Analysis of Solidification Cracking Using the Specific Crack Susceptibility

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Using a 2-dimensional finite element, the effects of carbon content, slab width, narrow face taper and casting speed on solidification cracking during continuous casting of slabs were analyzed. The possibility of solidification cracking during continuous casting of slabs was predicted using the "Specific Crack Susceptibility", $^S S_C$. The new proposed parameter, $^S S_C$, can represent the averaged possibility of solidification cracking of the strand during continuous casting in the mold. The surface crack formed near corner region of strand at the initial stage of solidification, and the internal crack was found in the internal regions of wide center, corner and off-corner at the middle and final stage of solidification. The carbon range sensitive to solidification cracking is between 0.1 wt% C and 0.14 wt% C steels. At the slab widths of 1 900 mm and 2 150 mm, the possibility of solidification cracking increased in the regions of wide center, corner and off-corner in comparison with the slab width of 1 600 mm. With increasing narrow face taper, the possibility of solidification cracking decreased along the region of wide face due to the mechanical compression imposed by the narrow face taper. With increasing casting speed, the possibility of solidification cracking increased in the regions of wide center, corner and off-corner, because the shell thickness is largely decreased due to decrease of dwelling time of strand within the mold. These predictions at various casting conditions were in good agreement with the experimental observations in industry.

KEY WORDS: specific crack susceptibility; solidification cracking; carbon content; slab width; narrow face taper; casting speed.

1. Introduction

The continuous casting process has been adopted world-widely by steel industries over last two decades owing to its inherent advantages of low cost, high yield, flexibility of operation, and ability to achieve a high quality cast product.¹⁾ In spite of these advantages, the quality of the strand suffers considerably from the presence of various defects, such as longitudinal and transverse surface cracks and internal cracks, breakouts and so on. The continuous casting process has been mathematically modeled to increase the understanding of the roles of important process variables on the defects.^{2–10)} Despite such intense studies, the thermo-mechanical behaviors of the stand and the mold during continuous casting are not fully understood due to the complex operating conditions of continuous casting process. In particular, a complexity arises in the formation of an air gap between the solidifying shell and the mold wall as a result of thermal and δ/γ transformation contractions.

Understanding the mechanical behavior of the mushy zone during continuous casting is very important to obtain good quality cast products, because all cracks observed in continuously cast steels originate and propagate along the

interdendrites in the mushy zone. Especially, internal cracks tend to occur in a brittle temperature range, ΔT_B , due to the thermal contraction, mechanical deformation and δ/γ phase transformation.¹¹⁾ The ductility loss of the mushy zone is associated with microsegregation of solute elements between solidifying dendrites.¹²⁾ A tensile deformation applied to the brittle temperature range causes the separation of dendrites. Hot tears can take place under a small strain when the interdendritic liquid film is isolated to resist feeding of the surrounding liquid through the dendrite arms. It is difficult to model this phenomenon since it depends on steel composition, microstructure, dendrite arm spacing and so on.¹³⁾ Thus the mathematical model describing the thermo-mechanical behavior of the mushy zone as a function of temperature and steel composition, have to be developed to calculate the temperature and stress distribution in the solidifying shell accurately, and to examine their influence on the crack formation.

To estimate the solidification cracking tendency during continuous casting, many researchers have proposed cracking conditions over the last two decades.^{3–6,14–18)} Previous reports on the cracking condition in continuous casting of steels are listed in **Table 1**. Clyne *et al.*¹⁴⁾ proposed the crack susceptibility coefficient to estimate the cracking ten-

Table 1. Representative cracking condition in continuous casting of steels.

Researcher	Applied Range of Strand	Cracking Condition
Clyne <i>et al.</i> ⁽¹⁴⁾	$t_v=0.9 < f_s < 0.99$, $t_c=0.4 < f_s < 0.9$	$CSC=t_v/t_c$
Kinoshita <i>et al.</i> ⁽³⁾	In the solidifying shell	σ_{max} and σ_{trans}
Thomas <i>et al.</i> ⁽⁵⁾	In the solidifying shell	σ_{max}
Kim <i>et al.</i> ⁽¹⁵⁾	In the solidifying shell	σ_{max}
Kristiansson ⁽⁴⁾	$T > T_s-100^\circ\text{C}$	$\varepsilon_c=0.2\%$
Yamanaka <i>et al.</i> ⁽¹⁶⁾	$ZST(f_s=0.8) > T > ZDT(f_s=0.99)$	$\varepsilon_c=1.6\%$
Kelly <i>et al.</i> ⁽⁶⁾	$T > T_s-70^\circ\text{C}$	σ_{hoop}/σ_y
Kim <i>et al.</i> ^(17,18)	$LIT(f_s=0.9) > T > ZDT(f_s=0.99)$	σ_{max}/σ_y

