Modeling & Cell Design for Metal Deposition Processes with Complex Geometry

By J. Zoric, I. Rousar and K. Bousek

Secondary current distribution was calculated for a metal deposition process on a cathode of complex geometry. Uniform thickness of the deposited metal layer is desired over the entire surface of the cathode, even in cases when the shape of the cathode is very complex. The uniformity of the deposit may be improved by inserting screening elements, auxiliary anodes or auxiliary cathodes (robbers) near the most exposed corners; also by choosing a convenient shape and position of the anodes, which may be connected to different DC sources.

Modelling of the current distribution^{1,2} is often used in electroplating (ECP), electrochemical machining (ECM) and electrochemical micromachining (EMM). In electroplating, it is desirable to achieve uniform thickness of the deposited metal. The uniformity of the deposit depends on the current distribution over the cathode. The current distribution in the cell is primarily determined by the geometrical characteristics of the electrodes and of the cell. Non-conducting shields and auxiliary electrodes are used to achieve uniform current distribution on a cathode of complex shape. Design methods require many experiments based on practical experience to obtain uniform current distribution on cathodes of various shapes. Mathematical modeling of the current distribution is used to minimize the number of experiments. The optimal geometry of the electrodes (shape, position and number of electrodes) then assures uniform current distribution along the cathode.

Many studies concerning ECP, ECM and ENM have been made. They address the problem of the influence of the geometry on the thickness of the deposit and methods of improving its uniformity. By analyzing them, an interesting

review of numerical methods used can be found for modeling of the above mentioned problems, different approaches to the boundary approximation problem (the primary and secondary current distribution;^{1,2} also techniques used for simulation of the metal deposition or dissolution in ECP, ECM or EMM.

Calculation of the local cathodic current densities (cds) was performed for several geometries:

- (a) With screening elements
- (b) With additional cathodes
- (c) With two anodes of different dimensions positions and connected to different DC sources
- (d) Same as (c), but with additional insulating shields placed in the vicinity of the outer corners of the cathode

(e) Same as (d), with added auxiliary anodes in the vicinity of the inner corners of the cathode.

The calculations were confirmed by an experimental estimation of the thickness of the deposited nickel from a nickel sulfamate electrolyte. An arrangement with two different DC sources and with insulating shields placed in the vicinity of the outer corners of the cathode showed the most uniform thickness of the nickel deposit. The effect of local maxima was suppressed by approximately 30 percent. Auxiliary anodes placed in the vicinity of inner corners of the cathode have great effect also on the current densities. The numerical methods used most often for calculation of the potential distribution and electrode current densities (solution of the Laplace equation^{1,2}) were:

- The Finite Element Method (FEM)
- The Boundary Element Method (BEM)
- The Finite Difference Method (FDM)

The boundary approximations used most often were:

- The primary current distribution (PCD)
- The secondary current distribution (SCD)

Prior to an analysis of the most interesting references dealing with mathematical modeling, a few notes will be offered about boundary approximations.

To illustrate the problem of setting boundary conditions, Fig. 1.1 is useful. It shows a schematic of the potential distribution in an electrolyzer involving the potential drop in the electrodes.² In many cases, the potential drop in the electrodes can be neglected in ECP, ECM and EMM. In such cases, the Laplace equation (1) is solved only in the electrolyte space [*i.e.*, between the surface of the anode (which has



Fig. 1.1—Schematic of the potential distribution in an electrolyzer involving the potential drop in the electrode. The parameters $\varphi_{A,M}$ and $\varphi_{C,M}$ denote the inner potentials of the metal phase (anode, cathode), $\varphi_{A,S}$ and $\varphi_{C,S}$ the inner potentials of the electrolyte at the anode and cathode, δ_{HA} and δ_{HC} the corresponding thicknesses of the Helmholtz double layer and d denotes the distance between the electrodes (approximately the length of the current line, **1**).

the inner potential of the electrolyte at the anode surface of $\varphi_{A,S}$, see Fig. 1.1) and the surface of the cathode (with the inner potential of the electrolyte at the cathode surface of $\varphi_{C,S}$)].

