Effects of Snout and Support Roll on Transport Phenomena in a Hot Dip Plating Bath

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The fluid flow phenomena of plating melt, the motions of dross, and the dispersion of melting ingots in a continuous hot dip plating bath were investigated using a transparent cold model vessel with a reduced scale of one-tenth. This model was equipped with a snout and two support rolls. Water was used as a model for the plating melt. The flow pattern in the bath was basically the same as that in the bath without the snout and the support rolls, but re-circulating flows caused by the existence of the snout were observed in the entry region and in the region enclosed with the belt. Water supplied in the snout through the passage above the sink roll was carried by the belt and exhausted into the entry region. Most top dross and bottom dross were carried by the main flow in the entire bath. A part of the top dross floated on the bath surface and a part of the bottom dross accumulated on the bottom of the bath. The dispersion of tracer, being a model for melted ingots, was mainly controlled by the main flow. The mixing time became shorter in the presence of the snout and support rolls than in the absence of them.

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1. Introduction

The Sendzimir method has been widely used in the hot dip plating line since 1931.\textsuperscript{1–3} This method is a kind of gas reduction method. In this method, strip is immersed in the bath after it is annealed and then cleaned by gas. A snout was therefore developed to introduce the strip in the bath by preventing the direct contact with the atmosphere. The strip leaving the sink roll is slightly bent in the horizontal direction due to non-uniform attachment of the plating melt. The shape of the strip is corrected with two support rolls.\textsuperscript{4–6} Accordingly, a sink roll, a snout and two support rolls are immersed in the bath. The fluid flow in the hot dip plating bath is mainly driven by the strip motion in the bath. The transport phenomena in the bath are characterized by the fluid flow of plating melts, the motions of top and bottom dross, and the dispersion of melting ingots. Although many investigations have been carried out on the transport phenomena, many problems are left unsolved.

Considering these circumstances, as a first step of this research series, we carried out model experiments in the absence of the snout and support rolls in the previous studies.\textsuperscript{23–27} In this study we used the same experimental apparatus as that used in the previous studies.\textsuperscript{23–27} The snout and support rolls were, of course, equipped. The experimental apparatus has a one-tenth scale of the real bath. The above-mentioned transport phenomena in the bath were experimentally investigated.

2. Experiment

2.1 Concept of model design

The size and shape of the experimental apparatus were determined based on the following Reynolds number similitude. The plating melt was modeled with tap water.

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

(1)

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 chosen in this study. It was difficult to let the Reynolds number for the model coincide that for the real bath, so that the dynamic similitude was relaxed because the flow in one-tenth cold model bath was turbulent.\textsuperscript{23} 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\textsuperscript{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. The model is a reduced scale of one-tenth. A sink roll was immersed in the bath. An endless belt was driven by two driving rolls, though they were omitted in Fig. 1 to avoid

![Fig. 1 Experimental apparatus for 1/10 cold model.](image-url)

Table 1 Main specifications of cold model.

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sink roll</td>
<td>(\phi 70 \times 210\text{ mm})</td>
</tr>
<tr>
<td>Belt</td>
<td>(r0.2 \times w120\text{ mm})</td>
</tr>
<tr>
<td>Vessel</td>
<td>(r5 \times w410 \times D310 \times H229\text{ mm})</td>
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</table>
2.4.1 Design of model for dross

Polystyrene particles were used as the model for the dross and aqueous NaCl solution was used as the working fluid. The diameter of the tracer particles was 1.2 g/cm³. The diameter was 2.0 mm. The density of the liquid in the bath was adjusted to be equal to that of the tracer particles by adding salt into the bath. The flow pattern in the bath was observed by eye inspection.

2.4.2 Observation of the behavior of dross particles

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 defined as the streak line. The streak lines of model particles were observed by eye inspection. Polystyrene particles of 32 g in mass were charged onto the surface of the entry region. The belt velocity was 1.5 m/s.

2.4.3 Measurements of particle passing frequency and particle holdup

The particle frequency is defined as the number of model particles passing through a laser beam in one second. The particle holdup is defined as the total residence time of particles in the laser beam to the measurement time. These quantities were measured with a system working based on the electro-light effect, as shown in Fig. 1. This system consists of a light source and a light detection unit. The output signal changes when particles pass through the laser beam.

The particle frequency, \( f_{ps} \), and the particle holdup, \( \alpha_{ps} \), can be calculated from the following equations.

\[
\alpha_{ps} = \left( \frac{\Sigma t_i}{t_M} \right) \times 100(\%)
\]

\[
f_{ps} = N/t_M (\text{Hz})
\]

where \( t_i \) denotes the passing time of the i-th particle, \( t_M \) is the measurement time, and \( N \) is the total number of particles passing through the laser beam. The subscript \( s \) denotes the case that the snout and the support rolls are present.

