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 $\delta \rightarrow \gamma$ phase transformation is involved. For example, the TLE of 0·05% carbon steel is calculated to be $21{\cdot}3 \times 10^{-6}$ K^{-1}, while the TLE of 0·60% carbon steel is shown to be $19{\cdot}88 \times 10^{-6}$ 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 $111{\cdot}81 \times 10^{-6}$ K^{-1}.

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

List of symbols

a_λ	lattice parameter of λ phase, Å
f_s, f_{liq}	fractions of solid steel and liquid steel respectively
f_δ, f_λ	fractions of δ-Fe and λ-Fe respectively
T	temperature, °C
T_l	the liquidus temperature, °C
T_{max}	temperature of phase transformation at the beginning, °C
T_{min}	temperature of phase transformation at the end, °C
T_s	the solidus temperature, °C
TLE	thermal linear expansion coefficient, K^{-1}
V_{REF}	specific volume of steel at the reference temperature T_{REF}, cm^3
V_T	specific volume of steel at given temperature T, cm^3
V_δ, V_λ, V_{liq}	specific volume of δ-Fe, λ-Fe and liquid steel, cm^3 g^{-1}
ΔV	ratio of change in specific volume
Wc	carbon content of the phase, wt-%

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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 cleanness 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.[1–7]

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.

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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

$$\Delta V = 1 - \left(\frac{V_{\mathrm{T}}}{V_{\mathrm{REF}}}\right)^{1/3} \quad (1)$$

$$\mathrm{TLE} = \frac{\partial(\Delta V)}{\partial T} \quad (2)$$

where

$$V_{\mathrm{T}} = (V_{\delta} f_{\delta} + V_{\lambda} f_{\lambda}) f_{\mathrm{s}} + V_{\mathrm{liq}} f_{\mathrm{liq}} \quad (3)$$

$$V_{\lambda} = 0{\cdot}1234 + 9{\cdot}38 \times 10^{-6}(T-20) \quad (4)$$

$$V_{\delta} = 0{\cdot}1225 + 9{\cdot}45 \times 10^{-6}(T-20) + 7{\cdot}688 \times 10^{-6} \quad (5)$$

At the end of cooling, it is assumed that only the austenitic λ phase is present in the system. The lattice parameter a of the γ phase for given carbon content and temperature is calculated using the formula developed by Park *et al.*[11,12]

$$a_{\lambda} = a_{\lambda\mathrm{c}=0} + (0{\cdot}0317 - 11{\cdot}65 \times 10^{-7} - 0{\cdot}05 \times 10^{-7} T^{-2}) Wc \quad (6)$$

$$a_{\lambda\mathrm{c}=0} = 3{\cdot}5736 + 7{\cdot}8236 \times 10^{-5} T \quad (7)$$

The TLE can be calculated as follows

$$\mathrm{TLE} = \frac{\partial\left(\Delta\alpha_{\gamma}/\alpha_{\gamma}\right)}{\partial T} \quad (8)$$

The values of $f_{\delta}, f_{\lambda}, f_{\mathrm{s}}, f_{\mathrm{liq}}$ and T_{REF} are calculated using the Fe–C phase diagram[13] and tabulated as shown below

(i) for $Wc < 0{\cdot}1\%$

$$T_{\mathrm{s}} = 1541 - 477{\cdot}7 Wc \quad (9)$$

$$T_{\mathrm{l}} = 1541 - 81{\cdot}13 Wc \quad (10)$$

$$T_{\max} = 990 Wc + 1394 \quad (11)$$

$$T_{\min} = \frac{99}{0{\cdot}18} Wc + 1394 \quad (12)$$

Fractions of various phases for $Wc < 0{\cdot}1\%$ are

for $T > T_{\mathrm{l}}$, $T_{\mathrm{REF}} = 1600^{\circ}\mathrm{C}, f_{\mathrm{liq}} = 1, f_{\mathrm{s}} = 0, f_{\delta} = 0, f_{\lambda} = 0$

