Surface Coating Thickness Distribution in Electrodeposition: A Case Study on Copper Plating of a Tube Inner Surface

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A major concern in plating tube-shaped inner surfaces of metal pieces, such as tubes, cylinders and gears, is coating thickness and its uniformity. In production, the coating thickness cannot be measured during plating. Therefore, the coating quality can be only inspected after manufacturing, which is a passive means of quality control. For proactive quality control, the first step is to reveal the details of the coating thickness development process. This can be realized through developing a computer-simulation-based approach. In this work, a simulation approach is introduced to study a copper plating system where the inner surface of the tube-shaped workpieces needs to be plated. This simulation is conducted by utilizing a commercial software tool, Cell-Design®. To achieve superior coating quality in terms of thickness and uniformity, a number of design scenarios are investigated. Detailed comparisons can provide the most desirable design, and in this case, the coating quality can be improved significantly as compared to the original design.

Keywords: *Electroplating, product quality control, coating thickness, computer simulation*

Introduction

In order to compete effectively in today's marketplace, companies must find ways to improve the quality of their products while lowering the cost of production. Continuous quality improvement and cost reduction are necessary for staying in business and improving their market share.[1]

An important dimension of the quality of a manufactured product is the total loss generated by the off-spec product to society. Taguchi has given a very important dimension of quality: the societal loss caused by the product.[2] In his seminal work, quality is reflected by the variation from the target. A continuous quality improvement program includes reduction in the variation of product performance characteristics about their target values. However, a product's quality cannot be improved unless the product quality characteristics can be identified and measured. The objective of a continuous quality improvement program is to reduce the variation of the product's quality characteristics around their target values.[3]

A high quality product performs near the target value consistently throughout the product's life range and under all different operating conditions. The variation of a performance characteristic about its target value is referred to as performance variation. The smaller the performance variation about the target value, the better is the quality. All target specifications of continuous performance characteristics should be stated in terms of nominal levels and tolerances about the nominal levels.

The final quality and cost of a manufactured product are determined to a large extent by the engineering design of the product and its manufacturing process. A product's development cycle can be divided into three stages: product design, process design and manufacturing.[4] Because of the increasing complexity of modern products, product and process design play crucial roles in proactive quality control.

Quality control must begin from the first step in the product's development cycle and it must continue through all steps. The best opportunity to eliminate product quality variation is during the design phase of a product and its manufacturing process. Any variation in the product performance characteristic about its target value causes a loss to the customer. Quite often, the customer's loss due to a product's performance variation is approximately proportional to the square of the deviation of the performance characteristic from its target value.[5] Quality engineering should start with an understanding of the cost of poor quality in various situations. Taguchi specified three types of loss functions: (1) the smaller the better (S type); (2) the larger the better (L type) and (3) on-target, minimum-variation (N type).[6]

An S type tolerance involves a non-negative characteristic, whose ideal value is zero. A typical example of such a characteristic is impurity. "The-Larger-The-Better" is applicable to characteristics such as the strength of materials and fuel efficiency. In these cases, there are no predetermined target values and the larger the value of the characteristic, the better it is. "The-Nominal-The-Best" quality characteristic is the most common situation among the three types of loss functions. This type of tolerance is required for many products, parts, elements and components when a nominal size (or characteristic) is preferred. The loss caused by deviation from the target value is estimated as:

$$L = \frac{A}{\Delta^2} Var^2(Y) \tag{1}$$

where
L is the customer's loss due to a product performance variation,
A is the coefficient of loss caused by shifting away from the nominal value
2Δ is the tolerance limit[7] and
$Var(Y)$ is the standard deviation of the quality characteristic, which can be evaluated as:

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$$Var(Y) = \sqrt{\frac{1}{N}\sum (Y_i - \overline{Y})^2} \quad (2)$$

It is obvious that the electrodeposition thickness has the nominal-the-best quality characteristic. If the potential quality loss can be prevented from the early stage of the product development cycle, *i.e.*, product design and process design, it will bring tremendous benefits to the manufacturers. However, the lack of on-line measurement of the deposition thickness distribution causes many difficulties in quality control. Computer simulation has been successfully used in many applications, including profitable pollution prevention in electroplating,[8] and it will be a viable way to predict the growth of the deposition from the given design and operating parameters of an electroplating process.

