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THE MEASUREMENT OF WALL THICKNESS OF METAL FROM ONE SIDE ONLY, BY THE DIRECT CURRENT CONDUCTION METHOD

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J. G. BUCHANAN, F. W. MARSH, & R. C. A. THURSTON

PHYSICAL METALLURGY DIVISION

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The Measurement Of Wall Thickness Of Metal From One Side Only, By The Direct Current Conduction Method

BY J. G. BUCHANAN*, F. W. MARSH* AND R. C. A. THURSTON**
Ottawa, Ontario, Canada

A direct-current conduction method is described for the measurement of wall thickness of metal from one side only. Essentially the method involves the measurement of the resistance of an area, roughly circular, by means of a 4-electrode array; an increase in the 'resistance' indicates a decrease in thickness, and vice versa.

The theory of the method is developed, and equations derived for the relationship between the ratio V/I (potential difference/current) and the wall thickness for the general and the two-dimensional case. In the latter, the thickness is directly proportional to the current, if the potential difference is maintained constant. From the equations the most suitable electrode spacing can be determined for any specific application. Edge correction factors for arrays parallel and perpendicular to an edge are tabulated.

Full details of the apparatus, current circuit, potential circuit, and electrode head are given, together with a satisfactory testing procedure. A modification using 6 electrodes is suggested for cases where the resistivity of the material is not known, and no sample of the material of known thickness is readily available.

Finally, examples of the practical application of the method and equipment for measuring corrosion thinning in steel plates, defects in plates, wall thinning of tubes, and lack of bonding are presented.

INTRODUCTION

Many different methods of measuring the wall thickness of metals from one side only are in use, e.g. the resonant acoustic, radiation scattering, eddy current, induction and magnetic methods, but there are drawbacks to each of them which make their use in certain circumstances difficult or even impossible.

The purpose of this paper is to describe a simple method of wall thickness measurement which has been used successfully by others (3, 6) and to give the theoretical background which places the method on a firmer foundation and also makes it more useful.

Basically the method involves the measurement of the "resistance" of an area of metal with a 4-electrode array. An increase in the "resistance" indicates a decrease in thickness, and vice versa. Using four point electrodes, two being current electrodes and two potential electrodes, this resistance can be measured independently of the contact resistance between the electrode points and the metal surface, by a method described later.

The theory of the 4-electrode array was first worked out by Wenner(5), who applied the method to the measurement of earth resistivity. It was further developed by many other geophysicists including Roman(4), who established the corrections for finite thickness beds (plates) of varying thickness overlying a bed with different resistivity.

The method was applied to metals by Putnam(6) for measuring plate thickness, and was used quite extensively by Thornton and Thornton(3) on a wide variety of problems in nondestructive testing, including wall thickness of pressure vessels, ship hulls and boiler tubes, as well as the detection of core shift in castings. The method can also be used for crack detection and crack depth measurement(1).

THEORY OF THE METHOD

Consider the potential distribution caused by a current I (amp.) flowing into a slab of material of resistivity ρ (ohm-cm.) and thickness T (cm.) through a point electrode, as illustrated in Fig. 1(a). For the moment, assume that the sink or return for this current is remote from the electrode so that the current flow and potential field are axially symmetric. Then the potential at any point on the upper surface distance r (cm.) away from the source is given by(4)

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**Engineering Physicists and* ***Head, Engineering Physics Section, Physical Metallurgy Division, Mines Branch, Department of Mines and Technical Surveys, Ottawa, Ontario, Canada.*

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$$* \quad V = \frac{I\rho}{2\pi r} - \frac{I\rho}{4\pi T} \cdot M\left(\frac{r}{2T}\right) \tag{1}$$

where M is a function tabulated by Uhlir(2) and in a slightly different form by Roman(4). In the latter case the author tabulates a function $W\left(\frac{r}{2T}\right)$ where $W = -1/2M$.

To complete the circuit, a negative source (or sink) having the same current I can be placed on the same plate some distance away from the positive source, and then the potential at any point (or the potential difference between two points) can be found by superposition of the potentials due to the positive and negative sources.

