Thermo-mechanical Modeling in Continuous Slab Casting Mould and Its Application

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In order to understand the thermal and mechanical behavior during solidification of the strand in the slab casting mould, a two-dimensional coupled thermo-mechanical finite element model was built and the corresponding FEM program was developed. The model simulates a quarter of the transverse section of the strand as it moves down in the mould at the casting speed. The heat transfer in the mould and the strand is analyzed with the steady model and the transient model, respectively. A thermo-elastoplastic plane stress model is used for analyzing the strand deformation. The heat transfer and the deformation are coupled through the interfacial thermal resistance between the strand and the mould. The model was used to investigate the effects of mould corner configuration and mould taper on the crack formation tendency of strand. The results show that employing a chamfered mould with proper corner size could modify the 2D heat transfer conditions at slab corners, hence reducing the risk of transverse corner cracks. Likewise, employing an optimized parabolic mould taper could remarkably achieve better uniformity of the strand temperature and stress, and simultaneously reduce the peak value of the stress, thus resulting in less crack occurrence, which favorably coincides with the theoretical expectation. The successful application of the coupled thermo-mechanical model demonstrates its tremendous potentialities for further understanding of the internal crack formation and for the optimization of operation parameters and the mould configuration.

KEY WORDS: thermo-mechanical analysis; continuous slab casting; finite element method.

1. Introduction

During the continuous casting process, the molten steel solidifies in the mould and forms a shell with a desirable shape and thickness. As the temperature decreases, the shell attempts to shrink away from the mould wall and to form a gap due to thermal contraction. The much larger thermal resistance of the gap will diminish the quantity of heat transfer and cause a hotter and thinner shell around the strand corner, which makes the corner a crack-sensitive region. The formation of gap in the continuous casting mould is very complex, many models have been provided to analyse this process. The numerical models help a lot in the understanding of the complex thermo-mechanical behaviour of strand in the mould.

Brimacombe and co-workers first used a two-dimensional plane stress model and analyzed a transverse billet section as it moved down in the mould.1,2) Later, more attention was paid to the coupled thermo-mechanical models based on the interfacial gap between the mould wall and the strand shell. Wang et al.3) used a modified equation to consider the influence of air gap on the boundary heat extraction, and the effect of mould taper was analyzed. Li and Thomas4) used a thermal resistance model to deal with the heat transfer coefficient between the shell and the cooling water in the mould. More complicated models calculated both the mould and the strand domains5–8) and different interfacial thermal resistance models between mould and strand were used. However, it is still a challenging work to investigate thermo-mechanical behavior with practical metallurgy process and phenomena.

In this paper, a coupled model is established to investigate the thermal and mechanical behavior in the mould during the continuous slab casting. The mould temperature is calculated together with the strand temperature to provide more precise heat transfer boundary for the strand. The steel elements’ diffusion behavior and phase transformation process are considered by a micro-segregation model. An interfacial thermal resistance model considering the influence of mould flux phase transformation is used to link the heat transfer and strand deformation. Then, a finite element program is developed to explore the formation of gap and the influence of mould corner configuration as well as the mould taper on the temperature and stress distributions in a slab casting.

2. Model Description

The model tracks a quarter of the transverse slice of the strand and the mould along the casting direction, as sche-
The coupled model consists of two parts, i.e., the heat transfer model and the deformation model. These two models are coupled through the interfacial gap between the mould and the strand, and are solved with the finite element method.

### 2.1. Heat Transfer Model

The assumptions used in the heat transfer model involve that (1) the casting process is in steady state, so the casting conditions do not vary during the analysis period; (2) the heat transfer in the casting direction is small and negligible relative to that in the cross section, so a two-dimensional model is applicable; (3) temperature at the melt surface is uniform and is assumed to be the pouring temperature.

