Hierarchical Optimization of Cleaning & Rinsing Operations in Barrel Plating

By Q. Zhou & Y.L. Huang

Cleaning and rinsing are two key unit operations in achieving high plating quality in an electroplating process. These two operational steps, however, are identified as major sources of waste, such as wastewater, spent solutions and sludge. In practice, the operations in plants are far below optimal, consuming excessive chemical solvents, water and energy. In order to improve environmental quality significantly and to maintain economical competitiveness for electroplating, the cleaning and rinsing operations must be optimized. In this paper, a practical optimization methodology is introduced to optimize the operations in the cleaning and rinsing steps. With this methodology, both optimal production and pollution prevention are realized in a cleaning and rinsing system. Since hierarchical dynamic optimization is difficult to implement, a statistical function approach is proposed to transform the bilevel programming problem into a single level optimization problem. Case studies are shown that demonstrate the desirability of adopting the method in plating lines.

Tremendous efforts have been made by electroplaters to improve operation and reduce waste. However, the cleaning and rinsing operations in the industry are far below optimum. Process optimization is one of the most important engineering tools for cost reduction and pollution prevention in the chemical industry.[1] A basic concept of optimization and its potential for pollution prevention (P2) in electroplating plants has been introduced by Load *et al.*[2] and Cushnie.[3] Recently, Lou and Huang introduced a profitable pollution prevention (P3) concept that has led to the development of various effective methodologies.[4]

Huang and his associates have focused on source reduction and operational improvement in plating lines for several years. An expert system-based software package* was successfully developed.[5] It can classify and compare different P2 techniques and provide decision support.

Successful implementation of the source reduction strategies requires sufficient process information at a quantitative level. Various process dynamic models for a general cleaning-rinsing system have therefore been developed.[6] Very detailed quantitative analysis is conducted on process dynamics and environmental impacts under different operating conditions.

Based on these quantitative and qualitative analyses on the behavior of electroplating lines, a new type of proactive approach for wastewater reduction has been introduced.[7] It focuses on the modification of the existing rinsing system to determine the optimum water flow pattern and system configuration under the constraints of rinsing quality. Furthermore, an integrated wastewater reduction technology has been introduced by combing the superstructure-based optimization and dynamic model-based water flow schedule.[8]

This paper centers on the development of a rigorous optimization methodology to optimize the operations in cleaning and rinsing steps. The optimization will simultaneously lead to optimal operation and pollution prevention (P2) in a cleaning and rinsing system. The methodology is general for either barrel or rack plating, regardless of the number of rinse tanks involved. For a rinse subsystem consisting of two or three counterflow rinse tanks, the optimization procedure mathematically treats that system as one integrated unit.

Dynamic Models

A cleaning-rinsing system usually consists of a cleaning tank followed by one or more rinsing units. A dynamic model should characterize the surface cleanliness of parts, the chemical concentration in a cleaning tank, and the pollutant composition in a rinsing tank.

In a cleaning tank, the soils on part surfaces are removed by applying energy of some form. It is assumed that the concentration difference is the driving force for cleaning. When a barrel enters the tank, the mixing of the solution in the barrel and the solution in the tank outside the barrel is assumed to be instantaneous. The concentration in the barrel, therefore, is assumed to be the same as in the tank. Because the cleaning effectiveness is determined by the solution concentration, the volume of the barrel and the displacement of solution have no significant influence. The rate of change of soil on the parts is inversely proportional to a soil-removal rate. This rate is determined by the type of chemicals used and their concentrations, and the type and

Nuts & Bolts: What This Paper Means to You

No plating process can work unless there is adequate cleaning and rinsing. At the same time, these operations generate wastewater, spent solutions and sludge, and as a result, use too much water, energy and chemicals ($$$). This paper covers a mathematical means of providing the most effective cleaning and rinsing with the least production of waste and consumption of resources. While the math may be daunting to some, there is likely an engineer in many organizations who could put this information to good use.

*WMEP-Advisor

amount of soil on the parts. The soil removal model can be established as follows.[6]

$$A_p \frac{dW_{Pc}(t)}{dt} = -r_{Pc}(t) \quad (1)$$

$$r_{Pc}(t) = \gamma_c(t)\, C_a(t)\, W_{Pc}(t) \quad (2)$$

$$\gamma_c(t) = \gamma_0 (1 - e^{-\alpha(t-t_0)}) \quad (3)$$

where A_p is the total surface area of the parts in a barrel, $C_a(t)$ is the chemical concentration in the cleaning tank, $r_{Pc}(t)$ is the soil removal rate in the tank, $W_{Pc}(t)$ is the amount of soil on the parts, and $\gamma_c(t)$ is the looseness of the soil on the parts. The (t) is a time function.

