

MONITORING OF STEAM PIPELINE MATERIAL DEGRADATION USING SMALL PUNCH TEST (SPT) METHOD

¹ Ondřej DORAZIL, ¹ Miroslav FILIP, ¹ Zdeněk KUBOŇ

¹ Material and Metallurgical Research Ltd., Czech republic, EU, ondrej.dorazil@mmvyzkum.cz,
miroslav.filip@mmvyzkum.cz, zdenek.kubon@mmvyzkum.cz

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Abstract

Long-term operation of steam pipelines in power plants, due to high temperatures and pressures, leads to gradual material degradation and changes in mechanical properties. Therefore, it is necessary to apply appropriate diagnostic methods to assess the current condition of the material and estimate the residual service life of the pipeline.

This paper focuses on the application of the Small Punch Test (SPT) method to monitor changes in material properties of steam pipelines during periodic inspections. The SPT method enables the determination of characteristic parameters of mechanical behavior using small samples extracted from components in service.

The study analyses the evolution of material properties as a function of operating time and discusses their relationship with degradation processes occurring in the microstructure during long-term exposure to elevated temperatures. The results contribute to a more accurate estimation of the residual service life of pipelines and to the optimization of operational monitoring strategies.

Keywords: Small Punch Test, Degradation of Materials, Steam Pipelines, Residual Service Life

1. INTRODUCTION

This paper deals with a comprehensive assessment of the degradation of material properties of steam pipelines after long-term operational exposure significantly exceeding the design life. A key aspect of the diagnostics was the use of the Small Punch Test (SPT), which represents a suitable tool for monitoring changes in the mechanical behavior of components without the risk of violating their structural integrity. To obtain the experimental material, a special sampling device was used, which allows semi-destructive sampling of material directly from operating units while creating miniature test specimens. The work analyses in detail the correlations between the operating time, the kinetics of microstructure degradation due to high temperatures, and the resulting mechanical properties. The results of the study demonstrate that the implementation of the SPT methodology into diagnostic plans significantly improves the prediction of residual life and enables effective optimization of operational monitoring strategies for critical energy equipment.

2. HISTORICAL DEVELOPMENT AND STANDARDIZATION OF THE METHOD

Small method Punch Test (SPT) was originally developed in the 1980s, primarily for the needs of the nuclear industry, where there was a requirement to evaluate radiation embrittlement of materials from very small sample volumes. Over time, the use of SPT has expanded to the classical energy and petrochemical industries, especially for monitoring components operating in the creep range, where minimal intervention in the device design and the absence of subsequent repairs is also advantageous. A key milestone in the European context was the publication of the CWA 15627 document [1] in 2007, which laid the foundations for

the standardization of testing, which was subsequently followed by the current ČSN EN 10371 [2] standard from 2021, defining precise procedures for performing and evaluating SPT.

The company MATERIALOVY A METALURGICKY VYZKUM s.r.o. (MMV s.r.o.) played a significant role in the development of this methodology both in the Czech republic and internationally, with active involvement in the issue of miniaturized test specimens since the 1990s. Long-term research and subsequent orientation to the SPT method resulted in a number of professional publications and the successful introduction of the methodology into industrial practice in the evaluation of critical components of energy units [3].

3. MATERIAL COLLECTION PROCESS AND EVALUATION OPTIONS

The sampling locations are determined by an authorized person (e.g. technologist or designer) regarding operating conditions, stress characteristics, or design limitations. Periodic sampling of experimental material for SPT diagnostics of the pumping life of a steam pipeline takes place at specified/recommended time intervals. The case described concerns a repeated investigation of the current material characteristics of a high-pressure steam pipeline, which is operated at a temperature of 450 °C and a pressure of 4.6 MPa for 380,000 hours. The nominal size of the steam pipeline is 273 mm x 16 mm and was made of steel 15 111 [4]. The locations investigated on the high-pressure steam pipeline are shown in **Figure 1**.

