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Assessing the Condition of the Material of Pressure Vessel after Their Long-Lasting Operation in the Petrochemical Industry Using Non-Destructive Acoustic Methods and Structural Stress Field Analysis

Abstract: The article discusses complex tests of an actual pressure vessel after its long-lasting operation in a petroleum distillation system. As a result of exposure to extreme conditions, the structural material of the vessel degraded and corroded significantly. The corrosion damage was identified and imaged using a Phased Array technique-based ultrasonic method. The subsequent stage of investigation involved hydraulic tests and the recording of acoustic emission signals. Stress concentration fields in damaged areas were identified using the FEM-based simulation method. The test results will be used to develop the complex methodology enabling the evaluation of the technical condition of pressure vessels used in the petrochemical industry. The above-named objective constitutes the primary goal of Programme LEADER VII, funded by the National Centre for Research and Development.

Keywords: acoustic emission; pressure equipment, material degradation, carbon steel

Introduction

Most of the pressure devices used in the petrochemical industry (technological pipelines, pressure vessels, reactors, boilers and columns) are exposed to harsh conditions including aggressive substances and variable pressure. The structural elements of many devices, particularly those built in the second half of the 20th century, contain discontinuities formed, for instance, as a result of deviations from the manufacturing technology. The multiannual operation of such objects may result in the development of the above-named discontinuities, leading to the damage of the structural material and welded joints as well as surface depletion and structural changes in the material volume. The development of the aforesaid discontinuities during operation could lead to their instability and, as a result, to the failure of a device or even the breakdown of the entire system.

Because of the foregoing, in order to improve the safety and reliability of pressure vessels used

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for many years in the petrochemical industry, there is growing demand for new diagnostic methods enabling the accurate assessment of the technical conditions of the above-named equipment, with particular attention paid to material degradation.

The tests discussed in this article aimed at developing the fundamentals of a new diagnostic methodology focused on the assessment of the technical condition of pressure vessels after their multiannual operation. It was ascertained that only the complex application of testing techniques and methods when assessing the technical condition of equipment enables the complete and precise analysis of changes occurring in the material. As a result, a proposed diagnostic methodology was based primarily on acoustic emission (AE), portable technique-based material tests and FEM-based analyses of stress field distribution, indicating the "sensitive" areas of stress concentration. The interpretation of results of such tests and analyses, combined with the identification of related correlations, will provide effective solutions to the current issues of the diagnostics of petrochemical systems related to assessment of their technical condition and the determination further operation conditions, particularly in view of multiannual operation-induced non-critical damage.

The first successful attempts at the use of acoustic emission (AE) in industrial tests were made in the 1970s [1-4]. The development of measurement equipment and signal processing methods increased the application range of AE, making it possible to solve industrial problems and improve the diagnostics of pressure vessels both in Poland and abroad [5-7]. Presently, there are a number of standards and procedures [8-10] specifying principles to be applied when testing the above-named structures using the AE method. Such standards and procedures are primarily focused on identifying the activity and locating the sources of AE, yet they do not describe processes occurring in the material and triggering the emission of elastic waves.

The MONPAC [11] technology (invented in the USA), based on Severity and Historic Index parameters, makes it possible to assess the condition of industrial equipment. The above-named criteria are based on the number of analysed cases and commonly used in industrial practice.

Scientific publications contain little information about the attempted simultaneous use of several non-destructive techniques [12-14] when assessing the degradation of the material of industrial objects. The above-named non-destructive techniques included the AE method combined with the detailed analysis of the material condition involving the use of portable techniques, e.g. metallographic tests performed using portable light microscopy (PLM).

All of the tests, the results of which are presented in this publication were performed within the confines of the project New Complex Method of Assessing the Technical Condition of Pressure Vessels used in the Chemical and Petrochemical Industries, Involving the Use of Acoustic Emission Signals, the Stress Field of the Structure and the Level of Material Degradation financed by the National for Research and Development within Programme LIDER VII.

Test object

The object used in the tests was a cylindrical pressure vessel (having a volume of 2.6 m³ and 8 mm thick walls, decommissioned after more than 40 years of service in the crude oil distillation system in one of petrochemical plants. The shell material was carbon steel grade St41K characterised by a yield point of approximately 400 MPa and a tensile strength of approximately 500 MPa [15]. The chemical composition of steel St41K is presented in Table 1.

