Mechanism of silicon influence on chills in ductile iron

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Abstract

In the present work an analytical expression that combines the susceptibility of liquid cast iron to solidify according to the Fe-C-X metastable system (also known as the chilling tendency of cast iron, CT) is proposed. A relationship between CT and several factors has been developed. In particular the CT is related to the critical wall thickness (s cr), below which the chill is formed. Theoretical calculations of s cr were made and then compared with experimental outcome for ductile iron melts. The predictions of the theoretical analysis are in rather good agreement with the experimental data. The results can be used as a guide for a better understanding of the effect of technological variables such as the melt chemistry, the holding time and temperature, the spheroidizing and inoculation practice, the resulting nodule count and the type of mold material and pouring temperature, on the resultant chill of the ductile iron.

Key words: thin wall ductile iron, chilling tendency, chill,

1. Introduction

Significant efforts have been conducted recently towards the study of several aspects related to the production of thin wall ductile iron (TWDI) in order to introduce ductile iron pieces into the light parts market. Considerable efforts have been made in correlating various factors of technological relevance, such as chemical composition [1-4], pouring temperature [2], spheroidization and inoculation practice [2,3,5,6], casting geometry [7], plate thickness [2,3,7], mold material [8], and nodule count [1] with the chill of cast iron.

These experimental relationships are very useful but they are limited in their physical meaning. Accordingly, in this work an analytical expression is presented aiming to estimate quantitatively the chill formation.

2. Experimental procedure

TWDI plates, cast for a previous work [4] at the foundry pilot plant of the INTEMA Research Institute, have been used to validate the theoretical calculations.

Three unalloyed ductile iron melts were produced by using a 55kg capacity medium frequency induction furnace. Charges were made using regular quality raw materials. The melts were superheated up to 1550ºC before tapping. Nodularization was carried out using the sandwich method and 1.4% of Fe-Si-Mg (6% Mg). They were inoculated with 0.8% Fe-Si (75% Si) in the stream. The melts had similar carbon content, but different percentages of silicon.

Plates were cast using a horizontal model. Moulds were made of resin bonded 60/62 sand and the inner surfaces were coated with graphite paint. Six plates of 120 x 40 mm were obtained from each mould. Three of them had 1.5mm thickness, while the others had 2, 3 and 6 mm thickness, respectively.

The microstructure of the samples was characterized on surfaces obtained by cutting the plates in the central zone. The microstructure characterization was aided by the use of the Image analyzer software. Nodule count was measured on unetched samples considering a nodule diameter threshold of 5 microns. In ductile iron the graphite nodules are characterized by Raleigh distributions [9] so the volumetric nodule count (nodule count per
unit volume), $N$ can be related to the planar nodule count (nodule count per unit area), $N_F$ using the Wiencek equation [10]:

$$N = \frac{N_F^2}{f_{gr}}$$ (1)

where $f_{gr}$ is the volume of graphite at room temperature, $f_{gr} \approx 0.11-0.14$.

The amount of carbides (area percentage) has been measured after etching with ammonia persulphate (10%). Reported values of nodule count and carbide content are the average of at least five readings on each sample, at x100 magnification.

3. Analysis of results and discussion

Table 1 shows results, for both, chemical composition and wall thickness, as well as the exhibited nodule count and cementite fractions.

A theoretical analysis for the solidification of ductile iron [11] indicates the critical wall thickness $s_{cr}$ below which, the chill is formed can be given by

$$s_{cr} = 2pCT$$ (2)

Table 1. Chemical composition, wall thicknesses, nodule count, cementite fraction and chilling tendency $CT$

