Predicting the Distribution of Electroplated Coatings Using ANSYS

Richard Eberhart
Fisher Controls Intl., Inc.

Abstract

The performance of control valve internal parts can be greatly enhanced by coating critical surfaces with a layer of chromium. The chromium is typically deposited by an electrolytic process in which the part to be coated is immersed in an electrolyte containing chromium ions. A direct current flow is then maintained between an immersed anode and the work part, which acts as the cathode. The distribution of the resulting chrome deposit is influenced by a multitude of factors including the geometry of the part to be coated and of the supporting fixture. The electric field analysis capability of ANSYS provides a method of predicting the distribution of chrome deposits. In addition to the work part and supporting fixture, the model must also include the anode as well as the electrolyte. Material property inputs for the electrolyte must be calibrated to accurately simulate the process of interest. The deposit thickness over the critical surfaces is then determined from the relationship between surface current density and rate of deposition. Once developed and calibrated, the model can be used to optimize the distribution of the chrome deposit. The above technique is illustrated by an example in which ANSYS is used to predict the distribution of the chrome deposited on the surface of a ball valve control element.

Introduction

The performance of control valve internal parts can be greatly enhanced by coating critical surfaces with a layer of chromium. The chrome coating provides for significantly longer service life by increasing resistance to wear and corrosion. The lower friction resulting from the chrome coating can also enhance control performance.

The chromium is typically deposited by an electrolytic process in which the part to be coated is immersed in an electrolyte containing chromium ions. The source of the chromium ions is usually chromic acid (CrO₃). A sulfate catalyst (SO₄) is also necessary for the chromium to deposit. A direct current flow is maintained between an immersed anode and the work part, which acts as the cathode.

The length of time that the part is immersed in the electrolyte is a major factor in determining the thickness of the resulting deposit. The thermal, chemical, and electrical characteristics of the electrolyte bath also heavily influence the deposition process. The distribution of the deposit on the work part is determined by the distribution of the current flow in the electrolyte surrounding the work part. The location of the cathode (work part) relative to other cathodes, the anode, and sides of the tank has a significant effect on the current distribution. The geometry of the cathode also plays a major role. For example, current densities are greater around sharp corners and other convex surfaces and relatively less in the vicinity of fillets and similarly concave surfaces. Unlike electroplating processes using most other metals, chromium electrolytes will not deposit metal below a minimum value of current density. Thus, surfaces where the current density is below the minimum will not be coated at all.

Considering the array of variables involved in general and the significant effect of work part geometry in particular, a simulation tool to predict the distribution of chrome deposits would be useful. The focus of this paper is to document a method of predicting the distribution of chrome deposits on a work piece subjected to a given electroplating process.
**Procedure**

The electric field analysis capability of ANSYS provides a method of predicting the distribution of chrome deposits. Electric field analysis can be used to perform a steady-state current conduction analysis of a conductive system. Electric potential (voltage) is the only degree of freedom required. The usual approach is to specify a zero voltage at the negative or grounded terminal of the circuit and a known voltage or direct current at the positive terminal. Unknown voltages can then be solved for. As current is assumed proportional to voltage, the current density can also be calculated at any point of interest. As discussed above, deposit thickness is a function of time and current density at the surface of the cathode. Given the relationship between time, current density, and deposit thickness, the distribution of the deposited coating over critical surfaces can be determined at any time of interest.

As the electroplating problem is, in effect, a current conduction problem, all elements of the circuit must be represented in the model. Thus, in addition to the part to be plated and supporting fixture, the model must also include the anodes as well as the electrolyte.

Material property inputs for current conduction analyses are in terms of resistivity. The literature more commonly reports conductivity, which is the reciprocal of resistivity. Values for conductivity can be readily found for the materials typically used for the anode and cathode. Conductivity values for various concentrations of electrolytes in aqueous solutions can be more difficult to locate but are available (e.g. Reference 2). The resistivity of the electrolyte is dependent on many variables such as concentration of chromic acid, concentration of catalyst, presence of contaminating elements, temperature, and time. Thus, the initial value input for the electrolyte should be considered an estimate. To accurately simulate the process of interest, electrolyte resistivity must be calibrated. The initial estimated resistivity value must be altered as needed to obtain the correct voltage differential between the anode and cathode at the given current input.

