DOI: 10.21062/mft.2025.046 http://www.journalmt.com

Crack Detection and Monitoring of Their Growth in Critical Parts of Steam Pipeline by Electric Potential Drop Method

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An innovative way of using DCPD (Direct Current Potential Drop) method for off-line and online monitoring of critical parts of energy equipment in operation is presented. There are only a few NDT methods that allow detection and monitoring of defect growth in components at high temperatures and pressures. Monitoring of steam pipes and critical pipeline components in operation has been carried out for several years with different results. a relatively new way of using the DCPD method outside the laboratory is described. The carried-out tests were intended to resemble operational loads as much as possible. Therefore, the tests were performed at a temperature of 20 °C and at an increased temperature of 550 °C. By gradually deepening the groove (slot) simulating the crack type defect in predefined steps, the growth of the defect was simulated up to the full wall thickness of the test sample. The primary evaluation was carried out from the absolute and relative values of measured resistance. The disadvantage of these values is their dependence on the temperature of the monitored area of the test sample and on possibly interfering DC voltages.

Keywords: Direct Current Potential Drop, NDT, pipeline

1 Introduction

One of the non-destructive tests used to measure crack growth in test specimens is the Potential Drop (PD) method. This can be divided into two sub-methods according to the excitation current: ACPD (Alternating Current Potential Drop) and DCPD (Direct Current Potential Drop). Both alternatives have been used in materials laboratories for a very long time. A relatively new way of using these methods is in industry. There, voltage drop methods are used for monitoring surface crack growth [1] and for monitoring corrosion and erosion on the inner surface of pipes, containers, pressure vessels etc. [1]. Both methods are based on the principle of electric current conduction through the monitored body, therefore they are only applicable to bodies and parts made of electrically conductive materials, most often carbon or stainless steel. The advantage is the possibility of using them under operational loads like, for example, high temperature and pressure of the medium flowing through the monitored component. It is also usable in environments with high concentrations of hazardous substances and ionizing radiation. It is possible to expand the possibilities of using PD methods by increasing the accuracy of concerned measuring systems.

The instituite hosting the authors of this article has been developing the PD method for industrial use for some time. Available systems are tested, while focusing on developing new ones. The intention is to increase the sensitivity and reliability of the monitoring device, thus increasing the safety and operability of the monitored component and reducing its maintenance costs. New derived parameters have been prepared for the online monitoring system under development, which eliminate influencing factors and make the evaluated results more precise.

As a part of the development of a new measuring device (named DROPOT), a significant number of tests were carried out. The tests were primarily intended to verify the sensitivity of not only the new device, but also the DCPD method itself. To verify the results, three independent measuring systems were used. The design of test specimens, including imitated defects, were created in respect to the real components. Additionaly, current field simulations were conducted simultaneously. Verified computational model will be used in specific applications for future optimization of the electrodes position.

2 Basic description of the PD method

For monitoring critical parts of steam pipelines of energy sources, the DCPD method or a combination of ACPD and DCPD appears best suited. In general, it can be stated that the ACPD method is suitable for monitoring surface defects because it utilizes the skin effect. This is a physical process in which an electric current is apparently pushed to the surface of the conductor by changing magnetic field. The skin effect penetration depth depends on the specific conductivity of the material, the frequency of the current and the permeability of the material. If the outer surface of the conductor is affected by discontinuity, the overal resistence rises. Usually, the level of interference in the industrial environment is rather high, so the sensed AC signals can be significantly affected. However, methods mending this problem exist [7, 8].

For checking the entire volume (full wall thickness, including the inner surface) of the monitored area, the DC method is more suitable. The most used is the four-wire Kelvin connection for measuring very small resistences [3]. An input current is injected into the monitored part from a pair of excitation electrodes. In this area, the potential difference is measured on the surface of the body using a second pair of measuring electrodes. Most often, each measured location is equipped with a set of electrodes welded on surface of the assessed body. The number of electrodes, their material and type of insulation are always adapted to the operating conditions of a specific application. The challenging part is to optimize the distribution of electrodes for maximum sensitivity to the formation of a crack or loss of wall thickness of the monitored area (in industry, most likely a pipeline) [2].

The measurement of DC signals can be affected by interfering both DC and AC voltage. The example of an interfering DC voltage is a thermoelectric voltage that can arise at the junction of the electrodes and the monitored object. These interfering signals can usually be eliminated by the measurement method. Alternating interference signals can be filtered out during measurement by a low pass filter.