In the case study discussed in the next section, process simulation techniques are combined with quality engineering principles in order to identify the optimal design of the process for electroplating product quality improvement.

The software package, Cell-Design® 2000 (L-Chem, Cleveland, OH) was utilized in this work. This software simulates the operation of electrochemical cells with user specified geometry, chemistry and operating conditions. The simulation results include: current and potential distributions, deposit thickness distribution, overpotentials (polarization) along electrodes, deposit growth and dissolution, etc.[9] Results are provided as graphical displays and detailed numerical tables. These can be plotted, printed or stored for later recall. In this project, a process of copper gear rack plating was simulated to illustrate the efficacy of computer-aided process design for product quality improvement.

Electroplating deposition quality indicator

For surface coating and metal finishing, two quality indicators are usually considered for deposit thickness. First, how close is the mean value of coating deposit thickness to the target value? Second, how large is the variation of the coating deposit at different locations, which is usually represented by the standard deviation term? Stemming from the aforementioned "N type" function, a general quality indicator *J* for electroplating deposition thickness is defined below.[10] Obviously, the minimal value of *J* is desired.

$$J = a\,|\,(E(Y_i) - Y^s)\,| + (1-a)(Var(Y_i))^2;\ \ i = 1, 2\ldots n \quad (3)$$

where

Y^s is the specified deposit thickness standard,

$E(Y_i)$, $Var(Y_i)$ are the mean and standard deviation, respectively, and

a is a weight which can be chosen in the range of [0, 1].

If *a* is set to be 0.5, it indicates that the deposition thickness and the standard deviation are considered equally important. In this work, the value of 0.5 is adopted for *a*. In case multiple parts are used in electroplating, the user can use the summation of the *J* value of each part ($\sum J$) to express the overall plating quality for multiple parts.

Process description

The process specifications and data were obtained for a copper plating line using inert anodes. A typical copper plating solution is used. Note that the coating material came from the plating solution rather than a dissolved anode. The plating solution composition was checked regularly. The operating conditions and the arrangement of the plating tank are briefly presented below.

Operating conditions

One or several racks of workpieces were immersed in the plating bath. The bath temperature was set between 57 and 66°C (135 and 150°F), the potential was 4 V and the current was 200 A. Each rack of workpieces took 60 min to be plated in the bath.

Plating tank, rack, parts, cathode and anode information

The parts to be plated (gears) were packed into tubes. The parts were packed so closely that only inner surface (a cylinder) of each part was plated. Each rack contained 16 tubes and each tube contained 29 gears. Each tube had one anode (a thin long rod), which was positioned through the center of tube but without touching the parts. The rack of parts was the cathode. Normal production required three racks of parts to be plated simultaneously in a single plating tank.

Simulation and analysis of the original process

Using Cell Design®, the current density, overpotential and deposit thickness distribution on the cathode surface were simulated. Data inputs include the following:

Geometry. The dimensions of the electroplating tank are: depth Z = 1.07 m, width Y = 1.83 m, and length X = 3.05 m. The geometry profile represents a cross-section (2D) view of the tank. There is one anode in the middle of each tube. It is assumed that the anode and the tube have the same height of 50.80 cm.

Electrode properties. The voltage and current applied to each electrode were specified, and other parameters were given depending upon whether the cell was primary, secondary or ternary. In this case, the cell was secondary.

Major reactions in the electroplating tank. For the typical copper plating process, the major reactions include:

Anode reaction:

$$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$$

Cathode reactions:

$$[Cu(CN)_3]^{2-} + e^- \rightarrow Cu + 3CN^-$$

$$H_2O + e^- \rightarrow \frac{1}{2}H_2 + OH^-$$

After inputting all of these details, we ran the simulation to get the point-wise distribution of the overpotential, current density and deposit thickness on the electrode.

