NONDESTRUCTIVE MEASUREMENT OF THE RESPOSE OF REAR-WALL FLAWS IN THICK-WALLED STRUCTURES USING DC FOUR-POINT-PROBES TECHNIQUE

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Abstract

Repeatable and accurate evaluation of flaws from the inaccessible sides of thick-walled structures is still remained as one of the hurdles in the field of NDE of flaws. The present paper describes the development of an effective DC potential-drop measuring system for evaluating the response of rear wall flaws, especially in thick-walled structures, in which an ideal averaging scheme is introduced with the help of an adjustable four-point-probes system. The capability of the present measuring system is extended here to the evaluation of rear-wall cracks as well as the reduction of wall thickness for the case of thick stainless steel structures. The reliability as well as accuracy of the measured potential drop responses is verified by comparing them with the corresponding responses obtained by theoretical analysis.

1. Introduction

The potential-drop method of evaluation is based on the principle that the electrical resistance of a body/location changes due to the presence of a geometrical defect or the change in the local electrical property of the material (*i.e.*, conductivity); the corresponding electrical potential across the defect/flaw is thus measured by sending a pulsed current to the test piece and compared with that at the position of no defect. The simplest version of the potential-drop measuring system uses two pairs of probes – one for current input and output, and the other for measuring the potential-drop.

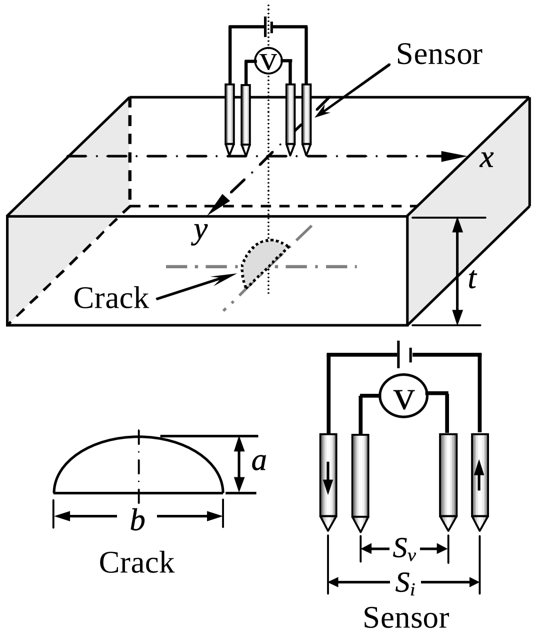
Both the DC [1-2] and AC [3-4] versions of the potential-drop method have been investigated. The Direct Current Potential Drop (DCPD) technique has gained wide acceptance in the field of nondestructive evaluation (NDE) as one of the most accurate and efficient methods of evaluation for the material flaws. The application of the method is, now a days, not only limited to the evaluation of material flaws/defects, rather it also includes metal sorting and alloy identification, monitoring the heat treatment of metallic alloys, evaluation of thickness reduction of pressure vessels, measuring the surface topography to determine local material conductivity, and so on.

Besides the simplicity as well as ease in its application, the DC potential drop method of testing has a number of specific advantages over other electromagnetic techniques of testing. For example, the alternating current flow is usually restricted to the regions near the surface of the test piece because of its skin effect, which eventually makes the ACPD and eddy current testing especially suitable for shallow defects on the measuring surface. The AC potential drop is related to frequency, magnetic permeability and material resistivity, along with those of current and geometrical parameters. However, DCPD measurements have the advantage of being independent of the magnetic permeability of the metal, so that the technique can be used to test the ferrous metals, whereas ACPD and eddy-current methods cannot. Special cares have to be taken in the measurement of ACPD as the induced electromotive force gives rise to a voltage in addition to that due to the flaw/defect, which is considered as the noise. Moreover, the design of a constant AC source is more complex than its DC counterpart. The DCPD method also works well for low-conductivity materials such as semiconductors and in geophysical applications because the measured potential is inversely proportional to material conductivity and, therefore, the signal-to-noise ratio improves as conductivity decreases. Eddy current methods lose accuracy as conductivity decreases.