3 Application of DCPD for monitoring critical parts in industry

Following the experience with the PD method in industry, where usually the critical parts of steam pipeline of nuclear and conventional power plants are online monitored, there is demand for a new device and improved methodology. The monitoring system, which is currently being deployed, is intended to serve to identify the occurrence and monitor the growth of defects even at high temperatures and pressures of the flowing medium. However, its results are not always clear-cut. We are looking for the optimal location of sensing electrodes to obtain sufficient sensitivity of the method itself.

The main task of the project is the development of a new multi-channel online device for early detection of cracks or changes in the wall thickness of the monitored part. The derived monitored parameters are also investigated as part of the development of this device. These parameters must be clean and uniform for operators to evaluate. This should also limit false indications and partially reduce the influencing factors of the measurement such as the influence of different temperatures during long-term monitoring.

Fig. 1 *Monitored section of steam pipeline in industry*

4 Experimental tests

The tests were carried out on samples of a material, which correspond to real parts of the power plant's steam pipelines. To assess the effect of defect production, basic tests were carried out on straight steel prisms. Cracks were produced by cyclic loading of first test samples on a three-point bend. The artificial defect in other 6 samples was a very thin groove produced by Electrical Discharge Machining (EDM). The artificial defect was made to a depth of 2 mm and then further gradually deepened in steps of 2 mm. The samples were divided into three groups: some of the samples were tested at ambient temperature (20 °C) other samples were tested at operating temperature (550 °C) and selected samples, the *as real* configuration described below, were tested at both ambient and operating temperature. The results of these tests were compared with simulation results from Ansys Maxwell. The trends are shown in the graph below (Fig. 2). Because the influence of the defect production method on the measured results was not confirmed, the EDM technology was used for the *as real* test specimens.

The basis of the samples simulating real defects are pipes with excitation and measuring electrodes welded on the surface. Support feet and thermocouples were also accessories of the samples. Two types of samples were produced, thin-walled and thick-walled. In both types of samples, artificial defects were made in the middle part of the body. The location of the defect origin is outside the axis of the current channel of the excitation electrodes on the outer surface of the test sample. The reason for this configuration is to monitor the sensitivity of the DCPD method to real defects that are initiated generally in random position to the electrodes. In the thin-walled sample (Fig. 3), the defect was designed at an angle of 30 ° simulating a taper in the base material and the heat-affected zone of the weld joint. In the thick-walled sample, the defect was perpendicular to the axis of the body. Fig. 3 also shows the detailed views of the complete location of the electrodes placement. Reference measurements on the tested samples were always without defects at room temperature and increased (operating) temperature. The crack growth was in predefined steps for both test samples types. The defect was stopped at a depth corresponding to the wall thickness of the test sample (all the way through the material). The signals of all channels were measured at each step by three independent systems at different excitation currents. To reduce signal disturbance due to noise and parasitic DC voltages, rather large currents (up to 20 A) were used. Fig. 4 shows the effect of such disturbance at a low excitation current (1 A). In contrast, Fig. 5 shows the voltage values for different depth of cracksat an excitation current of 10 A. There, the measured voltage values is uniform (monotonic) as expected. All measured primary voltages were compared with calculated values and transformed to graphs.

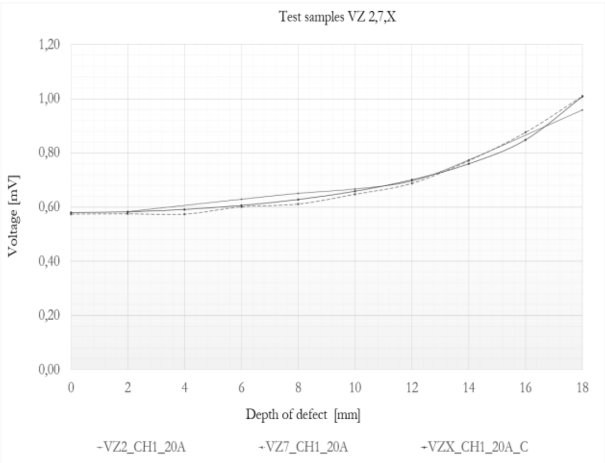

Fig. 2 *Comparison of signals from testing samples with crack, EDM slot and numerical calculations for current 20 A*

5 Position of measuring channels

Usual electrode configurations are briefly listed in [2]. The DROPOT system uses yet another approach. Refering to Fig. 3, there were eight electrode bundles in predefined measuring points divided into two groups (A and B). The four measuring points of group A, located in the longitudinal axis of the specimen, were assigned to the channels CH1A – CH4A of the monitoring system. The arrangement of the electrode bundles was rotated from the defect axis by 22.5 ° for channel CH1A, and the individual channels 1 - 4 of group A were always rotated by 90 ° relative to one another. Multichannel measuremet on a single monitored part enables use of derived parameter described later.

