Shrinkage of carbon steel by thermal contraction and phase transformation during solidification

L.-G. Zhu*1,2 and R. V. Kumar*2

In high speed continuous casting, optimisation of mould taper is important for intensifying heat transfer and improving the quality of cast products. In order to calculate the shrinkage during cooling, the thermal linear expansion coefficient (TLE) model has been developed and combined with phase transformation relevant to continuous casting of steel. In the present paper, a model to predict the shrinkage and to optimise mould taper for high speed casting is presented by taking into account variations in the TLE of steel and the effect of phase transformation during solidification of steel with varying carbon content. The TLE of steel purely from thermal contraction is nearly independent of carbon content when no δ→γ phase transformation is involved. For example, the TLE of 0.05% carbon steel is calculated to be 21.3 × 10⁻⁶ K⁻¹, while the TLE of 0.60% carbon steel is shown to be 19.88 × 10⁻⁶ K⁻¹. However, phase transformation processes which are greatly dependent upon the carbon content account for large difference in the shrinkage behaviour between the various grades of steel and extremely high apparent TLEs are calculated for low carbon steels; for example the apparent TLE for a 0.05 wt-%C steel is calculated to be 111.81 × 10⁻⁶ K⁻¹.

Keywords: Continuous casting, Thermal linear expansion coefficient, Steel shrinkage, Phase transformation, Peritectic reaction

Introduction

Since 1990, many improvements in continuous casting operation and control related to the billet quality and productivity have been achieved, the two most notable ones being the high speed of casting and the high cleanliness of products. For a typical 120 mm square section billet, the casting speed has been increased from 1.8 to 4.0 m min⁻¹. But a significant increase in casting speed has undoubtedly increased the turbulence and decreased the dwelling time of molten steel in the mould so as to increase the propensity for many surface defects and accidental damage such as depressions, cracks and off squareness as well as breakouts. The main reasons causing the above defects are poor and uneven heat transfer arising owing to steel shrinkage and shorter dwelling time in the mould resulting from the higher speed.1–3

Studies on steel shrinkage in mould during high speed casting have provided useful information; however, the variations in the thermal linear expansion coefficient (TLE) of steel for steels with different carbon contents and effects of phase transformation have received little attention.8–10 In the present paper, a model to predict the shrinkage and to optimise mould taper for high speed casting, is presented by taking into account variations in the TLE of steel and the effect of phase transformation during solidification of steel with varying carbon content.

List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>aₙ, aₜ</td>
<td>lattice parameter of δ, λ phase, Å</td>
</tr>
<tr>
<td>fₛ, fₐq</td>
<td>fractions of solid steel and liquid steel respectively</td>
</tr>
<tr>
<td>fₛ, fₐ</td>
<td>fractions of δ-Fe and λ-Fe respectively</td>
</tr>
<tr>
<td>T</td>
<td>temperature, °C</td>
</tr>
<tr>
<td>Tₗ</td>
<td>the liquidus temperature, °C</td>
</tr>
<tr>
<td>Tₘₐₓ</td>
<td>temperature of phase transformation at the beginning, °C</td>
</tr>
<tr>
<td>Tₘᵟₐᵦ</td>
<td>temperature of phase transformation at the end, °C</td>
</tr>
<tr>
<td>Tₛ</td>
<td>the solidus temperature, °C</td>
</tr>
<tr>
<td>Vₑₐₚ, Vₑₙ</td>
<td>TLE thermal linear expansion coefficient, K⁻¹</td>
</tr>
<tr>
<td>Vₑₕₑₜ, Vₑₕₑₜ</td>
<td>specific volume of steel at reference temperature Tₑₕₑₜ, cm³</td>
</tr>
<tr>
<td>Vₑₜ</td>
<td>specific volume of steel at given temperature T, cm³</td>
</tr>
<tr>
<td>Vₛ, Vₐ, Vₐₐₛ</td>
<td>specific volume of δ-Fe, λ-Fe and liquid steel, cm³ g⁻¹</td>
</tr>
<tr>
<td>ΔV</td>
<td>ratio of change in specific volume</td>
</tr>
<tr>
<td>Wₑ</td>
<td>carbon content of the phase, wt-%</td>
</tr>
</tbody>
</table>

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Mathematical models

Conversion of molten metal into a solid semifinished shape involves a decrease in temperature by the removal of heat and shrinkage of the steel. The volume of steel will change owing to the combined effects of thermal contraction and phase transformation. Shrinkage in the liquid, during solidification and in the solid state as well as during the phase transformations are considered in this model.

