Cold model experiment on dynamic behavior of dross in hot dip plating bath

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Abstract

The motions of top and bottom dross in a continuous hot dip plating bath were investigated using a transparent cold model vessel with a reduced scale of one-tenth. The flow field in the model bath was classified into three regions as usual; the entry region, the exit region, and the region enclosed with a belt. This belt was used as a model for a strip. Polystyrene particles were used as models both for the top and bottom dross while NaCl aqueous solutions of different densities were used as models for plating melts. The motions of model particles were observed by eye inspection and by using a high-speed video camera. Local particle frequency and particle holdup were measured with a newly developed sensor. Typical streak lines for the top and bottom dross particles were similar to main stream lines in the bath. Both the top and bottom dross particles were rich in the region enclosed with the belt. A lot of top dross particles floated on the bath surface near the side walls, while many bottom dross particles stayed on the bottom wall in the entry region. © 2001 Elsevier Science Ltd. All rights reserved. 

Keywords: Hot dip plating bath; Top dross; Bottom dross; Cold model; Froude number; Streak line; Stream line; Particle frequency; Particle holdup; Strip compositions of the plating melts. The compositions are varied over a wide range.

1. Introduction

Many kinds of intermetallic compounds and oxides called dross are formed in a continuous hot dip plating bath due to chemical reactions between plating melts and strips and those between the melts and atmosphere. The dross thus generated are usually classified into two types; top dross and bottom dross. The density of any kind of top dross is smaller than the plating melt density while the density of any kind of bottom dross is larger than the plating melt density.

The quality of hot dip plated steel sheets is significantly lowered by the adhesion of the two sorts of dross to the steel sheets. The motions of top and bottom dross are closely associated with fluid flow phenomena in the plating bath and the density difference between the dross and plating melt, i.e. molten zinc. Information on the effects of these parameters on the motions of the top and bottom dross is, however, very limited [1–4]. This is mainly because the plating melts are opaque and the dross formation in real hot dip plating baths is strongly dependent on the chemical
and the fraction of the residence time of the particles at that position were measured with a newly developed sensor.

2. Experiment

2.1. Concept of model design

The following Reynolds number was used to provide a dynamic similitude between the fluid flows in a real hot dip plating bath and its cold model bath:

\[ Re = \frac{\rho_L v L}{\mu_L} \]  

(1)

where \( \rho_L \) is the density of the plating melt, \( L \) a characteristic length, \( v \) the strip velocity, \( \mu_L \) the viscosity of the plating melt. The diameter of the sink roll was chosen as the characteristic length \( L \). It is eventually difficult to let the Reynolds number for the model coincide with that for the real bath due to very high strip velocity. However, the relaxation of the dynamic similitude is allowed because the flow in the one-tenth cold model is turbulent [5]. On the basis of Eq. (1) and the relaxation, the Reynolds number in this model was decided to be the order of magnitude of 10^3.

Polystyrene particles were used as models both for the top and bottom dross, while NaCl aqueous solutions of different densities were chosen as models for the plating melts. The following modified Froude number was employed to provide a dynamic similitude for determining the size and density of the model particles and the density of the model liquids:

\[ Fr = \frac{\rho_L v^2}{\rho_p g} \]  

(2)

where \( \Delta \rho = \rho_p - \rho_L \) is the density difference between the dross and the plating melt, \( g \) the acceleration due to gravity and \( d_p \) the diameter of the dross.

Eq. (2) gives the following relation:

\[ \Delta \rho d_p / \rho_M = (\Delta \rho / \rho_M) (v_M / v_R)^2 (d_p / d_M) \]  

(3)

where the subscripts M and R designate the model and real processes, respectively. Eq. (3) is used to determine the densities of the models for the dross and plating melt.

Polystyrene particles with a mean diameter of 1.0 mm and a density of 1.05 g/cm^3 were used as models both for the top and bottom dross. Hereafter, the model particles for the top and bottom dross are called top dross particles and bottom dross particles, respectively. The size and density of the model particle, therefore, were fixed regardless of the sort of dross, while the density of the model liquid or NaCl aqueous solution was changed depending on the sort of dross.