The correlation between the deposit thickness and the current density. According to Faraday's Law, if the copper deposition is assumed to be uniform on the workpiece surfaces during plating, a simplified copper thickness dynamic model is derived:[11]

$$\frac{d\theta(t)}{dt} = \left(\frac{RcM}{2F\rho}\right)i \quad (4)$$

where $\theta(t)$ is the deposit thickness, m; M is the molecular weight of copper, kg/mol; ρ is the copper density, kg/m^3; t is the plating time, sec; F is Faraday's constant (96,485 C/mol); Rc is the current efficiency of the cathode and i is the current density, A/m^2.

The correlation between the current density and overpotential. This correlation can be expressed as follows:

$$i = i_0\left(e^{\frac{\alpha F}{RT}\eta} - e^{\frac{-\beta F}{RT}\eta}\right) \quad (5)$$

where i is the current density, A/m^2; i_0 is the exchange current density, A/m^2; R is the gas constant (8.314 J/K.mol); T is the plating temperature, K; η is the overpotential, V and α and β are transfer coefficients.[9]

Simulation results

The distribution of the current density, overpotential and final deposit thickness at the end of plating (60 min) along the inner surface of a stack of five gear parts in a tube is depicted in Figs. 1 thru 3. The points on the curve denote the simulation results of thirty-seven points along the parts. Due to the special design (*i.e.*, the tank is well mixed, each tube has its own anode and an insulator is placed outside of each tube), the profile differences among those tubes can be neglected.

The target value of deposit thickness was 14.25 μm. It is shown in Fig. 3 that the final deposition thickness along the parts in the tube ranged from 14.20 to 17.00 μm. At the end points, the deposit was much thicker than at the middle points. Among the five parts, Part 4 exhibited the most uniform distribution of deposit thickness.

Deposit thickness dynamics

After 5, 30 and 60 min, the distribution of deposit thickness at every point along the parts in the tube was recorded and the results are depicted in Fig. 4. Furthermore, the deviation of the film thickness from the average at each time instance can be calculated by exporting the Cell Design® simulation results to an Excel spreadsheet depicted in Fig. 5.

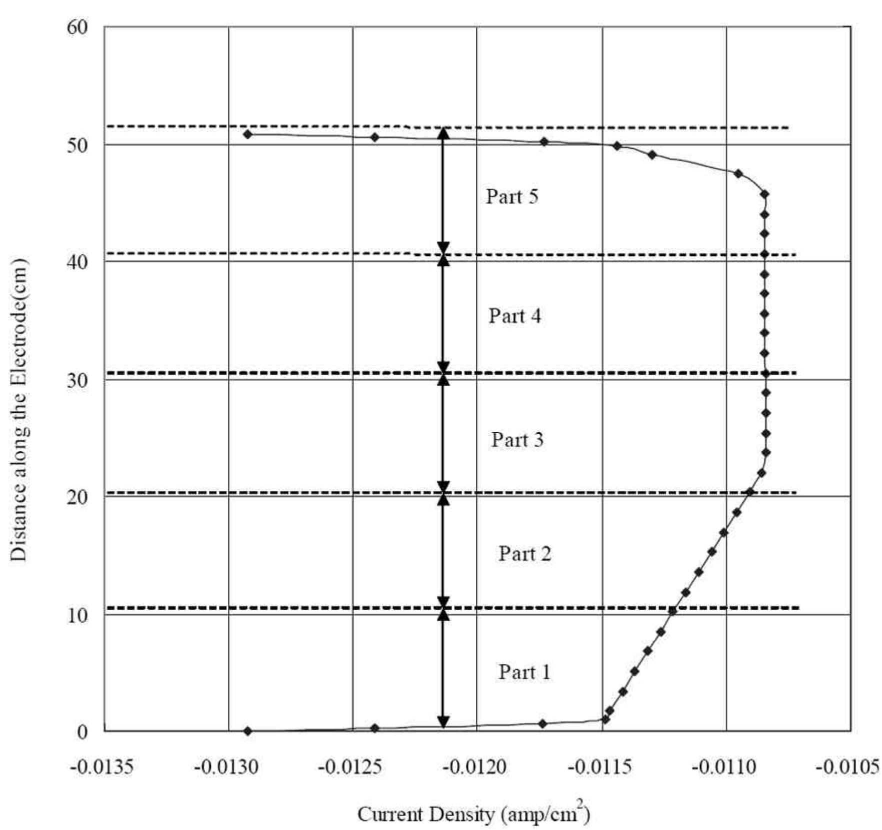

Figure 1—Current density along the electrode after 60 min.