Once the electrolyte resistivity is calibrated and a valid solution is obtained, the thickness of the deposited chromium must be calculated using the relationship between deposit thickness, current density and time. The relationship can be determined by data taken from the process to be simulated or tabulated in the literature. In either case, a polynomial equation can be fit to the data such that deposit thickness is expressed as a function of current density for a given time of immersion. The selection capabilities of ANSYS can be used to select the subset of electrolyte elements adjacent to the surfaces of interest. The current density results of those elements can then be used to calculate the corresponding deposit thickness. The resulting thickness can then be displayed or listed similarly to any other result.

**Analysis**

The above technique is illustrated by an example in which ANSYS Version 7.1 is used to evaluate the distribution of the chrome deposited on the surface of a ball valve control element. The plating process to be simulated occurred in a 96 inch by 36 inch by 12 inch deep rectangular tank containing a total of twenty anodes: ten equally spaced per side. Each anode was a 2.5 inch diameter by 11 inch long cylinder located 0.5 inch from the side of the tank. The anode material was an alloy of 96% lead and 4% antimony. Each of the five cathodes was comprised of one 4 inch ball, two spacers, two nuts, and a 0.75 inch diameter threaded rod. The ball and spacers were placed over the threaded rod. The spacers were used to vertically center the ball in the electrolyte. A nut was placed on each end of the rod and then tightened to secure the ball between the spacers. The assembled cathodes were then submersed along the centerline of the tank with equal spacing. The balls were stainless steel. The rod and nuts were low carbon steel. Spacers were made from lengths of PVC pipe. The electrolyte bath consisted of a low concentration of chromic acid in water (32 oz per gal). The constant-current power source supplied 650 amperes at 10 volts. The electrolyte was maintained at 130 F. No agitation effects were present.

**Model Geometry**

To arrive at the current density in the electrolyte around the surface of the ball, the model needed to include the anodes and cathodes in addition to the electrolyte. For the problem under consideration, symmetry of
geometry and boundary conditions allowed only a portion of the plating tank to be modeled. Thus, the model represented a 19.2 inch by 36 inch by 12 inch deep section. Due to non-symmetrical geometry of the valve ball, the model included one complete cathode assembly and four adjacent anodes. Two vertical symmetry planes located 4.8 inches from the centerline of the modeled anodes bounded the model.

Figure 1. Mesh plot of entire model

Figure 2. Mesh plot of cathode assembly
Figure 3. Mesh plot of valve ball - inside view

Figure 4. Mesh plot of valve ball - outside view
Once created, the geometry was meshed with Tetrahedral Coupled-Field Solid elements (SOLID98). This element type can be formulated in terms of the volt degree of freedom required to simulate electric fields. The combination of the mid-side nodes and the tetrahedral shape allowed the complex geometry of the valve ball to be readily meshed. As the current density surrounding the ball was of primary interest, a fine mesh was used in this region. The mesh became coarser with increasing distance from the ball. Figure 1 shows the mesh density at the model boundaries. Figure 2 shows the mesh for the entire cathode assembly. Figures 3 and 4 detail the mesh used for the ball.

**Material Properties**

The only material property required was the resistivity. The resistivity values used for each component are listed in Table 1.

