Size Effect on Dynamic Behavior of Dross in Model Hot Dip Plating Bath

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The motions of top and bottom dross with different diameters in hot dip plating baths were investigated using a transparent cold model vessel with a reduced scale of one-tenth. Polystyrene particles of the same density and diameter were used as models both for the top and bottom dross, and NaCl aqueous solutions with different densities were used as models for the plating melts. The typical streak lines of the top and bottom dross model particles were nearly the same as the main stream lines in the model bath regardless of the dross diameter. The top and bottom dross model particles were enriched in the region enclosed with the belt. Some of the model particles were trapped in the clearances between the sink roll and the belt. As the dross diameter became large, the number of top dross model particles floating on the bath surface increased and that of bottom dross model particles staying on the bottom wall increased.

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Keywords: hot dip plating bath, top dross, bottom dross, cold model, Froude number, streak line, particle frequency, particle holdup

1. Introduction

Intermetallic compounds and oxides, usually called dross, are generated in a continuous hot dip plating bath through chemical reactions between the plating melts, strips and oxygen in the atmosphere.1-16) There are two types of dross; chemical reactions between the plating melts, strips and are generated in a continuous hot dip plating bath through1-16) There are two types of dross; chemical reactions between the plating melts, strips and

2. Experiment

2.1 Concept of model design

Although details of two dynamic similarity laws used for model design are given in the previous paper,7) some important aspects of them are reproduced here for a better understanding of the flow field considered. The dynamic similitude for the fluid flow phenomena between a real hot dip plating bath and its cold model bath is given by the following Reynolds number.6)

\[ \text{Re} = \rho_L \nu_s / \mu_L \]  \hspace{1cm} (1)

where \( \rho_L \) is the density of the plating melt, \( L \) is the characteristic length, \( \nu_s \) is the strip velocity, \( \mu_L \) is the viscosity of the plating melt. The sink roll diameter was chosen as the characteristic length, \( L \). The Reynolds number in the model was decided to be the order of magnitude of \( 10^3 \) as the flow in the bath is turbulent.

Concerning a real hot dip plating bath, the physical properties of the melt is fixed and the diameters and densities of the top and bottom dross are different. However, it should be noted that in this model experiment polystyrene particles with a mean diameter, \( d_p \), of 1.0 mm and a density, \( \rho_p \), of \( 1.05 \times 10^3 \) kg/m\(^3\) are used as models both for the top and bottom dross. The size and density of the model particles therefore were fixed regardless of the type of dross. NaCl aqueous solutions with different densities were chosen as the models for the plating melts. The density of the NaCl aqueous solution was changed depending on the type of dross.

The following modified Froude number was employed to provide a dynamic similitude for the determination of the density of the model liquids.

\[ \text{Fr} = \rho_p v_s^2 / (\Delta \rho g) \]  \hspace{1cm} (2)

where \( \Delta \rho \) is the density difference between the dross and the plating melt, \( g \) is the acceleration due to gravity.
Table 1 The densities of model working fluids.

<table>
<thead>
<tr>
<th></th>
<th>Cold model</th>
<th>Real process</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$d_{pM}$</td>
<td>$\rho_{pM}$</td>
</tr>
<tr>
<td>Top dross</td>
<td>1.0</td>
<td>1.05 x 10^3</td>
</tr>
<tr>
<td>particle</td>
<td>1.0</td>
<td>1.05 x 10^3</td>
</tr>
</tbody>
</table>

Table 2 Main specifications of cold model.

<table>
<thead>
<tr>
<th></th>
<th>Top roll</th>
<th>Belt</th>
<th>Vessel</th>
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<tr>
<td></td>
<td>$\phi 70$ mm $\times$ 210 mm</td>
<td>10.0 mm $\times$ 120 mm</td>
<td>0.5 mm $\times$ w410 mm $\times$ D310 mm $\times$ H229 mm</td>
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$\rho_{p}$ is the diameter of dross, and the strip velocity, $v_s$, is used as the characteristic velocity.

Equation (2) gives the following relation between a real process and its model.

$$\Delta \rho_M/\rho_{pM} = (\Delta \rho_R/\rho_{pR})(m_t/v_M)^3(d_pR/d_pM)$$

(3)

where the subscripts M and R designate the model and real processes, respectively. Fe$_2$Al$_3$ and FeZn$_7$ were chosen as representative top and bottom dross, respectively. The density of Fe$_2$Al$_3$ is $4.2 \times 10^3$ kg/m$^3$ and that of FeZn$_7$ is $7.25 \times 10^3$ kg/m$^3$. By referring to previous investigations, the diameters of the top dross, $d_{pR}$, were assumed to be 40, 60 and 100 $\mu$m and those of the bottom dross were assumed to be 60, 150 and 300 $\mu$m.