The amount of chemical in the tank changes with consumption to remove the soils or with replenishment. Also, the chemical is carried over through drag-out to succeeding tanks. A chemical concentration model can be established as follows:

$$V_c \frac{dC_a(t)}{dt} = -\frac{r_{Pc}(t)}{\eta} - C_a(t)\, D_o(t) + W_c(t) \quad (4)$$

where V_c is the capacity of the cleaning tank, $W_c(t)$ is the flow rate of the chemical added to the cleaning tank, $D_o(t)$ is the drag-out flow rate, and η is the chemical capacity for soil removal.

To run these models, the initial dirt and chemical concentration in the tank must be obtained through experiment. The kinetic constant and the chemical capacity can be determined by the type of chemical used.

A rinse model was also established by Gong *et al.*,[6] *i.e.*,

$$V_r \frac{dX_r(t)}{dt} = -F_r(t)X_r(t) + R_r(t)Z_r(t) + D_i(t)Z_i(t) \quad (5)$$

where $F_r(t)$ is the flow rate of rinsewater, $X_r(t)$ is the pollutant composition in rinsewater, $R_r(t)$ is the recycle flow rate, $Z_r(t)$ is the pollutant concentration in influent rinsewater, $D_i(t)$ is the drag-in flow rate, and $Z_i(t)$ is the pollutant concentration in drag-in.

The model is based on the following assumptions: (1) uniform chemical concentration in the rinse tank and (2) no chemical reaction in the tank. If a rinse step consists of two or more rinse tanks, the model can be applied to each tank. The water flow rate variables will be determined based on the rinse system configuration.

Hierarchical Optimization—First Stage

An electroplating plant has a number of cleaning and rinsing steps. Cleaning operations consume a huge amount of expensive chemicals for removal of soils from parts and barrels, as well as consumption through drag-out. Moreover, the chemicals consumed constitute the major pollutants in wastewater. A rinsing operation consumes a great amount of water for rinsing purposes, and therefore generates a similar amount of wastewater. From the standpoint of cost reduction, chemical and water consumption should be minimized. From the P2 point of view, the chemicals in the wastewater and the volume of wastewater should be reduced to the maximum extent; they can also be implemented through minimizing chemical and water consumption. To achieve these targets, it is necessary to understand the characteristics of the process. Because the cleaning and rinsing operations are multi-step batch processes, each cleaning or rinse tank can be independently modeled based on the dynamic modeling method described earlier.

The typical dynamics in a cleaning tank are depicted in Fig. 1. The dynamic variation of the soil on the parts in barrels is determined by the chemical concentration in the tank, as well as several other constant parameters. The cleaning quality is expressed in terms of the soil remaining on the parts when the barrel is removed from the cleaning tank. The cleaning time is the time the parts are immersed in the tank. To minimize chemical cost and waste generation, the chemical concentration should be minimized while the cleaning quality is maintained within the desired cleaning time.

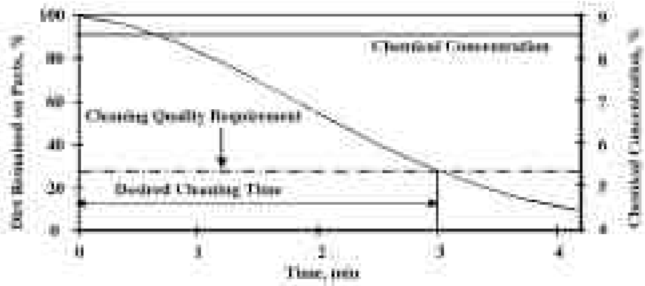

Fig. 1—The first stage of optimization for cleaning operation.

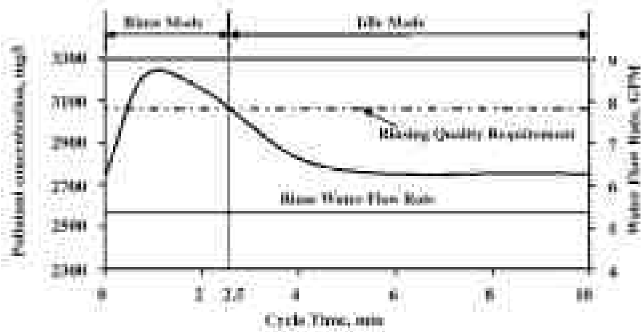

Fig. 2—The first stage of optimization for rinsing operation.

