

The Mass Transfer Rate of an Array of Rectangular Pins in a Channel Flow Cell

*Dr. Kan-Lin Hsueh
NanoSciences Corporation
Lancaster, PA U.S.A.*

and

*Marjorie K. Myers
Tyco Electronics
Harrisburg, PA U.S.A.*

In reel-to-reel plating process, parts are commonly plated in a channel flow cell. The bath agitation inside the cell is an important plating parameter to be controlled. A computer was used to simulate the hydrodynamics of the reel-to-reel plating process with an array of rectangular pins in a channel flow cell. The local mass transfer rates on each pin were calculated and were correlated as a function of line speed and pin dimension. This information can be used as a guideline for laboratory experiment so that the agitation condition of the experiment is equivalent to the reel-to-reel plating condition.

Reel-to-reel strip plating

Reel-to-reel plating (continuous strip) plating processes are commonly used in the electronics industry. In this plating process, an array of pins moves through a channel where the metal is plated as shown on Figure 1. Various plating techniques are used to selectively deposit metal on the strip¹.

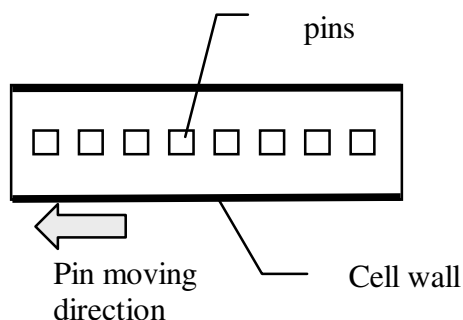


Figure 1 A scheme of a strip plating process (eight pin array model).

Gap between lab experimental conditions and manufacturing conditions

To improve plating performance; the plating cell, plating conditions, and bath chemistry have to be extensively evaluated. To reduce cost, most evaluations are conducted using small-scale laboratory equipment such as a Hull cell, rotating disk electrode (RDE), rotating cylinder electrode (RCE), etc. The plating parameters used in the lab must be the same as used in the production process for the results to correlate. Parameters such as current, time, and temperature can be set in the lab to be the same as used on the production line; and plating bath can be taken directly from the plating line. However, the hydrodynamics and mass transfer phenomena of the plating cell used in the production process are not well understood. Also, lab instrument bath agitation is different than production equipment bath agitation. Chin² and others have studied the mass transfer rate of a continuous moving strip, but the mass transfer of an array of pins was not found in the literature.

This work reports the results of a simulation of the hydrodynamics and mass transfer phenomenon of an array of pins moving through a channel cell using commercially available computer software⁵. The mass transfer rate on

the surface of a pin was then correlated to the mass transfer rate of RDE, RCE, and a Rotating Hemisphere Electrode (RHE).

Two computer models and their assumptions

Two models were used in the simulation:

1. An array of eight pins in a channel cell as shown on Figure 1, and
2. A single pin with periodical boundary conditions as shown on Figure 2.

The purpose of the first model was to examine the hydrodynamics around a leading and a trailing pins. The second model is equivalent to a long array of pins where the influences of leading and trailing pin on other pins were not important.

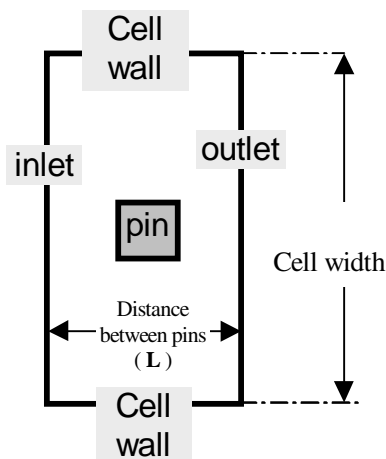


Figure 2 Scheme of single pin model

The model assumes:

- bath flow is slow compared to pin movement
- pin movement induces bath agitation
- Square pins are located at the middle of the cell.

The computer program calculates the hydrodynamics and the mass transfer rates at different conditions using the following variables.

1. Distance between pins (pin centerline-to-centerline, L)
2. Line speed (pin moving speed, V)
3. Pin location (distance measured from the inlet to the centerline of each pin, X_c)

The following bath properties and cell dimensions were used for all simulations reported here.

