Cold Model Experiment on Dispersion of Melted Ingots in Hot Dip Plating Bath

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The dispersion of melted ingots in a continuous hot dip plating bath was investigated using a transparent cold model vessel with a reduced scale of one-tenth. The used tracers were CaCO₃ particles with a mean diameter of 1.0 µm and 5.0 mass% KCl aqueous solution. The dispersion of the CaCO₃ particles in the bath was observed by eye inspection. The mixing time and the local concentration of the two kinds of tracers were measured with an electrical conductivity sensor and a laser beam sensor. The dispersion of the CaCO₃ particles was mainly controlled by the main stream of liquid caused by the motion of the belt in the bath. The mixing time and the local concentration of the tracer were dependent on the measurement position. The mixing time was shortest when the tracer was introduced in the exit region, i.e., the belt out-going region. This fact suggests that the mixing time in the real bath was shortest by introducing ingots into the exit region.

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1. Introduction

In a continuous hot dip galvanizing line, the compositions in the plating melts are controlled by providing Zn or Al ingots. The melted ingots melt and disperse in the whole plating bath with a lapse of time. The rapid dispersion of the ingots is important to homogenize the compositions of the plating melts and to produce the hot dip plated sheets efficiently. The term “dispersion” means the spreading of tracers such as particles in a fluid medium due to diffusion and convection. Furthermore, it is an essential factor for grasping the amount of dross produced through chemical reactions between the plating melts and the steel sheets. Information on the dispersion of melted Zn and Al ingots however is limited at present.¹-³)

Considering these circumstances, in the first paper of this research series we investigated the fundamental fluid flow phenomena in the hot dip plating bath using cold models with a reduced scale of one-fifth and one-tenth.⁴) The flow in the bath was basically three-dimensional and there existed a large scale circulating flow driven by the belt (strip) motion. The flow field in the bath was mainly classified into three regions: the entry region, the exit region and the region enclosed with the belt. The mean flow velocity, the root-mean-square value of the turbulence component and the Reynolds shear stress were highest in the vicinity of the belt in the exit region. The melted ingots would be highly mixed there.

In this study, cold model experiments were carried out to investigate the dispersion of melted Zn ingots in the hot dip plating bath. The experimental apparatus has a reduced scale of one-tenth. The Reynolds number similitude was used to provide the dynamic similitude between the real hot dip plating bath and the cold model bath.

\[ Re = \frac{\rho_L D v_s}{\mu_L} \]  

where \( \rho_L \) is the density of the plating melt, \( L \) is a characteristic length, \( v_s \) is the strip velocity, \( \mu_L \) is the dynamic viscosity of the plating melt. As the characteristic length, \( L \), the diameter of the sink roll, \( D \), was selected in this study. It was difficult to let the Reynolds number for the model coincide with that for the actual bath, so that the dynamic similitude was relaxed because the flow in one-tenth scale cold model bath was turbulent.⁴) On the basis of eq. (1) and this relaxation, the Reynolds number for the model bath was set to be the order of magnitude of \( 10^5 \).

2.2 Experimental apparatus

Figure 1 shows a schematic of the experimental apparatus. Main specifications of the cold model are listed in Table 1. A sink roll was placed in the transparent acrylic vessel. An endless belt was driven by two driving rolls, though they were omitted in Fig. 1 to avoid crowding in the figure. 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 Fig. 1. The flow field in the bath was divided, for convenience, into three regions, as mentioned earlier; the entry region, the exit region, and the region enclosed with the belt.

2.3 Observation of dispersion pattern of tracer particles

We investigated the dispersion of tracers which were used as models for Zn ingots and the mixing time in the bath. The dispersion patterns were observed by eye inspection. The experimental conditions are listed in Table 2. CaCO\(_3\) particles of an amount of 2.0 cm\(^3\) were introduced into the entry region from the geometrically same position as the real bath. The diameter and the density of the CaCO\(_3\) particles were 1.0 \(\mu\)m and 1.77 \(\times 10^3\) kg/m\(^3\), respectively. The CaCO\(_3\) particles were used because they were so small that could follow the liquid motion. Namely, the particles Reynolds number was less than unity. The belt velocity, \(v_{SM}\), was set at 1.5 m/s.

