Prediction of Thickness Distribution Of Electrodeposited Coatings Using a Low-Cost Boundary Element Method

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Whether regarded in terms of the skills and time required, or the financial cost of commercial software, considerable resources are usually required to determine coating thickness distribution in electroplating processes numerically. If care is taken, however, good results can be obtained using low-cost boundary element software intended for thermal analysis. The determination of coating thickness distribution on a turbine blade profile, using such software, is compared to results obtained with specialized electrochemical software.

Electrodeposition carried out for the production of high-temperature, oxidation-resistant coatings usually requires very special attention to thickness uniformity, because it is not unusual for thickness tolerances of less than 10 percent to be specified. Very careful choice and control of the process conditions are needed to ensure this degree of uniformity and to avoid unnecessary costs and damage resulting from stripping unsatisfactory deposits from valuable components. In many electroplating processes, where good thickness uniformity is essential, it is still the usual practice to rely largely upon experimental results obtained by plating test panels with different cell configurations and arrangements of anode and shield positions. Although it may be possible in some cases to reduce the amount of experimentation by using simple calculations that indicate the modifying effect of shield placement,[1] etc., the tentative approach is both time consuming and uncertain. If the shape and size of components being processed are frequently being changed, or the processing time is long because the plating rate is low, it becomes even more important to consider whether it is feasible to obtain a numerical prediction of the coating distribution.

The thickness distribution of the coating will depend both upon the manner in which the current efficiency of the plating process varies with current density and upon the distribution of the cathode current density. If the current efficiency increases with increase in current density, then the distribution of coating thickness will be more uneven than the distribution of the current suggests, whereas decrease in the current efficiency with increasing current density will promote improved uniformity of thickness distribution. Fortunately, it is generally a straightforward matter to determine the current efficiency variation with current density, so that its effect upon coating thickness uniformity can be easily assessed and taken into account. Determination of the current distribution, however, is a much more difficult problem, which will require considerable resources, either in terms of in-house mathematical and computing skills, or finance to purchase commercially available software. Only in the case of very simple cell geometry is it possible to attempt to calculate the current distribution directly by analytical means. In the great majority of cases, it is necessary to employ complex numerical procedures and computational algorithms that will be expensive in terms of time spent or monetary cost. The procedures that can be used include finite and boundary element methods[2-4] and, more recently, probabilistic methods.[5-7]

Conduction in Engineering Fields

Electrical conduction in electroplating cells is governed by the same unified mathematical field theory as are electrostatics, magnetism, gravitation, conductive heat transfer, ideal fluid flow, and flow through permeable media. The essential governing equation in field theory is Laplace's equation, which, in the three Cartesian directions, x, y and z, is

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

where ø is a scalar potential having meaning dependent on the type of field being considered. For thermal and electrical conduction, and flow through porous media, the scalar potential is shown in Table 1 as temperature, electrical potential and pressure, respectively. The quantities flowing or being conducted in these fields are also given in Table 1, together with the meaning and dimensions of the constant that relates the gradient of the scalar potential to the flux density in accordance with

$$\text{Flux density} = -k\frac{\partial ø}{\partial n}$$

where n is the direction of flow. In this equation, the negative sign is added to ensure that the flux density is a positive quantity. Determination of the flux density requires Laplace's

Table 1
Some Analogous Quantities in Field Theory

	Thermal Conduction	**Electrical Conduction**	**Flow Through Porous Media**
Flux	Heat flow Q (Watts)	Current I, A	Fluid flow Q, m^3/sec
Flux density	q W/m^2	i A/m^2	Velocity v, m/sec
Field intensity	Temp gradient K/m	Potential gradient E, V/m	Pressure gradient, Pa/m
Constant	Conductivity k, W/mK	Conductivity k, $\Omega^{-1}m^{-1}$	Permeability k, m^3sec kg^{-1}
Scalar potential	Temp T, K	Potential ø, V	Pressure P, Pa

Table 2
Comparative Quantities in Thermal & Electrical Conduction

	Thermal analysis	Conduction in electrodeposition cells
Conductivity	k $Wm^{-1}K^{-1}$	k $\Omega^{-1}m^{-1}$
Surface resistance	R_t $W^{-1}K$	R Ω
Surface transfer coeff.	h $Wm^{-2}K^{-1}$	$(d\eta/di)^{-1}$ $\Omega^{-1}m^{-2}$
Ambient scalar potential	Temp °C	Electrode potential with no current flow, V

equation to be first integrated. This is accomplished by taking into account the physical geometry of the conducting media and conditions at all of the internal and external boundaries. These boundary conditions will be specified so as to indicate

(1) the position of non-conducting vessel walls or added internal shields where the scalar potential gradient normal to the boundary is zero;
(2) the position of sources or sinks of heat, electrical current (electrodes) or fluid where the magnitude of scalar potential or the scalar potential gradient is specified.