- bath density = 1.0 g/cm^3 (10^3 kg/m^3),
- viscosity = 0.01 g/cm.s (10^{-3} Pa.s),
- species diffusivity = $1 \times 10^{-2} \text{ cm}^2/\text{s}$ ($10^{-6} \text{ m}^2/\text{s}$).
- cell width = 2.54 cm , and
- width of square pin = 0.1 cm .

Boundary conditions

The model coordinate origin is centered on the pin. The pin is stationary as the cell wall moves at speed of \mathbf{V} . Therefore, the boundary conditions of velocity were

$$\begin{bmatrix} \text{velocity} \\ \text{on the pin} \end{bmatrix} = 0, \text{ and } \begin{bmatrix} \text{velocity on} \\ \text{the cell wall} \end{bmatrix} = \mathbf{V} \quad [\text{Eq.1}]$$

The model assumes that an electrochemical active species is consumed on the cathode (the pin). The boundary conditions of this species were

$$\begin{bmatrix} \text{Species} \\ \text{concentration} \\ \text{on the} \\ \text{pin surface} \end{bmatrix} = 0, \text{ and } \begin{bmatrix} \text{Species} \\ \text{concentration} \\ \text{on the wall} \end{bmatrix} = 1 \quad [\text{Eq.2}]$$

For the eight-pin array model; the velocity at the inlet is set to be \mathbf{V} and the species concentration at the inlet is set to be one. For the single pin model, periodical boundary conditions of velocity and species concentration are imposed on the inlet and outlet. The boundary conditions of the inlet and outlet are re-iterated during numerical computation until the condition at inlet equals the condition at the outlet.

Commercial software was used to solve the momentum conservation and the species

conservation equations with above boundary conditions. The software uses a finite element numerical method and the model uses a gradient mesh with fine mesh at the vicinity of the pin. The diffusivity in aqueous solution ranges between 1×10^{-4} and $1 \times 10^{-5} \text{ cm}^2/\text{s}$. The model used $1 \times 10^{-2} \text{ cm}^2/\text{s}$ to reduce the mesh number required for the calculation.

Concentration profile of active species in a cell with array of pin

The species concentration profile of eight consecutive pins is plotted on Figure 3. The species are depleted in the vicinity of the pins. The species depleted region of the preceded pin extends into the following pin region, and species concentration between the pins is not replenished due to lack of agitation. This phenomenon is exaggerated because a higher value of diffusivity was used in the calculation.

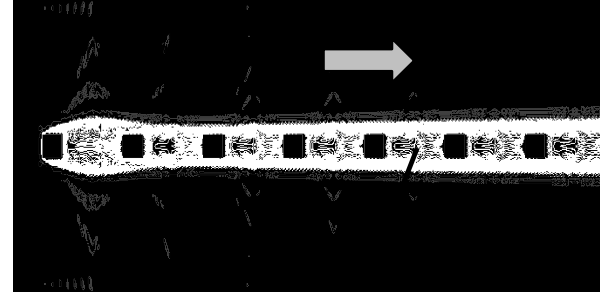


Fig. 3 Concentration profile at line speed of 5 fpm. The cell width was 2.54 cm distance between pins was 0.3 cm , and the pin width was 0.1 cm .

Concentration profile of two consecutive pins

A close look at the concentration profile between two pins is given on Figure 4. At low line speed (5 fpm), the influence of proceeding pin on the following pin is minor. At high line speed (30 fpm), the solution depleted region of a proceeding pin is extended to the following pin.

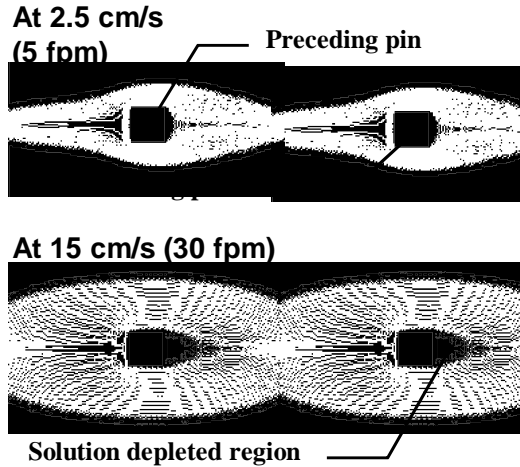


Fig. 4 The concentration profiles of electrochemical active species

Definition of the local mass transfer coefficient, k_m

The local mass transfer coefficient (k_m) indicates how fast the species consumed on the electrode surface can be replenished from the solution. It is equivalent to the local mass flux (j_m) because the model assumes the concentration on the pin (C_s) is zero and in the bulk (C_b) is one.