The PCD on the electrode surface is obtained by solving the Laplace equation (1) for the potential in the electrolyte,

(1)

 $\nabla^2 \mathbf{\phi} = 0$

on the assumption that both electrodes are non-polarizable and that $\varphi_{A,M} = U$ and $\varphi_{C,M} = 0$, the potentials in the electrolyte at the cathode and anode surfaces, are given by Eqs. (2) and (3).

$$\varphi_{A,S} = U - E_{A,rev} \qquad (2)$$
$$\varphi_{C,S} = -E_{C,rev} \qquad (3)$$

where U is the cell voltage (V), E is the electrode potential (V), and φ is the Galvani potential of the electrode (V). Subscripts C and A mean cathode and anode, rev means reversible, M is the potential in the metal of the electrode and S is the potential in the electrolyte at the electrode surface. By Eqs. (2) and (3), the boundary conditions for the electrode surfaces are defined for the PCD.

The PCD is easy to program. The calculations can also be made by using commercial software for calculation of the electrical field or calculation of the temperature field (by using the mathematical analogy between those two fields). The definition of the boundary conditions is simple and in many practical cases, sufficiently accurate as a tool for choosing the optimal cell geometry. More about the primary current distribution can be found in Refs. 1 and 2, as well as in the other references.

More accurate current densities can be obtained by using the SCD. The solution of the Laplace equation in the electrolyzer space is calculated on the assumption that the electrode potential depends on the current density and that



Fig. 2—Polarization curves for deposition and dissolution of nickel in nickel sulfamate electrolyte, measured using a rotating disc electrode at a fixed speed of 1000 rpm and polarization curve for hydrogen evolution.



Fig. 1.2—2D sketch of a steel vessel on the inner side of which nickel is deposited: (a) 2D cross section of the steel vessel with anodes: (b) 2D cross section used for the calculation and experiments. All dimensions in the enlarged 2D cross section are in mm. Dimensions of the sides of the cathode: a = 240 mm, b = 126 mm, c = 235 mm, d = 98 mm, e = 125 mm, f = 115 mm, g = 80 mm.

mass transport plays no role. The temperature and the concentration of the electrolyte are considered constant. By assuming that $\phi_{A,M} = U$ and $\phi_{C,M} = 0$, and having equations for the anode and cathode overvoltage, respectively,

$$\eta_{A} = a_{A} + b_{A} \ln j_{nA}, \ b_{A} > 0 \tag{4}$$

$$\eta_{\rm C} = a_{\rm C} + b_{\rm C} \ln |j_{n,\rm C}|, \ b_{\rm C} < 0 \tag{5}$$

the equations for the Galvani potential in the electrolyte at the anode and cathode surface follow:

$$\varphi_{A,S} = U - E_{A,rev} - a_A - b_A \ln j_{n,A}$$
 (6)

$$\varphi_{C,S} = -E_{C,rev} - a_C - b_C \ln |j_{n,C}|$$
 (7)

where j is the current density (A/cm²), η_A and η_C are the anode and cathode overvoltages (V), and a_A and a_C (V), b_A and b_C (V/ decade) are the Tafel coefficients for the anode and cathode, respectively.

From the programming point of view, the calculation for the SCD is more complicated. It requires development of routines for improving the boundary conditions during the calculation. It means that the potentials on the surface of the electrodes must be improved by using the newly calculated current densities (which are also improved during calculation). Most often, it is solved by using iterative methods for the solution of the resulting system of linear equations.² For that calculation, it may be practical to buy a commercial program and add to it a program for the SCD, or develop a proprietary program. In this study, we developed our own programming code for the SCD. More about the SCD can be found in Refs. 1 and 2.