dency during continuous casting of steels. They divided the mushy zone into the mass/liquid feeding zone ($0.4 < f_s < 0.9$) and the cracking zone ($0.9 < f_s < 0.99$). Cracks formed in the mass/liquid feeding zone are refilled with the surrounding liquid, whereas cracks formed in the cracking zone can not be refilled with the liquid, because the dendrite arms are close enough to resist feeding of the surrounding liquid. They proposed the critical solid fraction to resist feeding of 0.9. However, the crack susceptibility coefficient can be increased with increasing carbon content, because the mushy zone increases with increasing carbon content. Many researchers^(3,5,15) estimated the possibility of cracking in comparison with the maximum principal stress and transverse stress along the wide and narrow face. And, some investigators^(4,16) have used a strain based fracture criterion in the mushy zone, assuming that the material fractures if the total mechanical strain exceeds 0.2%⁽⁴⁾ and 1.6%.⁽¹⁶⁾ However, the comparison of the absolute stress and strain values is not enough to investigate the possibility of cracking during continuous casting, because the stress in the solidifying shell changes as a function of temperature and the mushy zone solidifies in almost stress free state, even though the strain occurs in the mushy zone. Kelly *et al.*⁽⁶⁾ and Kim *et al.*^(17,18) proposed that the solidification cracking occurs in the mushy zone, when the maximum principal stress exceeds the yield stress at that temperature. However, the cracking conditions were estimated in the restricted carbon content range and the same operation conditions. Recently, Won *et al.*⁽¹⁹⁾ proposed a cracking criterion based on plastic deformation energy in the brittle temperature range to predict the cracking phenomenon of whole carbon range.

The objective of the present study is to analyze the crack susceptibility during solidification, using a 2-dimensional coupled thermo-elasto-plastic finite element model. To accomplish this, the new parameter of "Specific Crack Susceptibility" has been proposed, which is based on the critical fracture stress and critical strain. The specific crack susceptibility, which is a generalized thermo-mechanical property model of the mushy zone, can be applied at various steel compositions and operation conditions. Using the specific crack susceptibility, the effects of carbon content, slab width, narrow face taper and casting speed on solidification cracking were studied.

2. Cracking Criterion

2.1. Critical Strain and Critical Fracture Stress for Crack Formation

Figure 1 shows a schematic diagram of the mechanical

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

properties of mushy zone and corresponding structure of solid/liquid interface during casting. Above zero strength temperature (ZST), the steel has no strength and no ductility, and behaves as a liquid. Hot tears which formed between ZST and liquid impenetrable temperature (LIT) can be refilled with the surrounding liquid and leave no crack as shown in Fig. 1. In the temperature range between LIT and ZDT, which is known as the brittle temperature range, ΔT_B ,⁽¹¹⁾ the solidifying steel begins to behave like solid susceptible to crack due to the presence of the interdendritic liquid films caused by the microsegregation of solute elements. The cracks can be initiated in the brittle temperature range, when the accumulated strain exceeds the critical strain and/or the applied tensile stress exceeds the critical fracture stress during solidification.

The main factors affecting the critical strain at which cracks form, are reported to be the brittle temperature range and strain rate by many researchers.⁽²⁰⁻²⁴⁾ Recently, authors take into account the brittle temperature range and strain rate to predict the critical strain as follows.⁽¹⁹⁾

$$\varepsilon_c = \frac{\varphi}{\dot{\varepsilon}^{m^*} \Delta T_B^{n^*}} \quad \text{.....(1)}$$

where φ is the constant, m^* is the strain rate exponent on the critical strain and n^* is the brittle temperature range exponent on the critical strain. The critical strain decreases with increasing strain rate and with increasing brittle temperature range, which is dependent on cooling rate and solute element. The experimental data of critical strain were best fitted to Eq. (1) by a non-linear fitting method to obtain parameters of $\varphi=0.02821$, $m^*=0.3131$ and $n^*=0.8638$.⁽¹⁹⁾

