3D Simulation and Validation of a Ni plating Process for Reflector Applications

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Due to the high uniformity demands, nickel deposition processes for producing reflector coatings often make use of dedicated plating cell configurations. Computer simulations can drastically speed up the trial and error stage for optimizing the plating cell design. In this paper, the nickel deposition distribution for a reflector application is simulated using the Elsyca PlatingMaster software tool. Results are compared to experimentally mapped data over the deposition surface. The quantative accuracy of the simulation results depends upon the electrolyte bath characteristics input. Dedicated laboratory measurements are performed (Rotating Disc Electrode set-up) to produce reliable electrolyte bath characteristics for different bath concentrations and operating temperatures. Simulations which make use of these dedicated input data turn out to match closely the experimental results. This observation justifies the cost of manpower and equipment for measuring relevant plating bath characteristics to be used in the Elsyca PlatingMaster software tool before performing any simulations for plating cell optimization:

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Introduction and Overview

Electroforming manufacturing processes, in particular the custom developed Ni electroforming metal reflector manufacturing processes from eele Laboratories allow its electroforming manufacturing department (*eele*Electroforming) to produce very high performance metal reflectors[1]. However, conventional electroforming manufacturing processes are not able to manufacture such high performance reflectors in high volume and at low cost. Thus alternative manufacturing methods need to be researched and the cost / performance benefit of different design choices quantified.

The optical performance quality of an electroformed Ni reflector is related to the uniformity of the plating deposition process. In principle, with customized dedicated plating cell configurations the deposition uniformity can be dialed in and maintained, even for highly curved and complex reflector geometries (with and without flanges, necks, etc.). To validate the simulation results as well as to test *eele*Electroforming's ability to turn an advanced plating design concept into reality, a first generation implementation of a possible next generation plating cell design solution (optimized for higher speed plating with smaller floor space requirement) was implemented and the resulting reflector plating uniformity thickness determined, both experimentally as well as theoretically with Elsyca's PlatingMaster 3D modeling software tool[2,3].

The quantative accuracy of these simulation results depends upon the accuracy of the electrolyte bath characteristics, typically described with polarization data sets, one for the anode and one for the cathode. It also depends on the accuracy of the spatial dimension of the cathode, anode and masking components between the anode and cathode as well as on other relevant spatial dimensions of the plating cell. The resistance drop of the Ti mesh anode basket containing the anode material (Nickel pellets) is another factor that needs to be incorporated into the simulation. To increase the modeling accuracy we used dedicated laboratory measurements (Rotating Disc Electrode set-up) to measure and extract the polarization data parameters for a respective Ni electroforming bath operation. Simulations which make use of these dedicated input data turn out to match more closely the experimental results.

After completing the tasks listed above the difference between the experimental measured and simulation calculated thickness distribution data was within a few percents over more than 95% of the reflector surface area and therefore gave us much confidence in both the ability of the Elsyca's PlatingMaster software to model accurately layer thickness distributions in a plating cell, and in *eele*Electroforming's ability to turn a given novel plating cell design into reality.
To investigate the effect of different bath solutions and operational bath parameters on a novel plating cell design, *eele*Electroforming prepared an industry standard Ni sulfamate bath solution as well as a bath consistent of a 56% higher Ni concentration. Both solutions were tested at an industry standard and at a 17% higher bath temperature. In an industry standard electroforming manufacturing operation the temperature is typically controlled to +/- 1°C and the Ni concentration

to +/- 20%. The range of the parameters chosen therefore exceeded the typical control parameter range by 10x for temperature and by 3x for the Ni concentration.

A rotating disk electrode set-up was used again to obtain the respective polarization data for the four different bath conditions. Together with the measured bath conductivity data, these bath parameters where imported into Elsyca's PlatingMaster software to estimate the influence of this much larger than typical process window on the plating uniformity distribution. This two dimensional key parameter search made it possible to determine, theoretically, how sensitive the chosen novel cell design is to large plating bath parameters changes. In particular it allowed to better estimate the investment risk in selecting and implementing a high volume production line based on a still relatively unproven, dedicated, next generation electroforming tank/reactor design.