Substitution of the diameters and densities of the top dross, bottom dross, model particles and plating melt (molten zinc) into eq. (3) gives the densities of the model working fluids, as shown in Table 1. The densities of the model working fluids, $\rho_{pM}$, were 1.06 $\times$ 10$^3$, 1.07 $\times$ 10$^3$ and 1.08 $\times$ 10$^3$ kg/m$^3$ for the top dross of $d_{pR}$ = 40, 60 and 100 $\mu$m, respectively. Those for the bottom dross of $d_{pR}$ = 60, 150 and 300 $\mu$m were 1.04 $\times$ 10$^3$, 1.03 $\times$ 10$^3$ and 1.02 $\times$ 10$^3$ kg/m$^3$, respectively. Accordingly, 8.6%, 10.0%, and 11.5% NaCl aqueous solutions were used for the top dross model particle measurements and 6.0%, 4.5%, and 3.0% NaCl aqueous solutions were used for the bottom dross model particle measurements.

2.2 Experimental apparatus

Figure 1 shows a schematic of the experimental apparatus. The main specifications of the cold model are shown in Figure 2. A sink roll was placed in a transparent acrylic vessel. An endless belt was driven by two driving rolls. The origin of the Cartesian coordinate system (x,y,z) was placed at one of the corners of the vessel. The flow field in the bath was divided into three regions as mentioned in the previous paper, the entry region, the exit region, and the region enclosed with the belt. The belt velocity, $v_{IM}$, was set at 1.5 m/s.

Model particles of 32 g in mass were fed into the bath from the bath surface in the entry region for every measurement. This amount of model particles were chosen so that the measurements of streak lines, particle frequency and particle holdup could be carried out with sufficient accuracy.

2.3 Streak line measurement

A streak line is defined as the line on which lie model dross particles that at some earlier instant passed through a certain point in the bath. In other words, the resulting particle trail is called the streak line. The streak lines of model particles were observed using a high-speed video camera at 200 frames per second.

2.4 Measurement of local particle frequency and local particle holdup

The particle frequency, $f_p$, and particle holdup, $\alpha_p$, can be calculated from the following equations (see Fig. 2).

$$f_p = N/t_M (Hz)$$

$$\alpha_p = (\Sigma I_p/t_M) \times 100(\%)$$

where $N$ is the number of particles crossing the laser beam of the particle detection sensor which is already shown in Fig. 1. $t_M$ is the total measurement time and $t_{pi}$ is the time duration for the i-th particle to cross the beam. The distance between the light source and the detector, the sampling frequency of the output signal and the total measurement time $t_M$, were set at 20 mm, 5 kHz and 2 min, respectively. The accuracy of the present measurement method is given in the previous paper. It should be stressed that the measurements were carried out
after the flow in the bath became steady.

It should be noted that when both the particle frequency, \( f_p \), and particle holdup, \( \alpha_p \), are high at a measurement position, many dross particles pass there slowly. Namely, the dross particles are enriched around there.

3. Experimental Results and Discussion

3.1 Typical streak lines

3.1.1 Top dross model particles in the entry and exit regions

Some typical streak lines of top dross model particles for \( d_{pR} = 60 \mu m \) and \( \nu_{M} = 1.5 \text{ m/s} \) are reproduced from the previous paper \(^7\) and shown in Fig. 3. The most definite streak line is denoted by \( a_T \), where the subscript \( T \) designates the top dross model particle. The streak lines denoted by \( b_T, c_T \) and \( d_T \) are also pronounced. These streak lines are similar to the main stream lines reported in the previous paper. \(^5\)

The streak lines of top dross model particles for \( d_{pR} = 40 \mu m \) and \( 100 \mu m \) were approximately the same as those shown in Fig. 3. Since the density of the top dross model particle was slightly smaller than that of the NaCl aqueous solution, many top dross model particles gathered on the two parts of the bath surface denoted by \( A \) and \( B \).