The calculated critical fracture stress at which cracking occurs, can be used as the standard of fracture using the critical strain for crack formation. The critical fracture stress of pure δ -phase and γ -phase for crack formation in the brittle temperature range is calculated using the Eq. (1) and the constitutive equation proposed by Han *et al.*⁽²⁵⁾

$$\begin{aligned} \sigma_c^\delta &= \frac{\varepsilon_c^{n_s}}{\beta_\delta} \cdot \sinh^{-1} \left[\frac{\dot{\varepsilon}}{A_\delta} \exp \left(\frac{Q_\delta}{RT} \right) \right]^{m_s} \\ &= \frac{\varphi^{n_s}}{\dot{\varepsilon}^{m^* \cdot n_s} \Delta T_B^{n^* \cdot n_s} \beta_\delta} \cdot \sinh^{-1} \left[\frac{\dot{\varepsilon}}{A_\delta} \exp \left(\frac{Q_\delta}{RT} \right) \right]^{m_s} \quad \text{.....(2)} \end{aligned}$$

Table 2. Parameters in Eqs. (2) and (3) for δ -phase and γ -phase.

	$\beta(\text{MPa}^{-1})$	n	$A(\text{sec}^{-1})$	$Q(\text{kJ/mol})$	m
δ -phase	0.0933	0.0379	6.754×10^8	216.9	0.1028
γ -phase	0.0381	0.2100	1.192×10^{10}	373.4	0.2363

$$\sigma_c^\gamma = \frac{\varepsilon_c^{n_\gamma}}{\beta_\gamma} \cdot \sinh^{-1} \left[\frac{\dot{\varepsilon}}{A_\gamma} \exp \left(\frac{Q_\gamma}{RT} \right) \right]^{m_\gamma}$$

$$= \frac{\varphi^{n_\gamma}}{\dot{\varepsilon}^{m^* n_\gamma} \Delta T_B^{m^* n_\gamma} \beta_\gamma} \cdot \sinh^{-1} \left[\frac{\dot{\varepsilon}}{A_\gamma} \exp \left(\frac{Q_\gamma}{RT} \right) \right]^{m_\gamma} \dots\dots(3)$$

Table 2 gives the parameters for δ -phase and γ -phase used in Eqs. (2) and (3) obtained by a non-linear fitting method based on the experimentally measured data.¹⁹⁾

The critical fracture stress of the mushy zone for carbon steel, σ_c , can be given from the critical fracture stress of the δ -phase and the critical fracture stress of γ -phase through the rule of mixtures as follows.

$$\sigma_c = \left(\frac{f_s - c f_s}{1 - c f_s} \right) \cdot [f_s \sigma_c^\delta + f_s \sigma_c^\gamma]$$

for $ZDT \leq T \leq LIT$ (4)

Below the critical solid fraction, $c f_s$, the critical fracture stress of the mushy zone becomes zero: that is $\sigma_c = 0$. The critical fracture stress of mushy zone, σ_c , is supposed to increase linearly with increasing solid fraction between ZST and ZDT.

Many investigations^{11,19,26)} on the relationship between the crack index by the industrial observations and the carbon content have reported carbon content of maximum cracking as the carbon range between 0.08 wt% C and 0.25 wt% C. Thus, the cracking prediction from critical strain or critical fracture stress has to show possibility below 0.08 wt% C and above 0.25 wt% C steels. But, Won *et al.*¹⁹⁾ pointed out that the cracking prediction based on critical strain or critical fracture stress can not explain the cracking phenomenon of whole carbon range, even though the calculated critical strain and critical fracture stress are in good agreement with the experimentally measured data. Recently, to predict the cracking tendency of whole carbon range, Kim *et al.*¹¹⁾ and Won *et al.*¹⁹⁾ proposed a cracking criterion based on strain in the brittle temperature range and plastic deformation energy in the brittle temperature range, respectively. However, the effects of operating conditions of continuous casting process, such as slab dimension, narrow face taper, casting speed and so on, on solidification cracking during continuous casting cannot be predicted by proposed models.