$$j_m = k_m (C_b - C_s), \text{ or } j_m = k_m \quad [\text{Eq.3}]$$

The k_m value of a single pin was not uniform

k_m along the surface of a square pin is plotted in Figure 5 as a function of the location on the pin (X). X is defined on the insert diagram. Side 4 is the leading side of the pin and side 2 is the tailing side of the pin. The four sharp corners have the highest value of k_m and the tail side of the pin (side 2) has lower k_m value. The value at the corners is higher than to be expected because in production pin are more round.

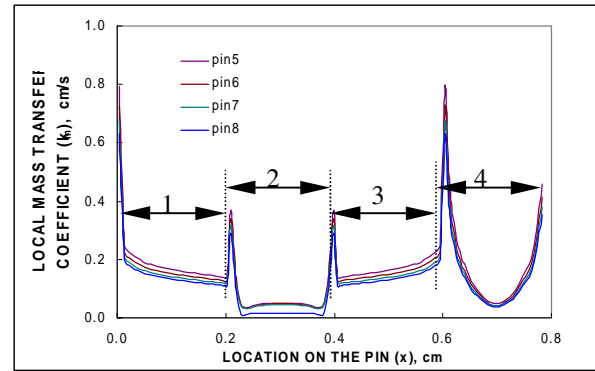
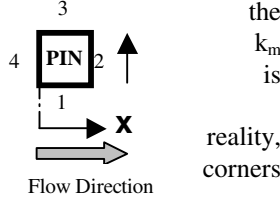


Fig. 5 Plot of local mass transfer coefficient as a function of location on the pin. The line speed was 5 ft/min, the cell width was 2.54 cm, the cell length was 0.3 cm, and the pin length was 0.1 cm.

Proceeding pin reduces the mass transfer rate of following pins

The species depleted region of the proceeding pin extends into the following pin region as shown on Figure 3 and 4. The influence of a proceeding pin on the mass transfer rate of a following pin is quantitatively presented on Figure 6. K_m is the averaged mass transfer coefficient; the mean value of k_m averaged over the entire pin boundary. K_m of each pin is plotted in Figure 6 as a function of each pin location (X_c) in the plating cell. The leading pin (pin 1) had the highest K_m value. Pin 2 had the second highest K_m . And pin 8 has the lowest K_m . The value of K_m decreases asymptotically as the pin location number increases (i.e. the further away from the first pin, the lower the K_m value).

The influence of line speed (V) and distance between pins (L) on the value of K_m

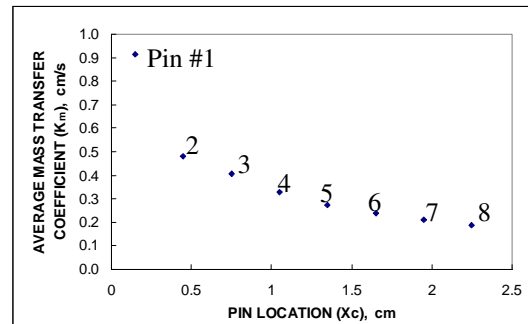


Fig. 6 Plot of average K_m value as a function of pin location

Figure 7 is a plot of K_m as a function of line speed (V) and the distance between pins (L). K_m of a single pin linearly decreases as the line speed increases. The pins located further apart (large cell length, i.e. 0.8 cm) are more sensitive to changes in line speed than pins located close together (small cell length, i.e. 0.3 cm). Also, pins placed further apart (large cell length) have a higher K_m than pins placed closer together (small cell length).

The K_m value depends on the line speed (V), and the distance between pins (L), as shown in Fig. 7. It can also be expressed using Equation 4.