In practice, the solution of Laplace's equation will require a numerical procedure, such as the boundary element method. This is now a firmly established engineering tool for the solution of conduction problems in thermal analysis.[8] It has also found some application in the solution of cathodic protection problems[9] and has been applied to the determination of current distribution in electroplating cells.[2-4,10] The boundary element method is especially useful for solving problems with singularities or with large gradients of scalar potential. Although much of the commercial software available is not able to deal very well with nonlinearity in material properties, this is not likely to be a problem with electrodeposition processes, where a constant value for the solution electrical conductivity can be assumed.

The commercial cost of specialized boundary element software available for use with electrochemical systems is generally high, being on the order of several thousand pounds in the UK for a single user license. Provided care is taken with regard to equivalence of the various quantities and specification of the correct boundary conditions, however, it is possible to take a method intended to solve Laplace's equation for one field application and use it to solve for the flux density in a different application. In this way, much more widely available and less costly software intended for thermal analysis can be readily used on a PC platform to predict coating thickness distribution in plating cells. Such software is now commercially available for two-dimensional boundary element analysis for a fraction of the cost of specialized software packages. Moreover, the cost of necessary fast personal computers to run numerical analysis software has in recent years dropped dramatically, putting the possibility of using boundary element software to predict coating thickness distribution within the reach of even small plating shops.

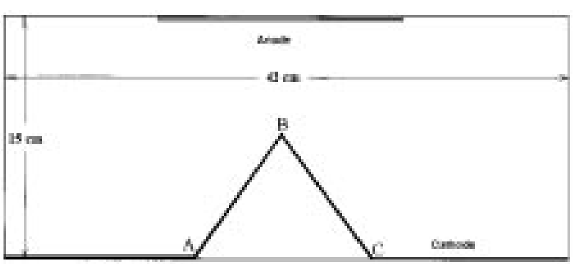

Fig. 1—Simple plating arrangement used in simulations to assess errors in computations with linear approximation of polarization slope.

Boundary Conditions In Electrical & Thermal Conduction

To solve for primary current distribution or simple heat conduction that depends wholly upon the geometry of the system, it is necessary only to assign comparatively simple boundary conditions. For insulating walls or shields, the potential or temperature gradient at the boundaries will be designated as zero, whereas the boundaries of the electrodes or heat sources or sinks will be specified directly in terms of constant potential or temperature values. While the actual current density or heat transfer rates will also depend upon the magnitude of the conductivity constant and the designated anode and cathode potentials, the shape of the distribution will not. Accordingly, to determine the distribution of primary current density requires only that the configuration of the plating cell is indicated.

Although determination of primary current distribution may be adequate for many purposes, in situations where more accurate simulations are required, it is necessary to determine the secondary current distribution where the modifying effect of electrode polarization is taken into account. In this case, it is necessary to specify not only the configuration of the plating cell, but the size of the cell also, as well as the solution conductivity and electrode polarization. The effect of electrode polarization on the current distribution is to impose a surface resistance to current flow much as the way a convection boundary layer imposes resistance to heat flow.

The surface resistance associated with electrode polarization is indicated by the slope of the cathode overpotential vs. current density relationship. If this slope

$$\frac{d\eta}{di}$$

is expressed in units of Volts m^2/Amp (*i.e.*, Ω m^2), the surface resistance (Ω) is given by the slope divided by the area in square meters. Although the surface resistance will vary with the current density, as shown, it is usually the case that only a relatively limited range of current densities need be considered in any particular current distribution. Accordingly, provided the slope taken is that of the tangent to the curve at the average applied current density, then a constant value for

$$\frac{d\eta}{di}$$

can be taken to provide a reasonable approximation for the surface resistance. In comparison, the convective surface resistance in heat transfer studies equals 1/(ha), where h is the heat transfer coefficient in units of $Wm^{-2}K^{-1}$ and a is the area, again in square meters. From this, it is clear that the quantity equivalent to the heat transfer coefficient in thermal analysis is the reciprocal of the polarization slope in electrical conduction. A summary of the important quantities required for boundary element determination of current distribution is

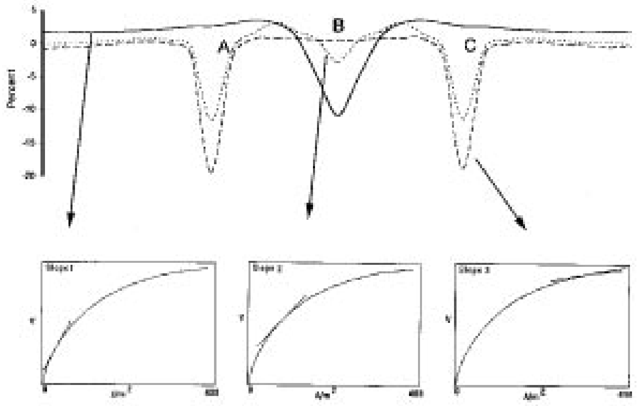

Fig. 2—Error variation of coating thickness computed for the plating arrangement of Fig. 1, using different linear approximations of the polarization slope. Slope 2 is the slope at the overall applied current density; slopes 1 and 3 correspond respectively to current densities smaller and larger than the overall value.

given in Table 2.