The governing equations of heat transfer process are:

\[
\rho \left( c - L \frac{\partial f_s}{\partial T} \right) \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2} + \lambda \frac{\partial^2 T}{\partial y^2} \quad \text{(for the strand)} \quad \ldots \quad \ldots \quad (1)
\]

\[
\lambda \frac{\partial T}{\partial x} + \lambda \frac{\partial T}{\partial y} = 0 \quad \text{(for the mould)} \quad \ldots \quad \ldots \quad (2)
\]

where \( \rho \) is density of steel, \( c \) is specific heat, \( L \) is latent heat, \( f_s \) is solid fraction, \( T \) is temperature, \( t \) is time, \( \lambda \) is thermal conductivity, and \( x \) and \( y \) are along strand width and thickness, respectively. All the physical parameters vary with temperature. The relationship of \( f_s \) and \( T \) is calculated with a micro-segregation model. 9)

The temperature-dependent density is determined by the volume fraction and density of each phase:

\[
\rho = (1 - f_s) \rho_L + f_s (f_S \rho_S + f_y \rho_y) \quad \ldots \quad \ldots \quad (3)
\]

Likewise, the temperature-dependent conductivity is determined by the volume fraction and conductivity of each phase:

\[
\lambda = (1 - f_s) \lambda_L + f_s (f_S \lambda_S + f_y \lambda_y) \quad \ldots \quad \ldots \quad (4)
\]

The effect of convective heat flow in the liquid region is taken into account using the effective thermal conductivity \( \lambda_e \) for molten steel, where \( m = 5-7 \). 10)

\[
\lambda_e = 39 m \quad \ldots \quad \ldots \quad (5)
\]

Meanwhile, the equivalent specific heat method is introduced to deal with the latent heat:

\[
c_{\text{eff}} = f_s c_s + (1 - f_s) c_L - L \frac{df_s}{dT} \quad \ldots \quad \ldots \quad (6)
\]

where \( L \) is the latent heat.

The boundary conditions of heat transfer vary with the distance from the meniscus. At the surface of water slot, the heat flux from the mould is:

\[
q_1 = h_w (T_M - T_w) \quad \ldots \quad \ldots \quad (7)
\]

At the interface between the mould and the strand, the heat flux from the strand to the mould is:

\[
q_2 = h_l (T_M - T_S) \quad \ldots \quad \ldots \quad (8)
\]

where \( h_w \) is heat transfer coefficient of cooling water in the mould, \( T_M \) is temperature of mould wall, \( T_W \) is temperature of cooling water, \( h_l \) is heat transfer coefficient between the mould wall and the solidified shell, \( T_S \) is temperature of strand surface.

In Eq. (7), the heat transfer coefficient \( h_w \) is calculated by Dittus-Boelter equation: 11)

\[
\frac{h_w D}{\lambda} = 0.023 \left( \frac{Du \rho}{\mu} \right)^{0.8} \left( \frac{c \mu}{\lambda} \right)^{0.4} \quad \ldots \quad \ldots \quad (9)
\]

where \( D \) is equivalent diameter of the water slot, \( u \) is average velocity of cooling water and \( \mu \) is dynamic viscosity. The temperature of cooling water is calculated from the temperatures of inlet and outlet by linear interpolation.

In Eq. (8), the interfacial heat transfer coefficient \( h_l \) is calculated from the thermal resistance model, as shown in Fig. 2:

\[
h_l = 1 / \left( R_{\text{Contact}} + R_{FS} + R_{FL} R_{\text{Rad}} / (R_{FL} + R_{\text{Rad}}) \right) \quad \ldots \quad \ldots \quad (10)
\]

where \( R_{\text{Contact}} \) is contact thermal resistance, which is related to the thickness of crystallized mould flux in the gap between the mould and the strand according to the work of Cho, 12) \( R_{FS} \) is the conductive thermal resistance of solid flux.
$R_{c}$ and $R_{rad}$ are the conductive and radiative thermal resistances of liquid flux. According to the interfacial thermal resistance model, $h$ is affected by the mould temperature $T_m$, the strand temperature $T_s$, the crystallization temperature $T_{MFR}$ and the thickness of the mould flux $d_{sp}+d_{L}$.

### 2.2. Deformation Model

The following assumptions are used in deformation model:

- The plane stress condition is satisfied.
- The thermal deformation of mould wall is neglected, and the mould taper is considered by moving the mould wall towards the strand.
- The solidified shell is treated as a thermal elasto-plastic material.

