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To cite this article: V I Surin *et al* 2020 *J. Phys.: Conf. Ser.* **1636** 012017

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Results of the application of the contact potential difference method to monitor NPP process equipment

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Abstract. The paper presents the results of nondestructive testing of-process equipment of nuclear power plants a welding unit for the collector of steam generators PGV 1000M, the hull penetration and surfacing of the process pipe performed in the factory. The purpose of the study was to justify the possible use of contact potential difference at the stage of technological assembly and control of welded joints of steam generators in the factory, as well as to determine the prospects for using this method in operating conditions of process equipment.

1. Introduction

Today, methods of electrophysical nondestructive testing, which are in the process of approbation and implementation, are entering the certification stage with the aim of wider practical application. One of the last planned stages, preceding the certification of the method of contact potential difference (hereinafter referred to as CPD) of the electrical type of NDT is the stage of experimental and methodological substantiation of the application of the CPD method at the enterprises of the nuclear industry.

Application of nondestructive testing that can locate defects and their size is very important in nuclear power plant, since safe operation of nuclear power plants and their essential components, such as steam generators, is considered extreme priority task. The electrical CPD method had overcome these drawbacks since it does not have thickness limitation and have high sensitivity. Implementing the CPD method is in the last planned stages where it is needed to experimental and methodological verification of the CPD method application in the nuclear industry. This stage of the research is supported by the Russian Foundation for basic research and a grant under contract no. 19-08-00266 /19 of 10.01.2019.

This article presents experimental results obtained at the enterprises of the nuclear industry, confirming the high efficiency of the developed CPD method. Steam generator collector PGV 1000M welding joints, as well as the hull penetration and process pipe welding joints were studied using point-by-point CPD measurements.



2. Improved contact potential difference method

In condensed matter physics, the work function is defined as the difference between the potential energies of an electron corresponding to the energy level of vacuum and Fermi energy. The applications of this method are widely described in [1–5].

Improved method CPD is newly developed nondestructive method, CPD principle is based on the principle of measuring the electrical potentials on the surface of the studied sample. It is well known that stress waves are generated from defects and cracks growth in metals [6, 7]. These waves propagate to surface and lead to increase number of contact spots and real contact area between sample surface and sensor, which consequently lead to change in contact potential difference between sensor and sample. The act of forming an inhomogeneous surface deformation causes a jump in the amplitude of the electrical signal due to changes in the local work function and the conductivity of the contacting surfaces. The greater the number and area of contact spots between two metal surfaces is, the higher the probability of electrons overcoming the dipole barrier is.

The CPD method was used to study relationship between deformation activity and potential difference on the surface [8]. Furthermore, it was used to study early stage formation and growth of embryonic fatigue cracks in metals [9].

Nondestructive testing methods are playing an important role in NPP plants. The advantage of radiography is that it provides a continuous visual record of the metal degradation pattern. The main disadvantages are: difficult control in hard-to-reach places, hazardous to the health of service personnel, does not provide a reliable distribution of defects over the depth [10]. Ultrasonic testing is the most common method used in investigation steam generators. The main disadvantage is that it is relatively insensitive to tight cracks. However, ultrasonic testing is used to find internal defects within weld or in metals being tested, though it has primary drawbacks limitation to materials above 6 mm thick and it is very dependent on skill of the operator [11].

The electrical signal is characterized by spectral density, amplitude, time and amplitude-time distribution, as well as the average value and dispersion in a given time interval. These signal parameters are associated with their generating physical processes and convey information about studied object [12].

The aim of this study is to present and analysis the results of detecting structural defects in welded joints of some NPP parts.

3. CPD results of NPP products and process equipment

The purpose of studying steam generator collector welding joints of PGV 1000M by the CPD method was to study the possibility to use CPD at the stage of assembly and testing of steam generators welded joints at the factory, as well as determining the prospects of using this method in operational conditions.

Before carrying out CPD measurements, the steam generator welded joints surface and the controlled area of sinking and surfacing of process pipe were prepared in accordance with Russian standard [13].

Evaluation of technical condition of welding in steam generators and detection of structural failures by the CPD method was carried out in the Atommash reactors factory, Volgodonsk city, Russia.

In order to record potentiometric measurements for the steam generator, a stationary sensor was fixed to the steam generator body using magnets. Sensors were made of steel 45 and steel KH18N10T. The area under study was divided into eight tracks and potential values were recorded along these eight tracks. Four of them were located to the left side of the welded joints (relative to the axis of

symmetry of the welded joints) and four – to the right. Measurements were performed by points-wise scanning using a pen sensor. Manual point-by-point scanning of welded joints in steam generators was carried out for about 5 mm step along eight measuring tracks, the distance between each track and the next was 1.5 mm.