Information on the chemical compositions of the two sorts of dross in real hot dip plating baths is available [6–13]. Among four sorts of dross known to date, Fe_2Al_5 and FeZn_7 were chosen as representative top and bottom dross, respectively. The densities of them are 4.2 and 7.25 g/cm^3 for Fe_2Al_5 and FeZn_7, respectively [14,15]. The two sorts of dross were assumed to be spherical in shape. By referring to previous investigations [12], the characteristic diameters of the real top and bottom dross were reasonably assumed to be 60 \( \mu \)m.

Substitution of \( d_p = 60 \mu \)m and the physical properties of the top dross, bottom dross and molten zinc into Eq. (3) gives the density of the model working fluid \( \rho_M \) of 1.07 g/cm^3 for the top dross particles and 1.04 g/cm^3 for the bottom dross particles. Accordingly, 10 and 6% NaCl aqueous solutions were used for the measurements. The temperatures of the NaCl aqueous solutions were controlled to be the same before and after the measurements.

2.2. Experimental apparatus

Fig. 1 shows a schematic of the experimental apparatus. The main specifications of the cold model are shown in Table 1. A sink roll was placed in the transparent acrylic vessel. An endless belt was driven by means of two driving
rolls. This apparatus was settled on an aluminum bed. The origin of the Cartesian coordinate system \((x,y,z)\) was placed at one of the corners of the vessel as shown in the figure. The flow field in the bath was divided, for convenience, into three regions as usual [5]: the entry region, the exit region, and the region enclosed with the belt. The belt velocity \(v_M\) was set at 0.75, 1.0, and 1.5 m/s based on the Reynolds number similitude.

### 2.3. Measurements of the motion of particle, local particle frequency and local particle holdup

A predetermined total volume of particles were supplied from the surface of the entry region. The motions of particles in the bath were observed after the flow became steady by eye inspection and using a high-speed video camera. The number of particles crossing a short beam for one second \(f_p\), and the fraction of residence time of the particles at the beam, \(\alpha_p\), were measured using a newly developed sensor. We defined \(f_p\) and \(\alpha_p\) as particle frequency and particle holdup, respectively. In what follows, only the distributions of \(f_p\) and \(\alpha_p\) are important because the magnitudes of them are dependent on the total volume of particles.

The detection unit of the measurement system is also schematically shown in Fig. 1. The distance between the light source and detector immersed in the bath was set at 20 mm. This system works through the photoelectric effect. When a particle crosses the laser beam of 1 mm in diameter, the output signal drops abruptly from 10 V to a very low level (see Fig. 2). After the passage of the particle, the output voltage immediately returns to its original value of 10 V. Therefore, when the output voltage becomes smaller than a threshold voltage, we can judge that a particle crosses the beam. The threshold value was set at 5 V. The output signal was digitized at a sampling frequency of 5 kHz with an A/D converter for 2 min at every measurement position.

The particle frequency \(f_p\) is readily obtained by counting the number of particles crossing the beam for 1 s and the particle holdup \(\alpha_p\) is calculated from the following equation:

\[
\alpha_p = \left( \frac{\sum t_{pi}}{t_M} \right) \times 100 \ (\%)
\]

where \(t_{pi}\) is the time duration for the \(i\)th particle to cross the beam and \(t_M\) the total measurement time as shown in Fig. 2. The accuracy of this measurement system was examined as follows: the particle frequency \(f_p\) and particle holdup \(\alpha_p\) were measured by letting particles of the prescribed number cross the beam at a constant velocity. A turn-table equipped
with a rod supporting a spherical particle of 1 mm in diameter was used for this purpose. The measurement time was 2 min and the sampling frequency was 5 kHz. The measured values of the particle frequency and particle holdup were compared with the prescribed values, as shown in Figs. 3 and 4, respectively. The subscripts e and c designate the measured and calculated values, respectively. In each figure, the measured values are in good agreement with the prescribed values within a scatter of ±20%.

