# Optimal Design of a Water Reuse System In an Electroplating Plant

By Y.H. Yang, H.R. Lou & Y.L. Huang

**Wastewater minimization has drawn great attention in the electroplating industry for decades. An effective way to reduce wastewater is to maximize the reuse of rinse-water in rinsing steps. Conventionally, the water flow patterns and flow rates in rinsing systems are determined based on experience and engineering practice. In this paper, a systematic, structure-based mathematical approach is introduced to design an optimal water reuse system. The attractiveness of the approach is demonstrated by solving a practical rinsing water minimization problem.**

The electroplating industry is one of the major fresh water consumers and wastewater generators in the manufacturing industries. In an electroplating plant, a huge amount of water is used daily to remove dirt and chemicals on metal parts in various cleaning and rinsing operations. The wastewater generated contains a variety of hazardous or toxic chemicals, metal and non-metal pollutants that are regulated by the EPA.[1] Facing more and more stringently environmental regulations, this industry has been under constant pressure to significantly reduce fresh water consumption, and certainly wastewater generation.

Over the past decades, tremendous efforts have been made in the industry to design more efficient rinsing systems and in-plant wastewater treatment facilities.[2,3] This has led to tremendous reduction of wastewater and optimization of cleaning, rinsing, and plating processes. This is a proactive pollution prevention approach that aims at wastewater reduction from the beginning. In recent years, our research group has developed a series of first-principles-based mathematical models for characterizing various cleaning and rinsing operations.[4-6] With these models, parts cleaning and rinsing standards can be scientifically set, chemical solutions through drag-in and drag-out can be quantified, and water contamination dynamics in rinsing tanks can be described. More recently, a set of sludge models has also been developed to characterize sludge generation in cleaning and rinsing steps.[7] These dynamic and steady-state models can provide deep understanding of cleaning and rinsing operations, which greatly facilitate the development of strategies for optimal water use and reuse in electroplating plants.

In this paper, we introduce another type of proactive approach for wastewater reduction. This approach focuses on the modification of existing rinsing systems through re-designing water flow patterns and optimizing their flow rates, under the constraints of parts rinsing quality and productivity. The approach is applicable to cleaning-rinsing systems containing multiple chemical pollutants.

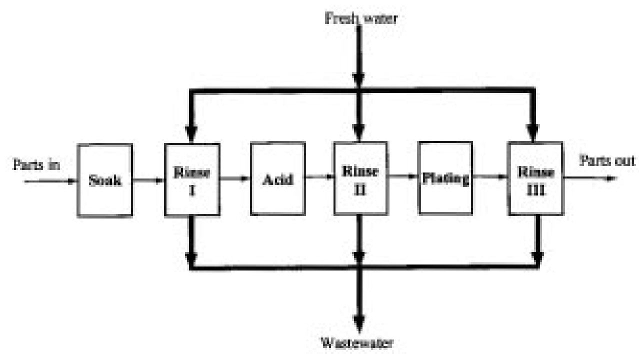


*Fig. 1—Diagram of a conventional electroplating process.*

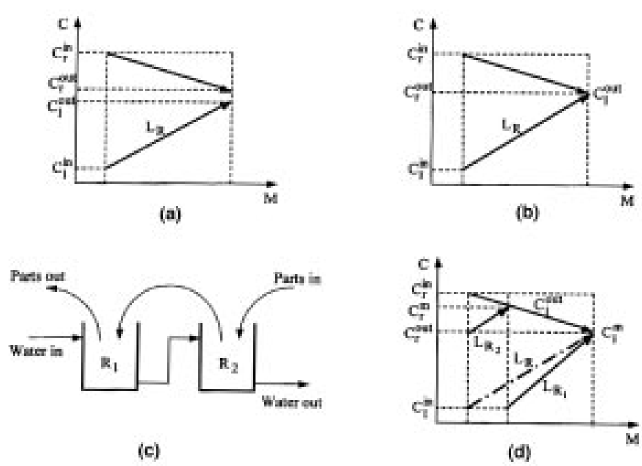


*Fig. 2—Mass transfer diagram for a rinsing process: (a) mass transfer between process and water streams; (b) uniform concentration in stream outlets; (c) counter-current two-rinsing-step process; (d) potential water reduction in two tanks in series.*

## Basic Strategies for Wastewater Minimization

A general plating process is depicted in Fig. 1. Parts in barrels pass through a series of cleaning-rinsing processes to remove dirt from their surfaces to achieve high plating quality. In the plating process, fresh water enters different rinsing processes to remove drag-out chemical solutions carried by parts from cleaning or plating tanks. The effluent water from rinsing tanks is mixed with different kinds of chemical contaminants. To evaluate the feasibility of reusing water, a basic mass balance relationship for all rinsing water streams must be established.