In the cases that mass transport cannot be neglected, or that the temperature and the concentration are not constant in the electrolyte, it is necessary to consider tertiary current distribution.^{1,2} In the journals mentioned in the references, there are also references dealing with tertiary current distribution, but for the purpose of this study and because of the general complexity of the calculations, it was eliminated from this analysis.

The most interesting references for the practice are cited below. Alkire *et al.*³ developed a numerical method for predicting two-dimensional shape changes at a cathode dur ing electrodeposition. The calculation used the FEM to obtain the SCD in an electrolysis cell. Sautebin et al.⁴ carried out a theoretical and experimental modeling of surface leveling in ECM under PCD. The FEM was employed for studying the influence of geometrical factors on the rate of leveling of a triangular surface profile during anodic dissolution in ECM at a constant inter-electrode gap. Riggs et al.5 developed a computer-implemented method for predicting ECM work piece geometry, which was verified experimentally with a commercial ECM machine for cavity sinking. The FDM and a successive over-relaxation method were used. A step-like approximation for taking cathodic charge transfer overpotential into account, rather than applying Tafel kinetics to each electrode surface element (grid points on the electrode) to represent a continuous function, has been found to reduce the number of iterations for a converted solution by about a factor of four. Prentice and Tobias⁶ reported a method for simulation of the electrode profiles undergoing deposition or dissolution. Ohmic losses, charge transfer overpotential, and mass transport limitations were accommodated in the model. The FDM, coupled with a successive over-relaxation method, was used as the basis of the solution technique. Simulation of deposition on a corner electrode was used to illustrate the utility of the method. A least-square smoothing was used to eliminate the comer effect. For smoothing purposes, the cathode profile was divided into five regions. Each curve was smoothed separately, then joined by splicing functions. Auxiliary electrodes and shields were also simulated.

Novak and Rousar⁷ calculated the anode profile at various stages of the electropolishing process using the FEM and the SCD. Clerc and Landolt⁸ dealt with anodic leveling. They carried out a simulation by using the FEM and calculated the influence of profile shape and cell geometry under the conditions of PCD. Deconinck et al.9 calculated the current distribution and the change of the electrode shape by the BEM. The PCD and SCD were calculated for applications including simultaneous deposition and dissolution on opposing electrodes. Dukovic and Tobias¹⁰ offered a model of the current distribution and the change of the electrode shape for electrodeposition in the presence of diffusion-controlled leveling agents. The mathematical model accounted for the combined influence of (i) changes of resistivity within the electrolyte, (ii) area masking on the electrode surface, which raised surface overpotential by increasing the effective current density, and (iii) decreased local supersaturation, which lowered the concentration overpotential. The coupled field equations were solved numerically, using the BEM. Landolt¹¹ reported an experimental study and theoretical modeling of an electrochemical metal dissolution process involving a shape change of the anode. He used the FEM and the PCD.

West *et al.*¹² reported shape change simulations of electrochemical etching of lines and holes in thin metal films sandwiched between a photoresistant mask and an insulating



Fig. 3—(a) Sketch of the cell with insulating shields or auxiliary cathodes showing the cases cat1-cat5; (b) the cell with changed dimensions, position and potential of the main anodes and shape of the insulating shields, showing the cases an1, an2, an3 and an4. The dimensions, distances and electrical parameters are given in Tables 1 and 2.

Faraday's law was used to deter-
mine the rate at which the anode
recedes, assuming a constant cur-
rent efficiency during the EMM pro-
cess.

Dimensions

From the above mentioned references, good use can be made of the methodology for the solution of the current distribution, and of the ideas for approximation of the boundary conditions, as well as a review of the mathematical methods used. Because of the importance of the geometry in modeling of the current distribution in a cell and its role in cell design (concerning also different factors such as heat transfer or hydrodynamics of the cell), the calculations must be repeated for every practical problem. Very seldom can a researcher adopt the calculated current densities to reach conclusions about a realistic industrial cell (just for some qualitative analysis).

