Application of a Corner Chamfer to Steel Billets to Reduce Risk of Internal Cracking during Casting with Soft Reduction

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In order to get the brittle temperature range for internal crack, the solidification phase transformation model is established and LIT and ZDT are calculated. Then the fully coupled thermo-mechanical finite element models are developed using the commercial software ABAQUS to investigate stress and strain states in the brittle temperature range of the chamfer billets during soft reduction. The relation between chamfer angle and maximal principal stress, as well as equivalent plastic strain is analyzed, and the influence of chamfer angle of billet on the internal crack is studied. The results indicate that the maximal principal stress and the tensile stress decrease with the increase of chamfer angle. Reducing the soft reduction can lower the stress and strain in the brittle temperature range. It can be obtained that the larger reduction effect and lesser internal crack risk by adjusting the chamfer angle of the billet.

KEY WORDS: chamfer billet; soft reduction; finite element model; solidification phase transformation model; internal cracks.

1. Introduction

In order to get the billet with high grade, the centerline segregation and center porosity are not demanded in the continuous casting. It is an effective way to minimize the segregation and porosity of the billet by reduction of the strand near the final solidification region to compensate for solidification shrinkage.1–6) However, internal crack is observed in some billets with soft reduction. They are perpendicular to the casting direction, and located between the surface and centerline of the billets. According to Ref.7) the cracks have a relation with the strength and ductility in the mushy zone between the liquid impenetrable temperature (LIT) and the zero ductility temperature (ZDT), which can be seen in Fig. 1. The steel has no strength and no ductility, and behaves as the liquid above the zero strength temperature (ZST). Hot tears can be refilled with surrounding liquid and leave no crack, which formed between ZST and LIT. The temperature between LIT and ZDT is known as the brittle temperature range. When the applied tensile stress exceeds the critical fracture stress or the accumulated strain exceeds the critical strain, the cracks will be initiated in the brittle temperature range.

Recently, the finite element methods for the couple analysis of fluid flow and heat transfer deformation behavior in the continuous casting process have been reported.8,9) The formation of internal cracks in the billet and the blooms with soft reduction are also investigated by finite element methods.10,11) The objective of the present study is to analyze the crack susceptibility and to lighten the internal cracks by the chamfer billet with soft reduction, using a 3-dimensional coupled thermo-elastic-plastic finite element model. A one roll finite element soft reduction model is created in order to research the method of reducing risk of internal crack formation. If the method is valid in one roll set-up, two or three rolls are also valid due to its effectiveness in each roll of multi-roll soft reduction apparatus. The finite element software ABAQUS is used to calculation. With the calculations, the stress and strain distributions in the brittle temperature range of the right-angle billet and chamfer billet are determined.

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Fig. 1. Schematic diagram of mechanical properties near melting point during continuous casting of steels.
2. Model Description

2.1. Solidification Phase Transformation Model

The mushy zone is divided into the mass/liquid feeding zone (0.4<\(f_s\)<0.9) by Clyne et al., and the cracking zone (0.9<\(f_s\)<0.99). Cracks are not formed in the mass/liquid, whereas cracks are formed in the cracking zone and they cannot be refilled with the liquid, because the dendrite arms are close enough to resist feeding of the surrounding liquid. In order to get the LIT and ZDT, the solidification phase transition model will be created.

In the continuously cast strand, the microsegregation has been calculated using the direct difference method suggested by Ueshima. The growing dendrite is shown in Fig. 2(a). The transverse cross section of them is approximated by a regular hexagon, one sixth of which is shown in Fig. 2(b). In the transverse section of the dendrite, the complete mixing in the liquid phase is assumed to give rise to the uniform solute concentrations. In the axial direction of dendrite, the diffusion in solid and liquid is assumed to be negligible. Between \(\delta\)-Fe and liquid phase, \(\gamma\)-Fe develops from the interface. The solute concentrations are assumed to be in the local equilibrium in the solid-liquid and \(\delta/\gamma\) interfaces. The equilibrium distribution coefficient between \(\gamma\)-Fe and \(\delta\)-Fe is assumed to be \(k^{\delta\gamma}\). During the \(\delta/\gamma\) transformation, sulfur, silicon and phosphorus, for which \(k^{\delta\gamma}\)<1, are redistributed from \(\gamma\)-Fe to \(\delta\)-Fe, but carbon and manganese, for which \(k^{\delta\gamma}\)>1, are redistributed from \(\delta\)-Fe to \(\gamma\)-Fe.