The investigation showed that the actual bath characteristics (Ni concentration and bath temperature) had only very small effects (1 % range) on the overall uniformity of the chosen reflector geometry. The large observed changes are near the edges. For the tested next generation plating cell design this parameter design variation study predicted a very wide production tolerance window as well as an opportunity for further improvements to the electroforming process with further optimizing bath chemistry and/or plating cell refinements. While this broad process window may or may not be typical for an industry standard electroforming processing tank, it is important to explore this sensitivity for any still unproven next generation plating design concept.

The results from this investigation justified the cost of manpower and equipment for measuring relevant plating bath characteristics (polarization data) before starting Elsyca Plating Master simulations for plating cell optimization. In summary the results of the presented process design validation study, as well as other not reported experimental and simulation results, gave us the confidence that *eele*Electroforming's new family of specialized, next generation, plating cell concepts can be designed to operate under a very wide process operation window where the electroforming deposition uniformity is nearly independent on the bath chemistry and the process tank operation. Therefore as long as the near-zero-stress process operation conditions are fulfilled independently for each plating bath / cell design, the basic plating cell structure is still usable to produce spatially highly uniform plating deposition rates on complex mandrel shapes.

In summary, the outcome of this simulation / experimental validation study gave the *eele*Electroforming department of eele Laboratories the confidence to go ahead with their capital investment plans in setting up a next generation plating cell line optimized for high volume, low cost production of metal reflectors. Based on the results achieved in this and other not here reported studies, *eele*Electroforming estimates that its next generation plating cell and process operation design can be pushed to produce high quality Ni reflectors in about 1/3-1/4 of the floor space and bout 2-5 times faster than conventional Ni reflector production lines.

Experimental Design and plating simulation verification

The electroforming department of *eele* Laboratories LLC, i.e. *eele*Electroforming ("*eele"*), has developed a variety of possible next generation Ni electroforming plating cell design concepts for the manufacture of high volume, low cost, high performance, Ni reflectors. To be able to test both the accuracy of Elsyca's PlatingMaster electroforming simulation software as well as to test the design implementation capabilities of *eele* for novel electroforming reactors and related process operation one of the possible design concepts was realized and investigated in detail.

A special plating cell has been developed whose purpose was to allow to Ni electroforming in a Ni sulfamate bath onto a non axial symmetric stainless steel reflector mandrel. The first test reflector shape chosen was that of a two sided truncated elliptical shaped reflector with no flanges that was cut along the longest axis of the ellipse at an offset from the center of the ellipse. This resulted in an axial asymmetric (no rotational, non symmetric to the center of the mandrel) mandrel shape (see Fig. 1) with a different edge feature left and right from the center of the mandrel. This shape was chosen to enable the exploration of how to manage the uniformity control for highly curved parts with different axial non symmetric features. To make this test even harder a typical reflector thickness of 1.5 mm was tested, to explore how the near edge uniformity (and related shape stress) can be handled for such thick Ni electroforming deposition layers.

An industrial standard Ni sulfamate plating bath solution was chosen for the first design verification test with one exception, i.e. the Ni concentration was chosen to be approximately 50-60% higher. The change in Ni concentration was one of the overall process parameter studies done at *eele* during this design concept validation phase and this particular data point is used here as a first reference point for the design implementation and simulation validation check.

Elsyca's PlatingMaster software version 1.0 was used by *eele* to simulate the Ni deposition uniformity for the chosen electroforming test cell geometry. Since the accuracy of the electroforming deposition distribution depends upon the accuracy of the available plating bath characteristics (electrode polarization data and conductivity), the actual non-standard Ni sulfamate solution was tested by the chemical testing department of Elsyca and provided to *eele* in the form of polarization database input files.