### Maximum Outlet Water Concentration

Figure 2a illustrates a mass transfer process between a pair of contaminated (rich) streams and rinsing water (lean)

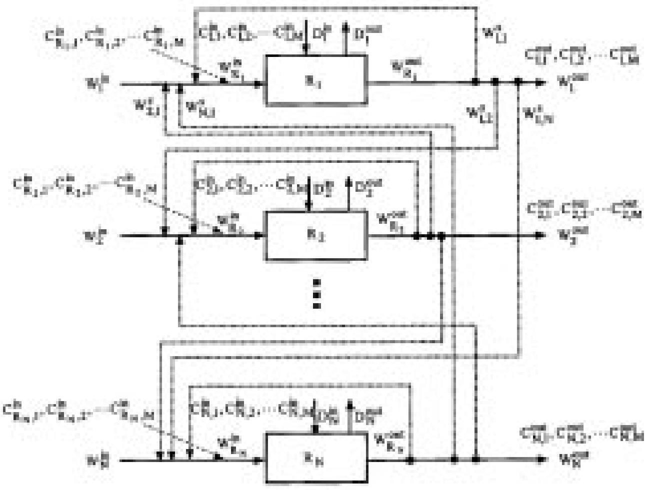

*Fig. 3—System representation of a reused-water rinsing process.*

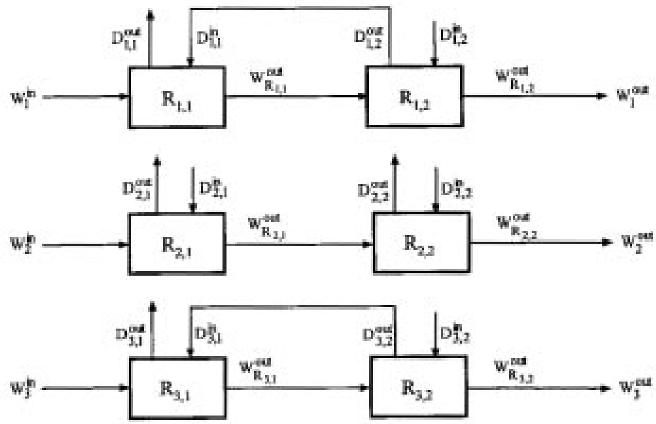

*Fig. 4—Original rinsing system in an electroplating plant.*

streams. The concentration in the rich stream, after a certain amount of contaminant is removed, is decreased from $C_r^{in}$ at the inlet to $C_r^{out}$ at the outlet of a rinsing tank. Meanwhile, the concentration in the lean stream is increased from $C_1^{in}$ to $C_1^{out}$, because the stream washes off chemical residue from the surface of the parts. Note that the slope of lean-stream line $L_R$ determines the water flow rate; the larger the slope, the smaller the required water flow. If the concentrations at the inlets of both rich and lean streams and at the outlet of the rich stream are specified, the amount of water required will depend on the outlet concentration of the lean stream. When the maximum outlet concentration of the contaminant is reached through mass transfer, water consumption is minimized.

For a specific rinsing process in a plating plant, a rich stream refers to chemical solution on the surface of parts. It is reasonable to assume that a complete mixing of water in a rinsing tank takes place. Thus, the chemical concentration in the rinsing tank can be considered nearly the same as that on the parts after rinsing. This is illustrated in Fig. 2b. The model developed by Huang *et al.*[5] has been used to determine the chemical concentration on the parts.