The influence of both temperature and passing a constant electric current through the sample, on structural inhomogeneities detection effectiveness were studied.

The depths of the defect locations were calculated by analyzing recorded results using developed signal filtration programs at various levels. Detection of small defects signal from noise signal was challenge while applying CPD.

Our experience of using discrete Fourier transform (DFT) with windowed functions gave positive results for changing processes over time, such as metal creep or fatigue strength. Under stress conditions, each type of defects has its own emitting capacity of elastic stress waves. The higher emitting intensity correspond to higher signal amplitude in potentiogram.

The classification of the detected structural inhomogeneities in the welding joints was performed by comparison with the structural inhomogeneities detected on a specially prepared control weld using radiographic control [12].

In order to determine the defect coordinates, a measuring tape was used to measure the distance from the reference point. With manual point-by-point control, the measuring tape allows to determine the coordinates of inhomogeneities with an error of 1–2 mm.

The value of the *SLS* location level was determined from the expression: $SLS = |g|\Delta\phi|$, where $\Delta\phi$ is the function of the electric potential difference.

Defects detection in welded joints of two steam generators PGV 1000M was performed using the EDSS-1RD rolling sensor (figure 1) and corresponding potentiograms were constructed. Figure 2 (a) shows distribution of potentials over the surface. The x-axis of the potentiogram displays the distance along the measuring tracks. The y-axis shows the track number. The detected inhomogeneities are distributed mainly in the upper and central parts of the welded joints.

From visual inspection of welded joints, it was concluded that the potential heterogeneity in the upper part of the welded joints is associated with numerous scratches and deep inclusions of small rust spots less than one mm in size. A small surface defect of about 4 mm was found in section 15 in the central part of the welding joint, which affected the scan result. The results of point-to-point measurements also indicate a large number of surface defects along tracks 1–4 and 7–8. The results of potential distribution for welding joints of the hot collector to the body of the steam generator are confirmed by the results of time-frequency analysis.



Figure 1. Manual CPD measurements of the input and output pipes in steam generator at the places where they were welded to the corresponding collectors.

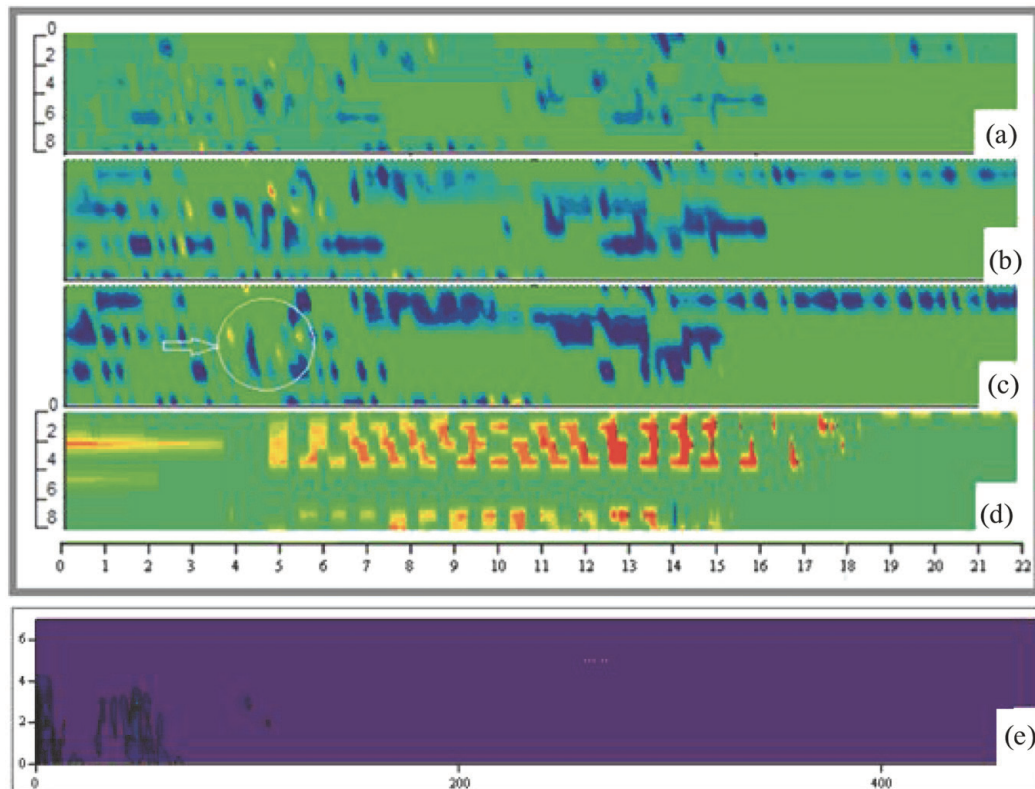


Figure 2. Surface potentiogram (horizontal scan) of hot collector welding joints to the steam generator body, constructed for different values of structure level signal (SLS): (a) 4.77; (b) 5.046; (c) 5.301; (d) results of point-by-point scanning, level 4.155; (e) results for point-to-point scanning. The corresponding scan counts are presented along the x axis.