The distance between the light source and the light detector is 20 mm. The output signal of the system was A/D converted at a sampling frequency of 5 kHz and then stored on a personal computer. The measurement time at each measurement position is 2 min. Some representative positions were chosen in the three sub-regions. The accuracy of the present measurement method is described in the previous papers. The measurements were carried out after the flow in the bath became steady.

It should be noted that when both the particle frequency, \( f_{ps} \), and particle holdup, \( \alpha_{ps} \), are high at a measurement position, many dross particles pass there slowly. Namely, the dross particles are enriched around there.
2.5 Dispersion of melted ingots

2.5.1 Observation of the dispersion pattern of tracer particles

The experimental conditions are listed in Table 3. For the observation of the dispersion of melted ingots, CaCO$_3$ particles of a mean diameter of 1.0 $\mu$m and a density of 1.77 g/cm$^3$ were used as tracer particles. The CaCO$_3$ particles were chosen because they were so small that could completely follow the liquid motion. Namely, the particle Reynolds number was less than unity. De-ionized water was used as the working fluid. The charging positions of the tracer particles on the bath surface are the same as that in the real process. The amount of the tracer particles was 2.0 cm$^3$, and the observation was made by eye inspection.

2.5.2 Measurement of local mixing time

The local mixing time, $T_{m,loc}$, was determined by measuring the local electrical conductivity, $\sigma$, of the fluid in the bath. A 5 mass% KCl aqueous solution was used as the tracer. The tracer was charged onto the same position in the entry region as that in the real process. The amount of the solution was 10 cm$^3$ in volume. The electrical conductivity, $\sigma$, was measured with a probe shown in Fig. 2. Its time constant was 0.25 s. The output signal was recorded on a pen recorder. Some representative measurement positions were selected in the three sub-regions. The measurements were carried out on a vertical plane located at $y = 151$ mm.

2.5.3 Definition of mixing time

Some kinds of definitions are known for the mixing time in engineering fields. Unfortunately, the concept of mixing time has never been introduced in the hot dip plating processing. The definition of mixing time familiar with researches in the steelmaking industry is selected in this study. Figure 3 shows the output signal of the probe. The local mixing time, $T_{m,loc}$, 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 and used to determine the local mixing time, $T_{m,loc}$. The tracer concentration at $t = T_{m,loc}$ is called the mixed concentration.

3. Results and Discussion

3.1 Fluid flow phenomena in the bath

3.1.1 Flow pattern

(1) Whole bath

Figure 4 shows the flow pattern in the whole bath. The flow pattern was basically similar to that in the absence of the snout and the support rolls. The main flow is directed from the entry region to the exit region (line $a$). The fluid which moved along the line $a$ returned to the entry region along the side wall (line $c$) as well as the bottom wall (line $b$). Accordingly, there exists a large-scale re-circulating flow in the bath. A part of the fluid returning to the entry region enters the region enclosed with the belt as shown by the line $d$. A part of the fluid flowing along the line $a$ is reflected from the support roll and moves upward to the bath surface in the exit region (line $q$). This flow is responsible for the floating of top dross particles on the bath surface in the exit region. Both the top and bottom dross are considered to be trapped in the clearances between the support roll and the strip in the real bath. The same labels will be used in the following Figs. 5 through 7 to indicate the flows shown in Fig. 4.

Figure 5 shows the flow pattern in the bath observed from a position above the bath surface. Re-circulating flows are clearly seen in the entry region (line $r$) and the region enclosed with the belt (line $s$).

(2) Region enclosed with the belt
Figure 6 shows the flow pattern in the region enclosed with
the belt. The flow pattern is basically the same as that in
the absence of the snout and the support rolls. However, the
flow indicated by the line \( o \) is remarkable in this case. The top
and bottom dross are carried into the snout by the flow along
this line \( o \).

(3) Vicinity of snout and support rolls

The flow pattern on the middle plane of \( y = 151 \) mm is
shown in Fig. 7. The details of the flow near the snout and
the support rolls can be more clearly understood. In particular,
the surface flows reflecting from the snout are remarkable
(line \( v \)). On the other hand, the flows entering the clearances
between the belt and the support rolls are strongly reflected
upward along the support rolls and finally reach the bath
surface (line \( q \)). In the region enclosed with the belt, a recirculating flow denoted by the line \( i \) and \( g \) is formed in the vicinity of the belt. This motion is more pronounced than in
the absence of the support rolls. The liquid in the clearance
between the sink roll and the belt is discharged from its
clearance by the motion of the belt. The flow indicated by
line \( g \) would be generated by supplying the liquid into the
clearance.

