APPLICATION OF SMALL PUNCH TEST FOR MONITORING THERMAL AGEING OF AUSTENITIC PRIMARY-CIRCUIT PIPING MATERIAL

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Abstract

Long-term operation of nuclear power plants requires reliable monitoring of thermally aged materials while minimizing the amount of removed material. This paper presents the application of the Small Punch Test (SPT) as an additional mechanical testing method for monitoring the properties of austenitic main circulation piping material. The initial properties of the unexposed material were determined by a combination of standard mechanical tests and SPT performed on discs with a diameter of 8 mm and a thickness of 0.5 mm in accordance with EN 10371. The SPT methodology was used to determine yield strength and ultimate tensile strength from characteristic forces on the load–displacement curve and to determine fracture-related SPT energy as the integral under the curve up to specimen perforation. The tensile properties derived from SPT are in good agreement with the results of standard tensile tests. The presented dataset demonstrates that SPT can be used not only as a supplementary tool, but as an effective method for long-term surveillance programs with limited material availability.

Keywords: Small punch test, austenitic steel, main circulation piping, thermal ageing

1. INTRODUCTION

Evaluation of the mechanical properties of the main circulation piping (MCP), one of the most important components of any nuclear power plant (NPP), is essential for ensuring its safe long-term operation [1]. Main circulation piping in the primary circuits of pressurized water reactors is manufactured from austenitic steels. During operation, these materials are exposed to elevated temperatures for decades, which may lead to gradual microstructural changes and, consequently, to changes in their mechanical properties. Therefore, long-term programs monitoring the thermal ageing of primary circuit materials also focus on tracking and comparing changes in thermally aged materials with respect to unexposed materials.

A major challenge in the evaluation process, however, is obtaining enough material required for the preparation of standard test specimens for conventional mechanical testing. One solution is the complementary Small Punch Test (SPT) method, which uses miniaturized test specimens. SPT is a miniaturized technique employing thin disc specimens loaded by a hemispherical punch until failure. It is an attractive method for long-term monitoring, especially when only a limited amount of material is available.

To obtain the most representative results, the SPT method is also combined with standard methods for testing material properties in the so-called initial condition. This paper summarizes the basic results for the unexposed base material of the MCP, which were also obtained within the SAMO-LTO project.

2. EXPERIMENTAL

Samples of BM of MCP for microstructural investigations were cylinders with 8 mm in diameter and height of 6 mm. Metallographic samples were prepared by standard preparation line and etched by electrochemical etching for the light microscopy and for the SEM-observation. The microstructure was recorded using the light microscope NIKON ECLIPSE MA200 with implemented AI-model for grain size evaluation and the scanning electron microscope JEOL JSM-IT210 device equipped with an EDS-detector, at an acceleration voltage of 20 kV.

Standard tensile testing was carried out at 20 °C and evaluated in accordance with STN EN ISO 6892-1, using a total of 6 test specimens. Miniaturized specimens with dimensions of d0 = 4 mm and a gauge length L0 = 16 mm were used for the tests. The tests were performed on a servo-hydraulic testing machine Instron 3 73.

The SPT (Small Punch Test) were conducted in accordance with the European standard EN 10371:2021, following an accredited procedure in the laboratories of VUJE, a.s. The SPT tests were performed on a LaborTech LabTest 5.10ST testing machine equipped with a load cell, crosshead displacement sensor, strain gauge, and a data acquisition system for recording the parameters load force – displacement relationship during loading.

In general, the SPT method is based on a punch with a hemispherical punch or ball which is pushed through a clamped disc specimen along its axis (**Figure 1**). The SPT is displacement-controlled, i.e. the punch is pushed at constant velocity of the cross head through the specimen and the force required to keep the punch moving is measured as a function of punch displacement (at the punch tip) or specimen deflection (measured on the opposite side of the contact point between the punch and the specimen) [2-9].