Similarly, the representative dynamics in a rinse tank are depicted in Fig. 2. The concentration of total dissolved solids (TDS) in the rinse tank is measured by a conductivity meter. The dynamic change of concentration in the rinse tank is primarily determined by fresh water flow rate, while the other parameters remain constant. The rinsing quality is defined as the solution concentration attached to the parts and barrels as the barrel leaves the rinse tank. As with the cleaning step, the rinsing time is the period that the barrel is immersed in the rinse tank. Therefore, it is necessary to determine the minimum fresh water flow rate to minimize water consumption and wastewater generation.

Hierarchical Optimization—Second Stage

The operation of cleaning and rinsing tanks is in a batch mode. The operational cycle (*i.e.*, the arrival time between two adjacent barrels in a plating line) is determined by the production rate. Currently, determining the cleaning time (*i.e.*, the time a barrel resides in the cleaning tank) and rinsing time (*i.e.*, the time a barrel resides in the rinse tank) is mainly by experience. Today's expertise in determining the right "cleaning package" already helps determine the cleaning time. The cleaning time is still very conservative, however, and determined without examining the process dynamics and performing an optimization. This has caused operating costs to be much higher than necessary and waste generation to be much more than expected. In the mathematical optimization methodology presented, the cleaning time is determined not only by cleaning dynamics in the tank, but also by the production schedule in the entire process. As for the production rate, the optimization does not change the existing production rate, which is determined by the plating capacity.

The chemical cost for a cleaning tank is heavily related to the cleaning time. If other process variables remain constant, the chem-

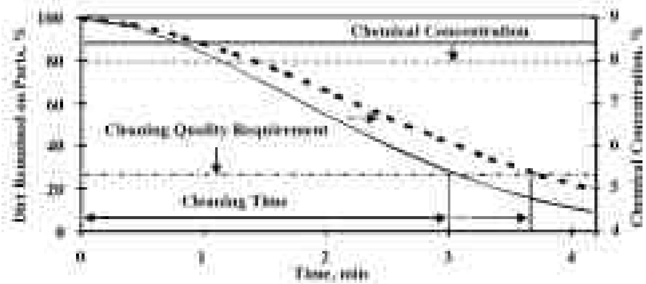

Fig. 3—The second stage of optimization for cleaning operation.

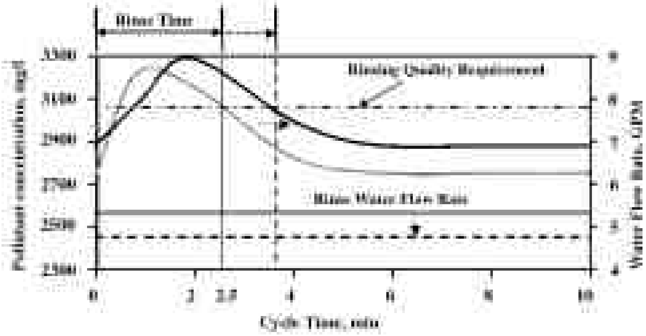

Fig. 4—The second stage of optimization for rinsing operation.

ical cost can be formulated as a function of a single variable, the cleaning time. The relationship between different chemical concentrations and cleaning time is explained in Fig. 3. Here it is given that the cleaning quality requirement is that 26 percent of the soil residue can remain on the parts (*i.e.*, 74% of the soils be removed). If the cleaning time for one barrel is increased from 3.00 to 3.67 min, the chemical concentration in the cleaning tank must be decreased (from 8.4 to 8.0%) in order to avoid overcleaning. The chemical consumption consists of two parts: (1) the chemicals consumed for soil removal and (2) that carried over by drag-out to the succeeding tank. Lower chemical concentration in a cleaning tank can tremendously reduce the chemicals lost through drag-out, therefore reducing the chemical cost. Because a longer cleaning time permits a lower chemical concentration, the chemical cost can be reduced by increasing the cleaning time, if possible.

The characteristics of different rinsing times in a rinse tank are depicted in Fig. 4. Here we assume that the pollutant concentration in a barrel is the same as that in the rinse tank. As shown, to reach the same rinsing quality, an increased rinse time of one barrel from 2.5 to 3.7 min can lower the rinsewater flow rate from 20.4 to 18.2 L/min (5.4 to 4.8 gal/min). Therefore, increasing the rinse time can reduce the rinsewater cost and, moreover, the wastewater treatment cost.

