A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
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THE TRANSITION FROM GREY TO WHITE CAST IRON DURING SOLIDIFICATION

PROBLEM PRZEJŚCIA ŻELIWA SZAREGO W BIAŁE PODCZAS KRYSTALIZACJI

It has been presented theory which enable to determine cooling rate of casting Q_t at the transition from solidification according to stable (grey cast iron) to metastable (white and mottled cast iron) Fe-C-X equilibrium system. It has been proved that this transition is a function of chilling tendency CT and depends on physicochemical state of liquid cast iron which is characterized by the temperature range $\Delta T_{sc} = T_s - T_c$ (where T_s, T_c are equilibrium temperature of the graphite and cementite eutectic, respectively) and grain density of graphite eutectic N_t. In particular it has been shown that cooling rate of casting Q_t depends on excess temperature range $\Delta T_c = T_m - T_c$ (where T_m is minimal temperature at the onset of eutectic solidification), which can be experimentally determined by the thermal analysis. Derived relationships can be applied in foundry practice because calculation based on them are in accordance with experimental results.

Przedstawiono teorię, pozwalającą określić szybkość stygnięcia odlewu Q_t przy której następuje przejście od krystalizacji według stabilnego (żeliwo szarego) do metastabilnego (żeliwo białe i połowiczne) układu równowagi fazowej stopów Fe-C-X. Wykazano, że to przejście jest funkcją skłonności żeliwa do zabieleń CT i zależy od fizykochemicznego stanu ciekłego żeliwa charakteryzowanego przez zakres temperatury $\Delta T_{sc} = T_s - T_c$ (gdzie T_s, T_c oznaczają odpowiednio równowagową temperaturę krystalizacji eutektyki grafitowej i cementytowej) oraz gęstość ziaren eutektyki grafitowej N_t. W szczególności wykazano również, że szybkość stygnięcia odlewu Q_t zależy od nadmiaru temperatury $\Delta T_c = T_m - T_c$, (gdzie T_m oznacza minimalą temepraturę eutektyki grafitowej na początku krystalizacji), który można określić doświadczalnie za pomocą analizy termicznej żeliwa. Wyprowadzone zależności mogą być stosowane w praktyce odlewniczej, gdyż uzyskane zgodnie z nimi wyniki obliczeń są w dobrej zgodności z wynikami doświadczalnymi.

1. Introduction

The transition from grey-to-white cast iron arises from the nucleation and growth competition between the stable graphite (grey) and metastable cementite (white) eutectics. Only a few attempts aimed at elucidating the mechanisms responsible for the transition from grey-to-white cast iron [1-4]. In addition, various numerical models have been proposed [5-7] to predict whether a given casting or part of it will solidify according to the stable or metastable Fe-C system. However, their application is tedious due to extensive numerical calculations.

In the literature [1, 2, 8-11] the transition from graphite to cementite eutectic during solidification is also related to the so called chill of cast iron. Chill testing of cast iron is commonly measured using the ASTM Designation A 367-55T (Fig. 1a). By these means it is possible to identify three regions in a chill specimen; grey (graphite eutectic), mottled (mixed structure of graphite and cementite eutectic), and white (cementite eutectic). The regions containing mottled and white structures are also known as the chill for castings. In general, the greater is the susceptibility for the transition from grey to white cast iron (chilling tendency) during solidification, the greater is the chill developed in cast iron.

An application of cast iron depends on its chilling tendency. In particular, cast irons possessing a high chilling tendency tend to develop zones with cementite eutectic. In consequence, inhomogeneity of mechanical properties can be observed and considering that these regions can be extremely hard, their machinability can be severely impaired. Alternatively, if white iron is the desired structure or castings with chill layers a relatively small chilling tendency will favor the formation of grey

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iron and will decrease thickness of chill layer. This in turn leads to low hardness and poor wear properties in the as-cast components.

As it was mentioned the transition from grey to white cast iron during the solidification process is often determined by the resultant structure obtained in standard wedge-shaped castings. Figure 1b shows schematically the effect of cooling rates and cooling range on the structure of standard wedge-shaped castings. Accordingly, two cooling ranges are clearly distinguished. In the first range, grey cast iron is the stable structure, while in the second range white and mottled cast iron is found to solidify. In particular, notice that as the second range of cooling rates widens, the width of chill of wedge increases.

