A New 3D Electroplating Simulation & Design Tool

By F. Druesne, M. Afzali & R. Mouton

Electroplating process energy and material costs are very important considerations in product manufacturing. The most important plating criteria, however, are quality and plated uniformity of the deposited metals. Simulation tools can help to obtain better plating results. New plating simulation tools are now available that will run on PC/Windows® computers and can point the way to optimizing many common electroplating processes. Software packages are available that are versatile and user-friendly. These tools have been designed to optimize electroplating cells and racks. An accurate analysis is required to determine distribution of deposited thickness, current densities, and electrode potentials. A good plating simulation tool can help an engineering team find the most reliable rack configuration based on the geometrical description of rack, the parts to be plated, and from calculation of the electrochemical properties of the process being studied.

The design of an electroplating rack requires many preliminary steps, including: (1) the choice of the electrolyte, and (2) the location, shape and number of electrodes, masks and current thieves. These parameters affect deposit thickness and plating distribution. Preliminary steps taken to optimize a plating process might be very time consuming if they are performed in a trial-and-error fashion (*i.e.*, plating parts, measuring thickness, plating again, etc.). If those trial-and-error steps can be simulated accurately, large gains can be made in overall plating cost reduction and the time-to-market of new part designs.

Plating parts in actual production requires that several parts be placed in the same electrolytic plating tank. The primary difficulty is in obtaining uniform deposits on each part, and from part to part, to satisfy plating thickness tolerances assigned by the plating performance specification. We must often deposit more metal on a given area to achieve the necessary minimum plating thickness in another area. This not only increases overall cost, but may also require additional remedies in areas where there is an excess of plated metal.

Nuts & Bolts: What This Paper Means to You

The most critical measurements in plated products are quality and thickness. Computer simulations are getting better and better, moving into 3D representations. This paper shows just what can be done nowadays, as the designer sees how plate distribution plays out in a given tank and/or rack design, long before it is built. Trial and error is much cheaper on a computer screen. For those interested, some of the math going into these programs is discussed, while for most of us, case histories show what can be accomplished.

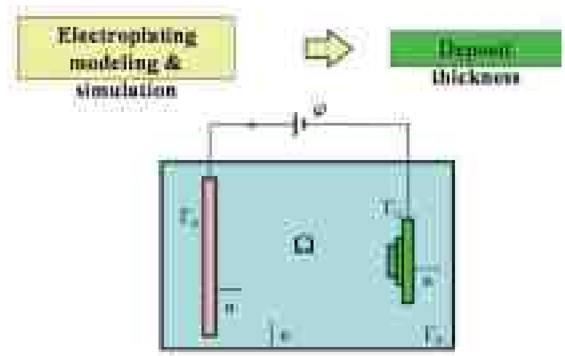

Fig. 1—Representation of an electrochemical system.

Effective electrolytic plating thickness simulation, therefore, can help the plating industry design the most appropriate rack and tools to produce the best deposit uniformity on each part. Many industrial electroplating applications have been optimized by the use of new plating simulation software. The software is based on an original numerical method, called boundary element analysis. For the last 20 years, the reliability of this kind of engineering tool and the accuracy of the results achieved have been proven in many industrial applications.[1-2]

Mathematical Modeling

The electrolytic domain Ω is bounded by $\Gamma = \Gamma_A \cup \Gamma_C \cup \Gamma_R$. The boundary is constituted by the insulating part Γ_R, the anodic boundary Γ_A and the cathodic boundary Γ_C (Fig. 1). In the electrolytic domain Ω the electrical potential is constructed with Equation 1 below, which describes ionic migration. Boundary conditions are as follows:

- In the electrolyte Ω, Equation 5 links the potential u and current density j, on the insulating part Γ_R.
- The zero current value is applied (Equation 2), on cathodic boundary Γ_C and on anodic boundary Γ_A.
- Experimental polarization laws are assigned, as in Equations 3 and 4.