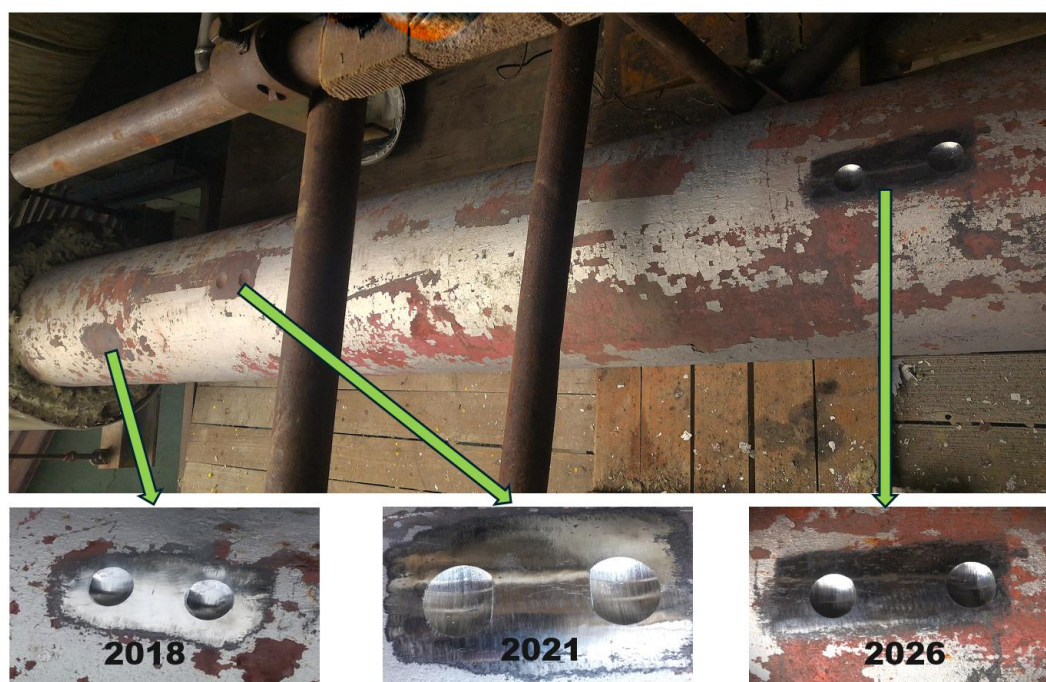


Figure 1 Experimental sampling locations in individual years

The principle of taking experimental material using a special sampling device consists of grinding off the intermediate layer of material between the sample being taken and the rest of the part using a rotating hat-shaped tool with a thickness of about 0.7 mm (**Figure 2**).

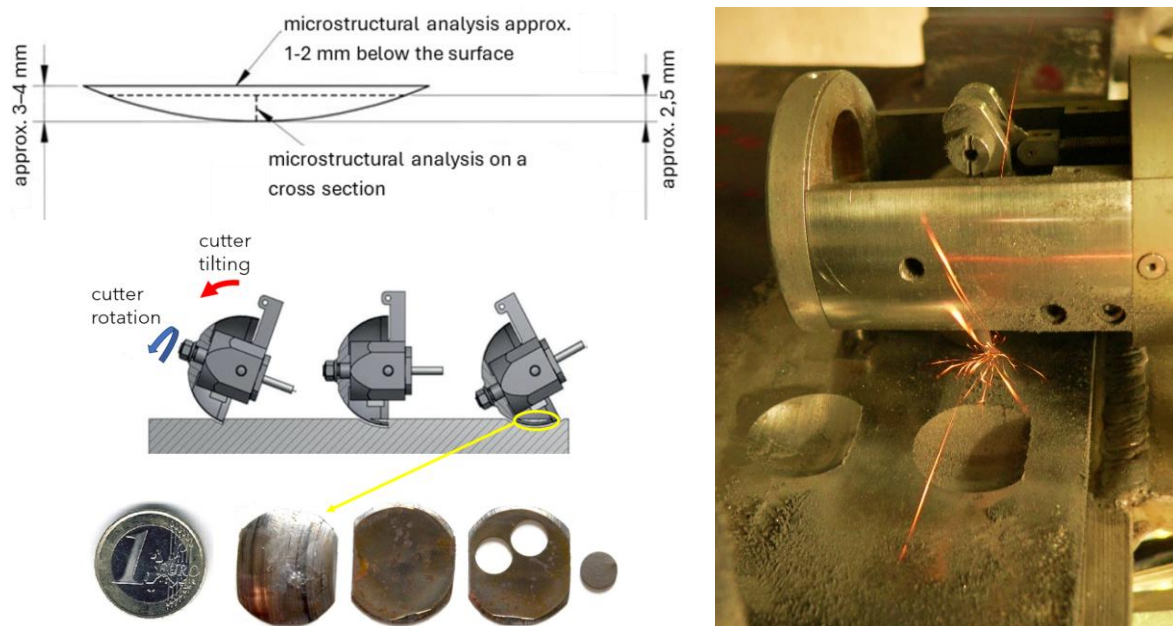


Figure 2 Scheme of obtaining experimental material for SPT diagnostics including photos from real operation

The sampling of the test material in the shape of a spherical canopy with a diameter of approx. 30 mm and a thickness of approx. 2.5 to 3 mm takes approx. 1.5 hours. The sampling principle and the size of the experimental material are shown in **Figure 2**. Elimination of the thermal-deformation influence of the sample and the parent component is achieved by optimizing the cutting conditions, specifically by combining high cutting speed and low tool feed values.

