The degree of peritectic solidification is a strong indicator of the cracking tendency of steel during continuous casting. To predict the crack susceptibility of regular carbon steel slabs, the characteristic index of solidification shrinkage ($R_V$), which is determined by the volume shrinkage of the peritectic solidification and the remaining liquid phase after the peritectic solidification, is proposed as a means of evaluating the cracking tendency. In this study, $R_V$ was calculated for different steel grades under equilibrium condition. Then the segregation of the elements and the zone of the peritectic solidification under non-equilibrium condition were discussed with respect to the cooling rate. The results show that the calculated $R_V$ was in good agreement with experimental observations made on steel slabs, based on the zone of peritectic solidification under non-equilibrium condition. $R_V$ can therefore be used to predict the crack susceptibility of regular carbon steel slabs.

KEY WORDS: continuous casting; crack susceptibility; characteristic index of solidification shrinkage; non-equilibrium.

1. Introduction

The characteristics of peritectic solidification in continuous casting have a great effect on the continuously cast slabs. During the actual process of producing peritectic steel, a large volume shrinkage occurs in the transformation from austenite to ferrite, which produces a large shrinkage stress and causes the solidified shell to grow unevenly. Longitudinal cracks will occur in the surface of the solidified shell if the meniscus region cannot conduct heat uniformly.\(^1\)\(^-\)\(^5\)

During the peritectic solidification, the peritectic phase transition occurs in two stages: the peritectic reaction ($L + \delta \rightarrow \gamma$) and the peritectic transformation ($L \rightarrow \gamma$ and $\delta \rightarrow \gamma$).\(^6\) Once the peritectic reaction is complete and the L/\($\delta$\) interface is covered by austenite, the peritectic transformation begins. The rates of both the peritectic reaction and the peritectic transformation influence the crack susceptibility by affecting the volume shrinkage.\(^7\)

Many researchers have proposed different methods to estimate the solidification cracking tendency during continuous casting. Matsumiya\(^8\) proposed using the density change during the peritectic solidification to analyze the crack susceptibility, and they suggested that the strain developed in a brittle temperature range of $T_a - 30^\circ\text{C} < T < T_a$ was maximized at 0.14 mass\% C, where $T_a$ was the temperature at a solid fraction of 0.85 in the Fe–C binary system. Harste\(^9\) used mechanical model and thermal model to predict the crack susceptibility, they found that there was a shrinkage peak at about 0.1 mass\% C. However, the effect of other solute elements on the cracking tendency was ignored in the above research. Clyne\(^10\) proposed a crack susceptibility coefficient to estimate the cracking tendency, they divided the mushy zone into the liquid feeding zone and the cracking zone. Meanwhile, some other researchers estimated the cracking tendency based on the strain and stress. Specifically, Won\(^11\) proposed the concept of “Specific Crack Susceptibility” to analyze the cracking tendency based on the critical fracture stress and critical strain. However, too many parameters were introduced in their model and the calculation process was also too complicated to be adopted for widespread application in actual production processes.

Therefore, the present study proposes a quantitative model that is more easily understood for the comprehensively analysis of the crack susceptibility. The degree of the peritectic solidification, which depends on the volume shrinkage and the mass of the peritectic solidification, was considered, and a characteristic index of solidification shrinkage is proposed to interpret and predict the crack susceptibility of regular carbon steels slabs.

2. Characterization of Shrinkage during Solidification Process

The shrinkage of steel during the solidification process is related to the carbon content, as shown by the example for Fe–C steel in Fig. 1 with 0.34 mass\% Si, 1.52 mass\% Mn, 0.012\% P, 0.015 mass\% S and 0.03 mass\% Al.