As a fairly general case, consider a pair of potential electrodes placed centrally between the two current electrodes and in line with them, such that the distance between potential electrodes is B (cm.) and the distance from either current electrode to the adjacent potential electrode is A as in Fig. 1(b). Calling the electrodes C_1, P_1, P_2, and C_2, we have

$V_{p1\ p2}$ due to $+I$ at C_1

$$= \left[\frac{I\rho}{2\pi A} - \frac{I\rho}{4\pi T} \cdot M\left(\frac{A}{2T}\right)\right] - \left[\frac{I\rho}{2\pi(A+B)} - \frac{I\rho}{4\pi T} \cdot M\left(\frac{A+B}{2T}\right)\right] \tag{2}$$

and $V_{p1\ p2}$ due to $-$ I at C_2

$$= -\left[\frac{I\rho}{2\pi(A+B)} - \frac{I\rho}{4\pi T} M\left(\frac{A+B}{2T}\right)\right] + \left[\frac{I\rho}{2\pi A} - \frac{I\rho}{4\pi T} M\left(\frac{A}{2T}\right)\right] \tag{3}$$

Therefore the total potential between P_1 and P_2 is

$$V = \frac{I\rho}{2\pi A}\left[\frac{2B}{A+B} + \frac{A}{T}\left\{M\left(\frac{A+B}{2T}\right) - M\left(\frac{A}{2T}\right)\right\}\right] \tag{4}$$

or

$$\frac{2\pi AV}{I\rho} = \left[\frac{2\frac{B}{A}}{1+\frac{B}{A}} + \frac{1}{\frac{T}{A}}\left\{M\left(\frac{1+\frac{B}{A}}{2\frac{T}{A}}\right) - M\left(\frac{1}{2\frac{T}{A}}\right)\right\}\right] \tag{5}$$

$$= K'$$

As T becomes small, the current flow becomes two-dimensional and in this case the potential due to a single electrode is

$$V = \frac{I\rho}{2\pi T}\ \mathrm{Log}_e \frac{1}{r} \tag{6}$$

and the potential difference between P_1 and P_2 in a 4-electrode array having the configuration shown in Fig. 1(b) is,

$$V = \frac{I\rho}{\pi T}\ \mathrm{Log}_e\left(1+\frac{B}{A}\right) \tag{7}$$

or

$$\frac{2\pi AV}{I\rho} = K' = 2\frac{A}{T}\mathrm{Log}_e\left(1+\frac{B}{A}\right) \tag{8}$$

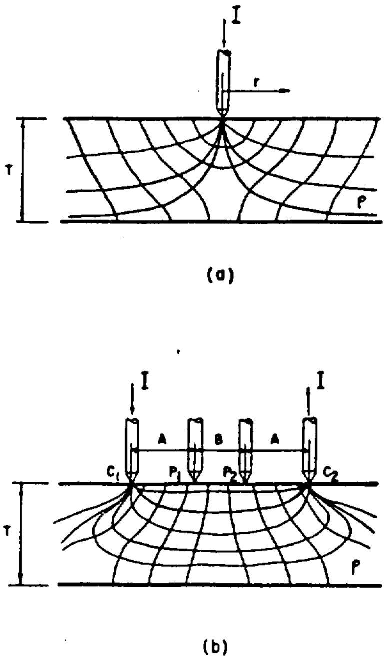

Figure 1—Current Flow Lines and Potential Surfaces In A Plate For
(a) A single electrode and
(b) A four electrode array

Equations 5 and 8 illustrate the way in which the ratio V/I, or the "resistance", changes with thickness, i.e. the ratio decreases as the thickness increases. In Fig. 2, K' is plotted against T/A with B/A as family parameter. Note that in the two dimensional case, equation 8, the thickness is directly proportional to the current if constant potential is maintained, and also, the potential depends on the ratio B/A but not A alone.

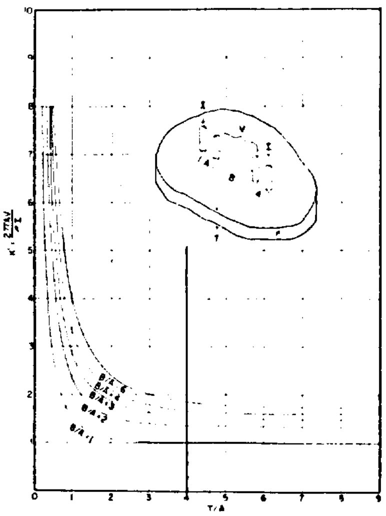

Figure 2—Calibration Curves For a Four-Electrode Array On An Infinite Plate

The two equations, 5 and 8, provide sufficient information to permit one to calculate the spacing which gives the required sensitivity and range for any particular case.

