Modeling for Sludge Estimation & Reduction

By K.Q. Luo, J.P. Gong & Y.L. Huang

Sludge reduction is one of the most important environmental issues in electroplating plants. The most effective way of sludge reduction is to minimize the sludge generated from each plating line. In this paper, a set of sludge models is developed to characterize the sludge generation in parts cleaning and rinsing. These models, together with a set of dynamic models for characterizing cleaning solutions, rinsewater, and parts, can be used to develop strategies for sludge reduction and quality assurance for cleaning and rinsing. Model-based simulation has demonstrated the desirability of adopting them in real processes.

The electroplating industry is one of the largest sludge generators in the manufacturing industries. A huge amount of sludge generated daily from more than 6,500 plating plants in the nation usually contains various chemical, metal, and nonmetal pollutants, such as chromium, iron, nickel, tin, cyanide, soil and oil. These pollutants are regulated by the EPA as hazardous or toxic waste.[1] This has cost the industry hundreds of millions of dollars per year for wastewater treatment and sludge disposal. On the other hand, landfill is severely restricted today by its reliability, environmental impact, site availability and cost.[2] Consequently, a significant reduction of both quantity and toxicity of sludge becomes an urgent need for this industry.

According to the EPA's waste minimization (WM) hierarchy, source reduction is of the highest priority because it aims at minimizing waste in the first place. In the industry, various WM strategies have been practiced that are valuable for sludge reduction. Drag-out minimization is one of the most important strategies, because the drag-out, which contains various chemicals and dirt, is a major source of sludge in wastewater.[3,4] From the standpoint of process operation, a low chemical concentration, plus high temperature in a bath, for instance, can reduce drag-out losses, and thus sludge. Bath life extension is another type of strategy for sludge reduction. It is known that dumping process baths improperly is costly and increases sludge as well. In rinsing systems, an improvement of rinse efficiency can not only cut operating costs for plating operations, but also reduce the cost for chemicals used in wastewater (pre)treatment.

While the current WM strategies are beneficial to sludge reduction, none can provide reasonably precise information as to the extent that sludge can be theoretically minimized and how much it can be practically reduced. Obviously, minimization of sludge must be based on deep understanding of the sludge generation mechanism. In this paper, we focus on the development of mathematical models for estimating sludge, only from cleaning and rinsing steps, and model-based strategies for sludge reduction. Computer simulations will show how the models can provide valuable guidance for minimization of sludge with improved process operation.

Sludge Classification

To minimize sludge effectively, we must correctly identify its sources, then classify the types of sludge from different sources. This will allow us to know what type of sludge can be reduced and to what extent it can be reduced economically.

In an electroplating process, parts are packed in barrels or placed on racks, then passed through a number of cleaning and rinsing steps before and after plating and stripping. The cleaning operations can be further classified as alkaline cleaning, electrocleaning and acid cleaning. The rinsing operations can occur in static or continuous rinse tanks with different configurations. In cleaning and rinsing, most of the dirt (oil, soil, grease, solid particles, etc.) on the surface of parts can be removed by chemicals into chemical solutions and rinsewater. The mixture of dirt and chemicals will eventually become sludge. This kind of sludge generation is unavoidable and is referred to as base sludge. The majority of this mixture is found in cleaning tanks, and the remaining portion will enter rinsing systems through drag-out from cleaning tanks. As a general strategy, the sludge should be more localized, that is, the sludge generated in one tank should not be sent to the next tank. More specifically, the sludge generated in cleaning tanks should be prevented from being carried into rinsing tanks whenever it is technically desirable and economically acceptable.

Note that most plating plants generate more sludge than necessary as a result of improper use of chemicals, high flow rate of rinsewater, excessive drag-out into rinsing tanks, and unnecessary dumping. The sludge generated from these sources is called avoidable sludge. Table 1 summarizes the major sludge sources. Apparently, quantitative estimation and minimization of avoidable sludge should be the target for practicality.