Figure 1 shows that the sequence of phase changes is:
The density of steel was obtained as follows:\(^{14}\)
\[
\rho_{L+\delta} = \rho_{L}^{0} + \Delta \rho_{L} \times f_{L} \times (10^{3} \text{ kg/m}^{3}) \quad \ldots (3)
\]
\[
\rho_{L+\gamma} = \rho_{L}^{0} + \Delta \rho_{L} \times f_{L} \times (10^{3} \text{ kg/m}^{3}) \quad \ldots (4)
\]
\[
\rho_{\delta} = 3.07 \times 10^{-4} \times (T_{\text{start}} - T) + 7.27 \times (10^{3} \text{ kg/m}^{3}) \quad \ldots (5)
\]
\[
\rho_{\gamma} = 4.80 \times 10^{-4} \times (T_{\text{start}} - T) + 7.41 \times (10^{3} \text{ kg/m}^{3}) \quad \ldots (6)
\]
\[
\rho_{\delta+\gamma} = \rho_{\delta} \times f_{\delta} + \rho_{\gamma} \times f_{\gamma} \times (10^{3} \text{ kg/m}^{3}) \quad \ldots (8)
\]

where \(\rho_{i}\) is the density of the \(i\) phase, \(\rho_{L}^{0}\) is the density at the liquidus temperature, and \(\Delta \rho_{L}\) is the difference of density between the liquidus and solidus of the i phase.

The temperature in the various solid fractions\(^{15}\) was calculated according to the Eqs. (9)–(12):
\[
T = 1.536 - [\Sigma f(Ci)] \times [1 - f_{L}(1 - 2\Omega k)]^{k-1} \quad (9)
\]
\[
[\Sigma f(Ci)] = 67.51 \times [\%C] + 9.741 \times [\%Si] + 3.292 \times [\%Mn] + 82.18 \times [\%P] + 155.8 \times [\%S] \quad (10)
\]
\[
\Omega = \alpha(1 - \exp(-1/\alpha)) - 1/2 \exp(-1/2/\alpha) \quad (11)
\]
\[
\alpha = 33.7R_{C}^{-0.244} \quad (12)
\]

where \(R_{C}\) is the cooling rate (0.01 K/s under equilibrium condition and 10 K/s under non–equilibrium condition), \(f_{L}\) is the solid fraction, and the value of \(k\) is 0.265.

Next, considering the complexity of the solidification process, values of \(R_{v}\) were calculated for different steel grades under equilibrium and non–equilibrium condition.

(1) Equilibrium condition

To calculate the \(R_{v}\) under equilibrium condition, the carbon contents of the peritectic starting point (\(C_{S}\)), peritectic point (\(C_{P}\)) and peritectic end point (\(C_{L}\)) were obtained by multi-component Fe–C phase diagrams calculated by FactSage. The mass fractions of the liquid phase (\(L\)), \(\delta\) and \(\gamma\) before and after the peritectic solidification were determined by the lever rule according to the Eqs. (13)–(20):

\[\text{① before the peritectic solidification} \]
\[
L = (C_{P} - C_{S})/(C_{L} - C_{S}) \quad (13)
\]
\[
\delta = (C_{L} - C_{P})/(C_{L} - C_{S}) \quad (14)
\]
\[
\gamma = 0 \quad (15)
\]

\[\text{② after the peritectic solidification} \]
\[
L = (C_{P} - C_{P})/(C_{L} - C_{P}) \quad (C_{O} > C_{P}) \quad (16)
\]
\[
L = 0 \quad (C_{O} \leq C_{P}) \quad (17)
\]
\[
\delta = 0 \quad (C_{O} > C_{P}) \quad (18)
\]
\[
\delta = (C_{P} - C_{O})/(C_{P} - C_{P}) \quad (C_{O} \leq C_{P}) \quad (19)
\]
\[
\gamma = 1 - L - \delta \quad (20)
\]

The temperature and density of steel before and after the peritectic solidification were then calculated by Eqs. (9)–(12) and (3)–(8), respectively, and \(R_{v}\) under equilibrium condition was thus obtained from the density of steel before and after the peritectic solidification and the mass fraction of the liquid phase after the peritectic solidification.

