball with the direct measurement of the specimen deflection on the opposite side of the specimen. Example of test data and the scheme of the test setup are shown on the Fig. 1. Obtained results can be correlated with standard tensile test results and this technique can be also used for the determination of fracture toughness properties and ductile to brittle transition temperature (DBTT).

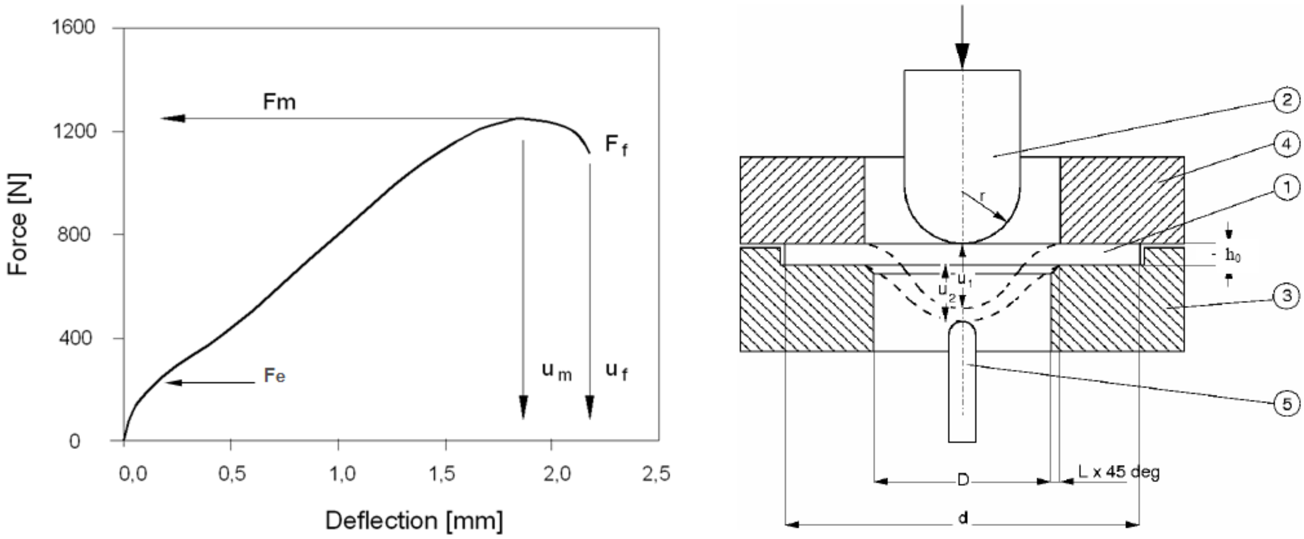

Figure 1. Example of test data (left), scheme of the test setup (right).

Automated ball indentation testing is based on the principle of strain controlled multiple indentations at a single penetration location on a polished surface by a small hemispherical indenter (various diameters from 0.508 to 2.5 mm) [1]. Instrumented test method is fully automatic and does not require the diameter of the indentation to be measured after testing. Scheme of the indent [2] and example of the test result is shown on the Fig. 2.