3.1.2 Bottom dross model particles in the entry and exit regions

Some typical streak lines of bottom dross model particles for \( d_{pR} = 60 \mu m \) in the NaCl aqueous solution of \( \rho_{LM} = 1.04 \text{ g/cm}^3 \) are also reproduced from the previous paper \(^7\) and shown in Fig. 4. The main streak lines denoted by \( a_B, b_B, c_B \), and \( d_B \) are approximately the same as the main stream lines mentioned above, where the subscript \( B \) designates the bottom dross model particle. As the density of the bottom dross model particle was slightly larger than that of the NaCl aqueous solution, many bottom dross model particles stayed on the bottom wall and some of them were frequently lifted up, \( i.e. \), ejected into the bulk of the bath, \(^4,5\) as indicated by the solid lines \( b_{B3}, b_{B4} \) and \( b_{B5} \).

Some typical streak lines of bottom dross model particles for \( d_{pR} = 150 \) and \( 300 \mu m \) are shown in Fig. 5. These streak lines are approximately the same as the streak lines shown in Fig. 4. Compared with Fig. 4, however, the number of particles lifted from the bottom wall decreased appreciably but that of particles staying on the bottom wall increased. Bottom dross model particles were hardly observed in the central part of the bottom wall.

3.1.3 Top and bottom dross model particles in the region enclosed with belt

Top and bottom dross model particles are most likely to gather in the region enclosed with the belt. The number of dross model particles in this region increased as the belt velocity, \( \nu_{M} \), increased. \(^7\) The typical streak lines of the top and bottom dross model particles in this region were very similar to the stream lines shown in Fig. 6. The stream lines shown in Fig. 6 were labeled with \( d, g, h, i, j, k, l, m \) and \( n \). The arrows denote the direction of flow. In addition, these streak lines were found to be hardly dependent on the diameter of the dross, \( d_{pR} \).

It is interesting to note that both the top and bottom dross model particles are carried deep into the clearances between the belt and the sink roll. The possibility that the dross particles are captured in the clearances is considerably high.
We therefore investigated the motions of the dross model particles moving in the two clearances more in detail.

The typical motions of top and bottom dross model particles in the two clearances were observed with a high-speed video camera in the middle plane of $y = 151$ mm. The results of the motions of the top and bottom dross model particles are schematically shown in Figs. 7 and 8, respectively. The time interval between successive particle images was the same. The velocity of a top dross model particle entering the clearance on the entry side decreased as it approached the bottom of the clearance, as shown in Fig. 7(a). This is because the particle have to move against a pressure rise or an adverse pressure gradient in the clearance. On the other hand, the velocity of a bottom dross model particle entering the clearance on the entry side hardly decreased, as shown in Fig. 8(a), because the density of the bottom dross model particles was larger than the NaCl aqueous solution. The streak lines of top and bottom dross model particles on the exit side clearance were approximately the same, as shown in Figs. 7(b) and (c) and Figs. 8(b) and (c). The velocity of a model particle entering the clearance on the exit side was considerably lower than that in the clearance on the entry side. The adhesion of the top and bottom dross model particles to the belt took place in the two clearances regardless of the dross diameter.

Both the top dross particles and bottom dross particles entered into the clearance between the sink roll and the belt. The velocity of the top dross particle entering the clearance on the entry side was different from that of the bottom dross particle.

3.2 Contour lines of particle frequency $f_p$ and particle holdup $\alpha_p$

3.2.1 Top dross model particle

The contour lines of particle frequency, $f_p$, of top dross model particles for $d_{p_t} = 40, 60$ and $100\mu m$ in the middle plane of $y = 151$ mm are shown in Figs. 9, 10 and 11, respectively. Data could not be obtained in the regions designed by white color mainly due to experimental difficulty. The distributions of particle frequency, $f_p$, were approximately the same regardless of the diameter of the top dross, $d_{p_t}$. The particle frequency, $f_p$, is eventually high near the belt in every figure, implying that many top dross model particles move along the streak line indicated by $a_T$ in Fig. 3.
In the region enclosed with the belt, the measured $f_p$ values are very high compared with those in other regions. This is because the model particles trapped once in this region are difficult to escape from there before a steady state is established.

The experimental results of particle holdup, $\alpha_p$, for $d_{pR} = 60\,\mu m$ in the middle plane of $y = 151\,mm$ are shown in Fig. 12. The measured $\alpha_p$ values are high in the lower part of the exit region, in the region enclosed with the belt, and in the left-half part of the entry region. The three sub-regions designated by $F_1, F_2$, and $F_3$ in the left part of the entry region are regarded as stagnant regions.

The contour lines of particle holdup, $\alpha_p$, for $d_{pR} = 40$ and $100\,\mu m$ in the middle plane of $y = 151\,mm$ are shown in Figs. 13 and 14, respectively. The stagnant regions shown in

![Fig. 9](image_url) Contour lines of particle frequency for top dross model particles ($d_{pR} = 40\,\mu m$).