Modeling for Sludge Estimation

Normally, sludge can be either dry or wet. Dry sludge refers to the net quantity of waste by weight. Wet sludge, however,

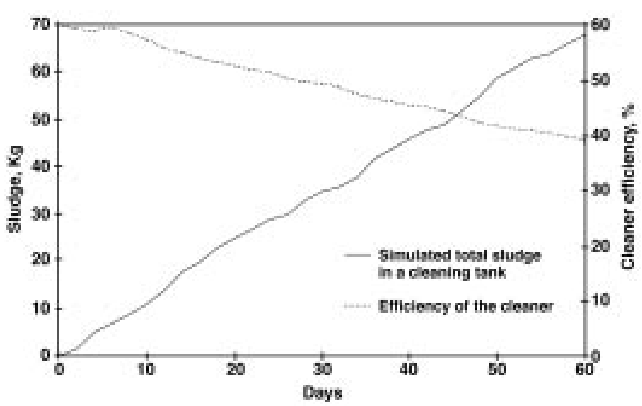

Fig. 1—Sludge accumulation in a cleaning tank.

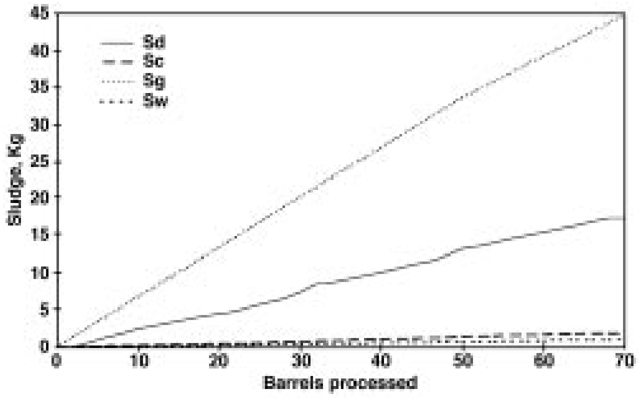

Fig. 2—Classification of sludge sources in a cleaning process.

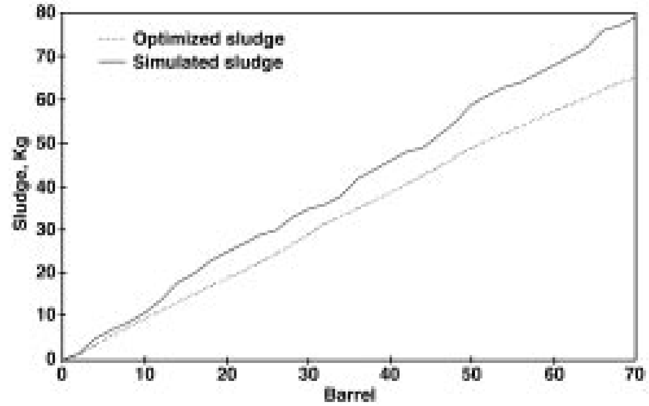

Fig. 3—Comparison of sludge accumulations before and after process optimization.

is always judged by its volume, which varies with the type of sludge and treatment methods (Table 2). In modeling, only dry sludge will be quantified. Quantification of dry sludge must rely on precise process information. This information can be provided by process models for main unit operations in cleaning and rinsing tanks.

Total Sludge

According to the sludge sources, the base sludge *(S_T)* can be found in cleaning and rinsing tanks. The base sludge in cleaning tanks includes the dirt (oil, soil, grease, solid particles, etc.) removed from the surface of parts *(S_d)* and the chemicals used to remove the dirt *(S_c)*. In rinsing tanks, the sludge resulting from natural contaminants in make-up water or rinsewater *(S_w)* and that from drag-out from cleaning tanks *(S_g)* should be considered. The total sludge is then the sum of all of them:

$$S_T = S_d + S_c + S_g + S_w \tag{1}$$

Each type of sludge can be quantified based on its sources. The sludge from cleaning tanks (*i.e.*, S_d *and* S_c), can be estimated by the following formulas:

$$S_d = \sum_{i=l}^{N_b} \left(A_i \sum_{j=l}^{N_d} W_{c_{i,j}} \right) \tag{2}$$

$$S_c = \sum_{i=l}^{N_b} \left(A_i \sum_{j=l}^{N_d} \frac{W_{c_{i,j}} \; k_{c_j}}{\mu_j} \right) \tag{3}$$

where

A_i = the total surface area of the *i*th barrel of parts (cm^2)
k_{cj} = the precipitation constant for the *j*th cleaner (g-sludge/L-cleaner)
N_b = the number of barrels of parts processed per day (bbl/day)
N_d = the number of kinds of dirt on the surface of parts
$W_{ci,j}$ = the amount of the *j*th kind of dirt removed from the surface of parts in the *i*th barrel (g-dirt/cm^2)
μ_j = the dirt removal capacity of the *j*th cleaner (g-dirt/L-cleaner)

The drag-out-related sludge from cleaning tanks into rinsing tanks consists of dirt and chemical solutions. This amount is estimated based on the drag-out rate in the following way.

$$S_g = \left(\sum_{i=l}^{N_b} A_i D_g \right) \tag{4}$$

where D_g = the rate of drag-out (solvent solutions and the mixture of dirt and chemicals) from cleaning tanks to rinse tanks (g-dirt-chemicals/cm^2).