for $T\mathrm{s} \leqslant T < T_{\mathrm{l}}$, $T_{\mathrm{REF}} = T_{\mathrm{l}}, f_{\mathrm{liq}} = (T - T_{\mathrm{s}})/(T_{\mathrm{l}} - T_{\mathrm{s}}), f_{\mathrm{s}} = 1 - f_{\mathrm{liq}}, f_{\delta} = 1, f_{\lambda} = 0$

for $T_{\max} \leqslant T < T_{\mathrm{s}}$, $T_{\mathrm{REF}} = T_{\mathrm{s}}, f_{\mathrm{liq}} = 0, f_{\mathrm{s}} = 1, f_{\delta} = 1, f_{\lambda} = 0$

for $T_{\min} \leqslant T \leqslant T_{\max}$, $T_{\mathrm{REF}} = T_{\max}, f_{\mathrm{liq}} = 0, f_{\mathrm{s}} = 1,$ $f_{\delta} = 1 - [(990 Wc + 1394 - \mathrm{T})/(990 Wc - \frac{99}{0{\cdot}18} Wc)],$ $f_{\lambda} = 1 - f_{\delta}$

for $T < T_{\min}$, $T_{\mathrm{REF}} = T_{\min}, f_{\mathrm{liq}} = 0, f_{\mathrm{s}} = 1, f_{\delta} = 0, f_{\lambda} = 1$

(ii) for $0{\cdot}1\% \leqslant Wc \leqslant 0{\cdot}18\%$

$$T_{\mathrm{s}} = 1493 \quad (13)$$

$$T_{\mathrm{l}} = 1541 - 81{\cdot}13 Wc \quad (14)$$

$$T_{\max} = 1493 \quad (15)$$

$$T_{\min} = \frac{99}{0{\cdot}18} Wc + 1394 \quad (16)$$

Fractions of various phases for $0{\cdot}1\% \leqslant Wc \leqslant 0{\cdot}18\%$ are

for $T > T_{\mathrm{l}}$, $T_{\mathrm{REF}} = 1600^{\circ}\mathrm{C}, f_{\mathrm{liq}} = 1, f_{\delta} = 0, f_{\mathrm{s}} = 0, f_{\lambda} = 0$

for $T_{\mathrm{s}} \leqslant T < T_{\mathrm{l}}, T_{\mathrm{REF}} = T_{\mathrm{l}}, f_{\delta} = 1, f_{\lambda} = 0,$ $f_{\mathrm{liq}} = (T - T_{\mathrm{s}})/(T_{\mathrm{l}} - T_{\mathrm{s}}), f_{\mathrm{s}} = 1 - f_{\mathrm{liq}}$

for $T_{\max} \leqslant T < T_{\mathrm{s}}$, $T_{\mathrm{REF}} = T_{\mathrm{s}}, f_{\delta} = 1, f_{\lambda} = 0, f_{\mathrm{liq}} = 0, f_{\mathrm{s}} = 1$

for $T_{\min} \leqslant T < T_{\max}$, $T_{\mathrm{REF}} = T_{\max}, f_{\mathrm{liq}} = 0, f_{\mathrm{s}} = 1,$ $f_{\delta} = (T - T_{\min})/(1493 - T_{\min}), f_{\lambda} = 1 - f_{\delta}$

for $T < T_{\min}$, $T_{\mathrm{REF}} = T_{\min}, f_{\mathrm{liq}} = 0, f_{\mathrm{s}} = 1, f_{\delta} = 0, f_{\lambda} = 1$

(iii) for $0{\cdot}18\% < Wc \leqslant 0{\cdot}51\%$

$$T_{\mathrm{s}} = (0{\cdot}51 - Wc)(1493 - 1400)/(0{\cdot}51 - 0{\cdot}18) + 1400 \quad (17)$$