2.2. Crack Susceptibility Coefficient

In order to predict the effects of operating conditions of continuous casting process on solidification cracking, the crack susceptibility coefficient, S_c , was proposed by Kim *et al.*^{17,18)} as follows.

$$S_c = \frac{\sigma_{\max}(T)}{\sigma_c(T)} \quad \text{for } ZDT \leq T \leq LIT \quad \dots\dots(5)$$

$$S_c = 0 \quad \text{for } LIT < T \leq T_L \text{ or } \sigma_{\max}(T) < 0$$

where $\sigma_{\max}(T)$ is the calculated maximum principal stress at that temperature using the thermo-mechanical models and $\sigma_c(T)$ is the critical fracture stress for cracking at that temperature, which was analyzed based on Eq. (4). It is reported that the cracks, originated from interdendritic liquid film, is mainly affected by the maximum principal stress.^{5,16)} Cracks can originate from the region where S_c exceeds 1 and the possibility of solidification cracking increases with increasing value of S_c . In this study, the corresponding solid fraction for LIT and ZDT were used to be 0.9 and 0.99, which is proposed by Clyen *et al.*¹⁴⁾ and Won *et al.*,²⁷⁾ respectively.

2.3. Specific Crack Susceptibility

The crack susceptibility coefficient, S_c , means the instantaneous possibility of solidification cracking at a position. The crack susceptibility coefficient is not related to the measured crack index, but the possibility of solidification cracking at a distance below meniscus. Thus, in order to estimate the possibility of solidification cracking of whole strand, which can be compared with the crack index by the experimental observations in industry, Kim²⁸⁾ proposed the total crack susceptibility, $^T S_c$, for crack formation as follows.

$$^T S_c = \int_0^{t_c} \int_{A_m} S_c dt dA_m \quad \dots\dots\dots(6)$$

where A_m is the area of mushy zone in the brittle temperature range, t_c is the casting time. Using the Eq. (6), Kim²⁸⁾ calculated the possibility of solidification cracking at various carbon and sulfur contents in continuously cast beam blank. However, the possibility of solidification cracking at various casting speeds, can not be explained by the total crack susceptibility, because the total crack susceptibility decreases with increasing casting speed due to decrease of dwelling time of strand within the mold, as shown in Eq. (6). Generally, the possibility of solidification cracking increases with increasing casting speed in industrial operations.²⁹⁾

All cracks which form at the solidification front during continuous casting, tend to originate in the brittle temperature, and can be propagated along the interdendrites as solidification proceeds, due to the thermal contraction, mechanical deformation and δ/γ phase transformation. The crack index by the experimental observations in industry, has been related to crack propagation, because the crack index implies the number of crack per unit area after solidification, which can be visible to the naked eye. Thus the total volume of the solidified shell should be taken into account the total crack susceptibility to predict the possibility of solidification cracking of whole strand. In this study, in order to take into account the effect of casting speed on solidification cracking of whole strand within the mold, authors divided the total crack susceptibility by total volume of solidified shell, because the crack initiation and propagation can proceed only in the solidified shell. Here authors propose the specific crack susceptibility, $^S S_c$, as follows.

Fig. 2. Initial finite element mesh for calculating the temperature and stress of slab and temperature of mold.

Table 3. The calculated total crack susceptibility, total volume of solidified shell and specific crack susceptibility as a function of casting speed.

Casting speed, m/min	Dwelling time, sec	tS_c	$\iint dt dA_s$	sS_c
0.8	57.75	37552.6	666120.4	0.05638
1.0	46.2	29318.6	454939.9	0.06445
1.2	38.5	22789.5	335852.7	0.06786
1.4	33.0	19009.8	256578.9	0.07409

$$^sS_c = \frac{\iint_{A_m} S_c dt dA_m}{\iint_{A_s} dt dA_s} \dots\dots\dots(7)$$

where A_s is the area of solidified shell. The specific crack susceptibility, sS_c , means the averaged possibility of solidification cracking of whole strand within the mold during continuous casting. **Table 3** shows the calculated total crack susceptibility, total volume of solidified shell and specific crack susceptibility as a function of casting speed. The calculated total crack susceptibility decreases with increasing casting speed, and the calculated total volume of solidified shell also decreases with increasing casting speed, due to decrease of total heat extraction. The specific crack susceptibility increases with increasing casting speed, because the variation of total volume of solidified shell is much larger than that of the total crack susceptibility. Thus the effect of casting speed on solidification cracking of whole strand within the mold has been studied using the specific crack susceptibility.