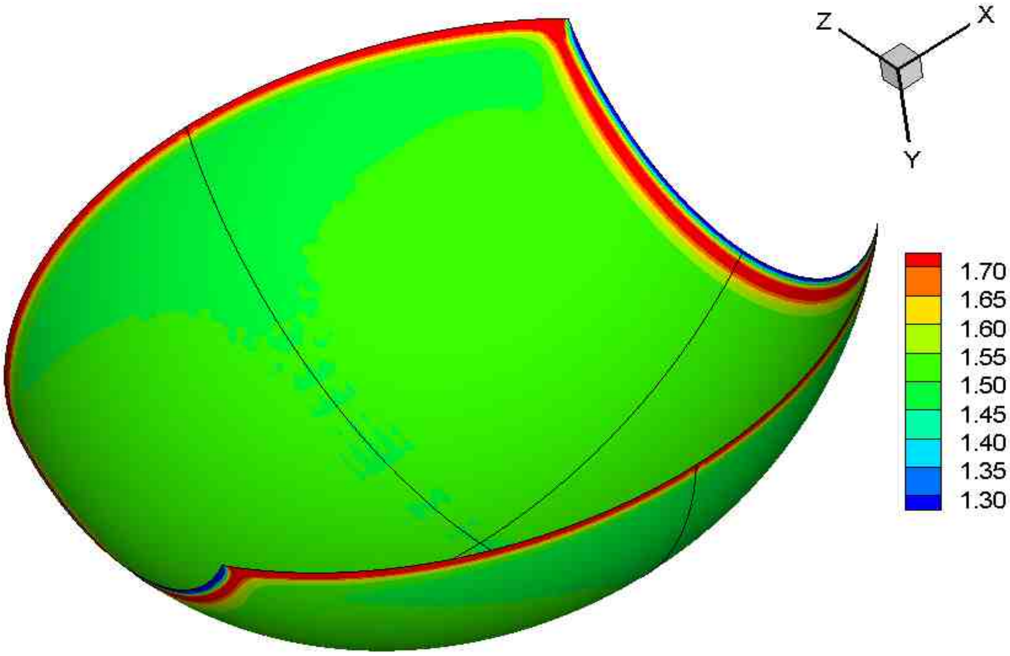


Fig. 1: *Calculated electroformed Ni deposition thickness distribution for axial asymmetric test reflector in one particular plating cell design implementation using a 56% higher Ni concentrated than a standard Ni sulfamate bath solution operated at industry standard bath temperatures.*

Fig. 1 shows the electroforming thickness distribution simulation results obtained with the provided polarization database and

Fig. 2 shows both the raw data as well as the extracted polarization data. To obtain the raw data a sample of the solution is measured in a heated test cell with a Potentiostat and with a rotating disk electrode, a saturated Ag/AgCl reference electrode and a working electrode (Pt mesh). Additionally the bath conductivity is being measured.

To obtain the polarization data of the electrolyte solution operated in a test cell at a set temperature these raw data are then processed to extract the polarization dependent current density versus a Hydrogen electrode. To account for the resistance drop across the Ti mesh that contains the Ni pellets, a simple geometrical model is developed where the combined anodic polarization behavior of the Ni pellets and the resistance drop across the Ti mesh is expressed as

$$\eta = \eta_{pol}(j) + j^*d/(\theta^*\sigma) \,, \qquad (1)$$

with η_{pol} [V] being the measured anodic polarization (Rotating Disc Electrode) for a given current density j [A/m^2], d [mm] being the thickness of the anode cell wall, θ being the ratio of total hole cross sectional area to total surface area exposed to the bath solution and σ [S/m] representing the conductivity of the electrolyte. In this approach, the Ti mesh is considered as an insulator wall with perforations that are filled with conductive electrolyte. It was verified by current density simulations (using PlatingMaster) for a detail of the Ti mesh that equation (1) is valid in a very good approximation.

In Fig. 1 more than 95% of the reflector surface area is within 5% from the center thickness. Only near the very edge a 10-20% thickness deviation can be seen. Note that the larger cutout on the right side of the image is slightly less uniform than the smaller left cutout suggesting that further refinements are possible with minor changes to the cell geometry.