## Reduction of Water Usage in Rinsing Processes

An effective way to reduce fresh water usage is to maximize the contaminant concentration of rinsing water at the outlet. Figure 2c shows a rinsing process with two tanks in series. A countercurrent process between parts and water flow is arranged in such a way that water flows through rinsing tanks $R_1$ and $R_2$, and parts are carried over through rinsing tanks $R_2$ and $R_1$. A mass transfer diagram of the process is depicted in Fig. 2d. The slope of line $L_{R1}$, determines the water flow rate required for a two-tank rinsing process. Obviously, because of the increment of contaminant concentration at the water outlet of the rinsing process, water consumption in this case can be reduced, compared with the consumption in a single tank that is represented by line $L_R$. Theoretically, based on a given rinsing requirement, the increment of the number of rinsing tanks in a rinsing process can significantly reduce water consumption. This may affect overall process operations, capital cost, and productivity, however. Industrial experience suggests that two or three rinsing tanks in series for each rinsing step are practical for most cases.

For a plating system containing various rinsing steps, the development of a general mathematical model characterizing a water reuse rinsing system is the first step toward minimization of water usage.

## Model Development

A general rinsing system in a plating process is sketched in Fig. 3. This system consists of N sub-rinsing systems, each of which is designed for rinsing off chemical solutions on parts carried by barrels from a preceding cleaning or plating operation. Each sub-rinsing system $R_i$ may contain more than one rinsing tank. As depicted, fresh water is sent to each sub-rinsing system. In the figure, dotted lines show all possible water reuse options in the system. Thus, this is a superstructure of the water reuse system. Certainly, a number of water reuse options will eventually be eliminated after system optimization. The mathematical model for this problem can be developed based on the following assumptions: (i) no chemical reaction in water, and (ii) uniform chemical concentration in a rinsing process, which means complete mixing taking place between water flow and chemical residues on parts. Of course, minimization of water usage must not violate process operational requirements.