The collected material is then subjected to metallographic analysis. In the case of long-term operation of the steam pipeline, the metallographic investigation is focused on structural changes resulting from prolonged operation and the presence of cavities. The chemical composition can be determined on the same sample, which can exclude any possible substitution of material during repairs or long-term shutdowns.

To determine the mechanical properties, the sample is cut into sheets, from which test specimens with a diameter of 8 mm are obtained using a cutting tool. These specimens are then wet ground on a metallographic grinder to the required thickness of 0.5 mm with the prescribed tolerance. The test specimens prepared in this way are then placed in a test cell and subjected to small punch test. The values obtained from the force-displacement dependence of the crossbar, or force-deflection, are used to determine the values of mechanical properties from the correlation dependences given in ČSN EN 10371 [2].

Table 1 Chemical composition of high-pressure steam pipe (wt%)

high pressure steam pipe	C	Mn	Si	P	S	Cr	V	Mo	Ni
KD2	0.11	0.57	0.22	0.010	0.016	0.58	0.34	0.26	0.05
15 111 (ČSN 415111) [4]	0.08	0.40	0.15	max.	max.	0.50	0.20	0.20	-
	0.16	0.70	0.40	0.040	0.040	0.75	0.35	0.40	

4. EVALUATION OF DEGRADATION OF MATERIAL PROPERTIES OF HIGH-PRESSURE STEAM PIPELINES

The determination of the control chemical composition from the collected experimental material is shown in **Table 1** and compared with the standard ČSN 41 5111 [4].

The mechanical properties of the investigated steam pipeline were determined at laboratory temperature (23 °C) and compared with the values obtained from the previous years 2018 and 2021. The mechanical properties of the steam pipeline (**Table 2**) show a gradual decrease during long-term exposure. The yield strength of the currently evaluated sample (year 2026) is already slightly below the required minimum value according to ČSN 41 5111 [4].

Table 2 Comparison of mechanical properties at laboratory temperature over the years

Year of sampling / operating hours	R _{p0.2} [MPa]	R _m [MPa]	HV10
2018/ 315,000 hours	349	504	162
2021/ 340,000 hours	326	510	158
2026/ 380,000 hours	284	470	155
15 111.5 (ČSN 415111) [4]	≥ 295	440–640	-

Although this decrease is acceptable from the perspective of the material and its operational changes during long-term exposure to elevated temperature (380,000 hours), it represents a significant reduction compared to previous analyses. The decrease is 40 MPa for both the yield strength and the tensile strength.. While the determination of the yield strength in the case of SPT is not based on a clear characteristic (e.g. maximum force) and is therefore much more prone to a large dispersion of results, it can be expected that these results truly reflect the reality and expected behavior of the material.

The microstructure of the analysed steam pipe was formed by ferrite of uneven size with precipitate and small pearlite islands, which, due to their size, cannot be accurately identified from the point of view of decomposition. A small amount of precipitate was observed along the grain boundaries. Long-term operation of steels at elevated temperatures is manifested by microstructural changes that precede the formation and development of defects, specifically, spheroidization of pearlite and decomposition of bainite into ferrite and carbides. The degree of transformation of the ferritic-pearlitic and ferritic-bainite structures due to prolonged exposure to elevated temperature (but not necessarily in the creep region) can be assessed using standards for low-alloy heat-resistant steels [5]. The process of degradation and changes occurring during long-term creep exposure is divided into 6 stages (I to VI) in this assessment, which are clearly shown in **Figure 3**, both for the ferritic-pearlitic and ferritic-bainite microstructure of the steel. Based on this assessment, the level of decay and degradation of the steam pipeline structure can be rated as level II.

This result is generally in good agreement with the results of mechanical properties tests, where only a small decrease in the yield strength below the lower limit of the requirement for the respective steel was confirmed. Cavitation damage does not occur in the assessed long-term operated steam pipeline, which is probably related to the fact that the steam pipeline is operated at a relatively low temperature.