3. Calculation Procedure

Figure 2 shows the initial finite element mesh for calculating the temperature and thermal stress of 1 600×224 mm slab and the temperature of Cu–0.1wt%Ag mold. A quarter section was modeled using symmetry conditions. The finite element calculation for stress analysis was carried out under the plane strain condition with 2-dimensional slice model. The thermal conductivity of strand and mold were assumed to be 36 W/m K and 380 W/m K.^{6,30)} Calculation was performed at the condition of casting speed of 1 m/min. The distance from meniscus to mold exit is 770 mm. The Coulomb friction law with the friction coefficient of 0.1 has been applied to the contact surface between strand and mold. The steel compositions used in the calculation are

Fig. 3. The calculated crack susceptibility distributions of strand at various distance below meniscus at the typical casting conditions.

0.05–0.6C–0.03Si–0.4Mn–0.02P–0.02S. The temperature at meniscus was taken as the temperatures which is superheated by 20°C such as 1 548, 1 544, 1 541, 1 537, 1 521 and 1 505°C at the carbon contents of 0.05, 0.1, 0.14, 0.2, 0.4 and 0.6 wt% C steels, respectively. Each thermal resistance component was explained in the previously published papers.¹⁰⁾

4. Results and Discussion

In previous work,^{10,31)} the calculated results of deformed geometries of the strand, temperature of strand and mold, the thickness of solidifying shell and the wear phenomenon of narrow side mold had been showed in good agreement with the experimental observations at the typical casting conditions in industrial operation of 0.1 wt% C, slab width of 1 600 mm, casting speed of 1 m/min and narrow face taper of 1.5%/m.

Figure 3 shows the calculated crack susceptibility distributions at various distances below meniscus at the typical casting conditions. At the initial stage of solidification, the calculated crack susceptibility is highest at the surface of strand as shown in Fig. 3(a). The surface cracks can origi-

Fig. 4. The calculated crack susceptibility distributions of strand at the mold exit as a function of carbon content.

nate from near corner region of strand at the initial stage of solidification, because the surface temperature of corner region is in the brittle temperature range. This type of surface cracks around corner region of slab is called the corner crack or edge crack. This prediction is in good agreement with the experimental observation.²⁹⁾ As solidification proceeds, the internal cracks can start to form in the internal regions of wide center, corner and off-corner, as shown in Figs. 3(b) and 3(c). At the mold exit, the internal cracks of off-corner and wide center can give rise to a breakout and longitudinal surface crack, respectively, as shown in Fig. 3(d). The depth of internal cracks is observed about 7–20 mm from the strand surface in industrial operation,²⁹⁾ these predictions and the calculated depth of internal cracks are in good agreement with the experimental observations.

4.1. Effect of Carbon Content

The effect of carbon content on solidification cracking at the conditions of slab width of 1 600 mm, casting speed of 1 m/min and narrow face taper of 1.5%/m has been analyzed. **Figure 4** shows the calculated crack susceptibility distributions of strand at the mold exit as a function of carbon content. At low carbon steels, the crack susceptibility is larger than that at medium and high carbon steels. At the carbon ranges from 0.1 wt% C and 0.14 wt% C steels, the crack susceptibility increases in the regions of wide center, corner and off-corner, as shown in Figs. 4(b) and 4(c), due to the shrinkage of the δ/γ phase transformation in the brittle temperature range. **Figure 5** shows the calculated specific crack susceptibility of whole strand, the strain in the brittle temperature range and experimentally measured corner crack index²⁹⁾ as a function of carbon content. The strain in the brittle temperature range introduced by Kim *et al.*,¹¹⁾ have been computed as a function of carbon content using the microsegregation analysis. The crack index was measured at a commercial plant as a function of carbon

Fig. 5. The calculated specific crack susceptibility of whole strand, the strain in the brittle temperature range and experimentally measured corner crack index as a function of carbon content.

content in continuously cast steel slabs.²⁹⁾ The strain induced by variation of temperature, is generally expressed as the sum of the thermal strain caused by cooling and the strain induced by δ/γ phase transformation. A dotted line indicates the calculated thermal strain and the hatched regions indicate the strain increase induced by δ/γ phase transformation. The calculated thermal strain linearly increases with increasing carbon content. But, the effect of δ/γ phase transformation on the strain in the brittle temperature range becomes dominant at the carbon ranges from 0.08 wt% C to 0.22 wt% C, at which the peritectic reaction occur, because all δ/γ phase transformation occurs in the brittle temperature range. The carbon range of maximum specific crack susceptibility is about between 0.1 wt% C and 0.14 wt% C steels, which agrees well with the calculated strain and experimentally measured corner crack index.²⁹⁾ Therefore the possibility of solidification cracking during continuous casting of slabs can be successfully predicted using the specific crack susceptibility.