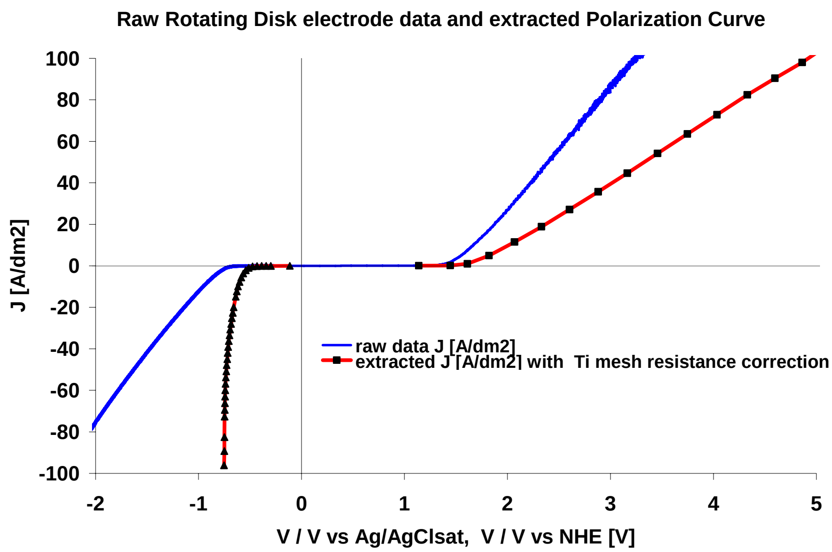


Fig. 2: *Raw Rotating Disk electrode data and extracted Polarization data for electroforming bath conditions of Fig 1.*

Fig. 3 shows the experimental thickness profile data together with the simulation profile data for the case shown in Fig 1. The two orthogonal black lines crossing the center of the reflector represent the cross sectional path that have been used below for the experimental and simulated thickness uniformity comparison.

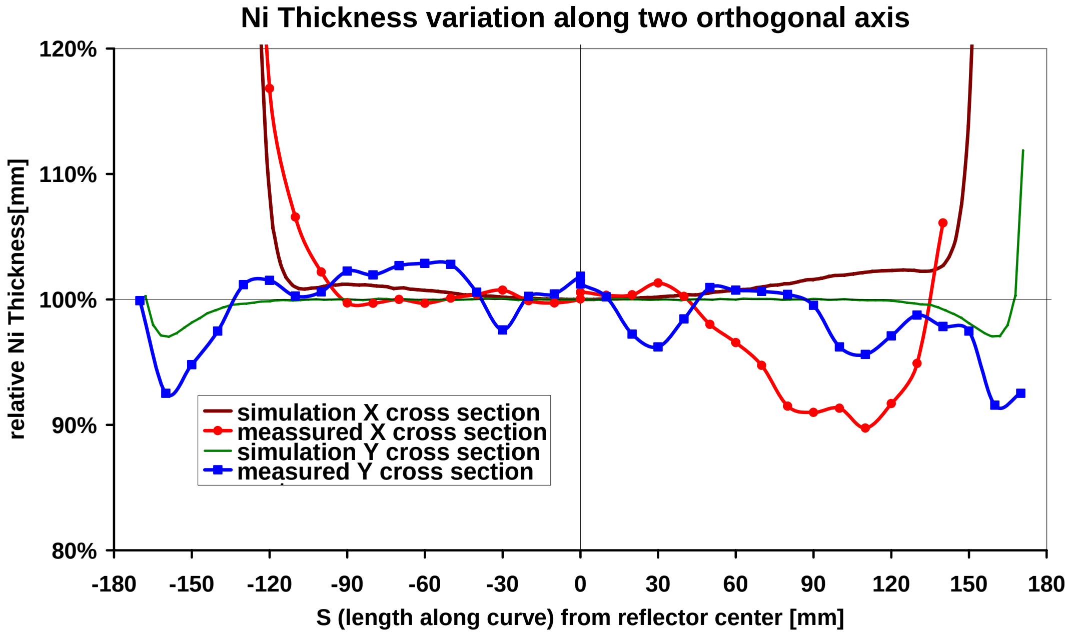


Fig. 3: *Electroforming Ni deposition thickness uniformity distribution for the measured reflector thickness and for the simulation data shown in Fig. 1 across the X=0 and Y=0 cross sectional lines*