The channels of group B used the excitation electrodes of group A, but the measuring electrodes were located along the diagonal line connecting these electrodes. The measuring points of group B were located in such a way that a larger area was monitored without the need to increase the number of supply electrodes. For supply electrodes, the cross-section of the connecting electrodes was increased due to the requirement for measurements at a higher excitation current. The same configuration of connecting electrodes was used for both tubular test specimens.

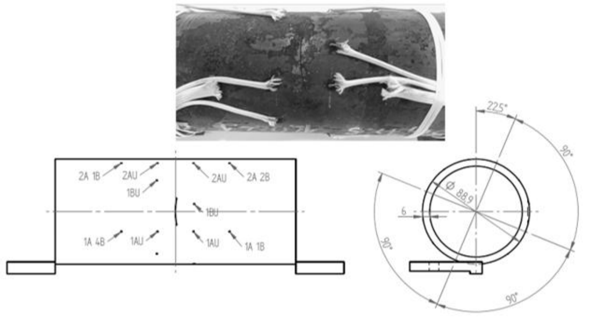

Fig. 3 *Location of electrodes on the surface of the ZT003 test specimen (thin-walled body)*

The formation and growth of a crack in the monitored location is indicated by the changes in the electric field potential measured using eight pairs of evenly spaced electrodes. Changes in the electric potential characterize the "deformation" of the electric field in the vicinity of the monitored location, which is caused by some inhomogeneity possibly caused by the formation and propagation of the defect. The same electrode arrangement was applied for all three measurement methods. The basic measurement used for evaluating the results was carried out with a laboratory voltmeter and a current source. As the second measuring device, POTERON PD-05 by Sobriety the critical parts monitoring system applied in the energy industry, was used. The main tested system was the new developed monitoring system. For a basic comparison of the measured values by the used systems, the results were converted to electric resistance. To compare the voltages obtained from each setup, those were converted to the voltage of the equivalent current, because the excitation current was not exactly same by all of the considered systems.

6 Processing and results

For illustration, the graphs in Fig. 4 and Fig. 5 show the voltage dependence on the depth of the defect. The graphs present results from test sample No. 2 (VZ2), channel 1 (blue) and channel 2 (green) of electrode groups A and B. The solid lines are the results measured with a laboratory microvoltmeter. The dashed lines are the results of the newly developed DROPOT unit in the legend marked with the letter D, and the red line (marked with the letter C) shows calculated values. Numerical simulations of the electric field are presented in the next section.

The measured voltage is largely influenced by the stability and accuracy of the power supply. This is a direct dependence, and therefore the results of some measuring systems might not be correct. In these systems, it is assumed that the value of the excitation current is constant (unchanging and equal to the set value), but this may not always correspond to reality. Oddly enough, it is not completely common to read the actual excitation current in all obtainable DCPD devices although it is necessary to make reliable resistance measurement. The DROPOT system uses calibrated high stability current sensing shunt.

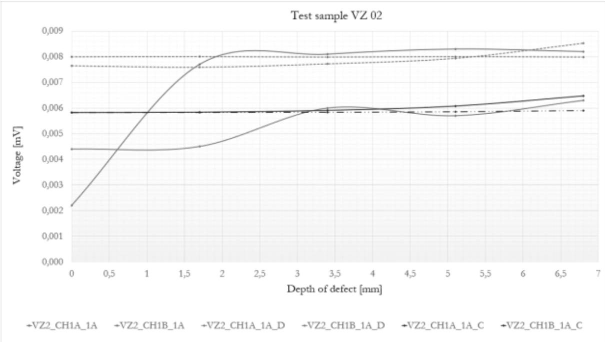

Fig. 4 *Comparison of electrode groups A, B of channel no. 1, 2 and calculated values for current 1 A*

