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E. G. Ramachandran, and K. V. Chinnappa

A METHOD FOR THE DETERMINATION OF STRESSES PRODUCED ON ELECTRO-DEPOSITION BY USING ELECTRICAL STRAIN GAUGES

By E. G. Ramachandran, M.Sc., Ph.D. (Sheffield)*
and
K. V. Chinnappa,† M.Sc., D.I.I.Sc.

ABSTRACT

It has been known from quite a long time that metals are electrodeposited in a state of stress. The stress is sometimes compressive and sometimes tensile, depending largely upon the metal and on the conditions of plating. Apart from throwing light on the mechanism and nature of electrodeposition, a knowledge of the stresses produced on electrodeposition is important wherever electrodeposition forms either an intermediate or the final operation in a fabrication process e.g., in electro forming, in making up the dimensions of working surfaces by electrodeposition, etc.

A few methods have been devised to determine the stresses produced on electrodeposition. These are largely dependent upon measuring by mechanical means, the distortion produced on a thin metallic strip during electrodeposition. While some extremely careful work has been done and quite reliable data have been obtained, there is scope for improvement in the methodology.

The accuracy and relative ease and simplicity by which stresses can be measured by employing electrical strain gauges prompted the authors to investigate the suitability of and devise a method for the determination of stresses produced on electrodeposition by employing electrical strain gauges. Certain initial difficulties were met and had to be overcome. Chief among these was the difficulty of keeping one side of the metallic strip free from electrodeposition which was finally resolved by coating the side required free from deposit with vaseline. A theory has also been developed relating the thickness of deposit with the stresses produced in the basis metallic strip and its distortion. The theory, based upon a recent paper appearing in the Journal of the Bureau of Standards, Washington, U.S.A., has been extended to enable calculation of stresses and also includes the case of thick deposits.

Experiments on the deposition of nickel on steel have been carried out. The stresses have been calculated from the formula derived relating the thickness of deposit with the deflection of the strip and compared with the values obtained by direct measurements from the strain gauges. The values have been found to agree to within 8%. Further experiments on these lines are currently in progress in this department.

INTRODUCTION

It has been known for quite a long time that metals are electrodeposited in a state of stress. Normally the metals belonging to the Iron

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* Dr. Ramachandran is the Assistant Professor of Metallurgy, Indian Institute of Science, Bangalore 3.

† Mr. Chinnappa is Research Assistant in the Department of Metallurgy, Indian Institute of Science, Bangalore 3.

group are deposited in a state of tensile stress, wheras others, notably zinc are deposited in a state of compressive stress. To a large extent, the conditions under which the metal is deposited determine the nature and value of the stress : as an extreme case, nickel which is normally deposited in the tensile state may under suitable conditions be deposited in a compressive state. Chromium, cobalt, copper, iron, nickel and silver are deposited in the tensile state, stresses in the case of chromium, cobalt and nickel reaching as much as 20-40 tons/sq. in ; in lead, cadmium and zinc the stress is compressive, and in the case of zinc the stress goes on increasing even after the deposition has been stopped.

A comprehensive knowledge of the factors governing the stresses set up during electrodeposition is of interest for two reasons. Firstly, from the theoretical stand point, such a knowledge would help in understanding the mechanism of electrodeposition ; in fact, no theory of electrodeposition which does not account for these stresses could be considered complete. Secondly, we have important problems in many fields in which these stresses play a no mean role. The plating of nickel and chromium to make up the dimensions of worn out working surfaces or to provide better wear resistant working surfaces, has been widely practised recently. The effect of such plating on the endurance limit of the underlying material is of considerable importance to the engineer as recently, there has been evidence connecting the fatigue resistance of plated materials with the stress developed in plating. Again, it is well known that electroforming has been practised with success for making components of complicated shape which are required to a high degree of dimensional tolerance and to have a hard surface. In such cases it is evident that the stress developed in plating should be kept to a minimum to avoid distortion in the finished component. Also, it might be mentioned that the stresses in the deposit, to some extent determine the quality of the surface finish. These problems thus illustrate the vital importance of an accurate idea of the nature and magnitude of the stresses developed on electrodeposition. Important references on earlier work on this subject are given in the Institute of Metals, London, Monograph on “Internal Stresses in Metals and Alloys”, page 117.