No local equilibrium and axial diffusion on the assumptions of the complete mixing in liquid, and the solute distribution in the three phase (\(\delta\), \(\gamma\), liquid) will be calculated. Diffusion of dendrite will be calculated in X direction of the triangular OPQ in Fig. 2(b) by one-dimensional diffusion, and the triangular cross section is divided into 100 parts parallel to vertical lines. When the liquid temperature (\(T_{Liq}\)) and the \(\delta/\gamma\) transformation temperature (\(T_{\delta\gamma}\)) become equal to the actual temperature of the sample, the \(\delta/\gamma\) transformation and solidification in one part are completed and the interface moves to the next part. \(T_{Liq}\) and \(T_{\delta\gamma}\) are shown in the following equations.

\[
T_{Liq} = 1536 - 78(\text{wt}\%\text{C}) - 7.6(\text{wt}\%\text{Si}) - 4.9(\text{wt}\%\text{Mn}) - 34.4(\text{wt}\%\text{P}) - 38(\text{wt}\%\text{S}) \quad (1)
\]

\[
T_{\delta\gamma} = 1392 - 1122(\text{wt}\%\text{C}) - 60(\text{wt}\%\text{Si}) + 12(\text{wt}\%\text{Mn}) - 140(\text{wt}\%\text{P}) - 160(\text{wt}\%\text{S}) \quad (2)
\]

Due to the above assumption, solute diffuses completely in the liquid phase, and diffuses limited in the solid phase. The solute concentration will be obtained by Fick's second law as the following Eq. (3). Where \(C_s\) is the solute concentration in the solid phase, \(D_s\) (\(T\)) is the diffusion coefficient in the solid phase when the temperature is \(T\).

\[
\frac{\partial C_s}{\partial t} = \frac{\partial}{\partial x} \left( D_s(T) \frac{\partial C_s}{\partial x} \right) \quad (3)
\]

The initial conduction is described as the Eq. (4), and the Eq. (5) is the boundary conditions of the model. Where \(C_0\) is the initial solute concentration in the liquid phase, \(\lambda_{\text{PDAD}}\) is the space between primary crystallization.

\[
\left( \frac{\partial C_s}{\partial x} \right) |_{x=0} = 0 \quad (4)
\]

\[
\left( \frac{\partial C_s}{\partial x} \right) |_{x=\lambda_{\text{PDAD}}} = 0 \quad (5)
\]

The weight solid fraction \(f_s\) is in the solid plus liquid phase, and the \(\delta\)-Fe fraction and \(\gamma\)-Fe fraction in the solid phase can be calculated. The chemical composition of the steel 45# is shown in Table 1. The brittle temperature range is between LIT (\(f_s=0.9\)) and ZDT (\(f_s=0.99\)). The LIT and ZDT will be calculated by the solidification phase transformation model.

2.2. Soft Reduction Model

It is the first step to calculated the temperature development in the billets when it is rolled by the soft reduction roll, temperature calculation model is introduced in detail elsewhere. Then the calculated temperature distribution is transferred to rolling model as the initial conditions. The rolling model is created by using ABAQUS/Explicit to calculate the stress and strain fields in the billets with soft reduction. The rolls are assumed to discrete rigid body, since loads acting on the rolls are small and the yield stresses of the rolls are much higher than that of the billet. One quarter of the billet is modeled, due to the symmetry of the deformation behavior of the billets in the soft reduction process. Figure 3 shows the geometry and mesh of the model. The symmetry faces of the billet in the thickness (X) and width (Y) direction are the symmetry boundary. The length of the billet is 1 000 mm, and the section temperature distributes along the Z direction evenly.

