Analysis of Mold Wear during Continuous Casting of Slab

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Using a 2-dimensional coupled thermo-elasto-plastic finite element model, the thermo-mechanical behaviours of the strand and mold were analyzed. The calculated geometry and temperature distributions of the solidifying shell and mold were compared with experimental observations. The calculated geometry around corner region was in good agreement with experimental observations. The mold wear was analyzed by a new dimensionless parameter of “Apparent Wear Parameter” which is inversely proportional to yield stress of the mold at service temperature and directly proportional to the interfacial pressure between the strand and mold. The effects of narrow face taper and carbon concentration of cast steel on mold wear were analyzed using the apparent wear parameter. With increasing narrow face taper, the possibility of mold wear increased due to increasing interfacial pressure. With increasing carbon concentration, the width of worn region of 35 mm at 0.05 and 0.1 wt% C steels decreased to 15 mm of 0.2 wt% C steel due to uniform thermal contraction of 0.2 wt% C steel during solidification. The calculated behaviours of mold wear were compared with used mold in industrial operation. The calculated worn region of mold based on the apparent wear parameter were in good agreement with industrial observations.

KEY WORDS: thermo-elasto-plastic finite element model; mold wear; apparent wear parameter; interfacial pressure; narrow face taper; carbon concentration.

1. Introduction

The continuous casting process has been adopted worldwide by steel industries over last two decades owing to its inherent advantages: low cost, high yield, flexibility of operation, and ability to achieve a high quality cast product. In spite of the advantages, the quality of a strand suffers considerably from the presence of various defects, such as break-outs, cracks of strand, mold wear, and others. Many mathematical models have been developed to understand and investigate the thermo-mechanical behaviours of the solidifying shell and mold during continuous casting. 1)-15) Despite such intense studies, the thermo-mechanical behaviours of the strand and mold during continuous casting of steel are not fully understood due to the complex operating conditions of continuous casting process, such as mold fluid conditions, superheat of melt, cooling water flow rate of mold, mold taper, slab dimension, steel grade, casting speed and so on. The formation of air gap between the strand and mold, and the stress state of solidifying shell have been analyzed with the coupled analysis of stress and heat transfer analysis. 1)-15,30-32,37) From the viewpoint of strand, these models have well explained the formation of surface and internal cracks, break-outs, and air gap in continuous casting process of slab. However, from the viewpoint of mold wear, the wear phenomenon of mold has not been fully studied yet. Grill et al. 2) reported that mold wear due to the physical abrasion of mold is related with the normal force which acts against the mold. And, they reported that wear occurs in regions of the mold where the air gap is fully closed.

The purpose of this study is to analyze wear phenomenon of the narrow side mold, using a 2-dimensional coupled thermo-elasto-plastic finite element model to compute the thermal and mechanical behaviours of shell and obtain the temperature profile of mold. To predict the possibility of mold wear, a new dimensionless parameter of apparent wear parameter has been proposed, which is based on the complex wear mechanisms of abrasive and adhesive wear. The effects of narrow face taper and carbon concentration on the mold wear were studied. The calculated wear behaviours of narrow face mold at a condition of continuous casting in industry were compared with the experimentally measured data of used mold in industry.

2. Mathematical Formulation

2.1. Calculation of Heat Transfer during Continuous Casting

The temperature distribution in the transverse slice of strand is calculated using an Eq. (1) for 2-dimensional transient heat conduction accompanying liquid-solid transformation

\[
\frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial t} \left( \rho C_p \frac{\partial T}{\partial t} \right) = \frac{\partial}{\partial t} \left( \rho C_p \frac{\partial T}{\partial t} \right) \tag{1}
\]

where \( T \) is the temperature, \( k \) is the thermal conductivity,
C is the heat capacity per unit volume, \( f_s \) is the solid fraction and \( L \) is the latent heat per unit volume. In this study, the enthalpy method\(^{12}\) was used to solve the solidification. The initial and boundary conditions are as follows.

\[
T = T_0, \quad -k_n \frac{\partial T}{\partial n} = q_n \quad \text{..............(2)}
\]

where \( T_0 \) is the initial casting temperature of molten steel, \( n \) is the direction normal to strand surface and \( q_n \) is the heat flux on the surface. The heat conduction equation was solved using the finite element method.\(^{16,18}\)

The following assumptions were used in this calculation.