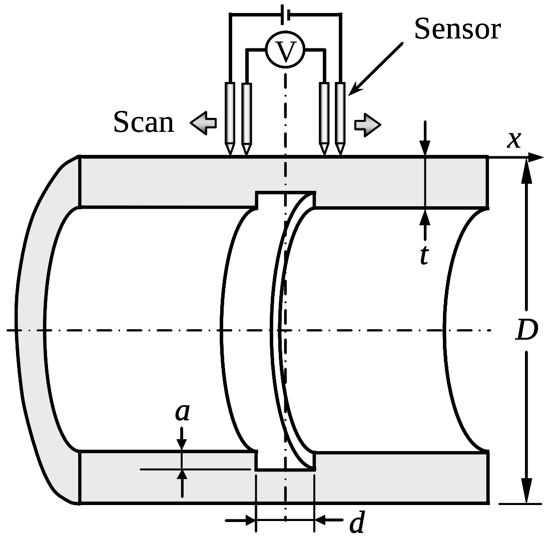
There is quite a long history of using DCPD technique to determine the size of surface cracks. However, the sensitivity of the method has recently been enhanced significantly by introducing the closely coupled probes potential drop (CCPPD) technique [2,5]. This technique, for the first time, makes the evaluation successful using a small measuring sensor which utilizes a small amount of current. It has been shown that DCPD technique can evaluate small closed cracks quantitatively, which has however not been successful using standard ultrasonic technique [6]. DCPD technique has not been successful only to the isolated cracks, but also the multiple cracks on the surface of a test sample [7].

Usually the electrical resistance across a rear-wall flaw is much lower than that of an identical flaw on the measuring surface and, this problem becomes more serious, especially for the case of thick-walled materials, which essentially requires a large current supply to penetrate deeper inside the material. For measuring the potential drop, the spring-loaded contact sensor comprising of both the current and potential probes, has recently found widespread acceptance. However, the potential-drop measured by the spring-loaded four-point-probes sensor usually shows scattering nature of variation of the measured data, even if the measurement is repeated at the same location. This scattering is primarily because of the given allowances between the spring loaded probes and the associated cylindrical passages guiding the probe, which is expected to be further influenced, to some extent, by the eccentricity of the probe-tip, the contact resistance between probe-tip and the material surface, and the electrical noises. These allowances provided for the fabrication of the spring-loaded sensor make the probe contact distances on the material surface different in successive application of the sensor, thereby showing random nature of variation of the measured potential drop. The scattering characteristic of the measured potential drop becomes more prominent when a large amount of current is injected for the evaluation. Therefore, to obtain the reliable responses of rear-wall flaws, accurate as well as repeatable measurement of the potential drop is of utmost importance.

In an attempt to enhance the measurement accuracy and repeatability, recently, an adjustable DC four-point-probes measuring system is developed. In the present approach, an averaging scheme is adopted for which the associated probe contact distances on the measuring surface are adjusted in successive measurements by refreshing the individual contacts of the spring-loaded probes to the surface. The present paper is an attempt to obtain the potential-drop responses for the evaluation of rear-wall cracks and thickness reduction of thick-walled structures using the measuring system developed.



(a) Semi-elliptical 3-D rear-wall crack



(b) Thickness reduction in a thick pipe

Figure 1: *Model of the measurement of rear-wall flaws*

The measurement of the potential drop is carried out using a new DCPD sensor [8-9], especially suitable for case of rear-wall flaws. The sensor has been designed in such a flexible way that the individual probe contacts can be refreshed during successive measurements without hampering the position of the sensor block. The optimum arrangements of the four probes are determined from the numerical simulation of the electric flaw problem, where a 3-D crack is considered as the limiting case [9]. Finally, the reliability as well as accuracy of the measured responses is verified by comparing them with those predicted by the finite-element method of simulation.