3. Experimental results and discussion

3.1. Typical streak lines

3.1.1. Top dross particles in the entry and exit regions

A streak line is defined as the trail of particles passed through a point in the bath. Some streak lines typical of the top dross particles for \( v_{SM} = 1.5 \) m/s are shown in Fig. 5. They are very similar to the main stream lines in the bath illustrated in the previous paper [5]. In addition, the main streak lines for the three belt velocities of 0.75, 1.0 and 1.5 m/s are approximately the same, although the evidence is not given here. As the density of the top dross particles is slightly smaller than that of the NaCl aqueous solution, many top dross particles stayed on the two parts of the bath surface denoted by A and B. Accordingly, the removal of dross should be made there. The most definite streak line is denoted by \( a_T \), where the subscript T denotes the top dross particle. A streak line for top dross particles moving from the exit region back to the entry region along the side and bottom walls is also very definite and hence it is denoted by \( b_T \). Some of the top dross particles moving along the streak

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**Fig. 7.** Typical streak lines for bottom dross particles for \( v_{SM} = 1.0 \) and 0.75 m/s.

**Fig. 8.** Flow pattern in the region enclosed with belt.

**Fig. 9.** Scatter of particle frequency data \((y = 151 \text{ mm}, \ v_{SM} = 1.5 \text{ m/s})\).

**Fig. 10.** Scatter of particle holdup data \((y = 151 \text{ mm}, \ v_{SM} = 1.5 \text{ m/s})\).
line $b_T$ were engulfed into the inner part of the bath as illustrated by $b_{T2}$, $b_{T3}$, $b_{T4}$ and $b_{T5}$. In addition, the streak lines indicated by $c_T$ and $d_T$ are pronounced.

3.1.2. Bottom dross particles in the entry and exit regions

Some streak lines typical of the bottom dross particles for $v_{SM} = 1.5$ m/s are shown in Fig. 6. The streak lines denoted by $a_B$, $b_B$, $c_B$, and $d_B$ are also similar to the main streak lines mentioned above, where the subscript B denotes the bottom dross particle. As the density of the bottom dross particles is slightly larger than that of the NaCl aqueous solution, many bottom dross particles stay on the two parts of the bottom wall denoted by C and D. Some of them were frequently lifted up, i.e. ejected in the inner part of the bath as drawn by the three lines denoted by $b_{B3}$, $b_{B4}$ and $b_{B5}$. The ejection of the bottom dross particles from the bottom of the bath was also reported by other researchers [3,12]. The streak line indicated by $b_{B2}$ separated from the main streak line $a_B$, passed near the side wall perpendicular to the belt and finally reached the bottom wall.

Furthermore, the streak lines typical of the bottom dross particles both for $v_{SM} = 1.0$ and 0.75 m/s, which are shown in Fig. 7, are approximately the same as those for $v_{SM} = 1.5$ m/s. The number of lifted particles, however, decreased and hence the number of particles on the bottom wall increased as $v_{SM}$ decreased. Consequently, the number of bottom dross particles moving in the bath varies depending on the belt velocity $v_{SM}$.

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

Main stream lines in the region enclosed with the belt are reproduced from the previous paper [5] and shown in Fig. 8. Although representative streak lines for the top and bottom dross particles are not shown here in order to avoid
Fig. 13. Contour lines of liquid flow velocity \( u_L \) in the bath \((y = 151 \text{ mm}, v_{SM} = 1.5 \text{ m/s})\).

crowding in the figure, they are very similar to the stream lines illustrated in Fig. 8. Furthermore, the streak lines for the three different belt velocities were approximately the same.

It is interesting to note that both the top and bottom dross particles are carried deep into the clearance formed between the belt and the sink roll in the entry region and that between the belt and the sink roll in the exit region by the fluid flows indicated by \( g \) and \( k \). This result suggests that adhesion of top and bottom dross to the strip would take place in the two clearances in real processes. Details of the dynamic behavior of the two sorts of particles will be discussed in a later section.

As shown above, the motions of top and bottom dross particles in the bath are essentially three-dimensional due to the complex flow field considered. Most of the particles are, however, conveyed by the large scale circulating flow driven by the belt.