The strain increment $\{d\varepsilon\}$ is divided into elastic strain increment $\{d\varepsilon_{el}\}$, plastic strain increment $\{d\varepsilon_{pl}\}$ and thermal strain increment $\{d\varepsilon_{T}\}$, as following:

$$\{d\varepsilon\} = \{d\varepsilon_{el}\} + \{d\varepsilon_{pl}\} + \{d\varepsilon_{T}\} \quad \text{........ (11)}$$

The thermal strain is expressed as:

$$\{d\varepsilon_{T}\} = (TLE(T) - TLE(T_0))\{1 \ 0 \ 0\}^T \quad \text{........ (12)}$$

and thermal linear expansion $TLE$ has a relation with the steel density:

$$TLE(T) = \left( \frac{\rho(T_{ref})}{\rho(T)} \right)^{1/3} - 1 \quad \text{.......... (13)}$$

where $T_{ref}$ is set to be the temperature when $f_s$ is 0.8. The thermal linear expansion has a significant influence on the thermal shrinkage of the solidified shell and the gap size.

The elastic modulus of steel decreases rapidly while temperature increases, and its value significantly influences the stress of the strand. However, the values of elastic modulus measured by different researchers differ a lot.\(^{1,3,4}\) The following expression of Kinoshita et al.\(^{13}\) is used in the present work:

$$E = 1.38 \times 10^{-2} T^2 - 225.6T + 3.146 \times 10^5 \quad \text{........ (14)}$$

The initial yield stress $\sigma_{S0}$ is obtained by the elastic strain limit $\varepsilon_{el}$ and elastic modulus $E$:

$$\sigma_{S0} = E \varepsilon_{el} \quad \text{......................... (15)}$$

The elastic strain limit $\varepsilon_{el}$ is calculated by:\(^{2}\)

$$\varepsilon_{el} = \begin{cases} 4.84 \times 10^{-4} - 3.68 \times 10^{-7} T & T < 1100^\circ C \\ 1.47 \times 10^{-4} - 8.00 \times 10^{-8} T & T \geq 1100^\circ C \end{cases} \quad \text{........ (16)}$$

Besides, the work hardening coefficient is considered 1/10 of elastic modulus at corresponding temperature.\(^{1}\)

The mould wall gives the shell a contact constraint, which allows the shell to shrink away from the mould and forms a gap, but the penetration is prohibited. Ferro-static pressure of the molten steel pushes the solidified shell towards the mould wall, and affects the gap size.

### 3. Model Application

A finite element program Visual Cast is developed based on the above model and the reliability is validated with the benchmark provided by the literatures and commercial software. Then, the program is used to investigate the influences of mould corner configuration and mould taper on the slab casting process with the practical conditions as shown in Table 1. Additionally, the mould size on narrow face (i.e. $y$) at the position $x$ from the inlet of the mould is calculated by a pre-processing module Taper Design as:

$$y = \begin{cases} 0 & 0 \leq x < tp \\ -\frac{kx + m}{2a} - \frac{b + \Delta y}{4a} & tp \leq x < h \end{cases} \quad \text{(17)}$$

In which, $k=0.025$, $m=1.531.821$, $tp=197$, $h=900$, $a=10.195.670.535$, $b=-26.628.844$, $c=17.387$, $\Delta y=0.011$. The steel grade is JBS275-B with composition in Table 2. A subroutine for the thermal-physical-mechanical properties is developed based on the microsegregation model and the calculated relationship of phase fractions ($\delta$ and $\gamma$) and temperature is shown in Fig. 3.

### 3.1. Solidification Validation

To validate the model, comparisons were made with thickness measurements on a breakout shell, which occurred at a caster under the casting conditions as shown in Table 3. The steel grade is 37Mn5 with composition in Table 4. Figure 4 shows the calculated and measured shell thickness along wide face where it can be seen that reasonable agreement is obtained.

### 3.2. Influence of Mould Corner Configuration

Four different mould corner configurations are considered, i.e., 10 mm×45°, 20 mm×45°, 30 mm×45° and 40 mm×45°. The casting conditions are the same as in Table 1.