In figure 2 (c), the white circle indicates a group of defects detected at high structural levels, which should be classified as inhomogeneities located in the subsurface layer. These defects are shown separately in figure 3, and may be associated with corrosion that penetrates the grain boundaries.

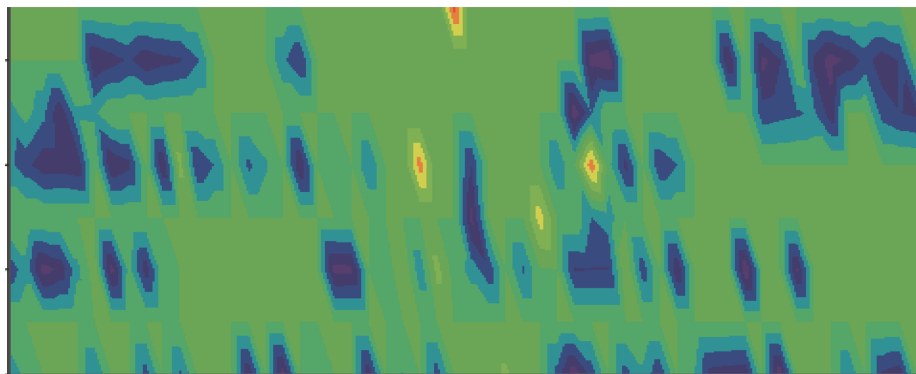


Figure 3. Group of structural imperfections (red spots) $SLS = 5.301$ enlarged in 5th and 6th tracks.