All of the above work applies to the example of a slab having infinite lateral extent, but in many cases thickness measurements are required near an edge and correction factors are required. The general method of obtaining theoretical correction factors for edges is to place identical current electrodes at mirror image positions with regard to the edge or boundary in question, and then recalculate $V_{p1\ p2}$ due to these four current sources, assuming the boundary does not exist. The method of "images" simulates the case where no current crosses the boundary, and therefore the solution must be true for two current sources and a real boundary. This calculation has been made for *equally* spaced electrodes for the two cases of (a) the line of electrodes parallel to a boundry and (b) the line of electrodes perpendicular to a boundary. Table 1, taken from Uhlir's paper, shows values of K' for these two cases for various values of L/A, where L is the distance

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*This relation has been rearranged from the original such that $M = -2W$, where W is the function tabulated by Roman.

Table 1(2). Values of K' for Equally Spaced Array $\left(\frac{B}{A} = 1\right)$ Near an Edge of a Semi-Infinite Plate.

T/A	ARRAY PARALLEL TO EDGE L = Distance from Line of Array to Edge.					ARRAY PERPENDICULAR TO EDGE L = Distance from Nearest Electrode to Edge.					
	L/A					L/A					L/A
	0	0.5	1	5	10	0	0.5	1	5	10	∞
10	2.002	1.52	1.19	1.004	1.002	1.450	1.333	1.060	1.004	1.002	1.001
1	3.009	2.45	1.98	1.534	1.512	2.033	1.730	1.638	1.522	1.510	1.504
0.2	13.863	11.51	9.28	7.078	6.969	9.282	8.047	7.599	7.022	6.960	6.932
0.1	27.726	23.03	18.59	14.156	13.938	18.563	16.094	15.198	14.043	13.920	13.863

of the electrodes from the edge (the nearest electrode in case (b).

Corrections for unequal electrode spacings can be obtained for any particular spacing by the method described above.

Applying the method to thickness measurement in practice requires that either the resistivity of the material is known to the required accuracy, or a reading be taken on a plate of known thickness and the same material as the plates to be tested. The latter method measures the resistivity in effect. This is not always possible, and in such a case two readings on the same plate with two different sets of electrode spacings will provide sufficient information to calculate the thickness. In practice, six electrodes(3) are used: one set of four for the first reading and the remaining two, along with two of the first electrodes, for the second reading. The calibration of the 6-electrode method can be done by calculation, using equation 5, or can be done directly on plates of varying thickness.

APPARATUS

The apparatus is similar to that used for crack depth measurement(1), and is shown schematically in Fig. 3 (equal spacing electrodes are shown, but unequal spacings can be used). For purposes of description the equipment can be divided into three components: the head, the current circuit, and the potential circuit. The head consists of the four electrodes (or six in some cases) and an insulating holder in which the electrodes can slide freely. Hardened drill steel makes good long-lasting electrodes.

The current circuit consists of a source of current, a meter, and a controlling rheostat. A source capable of delivering 10 amperes for the duration of the test will be required when working with large spacings or low resistivity metals, but smaller currents are frequently satisfactory. Providing current control for any given problem is not difficult. For example, if the problem is to measure thinning of 1/2 inch plate, and the constant potential method is used, current control over the expected range of thickness variations is sufficient, i.e., control from full scale current to 1/2 full scale covers the range from 1/2 inch to 1/4 inch. Providing control for a range of metals and spacings is more difficult.

The potential circuit is essentially a potentiometer consisting of a 1 1/2 volt dry cell, a dropping resistor, a voltage divider and a null galvanometer. The dropping resistor is calculated to give a voltage of about 100 microvolts across the voltage divider. The current in the current circuit should be adjusted so that the potential is at least 30 microvolts, this figure being chosen from experience to be larger than the thermal e.m.f.'s usually encountered.

When using a 6 electrode head the circuits are similar, with provision for switching the current circuit (or the potential circuit) from one pair of electrodes to another.