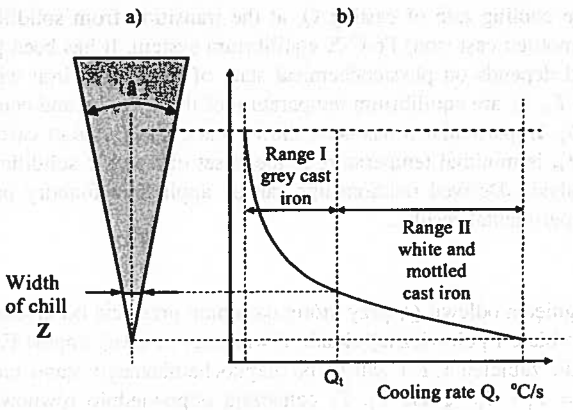


Fig. 1. Standard wedge – shaped specimen (a) and cooling rate ranges near the tip and along the axial direction of the wedge (b)

Thermal analysis has been commonly used for determinations of solidification kinetics in metallic systems. A dual thermal analysis in combination with chilled wedge-shaped castings can also be employed in predictions of the chill of cast iron. In this case, a simultaneous thermal analysis of the same cast iron is made in tellurium eutectometer cups and in a plain (non-tellurium) eutectometer cups. In tellurium eutectometer cups cast iron solidifies as white so the cementite eutectic formation temperature T_c can by recorded. Alternatively, in a plain eutectometer cups cast iron solidifies as grey and the minimal temperature T_m at the onset of graphite eutectic solidification as well as liquidus temperature T_l for austenite can be determined. Moreover, through statistical analysis, a relationship can be found between the width Z of chill and characteristics T_l, T_m and T_c temperatures and the carbon equivalent CE = %C + 0.25%Si + 0.5%P (where C, Si, P – contents of carbon, silicon and phosphorous in cast iron) or only carbon and silicon contents. According to the literature [12-14], various statistical relationships have been proposed (Fig. 2). From this figure results that the width Z of chill can be described by different correlations relationships though it is know that the mechanisms of the chill formation is only one and therefore only one equation should be exist. The foregoing relationships can be statistically correct, but they neither defining a physical sense of equations coefficients nor they have much to say with regards to the mechanisms involved during the chilling of cast iron. The regression Eqs. (1) to (5) are just an example of a type of "black box" which is fed with input parameters on one side and the final result is obtained at the other end of the box. The purpose of this work is of analytical derivation of the equation for the chill width Z in wedge-shaped castings which results from theory of solidification of cast iron and shows that this equation can be used in foundry practice.

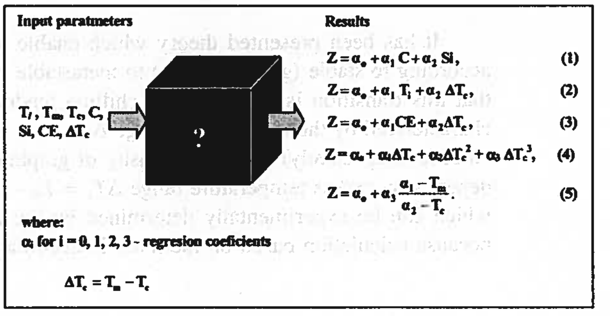


Fig. 2. Correlations relationships between various input parameters and width Z of chill

2. Theoretical analysis

Changes in the physical-chemical state of liquid cast iron can lead to different temperature variants in the cooling curves and ΔT_{sc} ranges as shown in Figure 3. In this figure, T_s, is the stable equilibrium solidification temperature for graphite eutectic, T_c is the cementite eutectic formation temperature and T_m is the minimum temperature for graphite eutectic solidification. Accordingly, various values of the excess temperature range $\Delta T_c = T_m - T_c$ are likely to be exhibited. From the work [15], it is evident that the wider the ΔT_c, the greater the critical cooling rate Q_t (Fig. 1b) needed under which white cast iron become the dominant solidification constituents. In other words, increasing of the excess a temperature ΔT_c, reduces the width of chill of wedge.

It is assumed that the same iron is poured into a mold with tellurium (to ensure the solidification of white cast iron structure) for recording the T_c temperature and into a plain, non-tellurium mold (to develop a grey cast iron structure) for the determination of the T_m temperature in the so-called reference casting. It is well know that as cooling rate of cast iron increase the undercooling $\Delta T_c = T_m - T_c$ and eutectic grain density N_o also increases.

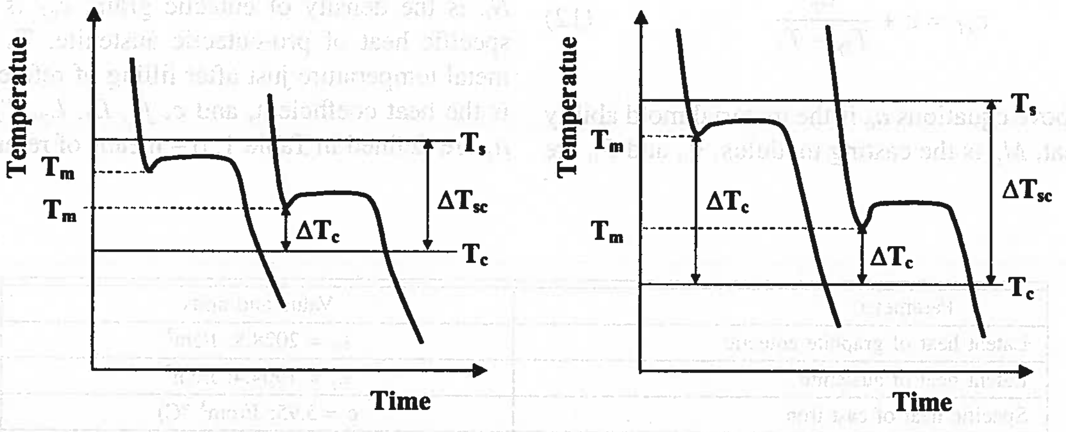


Fig. 3. Variants due to the influence of the physicochemical state of the liquid cast iron on the cooling curves and to the equilibrium temperature of graphite eutectic, T_s cementite eutectic, T_c, as well as ΔT_c and ΔT_{sc} ranges [15]