1. The heat conduction along casting direction is negligible compared with the heat flow to mold.
2. The effect of convective heat flow in liquid region is taken into account using the effective thermal conductivity, \( k_{eff} \), for molten steel.\(^{19}\) \( k(T) \) is the thermal conductivity of liquid steel at temperature \( T \).

\[
k_{eff} = k(T)[1 + 6(1 - f_s)^2] \quad \text{..............(3)}
\]

(3) The heat transfer between the mold and cooling water is characterized with the aid of a heat transfer coefficient, \( h_w \), determined from the following dimensionless correlation.\(^{20}\)

\[
\frac{h_w D}{k_w} = 0.023 \left( \frac{\rho_w u_w D}{\mu_w} \right)^{0.8} \left( \frac{C_{pa} h_w}{k_w} \right)^{0.4} \quad \text{..............(4)}
\]

where \( D \) is the hydraulic diameter, \( u_w \) is the velocity of cooling water, \( \rho_w \) is the density of water, \( \mu_w \) is the viscosity of cooling water and \( h_w \) is the heat transfer coefficient between the mold and cooling water. Thermo-physical data to calculate \( h_w \) are given in Table 1.\(^{21}\)

The thermal boundary condition between the solidified strand surface and mold is modeled using the interfacial heat transfer coefficient, \( h_T \), which is a function of air gap thickness and surface temperature of the strand. The interfacial heat transfer coefficient can be expressed as follows.

\[
h_T = 1/R_4 + h_{rad} \quad \text{..............(5)}
\]

where \( h_{rad} \) is the heat transfer coefficient for the radiative heat flow when the air gap occurs between the strand and mold, and \( R_4 \) is the thermal resistance between the strand surface and mold except radiation. The heat transfer coefficient for radiative heat flow, \( h_{rad} \), can be expressed as follows.

\[
h_{rad} = \frac{\sigma(T_s + T_m)(T_s^2 + T_m^2)}{} \quad \text{..............(6)}
\]

where \( \sigma \) is the Stefan–Boltzmann constant, \( T \) is the averaged emissivity of shell and mold surfaces, \( T_s \) is the temperature of shell surface and \( T_m \) is the temperature of mold. The averaged emissivity of shell and mold surface was assumed to be 0.8.\(^{22}\)

The thermal resistance, \( R_4 \), may be expressed as follows.

\[
R_4 = R_1 + R_2 + R_3 + R_4 \quad \text{..............(7)}
\]

The contact resistance between the mold and mold flux film, \( R_1 \), is given by \( R_1 = 1/h_1 \), where \( h_1 \) is the contact heat transfer coefficient at the mold surface, which was set to 3000 W/m\(^2\)K.\(^{23}\)

The resistance to conduction through the air gap, \( R_2 \), is calculated by \( R_2 = d_2/k_2 \), where \( k_2 \) is the thermal conductivity of air and \( d_2 \) is the thickness of air gap which is calculated from the thermo-elasto-plastic stress analysis. The conductivity of air was set to 0.1 W/m K.\(^{21}\)

The resistance to conduction through the mold flux film, \( R_3 \), is calculated by \( R_3 = d_3/k_3 \), where \( k_3 \) is the thermal conductivity of mold flux and \( d_3 \) is the thickness of gap filled with the mold flux. The thermal conductivity of mold flux is used to be 1.0 W/m K and the thickness of mold flux was set to 100 μm from the mold flux consumption and density of mold flux.\(^{24}\)

The contact resistance between the mold flux and strand surface is calculated by \( R_4 = 1/h_4 \), where \( h_4 \) is the heat transfer coefficient between the mold flux and strand surface. \( h_4 \) must depend on temperature due to the large change in viscosities of the mold flux over strand surface temperature range. The temperature dependency of \( h_4 \) is given in Table 2.\(^{21}\)