2. Model of measurement

The problem of measuring the potential-drop response of a flaw at the rear-wall of a three-dimensional test object is considered. Figure 1 illustrates the models of the measurement considered in the present article. Figure 1(a) shows the evaluation model of a three-dimensional semi-elliptical crack in a plate, where t is the wall-thickness, b the crack length and a the maximum crack depth. And, the evaluation model of wall-thinning for the case of a cylindrical pressure vessel is schematically illustrated in Fig. 1(b), where the corresponding depth and width of the material reduction are denoted by a and d, respectively. In order to evaluate the flaws from the opposite side, the constant direct-current, I is applied between the two symmetrical points with respect to the central position of the flaw on the measuring surface, which are at a distance of S_i from each other. The potential drop, V is measured between another two symmetrical points within the current input and output points, which are placed at a distance of S_v from each other. Therefore, the four-point-probes form a linear array on the measuring surface, the center of which coincides with the origin of the coordinate system shown in Fig. 1.

In the present measuring approach, the difference in two potential-drops obtained using the same measuring system under same operating conditions is used to evaluate the flaw. One of the measurements is made across the flaw (V_1), where the four-point-probes sensor is placed symmetrically at the centre of the flaw, and the other is made at a region of the object where the potential-drop is largely unaffected by the flaw, or in an identical sample having no flaw (V_0). The increase in the potential drop due to the flaw, ΔV is given by the following simple equation of measurement:

$$\Delta V = V_1 - V_0 \tag{1}$$

3. Numerical simulation of the electric problem having flaws

The electrical problems having rear-wall flaws are analyzed by the finite element method of solution in an attempt to predict the suitable measuring conditions as well as the increase in potential drop due to the flaw. The three-dimensional steady state direct current flow in a material is governed by the Laplace equation, which is,

$$\frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2} = 0 \tag{2}$$

where, f (x,y,z) is the electrical potential. The distribution of the potential within the material is obtained from the solution of Eq. (2). In obtaining the solution, the domain concerned is discretized using 8-noded isoparametric 3-D elements, in which very fine meshes are used, particularly around the position of the flaw as well as the contact regions of the two current and two measuring probes on the measuring surface. The electrical resistivity of the materials has been determined by the direct measurement on the samples using the CCPPD sensor [5], in which the distances between the current and measuring probes were S_i = 6 mm and S_v = 3 mm, respectively.

In the present paper, a test object having a thickness of 40 mm is considered as an example of a typical thick-walled structure. For the case of a 40 mm-thick plate/cylinder, the results of the numerical simulation show that the maximum increase in the potential drop, ΔV, due to a 3-D rear-wall crack can be obtained when the measuring points are selected at positions, $x = \pm 30$ mm along the x-axis, and these positions are found to be independent of distance between the current input and output positions [9]. A distance between the current input and output probes of S_i = 80 mm is selected to be the optimum one for the practical measurement of flaws in components having t = 40 mm. In an attempt to evaluate the reduction of wall thickness from the inner-wall of a pressure vessel, the electrical problem having a slot-like flaw at the rear/inner-wall is studied numerically for predicting the corresponding potential-drop response. Considering a small three-dimensional crack as the limiting case of the rear-wall flaws, the corresponding measuring conditions obtained from the simulation are used here for measuring the responses of both the cracks and wall thinning.

4. DCPD measuring system

The measuring system consists of a constant DC source, digital multimeter, shunt resistor, switching circuits, etc. The constant direct current supply source is used to inject the required current to the test material through the current input and output probes. For measuring the potential-drop, a digital multimeter having the resolution of 0.1μV is connected to the measuring probes. A shunt resistor is connected to the measuring circuit mainly to monitor the variation of the supplied current during the measurement. A simplified version of the circuit diagram of the measuring system is shown in Fig. 2. Two switches are adopted in the measuring circuit in order to bring the stability in current flow as well as to supply the pulsed current.

