# CAD Based Optimization of cCromium Plating Processes for cCmplex Parts

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ElSyCaWorks Plating, a new SolidWorks® based simulation tool to compute current density and deposit thickness distributions for electroplating processes, is presented. Complex three-dimensional shaped workpieces in arbitrarily designed reactors can be modeled. The software allows optimizing the reactor design (e.g. anode, screen and current thief configuration) and working conditions (e.g. total current, pulse parameters) for a large variety of plating processes. Additionally, it provides producers the analytical data to discuss the manufacturability of a product design with Design & Engineering. The application of ElsyCaWorks Plating to the prediction and optimization of a chromium deposition process for complex three-dimensional parts is illustrated.

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## 1. Introduction

Although advanced numerical methods exist and have been applied with great success in a broad range of engineering domains (hydrodynamics, aerodynamics, structural mechanics, heat transfer, etc…), the use of these methods for electrochemical plating applications remains rather limited. One of the main reasons is the complexity of the physical, chemical and electrical phenomena governing electrochemical reactor behavior. In general, a complex interplay of the following phenomena takes place: electrochemical electrode kinetics, electrolyte hydrodynamics, ionic mass transport, gas evolution, and heat generation in the bulk and at the electrode-electrolyte interfaces.

From an engineering point of view however, the main focus is on the current density and layer thickness distribution, which principally depend upon the following phenomena:

- ohmic drop in the electrolyte solution;
- cathodic polarisation and plating efficiency;
- anodic polarisation;
- reactor configuration including anode positioning, screens and current thieves;
- workpiece shape and dimensions;
- selective insulation of workpiece surfaces;
- number and position of workpieces on a rack;
- total current injected and anode + workpiece contacting method.

The modeling approach that takes into account these phenomena is commonly denoted as the 'potential model'[1]. In order to produce reliable simulation results, the physico-chemical input parameters (polarisation behavior, plating efficiency and electrolyte conductivity) need to be defined carefully for the electrolyte bath being used, at a given operating temperature.

In this work, the ElSyCaWorks Plating v1.0 software tool[2] is used to design a dedicated reactor for the selective chromium plating of an oil pump shaft. The current density and layer thickness distribution are evaluated for each step in the reactor design process. In a first step, the workpiece is partly insulated (taped), in order to redirect the current to the surfaces that will be subject to wear and corrosion in practical mechanical operation conditions of the pump. A tubular reactor with cylindrical anode mesh is used. In the next steps, the anodes are redesigned, abandoning the concept of a single faraway anode mesh for multiple anode meshes closer to the targeted surfaces (though still connected to one single current source). The anode positions and dimensions are optimized until a layer thickness distribution is obtained meeting certain minimum and maximum specifications. Plating within these product specifications avoids performing (expensive) additional grinding operations.

The ElSyCaWorks Plating tool is entirely integrated in the SolidWorks® CAD environment hence enabling a very fast adaptation of the reactor design at each step. The unique combination of a user-friendly and performant CAD tool with a fast and accurate current density and layer thickness distribution simulation tool allows to design and optimize the entire reactor within a couple of hours. The ElSyCaWorks Plating tool can also be used for the evaluation of current density and layer thickness distributions on electrodes with high internal resistivity e.g. wafers[3], or for electrochemical machining applications [4,5].

## 2. Mathematical model

A brief overview of the mathematical model behind the current density and layer thickness distribution simulations is given below.

Although cathodic deposition reaction mechanisms can become very complex, the polarisation behaviour for single metal deposition processes $Me^{z+} + ze^{-} \rightarrow Me$ is often quite accurately described by a Butler-Volmer type relation:

$$j_n = j_0 \cdot \left(e^{\alpha_a F/RT(V-U)} - e^{-\alpha_c F/RT(V-U)}\right) \qquad (1)$$

where $j_n$ is the amplitude of current density normal to the electrode surface, $j_o$ is the exchange current density, $R$ the gas constant, $T$ the temperature, $\alpha_a$ and $\alpha_c$ the anodic and cathodic charge transfer coefficients, and $E_{01}$ the equilibrium potential for the deposition reaction. $V$ and $U$ hold for the electrode respectively electrolyte potential.