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Resistivity (ohm inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode</td>
<td>96% Lead 4% Antimony</td>
<td>9.45E-6</td>
</tr>
<tr>
<td>Threaded Rod, Nuts</td>
<td>Carbon Steel (G10100)</td>
<td>7.09E-6</td>
</tr>
<tr>
<td>Spacer</td>
<td>Thermoplastic (PVC)</td>
<td>3.93E+11</td>
</tr>
<tr>
<td>Valve Ball</td>
<td>Stainless Steel (S31600)</td>
<td>2.99E-5</td>
</tr>
<tr>
<td>Electrolyte (Initial Value)</td>
<td>H₂O + CrO₃ + H₂SO₄</td>
<td>8.66E-3</td>
</tr>
<tr>
<td>Electrolyte (Final Value)</td>
<td>H₂O + CrO₃ + H₂SO₄</td>
<td>1.49</td>
</tr>
</tbody>
</table>

**Boundary Conditions**

As the total current output of 650 amperes was divided among the 20 anodes, 32.5 amperes (650/20) were applied to one node on the top surface of each anode. The remaining nodes on the top surface were coupled to the loaded node in the volt degree of freedom. All nodes on the top surface of the cathode were given a 0 volt potential. As free surfaces correspond to a current parallel condition, no additional boundary conditions were required.

**Solution**

As the problem is linear, no special solution settings are required. However, as mentioned above in the Procedure section, the resistivity value input for the electrolyte must be adjusted to obtain the correct voltage differential between the anodes and cathode. For the problem under study, the initial resistivity for the electrolyte resulted in 0.058 volt differential between the anodes and cathode. In reality, 10 volts are maintained, thus, a correction in electrolyte resistivity was required. As the problem is linear, the correct resistivity value can be predicted by multiplying the initial resistivity by the ratio of desired to resulting voltage. In this case, the final value was predicted to be 1.49 ohm inch (8.66E-3*10/0.058).

As re-solving with the 1.49 ohm inch value resulted in the correct 10 volt differential, the solution was considered to be a reasonable simulation of the electroplating process.
Figure 5. Deposit thickness at 130 minutes vs. current density

Postprocessing

The first task in postprocessing was to establish the relationship between deposit thickness, current density, and time. This relationship allowed calculation of the deposit thickness from the current density results. In this case, a second order polynomial was fit to data taken from Reference 1 (Table 7, page 176). Figure 5 plots deposit thickness versus current density for a 130 minute immersion time. The second order polynomial fit to the data is given by Equation 1.

\[ T = 5.916 \times 10^{-5} J^2 + 9.039 \times 10^{-4} J \]  

(1)

where:

\( T \) = deposit thickness in inches.
\( J \) = current density in ampere/inch\(^2\).

The current density required in Equation 1 was obtained from the electrolyte elements adjacent to the surfaces of interest. The selection capabilities of ANSYS were used to define the needed subset of electrolyte elements. The current density results from those elements were then stored in an element table. Element table mathematical functionality was then used to calculate the deposit thickness corresponding to each of the selected elements using Equation 1. The resulting deposit thickness was also stored in the element table. Once calculated and stored in an element table, deposit thickness can be displayed or listed similarly to any other element result.
Analysis Results & Discussion

Figures 6 and 7 contour the calculated thickness of chrome deposited on the exposed surfaces of the ball. As the above figures show, the thickest deposits occurred along the sharp corners at the edge of the spherical surface of the ball. This effect is especially pronounced at the sharply pointed ends of the leading
edge. Conversely, small holes received little deposit. Relatively thin deposits also occurred in regions of less extreme concave geometry such as the backside of the ball and the small fillets around the ball ears. The spherical surface on front of the ball was the most uniformly coated.

The distribution of chrome deposits predicted by the model agrees closely with that observed in practice. If required, Equation 1 can be adjusted to further correlate the calculated deposit thickness with measurements taken on critical surfaces of sample parts.

**Conclusion**

Once developed and calibrated, the model can be used to predict the distribution of the chrome deposited on a work part subjected to a given electroplating process. The effects of changing thermal, chemical, and electrical parameters can then be studied. The location and orientation of the work part relative to other work parts, the anodes, and tank sides can also be evaluated. Finally, the effects of modifying the geometry of the work part, holding fixture, and anodes on the distribution of chrome deposits can be predicted.

**References**