In other words, if the cast iron at cooling rate Q_o in reference casting reaches the temperature T_m (see Fig. 4) and grain density N_o then at the critical cooling rates, Q_t in test wedge casting the same iron reaches the temperature $T_m = T_c$ (see Fig. 4a) at higher grain density N_t ($N_t > N_o$) and the cementite eutectic solidifies.

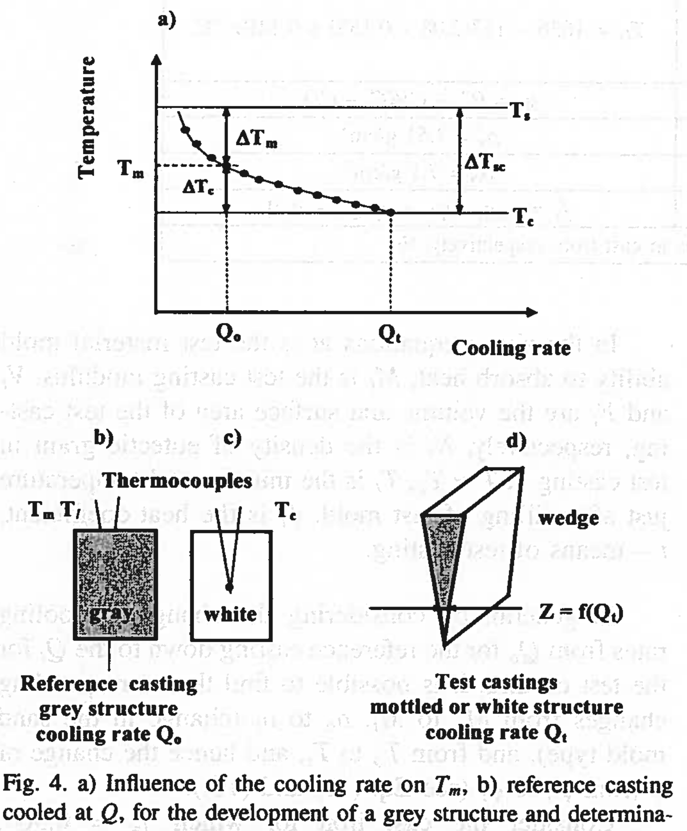


Fig. 4. a) Influence of the cooling rate on T_m, b) reference casting cooled at Q, for the development of a grey structure and determination of the T_m temperature, c) casting with a white cast iron structure used for recording T_c and d) test castings of the same cast iron cooled at Q_t to form a mottled or white structure

Accordingly, it can be concluded that the wider the excess temperature range, ΔT_c in the reference casting, the higher is the critical cooling rate Q_t needed for the development of a chill in the test casting. Thus, a determination of the critical cooling rates Q_t is key to establish the critical conditions for the development of the chill in the test castings. In order to establish the right dependence for the chill width, Z the following issue needs to be properly addressed.

This issue (see Fig. 2 and 4a) is related to the determination of the critical cooling rate, Q_t for the test casting (with mottled and white cast iron structure) from the cooling rate Q_o for the reference casting (with a grey cast iron structure) at a given $\Delta T_c = T_m - T_c$ (determined by thermal analysis).

The theoretical analysis of solidification process of grey cast iron [16] shows that between cooling rate of casting and the minimum temperature T_m for graphite eutectic at the beginning solidification exists following relationship

$$T_m = T_s - \left(\frac{4\, c_{ef}}{\pi^3\, L_e\, \varphi_o}\right)^{1/8} Q_o^{3/8}, \tag{6}$$

where:

$$Q_o = \frac{2\ T_s\ a_o^2}{\pi\ \phi_o\ c_{ef}\ M_o^2} \tag{7}$$

$$M_o = \frac{V_o}{F_o} \tag{8}$$

$$\varphi_o = N_o\, \mu_g^3 \left(1 - f_\gamma\right) \tag{9}$$

$$\phi_o = c\, B_o + c_{ef} B \tag{10}$$

$$B = \ln\frac{T_l}{T_s};\ B_o = \ln\frac{T_o}{T_l} \tag{11}$$

$$c_{ef} = c + \frac{L_\gamma}{T_{l\gamma} - T_s}. \quad (12)$$

In the above equations a_o is the material mold ability to absorb heat, M_o is the casting modulus, V_o and F_o are the volume and surface area of the casting, respectively, N_o is the density of eutectic grain, c_{ef} is the effective specific heat of pro-eutectic austenite, T_o is the initial metal temperature just after filling of reference mold, ϕ_o is the heat coefficient, and c, f_γ, L_e, L_γ, T_s, T_l, $T_{l\gamma}$ and μ_g are defined in Table 1. o – means of reference casting.