4.2. Effect of Slab Width

The effect of slab width on solidification cracking at the conditions of 0.1 wt% C, casting speed of 1 m/min and narrow face taper of 1.5%/m has been analyzed. **Figure 6** shows the calculated crack susceptibility distributions of strand at the mold exit as a function of slab width. At the slab widths of 1 900 mm and 2 150 mm, the crack susceptibility increases in the regions of wide center, corner and off-corner in comparison with the slab width of 1 600 mm. **Figure 7** shows the calculated specific crack susceptibility of whole strand and experimentally measured corner crack index²⁹⁾ as a function of slab width. Choi and Yim *et al.*²⁹⁾ measured the crack index in the corner of slab at various slab widths in industrial operation. They reported that the hair crack and longitudinal surface crack increase with increasing slab width in the corner and off-corner of slab, respectively. Thomas *et al.*³²⁾ also reported that decreasing slab width might be expected to reduce surface depression. The calculated behavior around corner region at various slab widths is in good agreement with the experimental observation.²⁹⁾

4.3. Effect of Narrow Face Taper

Breakout in continuous casting process of slab is closely related with inadequate amount of narrow face taper. When

Fig. 6. The calculated crack susceptibility distributions of strand at the mold exit as a function of slab width.

Fig. 7. The calculated specific crack susceptibility of whole strand and experimentally measured corner crack index as a function of slab width.

the narrow face taper is small, the strand continues to shrink and forms air gaps. The air gap reduces the heat flow from strand to mold, and increases the surface temperature of strand and reduces the thickness of solidifying shell. The hot spot at the thin shell can give rise to the breakout of strand. Thus, the proper narrow face taper is important to prevent breakout and corner rotation in the mold. The prevention of corner rotation helps to avoid forming the thin shell in the off-corner region, leading to the reduction of the longitudinal surface cracks and breakout.

When the narrow face taper is large, the strand is in strong contact with the mold during continuous casting, because large narrow face taper can compensate the shrinkage of solidifying shell and gives rise to no air gap on narrow face.³¹⁾ The strong contact between the strand and the mold increases the heat flow from strand to mold, and decreases the surface temperature of strand and increases the thickness of solidifying shell. Thus, at large narrow face taper, the hot spot does not form on the off-corner region, the possibility of breakout of strand becomes lower. However, the high value of interfacial pressure can give rise to the wear phenomenon of narrow face mold,³¹⁾ due to the strong contact between the strand and the mold.

The effect of narrow face taper on solidification cracking at the conditions of 0.1 wt% C, slab width of 1 600 mm and casting speed of 1 m/min has been analyzed. Figure 8 shows the calculated crack susceptibility distributions of strand at the mold exit as a function of narrow face taper. With increasing narrow face taper, the crack susceptibility decreases along the region of wide face, because the narrow face taper toward the wide face center compresses the solidifying shell along the wide face. Okamura *et al.*⁸⁾ showed

Fig. 8. The calculated crack susceptibility distributions of strand at the mold exit as a function of narrow face taper.

Fig. 9. The calculated specific crack susceptibility of whole strand as a function of narrow face taper.

that the increase of the narrow face taper might be expected to prevent the tensile stress of strand and to avoid the crack formation. Choi and Yim *et al.*²⁹⁾ reported that the breakouts and longitudinal surface crack at small narrow face taper are larger than those at large narrow face taper in the center and off-corner of slab, respectively, as shown in Fig. 8(a). Won *et al.*³¹⁾ showed that large narrow face taper could give rise to large wear of narrow side mold. Figure 9 shows the calculated specific crack susceptibility of whole strand as a function of narrow face taper. The possibility of solidification cracking decreases with increasing narrow face taper. For narrow face tapers of 0.65 %/m or less, the shell in the off-corner regions has a high surface temperature at the mold exit and is very thin and weak, due to the large gaps between the strand and mold created by insufficient

Fig. 10. The calculated crack susceptibility distributions of strand at the mold exit as a function of casting speed.