2.4 Definition of mixing time

Many criteria have been proposed to define the mixing time in the steel refining processes.\(^{5–12}\) No one has mentioned the mixing time in a hot dip plating bath. Figure 2 shows the output signal of a probe. The mixing time was defined as the time, \(t\), until the variation of the voltage converged within the range of \(\pm 5.0\%\) around the final voltage. This is called the 95.0\% criterion.

The mixing time was measured in two ways, local mixing time and line-averaged mixing time. A local change in the electrical conductivity of liquid due to arrival of a KCl aqueous solution was measured with an electrical conductivity sensor. The mixing time was determined based on the output signal of the sensor. This mixing time is called the local mixing time, \(T_{m,loc}\). On the other hand, the concentration of CaCO\(_3\) particles in the direction parallel to the sink roll axis was measured with a laser beam sensor which works on the photoelectric effect. Namely, the concentration of CaCO\(_3\) particles in that direction is proportional to the light scattered by the particles distributed in the volume of the laser beam. The mixing time was also obtained by analyzing this signal. The mixing time thus determined was called the line-averaged mixing time, \(T_{m,line}\).

### Table 2 Experimental conditions for observation of dispersion pattern of tracer.

<table>
<thead>
<tr>
<th>Belt velocity</th>
<th>1.5 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracer</td>
<td>CaCO(_3) particle ((\phi 1 \mu m))</td>
</tr>
<tr>
<td>Working liquid</td>
<td>Tap water</td>
</tr>
</tbody>
</table>

2.5 Mixing time measurement

The experimental conditions are listed in Table 3. The line-averaged mixing time, \(T_{m,line}\), was measured with a newly developed measuring system. The light source and the detector was placed outside the cold model vessel.\(^{5,13,14}\) CaCO\(_3\) particles with a mean diameter of 1.0 \(\mu\)m was also used as the tracer, and the amount of the particles was 2.0 cm\(^3\). When the CaCO\(_3\) particles cross the laser beam of a diameter of 1.0 mm, the intensity of laser beam, \(I\), measured with the detector varies in accordance with the concentration of the CaCO\(_3\) particles in the volume of the laser beam. The output voltage was recorded on a pen-recorder. The line-averaged mixing time, \(T_{m,line}\), was determined by analyzing this signal.

The local mixing time, \(T_{m,loc}\), was obtained by analyzing the output signal of the electrical conductivity probe.\(^{15–18}\) A 5.0 mass\%KCl aqueous solution of a density of 1.03 \(\times 10^3\) kg/m\(^3\) was used as the tracer, and it was poured onto the bath surface in the entry region. The amount was 10.0 cm\(^3\). The time constant of the electrical conductivity probe was 0.25 s. The details of the probe are shown in Fig. 3. The local mixing time, \(T_{m,loc}\), was measured on two planes located at \(y = 151\) and 51 mm. The former plane is located in the center of the bath and the latter plane is located near the side wall.

### Table 3 Experimental conditions for measurement of mixing time.

<table>
<thead>
<tr>
<th>Belt velocity</th>
<th>0.75, 1.0, 1.5 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working liquid</td>
<td>Tap water</td>
</tr>
<tr>
<td>Tracer</td>
<td>CaCO(_3) particle ((\phi 1 \mu m))</td>
</tr>
<tr>
<td></td>
<td>5 mass%KCl aqueous solution</td>
</tr>
</tbody>
</table>
3. Results and Discussion

3.1 Dispersion pattern of tracer particles (CaCO$_3$ particles)

The main dispersion pattern of CaCO$_3$ particles originally introduced in the entry region in the bath is shown in Fig. 4. Most CaCO$_3$ particles were pulled toward the belt due to the belt motion. After the particles reached the region near the belt, they moved along the belt and entered the exit region. A part of the particles returned to the entry region along the bottom wall and the side walls, and then dispersed in the entry region. A small part of the powder moving along the side walls entered the region enclosed with the belt and dispersed there. This dispersion pattern was almost the same as the fluid flow pattern in the bath as mentioned in the previous paper.4)