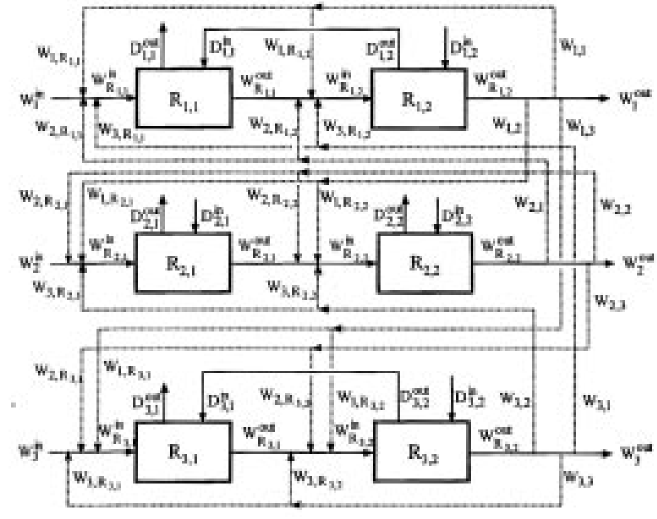

*Fig. 5—Superstructure of water reuse system for optimization.*

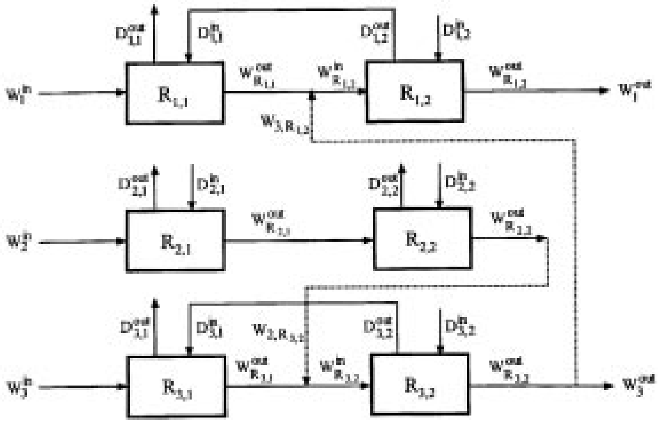

*Fig. 6—Modified rinsing system.*

## Problem Specification

Given drag-in rate $D_i^{in}$ and drag-out rate $D_i^{out}$ and their contamination levels of chemicals $C_{i,j}^{in}$ and $C_{i,j}^{out}$ ($i \in N$, $j \in M$) in rinsing process $R_i$, determine the minimum consumption of fresh water, $W_i^{in}$ ($i \in N$). This can be accomplished by maximizing water reuse and possible outlet wastewater concentration $C_{i,j}^{out}$, assuming that water can be reused from any effluent water stream to any source water stream with flow rate $W_{i,j}^{s}$ and concentration $C_{i,j}^{out}$. For the *i*th rinsing sub-system, it may receive N recycle streams from all sub-systems; these streams are mixed, then enter the sub-system at flow rate $W_{Ri}^{in}$ and concentration $C_{Ri,j}^{in}$. After rinsing, the effluent stream has an increment of chemical concentration of $C_{i,j}^{out}$.

## Optimization Model

With the characterization of stream concentrations and flow rates for each stream in Fig. 3, an optimization model can be developed as follows: The objective function is defined to minimize the total amount of fresh water used in the system, *i.e.*,

$$\min \sum_{i=1}^{N} W_i^{in} \qquad (1)$$

This optimization is subject to four types of constraints:

(i) Mass balances for mixers:

$$W_{R_i}^{in} = W_i^{in} + \sum_{i=1}^{N} W_{j,i}^{s} \qquad i=1, ...,N \qquad (2)$$

$$W_{R_i}^{out} = W_{R_i}^{in} + D_i^{in} - D_i^{out} \qquad i=1, ...,N \qquad (3)$$

(ii) Mass balances for splitters:

$$W_{R_i}^{out} = W_i^{out} + \sum_{j=1}^{N} W_{i,j}^{s} \qquad i=1, ...,N \qquad (4)$$

(iii) Mass balances for each component in each rinsing process:

$$C_{R_{i},k}^{in} W_{R_i}^{in} = \sum_{j=1}^{N} C_{j,k}^{out} W_{j,i}^{s} \qquad i=1, ...,N;\ k=1, ...,M \qquad (5)$$

| Table 1<br>Process Data & Constraints in a Rinsing System | | | | | |
|---|---|---|---|---|---|
| Symbol | Flow rate GPM | Concentration, ppm N | H | Z | P |
| $D_{1,2}^{in}$ | 0.52 | 2,000 | 0 | 0 | 0 |
| $D_{2,1}^{in}$ | 0.16 | 0 | 500 | 0 | 0 |
| $D_{2,2}^{in}$ | 0.24 | 0 | 0 | 13,000 | 0 |
| $D_{3,2}^{in}$ | 0.45 | 0 | 0 | 0 | 10,000 |
| $D_{1,1}^{in}$ | 0.75 | 180 | 0 | 0 | 0 |
| $D_{3,1}^{in}$ | 0.11 | 0 | 0 | 0 | 1,120 |
| $D_{1,1}^{out}$ | 0.75 | — | — | — | — |
| $D_{2,2}^{out}$ | 0.24 | — | — | — | — |
| $D_{2,1}^{out}$ | 0.16 | — | — | — | — |
| $D_{3,1}^{out}$ | 0.11 | — | — | — | — |
| $W_1^{in}$ | 6.0 | 0 | 0 | 0 | 0 |
| $W_2^{in}$ | 3.0 | 0 | 0 | 0 | 0 |
| $W_3^{in}$ | 4.0 | 0 | 0 | 0 | 0 |
| $W_{R1,1}^{out}$ | 6.0 | ≤30 | ≤30 | ≤30 | ≤30 |
| $W_{R2,1}^{out}$ | 4.0 | ≤30 | ≤30 | ≤30 | ≤30 |
| $W_{R3,1}^{out}$ | 3.0 | ≤30 | ≤30 | ≤30 | ≤30 |

$$C_{R_{i},k}^{out} W_{R_i}^{out} = C_{R_{i},k}^{in} W_{j,i}^{in} + C_{i,k}^{in} D_i^{in} - C_{i,k}^{out} D_i^{out}$$
$$i=1, ...,N;\ k=1, ...,M \qquad (6)$$

(iv) Process constraints:

$$C_{i,k}^{lim} \geq C_{i,k}^{out} \geq 0 \qquad i=1, ...,N;\ k=1, ...,M \qquad (7)$$

$$C_{R_{i},k}^{in} \geq 0 \qquad i=1, ...,N;\ k=1, ...,M \qquad (8)$$

$$W_i^{in}, W_{R_i}^{in}, W_{R_i}^{out} \geq 0 \qquad i=1, ...,N \qquad (9)$$

$$W_{i,j}^{s} \geq 0 \qquad i=1, ...,N;\ j=1, ..., N \qquad (10)$$

where $C_{i,k}^{lim}$ is the maximum permissible concentration of the ith chemical in the effluent stream of the *k*th rinsing process. The optimization is to determine the optimal structure of the water flow pattern and the optimal water flow rate of each recycle stream. This problem can be solved by a nonlinear programming approach.