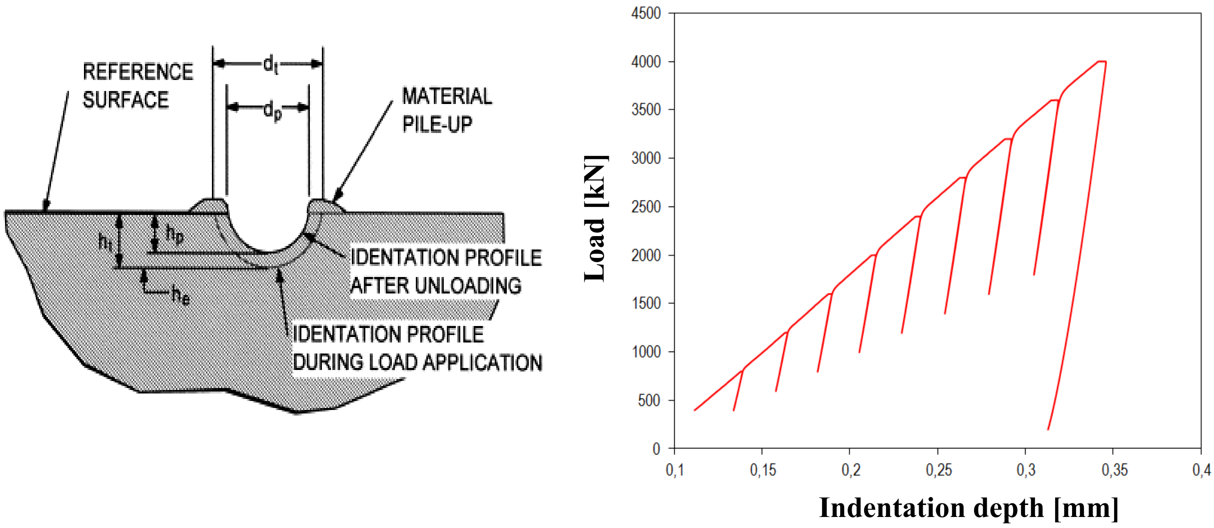

Figure 2. Scheme of the indent during the test (left), example of test data (right).

To determine the applicability of chosen test methods to the irradiated materials it was necessary to perform preparatory and supporting activities, e.g. finite element modelling and metallography of chosen material. FEM analyses, employed into process of ABI testing, were essential to determine the minimal necessary thickness of testing material in the terms of the plastic deformation affected zone size. Acquired results were also beneficial to determine the minimal distance of indents from the edge of the testing specimens due to the fact that most of the experimental work was performed on the standard Charpy type specimens. Metallography analyses in initial and irradiated state of material were performed mainly to determine that testing material has sufficiently fine grain structure to fulfill the recommendation to have at least 6 grains per diameter of the indenter.

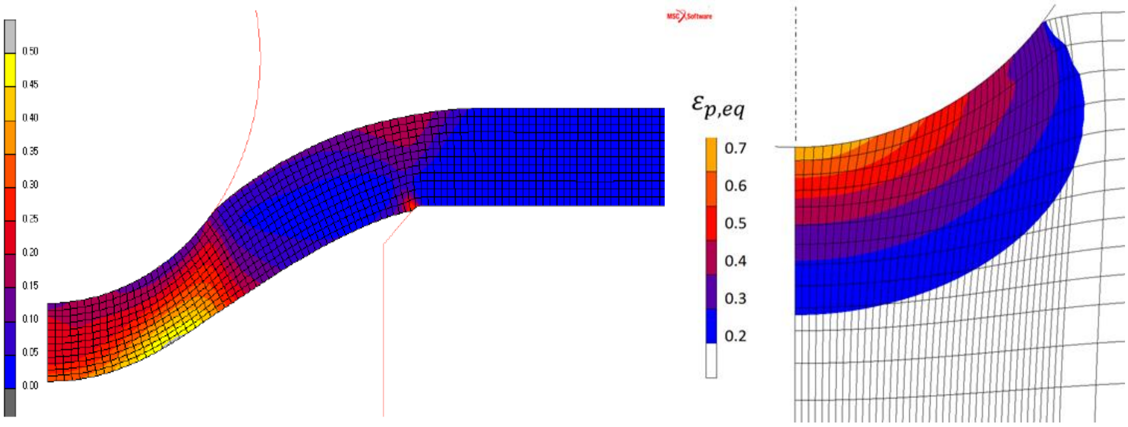

Figure 3. Examples of FEM analyses results for SPT (left) and ABI testing (right).

3 Testing results

3.1 Static tensile tests results

One of the first steps within the testing was to prepare data base of standard static tensile tests results for subsequent preparation of correlations with perspective methods of semi-destructive testing, SPT and ABIT.