The simulations are based on the polarization data from Fig. 2. Note that both experimental and simulated thicknesses are very close to the ideal relative target thickness of 100% over most of the reflector surface area. Only near the last 10 mm there are minor deviations from the target thickness. Given a typical target thickness tolerance of > +/- 20% this is still acceptable for the intended application. Note that the cross sectional area in the X plane shows that the experimental data have a minor (-10%) imperfection on the right hand side of the reflector shown in Fig. 1. A detailed analysis of this deviation pointed to a dimensional construction error during the manufacturing of *eele*'s custom electroforming cell. Also the measured X-cross section thickness data have a slight slope towards the right edge of the reflector. Although these errors are not critical for the intended reflector application, the thickness uniformity can still be further improved over that shown in Fig 3 with minor cell adjustments

Operational Parameter Sensitivity Study

To determine the sensitivity of the electroformed Ni deposition uniformity in the given plating cell, two key operational parameters are selected: temperature and Ni concentration. Table 1 displays the relative change of these process parameters. Note that for typical electroforming processes the bath temperature is being controlled to +-1°C and the Ni concentration to +/- 20%. The range of selected parameters therefore exceeds the typical control process window 10 times for temperature and by 3 times for the Ni concentration. The parameters have been normalized to 100% for the respective industry standard process parameters to facilitate easier relative comparison. Case III was used for obtaining the results shown in Fig. 1-3.

Table 1: *parameter change for two dimensional sensitivity study*

Ni concentration [g/l] \ Temperature [C]	100%	117%
100%	case I	case II
157.0%	case III	case III