$$T_{\mathrm{l}} = 1541 - 81{\cdot}13 Wc \quad (18)$$

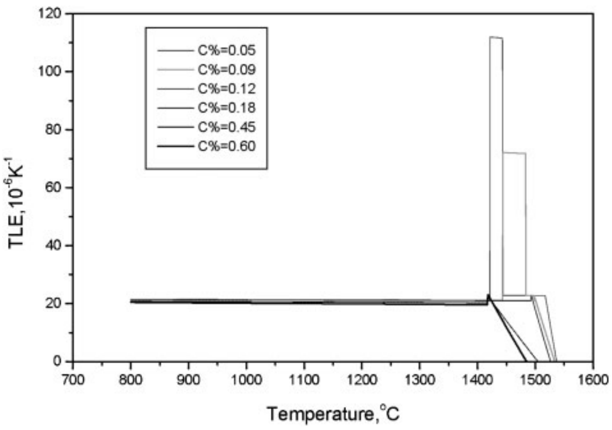
$$T_{\max} = T_{\mathrm{s}} \quad (19)$$

$$T_{\min} = T_{\max} \quad (20)$$

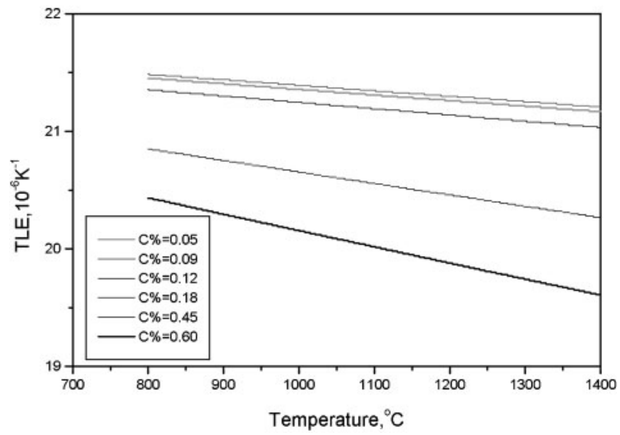
Fractions of various phases for $0{\cdot}18\% < Wc \leqslant 0{\cdot}51\%$ are

for $T > T_{\mathrm{l}}$, $T_{\mathrm{REF}} = 1600^{\circ}\mathrm{C}, f_{\mathrm{liq}} = 1, f_{\mathrm{s}} = 0, f_{\lambda} = 0$

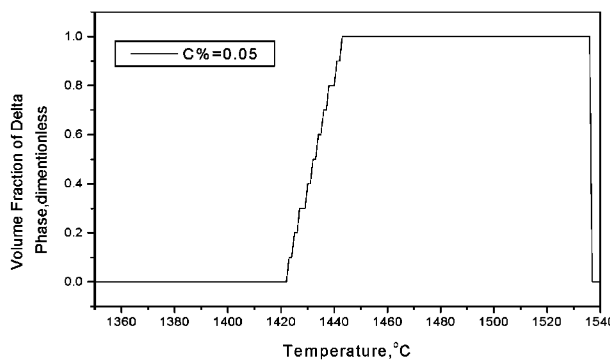
for $T_{\mathrm{s}} \leqslant T < T_{\mathrm{l}}$, $T_{\mathrm{REF}} = T_{\mathrm{l}}, f_{\delta} = 1, f_{\lambda} = 0,$ $f_{\mathrm{liq}} = (T - T_{\mathrm{s}})/(T_{\mathrm{l}} - T_{\mathrm{s}}), f_{\mathrm{s}} = 1 - f_{\mathrm{liq}}$



1 Thermal linear expansion coefficient of steel with different carbon contents versus temperature



2 Thermal linear expansion coefficient in temperature range 800–1400°C



3 Volume fraction of δ phase versus temperature for 0·05% carbon steel

for $T \leqslant T_{max}$, $T_{REF} = T_{max}, f_{liq} = 0, f_s = 1, f_\delta = 0, f_\lambda = 1$

(iv) for $Wc > 0{\cdot}51\%$

$$T_s = 1493 - 178{\cdot}8(Wc - 0{\cdot}18) \quad (21)$$

$$T_l = 1493 - 92{\cdot}04(Wc - 0{\cdot}51) \quad (22)$$

$$T_{max} = T_s \quad (23)$$

$$T_{min} = T_{max} \quad (24)$$

Fractions of various phases for $Wc > 0{\cdot}51\%$ are

for $T > T_l$, $T_{REF} = 1600°C, f_{liq} = 1, f_s = 0, f_\lambda = 0$

for $T_s \leqslant T < T_l$, $T_{REF} = T_l, f_\delta = 0, f_\lambda = 1, f_{liq} = (T - T_s)/(T_l - T_s), f_s = 1 - f_{liq}$

for $T \leqslant T_{max}$, $T_{REF} = T_{max}, f_{liq} = 0, f_s = 1, f_\delta = 0, f_\lambda = 1$

Results and discussion

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.