The main reaction occurring at inert impressed current anodes is oxygen evolution. Due to the thin passivation layer that is often present on the surface of this type of electrodes, a linear relation approaches the polarisation behavior:

$$j_n = A(V-U)+B\,, \qquad (2)$$

with $A$ *and* $B$ polarisation constants.
The ohmic drop effects in the electrolyte are described by the Laplace equation for the electrolyte potential $U$:

$$\overline{\nabla}(\overline{j}) = 0 \qquad \overline{j} = -\sigma\overline{\nabla}U\ . \qquad (3)$$

On insulating boundaries, the current density perpendicular to the surface should be zero, which results in the following boundary condition:

$$\overline{j}.\overline{1}_n = j_n = -\sigma\overline{\nabla}U.\overline{1}_n = 0. \qquad (4)$$

On electrodes, $j_n$ is given by equations of type (1) or (2).

The local metal thickness $d$ on the cathode is simply computed from Faraday's law:

 

$$\Delta d = \theta \frac{M \, \Delta t \, j_n}{\rho \, z \, F}, \qquad (6)$$

where $\theta$ is the efficiency for the deposition process (depending on the current density $j$). $M$ holds for the atomic weight of the metal, $\rho$ for the density, $z$ is the number of electrons exchanged in the metal deposition reaction, and $F$ is Faraday's constant.

The physico-chemical input data (polarisation behavior, plating efficiency and electrolyte conductivity) as used in this paper are those for a typical industrial hexavalent Cr bath.

## 3. Numerical solution method

As the conductivity of the electrolyte is constant, the Boundary Element Method (BEM) is well suited to solve the charge conservation equation (3) with boundary conditions (1), (2) and (4). When the BEM is applied, only the boundaries of the domain must be discretised. In three dimensions this means that all surfaces need to be subdivided (using e.g. triangular elements). The grid quality is of utmost importance for the accuracy of the results. Figure 1 shows a typical grid as being used for the oil pump shaft. The grid contains about 85000 elements and 45000 points. To be able to generate these kinds of grids, the ElSyCaWorks Plating tool has a fully integrated state of the art grid generator (ElSyCa Hygen). This tool is able to generate very high quality grids with minimum user interaction.