(2) Non–equilibrium condition

Mikio\(^{16}\) and Muojekwu et al.\(^{17}\) confirmed that the initial cooling rate of the solidifying shell is approximately 10 K/s–
100 K/s. In addition, Jablonka et al.\textsuperscript{18} presented a Fe–C phase diagram at different degree of supercooling, as shown in Fig. 2.

The thermal shrinkage also changes at different degree of supercooling,\textsuperscript{18} as shown in Fig. 3.

Figures 2 and 3 show that the peritectic point and the greatest thermal shrinkage move toward bottom left when the degree of supercooling is increased. On this basis, Hu. \textit{et al}.\textsuperscript{19} reported that the cooling rate causes the carbon content of the peritectic point to move toward the left by 0.03 mass\% for slabs and 0.07 mass\% for CSP, so the zone of the peritectic solidification under non-equilibrium condition would move toward the bottom left.

At the same time, the cooling rate promotes the segregation of the elements, the composition of elements in the solidified front will always be changing, as will the zone of the peritectic solidification.

Therefore, the segregation of elements and the zone of peritectic solidification under non-equilibrium condition were discussed with respect to the cooling rate.

\begin{enumerate}
\item Segregation condition

The solute element at the solidification front would produce segregation during the solidification process, the Brody–Flemings model was adopted to calculate the segregation of elements in this study.\textsuperscript{20} The equation of the Brody–Flemings model is shown as follows:

\begin{equation}
C_L = C_0 (1 + f_S (\beta k - 1))^{(1 - k)/(\beta k - 1)} \quad (21)
\end{equation}

where \( f_S \) is the solid fraction, \( k \) is the equilibrium distribution coefficient, \( C_0 \) is the initial concentration, \( C_i \) is the concentration of the solidification front, and \( \beta \) is the correction factor given as follows:

\begin{equation}
\beta = 2\alpha (1 - \exp(-1/\alpha)) - \exp(-1/2/\alpha) \quad (22)
\end{equation}

\begin{equation}
\alpha = 4D_S t_f / \lambda \quad (23)
\end{equation}

In Eq. (22), \( \alpha \) is the Fourier number of the solute, \( D_S \) is the diffusion coefficient of the solute in the solid phase, \( t_f \) is the local solidification time, and \( \lambda \) is the secondary dendrite arm spacing given as follows:

\begin{equation}
\lambda = \begin{cases} 
(169.1 - 720.9 \times [%CC]) \times R_C^{-0.4935} &\text{if } [%CC] \leq 0.15 \\
143.9 \times R_C^{-0.3616} \times [%CC]^{0.5501 - 1.996 \times [%Cc]} &\text{if } [%CC] > 0.15 
\end{cases} \quad (24)
\end{equation}

As the composition of steel varies among the different solid fractions, the iteration method was used to determine the solid fraction before and after the peritectic reaction. On this basis of it, \( R_V \) could be determined under solidification segregation condition. The process of calculation is shown in Fig. 4.

\item Zone of peritectic solidification under the non-equilibrium condition

To analyze the zone of peritectic solidification under non-equilibrium condition, the value derived by Hu that the cooling rate causes the carbon content of the peritectic point to move toward the left by 0.03 mass\% for slabs was employed. On this basis, this study assumes the following:

Firstly, the liquid solute can be mixed fully and the spread of the solid solute is limited. That is, the cooling rate has some effect on the peritectic starting point, but little impact

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Fe–C phase diagram at different degree of supercooling.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig3.png}
\caption{Thermal shrinkage at different degree of supercooling.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{Flowchart of calculating \( R_V \) under solidification segregation condition.}
\end{figure}
Secondly, the ratio of the liquid phase to $\delta$ under non-equilibrium condition is consistent with the equilibrium condition when the liquid phase and $\delta$ transform completely into $\gamma$ in the same system. This is determined by the conservation of mass, and can be used to describe the change in the peritectic starting point under non-equilibrium condition.