Boundary Element Prediction Of Thickness Distribution

The configuration of the plating cell must first be represented, either by manually entering the coordinates of the lines or shapes of its geometry, or by importing existing data from a design package. When the geometry has been defined, generation of the mesh and boundary elements is generally carried out automatically with very little prompting of the user. Electrode potentials, solution conductivity and polarization slopes must now be specified in the equivalent thermal analysis form, as discussed earlier. The conductivity is introduced as a general material property, whereas the ambient potential and polarization slopes are assigned specifically as boundary conditions at the electrodes.

Numerical computation is carried out when the problem has been completely defined and the discrete equations automatically set up and solved. The final post-process stage is to read in the values obtained in the solution and for the user to select the quantities to plot or display. If the plating current efficiency varies significantly with the current density, this may need to be taken into account by multiplying individual local current densities by the appropriate individual efficiency figure for that current density. The distribution obtained will be equivalent to that of the coating thickness distribution. Should it be required to display the actual coating thicknesses in the distribution, it then becomes necessary to take into account the density of the coating, and to apply Faraday's laws of electrolysis.

Simulation of High-Temperature, Oxidation-Resistant Coating Process

For aerospace applications, nickel-based composite coatings are deposited onto nickel superalloy aerofoil cross section components of precise dimensions. In the process, plating is carried out under carefully controlled hydrodynamic conditions.

The necessary electrochemical data for carrying out boundary element computation were obtained by measuring the electrical conductivity of the solution at the normal operating temperature and by determining the cathodic overpotential-current density relationship, using a potentiostatic technique. The current efficiency change with current density was also

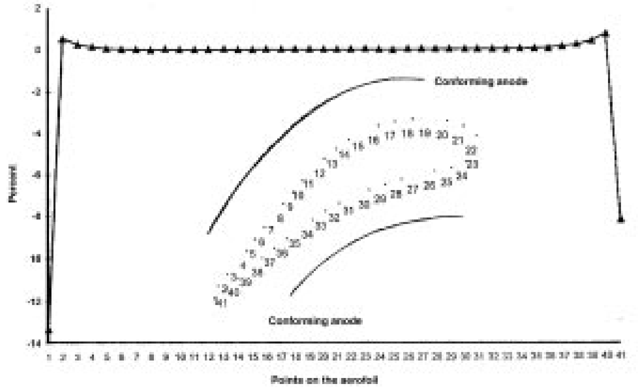

Fig. 3—Error in the predicted coating thickness distribution on an aerofoil profile, using the linear approximation of the polarization curve at the overall applied current density.

determined over the current density range 1-400 A/m^2, so that coating thickness distributions could finally be obtained.

The ability of the boundary element method to predict coating thickness distribution accurately, under the normal operating conditions for the process, was confirmed by comparing predictions with results obtained by depositing the coating onto carefully prepared segmented cathodes. After separating the segments at the completion of plating, the amount of coating material deposited was determined, using atomic absorption analysis. Close agreement was found between the experimentally determined distributions and distributions predicted using specialized electrochemical software for boundary element analysis.

A series of two-dimensional boundary element computations was carried out to assess the range of errors likely to be involved in using linear approximations of polarization slope with the thermal analysis software. The simple plating arrangement considered for the simulation is shown in Fig. 1. To provide an accurate determination of coating thickness distribution for comparison purposes, the first boundary element computation of current density distribution was carried out using the specialized electrochemical software that fully takes into account the non-linear nature of the polarization slope. Results obtained for an overall current density of 50 A/m^2 were then corrected for current efficiency variation to give the coating thickness distribution. This procedure was repeated using the thermal analysis software, considering in turn three different values of linear polarization slope, as shown inset in Fig. 2. The coating thickness distributions obtained were compared with those from the specialized software and error values computed. These results, given in Fig. 2, confirm that the error is smaller, overall, and more uniform when the linear value of the polarization slope is taken at the overall current density value (slope 2) rather than at lower (slope 1) or higher (slope 3) current densities. Where the polarization slope is taken at a high-current-density region, the errors will be insignificant, but considerable at low-current-density regions. The converse of course applies where the polarization slope is taken at a low current density.

The thickness distribution of coatings produced on a two-dimensional aerofoil cross section at a current density of 50 A/dm^2 with conforming anodes was next considered. Again, an initial determination was made using the specialized software able to take the entire variation of polarization with current density into account. This was repeated, using the thermal analysis software with a linear polarization slope value corresponding to the overall current density (slope 2, Fig. 2 inset), and the error values calculated, as shown in Fig. 3. It is clear from these results, that, except for the sharp trailing edge of the aerofoil (points 1 and 41), where the current density exhibits a sudden increase, there is, in this case, remarkably little error in the thickness distribution determined with the thermal analysis software.

Summary

It has been shown that, providing care is taken to obtain appropriate and reasonable linear approximations for the cathode polarization slope, very good results can be obtained using low cost and readily available boundary element software to determine electrodeposited coating thickness distribution. This can prove very beneficial in practice, resulting in great saving of time in the laboratory or plating shop. It is possible with relatively little effort to predict the effect on the coating distribution of repositioning anodes or shields in the plating cell or, for example, to determine the effect of changing the design of conforming anodes for a particular application.

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