The vessel was used for separating water and slight impurities from crude oil. In accordance with the technical documentation, the

Table 1. Chemical composition of steel St41K [15]

Chemical element	C	Si	Mn	P	S
Content, %	0.20	0.40	1.40	0.025	0.020

operating pressure of the vessel amounted to 0.25 MPa, whereas the design pressure amounted to 0.5 MPa.

Visual tests revealed that the material of the vessel shell contained numerous defects in the form of corrosion pits having various depths. Advanced critical corrosion damage located in the upper part of the shell was manifested by pits having diameters restricted within the range of 2 mm to 5 mm. The detailed UT-based measurements of the wall thickness at the bottom part of the shell revealed a minimum thickness of approximately 5.5 mm, i.e. a value by approximately 31% lower than the nominal thickness specified in the technical documentation. It should be noted that in

some areas of the shell, particularly in its upper part and in the area of the outlet pipe connector, the thickness of the plates was restricted within the range of 2 mm to 3 mm. The above-named areas of the shell were subjected to detailed ultrasonic tests involving the use of the Phased Array technique. Detected damage was identified and appropriately designated. Figure 1 presents maps of plate thickness distribution. The detailed analysis of the technical documentation and UT results revealed the significant thinning of the wall of the shell and the heads (even up to 2.5 mm) located above the internal technological bulkhead and in the area of the outlet pipe connector.

The material of the shell, containing critical corrosion damage, was cut out and replaced with (through butt welding) an appropriately shaped 3 mm thick sheet, made of a material characterised by a chemical composition similar to that of the shell material. All of the welds were subjected to heat treatment to eliminate residual welding stresses.

Material tests

The assessment of the material of the structural elements of the vessel involved a number of material-related tests performed using portable techniques. The microscopic observations of the metallographic specimens made on each shell plate using PMS (6 specimens designated *I* through *VII*) revealed the ferritic-pearlitic structure without clearly visible features of the secondary structure (Fig. 2). In accordance with the technical documentation, all of the plates used to make the vessel were subjected to heat treatment (normalising). Metallographic tests revealed that the material of the heads and of one of the shell plates (designated *IV* in Figure 5) were characterised by the clearly overheated microstructure, i.e. containing coarse grains and the directed shape of pearlite colonies. The material of one of the heads was characterised by the Widmanstatten structure. The above-named changes in the microstructure were formed through the overheating of the microstructure within the range of Ar3
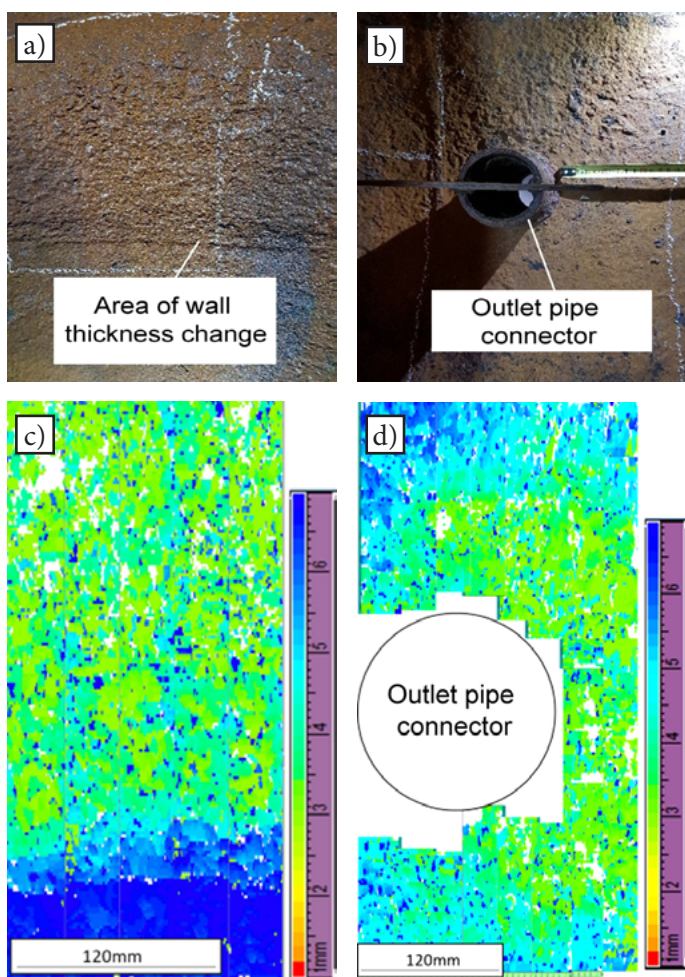