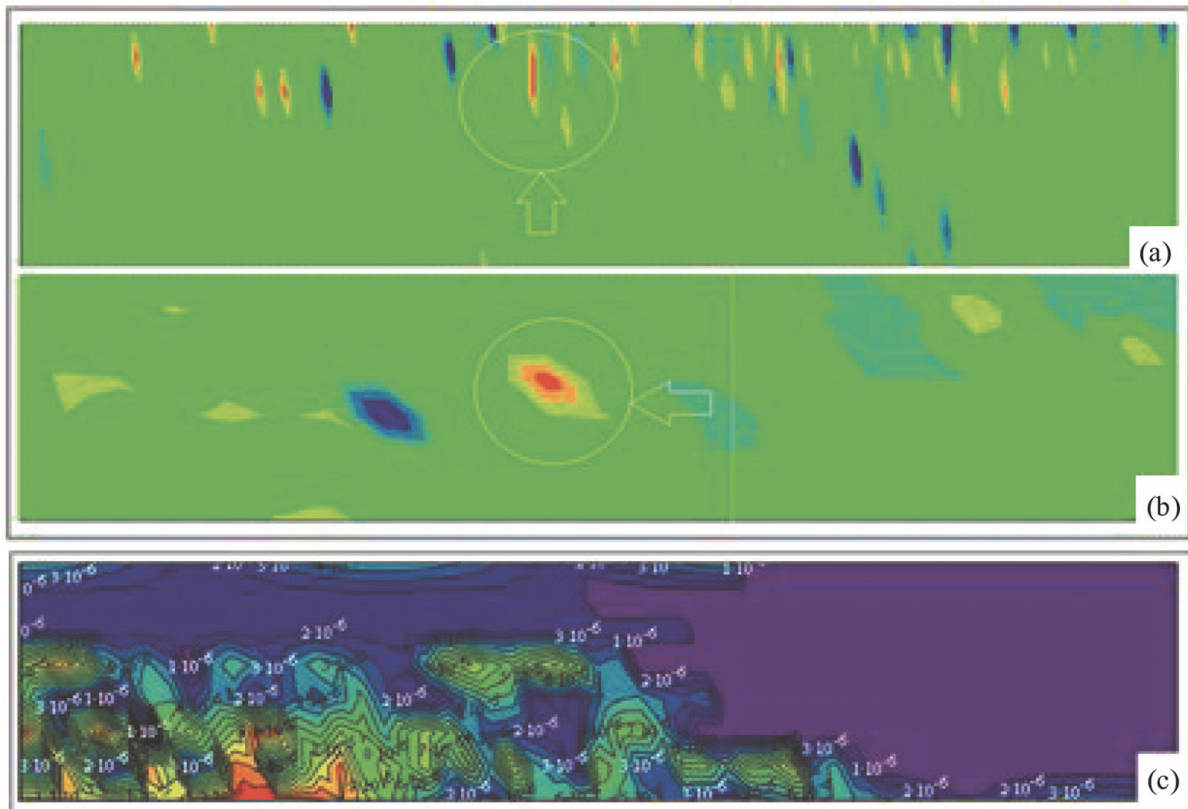


Figure 4. Surface potentiogram of cold collector welding joint to the body of the steam generator: (a) defects detected by the EDSS-IRD flow detector; (b) singularity detected in the control area; (c) the result of DFT

Potentiometric results of cold collector welding joints to the body of the steam generator are shown in figure 4. Attention is drawn to the set of surface defects concentrated along the axis of the welding joints. Visual inspection shows the presence of the same defects as in the hot collector. The potentiogram of these welding joints was constructed at the filtration level of 5.699 (figure 4 (a)). The same figure shows a potentiogram constructed while passing 0.7 A current through the welding joint, where defect was detected in the area of the 4th track (highlighted in a circle and shown by an arrow in figure 4 (b)). The presence of the detected singularity and the accuracy of its location were evaluated using the ultrasonic testing (Ultrasonic flaw detector A1214 Expert). Its depth from the surface of the welding joint was approximately 30 mm. Figure 4c shows the result of applying the DFT.

Figures 5–7 (in the upper part of the drawings) show the results of CPD hull penetrations–potentiogram of the welded joint of the hull to the disk. The CPD measurement was performed by manual scanning (transducer KH18N10T) in the temperature of 23 °C. The x-axis shows the coordinate along the axis of the welded joint, and the y-axis shows the number of the measuring track. Scanning was performed along eight measuring tracks. Before making measurements, the surfaces of the welded joint were polished and cleaned using acetone.

To analyze the results, the lower part of the figures shows the potentiograms of the control welding joints taken from [12]. Fragments of the hull penetrations are shown in figure 8. The red line in the figure indicates the axis of the welded joint along which the scan was performed.

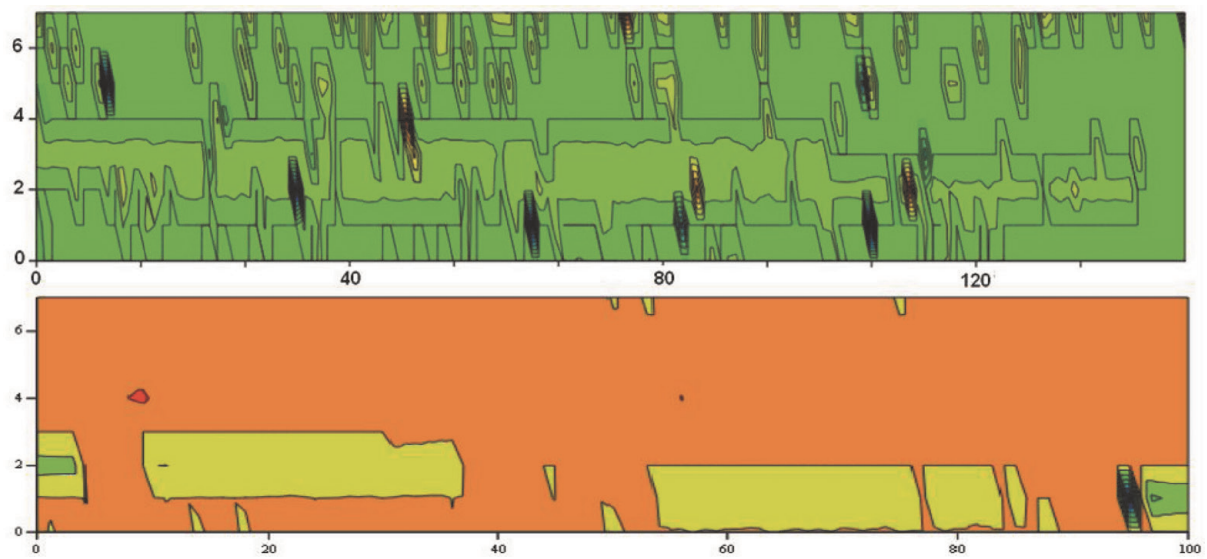


Figure 5. Comparison of CPD results for two welded joints: the hull penetrations (upper figure) and the control weld (lower figure). $SLS=3.944$.