In the Fe–C binary system, the carbon contents of the peritectic starting point, peritectic point and peritectic end point are 0.09, 0.17 and 0.53 mass%, respectively, under equilibrium condition. In addition, the ratio of the liquid phase to $\delta$ is 0.182:0.818 when they completely transform into $\gamma$. Thus the carbon contents of the peritectic point and peritectic end point are 0.14 and 0.53 mass%, respectively, with the existence of the cooling rate. The carbon content of the peritectic starting point is 0.054% to guarantee the ratio of the liquid phase to $\delta$, as shown in Fig. 5.

In a Fe–C multi-component system, for example, Fe–C with 0.3 mass% Si, 1.2 mass% Mn, 0.01 mass% P, 0.01 mass% S and 0.03 mass% Al, the calculation process can be shown in Fig. 6.

Figures 5 and 6 show that the cooling rate causes the carbon content of the peritectic starting point to move toward the left by 0.035%, the zone of the peritectic reaction is thus determined in this manner, then the method for calculating $R_v$ in the zone of the peritectic solidification under non-equilibrium condition is the same as that under equilibrium condition.

### 3. Industrial Testing and Validation

To interpret and predict the crack susceptibility of steel, data on slabs obtained from 4194 heats in 2010 and 3638 heats in 2012 at an actual steel plant were statistically analyzed. The cross section of the slabs from 2010 and 2012

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>sol. Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.18</td>
<td>0.28</td>
<td>1.16</td>
<td>0.0163</td>
<td>0.0065</td>
<td>0.026</td>
</tr>
<tr>
<td>0.17</td>
<td>0.3</td>
<td>1.24</td>
<td>0.0168</td>
<td>0.0056</td>
<td>0.03</td>
</tr>
<tr>
<td>0.16</td>
<td>0.28</td>
<td>1.18</td>
<td>0.0172</td>
<td>0.0067</td>
<td>0.028</td>
</tr>
<tr>
<td>0.15</td>
<td>0.27</td>
<td>1.14</td>
<td>0.0169</td>
<td>0.0065</td>
<td>0.03</td>
</tr>
<tr>
<td>0.14</td>
<td>0.25</td>
<td>1.02</td>
<td>0.0166</td>
<td>0.0064</td>
<td>0.031</td>
</tr>
<tr>
<td>0.13</td>
<td>0.23</td>
<td>0.83</td>
<td>0.0168</td>
<td>0.0068</td>
<td>0.032</td>
</tr>
<tr>
<td>0.12</td>
<td>0.22</td>
<td>0.71</td>
<td>0.0165</td>
<td>0.0072</td>
<td>0.031</td>
</tr>
<tr>
<td>0.11</td>
<td>0.22</td>
<td>0.67</td>
<td>0.0175</td>
<td>0.0072</td>
<td>0.03</td>
</tr>
<tr>
<td>0.10</td>
<td>0.21</td>
<td>0.74</td>
<td>0.0159</td>
<td>0.0046</td>
<td>0.026</td>
</tr>
</tbody>
</table>

Fig. 7. Relationship between carbon content and longitudinal crack ratio.

Fig. 8. Values of $R_v$ for 0.09–0.18 mass% C under different conditions.

Fig. 5. Calculation process in Fe–C binary system.

Fig. 6. Calculation process in Fe–C multi-component system.
were (200, 250, 300)×(2,000, 2,200, 2,500) mm² and (190, 220)×1,530 mm², respectively. The properties of the mold fluxes were similar, especially in the range of 0.07–0.13 mass% C. The casting speeds for the corresponding slabs were 0.9–1.2 m/min and 1.3–1.58 m/min. The relationship between the carbon content and the longitudinal crack ratio for each year’s data is shown in Fig. 7.