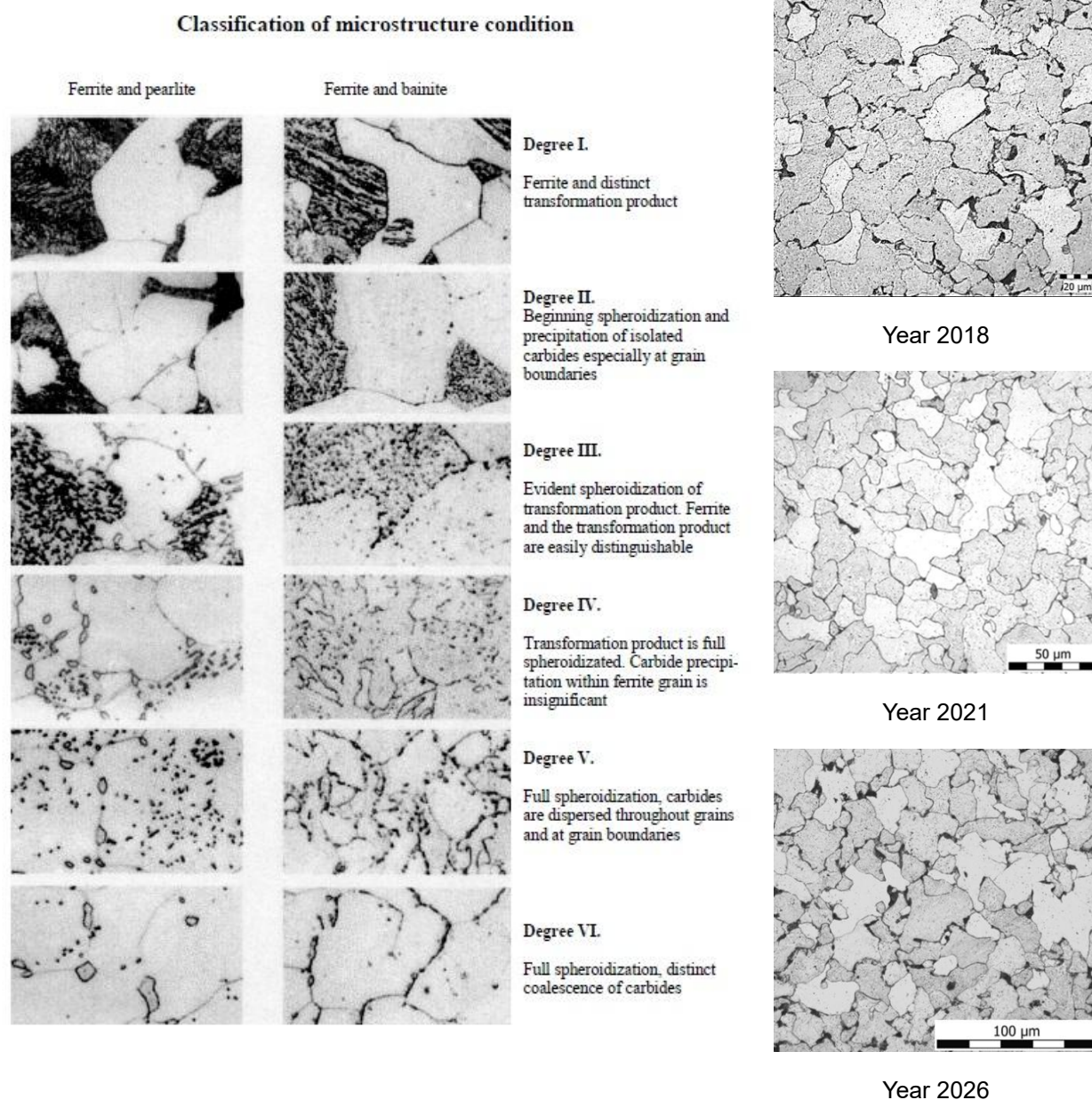


Figure 3 Structural change classification standards for low-alloy steels (left) [5] and images of the steam pipeline microstructure in the years studied (right)

CONCLUSION

Although the current state of the material does not show any signs of critical degradation, periodic inspection of the mechanical properties is necessary to ensure continued operational safety and timely detection of future changes. Given the need for minimal intervention in the integrity of the components, the Small Punch Test (SPT) is a suitable diagnostic method that allows the determination of current material characteristics and validation of the remaining service life of the equipment in regular cycles (e.g. every 30,000 operating hours), without disturbing the integrity of the monitored unit. Unlike predictive models, SPT provides a real, comprehensive picture of the material state at a given time, especially when combined with microstructural and chemical composition analyses.

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