The TLE, which can be determined in turn from the phase fractions found by microsegregation analysis and the specific volume \( V \) of each phase of the steel, can be calculated from

\[
\Delta V = 1 - \left( \frac{V_T}{V_{\text{REF}}} \right)^{1/3}
\]

(1)

\[
\text{TLE} = \frac{c(\Delta V)}{\partial T}
\]

(2)

where

\[
V_T = (V_d f_d + V_z f_z) + V_{\text{liq}} f_{\text{liq}}
\]

(3)

\[
V_z = 0.1234 + 9.38 \times 10^{-6} (T - 20)
\]

(4)

\[
V_d = 0.1225 + 9.45 \times 10^{-6} (T - 20) + 7.688 \times 10^{-6}
\]

(5)

At the end of cooling, it is assumed that only the austenitic \( \lambda \) phase is present in the system. The lattice parameter \( a \) of the \( \gamma \) phase for given carbon content and temperature is calculated using the formula developed by Park et al.\(^{11,12}\)

\[
a_{\lambda} = a_{\lambda_{\text{c}}} + \frac{(0.0317 - 11.65 \times 10^{-7} - 0.05 \times 10^{-7} T^{-2}) W_c}{(0.51 - 11.65 \times 10^{-7} - 0.05 \times 10^{-7} T^{-2}) W_c}
\]

(6)

The TLE can be calculated as follows

\[
\text{TLE} = \frac{c(\Delta a_{\lambda} / a_{\lambda})}{\partial T}
\]

(8)

The values of \( f_d, f_z, f_{\text{liq}}, f_{\text{REF}} \) and \( T_{\text{REF}} \) are calculated using the Fe–C phase diagram\(^{13}\) and tabulated as shown below

(i) for \( W_c < 0.1\% \)

\[
T_s = 1541 - 477.7 W_c
\]

(9)

\[
T_1 = 1541 - 81.13 W_c
\]

(10)

\[
T_{\text{max}} = 990 W_c + 1394
\]

(11)

\[
T_{\text{min}} = \frac{99}{0.18} W_c + 1394
\]

(12)

Fractions of various phases for \( W_c < 0.1\% \) are

for \( T > T_s \), \( T_{\text{REF}} = 1600 \degree C, f_{\text{liq}} = 1, f_0 = 0, f_{\lambda} = 0 \)

\[
f_\lambda = 0
\]

for \( T_s < T < T_1 \), \( T_{\text{REF}} = T_s, f_{\text{liq}} = (T - T_s)/(T_1 - T_s), f_0 = 0 \)

\[
f_\lambda = 1 - f_{\text{liq}}, f_\lambda = 1, f_{\lambda} = 0
\]

for \( T < T_1 \), \( T_{\text{REF}} = T_{\text{min}}, f_{\text{liq}} = 0, f_0 = 1, f_{\lambda} = 0 \)

\[
f_\lambda = 1 - f_{\text{liq}}
\]

(ii) for \( 0.1\% < W_c < 0.18\% \)

\[
T_s = 1541 - 81.13 W_c
\]

(14)

\[
T_{\text{max}} = 1493
\]

(15)

\[
T_{\text{min}} = \frac{99}{0.18} W_c + 1394
\]

(16)

Fractions of various phases for \( 0.1\% < W_c < 0.18\% \) are

for \( T > T_1 \), \( T_{\text{REF}} = 1600 \degree C, f_{\text{liq}} = 1, f_0 = 0, f_{\lambda} = 0 \)

\[
f_\lambda = 0
\]

for \( T_s < T < T_1 \), \( T_{\text{REF}} = T_s, f_{\text{liq}} = (T - T_s)/(T_1 - T_s), f_0 = 0 \)

\[
f_\lambda = 1 - f_{\text{liq}}
\]

for \( T < T_s \), \( T_{\text{REF}} = T_{\text{min}}, f_{\text{liq}} = 0, f_0 = 1, f_{\lambda} = 0 \)

\[
f_\lambda = 1 - f_{\text{liq}}
\]

(iii) for \( 0.18\% < W_c < 0.51\% \)

\[
T_s = (0.51 - W_c)(1493 - 1400)/(0.51 - 0.18) + 1400
\]