In this study, the SCD was calculated for an industrial cell in which nickel is deposited from a nickel sulfamate electrolyte. Different ge-

ometries were used to improve the uniformity of the thickness of the nickel deposit. The local influence of nonconducting shields and auxiliary electrodes was also measured and compared with the calculated results. An additional series of calculations was carried out in which the position and dimensions of anodes connected to different DC sources were changed to improve the uniformity of the local cathodic current densities.

using a linear element of the triangle type. Integrals with singularity resulting from the fundamental solution were computed analytically. This model suggests the optimum size of an auxiliary electrode, which minimizes the thickness variation through the entire area of a rectangular cathode for electrodeposition onto a lithographically patterned substrate. Shenoy and Datta¹⁴ analyzed an effect of mask wall angle on the shape evolution during through-mask electrochemical micromachin-ing. A mathematical model to predict shape evolution was developed. The BEM was used to solve the LE for the electrical potential with appropriate conditions that describe the metal dissolution process under ohmic control. The current distribution at the metal surface was determined solely by the ohmic effects and the elec-

trodes were defined as equipotential

surfaces (*i.e.*, the PCD was assumed.)



support. They used the BEM and the PCD was assumed. It was also explained that formulating the current distribution problem in terms of a stream function instead of an electric potential could improve the efficiency of the numerical procedure. Choi and Kang¹³ presented a three-dimensional calculation of the SCD in electrodeposition on a patterned cathode with an auxiliary electrode. The solution of the three-dimensional linear equation (LE) was obtained by the BEM,

cat1	cell without either auxiliary electrodes or insulating shields	
cat2	with insulating shields (thickness, 4 mm in all cases)	$d_1 = 20 \text{ mm}$ $d_2 = 40 \text{ mm}$ $d_3 = 20 \text{ mm}$
cat3	with insulating shields	$d_1 = 10 \text{ mm}$ $d_2 = 50 \text{ mm}$ $d_3 = 20 \text{ mm}$
cat4	with insulating shields	$d_1 = 20 \text{ mm}$ $d_2 = 40 \text{ mm}$ $d_3 = 30 \text{ mm}$
cat5	with auxiliary cathodes (avg. current density at the auxiliary cathode was 0.01 A/cm ²)	$d_4 = 10 \text{ mm}$ $d_5 = 20 \text{ mm}$

Table 1 Explanation & Dimensions for Experimental Cases cat1 - cat5

Case Comments

distance from the corners. In all these experiments, only one DC source was used, with a voltage of 2.68 V.

(See also Fig. 3a). Insulating shields or auxiliary cathodes were positioned at the

vicinity of the outer corners of the cathode (F, D, B) with the same dimensions and

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0.0350 -					
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0.0200 -		N.	1		СВ
0.0150 -	Ste hondin	1 4			
0.0100 -	-	11	11		corners of the cathode
0.0050 -	-	V	V		- calculated cds
0.0000 -		<u> </u>	- F -	<u></u>	7

Experimental Procedure

The experiments were carried out in a laboratory electrolyzer, sketched in Fig. 1.2, which represents a two-dimensional cross section of a real industrial cell. The figure shows the part of the cell used for laboratory experiments and for modeling. This is the part in which it is difficult to reach a uniform thickness of deposited nickel. The aim of this study was to calculate the cathodic current densities in this area and to compare the calculated results with experimental data.

The cathode was made from a steel plate 1 mm thick, 50 mm high, on which nickel was deposited during electrolysis. Anodes 1 and 2 were made from nickel plates 2 mm thick and 50 mm high. The dimensions aj (shown in Fig. 1.2b) are identical with the studied part of an industrial cell.

A heat exchanger at a working temperature of 50°C, connected to the system via pipelines and a pump, enabled the electrolyte to be circulated at a constant temperature. The deposition time was 10 hr.