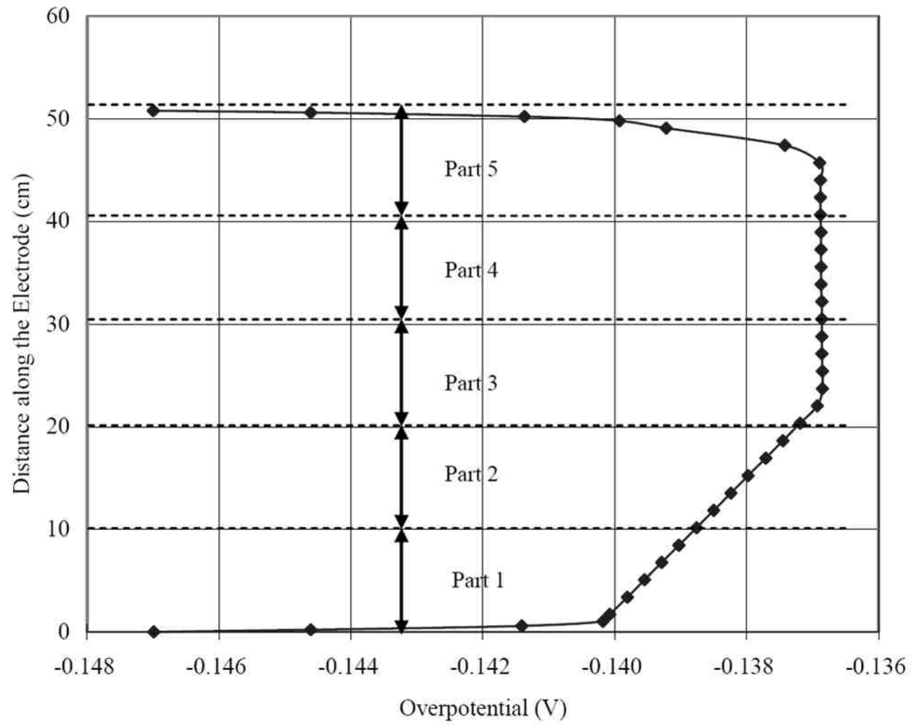

Figure 2—Overpotential along the electrode after 60 min.

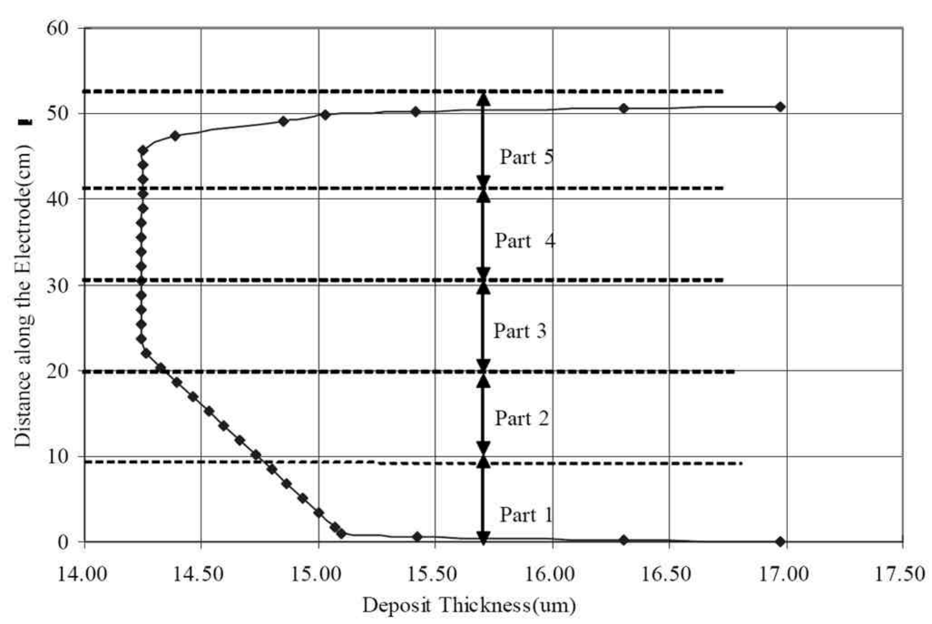

Figure 3—Deposit thickness along the electrode after 60 min.