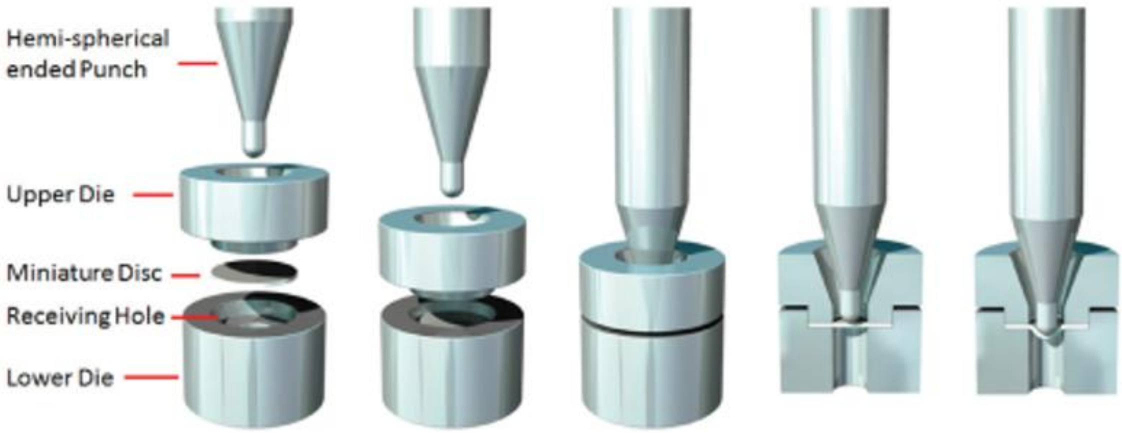

Figure 1 Schematic of a SPT

The testing can be performed on a standard tensile testing machine, equipped with a load and deflection recording device for the registration of load-deflection curves [10]. Special testing rigs, depending on the testing temperature are used for the realization of SPT test. The samples are machined from material blocks by electrical discharge machining (EDM) and subsequently polished with abrasive papers up to fine grinding P1200 to obtain required thickness. The polynomial function, because of compliance correction measurements, is introduced into the system. The tests at low temperatures (up to -185 °C) are carried out using special automatic liquid nitrogen dosing system controlled by a software algorithm.

The testing conditions applied in VUJE (listed in **Table 1**) were chosen according to the procedure accepted by the Nuclear Regulatory Authority of the Slovak Republic [8] and EN 10371 standard [9].

Table 1 SPT testing parameters

Specimen	Test piece diameter [mm]	8 ± 0.1
	Test piece thickness [mm]	0.5 ± 0.005
	Min. test pieces/material	3 pcs
Geometry	Punch tip diameter [mm]	2.5
	Receiving hole edge [mm]	R 0.2
Testing conditions	Temperature [°C]	23 ± 2
	Moment (torque) [Nm]	10
	Measured parameters	force- deflection
	Load rate [mm.m^{-1}]	0.5

3. EXPERIMENTAL MATERIAL

The investigated material represents an unexposed MCP base material with the nominal chemical composition listed in **Table 2**.

Table 2 Chemical composition of main circle pipe base material 08Ch18N12T

Element	**C**	**S**	**Mn**	**Si**	**P**	**Cu**	**Ni**	**Cr**	**Mo**	**V**	**Ti**	**Nb**	**W**	**Co**
required BM – MCP	max. 0.08	max. 0.02	max. 2.0	max. 0.80	max. 0.035	max. 0.30	11.0 – 13.0	17.0 – 19.0	-	-	0.5 – 0.6	-	-	max. 0.2
BM – MCP	0.050	0.003	1.730	0.450	0.015	0.099	12.100	18.070	0.09	0.058	0.36	0.018	0.013	0.031

By comparing the above values listed in **Table 2**, it can be concluded that the measured chemical composition is consistent with the specified values and corresponds to the chemical composition of the given steel grade and, most likely, also to the same material heat.

Figure 2 shows a light micrograph of the examined steel. The microstructure of the base material consists of typical polyhedral austenite with a relatively high fraction of annealing twins, a minimal amount of δ-ferrite, secondary phases, and non-metallic inclusions.