Table 1 Solidus, liquidus and phase transformation temperature of different steel grades, °C

Carbon content, %	T_l	T_s	T_{max}	T_{min}
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		

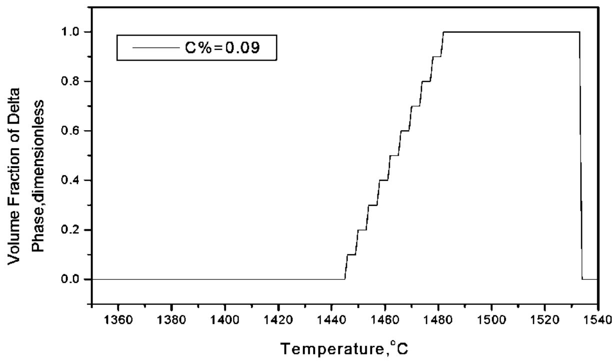
It can be seen that the TLE values of steels with different carbon contents do not vary much when no phase transformation is involved; the TLE values at the median temperature of 1200°C are listed in Table 2. However, the apparent TLE value increases sharply to a maximum when the δ phase begins to change into the γ 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.

Effect of phase transformation

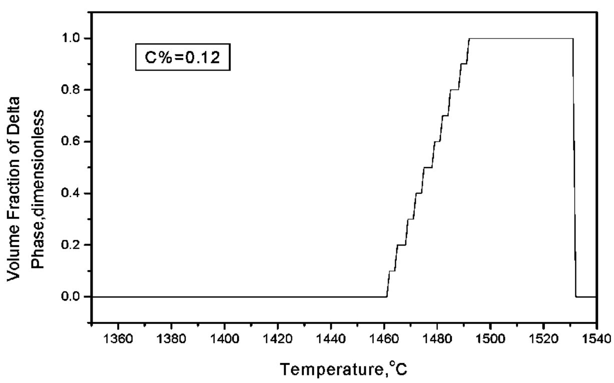
The effect of phase transformation on carbon steels of different grades are analysed by calculating the volume fraction of the δ phase and shown in Figs. 3–8 for carbon content varying from 0·05 to 0·6%. For a steel with 0·05% carbon, the calculated volume fraction of δ phase with temperature is illustrated in Fig. 3. The

Table 2 Median and maximum values of TLE of different steel grades, 10^{-6} K^{-1}

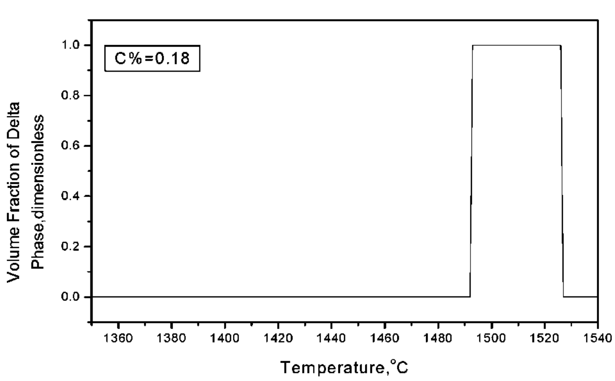
Wt-%C	0·05	0·09	0·12	0·18	0·45	0·60
Median	21·30	21·26	21·23	21·14	20·46	19·88
Max.	111·81	71·93	81·79			