These laws describe the kinetics of the reaction at the electrode.[3-4]

The problem (P_1) of electrochemical plating is to find the potential $u(x)$ in Ω for a known potential difference $\varphi \neq 0$ such as:[5-6]

$$
(P_1) \qquad \begin{cases} \operatorname{div}(-\sigma \cdot \operatorname{grad} u(x)) = 0 & \text{in } \Omega \qquad (1) \\ \sigma \dfrac{\partial u}{\partial n} = 0 & \text{on } \Gamma_a \qquad (2) \\ \sigma \dfrac{\partial u}{\partial n} = f(u(x)) & \text{on } \Gamma_c \qquad (3) \\ -\sigma \dfrac{\partial u}{\partial n} = g(u(x) - \varphi) & \text{on } \Gamma_A \qquad (4) \end{cases}
$$

The current density vector is determined with the local gradient of potential u(x) in the electrolytic domain Ω and is established with the Ohm's law (Equation 5). On each point x of the boundary Γ the current density *j*(x) is described by Equation 6.

$$
\begin{cases} \vec{j} = -\sigma \cdot \operatorname{grad} u & (5) \\ j(x) = \vec{j} \cdot \vec{n} = -\sigma . \partial u / \partial n & (6) \end{cases}
$$

Electrochemical behavior laws f and g are non linear, thus the system (P_1) is also non-linear. The problem is solved by boundary element analysis method coupled with the Newton-Raphson technique.

Only electrolytic domain boundaries are modeled, and the integral formulation is written for each point x of submerged surfaces Γ, as follows:

$$
\begin{cases} \forall x \in \Gamma \\ C(x)\, u(x) = -\int_{\Gamma} j^*(x, y)\, u(y)\, d\Gamma + \int_{\Gamma} j(y)\, u^*(x, y)\, d\Gamma \end{cases}
$$

C(x) = 1/2 for x ∈ Γ if tangent plane is continuous at point x
= 1 for x ∈ Ω (7)

where fundamental solutions of Laplace operators *j** and *u** depend only on the electrochemical characteristic σ and on y and x respectively, the generic point and source point. C is the free term coefficient. Physical variables *j* and *u* of the domain boundary are linked by boundary conditions (non-linear polarization laws). The boundary element analysis method is a mixed method that allows calculations of the unknown potentials *u* and current density *j* with the same accuracy. This is a specificity of the method itself.

At the generator, the dual global quantities (current I and potential difference φ) are linked by a non-linear function (a generalized Ohm's law). The resolution of (P_1) is not enough, so an algorithm has been developed, monitored by the global current I. This current input value corresponds to the working current density advocated by the plating bath supplier. When the convergence is reached, the numerical electrochemical balance is adjusted to the industrial process balance. Hence, the current densities obtained are used to determine thickness and distribution on the cathode via Faraday's law.

Model of a Rack

The plating rack and other electroplating hardware (masks or shields) can thus be described by a graphical tool in a three-dimensional space. Interactive solid modeling allows plating simulation of the complex geometry of the electroplating rack and the parts to be plated. This is the principal part of the simulation tool. The second feature is an electrolytic data manager composed of all the electrochemical characteristics needed to adequately simulate actual electrodeposition: electrolyte conductivity, cathodic and anodic polarization laws, cathodic efficiency law, properties of the deposited material and the working current density.

Figure 2 represents an actual industrial application, zinc electroplating of pulleys. This particular example was used as a model to study the plating rack and to optimize plate thickness uniformity. The pulleys are an automotive component with an exterior diameter of 95 mm (3.8 in.). The rack consists of a double framework to hold 216 pulleys.

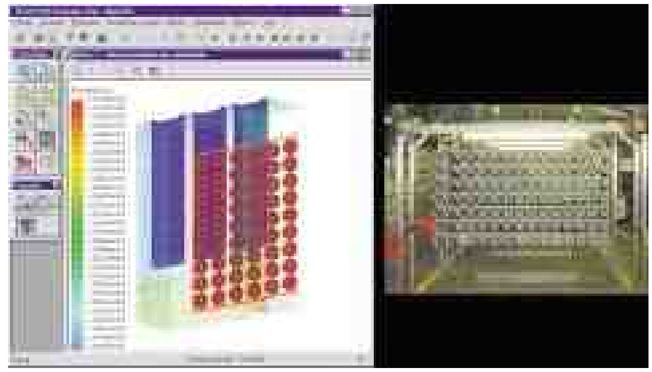

Fig. 2—Modeling of zinc electroplating of pulleys.