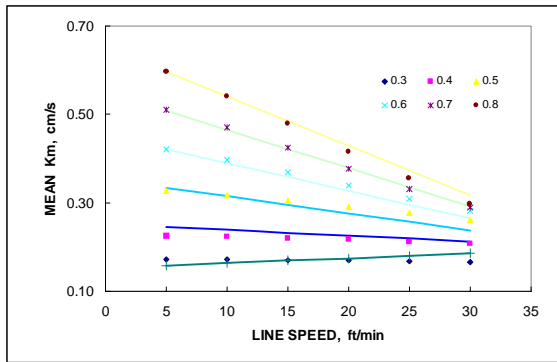


Figure 7 Plot of K_m of a pin as a function of line speed (V) and as a function of distance between pins (L).

$$K_m = a_1 + a_2 L + a_3 V + a_4 LV \quad [\text{Eq.4}]$$

Here a_1 to a_4 were constants:

$$a_1 = -6.9 \times 10^{-5}$$

$$a_2 = 4.65 \times 10^{-4}$$

$$a_3 = 3.97 \times 10^{-6}$$

$$a_4 = -1.1 \times 10^{-5}$$

[Eq.5]

The curves plotted in Fig.7 are calculated using Equation 5.

Correlation of K_m values among RDE, RCE, and RHE

In order to match the pin agitation condition to that of rotating electrodes, the K_m value of the pin should be equal to the K_m value of the rotating electrodes. K_m of a rotating electrode is dependent on the diffusivity of the electrochemical active species (D), viscosity of the bath (ν), electrode rotating speed (ω), and the Schmidt number (Sc). K_m of various rotating electrodes found in the literature are listed as follows.

For RDE, in laminar flow region³, Reynolds number ($Re_r, \omega r^2/\nu$) $< 200,000$

$$K_m = 0.62 \frac{D}{r} \left(\frac{\omega r^2}{\nu} \right)^{1/2} Sc^{1/3} \quad [\text{Eq.6}]$$

For RDE, turbulent flow³, $Re_r > 200,000$

$$K_m = 0.02 \frac{D}{r} \left(\frac{\omega r^2}{\nu} \right)^{0.8} Sc^{1/3} \quad [\text{Eq.7}]$$

For RCE, laminar flow³, $Re_d (4\omega r^2/\nu) < 200$

$$K_m = 1.178 \frac{D}{r} \left(\frac{\omega r^2}{\nu} \right)^{0.64} Sc^{1/3} \quad [\text{Eq.8}]$$

For RCE, turbulent flow³, $Re_d > 200$

$$K_m = 0.104 \frac{D}{r} \left(\frac{\omega r^2}{\nu} \right)^{0.7} Sc^{0.356} \quad [\text{Eq.9}]$$

For RHE, laminar flow⁴, $Re_r < 30,000$

$$K_m = 0.474 \frac{D}{r} \left(\frac{\omega r^2}{\nu} \right)^{1/2} Sc^{1/3} \quad [\text{Eq.10}]$$

For RHE, turbulent flow⁴, $Re_r > 30,000$

$$K_m = 0.0198 \frac{D}{r} \left(\frac{\omega r^2}{\nu} \right)^{0.8} Sc^{1/3} \quad [\text{Eq.11}]$$

As an example, Figure 8 depicts the K_m value of RDE, RCE, and RHE for rotating speed up to 4,000 rpm. Equation 6, 9, and 10 were used to compute the K_m value of RDE, RCE, and RHE, respectively. Equation 9 was used for RCE.

This is because the Reynolds number of RCE corresponding to the rotating speed plotted on Figure 8 exceeds 200.

The diffusivity (D) used is 10^{-5} cm²/s, the kinematic viscosity (ν) is 0.01 cm²/s, and the Schmidt number (Sc) is 1000. For a given electrode rotating speed, RCE gave the highest K_m value, RHE gave the lowest K_m value.

Correlation of K_m value of each pin as a function of V and X_c

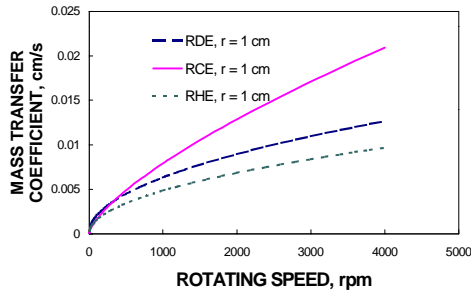


Figure 8 Plot of the mass transfer coefficient of RDE, RCE, and RHE as a function of electrode rotating speed.