3.2 Line-averaged dispersion phenomena in the bath

3.2.1 Variation of the concentration of tracer particles

Some examples of the intensity of the laser beam, $I$, are shown in Fig. 5. The variations of $I$ can be basically classified into three patterns, as denoted by the marks $\triangle$, $\square$, and $\bigcirc$, respectively. The fluctuation of the signal becomes large in the order of the marks $\square$, $\triangle$, and $\bigcirc$. The positions at which these signals appear are shown in Fig. 6. The signals indicated by the mark $\bigcirc$ appear in the vicinity of the belt in the entry region and are accompanied by intense fluctuations. These signals are induced because some of the tracer particles approaching the belt are highly mixed there. Most of the signals denoted by the mark $\triangle$ appear in the entry region. This signal has two steps. The first step is caused by the tracer particles coming from their introduction position. The second step is caused by tracer particles returning from the exit region. The signal indicated by the mark $\square$ appears mainly in the exit region, the region enclosed with the belt, and the region under the sink roll. Such a step wise change in the concentration with low fluctuation appears due to abrupt arrival of tracer particles.

3.2.2 Line-averaged mixing time and tracer concentration

The measured values of the line-averaged mixing time, $T_{m,line}$, are shown in Fig. 7. Each error bar denotes the scattering of data points. The measured value of the mixing time, $T_{m,line}$, varies from 21.6 to 37.8 s depending on the measurement position. The concentration of the tracer particles was found to hardly vary with time, $t$, for $t \geq 38.0$ s. At a glance, the line-averaged mixing time,
is long in the entry region and the region enclosed with belt, and short in the exit region. The long mixing time in the entry region is closely associated with the low mean flow velocity, $\bar{u}$, and the low root-mean-square (r.m.s.) value of turbulence component, $u_{rms}$. The r.m.s. value, $u_{rms}$, denotes the level of velocity fluctuations caused by turbulence. In the region enclosed with belt, the flow pattern is complicated, and, accordingly, the concentration of the particles is so difficult to reach the final value because $T_{m,\text{line}}$ becomes long.

As mentioned above, the line-averaged mixing time, $T_{m,\text{line}}$, is not uniform in the entire bath. This fact suggests that the mean flow velocity and the r.m.s. value of the turbulence component are closely associated with the line-averaged mixing time, $T_{m,\text{line}}$. The concentration of the tracer particles would also be different in the bath. The intensity of the laser beam, $I$, at time $T = 120.0\, \text{s}$ is shown in Fig. 8. The intensity, $I$, varies from 1.18 V to 1.38 V depending on the measurement position, revealing the existence of concentration distribution in the bath. According to the previous paper, the concentrations of Al measured at some positions in the real galvanising bath are different from one another. The correlation between the intensity of the laser beam in Fig. 8 and the line-averaged mixing time, $T_{m,\text{line}}$, in Fig. 7 is not clear.

### 3.3 Local dispersion phenomena of tracer in the bath

#### 3.3.1 Variation of the concentration of aqueous KCl solution

The temporal variations of the electrical conductivity which is a measure of the concentration of the tracer (KCl aqueous solution) are shown in Fig. 9. The belt velocity, $v_{SM}$, is 1.5 m/s. The variations can be divided into two patterns as denoted by the two marks (○, △). The signal indicated by the mark ○ shows that the electrical conductivity, $\sigma$, increases abruptly and then decreases to a final value accompanying large fluctuations. The mark △ shows that the $\sigma$ increases gradually accompanying relatively low fluctuations. The two types of signals measured at $y = 151\, \text{mm}$ are shown in Fig. 10. The mark ○ is distributed in the entry region and the region beneath the sink roll. This seems that the tracer (KCl aqueous solution) is strongly dispersed in the entry region after the tracer was charged onto the bath and then moves to the exit region. The mark △ is distributed in the exit region and the region enclosed with the belt.

