CHARACTERISATION OF MECHANICAL PROPERTIES USING THE INSTRUMENTED HARDNESS TEST METHOD

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Abstract

Monitoring the mechanical properties changes is very important to assure structural integrity of NPP components, especially within the context of their operational life extension. Determination of current mechanical properties of several structural materials of NPP components, especially reactor internals, is not possible using the standard testing methods, in connection with the material volume necessary for the testing. In comparison with reactor pressure vessel, reactor internals are usually not covered by the system of surveillance samples as well as other hardly replaceable components of the primary circuit, e.g. primary piping, steam generator etc. Sampling of the optimal material volume usually brings adverse consequences of affecting the integrity of component or in several cases destruction of the whole evaluated component. For standard size specimens, it is also necessary to take into account the high activity of the material, with influence on the collective dose of hot cell facilities personnel. Aim of this work is to present the advantages of the semi-destructive testing method (instrumented hardness test method) in the process current mechanical properties evaluation of the hardly replaceable long-term operated NPP components. Instrumented hardness test method is a semi-destructive testing method for direct measurement of mechanical and fracture properties of materials including yield strength, ultimate tensile strength (UTS), strain hardening exponent, and fracture toughness. Semi-destructive testing techniques use technological processes and equipment enabling the direct determination of mechanical properties from the component surface without affecting its integrity. Advantage of semi-destructive degradation mechanisms quantification could be very promising for use in the field of nuclear energy for components of NPP as well as in other industrial sectors, e.g. chemical and petrochemical industry.

Keywords: mechanical properties, nuclear power plants, instrumented hardness test method

1. INTRODUCTION

Facility – general overview

From 1970, ÚJV Řež, a. s., Division of Integrity and Technical Engineering, operates the fleet of 51 hot cells situated on the 3 floors of the Radiochemistry building. In the first period of operation until 1978, considerable attention was paid to verifying operational abilities of fuel elements. After the year 1980, most of activities are focused on the determination of degradation of NPP irradiated structural materials, especially from WWER components. At present, the main purpose of the facility is to support the Czech (Dukovany NPP, Temelín NPP), Slovak and several Ukrainian NPP`s within the frame of their reactor pressure vessel surveillance programs. Besides the portfolio of standard accredited mechanical tests (impact testing, fracture toughness, etc.) the laboratory is also focused on the development of innovative testing methods and their employment in the determination of irradiated material operational degradation. The instrumented hardness test method (ABI – automated ball indentation test method) is a non-destructive testing method for direct measurement of mechanical and fracture properties of the materials including yield strength, ultimate tensile strength (UTS), strain hardening exponent, and fracture toughness [1]. ABI testing is based on multiple indentations by a spherical indenter at same test location. Testing is automated, rapid and localized, and allows determination of the true stress versus true strain characteristic of metallic materials having matching and comprehensive strength properties [2]. The ABI test is particularly useful where a life extension evaluation is planned for a component and the materials property data are not available. Also, it can be used to measure properties for materials that may have service damage that has caused a change in tensile properties during service life (e.g. neutron embrittlement of nuclear pressure vessels). Another important application is the determination of yield strength of ferritic steel components, such as oil and gas pipelines, when documentation exists for the original or the repaired material and when deterministic fitness-for-service evaluation is required for safe operation at current or higher pressures [3]. The ABI test is a macroscopic/bulk technique that measures the properties on a small volume of material. This capability is valuable in mapping out property gradients in welds and HAZs (heat affected zones). The minimum diameter of the indenter must be large enough such that the spherical indentation, produced at the smallest practical depth/strain, covers at least three grains of the metallic sample. This requirement is the same for the minimum thickness of a tensile specimen in order to measure macroscopic/bulk properties. The ABI technique can be used to measure the stress-strain properties of the material that may have a sharp gradient of mechanical properties [2,3]. This, for example, exists in a weldment where the base metal and weld metal have different strength and ductility and the HAZ may have a very sharp gradient of properties. This paper presents results of the project *"Development of innovative semi-destructive method of high active material evaluation for nuclear reactor components lifetime assessment".* The proposed project is dedicated to the use of instrumented hardness testing methods for evaluation of the current mechanical properties of the long term operated hardly replaceable components of nuclear power plants - especially the components of the reactor and the primary circuit. The use of this method is enabled by the existence of technological processes and devices that allow the acquisition of a small amount of test material from the surface of component while maintaining the integrity and strength of material, eventually directly in the tested component using equipment with remote control during reactor outage. The benefits of semi-destructive quantification of degradation mechanisms can be used especially in the field of nuclear energy for evaluation of nuclear power plants irradiated components structural materials degradation, but also in other industrial areas, such as the chemical and petrochemical sector [2, 4, 5]. The main goals of the project are obtain a sufficient database of results from instrumented hardness tests as well as standard mechanical tensile and impact notch toughness test supplied by fractographic analysis of highly irradiated structural materials of nuclear reactor components and of other materials from difficulty replaceable components of nuclear power plant primary circuit subjected to environmental degradation. These results will be used to check the theoretical formulae and for the evaluation of the empirical correlations between of the standard tests and the instrumented hardness tests for assessment of property degradation of these materials during operation using specimens cut off from these components. Evaluate a certified procedure for testing and evaluation of instrumented hardness tests for determination of the effect of operation degradation on structural materials of critical nuclear reactor and primary circuit components from specimens cut off from these components during operation and apply this certified procedure on the assessment of lifetime of highly irradiated operating components of nuclear reactors and primary circuit components.