The existence of a stress arising from electrodeposition was first observed by Mills[1] in 1877. It was Stoney[2] who in 1909, first made a quantitative estimate of the stress arising from the deposition of Nickel. His experimental method consisted of plating on one side only a strip of steel and allowing it to bend continuously during the plating. Later Phillips and Clifton[3] and Soderberg and Graham[4] have made measurements of the stress by plating the strip also on one side only. In their studies the strip was firmly held during the experiments and allowed to bend at a later stage. In all these cases the radius of curvature was determined by measuring the chamber of the strip. Barklie and Davies[5], Marie and Thon[6], Hume Rothery and Wyllie[7], Martin[8] and Jaquet[9] also adopted the same technique of Stoney but have measured the deflection at the end of the strip to calculate the radius of curvature. Theoretically it has been shown that the deflection at the end is four times the camber for the same radius of curvature. Some attempts have been made to study the stresses by X-ray method but since the grain size factors influence the diffraction features, these results are difficult to interpret. Recently Aber Brenner and Seymour Senderoff[10] of the National Bureau of Standards, U.S.A.. have evolved a Spiral Contractometer for the measurement of these stresses. These authors have also discussed in detail the various methods employed by earlier workers and pointed out clearly the differences among the various methods, both from the theoretical as well as the practical stand points.

The simplicity and accuracy with which surface stresses can be measured by the use of bonded wire strain gauges permits the measurements of the surface stresses set up in a metallic strip during plating with considerable accuracy and speed. In the following pages is briefly described a method of such determination, evolved by the authors and believed to be the first application of strain gauge technique to the subject. A theory, relating the strain produced in a metallic strip with the thickness of plating has also been developed and applied to evaluate the stresses arising out of the plating of nickel on steel.

Calculation of the stress developed on Electrodeposition

The first calculations of the stress developed on electrodeposition were made by Stoney in 1909. His calculations were made for the case of thin deposits. These calculations can be extended to the case of thick deposits by writing his equations as differential equations. An extremely useful account of the mathematical derivations has been given in another recent paper of Brenner and Sonderoff[11] appearing in the Journal of the National Buréau of Standards in Washington.

For purposes of calculating the stresses developed on electrodeposition, let

	b	denote the	width of strip
	t	-do-	thickness of strip
	l	-do-	length of plated region
	Δ	-do-	deflection at the end of plated strip
	h	-do-	camber of the plated strip
	E	-do-	Youngs modulus of elasticity
	M	-do-	bending moment
	I	-do-	moment of inertia
	r	-do-	radius of curvature at any instant
	S	-do-	true stress in the electrodeposited layer
	d	-do-	thickness of plating
	y	-do-	distance of fibre from neutral axis
	f	-do-	stress at the non-plating surface within the plated region
	R	-do-	final radius of curvature
and	P	-do-	uniform compressive stress in the basis material due to the external bending stress.

Let us now consider a strip that has been plated with a coating of thickness x, so that the total thickness of the strip is (t+x). The bending moment is given by force× $\frac{(t+x)}{2}$ Now if an additional small thickness of dx is deposited the additional bending moment will be $dm=Sbdx\,\frac{(t+x)}{2}$