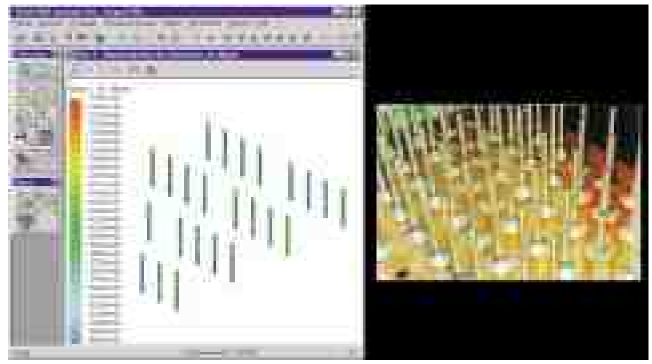

Fig. 3—Visualization of deposit thicknesses on valve spindles.

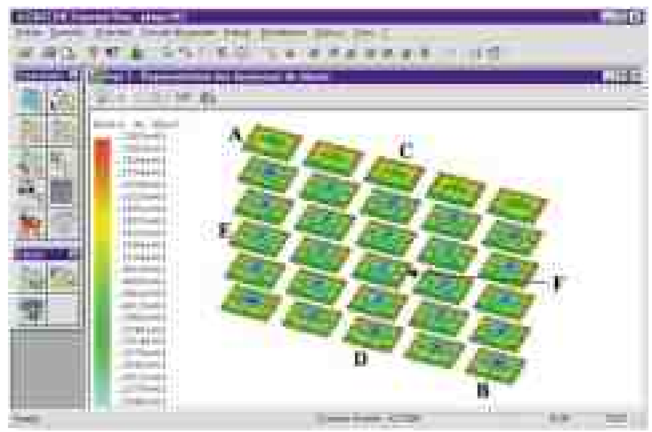

Fig. 4—Display of optimized depositing thickness on plates.

The zinc electrolyte was studied to determine its electrochemical properties. Polarization laws were identified to model the true electrochemical behavior of its electrodes. The software's electrochemical data manager included these properties, and from the geometric description of the rack components (parts, anodes, current thieves and masks), a model was prepared.

This model (Fig. 2) takes into account the complex geometry of the rack. After numerical analysis and electroplating simulation, the results were compared with the actual deposits (as measured X-ray fluorescence). Wherever plating thickness readings were taken on the rack, the simulated and actual deposited thicknesses measured were in good agreement.

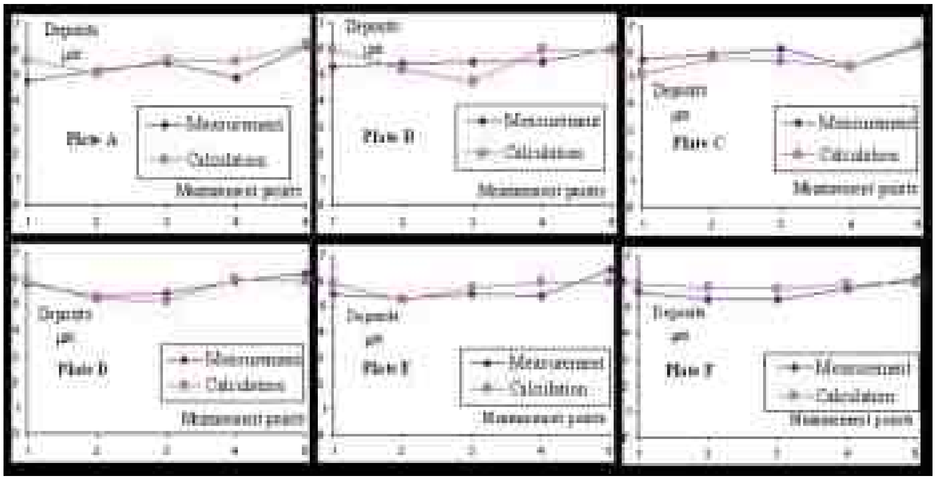

Fig. 5—Comparison between measured and calculated deposits for six plates.