In the rolling model, the thermo-physical properties are taken from Refs. which change with temperature such as density, specific heat capacity, thermal conductivity, thermal expansion coefficient, Young’s modulus. The flow
stress of billets is determined by the following Eq. (6).\(^{21}\)

\[
\sigma = \left[ A + B e^{\epsilon} \right] \left[ 1 + C e^{\epsilon} \right] \left[ 1 - T^m \right] \quad \ldots \ldots \quad (6)
\]

Where \( \epsilon \) is the equivalent plastic strain, \( T^* \) is the homologous temperature, the five material constants are shown in Table 2, which are determined by tests. The material model proposed was used to obtain the flow stress in the mushy zone at the temperature exceeding ZDT.\(^{22}\) The steel has neither strength nor ductility and behaves as a liquid above ZST.\(^{23}\)

The billet will be cooled down by the cold rolls through heat conduction. The temperature will drop sharp at the surface of the billets which contact to the rolls. Between the billet and the rolls, the heat transfer coefficient depends on the casting speed, billet and roll temperature, the thickness reduction, and the surface roughness of the billet and the rolls. It is assumed to be 7 000 W/(m\(^2\)·K)\(^{24,25}\) in this model. The friction coefficient is assumed to 0.33. The conversion factor of plastic heat generation is 0.9. The Eq. (7) describes the heat flux at the billet surface when the heat is led away to the atmosphere by radiation and convection from the billet surface in the area outside the roll gap.

\[
q = \sigma \epsilon \left( T_b^4 - T_\infty^4 \right) + 1.24(T_b - T_\infty)^{1.33} \quad \ldots \ldots \quad (7)
\]

Where \( \sigma \) is the Stefan-Boltzmann constant, \( \epsilon \) is the emissivity of the billet that is assumed to be 0.8,\(^{26}\) \( q \) is the heat flux at the billet surface, \( b \) and \( \infty \) denote the billet surface and the ambient.

### 3. Results and Discussion

There are six different billet will be discussed, which are distribution as the Fig. 4. In the figure, the length of \( b \) is 25 mm, and the angles (\( \alpha \)) of chamfer are 0°, 10°, 20°, 45°, 60° and 65°. There are two reductions (\( \Delta H \)) which are 2 mm and 4 mm in the soft reduction model. The larger tensile stress and the equivalent plastic strain than the critical fracture stress and critical strain is, the more easily the internal cracks form in the brittle temperature range. Therefore, in this article, besides the equivalent plastic strain, the maximal principal stress in the brittle temperature range will be also analyzed to establish the correlation between the stress state and the internal cracks.

They are calculated that LIT is 1 440°C and ZDT is 1 370°C by the solidification phase transformation model. Usually the possibility of internal cracks is estimated by comparison of the equivalent plastic strain with a critical strain in the brittle temperature range. Internal cracks will possibly be generated, when the equivalent plastic strain is larger than the critical strain. The cracks that form in the solidification front during soft reduction are sensitive not only to strain but also to stress. Therefore, besides the equivalent plastic strain, the maximal principal stress in the brittle temperature range is also analyzed in this article.

The rolled billet with 45° chamfer angle is shown in Fig. 5, which is casted for 45 s and reduced by 2 mm. Position 1 is the section of undeformed area, and position 2 is just blow the roll, while position 3 is after rolled. These three

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**Table 2.** Material constant.

<table>
<thead>
<tr>
<th>constant</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>n</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
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<td>496</td>
<td>434</td>
<td>0.28</td>
<td>0.307</td>
<td>0.804</td>
</tr>
</tbody>
</table>

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**Fig. 3.** Geometry and mesh of the finite element model. (Online version in color.)