From Figs. 4 and 5, it is clear that the trend of the deposit thickness change and the deviation from the average along the electrode at each time instance is almost the same. But the thickness and the deviation increase with time. The deposit thickness and the deviation at the boundary points are larger than those at the middle points. Once again, Figs. 4 and 5 confirm that the deposit thickness distribution of Part 4 was the most uniform.

Three specific points along the parts were chosen to illustrate the growth dynamics of the coating. The three points were chosen from Parts 1, 3 and 5. These three points were at the top, middle and bottom of the stack of parts, respectively. The time range of this simulation was from 0 to 60 min.

Figure 6 shows that whatever the point selected on Parts 1, 3 or 5, the coating thickness grows linearly with time. For the two points on Parts 1 and 5, the change was almost the same so that the two lines almost overlap.

Modified cases

Figure 6 also shows that in the original case, the thickness at the boundary is much larger than that at the mid-point. In order to reduce the variation in the product quality, in this work, attempts were made to change the geometry of the electrode (process design issue) to see which process design will bring out the best product quality. Accordingly, the original case with the anode length of 50.80 cm was considered to be Case 1. Three different electrode designs were considered, namely Cases 2, 3 and 4. In these three new cases, the geometry of the electrode was similar to Case 1 and it was still placed vertically in the middle of the tube. However, the length of the anode was shortened to 49.94 cm, 49.99 cm and 50.04 cm in Cases 2, 3 and 4, respectively. The distributions of the deposit thickness along the five parts in Cases 2, 3 and 4 are depicted in Fig. 7.

By comparing the results depicted in this figure, it is clear that in Cases 2 thru 4, the thickness difference between the boundary points and the mid-points is smaller than that found for Case 1 (Fig. 3). In order to identify which electrode design is the best, the deposit thickness along the parts in all four cases is listed in Table 1. As we can see, every part has the same length of 10.16 cm along the tube. For each part, the mean value and standard deviation value are calculated for every case. Note that these 37 points along the five parts are uniformly distributed from the top to the bottom, but due to the change in the length of the electrode, these 37 points in each case do not exactly refer to the same location in the tube.

In this work, Eq. (3) is adopted to quantify the electroplating quality. The specified deposit thickness X_i^s is 14.25 μm, and α equals 0.5. The calculated value of J in each part and each case is presented in Table 2. In Case 1, it is clear that Part 4 has the minimal value of J (0.003207 μm). Therefore, it is evident that the deposit thickness distribution is most uniform in Part 4 as seen in Fig. 3. For the overall electroplating process involving five gears, the plating deposit quality will be measured by $\sum J$. By comparison, it can be seen clearly that Case 4 gives the minimal value of $\sum J$ (0.126511 μm), which is a 93.70% reduction from Case 1 (2.00868 μm). The electrode design in Case 4 is therefore the best choice.

Another interesting phenomenon was noted. As shown in Table 2, in Cases 2, 3 and 4, the J value of Part 4 was reduced by 24.73% although the standard deviation in all these three cases was zero. By checking the deposition thickness data in Table 1, we found this was related to the fact that the mean value of the deposition in the three modified cases was shifted further from the desired value of 14.25 μm. This phenomenon demonstrates the importance of including both mean value and standard deviation terms in the quality indicator.