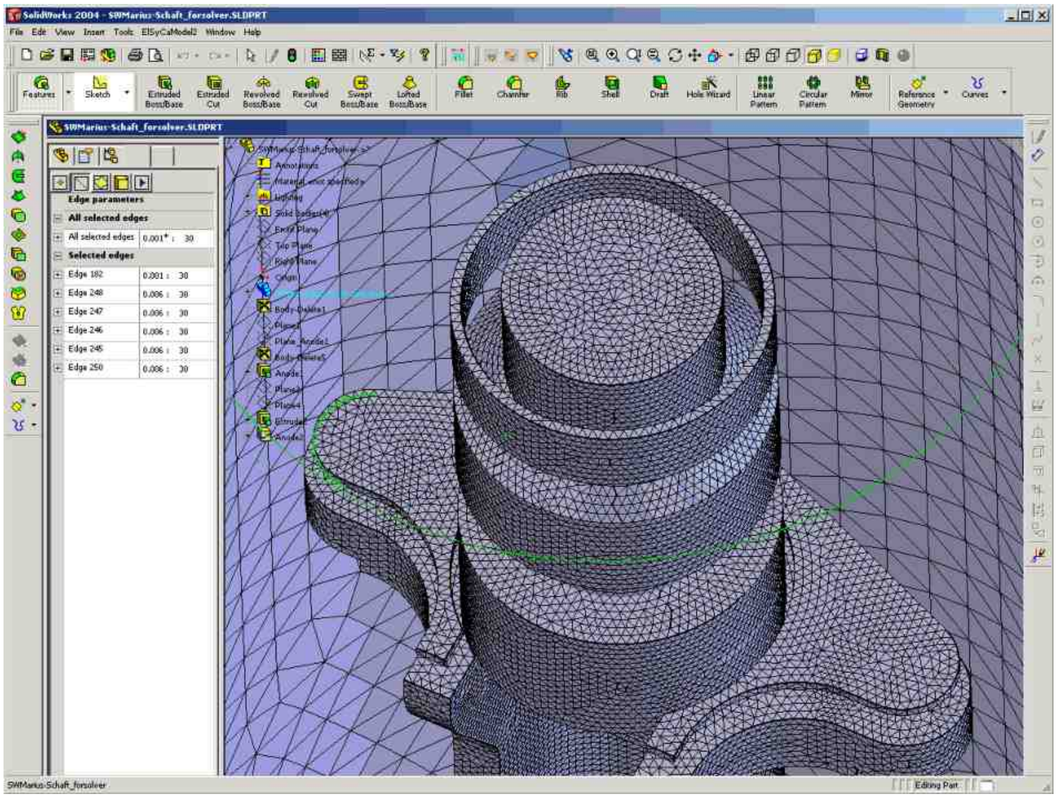


**Figure 1: triangular surface mesh for the shaft in the SolidWorks CAD environment**

## 4. CAD based reactor design

As a first step, a tubular plating reactor is defined, with an anode mesh stretching over the entire inner cylinder wall. Only the shaft surface areas to be plated are exposed to the electrolyte, the remaining surfaces being insulated (taped). The CAD representation of the reactor surrounding the shaft is depicted in figure 2 (left), with the anode mesh in red, the exposed surface areas in blue, and the insulated surfaces in gray.

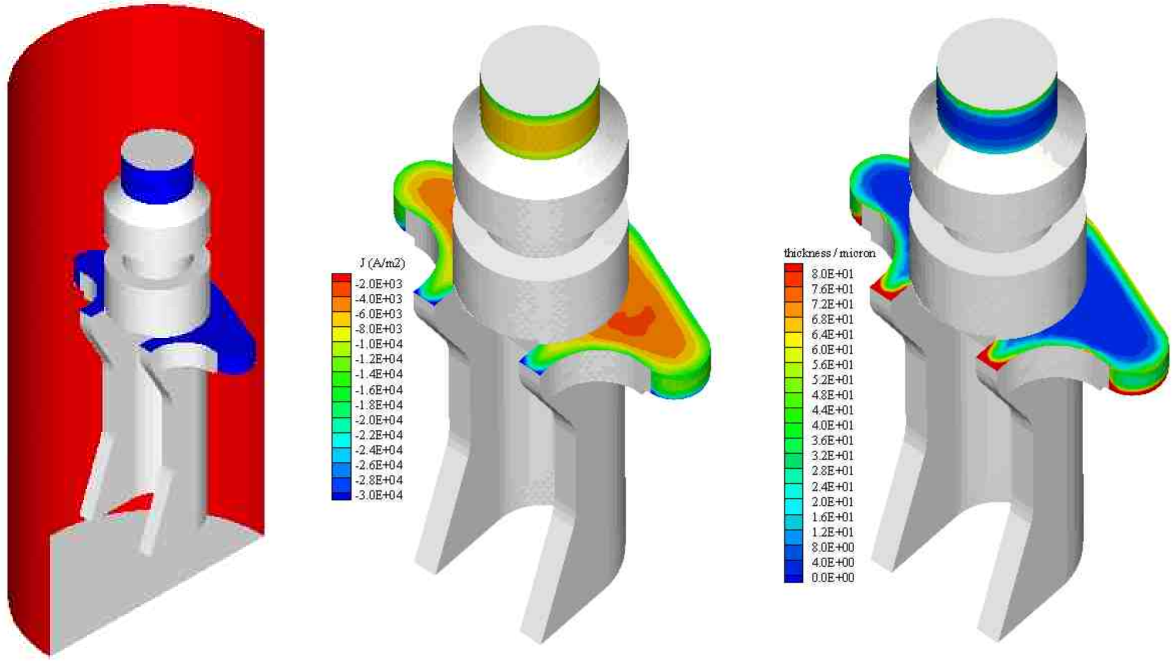


**Figure 2: basic reactor configuration (left), cathodic current density distribution (center) and layer thickness distribution (right)**

For this basic reactor configuration, the current density distribution over the exposed surfaces is plotted in figure 2 (center). The total current is *20 A* (DC regime), leading to a mean cathodic current density of $100\ A\ dm^{-2}$. The related deposit thickness distribution (for a total plating time of *3 hours*) is highly non-uniform (figure 2, right), ranging from $3\ \mu m$ in the central flat zones to $75\ \mu m$ near some of the edges.