**Fig. 4.** Section of chamfer billet during soft reduction.

**Fig. 5.** Maximal principal stresses in the brittle temperature range at different position along the longitudinal direction (in unit of MPa). (Online version in color.)
positions are along longitudinal direction, and the maximal principal stresses in the brittle temperature range are illustrated. It can be seen that the maximal principal stresses in position 2 is the largest, as well as the billets with other chamfer angles. Due to this reason, only the maximal principal stresses in position 2 are studied in the following discussions, which is just below the roll.

As shown in Fig. 6, the maximal principal stresses in the brittle temperature range of different billet with different chamfer are illustrated with the 2 mm reduction. The maximal principal stress decreases with the increase of $\alpha$. The stresses are always positive when $\alpha$ is less than 20°. The beginning decrease region of tensile stress is in the center of brittle temperature range, and the stress change to compressive stress when the $\alpha$ is large than 45°. The compressive stress and stress region increase with the incensement of $\alpha$. The stress distribution in the brittle temperature range with 4 mm reduction is the similar to it with 2 mm reduction. This implies that the risk of internal cracks occurrence reduces with the incensement of $\alpha$.

The deformation carries on with the soft reduction process. Equivalent plastic strain after rolling is larger than during rolling, which describes the billet deformation degrees. Therefore, the equivalent plastic strain after rolling will be discussed in position 3. It can be seen from Fig. 7 that maximum of maximal principal stress is always positive in the brittle temperature range of the billets with different chamfer. It implies that tensile stresses are existence and can be reduced by increasing $\alpha$. The maximum of equivalent plastic strain of 2 mm is lower than that with a soft reduction of 4 mm. The similar law can be seen in tensile stresses during soft reduction. According to the simulated results, the optimized soft reduction process can be developed to avoid the formation of internal cracks by the change of $\alpha$ and decrement of reduction.

In order to get better reduction effect and lesser risk of internal cracks, reduction efficiency is analyzed. The reduction efficiency is assumed by the following Eq. (8).27 Where $\Delta h$ is the reduction of liquid core thickness, $\Delta H$ is the reduction of the finite element model.

$$\eta = \frac{\Delta h}{\Delta H} \quad \text{(8)}$$

As the reduction efficiency is used to describe the billet after rolled, the $\eta$ is compared in the position 3. Figure 8 shows that the reduction efficiency can be improved obvi-
ously by enhancing $\alpha$ of chamfer billet. Reduction efficiency of 4 mm reduction is larger than it of 2 mm reduction when the chamfer angle is lesser than 45°, and they are distinguishable not clearly with the other chamfer angle. Thus it can be predicted that higher reduction efficiency can be created by increasing chamfer angle or by increasing the reduction. In order to reduce the risk of internal cracks in the brittle temperature range, increasing chamfer angle is more effective way to get higher reduction efficiency. The same reduction effect with larger reduction and lesser internal crack risk can be obtained by adjusting the chamfer angle of the billet.

4. Conclusions

The LIT and ZDT are calculated by the solidification phase transformation model. With fully coupled thermomechanical finite element models, which are developed using the commercial software ABAQUS, stress and strain states are calculated in the brittle temperature range of the billet during soft reduction. The relation between chamfer angle and maximal principal stress, as well as equivalent plastic strain is analyzed. The influence of chamfer angle of billet on the internal crack is studied, and the important results can be summarized as follows.

1) The brittle temperature range is between 1440°C and 1370°C which is calculated by the solidification phase transformation model. The analysis of stress and strain in the brittle temperature range of chamfer billet can receive the effect of the chamfer angle to the internal crack.

2) The maximal principal stress and the tensile stress decrease with the increase of chamfer angle. The stress change to compressive stress when $\alpha$ is large than 45°, and the compressive stress and stress region increase with the incensement of chamfer angle. The maximum tensile stress reduces with chamfer angle increment, especially larger than 45°.

3) Reducing the soft reduction can lower the stress and strain in the brittle temperature range. The maximum equivalent plastic strain reduces 50% with reducing the soft reduction from 4 mm to 2 mm.

4) The reduction efficiency can be improved obviously by enhancing chamfer angle. The larger reduction effect and lesser internal crack risk can be obtained by adjusting the chamfer angle of the billet.

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