## Application

A rinsing system in an electroplating plant is depicted in Fig. 4. The three-step rinsing can remove four types of chemical contaminants from parts surfaces. In the system, parts are withdrawn from a soak tank and charged into rinsing tanks $R_{1,2}$ and $R_{1,1}$ in series, where the concentration of chemical N on parts is reduced from 2,000 ppm to 20 ppm. The parts, after acid cleaning, are rinsed in rinsing tank $R_{2,1}$ where the concentration of chemical H is reduced from 500 ppm to 25 ppm. The effluent water stream from rinsing tank $R_{2,1}$ is then reused to wash out chemical Z on parts in rinsing tank $R_{2,2}$. After plating, the parts have a final rinsing in tanks $R^{3,2}$ and $R_{3,1}$ in series to remove chemical P on parts, through which the concentration is reduced from 10,000 ppm to 20 ppm. The process data and constraints are listed in Table 1. Note that drag-out rates $D_{1,2}^{in}$, $D_{2,1}^{in}$, $D_{2,2}^{in}$, and $D_{3,2}^{in}$ are from cleaning and plating processes; $D_{1,1}^{in}$ and $D_{3,1}^{in}$ indicate drag-out rates from tanks $R_{1,2}$ and $R_{3,2}$, respectively. The chemical concentration on the parts after rinsing in tanks $R_{1,1}$, $R_{2,1}$, and $R_{3,1}$ must be strictly controlled to equal or be below 30 ppm for each chemical contaminant. Figure 5 illustrates a superstructure of the water reuse system for optimization. The specific model for the system is formulated below.

$$\min \sum_{i=1}^{3} W_i^{in} \tag{11}$$

subject to

(i) Mass balances for mixers:

$$W_i^{in} = \sum_{j=1}^{3} W_{j,R_{i,l}} = W_{R_{i,l}}^{in} \qquad i=1, 2, 3 \tag{12}$$

$$W_{R_{i,l}}^{in} + D_{i,l}^{in} = W_{R_{i,l}}^{out} + D_{i,l}^{out} \qquad i=1, 2, 3 \tag{13}$$

$$W_{R_{i,l}}^{out} + \sum_{j=1}^{3} W_{j,R_{i,2}} = W_{R_{i,2}}^{in} \qquad i=1, 2, 3 \tag{14}$$

$$W_{R_{i,2}}^{in} + D_{i,2}^{in} = W_{R_{i,2}}^{out} + D_{i,2}^{out} \qquad i=1, 2, 3 \tag{15}$$

(ii) Mass balances for splitters:

$$W_{R_{i,2}}^{out} = \sum_{j=1}^{3} W_{i,j} + W_i^{out} \qquad i=1, 2, 3 \tag{16}$$

$$W_{i,j} = W_{i,R_{j,1}} + W_{i,R_{i,2}} \qquad i=1, 2, 3 \tag{17}$$

(iii) Mass balances for each component in each rinsing process:

$$\sum_{j=1}^{3} C_j^k W_{j,R_{j,1}} = C_{i,l} W_{R_{j,1}} \qquad i=1, 2, 3;\ k=P, H, Z, N \tag{18}$$

$$C_{i,l}^k W_{R_{i,1}}^{in} + C_i^k D_{i,1}^{in} = C_{i,2}^k \left(W_{R_{i,1}}^{out} + D_{i,l}^{out}\right) \qquad i=1, 2, 3;\ k=P, H, Z, N \tag{19}$$

$$C_{1,2}^k W_{R_{i,1}}^{out} + \sum_{j=1}^{3} C_j^k W_{j,R_{i,2}} = C_{1,3} W_{R_{i,2}} \qquad i=1, 2, 3;\ k=P, H, Z, N \tag{20}$$

$$C_{1,3}^k W_{R_{i,2}}^{in} + C_{1,4}^{in} D_{1,2}^{in} = C_i^k \left(W_{R_{i,2}}^{out} + D_{i,2}^{out}\right) \qquad i=1, 2, 3;\ k=P, H, Z, N \tag{21}$$