Fig. 11. The calculated specific crack susceptibility of whole strand as a function of casting speed.

taper. And, for narrow face tapers of 1.7%/m or more, the shell in the corner and off-corner regions has a high value of interfacial pressure between the strand and mold, due to the strong contact between the strand and mold created by excessive taper. Therefore, in this case at the given operation conditions, the optimum narrow face taper is about from 1.3%/m to 1.5%/m. In addition, the optimum multiple taper could be obtained to minimize the solidification cracking and mold wear at the same time, using the specific crack susceptibility and the apparent wear parameter.³¹⁾

4.4. Effect of Casting Speed

The effect of casting speed on solidification cracking at the conditions of 0.1 wt% C, slab width of 1600 mm and narrow face taper 1.5%/m has been analyzed. Figures 10 and 11 show the calculated crack susceptibility distributions at the mold exit and specific crack susceptibility of whole strand as a function of casting speed, respectively. With increasing casting speed, the crack susceptibility at the mold exit increases in the regions of wide center, corner and off-corner, as shown in Fig. 10. At the higher casting speed, the shell thickness is largely decreased due to decrease of dwelling time of strand within the mold, and the thin shell can give rise to the breakout of strand. Below the mold, higher casting speeds likely increase bulging, which worsens the longitudinal surface crack at the off-corner.³²⁾ The specific crack susceptibility largely increases with increasing casting speed, as shown in Fig. 11. These result are

in good agreement with the observation³⁴⁾ that the possibility of solidification cracking increases with increasing casting speed. Therefore, the effect of casting speed on solidification cracking could be analyzed not only in a conventional caster, but also in a thin slab caster using the specific crack susceptibility.

5. Conclusions

In order to predict the possibility of solidification cracking of strand during continuous casting in the mold, "Specific Crack Susceptibility", S_{SC} , was proposed. The new proposed parameter, S_{SC} , can represent the averaged possibility of solidification cracking of whole strand during continuous casting in the mold. The effects of carbon content, slab width, narrow face taper and casting speed on solidification cracking have been analyzed using the specific crack susceptibility.

At the initial stage of solidification, the possibility of solidification cracking was highest near corner region of strand, because the surface temperature of corner region is in the brittle temperature range. At the middle and final stage of solidification, the internal crack could be found in the internal regions of wide center, corner and off-corner. These predictions and the depth of internal cracks were in good agreement with the experimental observations in industry.

The calculated carbon range of maximum specific crack susceptibility was between 0.1 wt% C and 0.14 wt% C steels, which agrees well with the calculated strain and experimentally measured corner crack index in industry, because all δ/γ phase transformation occurs in the brittle temperature range. With increasing slab width and casting speed, the specific crack susceptibility increased in the regions of wide center, corner and off-corner. The shell thickness is largely decreased with increasing casting speed, due to decrease of dwelling time of strand within the mold, and the thin shell can give rise to the breakout of strand. With increasing narrow face taper, the specific crack susceptibility decreased along the region of wide face due to the mechanical compression imposed by the narrow face taper. Accordingly, the hot spot does not form on the off-corner region, the possibility of breakout of strand becomes lower. According to these results, the possibility of solidification cracking during continuous casting in the mold could be successfully predicted using the specific crack susceptibility. In the future, the design of optimum taper to minimize the solidification cracking and mold wear at the same time will be carried out.

REFERENCES

- 1) J. K. Brimacombe: *Metall. Trans.*, **24B** (1993), 917.
- 2) A. Grill, K. Sorimachi and J. K. Brimacombe: *Metall. Trans.*, **7B** (1976), 177.
- 3) K. Kinoshita, T. Emi and M. Kasai: *Tetsu-to-Hagane*, **65** (1979), 2022.
- 4) J. O. Kristiansson: *J. Thermal Stresses*, **7** (1984), 209.
- 5) B. G. Thomas, I. V. Samarasekera and J. K. Brimacombe: *Metall. Trans.*, **18B** (1987), 131.
- 6) J. E. Kelly, K. P. Michalek, T. G. O'Connor, B. G. Thomas and J. A. Dantzig: *Metall. Trans.*, **19A** (1988), 2589.
- 7) B. G. Thomas: *Proc. Modeling Casting, Welding and Advanced*