Fig. 1. Corrosion damage (*a, b*) and wall thickness distribution areas (*c, d*) in relation to the cylinder head (*a, c*) and the vessel shell plate part of vessel (*b, d*)

to Ar1s temperature and could not be ascribed to the operation of the equipment. The foregoing justified the conclusion that the changes in the material structure were most likely related to the time of manufacture and resulted from the lack of appropriate heat treatment (normalisation) after hot rolling. Steel containing the above-named structure is characterised by brittle cracking tendency, reduced toughness and lower mechanical properties during tension.
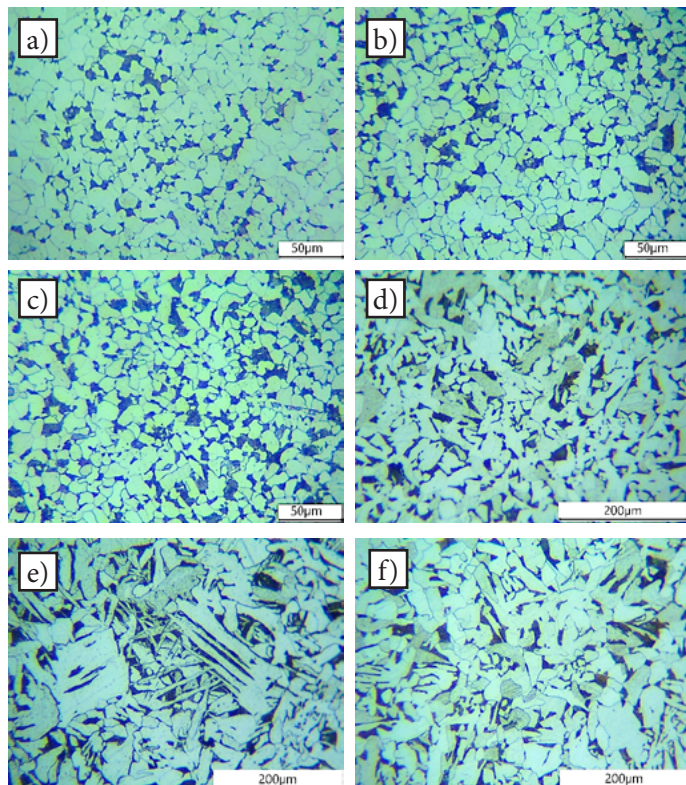

Fig. 2. Microstructures of the shell plates designated as I (a), II (b), III (c), IV (d), V (e) and VI (f):
a, b, c – magnification of 400×; d, e, f – magnification of 200×

FEM-based analysis of the stress field

The identification of the stress field (induced by internal pressure) present in the structural elements of the pressure vessel involved the development of a three-dimensional model taking into consideration the thinning of the walls of the shell plates and of the heads. The adopted boundary conditions related to the structure and the vessel operating parameters were consistent with the technical documentation of the vessel. The local thinning of the shell walls and heads, located at the upper part of the vessel as well as the defect located in the outlet pipe connector zone were modelled in accordance with data obtained during ultrasonic tests (UT). The calculations were performed using the Abaqus system and the PLGrid infrastructure. Exemplary FEM calculation results are presented in Figure 3.