Optimization Model

For a given cleaning and rinsing process, the maximum permissible pollutant concentrations in the tanks should be specified. The optimization problem is to determine the optimal cleaning time and rinse time as well as chemical concentration and water flow rate of each tank that leads to the minimum consumption of chemical and fresh water, while ensuring the cleaning and rinse quality . The optimization model has the following objective function:

$$\min \sum_i U_{ci} C_i + \sum_j U_{wj} W_j \tag{6}$$

where C_i is the chemical consumption in cleaning tank i within the cleaning time, W_j is the rinsewater consumed during the rinse time, U_{ci} is the unit cost of chemicals in tank i, and U_{wj} is the unit cost of fresh industrial water in tank j.

This optimization is subjected to following constraints:

(1) Chemical consumption estimation:

$$A_{Pi} \frac{dW_{Pci}(t)}{dt} = -r_{Pci}(t) \qquad i = 1,\ldots,N \tag{7}$$

$$V_{ci} \frac{dC_{ai}(t)}{dt} = -\frac{r_{Pci}(t)}{\eta_i} - C_{ai}(t) D_{oi}(t) + W_{ci}(t) \qquad i = 1,\ldots,N \tag{8}$$

$$C_i = \int_0^{T_{ci}} W_{ci}(t)dt \qquad i = 1,\ldots,N \tag{9}$$

(2) Rinsewater consumption estimation:

$$V_{rj} \frac{dX_{rj}(t)}{dt} = -F_{rj}(t) X_{rj} + R_{rj}(t) Z_{rj}(t) + D_{ij}(t) Z_{ij}(t) \quad j = 1,\ldots,M \tag{10}$$

$$W_j = \int_0^{T_{rj}} F_{rj}(t)dt \qquad j = 1,\ldots,M \tag{11}$$

(3) Process constraints:

$$W_{Pi}^{lim} \geq W_{Pci}(T_{ci}) \geq 0 \qquad i = 1,\ldots,N \tag{12}$$

$$X_j^{lim} \geq X_{rj}(T_{rj}) \geq 0 \qquad j = 1,\ldots,M \tag{13}$$

$$T^{lim} \geq \sum T_{ci} + T_{rj} \tag{14}$$

where W_{Pi}^{lim} is the maximum soil level on the parts coming out of the cleaning tank i, $W_{Pci}(T_{ci})$ is the soil residue on the parts out of the cleaning tank i, T_{ci} is the cleaning time in tank i, X_j^{lim} is the maximum pollutant level in the rinsewater coming out of the rinse tank j, $X_{rj}(T_{rj})$ is the pollutant concentration in the rinsewater coming out of the rinse tank j, T_{rj} is the rinse time in tank j, and T^{lim} is the time for one barrel to travel through the cleaning and rinsing system as determined by the cycle time and number of barrels.

Statistical Function Approach

Optimization is implemented in a two-layer computation scenario. At the lower layer, the objective is to minimize the unit operating costs and waste generation through adjusting the settings of control variables, such as chemical concentration and water flow rate, in each individual tank. At the upper layer, the objective is to perform global optimization over the whole cleaning and rinsing system. The overall objective is to minimize the overall operating cost and waste generation of the system through optimally setting the processing time in each tank. In the optimization procedure, the upper layer will deliver the chosen processing time to each unit tank at the lower layer. Based on the desired processing time, the corresponding minimum settings of chemical concentration or water flow rate will be found and sent back to the upper layer. The upper layer will evaluate the overall operating cost and waste generation based on the control variable settings received from the lower layer. When the upper layer optimization shows that an overall optimum has been reached for cost reduction and P2, the iteration will be stopped; otherwise, the upper layer will choose a different processing time and send the process down to the lower layer again.

We have proposed a statistical function approach to transform

Comparison of the Original & Optimal Operation

Operational steps	Original system	Optimized system
Cleaning 1	4.5 min	4.35 min
Cleaning 2	4.5 min	4.35 min
Cleaning 3	4.5 min	5.22 min
Total chemical cost	$ 89,916	$ 82,975
Rinse 1	1 min	0.72 min
Rinse 2	1 min	0.72 min
Rinse 3	1 min	1.14 min
Total rinsing cost	$ 20,724	$ 19,956
Total operating cost	$ 110,640	$ 102,931

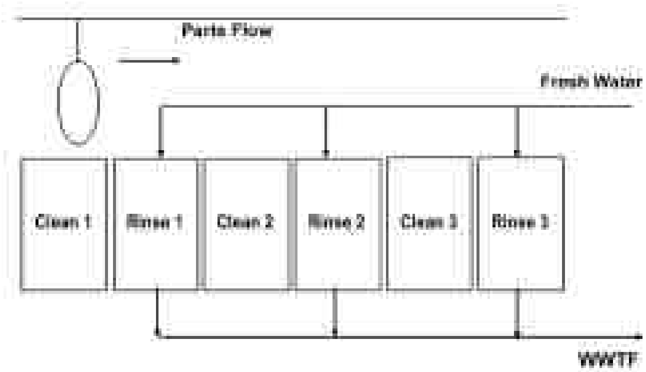

Fig. 5—Process flowsheet of a three-step cleaning and rinsing system.