<table>
<thead>
<tr>
<th>Table 1. Practical casting conditions.</th>
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<tbody>
<tr>
<td>Slab section size</td>
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<tr>
<td>Mould height</td>
</tr>
<tr>
<td>Mould corner</td>
</tr>
<tr>
<td>Meniscus lever</td>
</tr>
<tr>
<td>Mould taper</td>
</tr>
<tr>
<td>Casting speed</td>
</tr>
<tr>
<td>Pouring temperature</td>
</tr>
<tr>
<td>Cooling water temperature</td>
</tr>
<tr>
<td>38.0°C (outlet)</td>
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</table>

<table>
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<tr>
<th>Table 2. Composition of steel JBS275-B.</th>
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<tbody>
<tr>
<td>Element</td>
</tr>
<tr>
<td>Percentage, %</td>
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</tbody>
</table>

Fig. 3. Relation of volume fractions and temperature of 37Mn5.
Figures 5 and 6 show the temperature distribution on the shell outer surface FE and the diagonal line CG with different mould corner sizes at the mould outlet. With an increase of the corner size, the temperature of the shell increases while the thickness of the shell decreases distinctly, especially when the corner size is smaller than 30 mm. Meanwhile, when the corner size is larger than 20 mm, the highest temperature in the corner (between BD) is even higher than that in the wide and narrow faces due to bad cooling conditions of the corner caused by too large corner size.

The change of corner configuration will cause the variation of the stress distribution around the mould corner. As shown in Fig. 7, when the corner size is smaller than 20 mm, the maximum principal tension, which is the fundamental cause of the corner cracks, is located in the off-corner region obviously, but disappears when the corner size is larger than 20 mm. However, it is also important to note that the larger the corner size, the thinner the shell. Therefore, employing a chamfered mould with proper corner size could reduce the tension stress in the corner region and simultaneously avoid thin shell.

3.3. Influence of Mould Taper

The mould taper partially compensates for the strand shell shrinkage, thus reducing the influence of the air gap on the heat transfer. At the meantime, the mould taper compressed the solidified shell and changes the stress state around the strand corner region. According to the Square Radical Sign Law of Solidification, the optimal taper of the mould should be parabolic.

As shown in Fig. 8, in condition of parabolic taper, the gap size at an interested position C increases moderately, while in condition of constant taper, the gap size increases sharply at the beginning and decreases rapidly at the end, which indicates that the constant taper is too small as for the top of the mould but too big as for the bottom of the mould. Accordingly, smaller gap size in condition of parabolic taper achieves higher heat flux as shown in Fig. 9, which will benefit the cooling conditions of the strand.

In order to better estimate the thickness of the solidified shell around the corner, part of the corner region is mapped as shown in Fig. 10. Figure 11 shows the influence of
mould taper on the shell thickness of mapped region near the strand corner. Generally, the solidified shell is thicker in condition of parabolic taper than that in condition of constant taper, especially at the off-corner of narrow face, hence achieving better uniformity of shell thickness. 

**Figure 12** shows the influence of mould taper on the deformation of the solidified shell. The maximum principal stress is in extreme disorder in condition of constant taper because excessive taper at the bottom of the mould leads to considerable compressive stress in the strand. While in con-

**Figure 7.** Stress distribution with different mould corner configurations at the mould outlet.

**Fig. 12.** Maximum principal stress distribution at the outlet of the mould with different mould tapers.
dition of parabolic taper, uniformity of the stress distribution is significantly improved, which is favorably consistent with theoretical expectation.

4. Conclusions

A two-dimensional finite element program Visual Cast has been developed to investigate the influences of mold corner configuration and mold taper in the continuous slab casting mould with conclusions as following:

- On one hand, too large corner size worsens the cooling conditions of the corner, which gives rise to thinner shell. On the other hand, too small corner size makes no difference to the tensile stress concentration near the slab corner. Accordingly, employing a chamfered mould with proper corner size could modify the 2D heat transfer conditions at slab corners, hence reducing the risk of corner cracks.
- Employing an optimized parabolic mould taper could remarkably achieve better uniformity of the strand temperature, shell thickness and stress, thus resulting in less crack occurrence.

REFERENCES