The distributions of the two types of marks observed at $y = 51\, \text{mm}$ (near the side wall) are shown in Fig. 11. Most of the mark ○ are distributed mainly beneath the sink roll. The mark △ is distributed in the remaining region. The distributions of the marks ○ and △ observed at $y = 151\, \text{mm}$ (center plane) are much different from those at $y = 51\, \text{mm}$. The fluid flow pattern at $y = 51\, \text{mm}$ is characterized by the flow returning from the exit region to the entry region along the side wall. On the other hand, the flow field at $y = 151\, \text{mm}$ is mainly governed by the belt driven flow moving from the entry region to the exit region. This is the main reason for the difference.

The mean flow velocity, $\bar{u}$, and the r.m.s. value of
turbulence components, $u'_{z_{\text{rms}}}$ at $y = 51$ mm are high in the region under the sink roll, although the evidence is not shown here. The electrical conductivity signals ($\bigcirc$) observed in the exit region and under the sink roll therefore are closely associated with the high mean flow velocity, $\bar{u}$, and the high r.m.s. value of turbulence component, $u_{z_{\text{rms}}}$ near the side wall.

### 3.3.2 Local mixing time and concentration of aqueous KCl solution

The average value and the scatter of the local mixing time, $T_{m,\text{loc}}$, at $y = 151$ mm are shown in Fig. 12. The local mixing time, $T_{m,\text{loc}}$, varied from 29.8 s to 48.1 s. It appears that the $T_{m,\text{loc}}$ is longer in the entry region and the region enclosed with the belt than in the exit region. The concentration of the tracer at every measurement position therefore reaches a final value at about 48.0 s. The distributions of the increment of the electrical conductivity, $\Delta \sigma$, at $T = 300.0$ s are shown in Fig. 13. The increment of the electrical conductivity, $\Delta \sigma$, was defined as the difference between the electrical conductivity before the tracer introduction into the bath and that at measurement time of $T = 300.0$ s. The initial value of $\sigma$ was nearly zero. The concentration of the tracer varies significantly in the bath (7.78 to 28.1 $\mu$S/cm). In particular, the $\Delta \sigma$ is very low in the exit region and the region enclosed with the belt. The correlation between the $\Delta \sigma$ shown in Fig. 13 and the local mixing time, $T_{m,\text{loc}}$, shown in Fig. 12 is not clear at present. Consequently, a serious concentration difference exists on the middle plane in the bath even after the mixing time is reached.

The average value and the scatter of the local mixing time, $T_{m,\text{loc}}$, at $y = 51$ mm are shown in Fig. 14. The belt velocity, $v_{SM}$, is 1.5 m/s. The local mixing time, $T_{m,\text{loc}}$, is longer in the entry region than in the remaining regions. It ranges from 27.0 to 56.8 s. The distribution of the increment of the electrical conductivity, $\Delta \sigma$, at measurement time $T = 300.0$ s is shown in Fig. 15. The mean flow velocity, $\bar{u}$, and the r.m.s. value of turbulence component, $u'_{z_{\text{rms}}}$ at $y = 51$ mm were lower in the entry region. The local mixing time, $T_{m,\text{loc}}$, is thus influenced by the mean flow velocity and the r.m.s. value of the turbulence component in the bath. The maximum mixing time at $y = 51$ mm therefore was longer than that at $y = 151$ mm. The correlation between the increment of the electrical conductivity, $\Delta \sigma$, and the local mixing time, $T_{m,\text{loc}}$, shown in Fig. 14 is not clear.

As mentioned above, the local mixing time, $T_{m,\text{loc}}$, and the concentration of the tracer are not uniform in the bath.

### 3.4 Long-averaged value of tracer concentration

As mentioned above, the concentration of the aqueous KCl solution is not uniform even after the maximum mixing time has passed. This may be caused by a long-range variation of the concentration of the tracer. Accordingly, we measured the variation of the increment of the electrical conductivity, $\Delta \sigma$, for 60.0 min. This period is much longer than the maximum value of the local mixing time, $T_{m,\text{loc}}$. The electrical conductivity signals ($\bigcirc$) observed in the exit region and under the sink roll therefore are closely associated with the high mean flow velocity, $\bar{u}$, and the high r.m.s. value of turbulence component, $u_{z_{\text{rms}}}$ near the side wall.
conductivity was measured on the middle plane located at $y = 151$ mm. The tracer was charged onto the entry region. The belt velocity, $v_{SM}$, was 1.5 m/s. Three representative positions denoted by $M_1$, $M_2$ and $M_3$ were selected in the entry region, the region enclosed with the belt and the exit region, respectively. The variations of the electrical conductivity with time are shown in Fig. 16. The increment of the electrical conductivity, $\Delta \sigma$, was hardly dependent on time after $T = 300.0$ s at every measurement position, although $\Delta \sigma$ is dependent on the measurement position. The concentration of the chemical compositions of the plating melts would not be uniform in the hot dip plating bath.