TABLE 1

Parameter	Value and units
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 °C)
Growth coefficient of graphite eutectic	$\mu_g = 10^{-6}(9.2 - 6.3\ \mathrm{Si}^{0.25})$; cm/(°C^2 s)
Growth coefficient of cementite eutectic	$\mu_c = 2.5\ 10^{-3}$; cm/(°C^2 s)
Material mold ability to absorb heat	a = 0.10; J/(cm^2 s$^{1/2}$ °C)
Liquidus temperature for austenite	T_l = 1636 – 113(C + 0.25Si + 0.5P); °C
Graphite eutectic equilibrium temperature	T_s = 1154.0 + 5.25Si – 14.88P; °C
Cementite eutectic formation temperature	T_c = 1130.56 + 4.06(C – 3.33Si – 12.58 P); °C
$\Delta T_{sc} = T_s - T_c$	ΔT_{sc} = 23.34 – 4.07C +18.80Si + 36.29P; °C
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 when melt composition is equal to the maximum composition of carbon in austenite, $T_{l\gamma} = T_l\ (C_\gamma)$	$T_{l\gamma}$ = 1636 – 113(2.08 + 0.15Si + 0.14P); °C
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 austenite	$f_\gamma = \rho_m g_\gamma / [\rho_\gamma + g_\gamma (\rho_m - \rho_\gamma)]$
C, Si, P – content of carbon, silicon and phosphorus in cast iron, respectively, %	

At the critical cooling rate Q_t, T_m is equals T_c and ΔT_m is equal $\Delta T_{s,c}$, hence equation (6) can be rewritten as

$$T_c = T_s - \left(\frac{4\ c_{ef}}{\pi^3 L_e\ \varphi_t}\right)^{1/8} Q_t^{3/8}, \quad (13)$$

where

$$Q_t = \frac{2\ \mathrm{T_s}\ \mathrm{a_t^2}}{\pi\ \phi_t\ \mathrm{c_{ef}}\ \mathrm{M_t^2}}, \quad (14)$$

$$M_t = \frac{V_t}{F_t} \quad (15)$$

$$\phi_t = c\ B_t + c_{ef} B \quad (16)$$

$$B_t = \ln \frac{T_t}{T_l} \quad (17)$$

$$\varphi_t = N_t\ \mu_g^3 \left(1 - \mathrm{f_\gamma}\right). \quad (18)$$

In the above equations at is the test material mold ability to absorb heat, M_t is the test casting modulus, V_t and F_t are the volume and surface area of the test casting, respectively, N_t is the density of eutectic grain in test casting at $T \approx T_c$, T_t is the initial metal temperature just after filling of test mold, ϕ_t is the heat coefficient, t – means of test casting.

In general, by considering the change in cooling rates from Q_o for the reference casting down to the Q_t for the test casting, it is possible to find the corresponding changes from M_o to M_t, a_o to a_t (change in the sand mold type), and from T_o to T_t, and hence the change of ϕ from ϕ_o to ϕ_t (see Eq. (10) and (16)).

Consider the cast iron for which f_γ = 0.309, L_e = 2028.8 J/cm^3, μ =2,64 10^{-6} cm/(s°C^2), T_s = 1158.7°C, T_l = 1230.9°C and c_{ef} = 14.52 J/cm^3. If this iron in reference casting reaches a temperature T_m = 1135.2°C at a Q_o = 2°C/s (from Eq. (7) for M_o = 0.488 cm, a_o = 0.1 J/(cm^2 °C s$^{1/2}$), T_o = 1270°C so ϕ_o = 1.06 J/(cm^3 °C) (see Eqs (10) , (11) and grain density N_o = 59372 cm^{-3}), then the temperature $T_m = T_c$ = 1123.6°C for the same iron in the test casting is reached at a Q_t = 4.93°C/s (according to Eq. (13), for M_t = 0.35 cm, a_t = 0.12 J/(cm^2 °C s$^{1/2}$), T_t = 1301.8°C, so ϕ_t = 0.85 J/(cm^3 °C) (see Eq.(16), and grain density N_t = 890585 cm^{-3}).