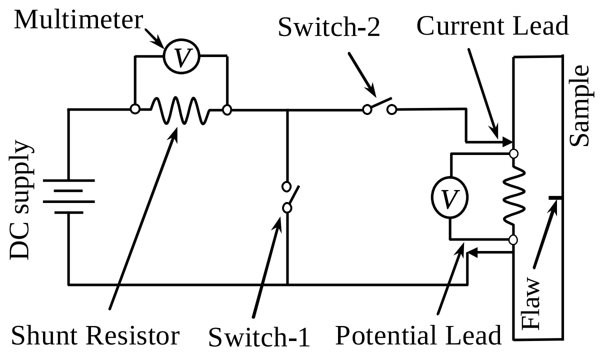


Figure 2 : *Simplified circuit diagram of the DCPD measuring system*

For designing the sensor, simple spring loaded contact probes are considered for both the purposes of current supply and measurement of the potential-drop. Following the results of numerical simulation, the current and measuring probes were synthesized to develop an accurate and compact four-point-probes sensor in such a way that measurements can be performed with various probes distances of interest. Figure 3 illustrates the details of the DCPD measuring sensor developed especially for the evaluation of rear-wall flaws. The metallic probes used for both the current supply and measurement were of same dimensions and made of stainless steel. The allowance between each probe and the associated cylindrical guide was set to be 0.05 mm

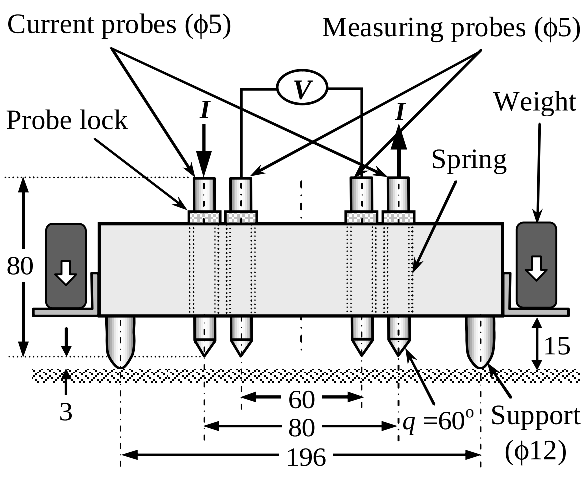


Figure 3 : *Details of the DCPD measuring sensor (dimensions in mm)*

for each of the probes. The sensor has a three-point supporting system, which makes the developed sensor equally effective for applying to the flat as well as curved surfaces of interest. The contact of every probe to the measuring surface is kept under constant pressure by the use of four identical compression springs attached with the probes, and constant dead weights at the two ends of the sensor block, as shown in Fig. 3. The probes are set in such a flexible fashion that the individual probe contacts can be refreshed before each measurement, which, in turn, allows fine adjustment of the associated probe contact distances in successive measurements without hampering the position of the sensor as a whole.

5. Measuring approach

Every new contact of the spring loaded sensor to the material surface causes the associated probe contact distances to slightly deviate from their true design values, the variation of which is random in nature. It has been verified by both experiment and calculation that, as far as the fabrication allowance/tolerance is concerned, refreshing the individual probe contacts in successive measurements would bring the corresponding effect of random variation of the probe contact distances on the material surface.