### 3.5 Influence of the tracer charge position on the local mixing time and the increment of the electrical conductivity

In the previous sections, the tracer was charged onto the entry region. We further investigated the influence of the tracer charge position on the local mixing time, $T_{m,loc}$. The tracer was charged onto the exit region and the region enclosed with the belt. The local mixing time, $T_{m,loc}$, and the increment of the electrical conductivity, $\Delta \sigma$, were measured on the middle plane located at $y = 151$ mm (see $M_1$, $M_2$, $M_3$). The belt velocity, $v_{SM}$, was 1.5 m/s. The variation of the increment of the electrical conductivity, $\Delta \sigma$, is shown in Fig. 17. When the tracer was charged onto the entry region as shown by the mark $I_1$ in Fig. 17, the $\Delta \sigma$ value was high at $M_1$ in the entry region and it is much different from those measured in the remaining two regions such as $M_2$ and $M_3$. When the tracer was charged onto the exit region or the region enclosed with the belt, the differences among the $\Delta \sigma$ values obtained in the three regions became smaller than when the tracer was introduced in the entry region. The variation of the local mixing time, $T_{m,loc}$, is shown in Fig. 18. The local mixing time, $T_{m,loc}$, became shorter when the tracer was introduced in the exit region or the region enclosed with the belt than when the tracer was introduced in the entry region. In addition, the measured local mixing time, $T_{m,loc}$, became more uniform.

Judging from the results shown above, the best position for charging ingots in a hot dip plating bath would be located in the exit region.

### 3.6 Influence of the belt velocity on the increment of electrical conductivity and local mixing time

The influences of the belt velocity on the variations of the increment of the electrical conductivity, $\Delta \sigma$, and the local mixing time, $T_{m,loc}$, were investigated. The tracer was charged onto the entry region, and the measurements were...
carried out at \( y = 151 \text{ mm} \). The distribution of the increment of the electrical conductivity, \( \Delta \sigma \), and the local mixing time, \( T_{m,loc} \), are shown in Figs. 19 and 20, respectively. The increment of the electrical conductivity, \( \Delta \sigma \), became smaller as the belt velocity, \( v_{SM} \), was decreased. The mixing time, \( T_{m,loc} \), became shorter as the belt velocity, \( v_{SM} \), became higher.

4. Conclusions

The dispersion phenomena of melted ingots in a hot dip plating bath were investigated using a cold model bath with a reduced scale of one-tenth, \( \text{CaCO}_3 \) particles and 5.0 mass\%KCl aqueous solution were used as tracer. The main findings are summarized as follows:

1. The dispersion of the tracer is closely associated with the fluid flow phenomena in the bath.

2. The variations of the concentration of the \( \text{CaCO}_3 \) particles with time can be classified into three types. The patterns are also influenced by the fluid flow pattern, the mean flow velocity, \( \bar{u} \), and root-mean-square value of turbulence component, \( u_{rms} \), in the bath.

3. The local mixing time, \( T_{m,loc} \), and the line-averaged mixing time, \( T_{m,line} \), are not uniform in the bath when the tracer was charged onto the surface of the exit region.

4. The non-uniformity of the mixing time values and the increment of the tracer concentration became smaller when the tracer was charged onto the exit region and the region enclosed with the belt. Hence, in the real hot dip plating bath, Zn ingots are recommended to be charged onto the surface of the exit region.

5. The local mixing time, \( T_{m,loc} \), became short as the belt velocity, \( v_{SM} \), was increased.

6. The aforementioned results suggest that the hot dip plated sheets can be efficiently produced by changing the flow pattern in the bath and by changing the ingot charging positions.

REFERENCES