Taking into consideration (see Fig. 4a) that $\Delta T_c = T_m - T_c$ and Eqs. (6) and (13) a relationship between the critical test casting modulus M_t and the excess temperature range ΔT_c can be obtained.

$$M_t = \frac{p_t}{\varphi_t^{1/6}\left(\Delta T_c + \frac{p_o^{3/4}}{M_o^{3/4}\varphi_o^{1/8}}\right)^{4/3}}, \tag{19}$$

where

$$p_t = \frac{2^{5/6} a_t \, T_s^{1/2}}{\pi \, \phi_t^{1/2} c_{ef}^{1/3} \, L_e^{1/6}} \tag{20}$$

$$p_o = \frac{2^{5/6} a_o \, T_s^{1/2}}{\pi \, \phi_o^{1/2} \, c_{ef}^{1/3} \, L_e^{1/6}}. \tag{21}$$

From [16] results that the chill width of the wedge can be related with the critical test casting modulus

$$Z = \frac{4\,n}{\cos(\beta/2)} M_t \tag{22}$$

or

$$Z = \frac{4\,n\,p_t}{\cos\,(\beta/2)}\,CT, \tag{23}$$

where

$$CT = \left(\frac{1}{\varphi_t \, \Delta T_{sc}^8}\right)^{1/6} \tag{24}$$

β is the wedge angle, n is the wedge size coefficient, CT is the chilling tendency of cast iron and $\Delta T_{sc} = T_s - T_c$.

Fig. 5. shows the effect of technological factors on chill and chilling tendecy of cast iron.

Combining Eqs. (19) and (22) following expression can be obtained

$$Z = \frac{A}{(\Delta T_c + B)^{4/3}}, \tag{25}$$

where:

$$A = \frac{4\,n\,p_t}{\varphi_t^{1/6}\cos(\beta/2)} \tag{26}$$

$$B = \frac{p_o^{3/4}}{M_o^{3/4}\varphi_o^{1/8}}. \tag{27}$$

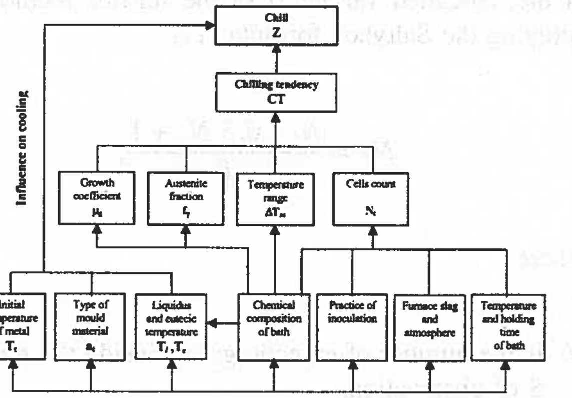


Fig. 5. Effect of technological factors on chill and chilling tendecy of cast iron

3. Basic experiments – I series

Experimental melts were made in an electric induction furnace of intermediate frequency in a 15 kg capacity crucible. The raw materials were pig iron, steel scrap, and commercially pure silicon. Melting was followed by liquid iron preheating at 1420°C and inoculation using FOUNDRYSIL with a 0.2÷0.5 cm granulation, and added as 0.5% of the total charge weight. Table 2 gives the chemical composition of the experimental cast irons. The cast iron before inoculation and after time 1.5; 5; 10; 15; 20 and 25 minutes calculated from the instant of inoculation, was poured into reference plate shaped molds of dimensions 0.6×10×10; 1.0×10×10; 1.6×14×14; 2.2×14×14 and 3.0×14×14 cm. The foundry molds were prepared using conventional molding sand and all plates had a common gating system. The thermocouple tips Pt/PtRh10 enclosed in quartz sleeves of 0.16 cm in diameter for plates of 0.6 and 1 cm in thickness, and of 0.3 cm in diameter for plates of other thickness were located in the geometrical center of each mold cavity. An Agilent 34970A electronic module was employed for numerical temperature recording. Figure 6 shows some typical cooling curves. These curves were then used for determinations of T_m temperature and of the initial metal temperature T_o just after filling of mold in order calculation of the ϕ_o coefficient.

After cooling, specimens for metallographic examination were taken from the geometrical centers of the plates. Metallographic examinations were made on polished and etched (Stead reagent) specimens to reveal graphite eutectic cell boundaries. Figure 7c shows a typical planar microstructure, with distinct eutectic grains. The grain density N_F, (average number of graphite eutectic grains per unit area) can be determined by means of the, so-called variant II of the Jeffries method, and applying the Saltykov formula [17].

$$N_F = \frac{N_i + 0,5\ N_w + 1}{F}, \tag{28}$$

where:

N_i is the number of eutectic grains inside the rectangle S of observation,
N_w is the number of eutectic grains that intersect the sides of S but not their corners,
F is the surface area of S.