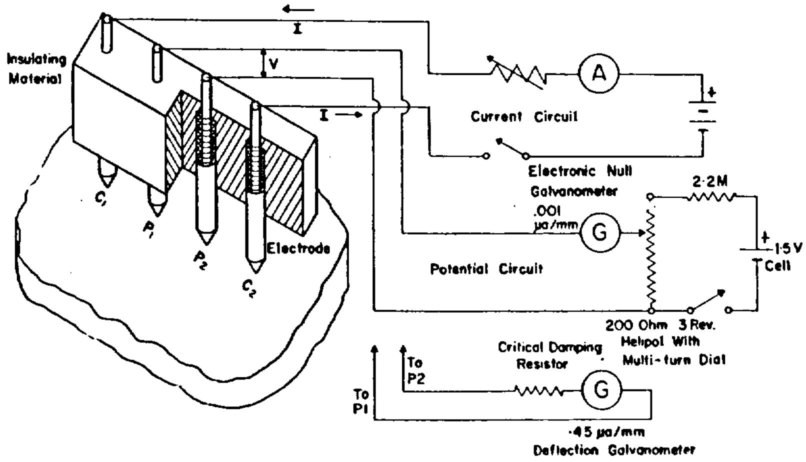

Figure 3—Schematic Illustration Of Equipment Used In Wall Thickness Measurement

TESTING PROCEDURE

Assuming that a suitable electrode spacing has been chosen for the particular problem at hand, the testing procedure is as follows:

1. Prepare the surface of a specimen of *known* thickness, so that electrical contact will be made at all electrodes. Freshly machined surfaces need no preparation, and mildly oxidized surfaces can be prepared easily by rubbing with emery cloth. For corroded or scaled surfaces, a convenient method is to scribe a heavy mark on the surface in the line where the electrodes are to be placed. Punch-marks at each electrode have also been used.

2. Apply the electrodes to the surface and make a steady contact. If the electrode head is hand-held, it should be designed so that the head itself can rest against the metal as the electrodes are pushed upwards. For magnetic materials a magnet attached to the head is useful. Clamping or weighting down the electrode head may also be used.

3. Energize the potential circuit (keeping the current circuit open) and balance out the thermal e.m.f. produced between P^1 and P^2 (or possibly other points in the potential circuit). This can be done either with a bucking-out circuit, or, more simply, by adjusting the zero on the galvanometer.

4. Apply a current I and measure V, the potential difference produced by this current flow (or some reading proportioned to V).

5. Repeat steps 1 to 4 on the specimen of unknown thickness, using either the same current as in the calibration procedure (constant current method) or the same potential (constant poten-

tal method).

6. Obtain the thickness from the ratio $\frac{V\ \text{test}}{V\ \text{cal}}$ (or $\frac{I\ \text{test}}{I\ \text{cal}}$) and a calibration chart.

APPLICATION TO SPECIFIC PROBLEMS

The first step in applying this technique is to choose the electrode spacing which will cover the range of thicknesses to be encountered with sufficient accuracy. For best sensitivity T/A should be less than 0.5, since for such values the current is proportional to the thickness (keeping the potential constant) thus making the calibration very simple. Using Fig. 2 or equations 5 and 8, the best spacing can be calculated. One controlling factor against increasing the spacing to an unlimited extent is that the method samples an area roughly circular in shape and encompassing all of the electrodes.

Having determined the spacing, the current required to produce a potential of at least 30 microvolts should be calculated from equation 5 or 8, and provision made to supply this current and give smooth control over the required range.

1. Corrosion Thinning in Steel Plate

Consider the problem of measuring corrosion thinning on mild steel hull plates which are nominally 1/2 inch thick, and whose thicknesses are to be measured from one side only to an accuracy of ± 1/64 inch, or 3%. As a trial spacing, assume A = 1 inch (T/A = 0.5) and B/A = 1. A comparison of values K′ calculated from equations 8 and 5 shows that they differ by less than 1% (2.77 and 2.78) and therefore with this spacing I would be proportional to T in the constant voltage method. Then a change of 3% in thickness would give a 3% change in meter reading, which would be quite readable. However, assuming a value of ρ equal to 15 x 10^{-6} ohm-cm., it can be shown (equation 8) that a current of 11.5 amperes is required to produce a potential difference of 30 microvolts. This current could be provided, but if a current less than 10 amperes was desirable, a value of 2 for B/A would increase K′ to 4.40 and reduce the current requirement to about 7 amperes. The latter choice of electrode spacing would sample a larger area, but would be subject to larger edge effects. For this spacing, a rheostat providing smooth control over the range 8 amperes to about 4 amperes (assuming a reduction in thickness of 50%) should be chosen.