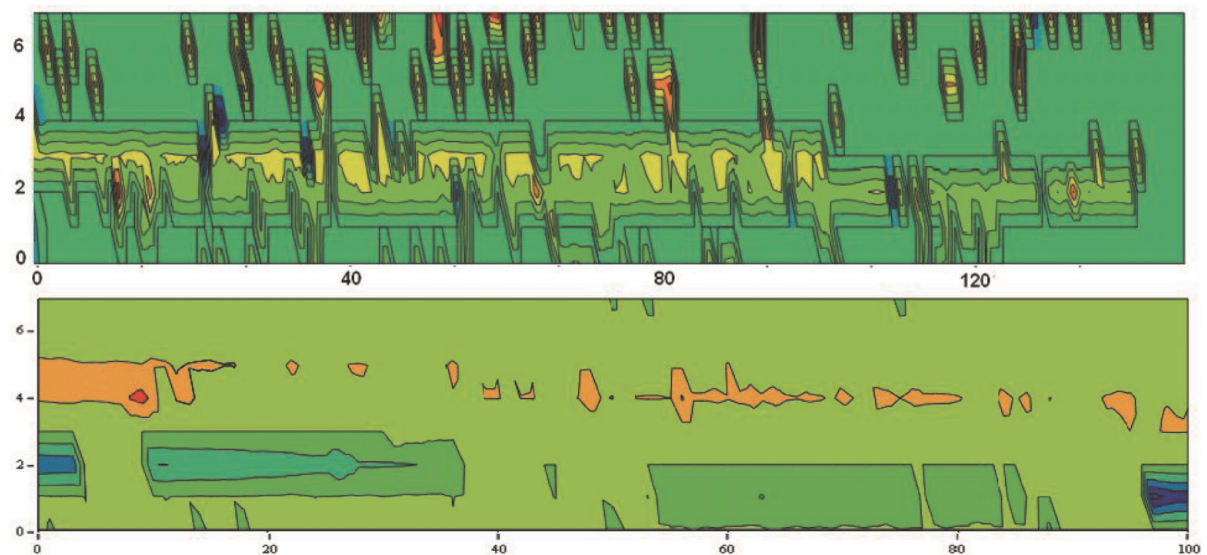


Figure 6. Same as in figure 5 with $SLS=4.531$.

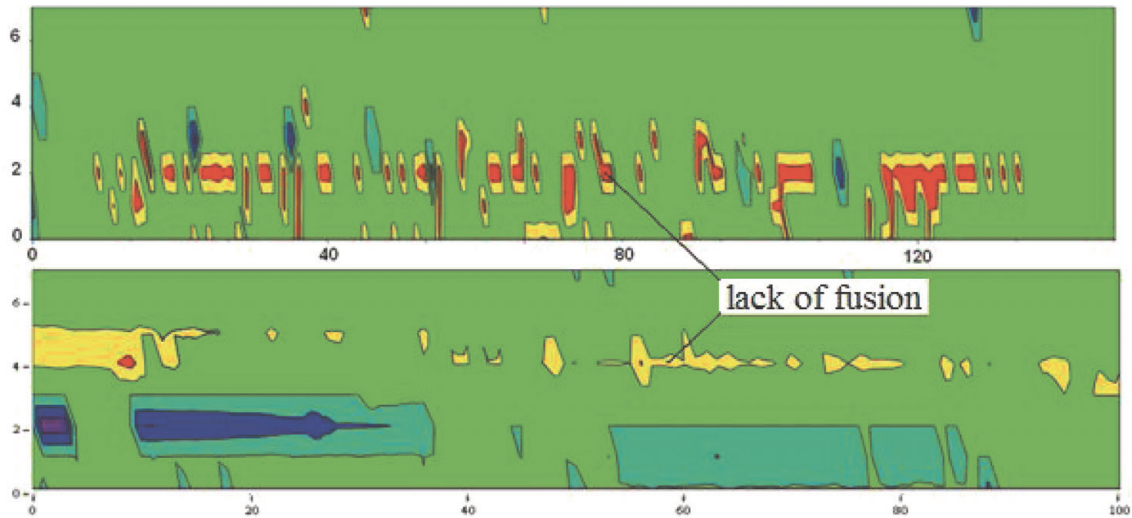


Figure 7. Same as in figure 5 with $SLS=4.857$.