<table>
<thead>
<tr>
<th>Melt No</th>
<th>C, %</th>
<th>Si, %</th>
<th>P, %</th>
<th>Wall thickness, mm</th>
<th>Nodule count $N_F$, mm$^{-2}$</th>
<th>Fraction of cementite %</th>
<th>Chilling tendency $CT$, $s^{1/2}$/$oC^{1/3}$</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Experimental s</td>
<td>calculated $s_{cr}$</td>
<td></td>
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<tr>
<td>I</td>
<td>3.40</td>
<td>2.70</td>
<td>0.046</td>
<td>6.0</td>
<td>2.9 - 4.1</td>
<td>588</td>
<td>0.68</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>1039</td>
<td>9.0</td>
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<td></td>
<td></td>
<td></td>
<td>1380</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>1311</td>
<td>34.0</td>
</tr>
<tr>
<td>II</td>
<td>3.45</td>
<td>2.91</td>
<td>0.044</td>
<td>6.0</td>
<td>2.6 - 3.6</td>
<td>854</td>
<td>0.60</td>
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<td></td>
<td>1037</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>1100</td>
<td>24</td>
</tr>
<tr>
<td>III</td>
<td>3.31</td>
<td>4.42</td>
<td>0.051</td>
<td>6.0</td>
<td>2.1 - 1.5</td>
<td>1127</td>
<td>0</td>
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<td>1726</td>
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<td></td>
<td>1890</td>
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<td></td>
<td></td>
<td></td>
<td>2027</td>
<td>9.3</td>
</tr>
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</table>

From experimental data and the theoretical perspective, the role of the silicon on the chilling tendency $CT$ of ductile iron and the critical wall thickness $s_{cr}$ below which, the chill is formed can be disclosed based on Eqs. (2) and (4):

- The coefficient, $\beta$ (in Eq.(4)) is related to the slopes of the solubility lines JE’, E’S’ and BC’ in Fe-C-Si system. It in neglected small degree depends on the silicon content and it can be assumed that it is constant $\beta = 0.00155$ $°C^{-1}$.
- The temperature range $\Delta T_{sc} = T_s - T_c$ (in Eq.(4)), depends on the melt chemistry (Table 2). For our melts values of carbon and phosphorus content in ductile iron range from 3.31 to 3.40 and from 0.046 to 0.051 % respectively. Taking into account, an average values $C = 3.38$% and $P = 0.047$% $\Delta T_{sc}$ can be described by

$$\Delta T_{sc} = 11.3 + 18.8Si; °C$$ (8)
Fig. 1. Cooling curves (a) and effect of the wall thickness on the minimal eutectic solidification temperature, $T_m$ and nodule count $N$; $N_{cr}$ and $s_{cr}$ are the critical nodule count and the critical wall thickness (b). Nucleation potential of graphite = const.

It can be observed that as Si contents increase, the $\Delta T_{cr}$ range also increases, and from Eqs. (2) and (4) the chilling tendency, $CT$ of ductile iron and the critical wall thickness, $s_{cr}$ of castings decreases.

Table 1. Selected thermophysical data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value and units</th>
</tr>
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<tbody>
<tr>
<td>Latent heat of graphite eutectic</td>
<td>$L_e = 2028.8$ J/cm$^3$</td>
</tr>
<tr>
<td>Specific heat of cast iron</td>
<td>$c = 5.95$ J/(cm$^3$ K)</td>
</tr>
<tr>
<td>Material mould ability to absorb heat</td>
<td>$a = 0.11$ J/(cm$^2$ s$^{1/2}$ K)</td>
</tr>
<tr>
<td>Formation temperature for cementite eutectic</td>
<td>$T_c = 1130.56 + 4.06(C-3.33Si-12.58P)$ °C</td>
</tr>
<tr>
<td>Graphite eutectic equilibrium temperature</td>
<td>$T_s = 1154.0 + 5.25Si - 14.88P$ °C</td>
</tr>
<tr>
<td>C, Si, P = content of carbon, silicon and phosphorus in cast iron, respectively, %</td>
<td></td>
</tr>
</tbody>
</table>