The specifications for this deposit thickness distribution to be met are much more severe, with a minimum of $5\ \mu m$ and a maximum $30\ \mu m$.



 

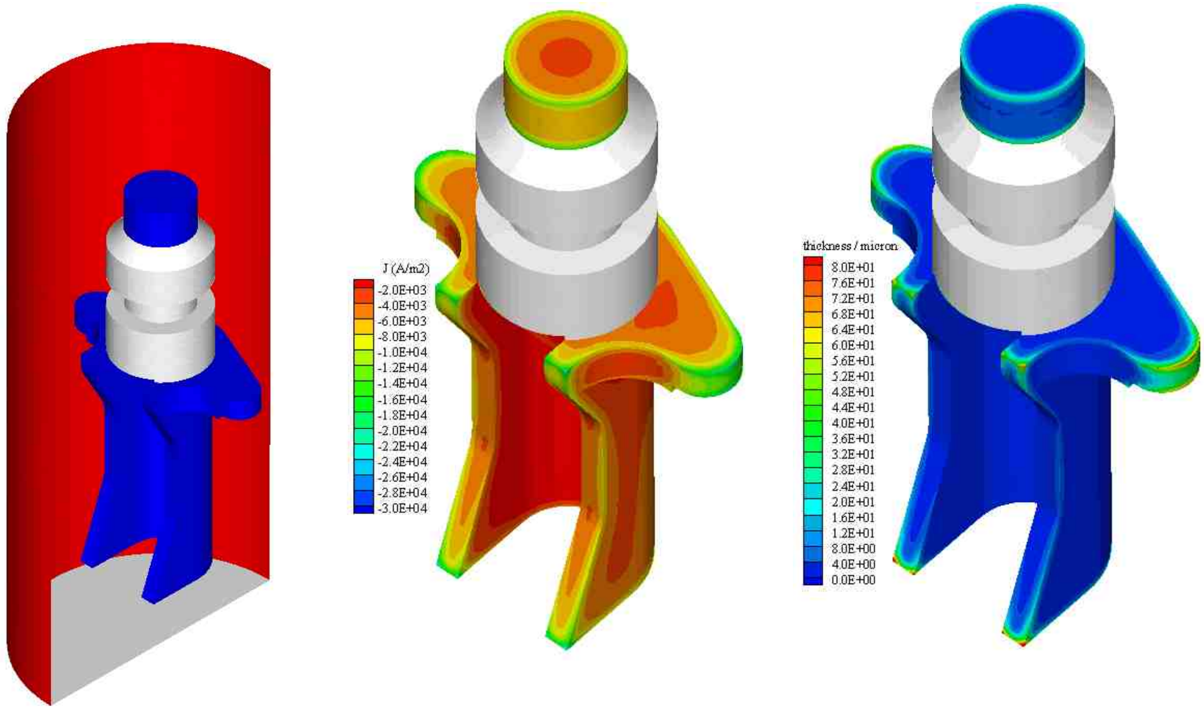


**Figure 3: step 2 configuration (left), cathodic current density distribution (center) and layer thickness distribution (right)**

Working towards these specifications involves some drastic improvements to the reactor. The second design step involves the exposition of additional shaft surfaces to the electrolyte, in order to reduce the edge effects on the targeted surfaces. The total imposed current is now *60 A*, in order to maintain a mean cathodic current density of $100\ A\ dm^{-2}$. The results are plotted in figure 3. A slight improvement of the layer thickness distribution on the targeted surfaces is noticed, mainly a reduction of the edge effects, but the overall uniformity is still far from reaching the specs.