The FEM-based analyses revealed that the greatest concentration of reduced stresses was detected in the area of corrosion damage, where the head was connected with the cylindrical part of the vessel. The local plasticisation of the material was observed after the exceeding of a pressure of approximately 0.9 MPa.
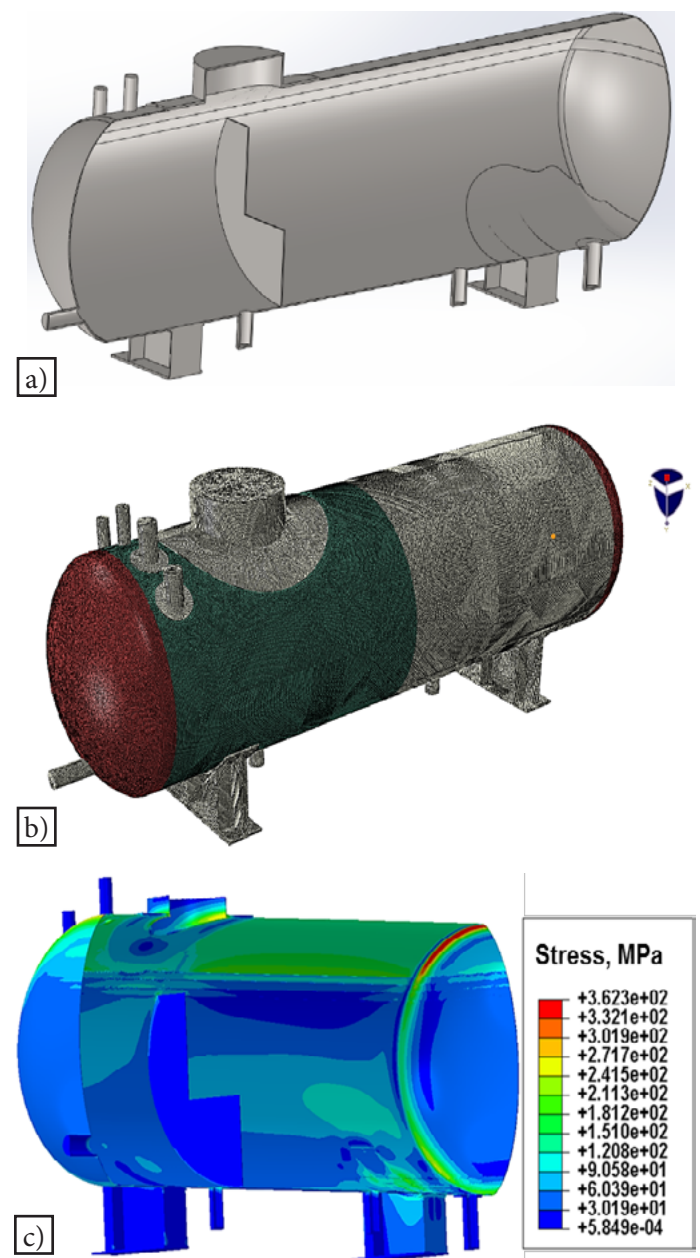

Fig. 3. Geometry (a), the FEM model (b) and the Huber-Mises stress distribution (c) in the shell under a pressure of 0.9 MPa

Pressure tests and AE recording

The development of the diagnostic methodology, focused on the detection and the assessment of the development of destructive processes, including the condition of the microstructure of the material of the pressure vessel, required a number of tests involving the recording of AE signals. Initially, the filling of the vessel with water was followed by the performance of tests of the propagation of AE waves generated by an artificial source of AE, among other things, the Hsu-Nielsen source, in accordance with the PN-EN 13554:2011 standard [16]. The tests aimed at identifying the propagation rate of AE waves, optimising the arrangement of AE sensors as well as the verification of the source location accuracy. The above-named tests were followed by hydraulic tests including the recording of AE signals. During the tests, pressure was gradually increased and held for approximately 10 minutes at individual loading stages. The recording of AE signals was performed using sensors (having a resonance frequency of 150 kHz) with pre-amplifiers (gain of 34 dB) and an AMSY-6 measurement system (Vallen).

Figure 4 presents the distribution of maximum amplitudes of AE signals and the Historic Index (HI) parameter in time as well as the zonal diagram showing correlations of Severity – Historic Index parameters (MONPAC criteria [11]). The first signals generated by the critical sources of AE (zone E in the Severity – Historic Index diagram in accordance with the MONPAC classification) were recorded after exceeding a pressure of 0.5 MPa, i.e. at the moment when a significant increase in the HI was recorded. An increase in the load was accompanied by an increase in the number of recorded AE signals – until the moment when, after exceeding a pressure of approximately 0.9 MPa, a significant amount of critical sources of AE was located and the measurement system started recording continuous emission. The exceeding of the aforesaid pressure was followed by the plastic strain of the significant volume of the material,