(4) Flow field in the snout

The fluid located on the right hand side of the belt in the
snout always moved downwards and went out of the snout
(line \( w \)). On the other hand, the fluid located on the left hand
side of the belt in the snout moved downwards with the belt
and issued out of the snout (line \( k \)), but a part of it returned
and entered again in the snout as indicated by the line \( o \). The
liquid in the snout is discharged from the snout by the motion
of the belt. The flow pattern indicated by line \( w \) would be
generated by supplying the liquid into the snout.

The top view of the flow pattern in the snout is shown in
Fig. 8. The flow pattern is not symmetrical with respect to the
belt, as readily suggested from Figs. 6 and 7. The dross
generated in the snout and that carried into the snout by the
flow indicated by line \( o \) would be carried by moving fluid
along the line \( p \) toward the side wall of the snout and
accumulated there. The dross in the real process is considered
to attach to the strip passing through the snout.

3.1.2 Comparison between mean velocities in the pre-
sence and absence of the snout and support rolls

Figure 9 shows the ratio of the mean velocity components
in the x direction with and without the snout and support
rolls, \( \bar{u}_x/\bar{u} \), where the subscript \( s \) denotes the case in
the presence of the snout and support rolls. The velocity
measurements were carried out along the line located at
\( y = 151 \) mm and \( z = 199 \) mm (20 mm beneath the bath
surface). The measured values of \( \bar{u}_x/\bar{u} \) were positive at every
measurement position, implying that the flow directions were the same in the two cases. The measured values were distributed around unity, and, accordingly, the flows in the two cases are basically similar. The velocity ratio, however, was larger than unity in the entry region, nearly equal to unity in the region enclosed with the belt, and smaller than unity in the exit region. In the entry region, \( \alpha_u \) became larger than \( \bar{u} \) due to the existence of re-circulating flow shown in Fig. 5. The effect of the support roll on the flow field in the region enclosed with the belt was not large. The reason why \( \alpha_u = \bar{u} \) is less than unity in the exit region can be explained by the fact that the upward flow along the belt, which causes the surface flow, is suppressed by the support roll.

### 3.2 Behavior of dross

#### 3.2.1 Top dross particles

Figure 10 shows the streak lines of top dross particles. The main streak line observed at the middle plane of the bath \((y = 151 \text{ mm})\) was nearly the same as the main stream line in the bath.\(^{24}\) The streak line was defined as the trail of particles passed through a point in the bath, as described earlier. Many top dross particles gathered on the bath surface in the entry region, as indicated by A. These particles are mainly carried there along the line \( b_{11} \). The ratio of the particle frequency \( f_{ps} \) to the particle frequency \( f_p \) obtained in the absence of the snout and support rolls is shown in Fig. 11. The particle holdup ratio, \( \alpha_{ps}/\alpha_p \), is shown in Fig. 12. These quantities were measured at representative 10 measurement positions. The two ratios were very smaller than unity at most measurement positions except near the bath surface in the entry region. These facts mean that it becomes difficult for the top dross particles to enter the exit region and the region enclosed with the belt due to the existence of the snout and support rolls.

Figure 13 shows the measured values of the ratio of the particle moving velocities, \( \bar{u}_{ps}/\bar{u}_p \). These quantities can be calculated from the particle frequency values, \( f_{ps} \) and \( f_p \), and the particle holdup values, \( \alpha_{ps} \) and \( \alpha_p \).\(^{24}\) The particle moving velocity, \( \bar{u}_{ps} \), is slightly higher than \( \bar{u}_p \) at most measurement positions except in the region enclosed with the belt and the bottom of the entry region. A detailed explanation can not be given on this fact because the liquid flow velocity ratio is approximately unity, as already shown in Fig. 9.

#### 3.2.2 Bottom dross particle

Figure 14 shows the main streak lines in the bath, being denoted by the lines \( a_b, b_{11}, c_b \) and \( d_b \). These main streak lines were located on the middle plane \((y = 151 \text{ mm})\) and nearly the same as the main stream lines in the bath. A large re-circulating flow therefore exists on the middle plane. As the density of the bottom dross particles was slightly greater than that of the aqueous NaCl solution, many bottom dross particles stayed on the bottom of the bath as indicated by C, D and E. Some of them were frequently lifted up as indicated by the streak lines \( b_{11}, b_{12}, b_{13} \) and \( b_{14} \). Such ejection of bottom dross particles were also reported elsewhere.\(^{7,14,16}\)

Figures 15 and 16 show the particle frequency ratio, \( f_{ps}/f_p \), and the particle holdup ratio, \( \alpha_{ps}/\alpha_p \). These ratio are
much smaller than their respective values in the absence of the snout and support rolls at most measurement positions except near the bath surface in the entry region. This is because the motions of bottom dross particles are suppressed by the snout and support rolls, and, accordingly stay on the bottom of the bath. Also, this situation is caused through the effect of the snout on the residence time of bottom dross particles as the mean velocity, $\bar{u}$, and the root-mean-square (r.m.s.) value of turbulence component, $u'_{rms}$, are low there.