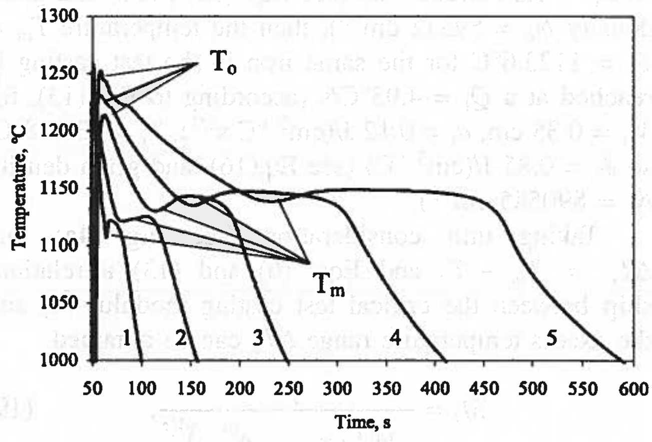
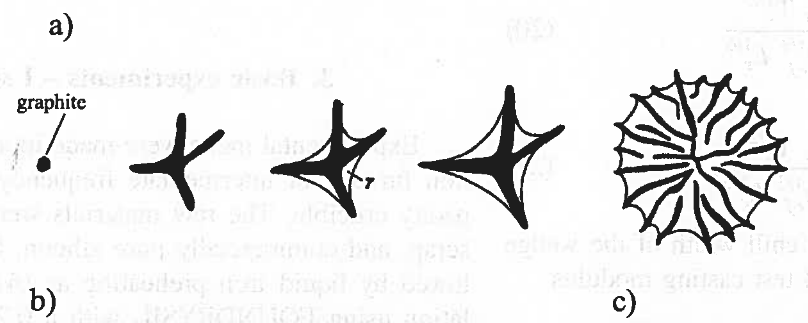


Fig. 6. Cooling curves of grey cast iron



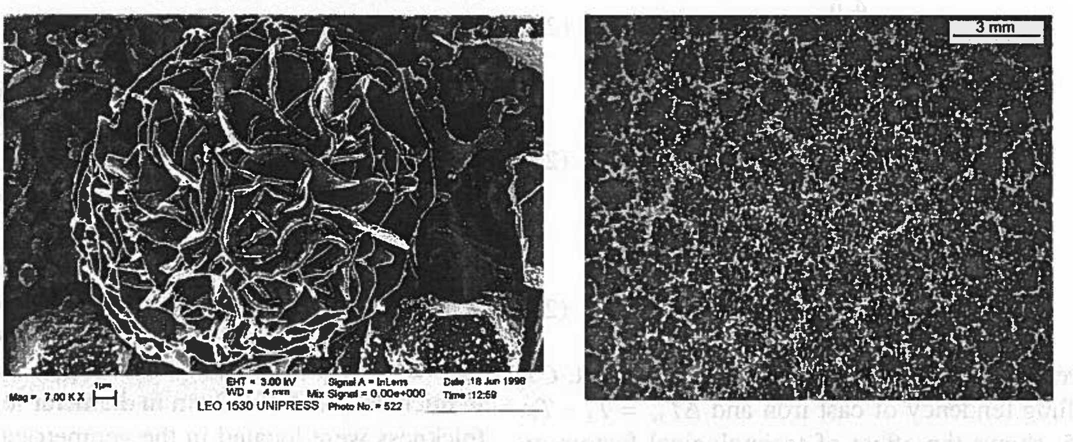


Fig. 7. Schematic of solidification of eutectic graphite- austenite cell and eutectic cell in flake graphite cast iron (a), graphite eutectic grain in casting (b) and planar structure of eutectic grains (c)

Using so-called Poisson-Voronoi model [18], the spatial grain density N (the average number of eutectic cells per unit volume) was calculated.

$$N \cong 0,568\ (N_F)^{3/2}. \tag{29}$$

Wedges (1.25 cm width, 2.5 cm height and 10 cm length) and samples for chemical composition were also cast simultaneously with the plates. Table 2 gives the chemical composition of the experimental cast irons. Thermocouple tips Pt/PtRh10 in mold wedges were used for determination of the initial metal temperature T_t just after filling of mold in order calculation of the ϕ_t coefficient. After puling of the wedges fracture, the width, Z of the total chill were measured at the junction of the grey cast iron microstructure with the first appearance of cementite precipitations. The Stead reagent was used to reveal of the eutectic grains boundaries (Fig. 8). The planar grain density N_F in the vicinity of that junction were converted into the volumetric grain density N_t using Eq.(29). The results of these measurements are given in Table 4.

TABLE 2

No. castings	Time after inoculation, min.	Chemical composition, wt. %				
		C	Si	Mn	P	S
I/1	base cast iron	3.25	1.17	0.13	0.085	0.047
I/2	1.5	3.14	1.98	0.13	0.091	0.067
I/3	5	3.18	2.05	0.11	0.093	0.061
I/4	10	3.16	2.04	0.13	0.095	0.065
I/5	15	3.21	2.01	0.14	0.095	0.053
I/6	20	3.20	2.08	0.13	0.098	0.050
I/7	25	3.16	2.08	0.13	0.091	0.052
Average composition		3.18	1.91	0.13	0.092	0.064