3.2. Contour lines of particle frequency \( f_p \) and particle holdup \( \alpha_p \)

Measured values of particle frequency \( f_p \) and particle holdup \( \alpha_p \) at representative three measurement positions in the bath for \( v_{SM} = 1.5 \text{ m/s} \) are shown together with error bars in Figs. 9 and 10, respectively. The data on the particle frequency \( f_p \) hardly scattered around a mean value at every measurement position except in the exit region. Large scatter in the exit region can be explained by the fact that particles directed from the entry region towards the exit region are dispersed violently there due to highly turbulent motion. On the other hand, the scatter of particle holdup \( \alpha_p \) for the bottom dross particles is very large in the central part of the bath (position \( m_2 \)). Such large scatter is due to the above-mentioned lift-up or ejection of the bottom dross particles from the bottom of the bath. At the other measurement positions, the scatter is very small.

Fig. 14. Contour lines of moving velocity of top dross particles \((y = 151 \text{ mm}, v_{SM} = 1.5 \text{ m/s})\).
In what follows, discussion will be given separately on the top and bottom dross particles.

3.2.1. Top dross particles

Contour lines of particle frequency \( f_p \) for top dross particles in the middle plane of \( y = 151 \) mm for \( v_{SM} = 1.5 \) m/s is shown in Fig. 11. Data on \( f_p \) could not be obtained in the regions designated by white color mainly because of experimental difficulty. Roughly speaking, the particle frequency \( f_p \) is high near the belt, implying that many top dross particles move along the streak line indicated by \( a_t \) in Fig. 5. In the region enclosed with the belt, the measured \( f_p \) values are very high because the particles trapped once in this region are difficult to escape.

Experimental results of particle holdup \( \alpha_p \) in the middle plane of \( y = 151 \) mm are shown in Fig. 12. The measured \( \alpha_p \) values are high in the exit region and in the region enclosed with the belt just like the \( f_p \) values shown in Fig. 11. In the three regions designated by \( E_1 \), \( E_2 \), and \( E_3 \) in the entry region, the \( \alpha_p \) values are high but the \( f_p \) values are low. These features are typical of the behavior of particles trapped in stagnant regions. The regions \( E_1 \), \( E_2 \) and \( E_3 \) are therefore considered to be stagnant regions. This is partly supported by the mean liquid flow velocity data shown in Fig. 13 [5]. The \( u_l \) values are very low around these three regions.

An ensemble-average value of particle frequency \( f_p \) called a spatial mean particle frequency and denoted by \( f_{pm} \) was determined in every one of the three regions in the middle plane of \( y = 151 \) mm to find out the regions where particles are rich. Top dross particles floating on the bath surface were excluded in the calculation. The \( f_{pm} \) values in the entry region, the exit region, and the region enclosed with the belt were 0.76, 3.3, and 6.5 Hz, respectively. Accordingly, particles are most likely to gather and stay in the last region.

The local particle velocity \( u_p \) can be calculated from the
following equation [16]:

$$u_p = kd_p f_p / \alpha_p$$  \hspace{1cm} (5)

where $k$ is a constant depending on the threshold value for the discrimination of particles, the diameter of the beam, the particle diameter $d_p$, and so on. In this study, $k$ (=0.61) was determined by assuming that all particles cross the beam at right angles.

Calculated $u_p$ values in the middle plane of $y = 151$ mm are shown in Fig. 14. The distribution of $u_p$ in this plane is similar to the mean liquid velocity distribution shown in Fig. 13, although the magnitude of $u_p$ is, of course, smaller than that of $u_l$.

### 3.2.2. Bottom dross particle

Contour lines of particle frequency $f_p$ for bottom dross particles are shown in Fig. 15. The $f_p$ values in the entry region are low while they are high in the exit region and the region enclosed with the belt just like those for the top dross particles.