4 Volume fraction of δ phase versus temperature for 0·09% carbon steel



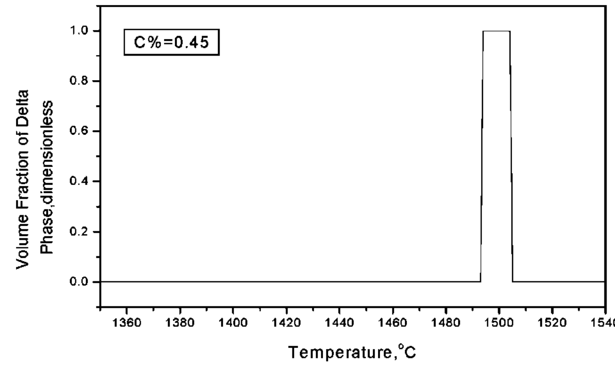
5 Volume fraction of δ phase versus temperature for 0·12% carbon steel



6 Volume fraction of δ phase versus temperature for 0·18% carbon steel

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 δ increases from 0 at T_l to 1 at the solidus temperature T_s (1517°C). The volume fraction of δ remains at 1 from T_s until the temperature falls down to T_{max}=1443°C corresponding to the start of $\delta \rightarrow \gamma$ transformation; however, the δ phase changes to γ phase completely by T_{min} (1421°C). Below 1421°C, the solid phase is only γ 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 $111{\cdot}81 \times 10^{-6}$ K^{-1}, which is the biggest for this steel grade.

The behaviour of steel containing 0·09% carbon is similar to that of a 0·05%C steel. Volume fraction of δ phase with temperature is illustrated in Fig. 4. It is shown that from the casting temperature of 1540°C to T_l

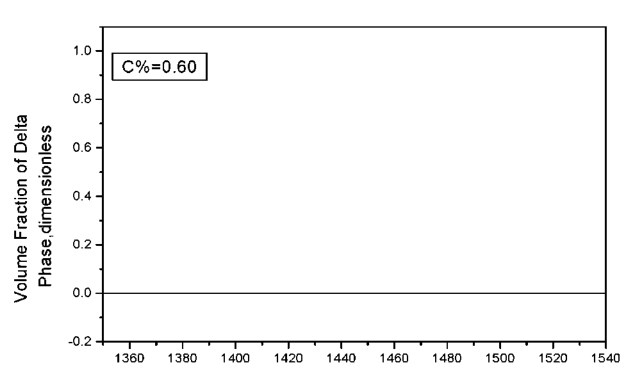


7 Volume fraction of δ phase versus temperature for 0·45% carbon steel

(1533°C), no solid phase appears, and then the volume fraction of δ increases from 0 at T_l to 1 at T_s (1498°C). The volume fraction of δ equals 1 below T_s until the temperature falls down to T_{max} of 1483°C, and then the δ phase changes to γ phase completely from T_{max} of 1483°C to T_{min} of 1443°C and below 1443°C, the solid phase is entirely γ phase. Because the temperature range of phase transformation 40 K, which is larger than that of the steel containing 0·05% carbon, the apparent TLE during $\delta \rightarrow \gamma$ is comparatively smaller at $71{\cdot}93 \times 10^{-6}$ 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 $\delta \rightarrow \gamma$ temperature range is very small, so the effect of this transformation on heat transfer at meniscus in mould will not be significant.

The steel with 0·12% carbon is hypoperitectic. The peritectic reaction, $L+\delta \rightarrow \gamma$, takes place between T_{max} of 1493°C and T_{min} of 1460°C. Because δ concentration is higher than equilibrium concentration of the peritectic reaction, only a part of the δ phase reacts with the liquid phase to produce γ; the rest of δ phase, changes to γ 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 $81{\cdot}79 \times 10^{-6}$ 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 δ phase reacts with the liquid phase to produce γ, forming 100% of the γ phase. A peritectic steel will suffer sharp change of volume in



8 Volume fraction of δ phase versus temperature for 0·60% carbon steel

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 $\delta \rightarrow \gamma$ 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 $\delta \rightarrow \gamma$ 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 $\delta \rightarrow \gamma$ change in the temperature range specified from the Fe–C phase diagram as T_{max} and T_{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 hypoperitectic, 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 $\delta \rightarrow \gamma$ 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.

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