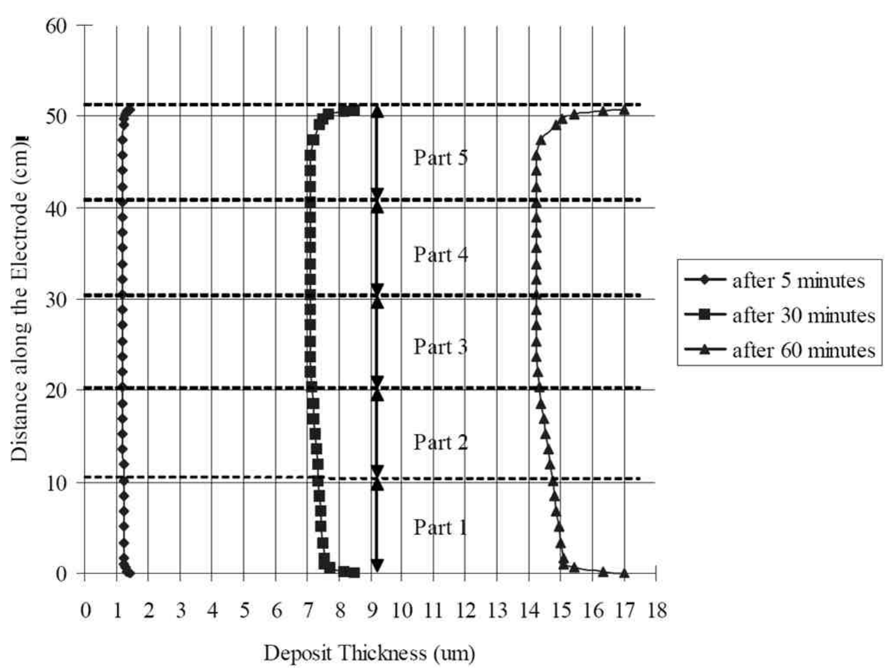

Figure 4—Deposit thickness along the electrode after the three different time instants.

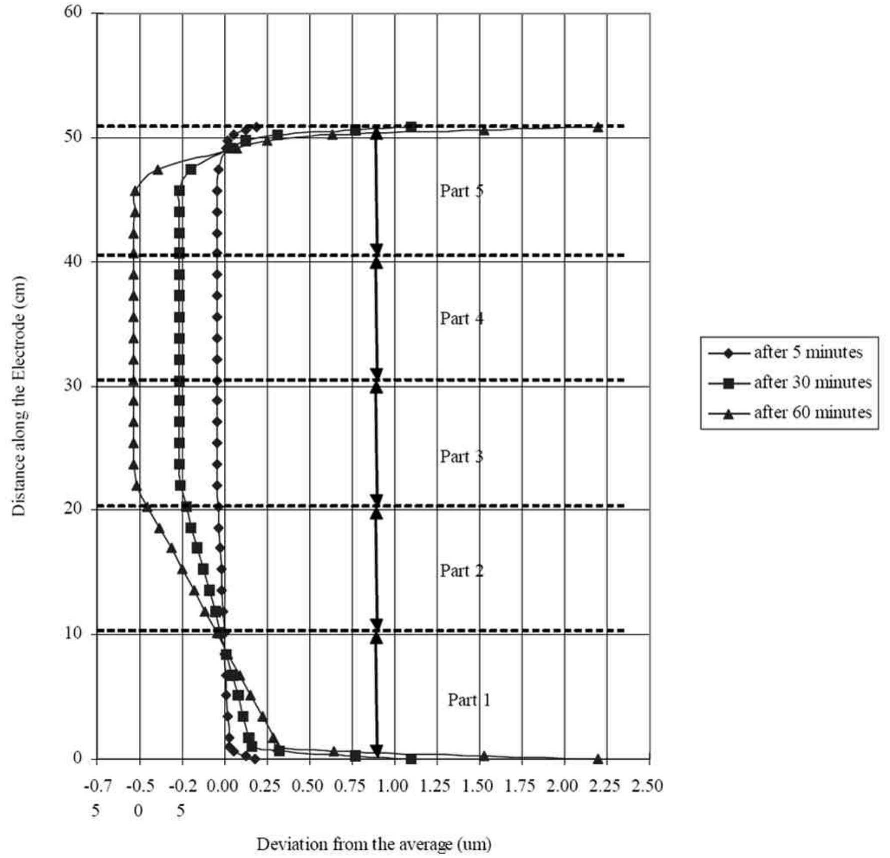

Figure 5—Deposit thickness deviation from the average along the electrode after the three different time instants.