As indicated, the natural contaminants in make-up water or fresh water will eventually be part of the sludge. This amount can be modeled as

$$S_w = k_w k_{pw} F_w \tag{5}$$

where

k_{pw} = the precipitation constant for the rinsewater (g-sludge/g-contaminant)
k_w = the hardness of the rinsewater (g-contaminant/cm^3)
F_w = the volumetric flow rate of make-up and fresh water into rinsing system (cm^3/day).

Note that drag-out cannot be completely prevented from entering the rinse system and thus into the wastewater. In the above formulation, any drag-out between two adjacent continuous rinse tanks will not be separately considered, because the contaminants enter the same water stream. The estimation of the sludge accumulation in each tank is of great importance, because it will determine the most appropriate dumping time of each cleaning tank.

Dirt Removal in Cleaning Tanks

In estimating the total sludge, the most difficult part is the estimation of the amount of dirt removed from each barrel of parts. Note that the amount of dirt initially on the surface of parts cannot be precisely determined, the shape of parts vary greatly and the cleaning efficiency in each cleaning tank changes dynamically. It is thus highly desirable to use dynamic models to determine the amount of dirt removed. Such models have not been available until recently.[5]

In cleaning, the dirt (soil, oil and other solid particles) on the surface is removed by applying to it certain kinds of energy, such as mechanical, chemical, thermal, electrical and/or radiation energy. A certain amount of the loose dirt on parts sinks to the bottom of the tank as sludge. The remaining dirt is carried over through drag-out to succeeding tanks. The amount of the dirt on parts is negatively proportional to a dirt removal rate. This rate is determined by the type of chemical used and its concentration and the type and amount of the dirt on parts. We have, therefore,

Table 1
Sludge Sources in a Plating Process

Sludge source	Reproducibility
Make-up and rinse water (natural contaminants)	*yes*
Dirt removed from parts (oil, metals, scaling, and smut)	*no*
Used chemical (metals, chelated cleaner, high pH value)	*yes*
Chemical loss (improper dumping, drag-out, leaking, spilling, etc.)	*yes*

Table 2
Sludge Concentration Based on Treatment Type

Sludge Concentration	Treatment
1-2%	gravity settling
3-5%	bridge type settling
8-14%	centrifuge
up to 50%	filter presses
90-98%	drying

$$A_i \frac{dW_{c_i}(t)}{dt} = -\gamma_c(t) C_a(t) W_{ci}(t) \quad (6)$$

$$\gamma_c(t) = \gamma_0 \left(1 - e^{-\alpha(t - t_0)} \right) \quad (7)$$

where

$C_a(t)$ = the chemical concentration in the cleaning tank at time t (cm^3-chem/cm^3-sol)
$W_{ci}(t)$ = dirt removed from the *i*th barrel of parts at time t (g-dirt/cm^2)
α = constant
$\gamma_c(t)$ = looseness of dirt on parts at time t ($cm^2 \cdot cm^3$-sol/cm^3-chem $\cdot$ min)
γ_0 = kinetic constant ($cm^2 \cdot cm^3$-sol/cm^3-chem $\cdot$ min)

The amount of chemical in the tank changes as it is consumed and/or added. It can be modeled thus:

$$V_c \frac{dC_a(t)}{dt} = k_d A_i \left(C_0(t) - C_a(t) \right) - \frac{A_i W_{ci}(t)}{\mu} + w_c \quad (8)$$

where
$C_0(t)$ = chemical concentration in the preceding cleaning tank at time t (cm^3-chem/cm^3-sol)
k_d = drag-out coefficient determined by temperature, drainage time, the shape of parts, and surface tension
V_c = capacity of cleaning tank (cm^3-soln)
w_c = quantity of chemical added to cleaning tank (cm^3-chem/min)
μ = chemical capacity for dirt removal (g-dirt/cm^3-cleaner)

To run these models, the amount of dirt on parts before cleaning $(W_{ci}(t_0))$ must be obtained through experiment or estimated, based on experience, and the initial chemical concentration in the tank $(C_a(t_0))$ must be specified. The kinetic constant (γ_0) and the chemical capacity for dirt removal (μ) can be determined by the type of chemical used. The larger the value of μ, the more efficient the dirt removal. By solving Eqs. (7) and (8), the total amount of dirt removed from each barrel can be calculated.