2. EXPERIMENTAL

2.1 Material

The steel 15Kh2MFA was chosen for the experiments (tempered bainitic steel used for the fabrication of pressure vessels of WWER 440-type nuclear reactors). The chemical composition of the steel 15Kh2MFA is shown in Tab 1.

Tab.1 Chemical composition of the steel 15Kh2MFA

	C	Mn	Si	P	S	Ni	Cr	Mo	V
min.	0.13	0.30	0.17	-	-	-	2.50	0.60	0.25
max.	0.18	0.60	0.37	0.025	0.025	0.40	3.00	0.80	0.35

This paper describes the correlations of conventional test methods with innovative testing method obtained for the non-irradiated material 15Kh2MFA in the circumferential and longitudinal orientations of the original block of material, at testing temperatures of 24 °C and 265 °C.

2.2 Tensile test results

The first step of experimental part was to prepare a database of standard static tensile test results for the subsequent correlation with the results of the instrumented hardness test. For the realization of the tensile tests, tensile test specimens were machined from the original block of the material 15Kh2MFA. Tensile test specimens with a 4 mm diameter and a 22 mm gauge length in the 2 orientations: C – circumferential, L – longitudinal. Standard tensile tests were carried out at temperatures of 24 °C and 265 °C, in accordance with ISO 6892 using a video extensometer for precise measurements of the elongation. The results of the tensile tests are summarized in Tab. 2. The experimental temperatures were chosen to enable a comparison with the tensile test results from surveillance program in the future.

Tab. 2 Results of the tensile tests (15Kh2MFA, circumferential and longitudinal orientation)

Number of Specimens	Test Temperatures [°C]	Orientation	Average $Rp_{0,2}$ [MPa]	Average Rm [MPa]	Used for correlation
3	24	L	502	603	ABI
3	265	L	470	550	ABI
3	24	C	526	647	ABI
3	265	C	469	549	ABI

2.3 Instrumented hardness test results

The method is based on multiple instrumented indentations at a single penetration location on a polished surface by a spherical indenter of various diameters (from 0.508 to 2.5 mm) [2]. The scheme of the indentation profile duting and after force removal is illustrated in Fig 1. Each cycle consists of indentation, unload and reload sequences (an example of the results obtained by ÚJV Řež, a. s., is shown in Fig. 2). A series of instrumented indentations were carried out using a 2.5 mm diameter and a 1,575 diameter tungsten carbide spherical indenter on an electro-mechanical testing machine INSTRON 5967 (modified to 10kN load in 30 kN reinforced frame). For the purpose of this project, an electro-mechanical testing machine INSTRON 5967 was installed into a semi-hot cell. The spherical indenter displacement was measured by a high sensitivity linear variable differential transformer (LVDT) extensometer RDPE lin 56. This transducer was used for the displacement/position measurement. It makes an accurate position measurement of the movement of the armature relative to the body of the displacement transducer. The LIN differential-inductance LVDT is inductive (similar to a LVDT sensor) and because there is no contact across the sensor element it is very robust. This sensor has been selected for high temperature, high pressure and high nuclear radiation position measurement applications. For the purpose of this project, a device to load the samples in the thermal chamber was developed (Fig. 3). Test specimens for instrumented hardness test, with 10 x 10x 55 mm gauge length in 2 orientation: C – circumferential, L –longitudinal, were made from original block of material 15Kh2MFA.