![Fig. 10](image_url) Contour lines of particle frequency for top dross model particles ($d_{pR} = 60\,\mu m$).

![Fig. 11](image_url) Contour lines of particle frequency for top dross model particles ($d_{pR} = 100\,\mu m$).

![Fig. 12](image_url) Contour lines of particle holdup for top dross model particles ($d_{pR} = 60\,\mu m$).

![Fig. 13](image_url) Contour lines of particle holdup for top dross model particles ($d_{pR} = 40\,\mu m$).

![Fig. 14](image_url) Contour lines of particle holdup for top dross model particles ($d_{pR} = 100\,\mu m$).
Fig. 12 cannot be seen and the measured $\alpha_p$ values in the whole bath were lower than those for $d_{pR} = 60\,\mu m$. At a glance, this result seems strange. The reason can be explained as follows: Under the present experimental conditions the relaxation time of a model particle is expressed by

$$\tau = \rho_{pM}d_{pM}(\rho_{LM} + \rho_{pM}/2)/(18v_{LM})$$

(6)

where $v_{LM}$ is the kinematic viscosity of the NaCl aqueous solution. The relaxation time is a measure for the response time of a particle to a change in liquid flow velocity around it. In eq. (6) $\rho_{pM}$ and $d_{pM}$ are fixed, $\rho_{LM}$ is lower for $d_{pR} = 40\,\mu m$ than for $d_{pR} = 60\,\mu m$, and $v_{LM}$ is higher for $d_{pR} = 40\,\mu m$ than for $d_{pR} = 60\,\mu m$. This fact means that the relaxation time is shorter for $d_{pR} = 40\,\mu m$ than for $d_{pR} = 60\,\mu m$. Accordingly, the top dross model particles for $d_{pR} = 40\,\mu m$ respond to a change in the liquid velocity more quickly than those for $d_{pR} = 60\,\mu m$. Therefore, top dross model particles for $d_{pR} = 40\,\mu m$ are less captured in the stagnant regions (F1, F2, and F3) than those for $d_{pR} = 60\,\mu m$.

On the other hand, the buoyancy force acting on a top dross model particle is expressed by

$$F_B = (\pi/6)(\rho_{LM} - \rho_{pM})gd_{pM}^3$$

(7)

This force increases as the density difference, $(\rho_{LM} - \rho_{pM})$, increases. Accordingly, particles for $d_{pR} = 100\,\mu m$ are more likely to be forced to move vertically upwards than those for $d_{pR} = 60\,\mu m$ and are not able to stay in the stagnant regions (F1, F2, and F3).

The spatial mean values of $f_p$, denoted by $f_{pm}$, were calculated for the three regions in the middle plane of $y = 151\,mm$ to find out the regions where the top dross model particles are enriched. The top dross model particles floating on the bath surface were excluded in the calculation. As shown in Figs. 9, 10, and 11, the spatial mean values in the entry region, the exit region, and the region enclosed with the belt were 0.76, 3.3 and 6.5 Hz for $d_{pR} = 60\,\mu m$, 0.67, 2.7 and 5.5 Hz for $d_{pR} = 40\,\mu m$, 0.56, 2.4 and 4.1 Hz for $d_{pR} = 100\,\mu m$, respectively. Accordingly, the top dross model particles of every diameters of dross, $d_{pR}$, are most likely to gather in the last region before a steady state is established. This result is consistent with the finding obtained by flow visualization with the high-speed video camera.

### 3.2.2 Bottom dross model particle

The contour lines of particle frequency, $f_p$, of the bottom dross model particles for $d_{pR} = 60, 150$ and $300\,\mu m$ are shown in Figs. 15, 16 and 17, respectively. The distributions of $f_p$ are similar to those for the top dross model particles shown in Figs. 9 through 11. The spatial distributions of $f_p$ were approximately the same for all the dross diameters, $d_{pR}$. The magnitude of $f_p$, however, became low everywhere in the bath as the $d_{pR}$ became large. The number of bottom dross model particles staying on the bottom wall increased as the $d_{pR}$ increased, because the gravitational force acting on the bottom dross particles increased as $d_{pR}$ increased, as suggested from eq. (7). The mechanism of the formation of these three stagnant regions can not be clearly explained at present. However, the existence of the three stagnant regions is very important because the efficiency of dross removed is lowered.