According to elementary beam theory

$$\frac{M}{I}=\frac{E}{R}=\frac{f}{y}$$

Writing this as a differential equation, we get

$$dm = E\,I\,d\,(1/r)$$

$$Or,\ S.\,b.\,dx.\frac{t+x}{2} = E.\ b\frac{(t+x)^3}{12}d\,(1/r)$$

Separating and integrating the variables, we get

$$S\int_0^d \frac{dx}{(t+x)^2} = \frac{E}{6}\int_{\infty}^{R} d\,(1/r)$$

$$Or\ S = \frac{E\,t\,(t+d)}{6\,Rd} \qquad (1)$$

The value of R can be obtained either by the Spherometer formula by measuring the camber of the strip or from the deflection at the end. If in (1) we put $R=\frac{l^2}{8h}$, the formula corresponding to the measurement of the camber, we get the formula

$$S = \frac{4\,E\,t\,(t+d)\,h}{3l^2\,d}$$

which corresponds to the Stoney formula.

If on the other hand the deflection at the end is measured, $\frac{1}{R}$ is given by

$$\frac{1}{R}=\frac{2\Delta}{l^2}$$

Then the formula becomes :

$$S = \frac{E\,t\,(t+d)\,\Delta}{3l^2\,d}$$

which is the Barklie and Davie formula.

The stress calculations are not however, so simple as these formulae would suggest ; complications are introduced by the stress relief occurring in the first deposited layers due to the deposition of subsequent layers.

The relief is due to two reasons :

(1) The compression of first layers of plating by the tension in the later increments ;

and (2) The bending of the first increments due to deposition of later increments. Since the last layer of coating is deposited in the curved condition itself, it is obvious that this layer does not undergo any stress relief.

The effects are considered later. First the equations for very thin deposits in which case these corrections may be neglected are worked out and then the order of corrections for thicker coatings given.

For equilibrium external bending moment must be equal to the internal bending moment and the total applied external forces must be equal to the total internal forces. If there is a coating of thickness d, the total external force will be b.S.d. and to counteract this there must be a uniform compressive force acting over the area b.(t+d). Equating the two forces, we get the value of the uniform compressive stress thus :

$$Pb\,(t+d)=b\;S\;d \text{ Or } P=S\,\frac{d}{t+d}=\frac{S.\,d}{t}\;\text{(if d/t is very small)} \qquad (2)$$

The forces arising out of bending are easily calculated.

From elementary beam theory

$$\frac{M}{I}=\frac{E}{R}=\frac{f}{y}$$

The bending moment is given by

$$M=\frac{S.b.d.t}{2},\quad \text{if } \frac{d}{t} \text{ is very small}$$

At the surface the tensile stress will be given by

$$f=\frac{M}{I}\,\frac{t}{2}=3\,S\frac{d}{t} \qquad \ldots(3)$$

This force will be tensile in the non-plating portion of the region inside the electrolyte and compressive in the plated portion. The resultant stress on the non-plating region is given by the algebraic sum of (2) & (3), which works out to be,

$$f=2\,S\,\frac{d}{t} \qquad \ldots(4)$$

The correction for the compression of the first layers by the later layers of the deposit and the relief due to bending may easily be obtained by writing (4) as a differential equation. If a thickness x has been deposited the change in the stress f due to the additional deposit dx is

$$d\,f=2\,S\,\frac{dx}{t+x}$$

$$\therefore\; f=2\,S\int_{0}^{d}\frac{dx}{t+x}=2\,S\,\log\frac{t+d}{t}$$

From this, we get to the approximation,

$$S=\frac{ft}{2d}\left[1+\frac{d}{2t}\right] \qquad \ldots(5)$$

Experimental

A steel rule has been employed as the basis strip on which nickel has been deposited. While it is cusomary to give a "flash" coating of copper on steel before further plating, this has been dispensed with as it has been found that a direct plating of nickel is quite adherent and satisfactory and also as a flash coating of copper may affect the final results. The plating was carried out in Nevo-Nickel bath using a pure nickel anode and a current density of 20 amps. per sq. ft.

Measurements of strip thickness and thickness of deposit were carried out by means of a spring dial gauge (reading to a 100th of a millimeter), mounted accurately on a surface plate. Measurements of Youngs Modulus of the plated strip have been made by the usual single cantilever method, the deflections being measured by the spring dial gauge.