The K_m value of each pin was correlated using the method used for a continuous moving strip². At a given line speed (V), the K_m of each pin is expressed as a function of X_c , the pin location. This is giving in Equation 12.

[Eq.12]

Figure 9, is a log/log plot of K_m versus X_c . A line with intercept (c) and slope (d) was obtained for each line speed (V). These lines are plotted in Figure 9. The c and d in equation 12, were

$$K_m = e^c X_c^d, \text{ or}$$

$$\log(K_m) = \frac{c}{2.303} + d \log(X_c)$$

then correlated as a linear function of V as shown Equation 13.

$$\begin{aligned} c &= c_1 + c_2 V & \text{and} \\ d &= d_1 + d_2 V \end{aligned}$$

[Eq.13]

Constants c_1 , c_2 , d_1 , and d_2 were obtained for different values of L, the distance between pins. Averaged value of c_1 , c_2 , d_1 , and d_2 were used. Substituting the c and d from equation 13 into equation 12, the K_m is expressed as a function of V and X_c .

[Eq. 14]

$$K_m = 10^{(c_1 + c_2 V)} X_c^{(d_1 + d_2 V)}$$

Here

$$\begin{aligned} c_1: & -0.8133 \\ c_2: & 0.0175 \\ d_1: & 0.4654 \\ d_2: & -0.0124 \end{aligned}$$

The above equation was correlated from the computer model with diffusivity of 1×10^{-2} cm²/s.

Check fitness of correlated equation

To check the accuracy of equation 14, K_m values calculated using equation 14 were compared to K_m values derived from the model. Figure 9 is a

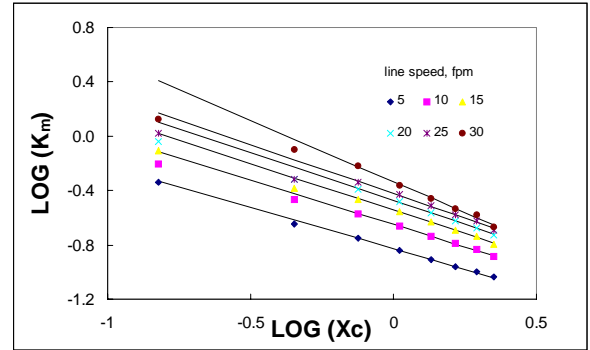


Figure 9 The plot of logarithmic K_m as a function of logarithmic X.

plot of the model K_m values versus the K_m value calculated using equation 14 at different L, V, and X_c . A total of 144 data are plotted in Figure 10 with L ranging from 0.2 to 0.8 cm, V from 5 to 30 fpm, and X_c from 0.15 to 6 cm. For a perfect fit, data points should be located on the diagonal. Using the constant values listed above; Equation 14 gives a good approximation of the K_m value, but not an accurate prediction.

Equivalent rotating speed of RDE, RCE, and RHE

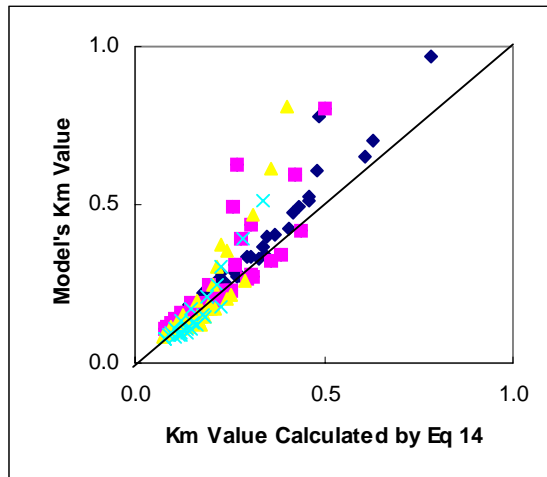


Figure 10 Plot of model's K_m value against the K_m value calculated by Equation .