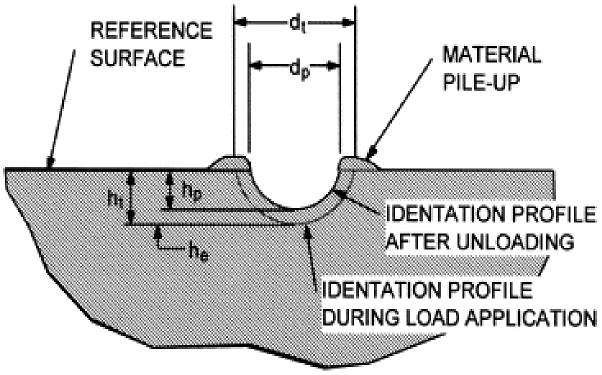

Fig. 1 ABI test indentation profile during force application and after force removal (complete unloading) [1]

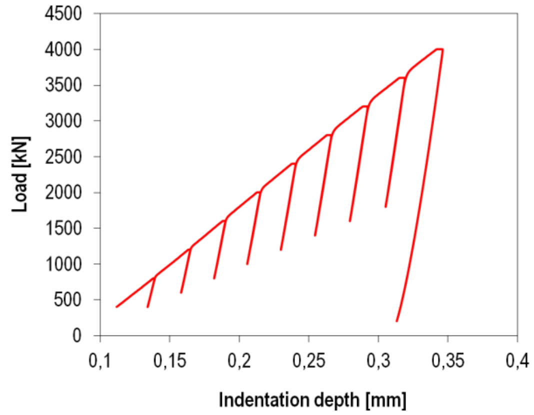

Fig. 2 Example of a multi – cycle ABI test record – loading diagram, ÚJV Řež, a. s.

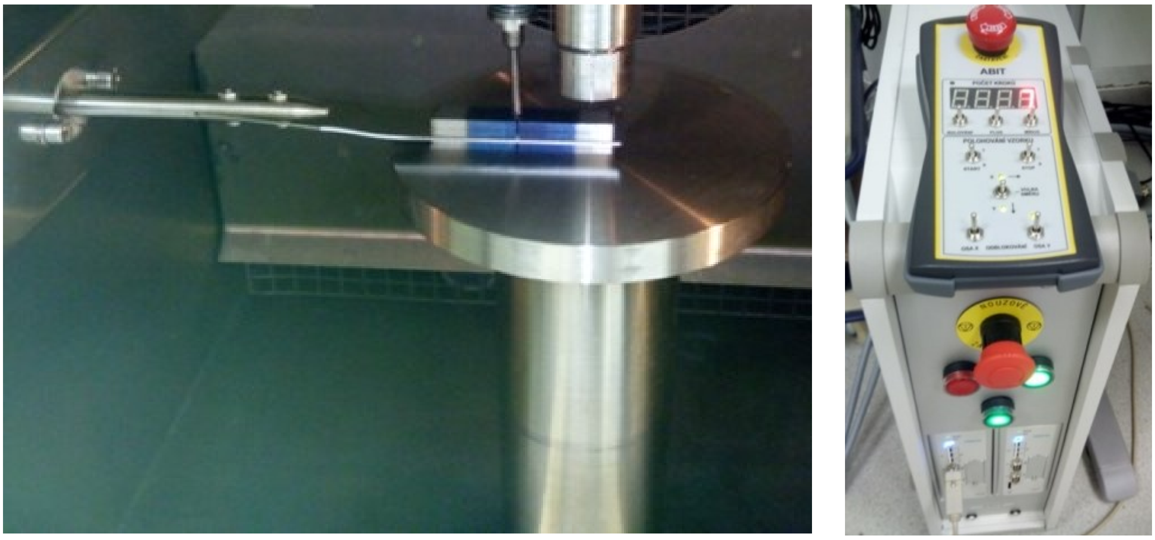

Fig. 3 Device to load the samples in thermal chamber, ÚJV Řež, a. s.