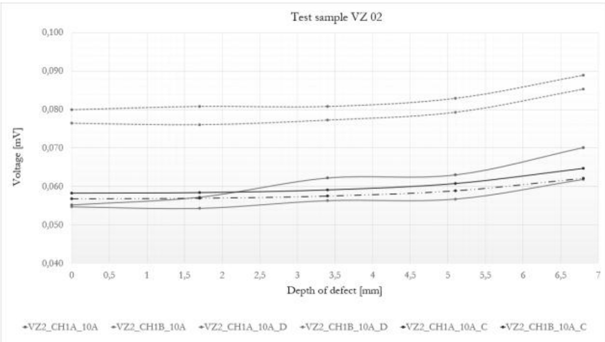

Fig. 5 *Comparison of electrode groups A, B of channel no. 1, 2 and calculated values for current 10A*

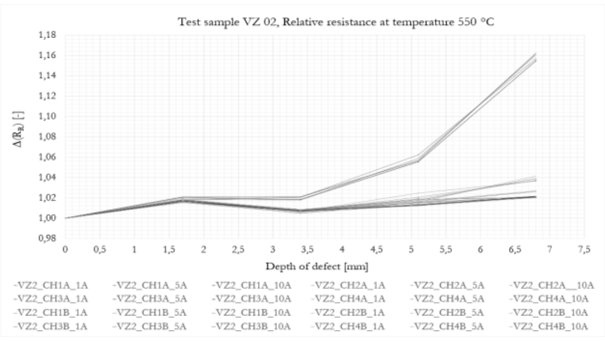

Fig. 6 *Changes in relative resistivity of electrode groups A, B of channel no. 1 – 4 at a temperature of 550 °C, Developed system*

As part of the evaluation, derived parameters were created from the measured values. One of the simpler one, the relative resistance (relative to the first value) curve shows the sensitivity to changes, see the graph in Fig. 6. The influence of temperature should be reduced and the evaluation method simplified. One of the applicable parameters is the relative resistance value normalized by the average resistance value of the channels of each group of the same configuration. The parameter is referred to as *Si* in the following analysis an is calculated according to equation (1). The example of the behavior of this parameter in the dependence on the change in the depth of the defect is shown on Fig. 7.

$$S_i = \frac{R_i}{R_{avg}} \; [-, \Omega] \tag{1}$$

Where:

$$R_{avg} = \frac{\sum_1^n R_i}{n} \; [\Omega] \tag{2}$$

Where:
R_i…Single channel resistance [Ω];
n…Number of channels [-].

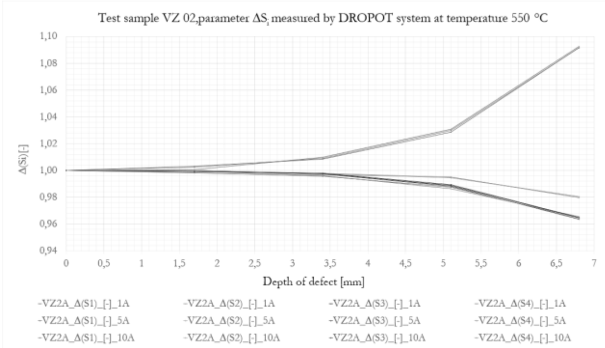

Fig. 7 *Trend of the new parameter ΔSi of electrode groups A of channel no. 1 – 4 at a temperature of 550 °C, Developed system*

7 Numerical calculations and field modelling

A 3D simulation was carried out to model the distribution of electric potential under steady-state DC conduction conditions. The numerical analysis was performed using the finite element method (FEM), implemented in Ansys Maxwell within the Ansys Electronics Desktop (version 2024 R2) environment. The selected solution type was Electric – DC Conduction. The simulated 3D geometry reproduced the actual experimental sample. Excitations were applied at specific points according to the physical setup. A current excitationalong with a ground potential, were introduced. Meshing was handled through adaptive mesh refinement, with Ansys Maxwell automatically refining the mesh to meet the predefined solution accuracy of 1 %. The Auto Mesh method was used, employing curved surface meshing with a normal deviation angle of 5°. Additionally, length-based local mesh refinement was applied around the excitations and at selected points, corresponding to the locations of the probes in the physical experiment, to further improve accuracy. The analysis setup was configured with the following parameters: a minimum of 2 converged passes, mesh refinement per pass set to 30%, and a non-linear residual tolerance of 0.001. The solution provided the voltage distribution across the sample surface, along with specific values at selected points. This distribution was visualized using Field Overlays (see Fig. 8).