The rms value, $u'_{rms}$, denotes the level of velocity fluctuations caused by turbulence. The reason why both $f_{ps}$ and $\alpha_{ps}$ are larger than $f_p$ and $\alpha_p$ at the measurement position 10 can be explained by the fact that many particles lifted up along the streak lines $b_{B1}$ and $b_{B2}$. Figure 17 shows the particle moving velocity ratio, $\bar{u}_{ps}/\bar{u}_p$. At almost all measurement positions except near the bottom of the exit region, $\bar{u}_{ps}$ was smaller than...
At almost measurement positions except near the bottom of the exit region, $\bar{u}_{ps}$ was slightly higher than $\bar{u}_{ps}$. At almost measurement positions except near the bottom of the exit region, $\bar{u}_{ps}$ was slightly higher than $\bar{u}_{ps}$.

### 3.3 Dispersion of tracer

#### 3.3.1 Dispersion pattern

$\text{CaCO}_3$ particles and a KCl aqueous solution were used to investigate the dispersion of melted ingots such as Zn and Al ingots. The $\text{CaCO}_3$ particle was small enough to follow the fluid flow in the bath. Figure 18 shows the dispersion patterns of tracer particles of $\text{CaCO}_3$ in the bath. The tracer particles were supplied onto the bath surface in the entry region, and they moved along the snout, the belt, and the sink roll and entered the exit region. A part of the particles returned along the bottom wall and the side walls to the entry region. A small part of the particles moving along the side walls entered the region enclosed with the belt and dispersed there. These dispersion patterns of the tracer particles were very similar to the main flow pattern in the bath. The main flow was driven by the belt motion.

#### 3.3.2 Mixing time and concentration of aqueous KCl solution

Figure 19 shows the wave forms of electrical conductivity, $\sigma$, of the liquid in the bath. The wave forms can be basically classified into two types; (a) and (b). The wave form
classified into (a) shows a gradual increase in $\sigma$ with time, $t$, while that classified into (b) shows a sudden increase accompanied by gradual decrease in $\sigma$. The type (a) was mainly observed in the exit region and the region enclosed with the belt. This is because the tracer enters these regions gradually. On the other hand, the type (b) was observed mainly in the entry region. The reason can be explained by the fact that the tracer was charged in this region.

Figure 20 shows the local mixing time, $T_{m,loc}$, measured at representative three positions in the bath. The measurement were repeated five times at every positions. The mixing time in the presence of the snout and the support rolls was approximately the same as that in the absence of them. The mixing time indicated by the solid circles was hardly dependent on the measurement position.

4. Conclusions

The influence of the snout and the support rolls on the transport phenomena in a hot dip plating bath were investigated by using a cold model with a reduced scale of one-tenth of an actual bath. The main findings are summarized as follows:

1. The flow pattern in the bath with the snout and support rolls were basically the same as that in the bath without them. The flow near the snout and support rolls were somewhat complicated.

2. The flows heading to the clearances between the belt and the two support rolls were reflected from there and moved a toward the bath surface. In the region enclosed with the belt, a strong re-circulating fluid motion could be observed very near the belt beneath the support roll.

3. In the snout, the fluid beneath the belt moved downward along the belt. On the other hand, the fluid just above the belt was carried downward by the belt, but a reversing flow can be seen beneath the upper wall of the snout.

4. Concerning the bath surface, the mean velocity, $\bar{u}_s$, in the presence of the snout and the support rolls was slightly higher in the entry region and slightly lower in the exit region than the mean velocity, $\bar{u}$, in the absence of them.

5. The main streak lines of top dross particles were very similar to the main stream lines. Many top dross particles were accumulated near the bath surface in the entry region.

6. The main streak lines of bottom dross particles also were similar to the main stream lines. Many bottom dross particles accumulated on the bottom of the bath. Some of them were frequently ejected into the bulk of the bath due to the flow coming back to the entry region along the bottom of the bath.

7. The passing frequency, $f_{ps}$, and particle holdup, $\phi_{ps}$, in the presence of the snout and support rolls became lower than their respective values measured in the absence of the snout and support rolls. This is because the numbers of top and bottom dross particles accumulated on the bath surface and the bottom of the bath were greater in the presence of the snout and support rolls. Accordingly, the number of particles moving in the bath was smaller in the presence of them.

8. The main dispersion patterns of tracer were nearly the same as the main flow patterns. The local mixing time, $T_{m,loc}$, in the presence of the snout and the support rolls was approximately the same as that measured in the absence of them.

REFERENCES