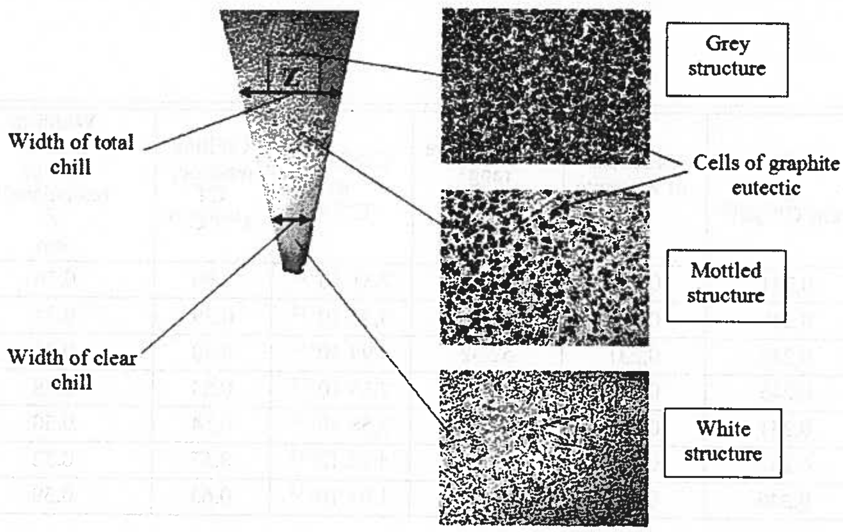


Fig. 8. Exhibited microstructures in wedge shaped castings

4. Reults of basic experiments

Taking into account the chemical composition of the cast iron (Table 2), any relevant thermo physical data (Table 1), the grain density, the average initial temperature $T_{o,a}$ in of reference and $T_{t,a}$ in of test castings (Table 3), and using a wedge size coefficient n, which for our wedges is 0.87, the theoretical width of the chill can be calculated from Eqs. (23) and (25). The results from these calculations are given in Tables 4 and 5. Notice that comparisons between the theoretical and experimental results yield a rather good agreement. It is worth pointing out, that for the same cast iron (for example castings I/7) the width, Z of the total chill is constant and not depends on of reference castings moduli M_o (Table 5).

For calculation the width, Z of the total chill in all range of the excess temperature range ΔT_c a average values for castings I/1-I/7 can be used

$$A = 903,16(\text{cm}\ {}^\circ\text{C}^{1/3})/\text{s}^{1/2} \text{ and } B = 20,10^\circ\text{C} \qquad (30)$$

After transformation Eq. (25) into of Taylor series, the first four terms were calculated in the vicinity of $\Delta T_c = 25^\circ$C for data (30) and can numerically be described by polynominal

$$Z = \alpha_o + \alpha_1\ \Delta T_c + \alpha_2\ \Delta T_c^2 + \alpha_3\ \Delta T_c^3 \qquad (31)$$

where:

$$\alpha_o = 14,1295 \text{ mm};\ \alpha_1 = -\ 0,580206^\circ\text{C}^{-1};$$
$$\alpha_2 = 0,0122526^\circ\text{C}^{-2};\ \alpha_3 = -\ 0,0001060^\circ\text{C}^{-3}$$

TABLE 3

No.	Reference casting M = 0.8 cm					Test casting		
	Eutectic temperature (measured) $T_{m,o}$ °C	Eutectic temperature (calculated[1]) $T_{m,o}$ °C	Grain density N_o cm^{-3}C	Excess of temperature range (measured.) $\Delta T_c = T_{m,o} - T_c$ °C	Excess of temperature range (calculated[1]) $\Delta T_c = T_{m,o} - T_c$ °C	Grain density N_t cm^{-3}C	Width of chill of wedge (calculated) Z mm	Width of chill of wedge (measured) Z mm
1	2	3	4	5	6	7	8	9
I/1	1138.0	1141,2	3312	14.4	17,6	59372	8.6	7.9
I/2	1146.9	1145,6	15157	33.8	33,8	1675225	3.3	3.3
I/3	1147.5	1144,4	9500	36.4	33,4	1131065	3.4	3.6
I/4	1146.5	1144,2	8600	35.6	33,3	207664	4.5	4.0
I/5	1143.0	1142,0	3945	31.4	30,4	198353	4.8	4.5
I/6	1137.8	1140.7	2450	27.4	30,3	137924	5.6	4.8
I/7	1137.6	1139,2	1326	27.0	28,7	58133	6.1	5.5

T_s and T_c temperatures were calculated on base chemical composition (table 1) and relationships given in table 2

$T_{o,a}$ = 1270°C; $T_{t,a}$ = 1240,4°C

TABLE 4

No.	Coefficient pt (cm°C$^{1/3}$)/s$^{1/2}$	Fractions of austenite f_γ	Temperature range ΔT_{sc} °C	Coefficient φ_t °C^{-6} s^{-3}	Chilling tendency CT s$^{1/2}$/°C$^{1/3}$	Width of chill of wedge (calculated) Z cm	Width of chill of wedge (measured) Z cm
I/1	0,231	0,309	35,20	7,31 10^{-13}	0,90	0,76	0,79
I/2	0,240	0,206	51,10	3,36 10^{-12}	0,39	0,34	0,33
I/3	0,248	0,231	52,32	3,99 10^{-12}	0,40	0,36	0,36
I/4	0,245	0,242	52,29	7,33 10^{-13}	0,53	0.48	0,40
I/5	0,251	0,220	51,49	7,58 10^{-13}	0,54	0,50	0,45
I/6	0,252	0,215	52,99	4,72 10^{-13}	0,57	0,52	0,48
I/7	0,246	0,238	52,90	1,93 10^{-13}	0,66	0,59	0,55