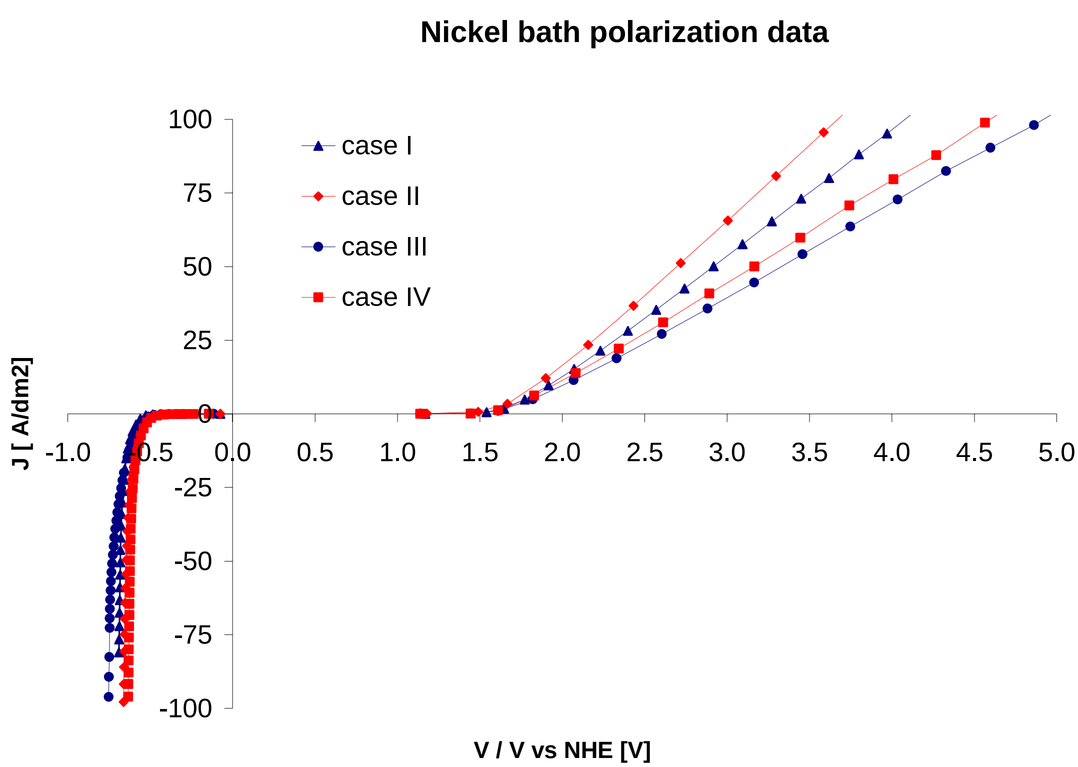


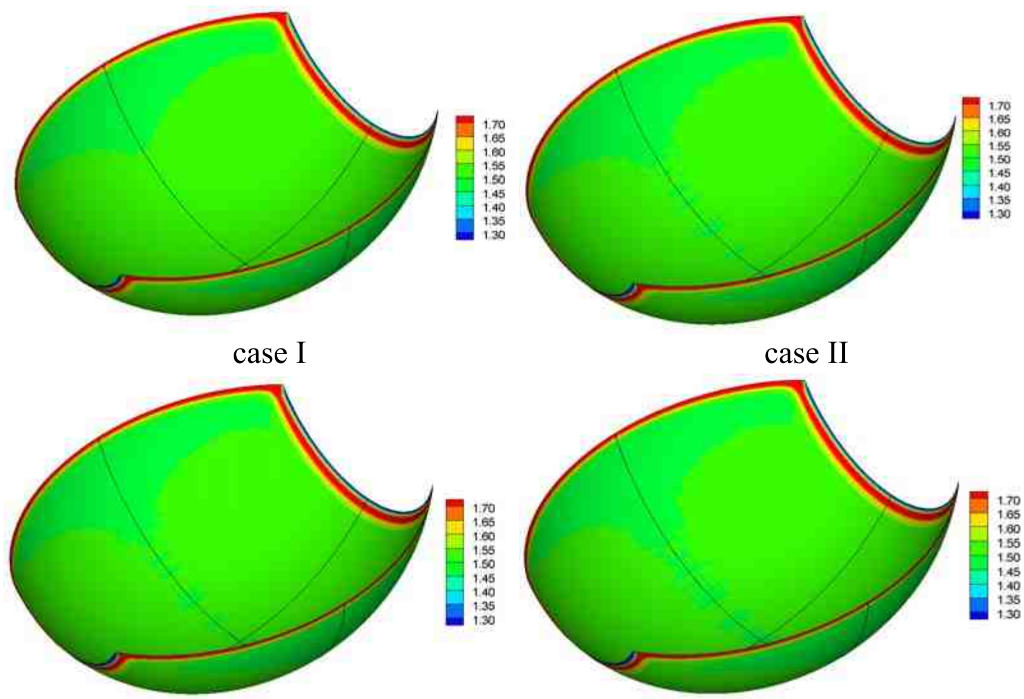
Fig. 4: *Polarization data for the electroforming bath conditions of case I to case IV outlined in Table 1 and 2.*

The two different bath solutions (only difference was Ni concentration, the rest of the materials where at there nominal target range at standard bath temperatures) where then measured by Elsyca at two different bath temperatures and the respective electrolyte conductivity and electrode polarization data extracted. Note that the concentration of the various constitutes of the two electrolyte solutions was not adjusted to stay within normal process value range, nor was the solution tested for compliance with the standard process parameter window. While this is not ideal, for the purpose of this test it was believed to be a sufficiently good approximation.

__Table 2:__ Relative bath conductivity for the two dimensional sensitivity study

Relative Bath conductivity			
100%	case I	**121%**	case II
76%	case III	**85%**	case III

Table 2 shows the measured conductivity normalized to the case I (industry standard) conductivity. The change of the conductivity is approximately proportional to the bath temperature with higher bath temperature promoting higher bath conductivity, but the conductivity is less than inverse proportional to the Ni concentration.



case I case II

case III case IV

__Fig. 5:__ Thickness uniformity distribution for case I-IV as described in Table 1. Note the similarity in the thickness distribution despite the large change in process parameter range showing a wide process window capability of the chosen plating cell design.