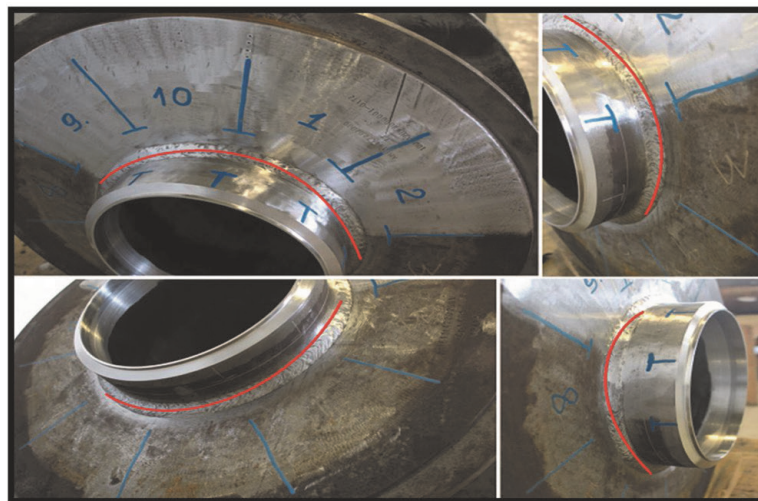


Figure 8. Fragments of hull penetrations. The red line indicates the axis of the welded joints of the housing with the disk.

From a comparison of the presented potentiograms for the hull penetrations and control welded sample, we can conclude that the root of the seam is incomplete, which is clearly visible in figure 7. Another reason may be the presence of contamination, foreign inclusions. At low SLS values, it can be also seen a numerous single structural inhomogeneities. In figures 5 and 6 internal lines of intersection of the cylindrical surface (body) with the plane (disk) are also visible.

Scanning of the surfacing with a manual sensor was performed on the outer surface, less than 30 mm wide, along eight measuring tracks. In accordance with the welding technology, before the welding operation, a lining ring is put on the end of the body and welded by manual argon-arc welding along the entire contour. Welding of the second and subsequent rollers is performed after cooling of the previous roller to a temperature below 100 °C. During the welding process, after each successive roller is completed, its surface and adjacent areas of the deposited metal are cleaned from slag and contamination. Welding is performed on the inner surface of the lining ring in one layer with the electrode EA-395/9. According to regulatory documents, the thickness of the first deposited layer is

controlled using a pattern. After all the technological requirements are met, the second layer is deposited with the EA-400/10T electrode. The welding requirements for the second layer are similar to those for the first layer.

After welding, the quality of the welding is checked by external inspection. Standards of acceptable defects for category II.

The potentiograms in figure 10 show the distribution of inhomogeneities along the welded joint (width less than 30 mm). In figure 9 the surface that was scanned is indicated by red arrows.

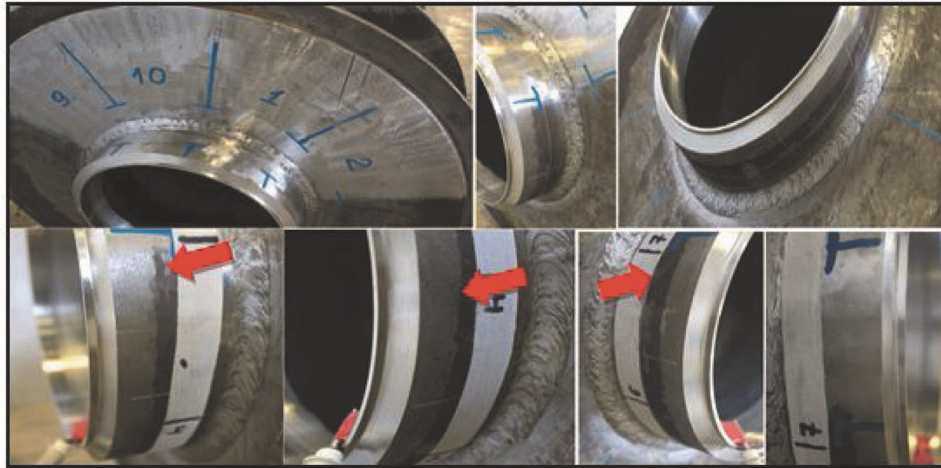


Figure 9. Fragments of the end part of the penetration. The red arrow indicates the outer surface of the surfacing, which was scanned by sensor.