the hierarchical optimization problem into a single-level problem. First, through simulation of the dynamic models, the regression models describing the relationship between the cleaning time and chemical concentration, as well as that between the rinse time and water flow rate, can be established. Originally, the upper-layer objective function was $\min_y\{F(x,y),\ y \in Y\}$ and the lower-layer objective function was $\min_x\{G(x),\ x \in X\}$. Through regression analysis, the relationship between x and y can be formulated as a function y(x). Thus, the hierarchical optimization problem can be reformulated as $\min_x\{F(y(x),x),\ x \in X\}$. It can be solved by using a conventional nonlinear optimizer.

Case Study

A cleaning and rinsing system in an electroplating plant is depicted in Fig. 5. It consists of three cleaning-rinsing subsystems in series. Parts in barrels are withdrawn sequentially from a cleaning tank and charged into the succeeding rinsing tank in series. The contamination level limits in the three rinse tanks are 2500, 2500 and 2000 mg/L, respectively. The chemical concentration ranges in the three cleaning tanks range from 6 to 8%, 6 to 8% and 6 to 9%, respectively. The cycle time between two adjacent barrels coming into the system is six min. There are, at most, three barrels in the system at any given time. Each barrel, therefore, requires 18 min to travel through this system.

To optimize production, the dynamic models are established for all the cleaning and rinse tanks. Through simulation of these dynamic models, a number of regression models are developed. With these regression models, a non-linear programming tool is then used to solve the optimization problem. The comparison of the original and optimized systems is given in the table. It shows that the total operating cost in this specific case study can be reduced by 6.9 percent.

Conclusions

A rigorous mathematical method is presented for optimizing cleaning and rinsing operations. The optimization is implemented in two layers. In the lower layer, the optimal settings for local control variables such as chemical concentration and water flow rate are identified for implementing profitable pollution prevention. In the upper layer, the optimal processing time in all the cleaning and rinse tanks are presented for realizing optimal production. The statistical function approach is proposed to coordinate the two-layer optimization. A case study has shown the significance of cost reduction in electroplating lines. This approach is applicable to any electroplating line.

Acknowledgment

This work was in part supported by AESF (Project No. 96), ACS (PRF 33679-AC9) and the Institute of Manufacturing Research of Wayne State University.

References

1. T.F. Edgar, D.M. Himmelblau and L.S. Lasdon, *Optimization of Chemical Processes,* 2nd ed., McGraw-Hill, New York, NY, 2001.
2. J.R. Load, P. Pouech and P. Gallerani, *Plating & Surface Finishing*, **83**, 28 (January 1996).
3. G.C. Cushnie, *Pollution Prevention and Control Technology for Plating Operations*, NCMS, Ann Arbor, MI, 1994.
4. H.H. Lou and Y.L. Huang, *Plating and Surface Finishing*, **87**, 59 (November 2000).
5. K.Q. Luo, and Y.L. Huang, *Int. J. of Eng. Appl. of Artificial Intelligence,* **10**, 321 (April 1997).
6. J.P. Gong, K.Q. Luo and Y.L. Huang, *Plating and Surface Finishing,* **84**, 63 (November 1997).
7. Y.H. Yang, H.H. Lou and Y.L. Huang, *Plating and Surface Finishing*, **86**, 80 (April 1999).
8. Q. Zhou, H.H. Lou, and Y.L. Huang, *Proc. AESF SUR/FIN '00, Chicago, IL*, AESF, Orlando, FL, 2000; p. 230.

About the Authors

Dr. Yinlun Huang is an associate professor in the Department of Chemical Engineering and Materials Science at Wayne State University, in Detroit, MI 48202 (e-mail: yhuang@wayne.edu). He holds a BS from Zhejiang University (China) and MS and PhD degrees from Kansas State University, all in chemical engineering. He has also been a Postdoctoral Fellow at the University of Texas in Austin. His research interests include process design and synthesis, process modeling and control, process simulation and optimization and industrial process pollution prevention and waste minimization. His research has been supported by AESF, the EPA, the National Science Foundation and various industries.

Mr. Qiong Zhou is a research assistant in the Department of Chemical Engineering and Materials Science of Wayne State University. He holds a MS degree in process control from Zhejiang University, China, and a MS in chemical engineering from Wayne State University. Currently, he is a PhD candidate in chemical engineering at Wayne State University.