In an attempt to bring repeatability in the measurement, considering the above facts, an ideal averaging scheme is adopted in our present measurement where the associated probe contact distances are adjusted in successive measurements by refreshing the random contacts of the spring-loaded probes individually, without disturbing the position of the sensor as a whole. In an attempt to get rid of the problem of Joule heating, the current is pulsed using an on/off operating system through the Switches-1 and 2, and is supplied only for the period of measurement. A total of 40~60 measurements are performed at every location of interest, the average of which is considered as the representative data. The response of the rear-wall slot was measured by using a scanning approach of the present sensor. The discrete measurements were performed by scanning the sensor along the *x*-axis with a pitch of 10mm, where the probes were kept under non-contact condition while sliding the sensor on the surface. The same averaging scheme is applied to obtain the representative data of the potential drop as a function of the sensor location on the measuring surface. The measurements were performed under a constant current supply of 20 A, at a room temperature of 25°C.

6. Measurement of responses against the rear-wall crack

A 3-D semi-elliptical crack at the rear-wall of a thick plate is tested for the evaluation of its depth using the measuring system developed. The sample was prepared as plate, as shown in Fig. 1(a), having the dimensions of (300x300x40) mm, from the original sample of austenitic stainless steel, SUS304, the electrical resistivity of which is found to be 71.5 × 10^{-8} Ωm. The crack in the sample has the following dimensions: a/t = 0.37, b/a = 4.7. The crack is modeled here by the machined slit having extremely narrow width, d = 0.5 mm.

The results of measurement for the crack are summarized in Table 1. The detailed measurement at a position of no crack (V_0) and at the position of the crack (V_1) and the associated standard deviations are presented in the table. For each of the potential-drops, V_1 and V_0, a total of sixty measurements were performed at the identical position of the sensor, the average of which is considered as the representative data. In order to take the random combination of the probe distances into account, the individual probe contacts were refreshed in successive measurements. The average of the measured potential drops across the position of the crack as well as no crack is also compared with the corresponding potential drops obtained by the finite-element method of simulation, which is also shown in Table 1. The average values of V_1 and V_0 and also the change in the potential drop due to the crack, ΔV are found to be in very good agreement with the theoretical prediction of the potential drops. Results of the present experiment and also the comparison with numerical simulation thus verify the potential of the present adjustable approach of DCPD measurement for evaluating 3-D rear-wall cracks in thick-walled structures.

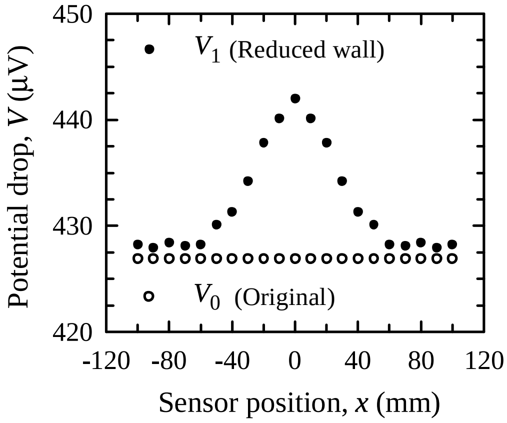
7. Measurement of responses against the reduction of wall thickness

There is a need from industry to develop suitable potential drop technique for the quantitative testing as well as monitoring of wall thinning of piping, especially in power plants. Corrosion and erosion in pipe flow causes the reduction of material from the inner wall of piping systems, which eventually leads to the problem of wall thinning, and is required to be tested nondestructively in order to ensure the overall safety as well as reliability of the power plants. The problem of evaluation of thickness reduction at the inner-wall of cylindrical pipe structures is modeled here by the machined slots as evaluated from the opposite sides of thick plate structures. Two samples having the dimensions of (500x300x40) mm are prepared as plates from the material of SUS304 for measuring the associated potential drop responses. One of the samples contains a shallow slot of dimensions a/t = 0.25, b/a = 30.0, d = 20.0 mm (Sample-A), and the other is a limiting case of the slot having the dimensions of a/t = 0.25, b/a = 30.0, and d = 1.0 mm. The plates used to prepare the present slot samples are taken from a different lot of stainless steel, the electrical resistivity of which is found to be 70.5 × 10^{-8} Ωm.