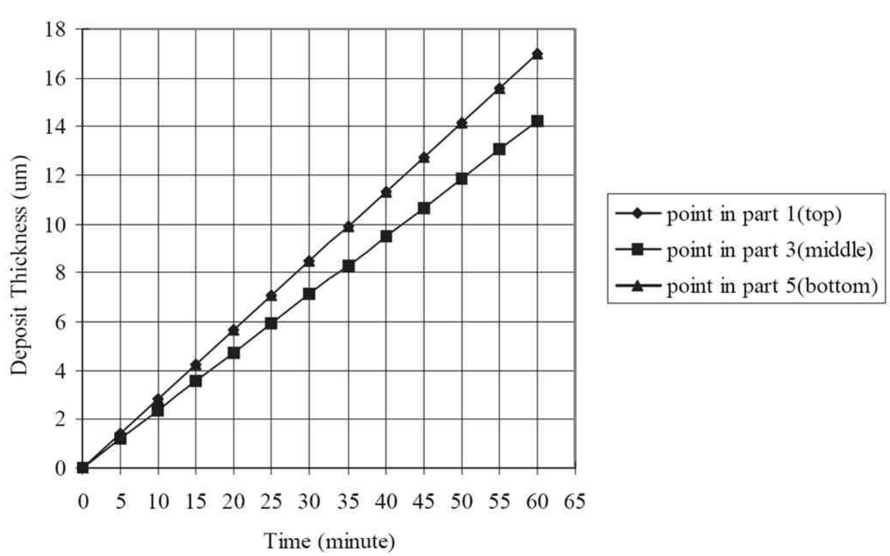

Figure 6—Deposit thickness dynamics at different point.

Table 1
Comparison of deposit thickness along the electrode in four designs

	Deposit Thickness (μm)					
	Point index	**Distance from the top of the table (cm)**	**Case 1**	**Case 2**	**Case 3**	**Case 4**
Part 1	1	0	16.9740	14.2130	14.3660	14.5190
	2	0.2032	16.3090	14.0650	14.1970	14.3270
	3	0.5842	15.4230	13.9690	14.0630	14.1540
	4	1.1016	15.0950	14.0410	14.1040	14.1650
	5	1.7018	15.0680	14.1360	14.1690	14.2010
	6	3.3782	15.0010	14.2220	14.2280	14.2340
	7	5.08	14.9340	14.2420	14.2420	14.2420
	8	6.7818	14.8660	14.2420	14.2420	14.2420
	9	8.4582	14.7990	14.2420	14.2420	14.2420
	10	10.16	14.7310	14.2420	14.2420	14.2420
	Mean		15.32	14.1614	14.2095	14.2568
	Standard deviation		0.738904	0.102074	0.083963	0.103913
Part 2	11	11.8618	14.6640	14.2420	14.2420	14.2420
	12	13.5382	14.5970	14.2420	14.2420	14.2420
	13	15.24	14.5290	14.2420	14.2420	14.2420
	14	16.9418	14.4620	14.2420	14.2420	14.2420
	15	18.6182	14.3950	14.2420	14.2420	14.2420
	16	20.32	14.3270	14.2420	14.2420	14.2420
	Mean		14.49567	14.2420	14.2420	14.2420
	Standard deviation		0.126041	0	0	0
Part 3	17	22.0218	14.2600	14.2420	14.2420	14.2420
	18	23.6982	14.2400	14.2420	14.2420	14.2420
	19	25.4	14.2410	14.2420	14.2420	14.2420
	20	27.1018	14.2410	14.2420	14.2420	14.2420
	21	28.7782	14.2420	14.2420	14.2420	14.2420
	22	30.48	14.2430	14.2420	14.2420	14.2420
	Mean		14.2445	14.2420	14.2420	14.2420
	Standard deviation		0.007662	0	0	0
Part 4	23	32.1818	14.2430	14.2420	14.2420	14.2420
	24	33.8582	14.2440	14.2420	14.2420	14.2420
	25	35.56	14.2450	14.2420	14.2420	14.2420
	26	37.2618	14.2450	14.2420	14.2420	14.2420
	27	38.9382	14.2460	14.2420	14.2420	14.2420
	28	40.64	14.2470	14.2420	14.2420	14.2420
	Mean		14.2450	14.2420	14.2420	14.2420
	Standard deviation		0.001414	0	0	0
Part 5	29	42.3418	14.2470	14.2420	14.2420	14.2420
	30	44.0182	14.2480	14.2410	14.2410	14.2410
	31	45.72	14.2490	14.2400	14.2410	14.2410
	32	47.4218	14.3870	14.2180	14.2250	14.2320
	33	49.0982	14.8470	14.1340	14.1670	14.2000
	34	49.784	15.0310	14.0410	14.1040	14.1650
	35	50.2158	15.4120	13.9700	14.0640	14.1550
	36	50.5968	16.3070	14.0650	14.1970	14.3280
	37	50.80	16.9760	14.2130	14.3660	14.5190
	Mean		15.07822	14.15156	14.20522	14.25811
	Standard deviation		0.988949	0.103186	0.087943	0.1102

