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Chilling Tendency and Chill of Cast Iron

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Abstract: An analytical expression is presented for 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). The analysis incorporates the nucleation and growth processes associated with the eutectic transformation. The CT is related to the physicochemical state of the liquid, the eutectic cells in the flake graphite, and the number of nodules in nodular cast iron. In particular, the CT can be related to the critical wall thickness, s_{cr}, or the chill width, W_{cr}, in wedge shaped castings. Finally, this work serves as a guide for understanding the effect of technical factors such as the melt chemistry, the spheroidizing and inoculation practice, and the holding time and temperature on the resultant CT and chill of the cast iron. Theoretical calculations of s_{cr} and W_{cr} compare well with experimental data for flake graphite and nodular cast iron.

Key words: chill; chilling tendency; gray cast iron; nodular cast iron

Introduction

The susceptibility of liquid cast iron to solidify according to the Fe-C-X metastable system (i.e. the chilling tendency, CT) of cast iron dictates its subsequent performance in many applications. In particular, cast irons possessing a high chilling tendency are prone to develop zones of white or mottled iron. Considering that these regions can be extremely hard, their machinability can be severely impaired. Alternatively, if white iron is the desired structure, a relatively small chilling tendency flavours the formation of grey iron which in turn leads to poor hardness and wear properties for the cast components. Hence, considerable effort has been made to correlate the various factors affecting the chill of cast iron such as chemical composition[1-4], pouring temperature[2], spheroidization and inoculation treatment[2,3,5,6], casting geometry[7], plate thickness[2,3,7], mold material[8], and nodule count[1].

Furthermore, some works[4,5] have given qualitative descriptions of the influence of the chemical composition and spheroidization and inoculation practice on the CT. These experimental relationships are very useful but are limited in their physical meaning. Accordingly, this work presents analytical expressions that explain the chill formation mechanism. For the sake of simplicity, this paper focuses on phenomena and results which still hold when one ignores the segregation effects of alloying elements, such as silicon, manganese, including the so-called inverse chill.

1 Analysis

A theoretical analysis of the solidification of cast iron[9,10] showed that the critical wall thickness, s_{cr}, (below which, the chill is formed) and the width of the total chill, W (ASTM A367-55T Standard) can be given by

$$s_{cr} = 2p\mathrm{CT} \tag{1}$$

$$W = \frac{4np}{\cos(\alpha/2)}\mathrm{CT} \tag{2}$$

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where for flake graphite cast iron,

$$p=\frac{a}{\pi}\left(\frac{2^5\ T_s^3}{L_e\ \phi^3\ c_{ef}^2}\right)^{1/6} \tag{3}$$

$$\mathrm{CT}=\left[\frac{1}{N_s\ \left(1-f_\gamma\right)\ \mu^3\ \Delta T_{sc}^8}\ \exp\left(\frac{b}{\Delta T_{sc}}\right)\right]^{1/6} \tag{4}$$

or

$$\mathrm{CT}=\left[\frac{1}{N_{cr}\ \left(1-f_\gamma\right)\ \mu^3\ \Delta T_{sc}^8}\right]^{1/6} \tag{5}$$

and for ductile cast iron,

$$p=a\ \left(\frac{T_s^3}{4\ \pi^5\ \beta\ B^2\ L_e^2\ z^2\ c^4}\right)^{1/6} \tag{6}$$

$$\mathrm{CT}=\frac{1}{D^{1/2}}\left[\frac{1}{N_s\ \beta\ \Delta T_{sc}^2}\exp\left(\frac{b}{\Delta T_{sc}}\right)\right]^{1/3} \tag{7}$$

or

$$\mathrm{CT}=\frac{1}{D^{1/2}}\left[\frac{1}{N_{cr}\ \beta\ \Delta T_{sc}^2}\right]^{1/3} \tag{8}$$

$$\Delta T_{sc}=T_s-T_c \tag{9}$$

$$\phi\ =c_{ef}B_1+cB_2 \tag{10}$$

$$B=\ln\frac{T_i}{T_l},\quad B_1=\ln\frac{T_l}{T_s},\quad B_2=\ln\frac{T_i}{T_l} \tag{11}$$

$$c_{ef}=c+\frac{L_\gamma}{T_{l\gamma}-T_s} \tag{12}$$

$$z=0.41+0.93B \tag{13}$$

In these equations CT is the chilling tendency of the cast iron; N_s and b are the nucleation coefficients for flake graphite or nodular cast iron; f_γ is the proeutectic austenite volume fraction; a is the material mould ability to absorb heat; c_{ef} is the effective specific heat of the proeutectic austenite; T_i is the initial metal temperature just after filling the mould; ϕ is the heat transfer coefficient; α is the wedge angle; $\Delta T_{sc}=T_s-T_c$ and c, D, L_e, L_γ, T_l, $T_{l\gamma}$, T_s, T_c, μ, and β are defined in Table 1; N_{cr} is the critical cells or nodule count at temperature $T\approx T_c$; and n is the wedge size coefficient which expresses the influence of wedge size on the chill width. The ProductLog [y]=x is the Lambert function, also known as the omega function which can be easily calculated by means of the instruction ProductLog [y] in Mathematica™.

Table 1 Selected thermophysical data

Parameter	Value
Latent heat of graphite eutectic	L_e=2028.8 J/cm^3
Latent heat of austenite	L_γ=1904.4 J/cm^3
Specific heat of cast iron	c=5.95 J/(cm^3 • ℃)
Growth coefficient of graphite eutectic	$\mu=\left(9.2-6.3\mathrm{Si}^{0.25}\right)\times10^{-6}$ cm/(℃^{2} • s)
Material mould ability to absorb heat	a=0.10 J/(cm^2 • s$^{1/2}$ • ℃)
The diffusion coefficient of carbon in austenite	D = 3.9 10^{-6} cm^2/s
Coefficient related with the slopes of the solubility lines JE', E'S', and BC' in Fe-C system	β= 0.001 55℃$^{-1}$
Liquidus temperature for austenite	T_l=[1636 –113(C+0.25Si+0.5P)]℃
Formation temperature for cementite eutectic	T_c=[1130.56+4.06(C–3.33Si–12.58P)]℃
Graphite eutectic equilibrium temperature	T_s=[1154.0+5.25Si–14.88P]℃
Carbon content in graphite eutectic	C_e=(4.26–0.30Si–0.36P)%
Maximum carbon content in austenite at T_s	C_γ=(2.08–0.11Si–0.35P)%
Liquidus temperature of austenite for austenite composition C_γ	$T_{l\gamma}$=[1636–113(2.08+0.15Si+0.14P)]℃
Weight fraction of austenite	$g_\gamma=(C_e-C)/(C_e-C_\gamma)$
Austenite density	ρ_γ=7.51 g/cm^3
Melt density	ρ_m=7.1 g/cm^3
Volume fraction of proeutectic austenite	$f_\gamma=\rho_m g_\gamma/[\rho_\gamma+g_\gamma(\rho_m-\rho_\gamma)]$

Note: C, Si, and P indicate content of carbon, silicon, and phosphorus in the cast iron, %.