Water Consumption in Rinsing Tanks

Minimization of water consumption in rinse systems depends largely on the cleanness of parts after rinsing. This requires a model to describe the dirt removal from parts and a model to quantify water pollution level. Gong *et al.* developed the models with the following structures:[5]

$$A_i \frac{dW_{r_i}(t)}{dt} = r_{r_i}(t) \quad (9)$$

$$V_r \frac{dx_r(t)}{dt} = r_{r_i}(t) + F_w(t)\left(z_r(t) - x_r(t) \right) \quad (10)$$

$$r_{r_i}(t) = k_r \gamma_c(t_e) \left(\theta \left(W_{r_i}(t) - W_{c_i}(t_e) \right) - x_r(t) \right) \quad (11)$$

where
$F_w(t)$ = the flow rate of rinsewater at time t (cm^3-water/min)
kr = mass transfer coefficient (cm^3-chem $\cdot$ cm^3-water/cm^3-sol $\cdot$ cm^2) $r_{ri}(t)$ = dirt removal rate in rinsing tank at time t (g/min)
V_r = capacity of rinsing tank (cm^3-water)
$W_{ri}(t)$ = amount of dirt on parts in a rinsing tank at time t (g/cm^2)
$W_{ci}(t_e)$ = amount of dirt on parts when leaving cleaning tank at time t_e (g/cm^2)
$x_r(t)$ = pollutant composition in rinsewater at time t (g/cm^3-water)
$z_r(t)$ = pollutant concentration in influent rinsewater at time t (g/cm^3-water)
$\gamma_r(t_e)$ = looseness of dirt on parts when leaving cleaning tank at time t_e ($cm^2 \cdot cm^3$-sol/cm^3-chem $\cdot$ min)
0 = unit conversion factor (cm^2/cm^3-water)

The effluent water stream of the rinsing tank contains various pollutants, such as dirt, chemicals and metal particles. The quantity of pollutants is related to the rinsing efficiency, water flow rate, the initial dirtiness of parts and the cleanness of the influent rinsewater. Because water in the tank is well mixed, the pollutant composition in the tank is the same as that of the effluent water. In the above equations, the initial amount of dirt on parts $(W_{ri}(t_0))$ can be estimated from computation of the models for the cleaning tank. The dirtiness of influent rinsewater $z_r(t)$ can be easily measured.

Model-Based Sludge Reduction

Sludge reduction is mathematically an optimization problem of minimizing S_T, which is expressed in Eq. (1). This can, in turn, be interpreted as the minimization of three types of avoidable sludge $(S_c, S_g, \text{and } S_w)$. Practically, the amount of dirt to be removed from a part cannot be minimized because of a plating requirement. This means that the term, S_d, should be excluded in optimization.

The sludge related to chemical solvents (S_c) can be minimized through reduction of chemical consumption by selecting a cleaner with greater efficiency (*i.e.*, large μ). The amount of chemicals required for dirt removal can be calculated by solving Eqs. (6) through (8).

The most undesirable sludge source is the drag-out from cleaning tanks to rinsing systems. Note that the main function of rinsing is to remove the cleaning solvents and the mixture of dirt and chemicals carried on parts through drag-out. The more drag-out, the more water consumption for rinsing. It will then become more difficult to treat wastewater and cost more for sludge handling as well. Practically, drag-out-related sludge *(S_g)* cannot be eliminated, but can be minimized through operational improvement, such as adjustment of chemical concentration settings in cleaning tanks using the models in Eqs. (6) through (8). The drainage time and bath temperature are always factors of drag-out reduction.

The last term in the total sludge expression (Eq. (1)) is the sludge resulting from natural contaminants in make-up water and fresh water for rinsing *(S_w)*. Equation (5) shows that it is proportional to the volume of rinsewater consumed. Reduction of rinsewater is, therefore, highly desirable when the rinsing quality is guaranteed. The models in Eqs. (9) through (11) can be used to determine the optimal flow rate of rinsewater necessary for the operation.