(iv) Concentration requirements:

$$C_{i,2}^k \le 30 \qquad i=1, 2, 3;\ k=P, H, Z, N \tag{22}$$

Table 2
Comparison of Fresh Water Consumption
Of the Original & Modified Processes

| **Water stream** | **Symbol** | **Flow rate, GPM** | |
|---|---|---|---|
| | | **Original** | **Modified** |
| Fresh water 1 | $W_1^{in}$ | 6.0 | 4.13 |
| Fresh water 2 | $W_2^{in}$ | 3.0 | 2.51 |
| Fresh water 3 | $W_3^{in}$ | 4.0 | 2.81 |
| Wastewater 1 | $W_1^{out}$ | 6.52 | 4.46 |
| Wastewater 2 | $W_2^{out}$ | 3.0 | 0.0 |
| Wastewater 3 | $W_3^{out}$ | 4.45 | 4.35 |
| Reused water 1 | $W_{2,R3,2}$ | — | 1.31 |
| Reused water 2 | $W_{3,R1,2}$ | — | 2.51 |
| Total fresh water | | 13.0 | 9.45 |
| Water reduction | — | — | 27.3% |

$$C_i^k;\ C_{i,j}^k \ge 0 \qquad i=1, 2, 3;\ j = 1, 2, 3;\ k=P, H, Z, N \tag{23}$$

$$W_{iR_{i,1}};\ W_{i,R_{j,2}} \ge 0 \qquad i=1, 2, 3;\ j=1, 2, 3 \tag{24}$$

The above formulation can be solved using a constrained non-linear programming. The optimal solution is obtained with the minimum water usage of 9.45 GPM. This is 27.3 percent of fresh water reduction compared with the water consumption in the original rinsing process (13 GPM). Table 2 lists all reused water flow rates and concentrations, as well as water usage for the original process. The solution is so simple that it needs only two reuse water streams for the original process. As shown in Fig. 6, the effluent stream from rinsing tank $R_{2,2}$ is completely returned to rinsing tank $R_{3,2}$, and about 36.5 percent of the effluent stream from tank $R_{3,2}$ needs to be returned to tank $R_{1,2}$.

## Summary

A structure-based mathematical representation developed in this study has provided a general model for characterizing rinsing processes with all possible water reuse options in an electroplating plant. The model with various specified process constraints generates an optimization problem that can be solved by systematic non-linear programming. The application to a practical rinsing problem has shown significant reduction of fresh water consumption and wastewater generation. This approach can be applied to design and modify any type of rinsing process with multiple chemical contaminants to achieve both economic and environmental goals in the electroplating industry.

***Editor's note:*** *Manuscript received, September 1998.*

## Acknowledgment

This study was in part supported by NSF (CTS-9525127), EPA (R-824732-01), and AESF (Proj. No. 96). The authors gratefully acknowledge valuable discussions with Mr. R. Groom of Reilly Plating Company, Dr. G. Loar of McGean-Rohco, Inc., and Dr. K.Q. Luo of Monsanto Company.

References
1. K.F. Cherry, *Plating Waste Treatment*, Ann Arbor Science, Ann Arbor, MI, 1982.
2. G.C. Cushnie, Jr., *Pollution Prevention and Control Technology for Plating Operations*, National Center for Manufacturing Sciences, Ann Arbor, MI, 1994.
3. S.A.K. Palmer, M.A. Breton, T.J. Nunno, D.M. Sullivan & N.F. Surprenant, *Metal/Cyanide Containing Wastes, Treatment Technology*, Noyes Data Corp., Park Ridge, NJ, 1988.
4. Y.L. Huang & K.Q. Luo, *Intelligent Decision Support System for Source Waste Reduction in Metal Finishing Plants*, in *Intelligent Systems in Process Engineering*, J.F. Davis, G. Stephanopoulos & V. Venkatasubramanian (Eds.), AIChE Symposium Series, Vol. **92**, 405, 1996.
5. J.P. Gong, K.Q. Luo & Y.L. Huang, *Plat. and Surf Fin*., **83**, 63 (Nov. 1997).
6. K.Q. Luo & Y.L. Huang, *Int'l. J. Eng. Applic. Artif. Intell*., **10**(4), 321 (1997).
7. K.Q. Luo, Y.H. Yang, J.P. Gong & Y.L. Huang, *Plat. & Surf Fin*., **85**, 59 (Oct. 1998).