The contour lines of particle holdup $\alpha_p$, for $d_{pR} = 60\,\mu m$ in the middle plane of $y = 151\,mm$ are shown in Fig. 18. The particle holdup, $\alpha_p$, was high in the central part of the exit region, the region enclosed with the belt and three sub-regions in the entry region. Around the sub-regions indicated by E1, E2, and E3 in the entry region, the $\alpha_p$ values were high, whereas the $f_p$ values shown in Fig. 15 were low there.
These regions are also considered to be stagnant regions. The contour lines of the measured $C_1[p]_1$ values for $d_{pR} = 150$ and 300 mm in the middle plane of $y = 151$ mm are shown in Figs. 19 and 20, respectively. The stagnant regions appearing in Fig. 18 cannot be seen and the measured $C_1[p]_1$ values in the whole bath were lower than those for $d_{pR} = 60$ mm through the effect of less buoyancy force acting on the model particles.

Fig. 18 Contour lines of particle holdup for bottom dross model particles ($d_{pR} = 60$ μm).

Fig. 19 Contour lines of particle holdup for bottom dross model particles ($d_{pR} = 150$ μm).

Fig. 20 Contour lines of particle holdup for bottom dross model particles ($d_{pR} = 300$ μm).

The spatial mean values of particle frequency, $f_{pm}$, were calculated for the three regions in the middle plane of $y = 151$ mm to find out the regions where the bottom dross model particles are enriched. The particles staying on the bottom wall were excluded in the calculation. As shown in Fig. 15, 16 and 17, the spatial mean values $f_{pm}$ in the entry region, the exit region, and the region enclosed with the belt were 0.76, 2.1 and 7.1 Hz for $d_{pR} = 60$ μm, 0.32, 0.89 and 2.5 Hz for $d_{pR} = 150$ μm, 0.07, 0.19 and 0.87 Hz for $d_{pR} = 300$ μm, respectively. Accordingly, bottom dross model particles of every diameters of dross, $d_{pR}$, are most likely to gather in the last region before a steady state is established just like the top dross model particles.

Judging from the present model experiments, it can be concluded that both the top and bottom dross in a real hot dip plating bath are likely to gather in the region enclosed with the strip regardless of the dross diameter. Kurihara et al. reported that the dross in real processes were abundant in the region enclosed with the strip. In the case of top dross, the dross of $d_{pR} = 60$ mm would stay longer in the bulk of the real bath without floating on the bath surface than those of $d_{pR} = 40$ mm and 100 mm. Also, in the case of bottom dross, the dross of $d_{pR} = 60$ mm would stay longer in the bulk of the real bath without sedimentation on the bottom wall than those of $d_{pR} = 150$ mm and 300 mm. Nomura et al. reported that the dross of diameters ranging from 50 to 80 mm are most abundant in the real baths.

4. Conclusions

Main findings obtained in this study can be summarized as follows:

(1) The typical streak lines for the top dross model particles in a model bath were approximately the same as the main stream lines in the bath. Many top dross model particles stayed on the bath surface in the vicinity of the side walls parallel to the belt in the entry and exit regions, as shown in Fig. 3.

(2) The typical streak lines for the bottom dross model particles were also approximately the same as the main stream lines in the bath. Many bottom dross particles stayed on the bottom wall under the sink roll and in the entry region. The number of particles staying on the bottom wall in the entry region increased and the particles moving in the bulk of the bath decreased as the dross diameter became large.

(3) The typical streak lines for the top and bottom dross model particles in the region enclosed with the belt were approximately the same regardless of the dross diameter. These streak lines were very close to the main stream lines in this region. The model particles were often carried deep into the two clearances between the belt and the sink roll, and some of them were caught in the two clearances. This may be one of the main causes for the adhesion of the dross to the strip in a real hot dip plating bath.

(4) The particle frequency, $f_p$, of the top dross model particles was hardly dependent on the dross diameter. The top dross model particles for $d_{pR} = 60$ μm were captured in the stagnant regions (F1, F2, and F3) in the
entry region. However, those for \( d_{pR} \) of 40 and 100\( \mu \)m were hardly captured in these regions.

(5) The particle frequency, \( f_p \), of the bottom dross model particles became low as the dross diameter, \( d_{pR} \), increased. Many bottom dross model particles for \( d_{pR} = 60\mu \)m were entrapped in the stagnant regions (\( E_1, E_2 \), and \( E_3 \)) in the entry region. However, the entrapment of bottom dross particles of \( d_{pR} = 150 \) and 300\( \mu \)m in the stagnant regions was not observed.

(6) Both the top and bottom dross model particles were most likely to gather in the region enclosed with the belt regardless of the dross diameter.

REFERENCES