Simulation

The models developed have been used to investigate the sludge generation and reduction in a plating process where three cleaning tanks and two rinse tanks are considered. The main task of this simulation is to determine an appropriate replenishment time for an individual cleaning tank, to distinguish quantitatively sludge generation and to identify opportunities for sludge reduction through process optimization. Three examples are discussed below.

Determination of Replenishment Time

The cleaning efficiency of a cleaning tank is closely related to the amount of sludge in it. As the sludge accumulates, the efficiency is decreased. When the efficiency is down to a certain point, parts cleaning is no longer satisfactory. The solvent solution must then be replenished. The replenishment point is difficult to detect in practice, however. Economically, the number of replenishments must be a minimum. This is also desirable to obtain smooth operation. On the other hand, delay of replenishment is detrimental to the cleaning quality. The sludge models can provide reliable information for replenishment in any cleaning tank. Figure 1 shows the simulation results for a cleaning tank for an operational period of two months. For simplicity, we assume the cleaning of 200 barrels of parts per day and with 180 kg of parts per barrel. The initial dirtiness of parts changes barrel by barrel, but not very significantly (0.008 to 0.045 g/cm^2). The chemical concentration is continuously maintained at eight percent. After two months, the cleaning tank contains nearly 190 kg of sludge, occupying 1.136 m^3 of the tank (see the solid line in the figure). As the sludge accumulates, the cleaning efficiency decreases. As indicated by the dotted line in the same figure, the efficiency is reduced to only 40 percent; here, fresh solvent with cleaner concentration of 10 percent is defined as 100 percent cleaning efficiency. This suggests that the cleaning tank be replenished with fresh cleaner.

Analysis of Total Sludge

As shown in Eq. (1), the total sludge *(S_T)* can be classified in four types, based on their sources. The model can be used to quantify each. In this case, 70 barrels of parts were simulated. These parts are assumed to have the same shape, and each barrel is equally loaded (180 kg/bbl). The initial amount of dirt on the parts' surface varies between 0.008 and 0.045 g/cm^2. The process simulated consists of a presoak tank, a soak tank, an electrocleaning tank and two rinse tanks in series. The chemical concentrations in the cleaning tanks are all kept at eight percent. The water flow rate through the rinse tanks is set to 0.023 m^3/min. Figure 2 shows how the sludge is accumulated. As indicated, after finishing the processing of 70 barrels, the drag-out related sludge *(S_g)* reaches 45 kg. The dirt-related sludge *(S_d)* is much lower, however (16 kg). The quantity of the other two types of sludge is very small; that is, the solvent-related sludge *(S_c)* and the natural contaminant-related sludge *(S_w)* are 2.3 kg and 1.4 kg, respectively. The total amount of sludge for this case is 64.7 kg. This indicates that 69.5 percent of total sludge is from drag-out. This suggests that the minimization of drag-out from cleaning tanks to rinse tanks is of utmost importance in sludge reduction.

Model-Based Sludge Reduction

As discussed in the preceding section, sludge can be reduced through operational improvement, such as the reduction of drag-out and that of chemical and rinsewater consumption. Here, we also simulate the same cleaning and rinsing process with the same operational settings as described in the preceding example. A total of 70 barrels of parts are still considered here. Figure 3 depicts the simulation results of the total sludge accumulation in the process. The original settings of chemical concentrations in the presoak, soak, and electrocleaning tanks are all eight percent. The water flow rate through the rinsing tank is set to 0.023 m^3/min. This process is optimized by the dynamic models, which leads to the chemical concentration settings in the presoak, soak, and electrocleaning tanks to 10, 8 and 6 percent, respectively. The drag-out rate is thus reduced from 0.012 to 0.009 g/cm^2. This also allows the reduction of rinsewater flow rate from 0.023 to 0.019 m^3/min. With these changes, the total amount of sludge can be reduced to 66 kg, which means a reduction of 15 percent.

Conclusions

Effective reduction of sludge requires deep understanding of sludge generation mechanisms. The classification and quantification of sludge need guidance based on chemical and electrochemical engineering principles. In this study, we have developed sludge models that can be used for reasonable estimation of sludge generation from different sources. Together with the dynamic models for cleaning and rinsing operations, these sludge models can be used to identify opportunities for optimal sludge reduction. Through their use, the replenishment points in cleaning tanks can also be predicted. These models should be attractive to platers to gain economic and environmental incentives.

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