For the realization of tests were machined tensile testing specimens with 4 mm diameter and 22 mm gauge length in the transverse orientation in original block of material. Tests were carried out at room temperature and +265 °C in accordance with the ISO 6892 [3, 4] using video extensometer for precise measurements of elongation. Results are summarized in the table 1.

Table 1. Tensile test results for the correlation with SPT and ABIT.

Number of specimens	Test Temperature [°C]	Neutron fluence (E > 0.5 MeV) [10^{18} cm^{-2}]	Average $R_{p0,2}$ [MPa]	Average R_m [MPa]
3	24	unirradiated	525	646
3	265	unirradiated	469	549
3	24	65.7	663	747
3	265	65.7	571	668

3.2 Small punch tests results

Small punch tests were carried out on the electro mechanical testing machine INSTRON in accordance with CWA15627 [5] document on the round specimens with the diameter of 8 mm and thickness of 0.5 mm (prepared with electric discharge machining and polishing).

Evaluated yield strength data were obtained from the SPT, by empirical correlations between SP and standardized test results based on the UJV Rez large database of ferritic base materials. It was observed that the nature of the load – deflection curve (Fig. 1) varies significantly with the specimen thickness h_0. The effect of test specimen thickness can be eliminated by correlating yield stress with parameter Fe/h_0^2. Results of tests are summarized in table. 2

Table 2. Results of Small Punch Testing (SPT).

Number of specimens	Test Temperature [°C]	Neutron fluence (E > 0.5 MeV) [10^{18} cm^{-2}]	Average $F_e/(h_0)^2$ [MPa]	Average $R_{p0,2}$ [MPa]	Average $F_m/(u_m .h_o)$ [MPa]	Average R_m [MPa]
15	24	unirradiated	843	510	2311	655
15	265	unirradiated	1029	495	1871	563
3	24	65.7	1999	660	3112	755
3	265	65.7	1577	588	2268	624

3.3 Automated ball indentation tests results

Experimental data were evaluated in several steps. For the yield strength assessment, for each loading cycle was determined force and the depth of indent h_t during load application (Fig. 2). From the depth of indent parameter d_t is calculated (idealized diameter of contact area) and is defined by the formula (1):

$$d_t = 2 \cdot \sqrt{h_t \cdot D - h_t^2} \qquad (1)$$

All data points of the dependence are fitted by a curve defined by the Mayer's law (2) -parameter A with the Mayer's index m is determined from the linear regression:

$$\frac{P}{d_t^2} = A \cdot \left(\frac{d_t}{D}\right)^{m-2} \qquad (2)$$

Parameter A is used for the calculation of yield strength approximation (3), where β_m is the parameter for evaluated material:

$$R_{p0,2}(APR) = \beta_m \cdot A \qquad (3)$$

Final value of the yield strength is calculated from the formula (4), where parameters a and b are determined by the calibration for the evaluated type of material.

$$R_{p0,2} = a + b \cdot R_{p0,2}(APR) \qquad (4)$$

For the ultimate strength evaluation, for each load cycle is determined a pair of values εp and σt where εp is logarithmic plastic deformation and σt is proportional to the actual stress in one-dimensional homogeneous deformation. If the resulting stress-strain curve is expressed by the exponential equation (5) it is possible to use obtained strain hardening coefficient K and strain hardening exponent *n* to estimate the ultimate strength approximation (6).

$$\sigma_t = K \cdot \varepsilon_p^n \qquad (5)$$

$$R_m(APR) = K \cdot \left(\frac{n}{e}\right)^n \qquad (6)$$

Calculation of the ultimate tensile strength is carried out in an analogous manner as for the yield strength (7), where parameters c and d are determined by the calibration for the evaluated type of material.

$$R_m = c + d \cdot R_m(APR) \qquad (7)$$

Evaluated results of ABI testing for both unirradiated and irradiated specimens were correlated with the results from standard tensile testing. Summarized results for the various types of indenter diameters are summarized in the Table 3.