The next step was to optimize the deposit distribution by introducing insulating masks and current thieves. Several configurations were studied.

Electroplating Validation

Chromium Electroplating of Valves

A second industrial application showed good correlation between the simulation tool and the measured plate thickness. The firm manufacturing the valves required a thorough study of their hard chromium plating operation. To fully optimize the manufacturing of the valves it was necessary to optimize the plating process. The distribution of hard chromium deposits had to be uniform along each valve while maintaining low minimum deposit thickness tolerances.

Based on a hard chromium electrolyte, the model and the simulation were applied to a framework of 112 valves where only the spindles were covered with chromium. The model accounted for the complexity of the entire system, including masks to channel current lines. The result is shown in Fig. 3.

Average Thickness Readings on Valve Spindles

	Measurements	Calculation	% difference
Foot	6.4 µm (256 µin.)	6.8 µm (272 µin.)	6
Head	4.8 µm (192 µin.)	5.6 µm (224 µin.)	16

The actual measured thicknesses are in good agreement with those calculated in the simulation, as illustrated in the above table. The values represent the deposit averages on the bottom and head of the valve.

Once this numerical model was validated, we tried to optimize the plate thickness by changing locations of different rack components. A configuration was tested and satisfactorily implemented.

Zinc Electroplating of Plates

Another electroplating rack configuration change confirmed the performance of the plating software. This particular manufacturer treated hundreds of small parts fitted together in 30 plates. These plates were modeled successfully and changes made to the plating configuration.

The manufacturer provided a rack for which configuration was described in terms of location, shape and number of electrodes. In order to set up a new production line, it was important to determine by simulation a rack configuration that would yield the best possible deposit thickness uniformity. From this configuration, we modeled several racks to optimize these parameters. We chose a model which gave, by simulation, the thickness visualization shown in Figs. 4 and 5.

The color display is necessary for proper interpretation. The deposit distribution is uniform. The workshop team made X-ray fluorescence measurements on individual parts to study the deposits on six plates. Figure 4 shows the plates chosen for comparing the simulation results to the actual measurements from the plating process. For each plate (ABCDEF), the deposit measurements at five points were compared to calculated values.

The correlation between measured and simulated deposits was excellent, further demonstrating the performance of the thickness simulation program. In Fig. 5, it can be seen that the required part-to-part uniformity was obtained.

This tank configuration is to be used to set up a new production line. This preliminary use of the three-dimensional plating simulation software enabled the choice of the optimum electrolyte and the position and dimensions of the different electrodes in the tank. The results of this zinc electroplating study saved time by allowing one to avoid accounting for the hundreds of individual parts, just the plates.

Copper Electroplating for Printed Circuit Boards

Electroplating process energy, plating time and raw material costs are also very important in electroplating printed wiring boards, but they are seldom given much consideration. The most important plating criteria are quality and more specifically, plated uniformity of the deposited metals. Three-dimensional electroplating simulation tools can help printed wiring board manufacturers to obtain dramatically better plating results.

The recent history of electroplating complex multilayer printed circuit boards, especially newer, more difficult-to-plate board designs, has been lackluster. Density of surface features such as SMT pads, fine line circuit traces and blind via holes make plating circuit boards with uniform electrodeposits a monumental challenge. Underplating of blind via holes can easily occur while simultaneously overplating other areas of the board and it is particularly difficult to understand and control the electrode potential of isolated traces or pads. It is not unusual to plate 50 to 70 µm (2.0 to 2.75 mils) of copper on some part of a printed circuit board to achieve a minimum plating thickness specification of 15 to 20 µm (0.6 to 0.8 mils) for blind vias and 20 to 25 µm (0.8 to 1.0 mils) for through-holes. An overall thickness of 25 µm (1.0 mil) is usually the specification for plated copper.

When plating printed circuit boards, the "picture-frame" effect of non-uniform plated deposits is as pronounced as in plating many flat objects. For printed circuit boards, however, the negative consequences are much greater. Complex multilayer boards are generally overplated to such a degree that subsequent printed circuit manufacturing operations are negatively affected, including resist stripping, solder mask coverage and assembly.