Tab. 3 The results of instrumented hardness tests (15Kh2MFA steel, circumferential and longitudinal orientation), testing temperatures 24 °C and 265 °C, spherical indenter 2,5 mm

Number of Specimens	Test Temperatures [°C]	Orientation	Average $Rp_{0,2}$ [MPa]	Average Rm [MPa]	Indenter ø [mm]
3	24	L	484	599	2,5
3	265	L	335	483	2,5
3	24	C	486	595	2,5
3	265	C	352	495	2,5

Tab. 4 The results of instrumented hardness tests (15Kh2MFA steel, circumferential and longitudinal orientation), testing temperatures 24 °C and 265 °C, spherical indenter 1,575 mm

Number of Specimens	Test Temperatures [°C]	Orientation	Average $Rp_{0,2}$ [MPa]	Average Rm [MPa]	Indenter ø [mm]
3	24	L	500	630	1,575
3	265	L	403	531	1,575
3	24	C	498	648	1,575
3	265	C	401	542	1,575

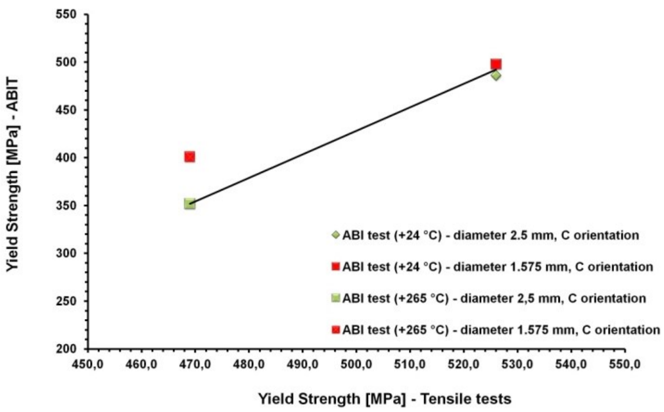

Fig. 4 Correlations of the yield strength of instrumented hardness tests results with the standard tensile tests results (15Kh2MFA, circumferential orientation)

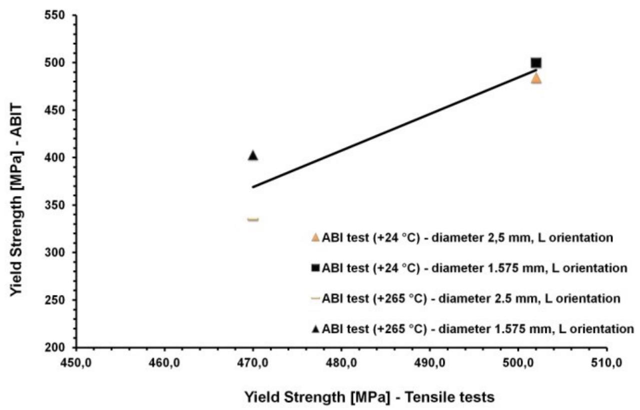

Fig. 5 Correlations of the yield strength of instrumented hardness tests results with the standard tensile tests results (15Kh2MFA, longitudinal orientation)

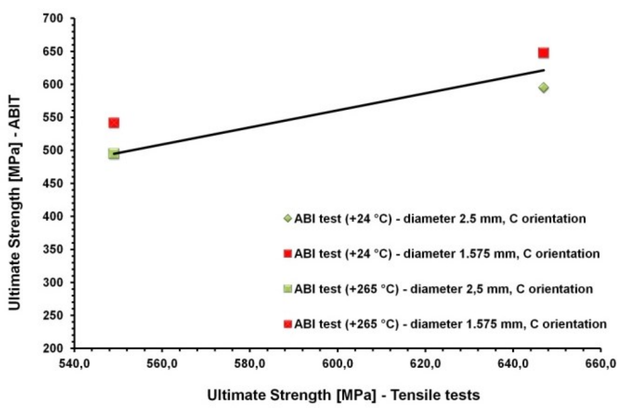

Fig. 6 Correlations of the ultimate strength of instrumented hardness tests results with the standard tensile tests results (15Kh2MFA, circumferential orientation)