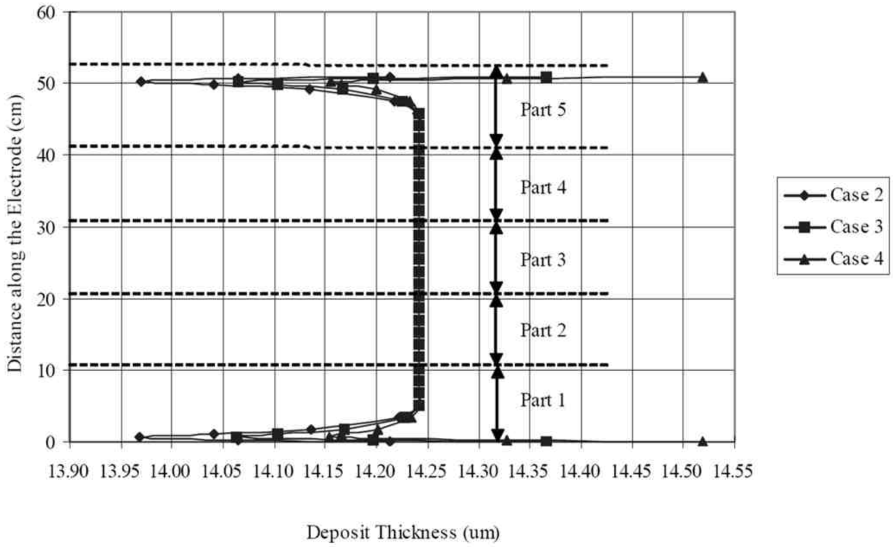

Figure 7—Deposit thickness along the electrode after 60 min in different cases.

Table 2
Calculation results of the deposit quality

	Case 1	Case 2		Case 3		Case 4	
	J (μm)	**J (μm)**	**% reduction of J from Case 1**	**J (μm)**	**% reduction of J from Case 1**	**J (μm)**	**% reduction of J from Case 1**
Part 1	0.904452	0.095337	89.46%	0.062232	93.12%	0.055356	93.88%
Part 2	0.185856	0.004	97.85%	0.004	97.85%	0.004	97.85%
Part 3	0.006581	0.004	39.22%	0.004	39.22%	0.004	39.22%
Part 4	0.003207	0.004	-24.73%	0.004	-24.73%	0.004	-24.73%
Part 5	0.908584	0.100813	88.90%	0.066362	92.70%	0.059155	93.49%
ΣJ	2.00868	0.20815	89.64%	0.140594	93.00%	0.126511	93.70%

Concluding remarks

Combining electroplating process simulation techniques and quality engineering principles can be an effective way to identify the optimal process design in order to improve electroplating product quality. This can save tremendous time, energy and cost in quality control in the downstream step: manufacturing. It can be a good avenue toward proactive quality control. This methodology is generally applicable to electroplating processes of any type.

In this study, only one tube is considered. In the future, this work can be extended to the array of multiple racks and multiple tubes. Currently, only one quality characteristic, electrodeposition thickness is considered. In the future, multiple quality characteristics, including mechanical and physical properties can be considered for a comprehensive quality control.

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