The particle holdup $\alpha_p$ was high in the lower part of the exit region, the region enclosed with the belt, the vicinity of the bottom wall and the central part of the entry region, as shown in Fig. 16. In the three parts indicated by $F_1$, $F_2$, and $F_3$ in the entry region, $\alpha_p$ is high but $f_p$ is low. These $F_1$, $F_2$, and $F_3$ regions are also regarded as stagnant regions.

The spatial mean values of particle frequency $f_{pm}$ in the entry region, the exit region, and the region enclosed with the belt were 0.76, 2.1, and 7.1 Hz, respectively. The bottom dross particles being at rest on the bottom wall of the vessel were excluded in this calculation. The bottom dross particles also were the richest in the region enclosed with the belt.

Judging from the present model experiments, it can be concluded that both top and bottom dross in a real hot dip plating bath are likely to gather in the region enclosed with the strip. In fact, Kurihara et al. [3] have reported that the dross in real processes is abundant there.

Contour lines of the mean velocity of bottom dross particles $u_p$ are shown in Fig. 17. They are similar to those of top dross particles shown in Fig. 14.

### 3.3. Effects of belt velocity $v_{BM}$ on particle frequency $f_p$ and particle holdup $\alpha_p$

The spatial mean values of $f_p$ and $\alpha_p$, denoted by $f_{pm}$ and $\alpha_{pm}$, in the three regions were calculated for the different three belt velocities to elucidate the effects of the belt velocity $v_{BM}$ on the motions of particles. The $f_{pm}$ values thus determined both for the top and bottom dross particles increased everywhere in the bath as the belt velocity $v_{BM}$ increased (see Fig. 18). In particular, the $f_{pm}$ values in the region enclosed with the belt increased drastically with $v_{BM}$.

The $\alpha_{pm}$ values both for the top and bottom dross

![Fig. 17. Contour lines of moving velocity of bottom dross particles ($y = 151$ mm, $v_{BM} = 1.5$ m/s).](image1)

![Fig. 18. Comparison of the spatial mean values of particle frequency ($y = 151$ mm).](image2)
particles, shown in Fig. 19, increased as the belt velocity $v_{BM}$ increased just like the $f_{pm}$ values shown in Fig. 18.

4. Conclusions

The dynamic behavior of top and bottom dross existing in a real hot dip plating bath was investigated using a cold model with a reduced scale of one-tenth. Streak lines of the two sorts of dross particles, which are models for the top and bottom dross, respectively, were determined using flow visualization techniques. Particle frequency $f_p$ and particle holdup $\alpha_p$ were measured with a newly developed sensor. Main findings obtained in this study can be summarized as follows:

1. Typical streak lines for top dross particles were similar to the main stream lines in the bath. This fact means that most of the top dross particles move along the main stream lines. Because the density of the top dross particles was smaller than that of the NaCl aqueous solution, i.e. the model for the plating melt in the bath, many top dross particles stayed on the bath surface in the vicinity of the side walls in the entry and exit regions, as shown in Fig. 5.

2. Typical streak lines for bottom dross particles were also similar to the main stream lines in the bath. As the density of the bottom dross particles was larger than that of the NaCl aqueous solution, many bottom dross particles stayed on the bottom wall under the sink roll and in the entry region. Some of the bottom dross particles staying on the bottom wall were lifted up nearly periodically, as shown in Fig. 6.

3. Typical streak lines for the top and bottom dross particles in the region enclosed with the belt were approximately the same. In addition, these streak lines were very close to the main stream lines there.

4. In the entry region, some stagnant regions were established both for the top and bottom dross particles. Meanwhile, the two sorts of particles were highly mixed in the exit region.

5. The particle frequency $f_p$ and particle holdup $\alpha_p$ both for the top and bottom dross particles increased as the belt velocity $v_{BM}$ increases. Accordingly, the number of top dross particles staying on the bath surface and the number of bottom dross particles staying on the bottom wall decrease as $v_{BM}$ increases. This is because the turbulent mixing in the bath becomes stronger as $v_{BM}$ increases.

6. Both top and bottom dross particles were most likely to gather in the region enclosed with the belt. Some of them were carried deep into the two clearances between the belt and the sink roll. This is one of main causes for the adhesion of dross to the strip in real processes.

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