The sulfamate electrolyte used for experiments was obtained from the factory GES (galvanization and engineering services) Prague, Czech Republic. Its composition was:

1.4 mol/L • $Ni(NH_2SO_2)_2$ 0.57 mol/L • H₂BO₂ • $N\tilde{i}Br_2$ 0.07 mol/L • $C_{12}H_{25}SO_4Na$ about 3.5 mmol/L (1 g/L), an additive that makes the surface tension of the

electrolyte about 40 dyn/c

· commercial additives

The conductivity of the electrolyte at 50 °C was measured; $\kappa = 0.084$ S/cm. The temperature during electrolysis T = 50 $^{\circ}$ C, pH = 4.3, and the average current density (cd) was 0.01 A/cm^2 .

The polarization curves shown in Fig. 2 were measured at a rotating disc electrode (RDE) with $\omega =$ 104.72 sec⁻¹ (the diameter of the RDE was 4 mm). During nickel deposition, hydrogen evolution occurs as a cathodic side reaction. At an average cd of 0.01 A/cm^2 , the fraction of the cd for hydrogen evolution represented 7.06 percent and for the total cd, 0.002 A/cm², it was 4.7 percent. These values were used for estimation of the polarization curve for hydrogen evolution. The polarization curve used for the mathematical modeling was obtained after the part of the current density representing hydrogen evolution was subtracted from the total current density.

Table 2 Explanation & Dimensions for Cases an1-an4

Case	Comments	Dimensions
an1	Anode 1 was moved upward and to the left from its position in cases cat1-cat5 .	j = 390 mm i = 80 mm h = 130 mm
an2	Anode 1 was moved upward and to the left from its position in cases cat1-cat5 . Three insulating shields were placed 2 cm away from the corners B, D and E. The dimensions of the shields were: Shield 1 - m = 20 mm, $m_1 = 78$ mm, $m_2 = 78$ mm Shield 2 - 1 = 20 mm, $l_1 = 55$ mm, $l_2 = 66$ mm Shield 3 - k = 20 mm, $k_1 = 58.5$ mm, $k_2 = 58.5$ mm	j = 390 mm i = 80 mm h = 130 mm
an3	Same position, shape and dimensions of shields, but anode 1 was moved 12 cm upward and 5 cm to the left from its position in cases cat1-cat5 .	j = 320 mm i = 80 mm h = 130 mm
an4	Same position, shape and dimensions as for an3 , but with two added auxiliary anodes (sketched in Fig. 3a). Aux. anode 1 had rectangular shape, with 4-cm side length, positioned 3 cm away from cathode sides FE and ED. Aux. anode 2 also had rectangular shape, with 6-cm side length, positioned 3 cm away from cathode sides CD and CB. Both aux. anodes had the same potential as anode 2	e 1

(See also Fig. 3b.)

Experimental Cases

In Fig. 3a and Table 1, the experimental cases cat1-cat5 are shown. These were experiments with insulating shields and auxiliary cathodes (robbers). All the shields or auxiliary cathodes had the same dimensions and positions corresponding to the outer corners of the cathode (F, D, B). In all these experiments, only one DC source

was used, with a voltage of 2.68.



Fig. 5—Local cathodic current densities obtained by calculation and estimated by measurement of the thickness of deposited nickel. The experimental case cat3 - cathode with non-conducting shields, dimensions and distances sketched in Fig. 3., are $d_1 = 10$ mm, $d_2 = 50$ mm, $d_3 = 20$ mm. In the sketch to the right, the positions of the corner cathode points A-H are shown.

A set of calculations with variable position, dimensions and shape of anode 1 was carried out (see Fig. 3b) as well. Anodes 1 and 2 were connected to different DC sources, as explained below. These changes were combined with addition of insulating shields close to the outer corners (B, D and F) of the cathode. The shape of the shield for corner D was changed, to cover better the shape of the cathode (see Fig. 3b). All the shields were enlarged compared to those of cases **cat1-cat5.** Some of the calculated cases, denoted as **an1-an4**, are sketched in Fig. 3b and explained in Table 2. In case **an4**, auxiliary anodes were used also, as explained in Table 2.