2. Defects in Plate

A successful application of the direct current conduction method was made to a problem of detecting lamination-type defects in silicon bronze plate which were produced during rolling. These defects, which were quite large in extent (about 6 inches x 6 inches), always occurred at the centre of the plate, thus halving the thickness in effect. Ultrasonic reflection and through transmission techniques could not be used on this material, due to the large number of extraneous reflections produced by this particular alloy.

Defects could occur in the plates at any stage of the rolling from 2 inches thickness down to 0.4 inch. A head was designed to detect changes from 2 inches to 1 inch as the worst case; defects at any later stage producing much larger anomalous readings. The resistivity of the material was approximately 28 x 10^{-6} ohm-cm. and the width of the plate was 18 inches. A spacing having A = 1/2 inch and B = 2 inches was chosen. For a thickness, T, of 2 inches, this gives a value of K′ = 1.66 (B/A = 4, T/A = 4). To produce 30 microvolts, the current I, found from equation 5 and the value of K′, is equal to 5.14 amp.; 6 amperes were used in the test. Examination of the curves in Fig. 2 shows that when T/A decreases to 2 from 4, the value of K′ changes from 1.66 to 1.25, which is a significant change. If constant current is employed, the potential will increase in proportion to K′.

Results from tests on actual plates are presented in Fig. 4. They show that the readings followed the theoretical values as the plate was rolled down in thickness. Defects were found only in plates of less than 1/2 inch thickness, and in such cases, readings taken with the head placed over a defective area were considerably higher than those indicated in Fig. 4. Thus, defective areas were readily delineated with precision, as confirmed when some defective plates were sectioned.

3. Wall Thinning of Tubes

Thinning of the walls of tubes, due either to eccentricity during manufacture or to corrosion during use, has been measured extensively by Thornton[3]. For this work he used several types of heads, including one similar to that shown in Fig. 3. For some cases a series of knife edge electrodes combined with a clamp were used. For measurements from the inside of boiler tubes Putnam[6] used spring-loaded contacts, and Thornton used two sets of small wheel electrodes, again spring-loaded, which took readings simultaneously at opposite sides of a tube diameter. The latter author found difficulty in making steady contact through scaled surfaces.

In this work they found that current was proportional to wall thickness for thin walls, but that in general a new calibration was required for each new geometrical condition. The values found from the infinite plate theory should

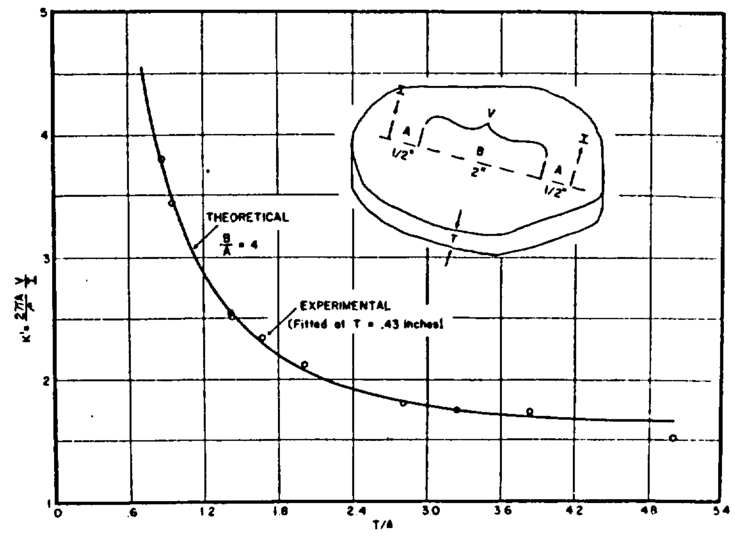

Figure 4—Theoretical and Experimental Values For Silicon Bronze Plate

hold to sufficient accuracy for the purpose of designing a suitable head.

4. Lack of Bond

The method can be used to determine lack of bond of a surface layer to an underlying layer. Equally-spaced electrodes with a spacing, A, equal to or greater than the upper surface layer thickness, can be used.

The method is not suitable if the ratio between the resistivities of the underlying layer and the surface layer is too high(4).

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