The chief problem during plating was that of limiting the plating to one side of the strip only. In the previous literature it has been stated that a coating of celluose varnish prevents plating; however, it was found that most of the paints and varnishes pealed off after one or two hours of immersion in the electrolytic bath. The following paints. varnishes and glues were tried but found unsatisfactory :

1. Durofix (thick and thin layer) ;
2. Black Varnish ;
3. "Arun" brand anti corrosive paint ;
4. Shellac ;
5. Celluose in acetone.

The difficulty was overcome by smearing a thin layer of vaseline on the side on which plating had to be prevented.

The strain gauges used to determine the stresses were approximately 100 ohms in resistance and manufactured by M/s : Tinsley & Co., London. The changes in resistance were measured by a Strain Indicator made by the same firm and which has a dial which can read directly strains up to 5 micro-inches per inch and on which estimates up to 1 micro inch per inch can easily be made. The strain indicator which is essentially a Wheatstone bridge with certain modifications was

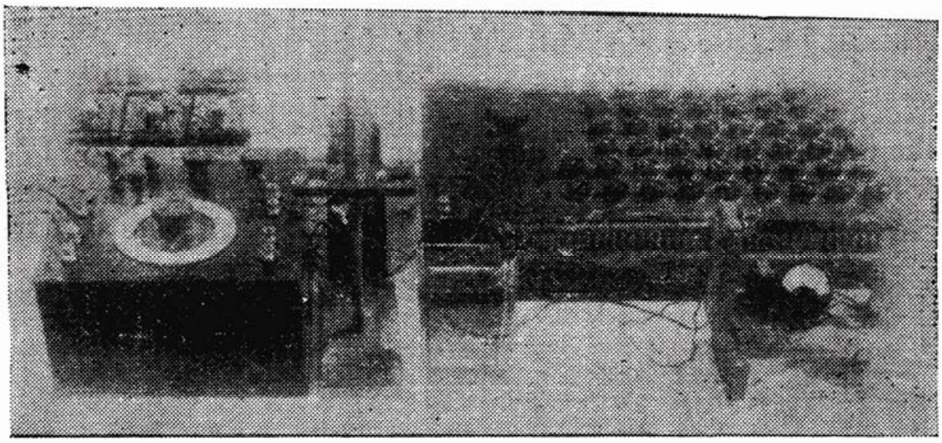

Plate A

used in conjunction with a galvanometer (made by M/s : Tinsley & Co.,) having a sensitivity of 800 divisions per micro amp. and an internal resistance of 1000 ohms. All the measurements were made by the null point method. The general experimental arrangement is shown in plate A.

EXPERIMENTAL RESULTS

First, as it was thought that there would be some bending even beyond the electroplated portions of the strip, two strain gauges were mounted on either side of the strip as shown in figure 1. Though there was a considerable bending observable in the plated region there was no indication by the strain gauges of bending beyond the plated region. To verify this, the position of the plated strip with respect to a stationary one was observed through a Cathetometer (Plate B). These experiments showed there was no bending beyond the plated region. This fact may well be expected from theoretical considerations, because there is no bending moment outside the plated region.