In a third step, the large anode mesh is replaced by 3 smaller anode meshes (one closed and 2 open), positioned much closer to the exposed shaft surfaces. The imposed current is reduced to *30 A*, which guarantees maintaining a mean current density of $100\ A\ dm^{-2}$ on the targeted surfaces. The specifications for the layer thickness distribution (figure 4) are still not met, but the deposit range is now reduced to [$5\ \mu m$, $43\ \mu m$]. This step incorporates adjusting the distance from the anodes to the targeted surfaces, in order to balance the current that is directed to each of the anodes (only one current source is used).

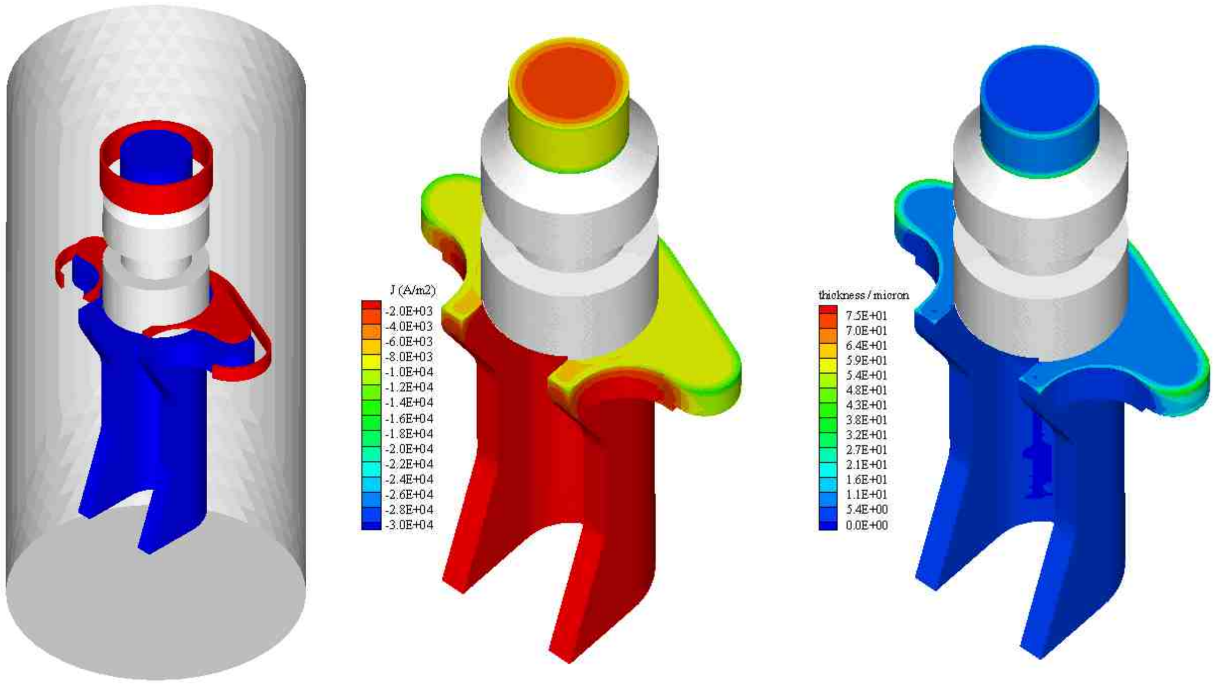


**Figure 4: step 3 configuration (left), cathodic current density distribution (center) and layer thickness distribution (right)**

The fourth and final step deals with the further optimisation of the dimensions and positions of the anode meshes. The dimension of the horizontally placed anode is slighly reduced in order to tackle the edge effects around both cams. The backside of the vertical anodes is shielded, for the same reason. The deposit thickness range [*8 μm, 36 μm*] is now within the industrial specifications.