Figure 7 shows that the longitudinal crack ratio, which is
defined as the ratio of the number of slabs with longitudinal cracks to the total number, reaches its peak at a carbon content of around 0.11 mass%, and the crack susceptibility was greater in the range of 0.1–0.12 mass% C for the 4194 heats in 2010 and in the range of 0.09–0.12 mass% C for the 3638 heats in 2012.

Next, the 4194 heats in 2010 were divided into 10 sections according to the carbon content from 0.09 to 0.18 mass%. The contents of Si, Mn, P, S and Al in steel were similar, and thus were averaged in the 10 sections, as shown in Table 1.

Subsequently, values of RV for 0.09–0.18 mass% C in the 4194 heats were calculated under different conditions, as shown in Fig. 8.

Figure 8 shows that the carbon content of largest RV is higher than 0.11 mass% C under equilibrium and solidification segregation conditions. It also shows that the RV at 0.15–0.18 mass% C is apparently higher than that at 0.09–0.12 mass% C, though the crack susceptibility for 0.15–0.18 mass% C is not high in actual production processes. This is probably because the Brody-Flemings equation was developed for the single phase solidification, which means both the peritectic reaction and transformation are beyond the model application. However, the values of RV calculated in the zone of the peritectic solidification under non-equilibrium condition is in line with the statistical data, and their values at 0.15–0.18 mass% C appears to be lower than those at 0.09–0.12 mass% C. Thus the present calculations for RV in the zone of the peritectic solidification under non-equilibrium condition can be used to predict the crack susceptibility.

To further validate the present calculations of RV in the zone of the peritectic solidification under non-equilibrium condition, the 3638 heats in 2012 were used to calculate RV for every grade of steel. In this case, the fluctuation of the composition in steel was larger. The results were then divided into four ranges according to the value of RV: (RV > 2.1), (RV = 1.9–2.1), (RV = 1.7–1.9) and (RV < 1.7). To interpret the crack susceptibility, the proportion of samples with RV larger than 2.1 or 1.9 was determined as shown in Fig. 9.

Figure 9 shows that the proportion of samples with RV larger than 2.1 is over 50% and that with RV greater than 80% in the range of 0.09–0.12 mass% C. This is in good agreement with experimental observations of actual slabs, thus further validating the calculations.

In addition, to further understand the crack susceptibility of steel, based on the zone of the peritectic solidification under non-equilibrium condition, the evolution of the mass fraction of phases during the solidification process was also obtained in the range of 0.1–0.15 mass% C according to Table 1, as shown in Fig. 10.

During solidification process, a brittle temperature zone is divided into a liquid feeding zone and a cracking zone, and the solid fractions of the liquid feeding zone and the cracking zone are 0.75–0.9 and 0.9–0.99, depending upon the solid fractions of ZST, LIT and ZDT. The cracks formed in the liquid feeding zone can be refilled with the surrounding liquid to some degree, whereas those formed in the cracking zone cannot because the dendrite arms are sufficiently compacted to resist feeding of the liquid.10,13,21 However, as shown in Fig. 10, the peritectic solidification was mainly found to occur in the liquid feeding zone where the carbon content was at least 0.14 mass%. Thus the crack susceptibility at 0.1–0.13 mass% C was higher than that at 0.14–0.15 mass% C, which is consistent with the statistical data.

4. Conclusions

In order to interpret and predict the crack susceptibility of regular carbon steels, the characteristic index of solidification shrinkage (RV), which is determined by both the volume shrinkage of peritectic solidification and the remaining liquid phase after the peritectic solidification, is proposed in present study. Statistical analysis on the longitudinal crack ratio at an actual steel plant was performed to validate the present calculations. The results show that the calculated RV, which was in good agreement with experimental observations made on steel slabs, based on the zone of the peritectic solidification under non-equilibrium condition, can be used to predict the crack susceptibility of regular carbon steels. The crack susceptibility of steel was further analyzed according to the evolution of the mass fractions of phases during the solidification process, and the results were consistent with experimental observations of steel slabs.

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