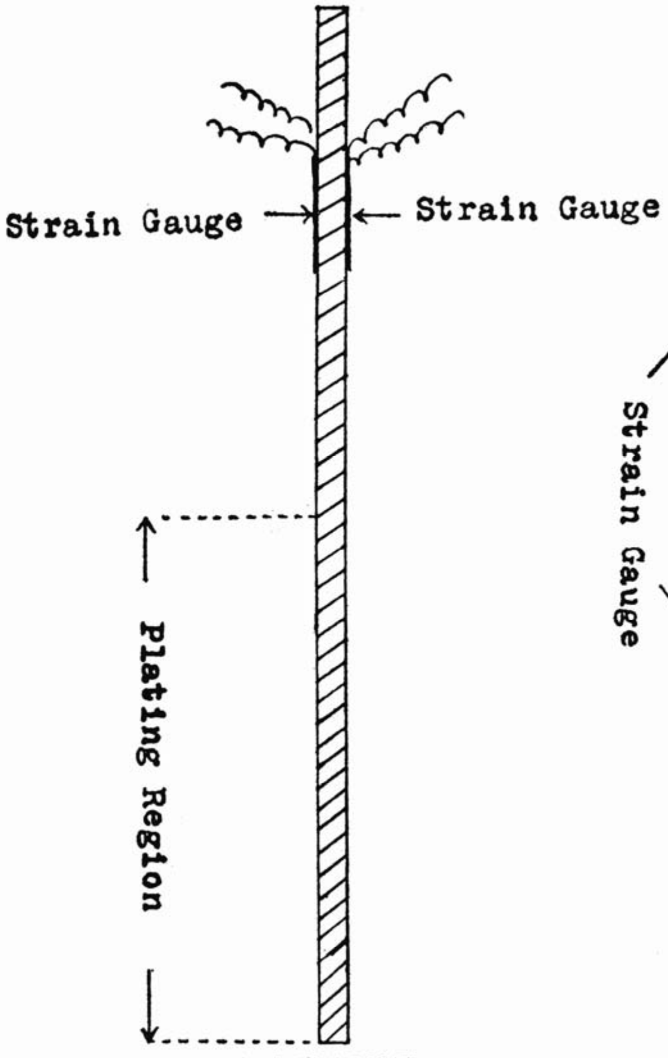

FIGURE. I.

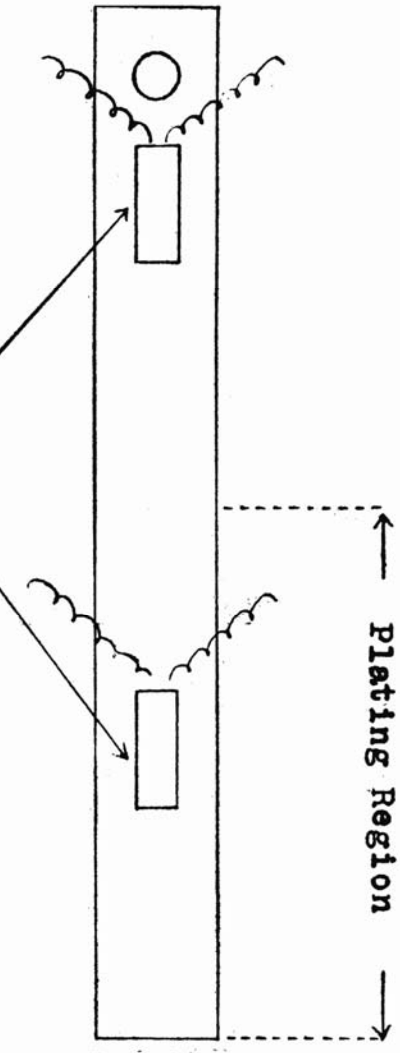

FIGURE. II.

Therefore to detect the stresses the strain gauge had to be mounted within the electrolyte itself, on the non-plating side of the strip (Fig. 2).

This region being inside the electrolyte, special precautions had to be taken to insulate the gauge from the plated strip as well as from the electrolyte. The insulation of the gauge from the strip was obtained by bending the leads so that they were within the breadth of the strip and pasting a paper on the non-plating side of the strip from the point where the free ends of the strain gauge leads started. A thick coating of vaseline was applied to insulate the gauge from the electrolyte.