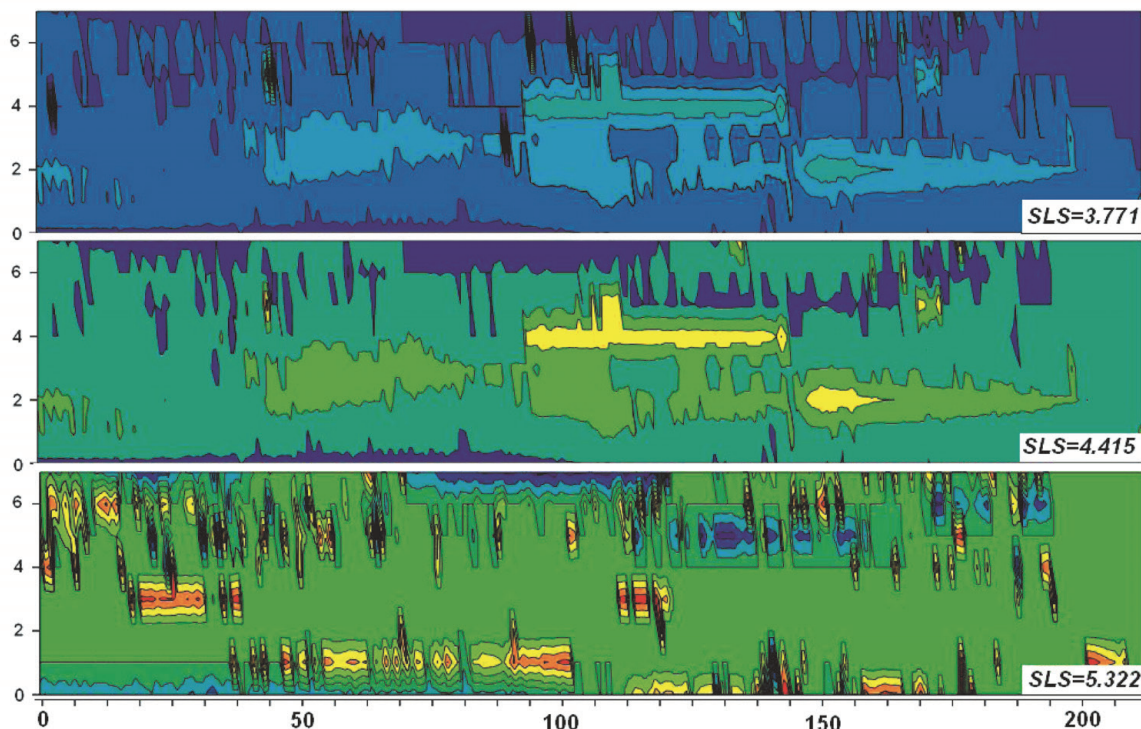


Figure 10. Potentiograms of the end part of the penetration body obtained for various structural signal levels.

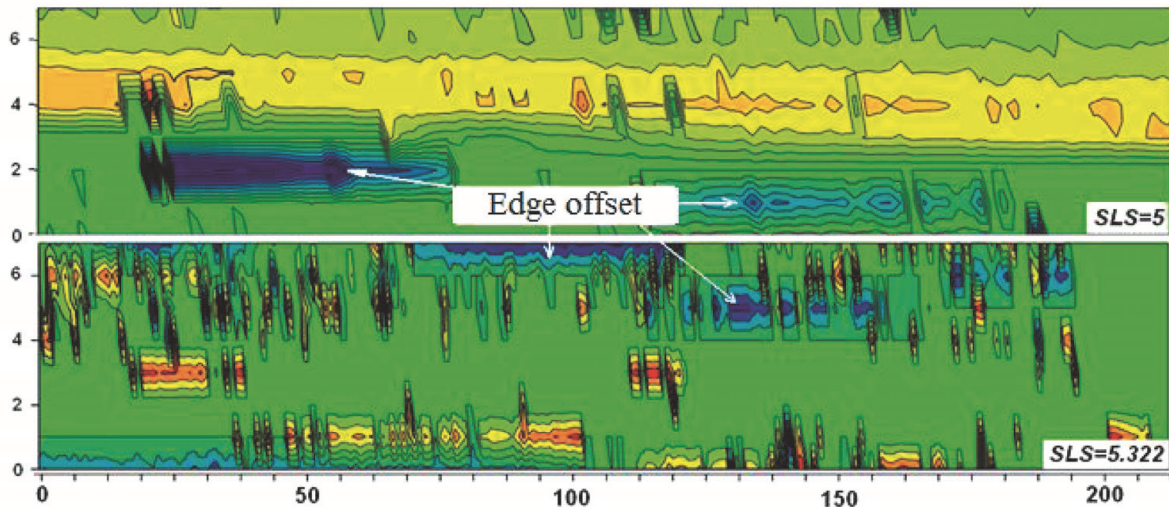


Figure 11. Comparison of CPD results for two welded joints: penetration body (lower figure) and control weld joint (upper figure) at $SLS=5.322$ and $SLS=5$, respectively.