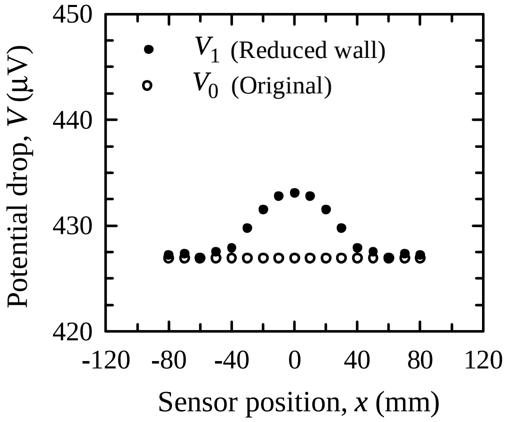
The potential drop responses against the rear-wall slots in the plates are obtained by changing the position of the sensor on the measuring surface along the x-axis, under the constant current supply of I = 20 A. For measuring the responses against the thickness reduction, a total of forty measurements were performed at each scanning position of the sensor, the average of which is considered as the representative potential drop, V_1 for a particular scan position. Figure 4 shows the average of the measured potential drops for the Sample-A and B, as a function of the sensor position on the measuring surface, along with that obtained for the case of no flaw. The measured responses clearly identify the reduction of plate

Table 1 : Results of measurement for the cracked sample (r = 71.5×10^{-8} Wm)

20	60	430.1	0.99	435.6	0.84	5.5	431.5	5.4



(a) Sample-A



(b) Sample-B

Figure 4 : *Measured responses of potential-drop against the thickness reductions in Sample-A and B* (*$r = 70.5\times10^{-8}$ Wm; $I = 20$ A*)

thickness from its original value; the reduction of thickness, in fact, increases the resistance to current flow, which, in turn, gives rise to a symmetrical increase in the potential drop around the slot center, compared to that obtained for the case of no reduction in its thickness. Finally, in an attempt to check the reliability as well as accuracy of the measured potential drop responses, the electric problems having the slots were also analyzed by finite element method of simulation. Figure 5 demonstrates the comparison of the distributions of the change in potential drops due to the reduction of thickness, as obtained by the direct measurement and FE simulation for both the cases of Sample-A. The responses obtained by the present adjustable measuring system are found to be in excellent agreement with the corresponding theoretical predictions, thereby verifying the potential of quantitatively testing the wall-thinning of piping systems with accuracy and reliability.

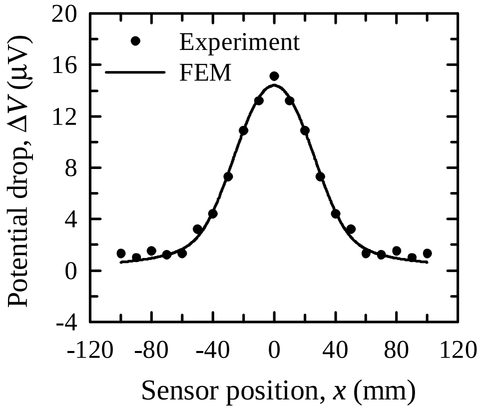


Figure 5 : *Comparison of measured and theoretical responses of potential-drop for Sample-A* (*$r = 70.5\times10^{-8}$ Wm; $I = 20$ A*)

8. Conclusions

An adjustable DC four-point-probes measuring system for testing rear-wall flaws, especially in thick-walled structures has been described, experimentally implemented, and verified by comparing with theoretical analysis. In the present approach, taking the random variations of the probe contact distances on the measuring surface into account, an ideal averaging scheme is adopted, in which the individual contacts of the spring-loaded probes to the surface are refreshed in successive measurements. The average value of the measured potential-drops is treated as the fixed value for a particular sensor, which shows sufficiently high repeatability as well as accuracy and, thereby establishes the appropriateness as well as suitability of the present measuring approach for the evaluation of flaws from the inaccessible side of thick-walled structures.

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9. References

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