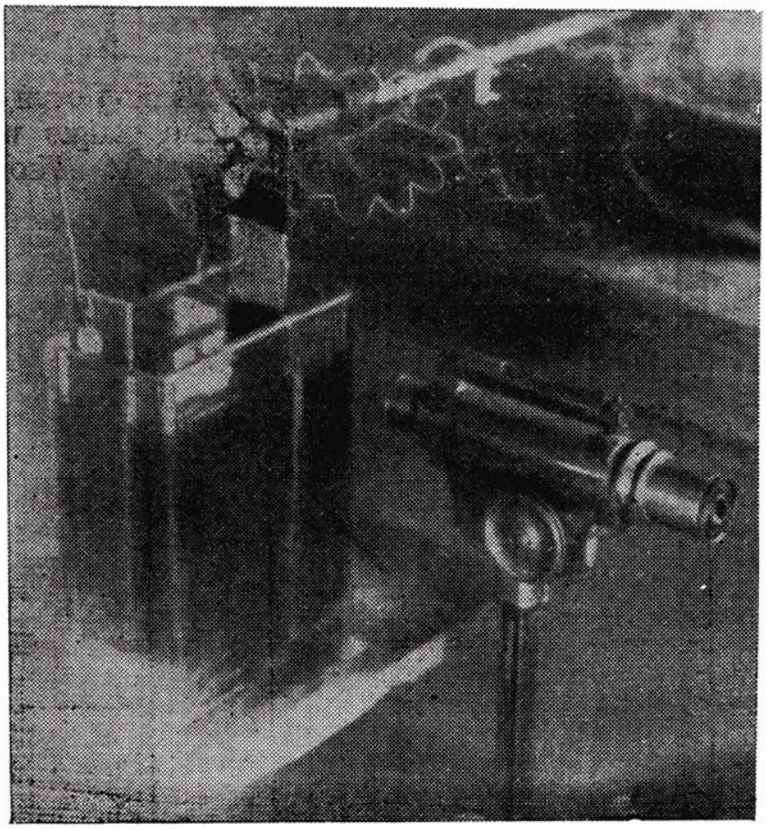

Plate
'B'

To get an idea of the order of the stress a determination of the stress was made by deflection methods by using a bale strip. The experimental values and the calculated stress are given below :

(a) $\Delta = 0.09''$, $t=0.014''$, $d=0.0018''$
$1=2.5''$
$S=8.3$ tons/sq. in.

(b) $\Delta = 0.45$ cm., $t=0.0144''$, $d=0.0022''$.
$1=3\frac{13''}{22}$

(Youngs modulus for the material was assumed to be 30×10^6 lb. per sq. in.).

The values obtained by measurement of stress on the surface of a steel rule is as follows :

(a) $f=102$ micro inches per inch.
$t=1.12$ mm., $d=0.09$ mm.
$S=7.7$ tons/sq. in.

on calculation Δ in this case comes out to be 0.055″.

(b) $f=148$ micro inches per inch.
$t=1.12$ mm., $d=0.2$ mm.
$S=5.6$ tons/per sq. in.
on calculation Δ comes out to be 0.083″.

(Youngs modulus for the material of the scale was determined experimentally and found to be 25×10^6 lb./sq. in. In case of (b) the deposit was found to be coarse and different from others).

Though these two values differ, they are of the same order and the difference can be attributed to the nature and thickness of the deposits. The agreement between the two sets of the values got by deflectional and stress measurement methods suggests possibility of standardization of the new method.

CONCLUSION

The correction factor in the formulae for thick deposits is d/t in the case of deflection measurement where as in the case of stress measurement it is $d/2t$.

Hence, it is seen that the deviation of the stress as calculated by the simple formula (i.e., neglecting d/t) is less in the case of strain measurements than in the deflection methods.

In the formula derived it is seen that Δ is proportional to $d|t^2$ whereas the f is proportional to $d|t$. Therefore for a constant $d|t$ the new method is accurate to the same extent independent of t, whereas in the conventional methods as t increases the deflection decreases Therefore this method when standardized will be capable of determing the stress in thicker layers to a greater degree of accuracy.

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