(17)

\[
T_1 = 1541 - 81.13 W_c
\]

(18)

\[
T_{\text{max}} = T_s
\]

(19)

\[
T_{\text{min}} = T_{\text{max}}
\]

(20)

Fractions of various phases for \( 0.18\% < W_c < 0.51\% \) are

for \( T > T_1 \), \( T_{\text{REF}} = 1600 \degree C, f_{\text{liq}} = 1, f_0 = 0, f_{\lambda} = 0 \)

\[
f_\lambda = 0
\]

for \( T_s < T < T_1 \), \( T_{\text{REF}} = T_s, f_{\text{liq}} = (T - T_s)/(T_1 - T_s), f_0 = 0 \)

\[
f_\lambda = 1 - f_{\text{liq}}
\]

for \( T < T_s \), \( T_{\text{REF}} = T_{\text{min}}, f_{\text{liq}} = 0, f_0 = 1, f_{\lambda} = 0 \)

\[
f_\lambda = 1 - f_{\text{liq}}
\]
for $T \leq T_{\text{max}}$, $T_{\text{REF}} = T_{\text{max}}$, $f_{\text{liq}} = 0$, $f_{3} = 1$, $f_{0} = 0$, $f_{2} = 1$

(iv) for $W_{c} > 0.51$

\[ T_{s} = 1493 - 178.8(W_{c} - 0.18) \quad (21) \]

\[ T_{l} = 1493 - 92.04(W_{c} - 0.51) \quad (22) \]

\[ T_{\text{max}} = T_{s} \quad (23) \]

\[ T_{\text{min}} = T_{\text{max}} \quad (24) \]

Fractions of various phases for $W_{c} > 0.51$

for $T > T_{s}$, $T_{\text{REF}} = 1600$, $f_{\text{liq}} = 1$, $f_{3} = 0$, $f_{2} = 0$

for $T_{s} \leq T < T_{l}$, $T_{\text{REF}} = T_{l}$, $f_{3} = 0$, $f_{1} = 1$, $f_{\text{liq}} = (T_{l} - T_{s})/(T_{l} - T_{s})$, $f_{3} = 1 - f_{\text{liq}}$

for $T \leq T_{\text{max}}$, $T_{\text{REF}} = T_{\text{max}}$, $f_{\text{liq}} = 0$, $f_{3} = 1$, $f_{3} = 0$, $f_{2} = 1$

\section*{Results and discussion}

\subsection*{Thermal linear expansion coefficient of steel with different carbon contents}

In Table 1 the transformation temperatures are listed for steels containing carbon varying from 0.05 to 0.6 wt-%. The calculated values of the TLEs of steels with different carbon contents are illustrated in Fig. 1 in the temperature range 800–1550°C and an amplified version in the temperature range 800–1400°C is shown in Fig. 2.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Carbon content, % & $T_{s}$ & $T_{l}$ & $T_{\text{max}}$ & $T_{\text{min}}$ \\
\hline
0.05 & 1536 & 1517 & 1443 & 1421 \\
0.09 & 1533 & 1498 & 1483 & 1443 \\
0.12 & 1531 & 1493 & 1493 & 1460 \\
0.18 & 1526 & 1493 & 1493 & 1493 \\
0.45 & 1504 & 1416 & 1493 & 1416 \\
0.60 & 1484 & 1417 & & \\
\hline
\end{tabular}
\caption{Solidus, liquidus and phase transformation temperature of different steel grades, °C}
\end{table}

It can be seen that the TLE values of steels with different carbon contents do not vary much when no phase transformation is involved; the TLE values at the median temperature of 1200°C are listed in Table 2. However, the apparent TLE value increases sharply to a maximum when the $\delta$ phase begins to change into the $\gamma$ phase at the starting temperature of the phase transformation; the maxima of TLE of steel with different carbon contents are given in Table 2. The maximum TLEs at the starting temperature of the phase transformation are calculated for steels with 0.05, 0.09, 0.12 and 0.18% carbon content, whereas for the steels with 0.45 and 0.60% which have no $\delta \rightarrow \gamma$ phase transformation, no maximum value can be reported. Thus the effect arising from $\delta \rightarrow \gamma$ phase transformation is clearly dominating in the shrinkage behaviour.