The composition of steel used in this study is given in Table 3. The liquidus temperature, \( T_L \), and the solidus temperature, \( T_S \), were calculated using the following equations.\(^{25}\)

\[
T_L = 1536 - 78(wt\% C) - 7.6(wt\% Si) - 4.9(wt\% Mn) - 34.4(wt\% P) - 38(wt\% S) - 4.7(wt\% Cu) - 3.1(wt\% Ni) - 1.3(wt\% Cr) - 3.6(wt\% Al) \quad \text{(8)}
\]

\[
T_S = 1536 - 415.5(wt\% C) - 12.3(wt\% Si) - 6.8(wt\% Mn) - 124.5(wt\% P) - 183.9(wt\% S) - 4.5(wt\% Ni) - 1.4(wt\% Cr) - 4.1(wt\% Al) \quad \text{(9)}
\]

The effective coefficient of thermal expansion was calculated from the following equation.

\[
\alpha = \left( \frac{V/T_{ref}}{T/T_{ref}} \right)^{1/3} - 1 \quad \text{..............(10)}
\]
Table 4. Specific volume of δ, γ and liquid steels.26)

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Specific volume, cm³/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05 wt% C</td>
<td>1.7035</td>
</tr>
<tr>
<td>0.1 wt% C</td>
<td>0.1234 + 9.38 × 10⁻⁷(T-293)</td>
</tr>
<tr>
<td>0.2 wt% C</td>
<td>0.0225 + 9.45 × 10⁻⁷(T-293) + 1.788 × 10⁻⁶ (wt% C)</td>
</tr>
</tbody>
</table>

Fig. 1. The effective coefficient of thermal expansion of 0.05, 0.1 and 0.2 wt% C steels as a function of temperature.

where \( V_{\text{ref}} \) is the specific volume of material at the reference temperature, \( T_{\text{ref}} \), and \( V \) is the specific volume at temperature \( T \). The effective coefficient of thermal expansion includes volume changes due to temperature change and \( \delta/\gamma \) phase transformation. The specific volumes for liquid, δ and γ steels are given in Table 4.26)

Using Eqs. (8) (10) and data in Table 4, the effective coefficients of thermal expansion of 0.05, 0.1 and 0.2 wt% C steels could be obtained as a function of temperature as shown in Fig. 1. The effective coefficient of thermal expansion at 0.2 wt% C steel shows almost constant value in the given ranges of temperature. But, at 0.05 and 0.1 wt% C steels, with decreasing temperature below \( T_{\text{ref}} \), the effective coefficient of thermal expansion sharply increased and after a maximum value, decreased. Because there is no \( \delta/\gamma \) phase transformation at 0.2 wt% C steel, the effective coefficient of thermal expansion is almost constant. At 0.05 and 0.1 wt% C steels, \( \delta/\gamma \) phase transformation gives rise to high value of effective coefficient of thermal expansion below starting temperature of \( \delta/\gamma \) phase transformation.

2.2. Analysis of Wear Phenomenon

The appropriate amount of mold taper is a very important design parameter during operation of continuous casting and typically the mold taper of narrow face is larger than that of wide face. At small narrow face taper, the solidifying shell is prone to break-outs, because large gap between the strand and mold causes the hot spot at the strand. At large narrow face taper, the high value of interfacial pressure between the strand and mold is developed and the narrow face mold can be easily worn. Therefore, the optimization of narrow face taper can decrease break-outs of the strand and wear phenomenon of the mold.

During sliding contacts, wear due to adhesive, abrasive and delamination wear could take place.27) Mold wear can occur at the interface between the strand and mold when the strand moves downward through the mold during casting. In adhesive wear, asperities on the sliding surface support the frictional load and high stress developed at the asperities. The high stress causes plastic deformation of the mold at asperity and subsequent deformation give rise to wear. In abrasive wear, during sliding between hard and soft metals, the hard asperity of hard metal cuts the soft asperity of soft metal.27) Typically, surface morphology of abrasive wear shows the groove shape due to the penetrating abrasive wear particles. Figures 2(a) and 2(b) show the scanning electron micrograph and EDS analysis at the narrow corner region of strand, respectively. Figures 2(c) and 2(d) show the scanning electron micrograph and EDS analysis at the worn mold surface of narrow side, respectively. At the strand surface, Cu was found as shown in Figs. 2(a) and 2(b), and at the mold surface, Fe was found with mold flux as shown in Figs. 2(c) and 2(d). Figure 3 shows the scanning electron micrograph at the worn mold surface of narrow side. Wear particles and wear grooves were observed in worn surface of mold as shown in Figs. 2 and 3, respectively. The wear mechanism of copper mold seems to be a complex wear of abrasive and adhesive wear. The amount of adhesive and abrasive wear in the sliding wear depends on the metallurgical, geometrical, tribochemical and environmental properties.28) In these various factors, wear phenomenon is significantly influenced by metallurgical properties such as hardness, work hardening and the applied load.