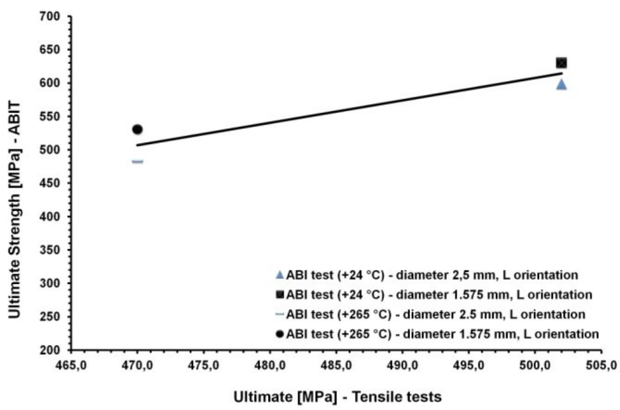

Fig. 7 Correlations of the ultimate strength of instrumented hardness tests results with the standard tensile tests results (15Kh2MFA, longitudinal orientation)

3. CONCLUSION

Based on the obtained yield strength $R_{p0.2}$ and R_m values of the base material 15Kh2MFA, a correlation between the standard tensile test and instrumented hardness test results was obtained. The preliminary results suggest that the instrumented hardness test method is promising in the assessment of structural NPP materials degradation. The results from instrumented hardness test differed depending on the indenter diameter. This paper presents a comparison of the results from instrumented hardness tests and tensile tests (Fig. 4 - 7) for the two experimental temperatures: 24 °C – room temperature and 265 °C of a WWER 440. For both temperatures (24 °C, 265 °C), good correlations of $R_{p0.2}$ (Fig. 4 - 5) and R_m (Fig. 6 - 7) were obtained for the indenters of 2.5 mm and 1.575 mm in diameter. At present, it is necessary to enlarge the experimental data volume for different types of used indenters, materials (irradiated and non-irradiated) and to perform testing at a wide range of temperatures. Finishing of these activities will enable the correlations to be improved. The main goal of future research is to obtain a sufficient database of results from the instrumented hardness tests as well as standard mechanical tensile and impact notch toughness tests of highly irradiated structural materials of nuclear reactor components and of other materials from difficulty replaceable components of nuclear power plant primary circuit subjected to environmental degradation. Instrumented hardness test was carried out in accordance with draft standard ISO/TC 164/SC 1N675. In this time, standard specification does not exist. ABI test method has a good potential to be standardized.

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REFERENCES

[1] MURTY K.L., MIRAGLIA P.Q., MATHEW M.D., SHAH V.N., HAGGAG F.M., Characterization of gradients in mechanical properties of SA-533B steel welds using ball indentation. International Journal of Pressure Vessels and Piping, Vol. 76, 1999, pp. 361-369

[2] ISO/TC 164/SC 3 N1109: NWIP of ISO-TC 164-SC 1 – Test Methods for Automated Ball Indentation (ABI) Testing of Metallic Samples and Structures to Determine Tensile Properties and Stress-Strain Curves, 2012

[3] P.HAUŠILD; A. MATERNA; J. SIEGL; M. KYTKA; R. KOPŘIVA: Characterization of Local Stress-Strain Behaviour in WWER 440 WELD and Base Metal by Instrumented Indentation Technique, ISSN 1013-9826, Key Engineering Materials Vol. 606 (2014), pp 15-18, Trans Tech Publications, Switzerland

[4] F. M. Haggag: In-Situ Nondestructive Measurements of Key Mechanical Properties of Pressure Vessels Using Innovative Stress-Strain Microprobe (SSM) Technology, Final Report DOE/ER/82115-1, 1997

[5] F. M. Haggag; G. E. Lucas: Determination of Lüders Strains and Flow Properties in Steels from Hardness/Microhardness Tests, Metallurgical Transactions A, Vol. 14A, 1983-1609