The equivalent rotating speed of RDE, RCE, and RHE can be calculated from equation 14, and equation 6 – 11. An example of the calculation procedure is given as follows:

1. Calculate the K_m from equation 14 as a function of line speed (V) by knowing the pin location ($X_c = 5$ cm)
2. Substitute the radius of rotating electrode (r , 1 cm), diffusivity (D , 10^{-2} cm²/s), the kinematic viscosity (ν , 0.01 cm²/s), and the Schmidt number (Sc , 1) into equations 6 – 11.
3. Solve the equivalent rotating speed by substitute the K_m value obtained from step 1 into equation 6 – 11.

The calculated results are plotted in Figure 11. The equivalent rotating speeds of RDE, RCE, and RHE are in the range of 400-1,600 rpm for a line speed of 5 –30 fpm.

Summary

Reel-to-reel plating is commonly used in electronic component plating processes. In order to apply laboratory result to production processes, the mass transfer rate used in the laboratory should match the mass transfer rate of the production process. Two computer models were built for this purpose. One was an array of eight square pins in a channel cell. The other was a single square pin in a channel cell. Commercially available software was used to calculate the mass transfer rate on pins at various

line speed, pin spacing, and pin location. The mass transfer rate of the pin increased as the line speed increased. Pins spaced further apart are more sensitive to line speed changes than closely spaced pins. The averaged mass transfer rate of pins was correlated as a function of line spacing and pin location. This correlation was used to estimate the equivalent rotating speeds of RDE, RCE, and RHE for a given line speed.

References

1. J.G. Donaldson, "Continuous Strip Plating of Electronic Components," in *Metal Finishing - 62nd Guidebook and Directory*

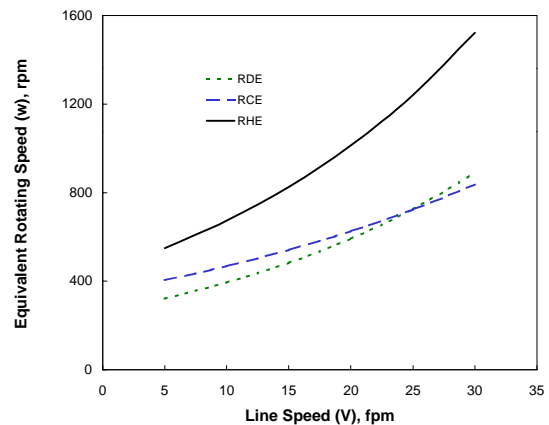


Figure 11 Plot of equivalent rotating speed of RDE, RCE, and RHE against the line speed.

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2. D-T. Chin, *J. Electrochem. Soc.*, vol. 122, no.5 1975, p.643
3. D.R.Gabe and F.C. Walsh, *J. Appl. Electrochem.*, vol.13, 1983, p.3
4. D-T. Chin, *Advances in Electrochemical Science and Engineering*, VCH Verlagsgesellschaft, Weinheim, Germany, 1990, p.172.
5. FIDAP, a computer program released by Fluent Inc.

Nomenclature

a_1	Constant	cm/s
a_2	Constant	1/s
a_3	Constant	----
a_4	Constant	1/cm
c	intercept in Eq. 12	----

c_1	constant in Eq. 13	----
c_2	constant in Eq. 13	min/ft
C_b	Bulk concentration of the electrochemical active species	g/cm^3
C_s	Concentration of the electrochemical active species on the pin surface	g/cm^3
d	slope in Eq. 12	----
d_1	constant in Eq. 13	----
d_2	constant in Eq. 13	min/ft
D	Species diffusivity	cm^2/s
j_m	Mass flux of the species on the pin	$\text{g/cm}^2.\text{s}$
k_m	Local mass transfer coefficient	cm/s
K_m	Average mass transfer coefficient	cm/s
L	Cell length, equivalent to pin centerline-to-centerline	cm
l	Pin length	cm
r	radius of rotating electrode	cm
Re_d	Reynolds number with the electrode diameter as the critical dimension	----
Re_r	Reynolds number with the electrode radius as the critical dimension	----
Sc	Schmidt number, D/v	----
v	Pin moving speed, equivalent to line speed or wall velocity in the model	cm/s
X_c	pin location measured from the inlet	cm
ν	kinematic viscosity	cm^2/s
ω	Rotating speed of electrode	rad/s