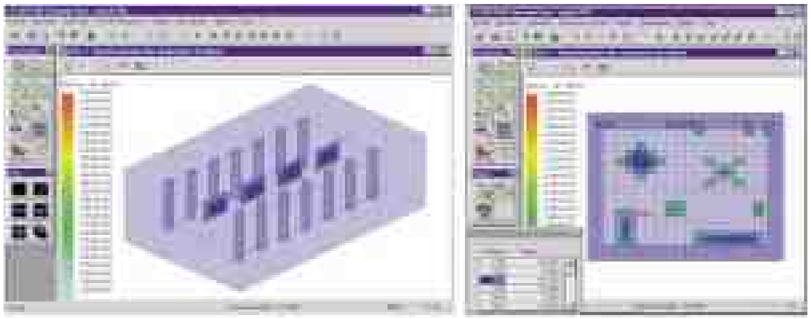

Fig. 6—Deposition of copper simulation on circuit boards (L); zoom on a circuit board (R).

Non-uniform plating is not the only negative issue. Productivity is also significantly affected. The above-mentioned plating deposit uniformity problems are commonly found in plating current density ranges of 1.1 to 1.6 A/dm^2 (10 to 15 A/ft^2). It is well known to most electroplaters, however, that conventional acid copper electrolytes made for printed circuit plating are easily capable of much higher current densities [*e.g.*, 3.8 to 5.4 A/dm^2 (35 to 50 A/ft^2)].

New plating simulation software now available will run on conventional PC Windows 95/98/2000, NT and XP operating systems and can point the way to optimizing many common electroplating processes for printed circuit boards. As seen in Fig. 6, the software is versatile and user-friendly. These new software tools have been specifically designed to optimize electroplating cells, plating racks and cathodes so that plating current can be focused where it is wanted and shielded from areas of a circuit board that would otherwise be overplated.

With better understanding of printed circuit board electrode potentials, as provided by circuit board design files, plating of circuit boards is expected to yield demonstrably better results. Sophisticated analyses and mathematical calculations are required to accurately simulate and determine circuit board electrode potentials, plating thickness distribution and optimum current densities. A good plating simulation tool can help an engineering team find the most reliable rack configuration based on the geometrical description of the rack, the parts to be plated and from calculation of the electrochemical properties of the process being studied.

Conclusions

For a considerable time, technically advanced plating simulation software has been tested and successfully used in many electroplating applications. The results obtained by simulating the electroplating process have been in close agreement with measurements taken from production plating results. When the preliminary steps of plating cell design, cathode design and rack design are simulated numerically, the results of the simulation help to achieve optimum plating configurations. One of the principal objectives of a plating simulation tool is to design the most appropriate cell, rack and ancillary tools needed to repeatedly produce optimum plating deposit uniformity on the cathode.

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About the Authors

Dr. Frédéric Druesne is an engineer at the Technical Center for Mechanical Engineering Industries (CETIM, Dpt. Calcul, 52 Avenue F. Louat, B.P. 80067, 60304 Senlis Cedex France, frederic.druesne@cetim.fr). His doctoral thesis concerned the numerical simulation of electrodepositing thickness, realized in collaboration between CETIM and Compiègne Technology University. He has more than 15 publications to his credit.

Mansour Afzali is head of the CAD/CAE Department at the Technical Center for Mechanical Engineering Industries (CETIM), Senlis, Cedex, France.

Roger Mouton founded EIMC, 29592 Pelican Cove, Laguna Niguel, CA 92677-1647 (roger.mouton@worldnet.att.net), focusing on advanced plating technologies and electroplating process development. He has experience in product and business development, sales, marketing and technical service with ROHCO, DuPont Electronics and Electrochemicals and has served in distributor representative positions with MacDermid, Inc. and Polyclad Technologies in printed circuits, electronics manufacturing and metal finishing. He has written articles in Printed Circuit Fabrication, CircuiTree Magazine *and* The Board Authority. *He holds a BA in economics from Loyola University in Los Angeles.*