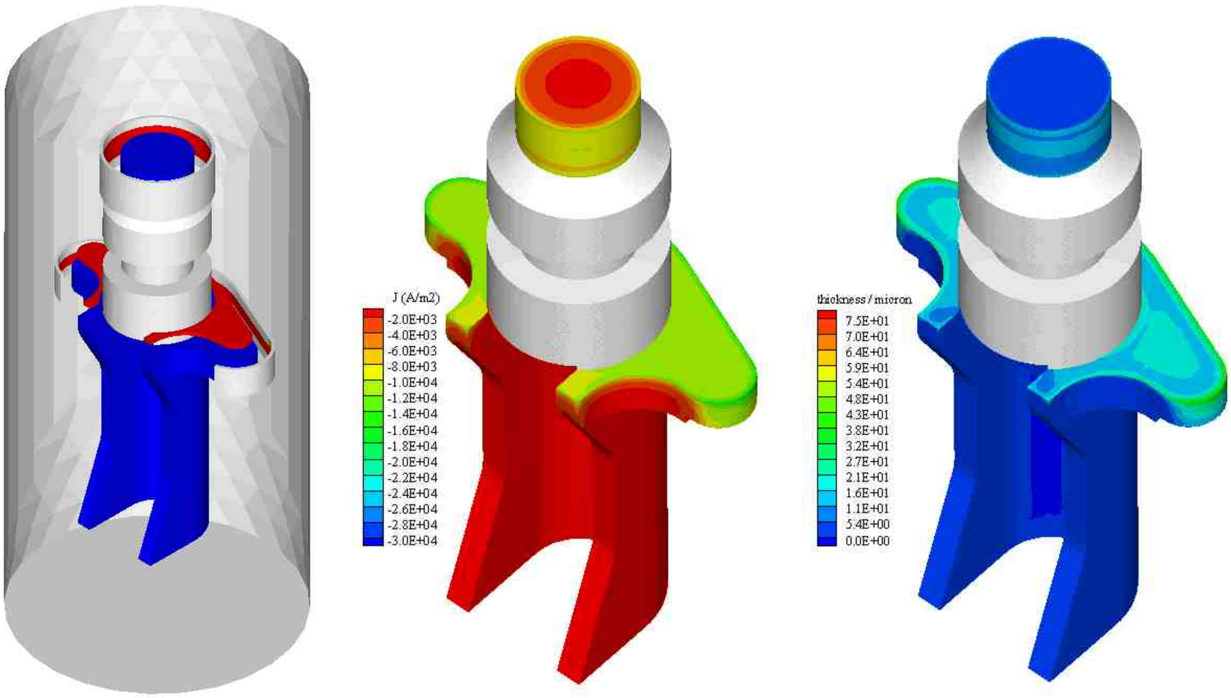


**Figure 5: step 4 configuration (left), cathodic current density distribution (center) and layer thickness distribution (right)**

## 5. Computational specifications

The ElSyCaWorks Plating tool runs under Windows. CPU times for the simulation of the current density distribution in any of the design steps as discussed in section 4 range around *10 minutes* on a *2.4 GHz* PC, including triangular mesh generation.

## 6. Conclusions

The capabilities of the ElSyCaWorks Plating tool for a fast CAD aided design of dedicated workpiece plating reactors have been illustrated.

For a moderately skilled SolidWorks® CAD user, defining the design improvements from one step to the next takes only about *10 minutes*. In general, about 3 to 10 design steps will be required to meet the specifications on the layer thickness distribution, depending on the complexity of the workpiece and the specifications for the deposit thickness distribution. Adding the CPU simulation time, the total manpower effort for each design step mounts to about half an hour. This means the entire reactor design and optimization, starting from scratch, can take place within one day (to be compared to days or weeks of trial and error), provided that a sound CAD file for the workpiece is available.

The subsequent steps as illustrated in this paper represent only one possible design approach strategy. For example, this approach does not make use of additional current sources or current thieves. Nevertheless, any combination of the commonly used auxiliary reactor design tool kit (i.e. anodes, screens, multiple current sources and current thieves) can be fully exploited and tested in the ElSyCaWorks Plating simulation environment.

For plating applications where the use of bipolar pulse current rectifiers can improve both the deposit quality and uniformity, ElSyCaWorks Plating also allows a full investigation of pulse current parameters (anodic and cathodic current, duty cycle, etc.), in combination with the standard reactor design tool kit.

Finally, the ElSyCaWorks Plating software enables manufacturers to discuss the manufacturability of a product (cost, quality) based upon sound analytical data with their customers of Design and/or Engineering departments.

## 7. References


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