The following equation can simply describe the Archard's wear law28,29) of abrasive and adhesive wears.

\[
W_{V/S} = \frac{W_V}{S} = k \cdot \frac{F_N}{H} \quad \text{(11)}
\]

where \( W_{V/S} \) is the volumetric wear intensity, \( W_V \) is the volume loss due to wear, \( S \) is the sliding distance, \( F_N \) is the applied normal load, and \( H \) is the hardness of the worn metal. Since surface pressure \( P_1 \) is given as \( P_1 = F_N/A \) at the given wearing area, linear wear intensity, \( W_{L/S} \), can be given as follows.29)

\[
W_{L/S} = \frac{W_L}{S} = k \cdot \frac{P_1}{H} \quad \text{(12)}
\]

where \( W_L \) is the linear amount of wear. \( k \) is the coefficient of wear, which is dependent on temperature and could be evaluated by measuring \( F_N \), \( P_1 \), \( W_{V/S} \), \( W_{L/S} \) and \( S \) from the wear test. But, during continuous casting, \( F_N \), \( P_1 \), \( W_{V/S} \), \( W_{L/S} \) and \( S \) cannot be measured. Even though mathematical or numerical analysis can give \( F_N \) and \( P_1 \), the values of \( k \), \( W_{V/S} \), \( W_{L/S} \) and \( S \) can not be evaluated from the numerical analysis or experimental observations of continuous casting.

In this study, authors propose "Apparent Wear Parameter", \( W_p \), which can describe the mold wear during continuous casting, assuming that the hardness of copper mold is proportional to the yield stress at the temperature during casting.
3. Calculation Procedure

Figure 4 shows the initial finite element mesh for calculating the temperature and stress of a 1600 x 224 mm slab and the temperature of Cu-0.1 wt% Ag mold. A quarter section was modeled using symmetry conditions. The finite element calculation for stress analysis was carried out at the plane strain condition. The thermal conductivity of Cu-0.1 wt% Ag mold was assumed to be 374 W/m K.  Tables 5 and 6 give the mechanical and thermal properties of strand as a function of temperature. Table 7 gives the mechanical properties of Cu-0.1 wt% Ag mold as a function of temperature. Calculation was performed at the condition of a casting speed of 1 m/min. The distance from meniscus to mold exit is 770 mm. The temperature at meniscus was taken as the temperature which is superheated by 20°C such as 1548, 1544 and 1536°C at the carbon concentrations of 0.05, 0.1 and 0.2 wt% C steels, respectively. The Coulomb friction law with the friction coefficient of μ=0.1 has been applied to the contact surface of strand and mold. The calculations were carried out at the various narrow face tapers of 0.65, 1.30, 1.50 and 1.70% and carbon concentrations of 0.05, 0.1 and 0.2 wt% C steels and slab dimensions of 1600 x 224 and 2150 x 224 mm.