- The diffusion coefficient of carbon in austenite, $D$ depends on temperature, $T$ and chemical composition of the austenite. The effect of Si, Mn and P on $D$ is not considered in this work, as there is not enough information available in the literature. An expression for the diffusion coefficient of carbon in austenite has been published [12] which is given by

$$D = \left(0.00453 + \frac{3.33957}{273.3 + T}\right) \exp\left(\frac{3.37065}{273.3 + T} - \frac{15176.273}{273.3 + T}\right)$$  \(9\)

Change of silicon content from 2.70% to 4.42% (Table 1) can range the temperature, $T$ during the eutectic transformation, from $T_s = 1176$ to $T_c = 1082$ °C so the $D$ values range form $5.6 \times 10^{-6}$ to $2.7 \times 10^{-6}$ cm$^2$/s. Thus, as Si contents increase, the $D$ can decreases, and from Eqs. (2) and (4) the chilling tendency, $CT$ of ductile iron and the critical wall thickness, $s_{cr}$ of castings increase.

- The critical nodule count, $N_{cr}$ (Fig. 2). It is well known that each nucleus graphite gives rise to a single nodule, so it can be assumed that measure of graphite nuclei count or nucleation potential of graphite is nodule count. An increase in the nodule count means that, for a given cooling rate, during eutectic transformation the nucleation potential of graphite also increases. According to Table 1, in melt I the transition from a wall thickness, $s = 6$ mm (without cementite) down to $s = 3$ mm (with cementite) is closely linked to a nodule count change from 588 to 1039 mm$^{-2}$. As a result, an average nodule count value of $N_{cr} = 813$ mm$^{-2}$ was used in this work. Similar determinations were made in melts II and III and $N_{cr}$ values of 945 and 1959 mm$^{-2}$ has been obtained, respectively. Figure 2 shows the relation between silicon content in cast iron and the critical nodule count, $N_{cr}$. In particular, on the basis of experimental research it can be concluded that as silicon contents increase the, $N_{cr}$ also increase and can be described by

$$N_{cr} = 3.01 \left(65590Si-98290\right)^{3/2}$$  \(10\)

Fig. 2. Correlation between silicon content in cast iron and the critical nodule count, $N_{cr}$.
Chilling tendency CT. For the calculation effect of Si on CT, Eq. (4) for D from $2.7 \times 10^{-6}$ to $5.6 \times 10^{-6}$ cm²/s and Eqs. (8), (10) can be used. Results of these calculations are shown in Fig. 3. Thus, it can be stated that as silicon content in ductile iron increases the chilling tendency decreases.

The critical wall thickness $s_{cr}$ below which the chill is formed (Fig. 4). From Table 1, it is apparent that in melts I and II the chill occurs in walls with thicknesses between 3 and 6 mm, while in melt III it happens at wall thicknesses between 1.5 and 2 mm. Hence, in order to compare these results with the theoretical predictions, estimations of $s_{cr}$ were made, using Eqs. (2)-(8) and (10). In these calculations it was assumed that $D = 2.7 \times 10^{-6} - 5.6 \times 10^{-6}$ cm²/s, $a = 0.11$ J/(cm² s ½ °C) and $T_i = 1250°C$, other relevant information was taken from Table 1. Results of these calculations are shown in Fig. 4. From this figure, it can be observed that as Si contents increase from 2.70 to 4.42 %, the critical wall thickness, $s_{cr}$ decreases from 2.9 - 4.2 to 1.5 - 2.1 mm. In addition, a comparison calculated $s_{cr}$ indicates that the predictions from the theoretical analysis are rather in good agreement with the experimental data.

4. Conclusions

A simple theoretical analysis is presented which enables the predict of chilling tendency and chill in ductile cast iron based on the knowledge of: chemical composition of the casting, inoculation and spheroidization practice, superheating temperature and bath holding times and selected thermophysical data of metal and mold material as well as metal temperature just after pouring of mold (through $p$ parameter).

References