Fig. 5 allows comparing the polarization data for the four cases outlined in Table 1 and 2. Note that the bigger change is on the Anode side of the data.

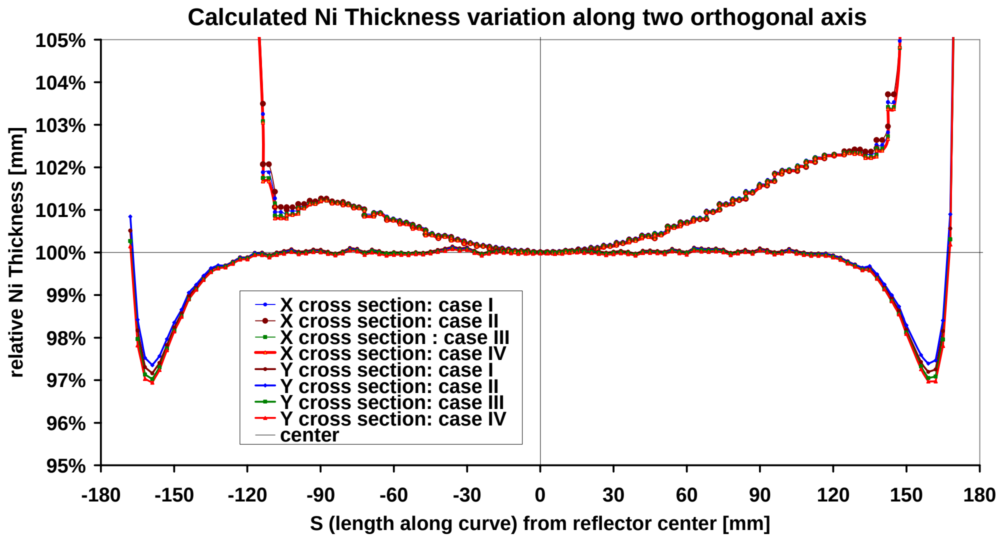


Fig. 6: *Thickness uniformity distribution of two orthogonal reflectors cross sectional profiles for cases I-IV as described in Table 1. Note the similarity in the thickness distribution despite the large change in process parameter range showing a wide process window capability of the chosen plating cell design.*

The simulation output data for the four cases based on the measured bath solutions is shown in Fig 6. Only near the edge, i.e. 3% of the total width or 10 mm near the edge of the part there is a small observable difference between the various cases. Again the final edge geometry is only very slightly (1% level) influenced by the change in polarization/bath conduction parameters.

This very low variation of the deposition thickness uniformity distribution, despite the quite large change in process parameters suggests that the uniformity deposition thickness distribution is quasi independent of the bath process parameters - at least for the chosen process parameters and cell geometry. Parameters which have not been reviewed in this paper are the influence of the liquid flow rate on the thickness distribution and on the local stress level distribution across the part. Note that in Fig 3. the X-cross sectional experimental data shows minor (5%) thickness variation which is caused by improperly located sparger heads causing minor localized deposition rate variations.

Therefore as long as the quasi-zero-stress process parameters are being maintained respectively for each process case the geometry of the deposition cell doesn't have to be modified, making this basically a setup problem. Once a given cell is dialed in, the uniformity distribution will be maintained over a very wide range of process parameters.

Conclusions

This research has shown that with exception of the fluid motions influence on the deposition rate, Elsyca's PlatingMaster software in conjunction with respective polarization data sets can be used to very efficiently explore the feasibility of various processes, processing equipment, and plating cell design changes. It can also be used to conduct at a great time and cost saving "What If scenarios" and it enables one to quickly study the stability and sensitivity of a chosen design change and its impact on the deposition uniformity distribution.

References

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