4. Results and Discussion

4.1. Analysis of Continuous Casting Process

Figure 5 shows the deformed geometries of the shell and the air gap near the slab corner at various distance below meniscus at the typical conditions in industrial
operation of 0.1 wt% C steel, slab width of 1600 mm, casting speed of 1 m/min and narrow face taper of 1.50% m/m. The deformed geometries of the strand are magnified by 5 times to see the formation of air gap. In the initial stage of solidification, the air gap was formed on both wide and narrow side corners as shown in this figure. The wide side corner of the solidifying shell separated away from the mold wall and the air gap became large with the solidification. As solidification proceeded, the air gap near the narrow side corner disappeared with the reduction of slab width by the narrow side mold taper. The air gap reduced heat flow from strand to mold and gave rise to a thinner shell in these regions which has been observed by previous researchers. In the final stage of solidification, the air gap near narrow side corner completely disappeared by the narrow face taper and the slight surface depression of strand denoted as "A" can be seen at the off-corner of narrow face as shown in Fig. 5. These trends correspond with the severe wear of narrow side mold observed in industrial operation. Figure 6 shows the observed geometry of solidifying shell, which was obtained from the break-out shell of 0.1 wt% C steel at a distance below meniscus of 200 mm and the calculated profile of solidifying shell at the distance below meniscus of 200 mm. The temperature lines of 1524, 1514 and 1485°C corresponded to the temperatures at which the solid fractions become 0.0, 0.6491 and 1.0, respectively. As shown in this figure, the shape of calculated solidifying shell are in good agreement with the observed result. This type of deformed geometry around corner region of slab was called as "corner rotation" of solidifying shell. Han et al. showed that the corner rotation of solidifying shell of slab is related with the inhomogeneous contraction of solidifying shell due to thermal contraction and δ/γ phase transformation. Figure 7 shows the variation of temperature at var-

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**Table 5. Mechanical properties of carbon steel.**

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>900</th>
<th>1200</th>
<th>1400</th>
<th>1450</th>
<th>$T_s$</th>
<th>$T_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus, GPa</td>
<td>20.46</td>
<td>7.738</td>
<td>4.300</td>
<td>3.385</td>
<td>0.297</td>
<td>0.99 x 10$^{-3}$</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>8.23 x 10$^{-3}$</td>
<td>0.278</td>
<td>0.499</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield stress, MPa</td>
<td>20.46</td>
<td>7.738</td>
<td>4.300</td>
<td>3.385</td>
<td>0.297</td>
<td>0.99 x 10$^{-3}$</td>
</tr>
<tr>
<td>Plastic modulus, MPa</td>
<td>1224</td>
<td>555.6</td>
<td>330.7</td>
<td>278.8</td>
<td>25.00</td>
<td>2.240</td>
</tr>
</tbody>
</table>

**Table 6. Thermal properties of carbon steel.**

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>25</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enthalpy, kJ/kg</td>
<td>117.7 + 0.648 T, $T_s &lt; T_c$</td>
<td>228.3 + 0.268 T + 1.67 x 10$^{-5}$ T$^2$, $T_s &lt; T_c$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latent heat of solidification, kJ/kg</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity, W/m·K</td>
<td>0.36</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latent heat of solidification, kJ/kg</td>
<td>272</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 7. Mechanical properties of Cu 0.1 wt% Ag mold.**

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>25</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus, GPa</td>
<td>117</td>
<td>117</td>
<td>117</td>
<td>117</td>
<td>117</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.36</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield stress, MPa</td>
<td>187.4</td>
<td>183.5</td>
<td>166.7</td>
<td>141.17</td>
<td>119.4</td>
</tr>
<tr>
<td>Plastic modulus, MPa</td>
<td>1100</td>
<td>1100</td>
<td>1100</td>
<td>1100</td>
<td>1100</td>
</tr>
</tbody>
</table>
The temperatures were measured along the mold by two thermocouples, which was installed at different depths of 17 and 20 mm from the wide and narrow hot face mold, respectively. The experimentally measured mold temperature increases sharply from meniscus and decreases along the mold. The measured temperature of wide face mold is higher than that of narrow face mold, because the position of thermocouple in wide face mold is closer to the strand than that in narrow face mold.

The effect of narrow face tapers of 0.65, 1.30, 1.50 and 1.70 %/m at the conditions of 0.1 wt% C steel, casting speed of 1 m/min and slab width of 1600 mm has been analyzed. Figures 10(a) and 10(b) show the deformed geometries of the shell and air gap near the slab corner at various distance below meniscus for the narrow face.
Fig. 10. Deformed geometries of the shell and the air gap near the slab corner at various distance below meniscus under the narrow face taper of (a) 0.65 and (b) 1.70%/m. The slab width of 0.1 wt% C steel is 1600 mm.