About the Authors

*Dr. Y.H. Yang holds a BS in chemical engineering from Southwest China University of Technology and MS and PhD degrees from Wayne State University. His primary research areas include process design and synthesis, process modeling and optimization, and pollution prevention in chemical and manufacturing industries.*

*H.R. (Helen) Lou is a graduate research assistant in the Department of Chemical Engineering and Materials Science at Wayne State University. She holds a BS from Zhejiang University in China and an MS from Wayne State University, both in chemical engineering. Her research interests include process modeling, process optimization, and pollution prevention in the chemical and coating industries.*

*Dr. YinLun Huang* is an assistant professor in the Department of Chemical Engineering and Materials Science at Wayne State University, 5050 Anthony Wayne Dr., Detroit, MI 48202. He holds a BS from Zhejiang University (China) and MS and PhD from Kansas State University, all in chemical engineering. He has also been a postdoctoral Fellow at the University of Texas at Austin. His research interests include process design and synthesis, process modeling and control, process simulation and optimization, and industrial process pollution and prevention and waste minimization. His research has been supported by the National Science Foundation, the EPA and AESF.*

** To whom correspondence should be addressed.*

Continued from page 79.

4. K.M. Yin & R.E. White, *AIChE J.,* **36,** 187 (1990).
5. S. Roy, M. Matlosz & D. Landolt, *J. Electrochem. Soc,* **141,** 1509 (1994).
6. A. Brenner, *Electrodeposition of Alloys, Principles and Practice,* **Vol. 1**, Academic Press Inc., New York, NY, 1963; pp. 558-573.
7. C.A. Ross, *Annual Rev. Mater. Sci.,* **24,** 159 (1994).
8. T. Tsalakos & A.F. Jankowski, *ibid.,* **16,** 293 (1986).
9. C. Madore, PhD Thesis, EPFL, Switzerland (1993).
10. S. Roy & D. Landolt, *J. Electrochem. Soc.,* **142,** 3021 (1995).
11. M. Eisenberg, C.W. Tobias & C.W. Wilke, *ibid.,* **101**, 307 (1954).
12. B. Gebhart & L. Pera, *Int. J. Heat Mass Transfer,* **14,** 2025 (1971).
13. V. Anantharaman, P.N. Pintauro & L. Nanis, *J. Electrochem. Soc.,* **136,** 1727 (1989).
14. S. Roy Devarajan, PhD Thesis, Tulane University, 1992, UMI Order Number 9229791.

About the Author

*Dr. Sudipta Roy is a lecturer in electrochemical materials processing in the Department of Chemical and Process Engineering, Merz Court, University of Newcastle, Newcastle upon Tyne, NE1 7RU, England.*

***List* of *Symbols***

| | |
|---|---|
| C | concentration, mol/cm$^3$ |
| D | diffusion coefficient, cm$^2$/s |
| F | Faraday's constant, 96487 C/mol |
| i | current, A/cm$^2$ |
| $i_p$ | peak current |
| $i._p$ | off current |
| $t_p$ | on time, sec |
| $t._p$ | off time, sec |
| $t_1$ | transition time, sec |
| t | time, sec |
| Q | copper discharged, Coulombs |
| R | ratio of $t_1/t_p$, dimensionless |
| z | number of electrons transferred in the reaction |
| V | potential, volts |
| β | Tafel constant |
| 0 | atomic percentage |
| | mass transfer boundary-layer thickness, cm |
| - | overpotential, V |
| * | dimensionless time |

***Subscripts***

| | |
|---|---|
| b | bulk |
| k | species |
| o | surface |
| rev | reversible |