particularly in the areas where the heads were connected with the cylindrical part of the vessel; the foregoing was also revealed by the FEM analysis results (Fig. 3).
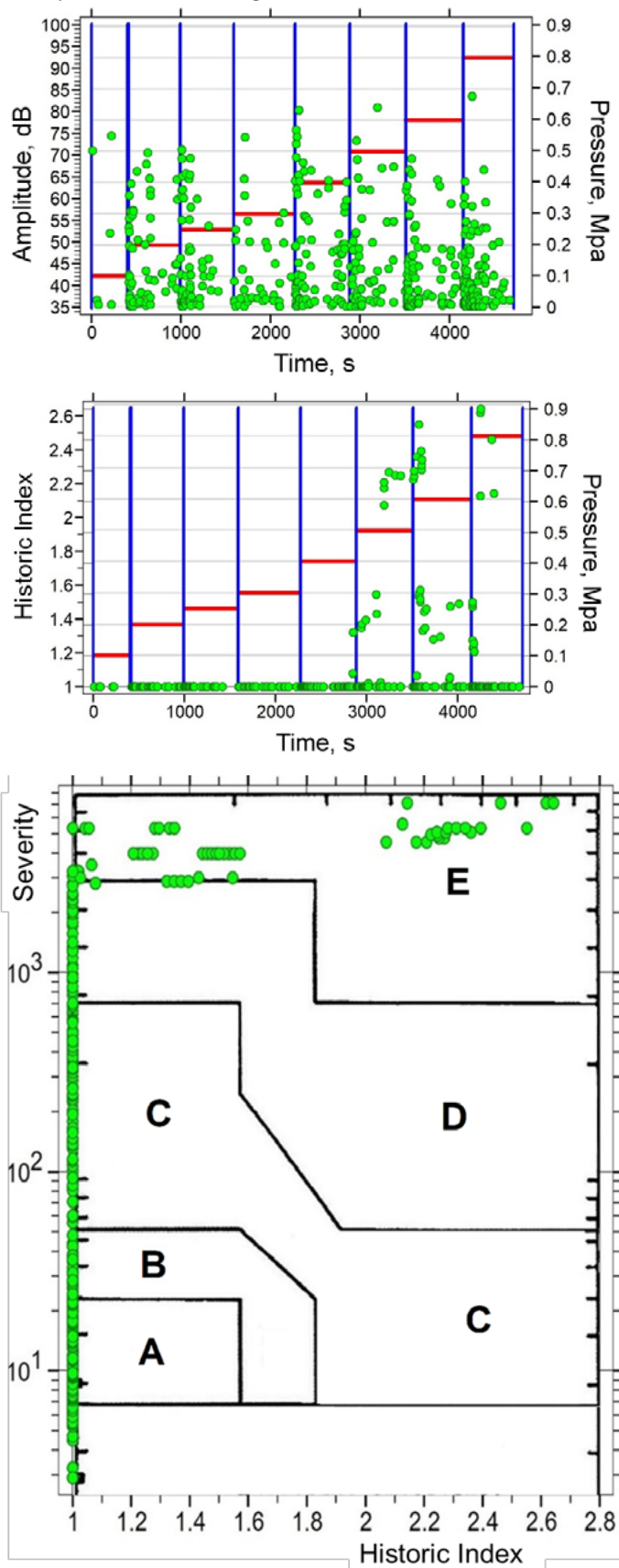

Fig. 4. Distribution of maximum amplitudes (a), the Historic Index parameter (b) and the Severity – Historic Index zonal intensity plot (c) in time

The vessel was depressurised in the area of damage located near the outlet pipe connector. Until the exceeding of a pressure of approximately 0.8 MPa, the shell of the vessel revealed the presence of two critical sources of AE, designated as z1 and z2 (Fig. 5). Source z1 was located where the outlet pipe connector was joined with the vessel head plate, whereas source z2 was located in the area of the longitudinal welded joint joining the shell plate with the welded patch. Most AE signals, generated by source z1, in accordance with the Monpac criteria, were classified as belonging to group E, representing critical damage demanding the immediate discontinuation of operation and the performance of detailed tests involving other NDT methods.

The pressure tests involving the AE recording was followed by the internal inspection of the vessel and cutting out fragments of the shell where the sources of AE, designated as z1 and z2, were located. Figure 6a presents a fragment sampled in the zone of the outlet pipe connector, cut along the axis of the container, precisely where source z1 was located. The macroscopic and microscopic observations of the metallographic specimen (made using the portable technique) revealed the presence of a crack having a length of approximately 0.8 mm. The detected imperfection propagated in the heat affected zone of the welded joint connecting the pipe of the outlet (pipe) connector with the shell plate. The morphology of the crack (see Figure 6b) revealed that it propagated at three stages, starting from a load of 0.5 MPa.

Conclusions

The shell material of pressure equipment made between the 1960s and the 1970s and operated in the petrochemical industry often contains hidden technological defects and changes in the microstructure, resulting from deviations from a related manufacturing technology. The foregoing was confirmed by tests concerning the material of the pressure vessel being the subject of the investigation discussed in the article. The material of certain plates of the shell contained the coarse-grained microstructure with clearly visible traces of overheating. Steel containing the above-named structure is characterised by brittle cracking tendency, reduced toughness and lower mechanical properties during tension.