The influence of different anode potentials was also studied. In cases **an1-an4**, the potential of the metal of anode 1 was

 $\Phi_{\text{M,anode 1}} = \Phi_{\text{M,anode 1}}^{\text{old}} + 0.5 \text{ V}$ (8)

and the potential of the metal of the anode 2 was $\Phi_{M,anode 2} = \Phi_{M,anode 1}^{old} - 1 V$ (9)

where $\Phi^{\text{old}}_{\text{M,anode 1}} = 2.68 \text{ V}$ was calculated to obtain the averaged current density of 0.01 A/cm² on the flat, lower part of the cathode (point A in Fig. 3).

Mathematical Modeling

The Laplace equation was solved in two dimensions, using the Finite Element Method (FEM) with triangles. The mesh generator was used from commercial software^a and a solver for the SCD was developed for this purpose. To simplify calculations the following assumptions were used.

1. It was assumed that concentration gradients were negligible because of vigorous mixing of the electrolyte. The distribution of potential can be obtained by solving the Laplace equation (1).

2. The electrochemical reactions at the cathode are: $Ni^{+2} + 2e^{-} \longrightarrow Ni$ (10)

 $2H^{+} + 2e^{-} \longrightarrow H_{2}$ (11)

and at the anode: $Ni = Ni^{+2} + 2e^{-1}$



(12)

Fig. 6—Comparison of the local cathodic current densities between the case **cat1**, without additional elements, and **cat3** with non-conducting shields ($d_1 = 10 \text{ mm}$, $d_2 = 50 \text{ mm}$, $d_3 = 20 \text{ mm}$); see also Fig. 3. In the sketch to the right, the positions of the corner cathode points A-H are shown.

The measured polarization curves, shown in Fig. 2, were fitted for a current density near 0.01 A/cm^2 over the current density range of interest (Eqs. 13-15). The anodic polarization curve is expressed as

$$E_{Ni^{+2}/Ni} = 0.6\bar{3}0 + 0.180 \log|j_{Ni^{+2}/Ni}|$$
(13)

and the cathodic curve as

$$E_{Ni^{+2}/Ni} = -0.845 - 0.146 \log |j_{Ni^{+2}/Ni}|$$
 (14)

The polarization curve for hydrogen evolution is $E_{H+/H^2} = -0.948 - 0.127 \log |j_{Ni^{+2}/Ni}|$ (15)

3. Conductivity of $\kappa = 0.084$ S/cm for T = 50 °C was assumed to be constant in the entire electrolyte.

Results and Discussion

Influence of Non-conducting Shields on the Local Cathodic Current Densities

In Figs. 4 and 5, the local cathodic current densities are shown, obtained both by mathematical modeling and estimated by measuring the thickness of deposited nickel. In all the figures, the abscissa is the length of the cathode boundary.

The cathode has a complex shape composed of rectangular parts, as shown in Fig. 1. To follow the position of the local current densities along the cathode, the coordinates x and y were translated to the cathode boundary length, starting with zero at point A in Fig. 1.2b and ending at point H. It should be noted that the part of the cathode surface from H to I was insulated (inactive during the electrolysis). The points A to H represent the corners of the cathode. Figures 4 and 5 show the measured and calculated current densities along the cathode for the cases cat1 and cat3. The local maxima of the current densities are positioned at the corners B, D and F. This corresponds to the open space for current lines around these points, the electrical field around them and the short distance between them and the anodes. At the points C, E and H, there are the local minima corresponding to the closed space around these corners, the electric field around them and the greater distances between them and anodes (see Fig. 1). As can be seen from Figs. 4 and 5, the difference between the current densities obtained by measuring the thickness of the

> deposited nickel (using a micrometer) and the calculated values is within 10 percent. A small difference exists at the corners (points B to H), but, at those points, it was difficult to measure the deposited nickel layer because of the corner effect.