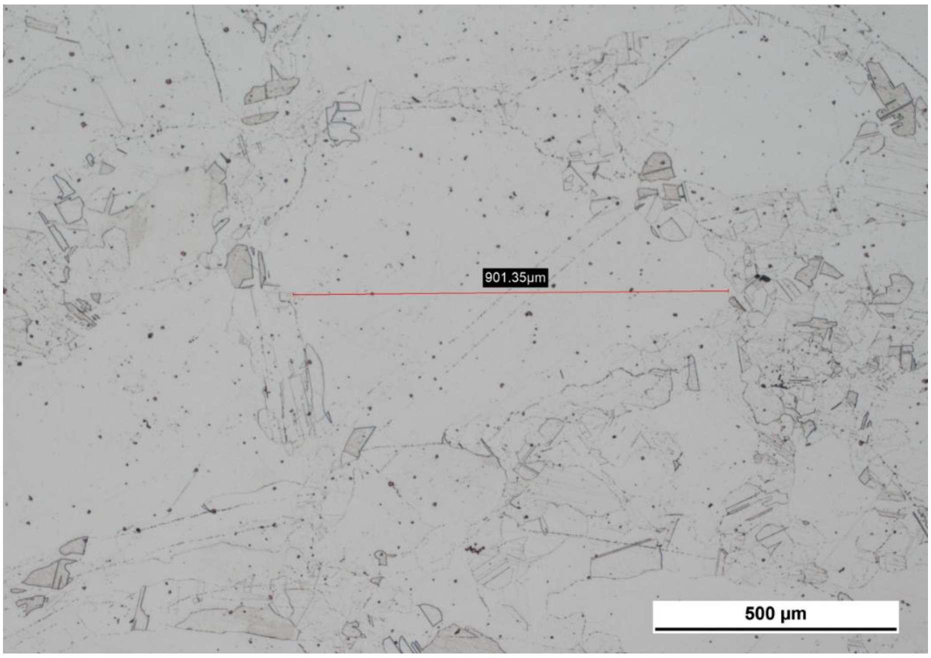

Figure 2 Light micrograph showing the microstructure BM of MCP

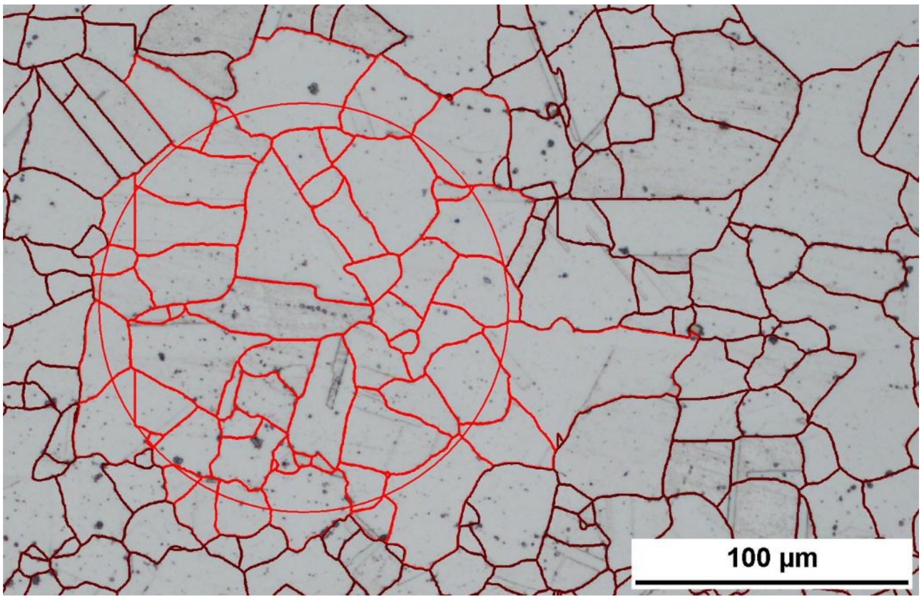

Figure 3 Grain size measurement

The average grain size was evaluated using an image analyser in accordance with STN EN ISO 643. The average grain size of the base material was determined to be 64 µm (G = 4). A high degree of grain size heterogeneity can also be observed. Fine-grained regions reach a grain size level of G = 8 (**Figure 3**) with an average grain length of approximately 10 µm, whereas the largest grains reach up to approximately 900 µm (**Figure 2**).