Table 3. Results of Automated Ball Indentation (ABIT).

Test Temperature [°C]	Indenter Diameter [mm]	Neutron fluence (E > 0.5 MeV) [10^{18} cm^{-2}]	Average $R_{p0,2}$ [MPa]	Average R_m [MPa]
24	2.500	unirradiated	488	612
	1.575	unirradiated	484	638
	0.762	unirradiated	489	632
	0.508	unirradiated	512	633
265	1.575	unirradiated	434	559
	0.762	unirradiated	444	552
24	2.500	65.7	554	693
	0.762	65.7	572	694
265	2.500	65.7	461	572
	0.762	65.7	477	591

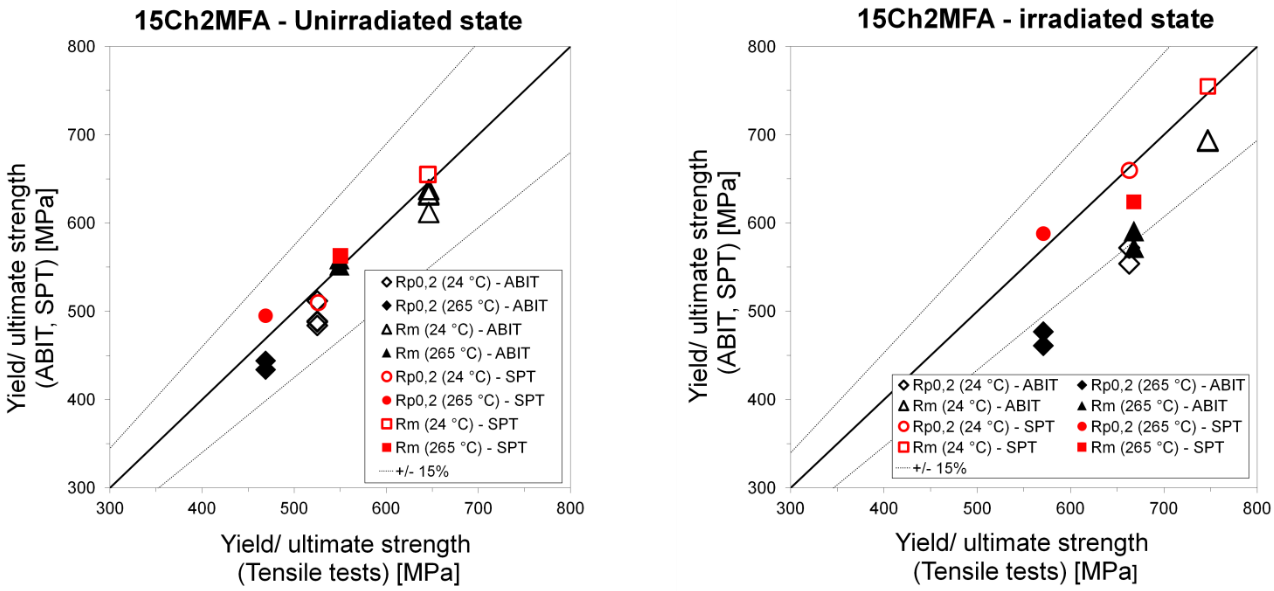

Figure 4. Correlation of standard tensile test results with the results of SPT and ABIT in initial unirradiated state (left) and irradiated state (right).

4 Conclusions

Based on obtained results on the 15Ch2MFA base material, correlations between standard tensile test and ABI tests was prepared as well as correlation with Small Punch test results (Fig. 4).

Both semi-destructive testing methods showed to be very promising for assessment of structuralirradiated NPP materials degradation. Evaluated results of ABIT and SPT show very good correlation with results from standard tensile testing.

At present, for the employment of the method into standard portfolio of laboratory test techniques is necessary to enlarge the experimental data volume for different types of used indenters, materials and to perform testing in temperature wider range from -190 °C to +350 °C.

Acknowledgement

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