Fig. 11. Calculated apparent wear parameter with distance below meniscus at 90 (solid symbol) and 110 mm (open symbol) from narrow face center under the various narrow face taper.

taper of 0.65 and 1.70%/m, respectively. As shown in Fig. 10(a), small narrow face taper of 0.65%/m gave rise to the large air gap on narrow face around off-corner region as the solidification proceeds, because the narrow face taper could not compensate the shrinkage of solidifying shell. Large narrow face taper of 1.70%/m could compensate the shrinkage of solidifying shell and gave rise to no air gap on narrow face, as shown in Fig. 10(b). As solidification proceeded, the air gap near the narrow side corner nearly disappeared with the reduction of width by large narrow side mold taper, and this hard contacts between the strand and mold could give rise to serious wear of narrow side mold.

Figure 11 shows the apparent wear parameter of narrow side mold from Eq. (13) with distance below meniscus for the various narrow face taper at 90 and 110 mm from the narrow face center. At the narrow face taper of 0.65%/m, apparent wear parameter was zero during continuous casting, because air gap gave no contact between the strand and mold. Above the narrow face taper of 0.65%/m, the apparent wear parameter at 110 mm from the narrow face center increases sharply from about 350 mm below meniscus, and the value of apparent wear parameter is higher with larger narrow face taper up to 1.70%/m. At the 90 mm from the narrow face center, the apparent wear parameter is lower than at 110 mm from the narrow face center and increases from about 500 mm below meniscus.

4.2.2 Effect of Carbon Concentration

The effect of carbon concentrations of 0.05, 0.1 and 0.2 wt% C steels at the conditions of slab width of
1600 mm, casting speed of 1 m/min and narrow face taper of 1.50% has been analyzed. Figures 12(a) and 12(b) show the deformed geometries of the shell and air gap near the slab corner at various distance below meniscus for the carbon concentration of 0.05 and 0.2 wt% C steels, respectively, and those of 0.1 wt% C steel can be referred to Fig. 5. In comparison with deformed geometry of 0.1 wt% C steel, the air gap near narrow side corner for the concentration of 0.05 wt% C steel nearly disappeared by the narrow face taper and the surface depression of strand reduced at the off-corner of narrow face as shown in Fig. 12(a). However, for the 0.2 wt% C steel, the narrow face taper could sufficiently compensate the shrinkage of solidifying shell and gave rise to no air gap on narrow face as shown in Fig. 12(b). And, the slight surface depression was not formed on narrow side as the solidification proceeds.

Figure 13 shows the variations of interfacial pressure between the strand and mold at mold exit with distance from narrow face center for the 0.05, 0.1 and 0.2 wt% C steels. With increasing the carbon concentration, the width of worn region decreases from 35 mm at the 0.05 and 0.1 wt% C steels to 15 mm at the 0.2 wt% C steel.

Figure 14 shows the apparent wear parameter with distance below meniscus for the 0.05, 0.1 and 0.2 wt% C steels at 90 and 110 mm from narrow face center. At 90 mm from narrow face center, the apparent wear parameter of 0.2 wt% C steel is smaller than that of 0.05 and 0.1 wt% C steels and shows almost constant value during casting. But, at 110 mm from narrow face center, the apparent wear parameter of 0.2 wt% C steel is larger than that of 0.05 and 0.2 wt% C steels and increases from about 200 mm below meniscus and shows the maximum value at mold exit. The different wear behaviours for the different carbon concentrations seem to be related with the effective coefficient of thermal expansion, as shown in Fig. 1. The effective coefficient of thermal expansion of 0.05 and 0.1 wt% C steels shows larger value below reference temperature, but that of 0.2 wt% C steel shows the constant value in whole range of temperature. Figure 15 shows the schematic diagram which shows the different wear behaviour for the 0.05, 0.1 and 0.2 wt% C steels. Figures 15(a), 15(b) and 15(c) show the solidification behaviours related with mold wear for the 0.05 and 0.1 wt% C steel at the initial,

![Fig. 13. Calculated interfacial pressure at mold exit with distance from narrow face center between the strand and mold under the various steel grades.](image)

![Fig. 14. Calculated apparent wear parameter with distance below meniscus at 90 (solid symbol) and 110 mm (open symbol) from narrow face center under the various steel grades.](image)