- Solidification Processes, TMS-AIME, Warrendale, PA, Vol. VI (1993), 519.
- 8) K. Okamura and K. Yamamoto: Proc. Modeling Casting, Welding and Advanced Solidification Processes, TMS-AIME, Warrendale, PA, Vol. VI (1993), 535.
- 9) T. G. O'Connor and J. A. Dantzig: *Metall. Trans.*, **25B** (1994), 443.
- 10) H. N. Han, J. E. Lee, T. Yeo, Y. M. Won, K. Kim, K. H. Oh and J. K. Yoon: *ISIJ Int.*, **39** (1999), 445.
- 11) K. Kim, T. Yeo, K. H. Oh and D. N. Lee: *ISIJ Int.*, **36** (1996), 284.
- 12) H. G. Suzuki, S. Nishimura and S. Yamaguchi: *Tetsu-to-Hagané*, **65** (1979), 2038.
- 13) B. G. Thomas: *ISIJ Int.*, **35** (1995), 737.
- 14) T. W. Clyne, M. Wolf and W. Kurz: *Metall. Trans.*, **13B** (1982), 259.
- 15) K. Kim, H. N. Han, T. Yeo, Y. Lee, K. H. Oh and D. N. Lee: *Ironmaking Steelmaking*, **24** (1997), 249.
- 16) A. Yamanaka, K. Nakajima and K. Okamura: *Ironmaking Steelmaking*, **22** (1995), 508.
- 17) K. Kim, H. N. Han, T. Yeo, Y. Lee, K. H. Oh and D. N. Lee: Proc. Conf. Melt Spinning, Strip Casting and Slab Casting, TMS, Warrendale, PA, (1996), 87.
- 18) K. Kim, T. Yeo, Y. Lee, H. N. Han, K. H. Oh and D. N. Lee: Proc. 2nd Pacific Rim Inter. Conf. on Advanced Materials and Processing, The Korean Inst. of Metals and Materials, (1995), 109.
- 19) Y. M. Won, T. Yeo, D. J. Seol and K. H. Oh: *Metall. Trans.*, (2000), in press.
- 20) K. Miyamura, K. Kanamaru, N. Kaneko and A. Ochi: *Tetsu-to-Hagané*, **62** (1976), S482.
- 21) H. Fujii, T. Ohashi and K. Hiromoto: *Tetsu-to-Hagané*, **62** (1976), S484.
- 22) K. Narita, T. Mori, K. Ayata and J. Miyazaki: *Tetsu-to-Hagané*, **64** (1978), S152.
- 23) J. Miyazaki, K. Narita, T. Nozaki and T. Mori: *Trans. Iron Steel Jpn.*, **21** (1981), B210.
- 24) T. Matsumiya, M. Ito, H. Kajioka, S. Yamaguchi and Y. Nakamura: *Trans. Iron Steel Jpn.*, **26** (1986), 540.
- 25) H. N. Han, Y. Lee, K. H. Oh and D. N. Lee: *Mater. Sci. Eng. A*, **206** (1996), 81.
- 26) T. Matsumiya, T. Saeki, J. Tanaka and T. Ariyoshi: *Tetsu-to-Hagané*, **68** (1982), 1782.
- 27) Y. M. Won, K. Kim, T. Yeo and K. H. Oh: *ISIJ Int.*, **38** (1998), 1093.
- 28) K. H. Kim: Ph. D. Thesis, Seoul National University, Seoul, Korea, (1996).
- 29) J. Park, J. Choi, C. H. Yim, I. Lee, J. Park, J. Y. Park and S. Lee: Technical Report, Iron & Steel Making Research Team, Technical Research Labs., POSCO, Korea, (1996).
- 30) M. R. Aboutalebi, M. Hasan and R. I. L. Guthrie: *Steel Res.*, **65** (1994), 225.
- 31) Y. M. Won, T. Yeo, K. H. Oh, J. Park, J. Choi and C. H. Yim: *ISIJ Int.*, **38** (1998), 53.
- 32) B. G. Thomas, A. Moitra and R. McDavid: Proc., Iron and Steel Society's Process Tech. Conf., ISS, Warrendale, PA, **13** (1996), 143.