At high structural levels, the concentration of inhomogeneities is visible, mainly in two adjacent bordering areas corresponding to the first and second welding (dark blue and green color areas). Differences in colors characterize the boundaries of areas with different values of residual stresses.

Potentiograms show that the forming structure of the weld metal is characterized by various types of inhomogeneities. First, it can be concluded that inhomogeneities are present in both the first and the second welding layer. Second, it can be seen the areas with non-uniformity of “edge offset” type (figure 11). The reason for this may be non-melting along the contact boundary of the two welding layers (figure 8), or in the part where the first welding is adjacent to the surface of the casing of the penetration.

By changing the limits of amplitude discrimination, it is possible to study the nature of the arrangement of structural inhomogeneities along the cross-section of the welding. Figure 10 shows that when approaching the inner surface, the inhomogeneities become more structured and less extended, which can be taken as an indicator of welding quality. The observed inhomogeneities occur mainly in the places where each subsequent roller is deposited on the previous roller and are probably associated with residual stresses of thermal origin. Another reason may be the occurrence of additional phases or small areas of formed slag and contamination. The width of inhomogeneities varies in a wide range: from a few millimeters to 10-15 mm or more (figure 10, upper potentiogram). The sources of formation of inhomogeneities structures in welding include:

- inhomogeneity of the chemical composition of welding;
- influence of the process of hot deformation when welding rollers (by the cross-section of the welding);
- influence of the roller cooling process, which causes uneven changes in the temperature of the metal cross-section.

For the surfacing of the process pipe at low structural levels ($SLS=1.699$ and $SLS=2.301$), numerous inhomogeneities are seen that are randomly arranged. At higher structural levels, inhomogeneities are divided into three bands along the centerline of the welding. The image of the bands is caused by intense emission of stress waves during cooling. A similar pattern has been repeatedly observed with CPD of various welded joints. The most likely reason for this is the formation of a layered structure of the welded joint. The observed band structure potentiogram connected with successive layers of molten metal to one another.

4. Conclusion

Electrophysical nondestructive testing with the use of contact potentiometry measuring tools was carried out in the factory at JSC AEM-technologies “Atomash”, Volgodonsk. The objective was to study the welded joints of the collector to the steam generator PGV 1000M.

The obtained results of pre-operational control are an archive of measuring information, which can be further supplemented and used for monitoring the state of the metal.

Testing of welded joints of the collector welded to steam generators PGV 1000M was carried out by manual point-to-point scanning and an electrophysical flaw detector EDSS-1RD. The measurements were carried out at eight measurement tracks. The absolute error in determining the coordinates of defects during manual control is from one to two millimeters. During the CPD, the measurement system was based on the asusx554l laptop with a measuring device agilent34401A multimeter.

The results of the control potentiograms constructed for different structural levels signal *SLS*. The classification of detected structural inhomogeneities in welded joints was performed by comparing them with known structural inhomogeneities detected earlier on specially prepared welded joints. The analysis of potentiograms was performed by sequential filtering of signals using a developed programmable amplitude discriminator of measuring signals with an adjustable scale of amplitude discrimination in the range of 40 dB. When analyzing CPD signals and evaluating the impact of noise components, the wavelet analysis was used. The signal-to-noise ratio during the measurement process varied from 10 to 50 dB depending on the level of the control signal.

The character of mutual arrangement of structural inhomogeneities along the cross-section of the welding was studied for the hull penetration. From the analysis of potentiograms at various levels of fixation, it follows that approaching the inner surface, the inhomogeneities become more structured and less extended, which can be taken as an indicator of the quality of welding. The observed inhomogeneities occur mainly in the places where each subsequent roller is deposited on the previous roller and are probably associated with residual stresses of thermal origin. Another reason may be the occurrence of additional phases or small areas of formed slag and contamination. The width of inhomogeneities varies in a wide range: from a few millimeters to 10-15 mm or more.

For welding pipes at low structural levels ($SLS=1.699$ and $SLS=2.301$), numerous, randomly arranged inhomogeneities are visible. At higher structural levels, inhomogeneities are divided into three bands along the centerline of the welding. The image of the bands is caused by the intense emission of elastic stress waves during cooling.

Acknowledgements

The authors would like to thank the welder Mr. Y.A. Kolykhalov for welding the sample.

This project was supported by the Russian Foundation for Basic Research (RFBR) under grant 19-08-00266/19 of 10.01.2019.

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