An important aspect of diagnostic practice concerning industrial systems subjected to long-lasting operation is the supplementing of NDT with data acquired in FEM-based analyses
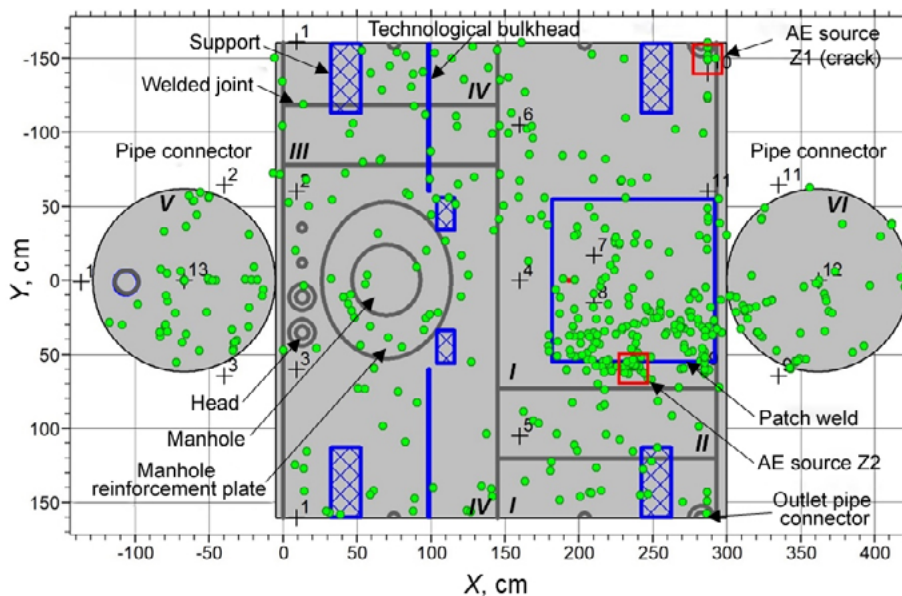

Fig. 5. Location of AE signals generated under pressure restricted within the range of 0.1 MPa and 0.8 MPa (1 ÷ 11 – sensors, I ÷ VI – numbers of shell plates)
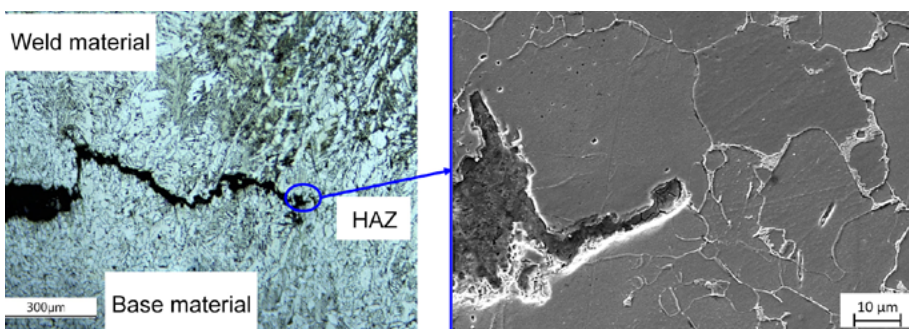

Fig. 6. Microphotographs of the crack located using the AE method

performed to determine the field of stresses and strains generated in elements of the structure by working loads. The FEM calculations performed within the above-named works revealed that changes in the geometry of the device, the inlet and outlet of the system as well as local corrosion damage to the material result in the generation of significant concentrated stresses in the shell of the pressure equipment. In the aforesaid zones it is often possible to observe plasticisation and the development of defects by working loads.

Hydraulic tests including the AE recording of the pressure vessel containing considerable corrosion damage resulting from over 40 years' long operation in a crude oil distillation system made it possible to verify the effectiveness and the sensitivity of the AE method as well as enabled the development of other AE method-based techniques applied when testing the aforesaid type of structures. The tests made it possible to detect and locate the process of nucleation and the development of the critical source of AE. The subsequent destructive tests revealed that the zone of the located source of AE contained an approximately 0.8 mm long crack.

The above-presented test results made it possible to develop and verify the basis of the new methodology of non-destructive tests of objects subjected to multi-annual operation. The above-named methodology is based on the combination of numerical simulations performed during the operation of the equipment, the assessment of the material state and the detailed analysis of the parameters of acoustic emission signals generated as a result of the development of degradation processes. The optimum combination of the above-presented analyses along with the identification correlations will enable the solving of today's issues concerning the diagnostics of chemical systems, their technical condition and the determination of conditions affecting their further functioning, particularly in relation to units which, because of long-lasting operation, have developed non-critical damage.

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