\subsection*{Effect of phase transformation}

The effect of phase transformation on carbon steels of different grades is analysed by calculating the volume fraction of the $\delta$ phase and shown in Figs. 3–8 for carbon content varying from 0.05 to 0.6%. For a steel with 0.05% carbon, the calculated volume fraction of $\delta$ phase with temperature is illustrated in Fig. 3. The
results show that no solid phase appears from the casting temperature of 1540°C to the liquidus temperature $T_l$ (1536°C), below which the volume fraction of $\delta$ increases from 0 at $T_l$ to 1 at the solidus temperature $T_s$ (1517°C). The volume fraction of $\delta$ remains at 1 from $T_s$ until the temperature falls down to $T_{\text{max}}$ (1483°C), corresponding to the start of $\delta \rightarrow \gamma$ transformation; however, the $\delta$ phase changes to $\gamma$ phase completely by $T_{\text{min}}$ (1421°C). Below 1421°C, the solid phase is only $\gamma$ phase. Because the temperature range of $\delta \rightarrow \gamma$ phase transformation is very small, just 12 K, the apparent TLE during $\delta \rightarrow \gamma$ is comparatively smaller at 71.93 x 10^6 K^{-1}. These two low carbon steels with 0.05 and 0.09% carbon are not peritectic steels, and especially, for the steel with 0.05% carbon, the $\delta$-to-$\gamma$ temperature range is very small, so the effect of this transformation on heat transfer at meniscus in mould will not be significant.

A steel containing 0.12% carbon is hypoperitectic. The peritectic reaction, $L + \delta \rightarrow \gamma$, takes place between $T_{\text{max}}$ of 1493°C and $T_{\text{min}}$ of 1460°C. Because $\delta$ concentration is higher than equilibrium concentration of the peritectic reaction, only a part of the $\delta$ phase reacts with the liquid phase to produce $\gamma$; the rest of $\delta$ phase changes to $\gamma$ phase gradually when the temperature falls. As shown in Fig. 5, the temperature range of the $\delta \rightarrow \gamma$ transformation is 33 K, falling in between the values of 0.05 and 0.09%C steels and the corresponding apparent TLE value at 81.79 x 10^6 K^{-1} is also in between the apparent TLE values of the 0.05 and 0.09%C grade steels.

A steel containing 0.18% carbon is peritectic. Under equilibrium conditions the peritectic reaction, $L + \delta \rightarrow \gamma$, takes place at 1493°C. All of the $\delta$ phase reacts with the liquid phase to produce $\gamma$, forming 100% of the $\gamma$ phase. A peritectic steel will suffer sharp change of volume in
mould at the meniscus, thus in continuous casting a peritectic grade should normally be avoided.
In a hyperperitectic steel containing 0-45% carbon, the amount of the liquid phase is more than that required for reacting with δ-Fe, thus the γ phase and residual molten steel coexist after the peritectic reaction is completed, and the change of volume owing to δ→γ need not be considered in the presence of molten steel.
Finally, for the steel containing 0-60% carbon content the peritectic reaction is absent and does not undergo the δ→γ phase transformation, hence, steel shrinks only by thermal contraction below the solidus temperature.

Conclusions
In the present work, the TLEs of steels with different carbon contents are calculated by taking into account the phase transformation and the peritectic reaction.
1. TLEs of steels with different carbon contents are close to each other when no phase transformation is involved. It increases sharply to the maximum when phase δ begins to change into phase γ at the starting temperature of this phase transformation.
2. The solidification shrinkage and phase transformation process are different for steel grades with different carbon contents. The steels with 0-05 and 0-09% carbon content undergo the δ→γ change in the temperature range specified from the Fe–C phase diagram as $T_{\text{max}}$ and $T_{\text{min}}$, but are not peritectic. Steels containing 0-12, 0-18 and 0-45% carbon involve the peritectic reaction, with the 0-12% carbon steel being hyperperitectic, i.e. after the peritectic reaction, the δ and the γ phases coexist. The 0-45% carbon steel is hyperperitectic and after the peritectic reaction, liquid phase coexists with the γ phase; while the 0-18% carbon steel is peritectic, just below the peritectic temperature only the γ phase exists. Finally, for the steel containing 0-60% carbon the peritectic reaction is absent and does not undergo the δ→γ phase transformation. Hence, steel shrinks only by thermal contraction below the solidus temperature.
3. In order to calculate the shrinkage during cooling, the TLE model has been developed and combined with phase transformation relevant to continuous casting of steel.

References