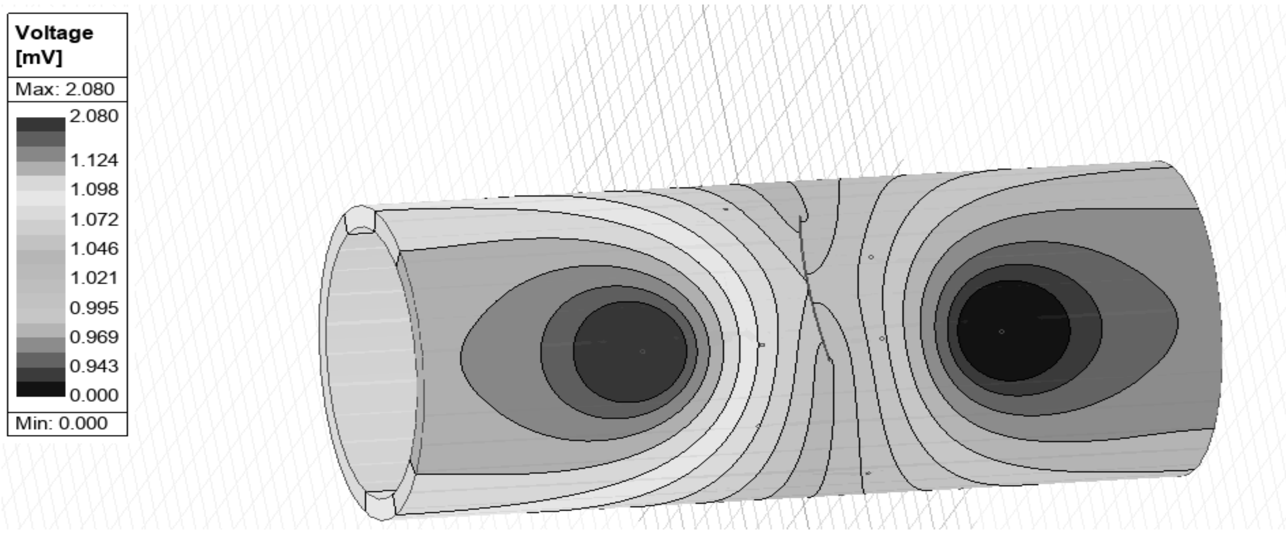

***Fig. 8** Distribution of the electric field (electric potential) in the test sample*

8 Summary and conclusion

Research centre Řež, as part of its long-term development concept, is engaged in the development of non-destructive testing methods. This involves the detection of operational defects and monitoring their growth with the aim of increasing the reliability of operation of all types of power plants. Above all, it involves the early detection of the risk of a fault condition and thus preventing unexpected production outages.

Presented is a technical solution of a newly developed measuring device, and a summary of experience gained from experimental tests. The current development of the PD method is focused on an online diagnostic system for measuring and evaluating critical points of steam pipelines, fittings and other components in real time. The tests were carried out in order to assess the sensitivity and reliability of the developed monitoring system. These evaluation measurements were performed on test specimens with various types of crack damage development for the purpose of verifying its detection. The measured results were compared with simulations based on the FEM, performed using Ansys Maxwell

To ensure high signal quality of the DCPD method, it is crucial to use sufficiently large excitation current. The current should reflect the dimensions of the monitored component. To eliminate the influence of thermoelectric voltage and other DC parasitic signals, it is advisable to measure a sufficient number of samples in reversed polarities. AC interference must be filtered out to prevent signal disturbance. New configuration of electrode (connection) placement was also proposed to increase sensitivity.

The evaluation method created and tested is sensitive enough to determine the condition of the monitored parts of the steam pipelines. The results so far indicate that the response of the developed DCPD measuring device is sufficient to practical applications and thus is suitable for online monitoring of cracks and changes in wall thickness in local areas of piping including steam pipes, fittings, T-pieces, etc. during operational loads.

The current development for further improving this method is now focused on the connection to the examined body. The goal is to minimize the line losses and to ensure most reliable attachment to the surface. The mathematical model, once verified, will serve to optimize the electrodes location.

Acknowledgement

The presented work has been realized within Institutional Support by Ministry of Industry and Trade of the Czech Republic.

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