4. RESULTS AND DISCUSSION

The following chapter compares the tensile properties of the BM MCP obtained from the standard tensile tests with the tensile properties derived from the SPT. Standard tensile tests provided average values of $R_{p0.2}$ = 251.7 MPa and R_m = 546.5 MPa at 20 °C as the **Table 3** summarizes. **Figure 3** shows the measured values together with the minimum limits specified by the manufacturer. The properties derived from the SPT at 20 °C were R_m = 537 ± 11 MPa and $R_{p0.2}$ = 314 ± 2 MPa.

Table 3 Comparation of standard tensile values and SPT tensile values

Test (20 °C)	Standard R_m	SPT R_m	Standard $R_{p0,2}$	SPT $R_{p0,2}$
R_m / $R_{p0,2}$ (MPa)	546,5	537 ± 11	251,7	313,91 ± 2

The R_m and $R_{p0,2}$ value measured by the SPT is very similar to the R_m and $R_{p0,2}$ value obtained from the standard tensile test, which confirms a good agreement for the ultimate tensile strength (**Figure 4**). However, a higher $R_{p0.2}$ value was obtained from the SPT compared to the result of the standard tensile test, which indicates that the yield strength correlation is sensitive to the calibration constants derived from the standard.

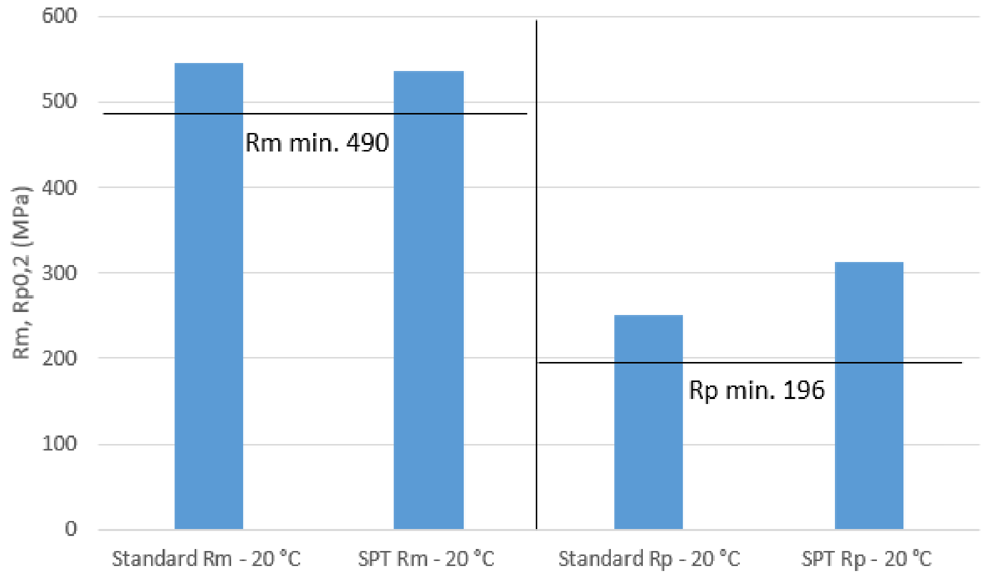

Figure 4 Comparation of standard and SPT tensile values

Minor deviations in yield strength values were expected given the material's grain size heterogeneity. Improving the accuracy of the complementary SPT method and the use of more precise calibration constants within the framework of the SPT standard for these types of materials is one of the long-term objectives of the laboratories of VUJE, a.s.

5. CONCLUSION

The presented results confirm that the Small Punch Test (SPT) can be successfully applied as a complementary method for the evaluation of the mechanical properties of unexposed austenitic main circulation piping base material. The ultimate tensile strength derived from the SPT showed very good agreement with the results obtained from the standard tensile tests, confirming the applicability of this method for long-term monitoring programs.

From a practical point of view, the obtained dataset represents an important reference initial state for future comparison with thermally aged material. The combination of standard tensile testing and SPT in the initial condition provides a suitable basis for further monitoring of property changes during long-term operation.

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