> In Fig. 6, a comparison between the local current densities obtained by the cases **cat1** (without auxiliary elements) and **cat3** (with non-conducting shields) is shown. The positions of the shields (see distances and dimensions d_1 , d_2 and d_3 in Fig. 3a and Table 1) were changed as explained above. The non-conducting shields suppressed the local maxima at points B, D and F by 10 to 34 percent, depending on the position of the insulating shield relative to the corner. Similar results were obtained for cases **cat2** to



Fig. 7—Local cathodic current densities calculated for the cases **cat1**, **an3** and **an4**. The calculated geometries are shown in Fig. 3 and Tables 1 and 2. In the sketch to the right, the positions of the corner cathode points A-H are shown.

cat5. Because of the great difference between the dimensions of the insulating shields and that of the entire cell, the effect of the insulating shields had a local character that extended several centimeters around their positions, affecting the local current densities a few centimeters around the local maxima.

Influence of Changes in Position, Dimensions, Shape and Potential of Anodes Combined with Insulating Shields and Auxiliary Anodes

In Fig. 7, the cathodic current densities are shown for cases **cat1**, **an3** and **an4**. The thin solid line shows the case **cat1** (cathode without screening elements and auxiliary electrodes).

The change of the potential of the metal of anodes 1 and 2 (carried out in the cases **an3** and **an4**) lowered the average cd at the flat part of the cathode. Technologically, the low ratio between the average cd in that zone and the local cd at the points of minimum (C, E) is beneficial for electrochemical metal deposition. If these ratios are large, either points C and E will represent points with a thinner layer of deposited metal, or after a longer deposition time, the whole cathode will have to be polished to get a satisfactory layer of deposited metal. In the calculated cases, **an1 to an3**, the current densities at points C and E increased by 11 to 72.3 percent, depending on the geometry.

When the potential of the metal of anode 1 was increased by 0.5 V and the potential of anode 2 was decreased by 1 V (case **an1**) the local maximum at the corner B decreased by 53.1 percent, but the local maxima at the corners D and F increased by 67 and 65.5 percent, respectively. The local minima (points C and E) increased by 64.7 and 22.7 percent, respectively.

Cases **an2** and **an3** are examples of calculations to check the combined effect on the local cathodic current densities of the insulating shields and the anodes connected to different DC sources. Both cases suppressed significantly the local maxima (approx. 20 percent) at the outer corners, but they caused two smaller maxima instead of one larger.

Case an4 showed that adding auxiliary anodes, close to the inner corners (C and E) of the cathode, improved the current distribution along the cathode; also, the local minima showed a 100 percent increase compared to the other cases. To optimize the current densities, the parameters that must be changed are the geometry and the positions of the auxiliary anodes. Of course, it is not certain whether these solutions are acceptable from a practical point of view.

Conclusions

The secondary current distribution was calculated for a metal deposition process on a

cathode of complex geometry. The calculated current densities were in good agreement with values experimentally estimated, using the measured thickness of the deposited nickel from a nickel sulfamate electrolyte. Auxiliary cathodes and insulating shields had a local effect on the cathodic current densities (i.e., several centimeters around them). An arrangement with two different DC sources and with insulating shields placed in the vicinity of the outer corners of the cathode gave the most uniform thickness of the nickel deposit. The local maxima were suppressed by approximately 30 percent. Auxiliary anodes placed in the vicinity of the inner corners of the cathode influence the local current densities to a great extent. To obtain better results, optimization of their parameters should be carried out in future work. Useful information was obtained about the influence on the cathodic current densities of auxiliary electrodes, insulating shields and geometrical and electrical parameters of the main anodes. That is a necessary step before further optimization of the cell geometry and the selection choice of an acceptable cell for the metal deposition process.

The results show that for cells with a complex geometry mathematical modeling should be used to minimize the time needed for choosing a convenient configuration, shapes and parameters of electrodes.

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Editor's note: Manuscript received, April 1997.

Acknowledgment

The authors would like to thank Professor Jomar Thonstad (NTNU Trondheim, Norway) for his continuous interest, help and encouragement.

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