![Fig. 15. Schematic diagram of corner rotation of solidifying shell in continuous casting slab. (a), (b) and (c); 0.05 and 0.1 wt% C steels, (d), (e) and (f); 0.2 wt% C steel.](image)
middle stage and mold exit, respectively. Figures 15(d), 15(e) and 15(f) show the behaviour for the 0.2 wt% C steel. The length of arrow in the figure indicates the amount of thermal contraction. For the 0.05, 0.1 and 0.2 wt% C steels, at the initial stage of solidification, uniform solidifying shell forms as shown in Figs. 15(a) and 15(d). The thermal contraction of 0.05 and 0.1 wt% C steels near solidification front is larger than that of surface of solidifying shell. For the 0.2 wt% C steel, thermal contraction in the solidifying shell is uniform as shown in Fig. 15(d). At the middle stage of solidification of 0.2 wt% C steel, the thermal contraction gives rise to air gap around corner region and narrow face taper reduces the air gap around narrow off-corner region. At the mold exit, narrow face taper gives rise to no air gap around narrow off-corner region as shown in Figs. 15(e) and 15(f). At the 0.05 and 0.1 wt% C steels, large thermal contraction near solidification front can give rise to a depression on the surface of solidifying shell, which was called "corner rotation." Thus, interfacial pressure for the 0.05 and 0.1 wt% C steels shows the largest peak at the narrow corner and second largest peak around narrow off-corner region. But, for the 0.2 wt% C steel, the interfacial pressure at corner shows the largest peak and second largest peak found in 0.05 and 0.1 wt% C steels disappears.

4.2.3. Prediction of Wear Map of Narrow Side Mold

Figures 16(a) and 16(b) show the photographs of observed mold wear of narrow side at the front side and bottom side at the narrow face taper of 1.50%/m, respectively. The mold was typically used for the continuous casting of 0.1 wt% C steel and slab width of 2150 mm, after over several hundred heats. The mold wear at the front side started from about 200 mm from meniscus, and the width of mold wear at the bottom side is observed as about 30 mm.

Figure 17 shows the predicted wear map of narrow side mold at the various conditions in industrial operation. Calculated apparent wear parameter level at narrow side mold is denoted as "A, B, C and D" in this figure. Figure 17(a) shows the predicted wear map at the conditions of 0.1 wt% C steel, narrow face taper 1.50%/m, casting speed of 1 m/min and slab width of 2150 mm. The mold wear at the front side started from about 200 mm from meniscus, and the width of mold wear at the bottom side is predicted as about 30 mm. This predicted wear map are in good agreement with the observed wear phenomenon at the same casting conditions as shown in Fig. 16. Figure 17(b) shows the predicted wear map at the conditions of 0.1 wt% C steel, narrow face taper 1.50%/m, casting speed of 1 m/min and slab width of 1600 mm. In this case, the mold wear at the front side started from about 350 mm from meniscus, and the width of mold wear at the bottom side is predicted as about 35 mm. Figure 17(c) shows the predicted wear map at the conditions of 0.2 wt% C steel, narrow face taper 1.50%/m, casting speed of 1 m/min and slab width of 1600 mm. But, in this case, the mold wear at the front side started from about 150 mm from meniscus, and the width of mold wear at the bottom side is predicted as about 15 mm as shown in Fig. 17(c).
5. Conclusions

Using a 2-dimensional coupled thermo-elasto-plastic finite element model for the slice of strand in continuous casting process of slab, the thermo-mechanical behaviour of strand and mold, and the wear phenomenon of narrow face mold has been analyzed. The calculated results of deformed geometries of the strand, temperature of the mold, thickness of the solidifying shell and wear phenomenon of the narrow side mold at the typical condition of continuous casting in industry are in good agreement with the experimental observation.

To predict the possibility of mold wear, a new dimensionless parameter of "Apparent Wear Parameter", \( W_p \), which is inversely proportional to yield stress of the mold and directly proportional to the interfacial pressure between the strand and mold, was proposed. The effect of narrow face taper and carbon concentration on the mold wear has been studied. With increasing narrow face taper at the conditions of 0.1 wt% C steel, casting speed of 1 m/min and slab width of 1 600 mm, mold wear increased. Because large narrow face taper gives large interfacial pressure between the strand and mold. With increasing the carbon concentration, the width of worn region decreased from 35 mm at 0.05 and 0.1 wt% C steel to 15 mm at 0.2 wt% C steel. The smaller wear region of the 0.2 wt% C steel seems to be related with forming thermal contraction due to constant effective coefficient of thermal expansion.

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