TABLE 5

Moduluc M_o cm	Grain density N_o cm^{-3}	Eutectic Temperature (calculated[1]) °C	Excess of temperature (calculated) $\Delta T_{c,o}$ °C	Width of chill of wedge (calculated[2]) Z mm	Width of chill of wedge (measured) Z mm
0,3	16632	1126.6	16,0	5.9	
0,5	5012	1134.3	23.7	5.9	
0,8	1326	1139,2	24.0	5,9	5,5
1,1	437	1141,5	31,0	5,9	
1,5	183	1144,1	33,2	5,9	

T_s and T_c temperatures were calculated on base chemical composition (table 1)

The grain density in wedge N_t = 58133 cm^{-3}

$T_{o,a}$ = 1270°C; $T_{t,a}$ = 1240,4°C

Thus, it is worth pointing out that Eq. (31), which is based on the theoretical analysis is identical to Eq. (4), which are based on a statistical analyses of the experimental data.

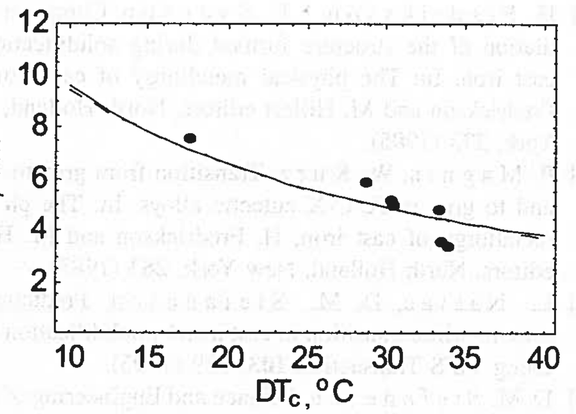


Fig. 9. Influence of the excess temperature ΔT_c in reference casting on the width Z of chill of wedge for castings I/1÷I/7 ——— Eq. (25), - - - - - - Eq. (31) • calculated

In addition, data from table 3 and the predictions from Eqs. (25) and (31) for data (30) are graphically shown and compared in Figure 9. From this figure is apparent that experimental points are rather close to the curves given by Eqs. (25) and (31). in spite of that the excess temperature ΔT_c was calculated on the ground a lot of indirect data which automatically introduce a various inaccuracy. To avoid this inaccuracy, II series of experiments has been done where the width Z of the total chill, as well as temperature T_m and T_c and then the excess temperature ΔT_c were measured directly.

5. Industrial investigacions – II series

Investigations has been done in a foundry of cast iron equipped with electric induction furnace and device for thermal analysis in tellurium eutectometer TECTIP cups for recording Tc temperature and in a plain (non-tellurium) eutectometer TECTIP cups for T_m determination. Object of investigations was in inoculated cast iron with the carbon equivalent 3.5 < CE < 4.25. After pouring of cast iron into TECTIP cups, the rest of it from hand ladle was poured into wedge shaped molds of dimensions: 1.0 cm width, 3.2 cm height and 12 cm length. After puling of the wedges fracture, the width, Z of the total chill were measured. Table 6 and Fig. 10 shows results these investigations.

TABLE 6

No	Graphite eutectic temperature T_m °	Cementite eutectic temperature T_c °C	Excess of temperature $\Delta T_{c,o} = T_m - T_c$ °C	Width of total chill of wedge Z mm
1	1128.3	1122.2	6,1	6,9
2	1136,7	1121,7	15,0	3,9
3	1143,9	1112,2	31,7	2,0
4	1130,0	1121,1	8,9	5,8
5	1144,4	1112,8	31,7	2,3
6	1125,7	1116,7	8,30	5,7
7	1134,4	1117,8	16,6	3,9
8	1130,6	1119,4	11,1	4,6
9	1128,9	1122,8	6,1	6,7
10	1136,7	1113,7	23,3	3,0
11	1133,5	1123,5	20,0	3,3
12	1135,5	1121,8	13,7	4,1
13	1146,3	1110,2	36,1	2,0
14	1132,2	1120,2	12,0	4,9

It can easy be demonstrated that results of investigations describe Eqs (25) and (31), which for data in table 6 assume following particular form.

$$Z = \frac{342,90}{(12,94 + \Delta T_c)^{4/3}}; \quad mm \tag{32}$$

$$Z = 8,9948 - 0.50611\ \Delta T_c + \\ + 0,014078\ \Delta T_c^2 - 0,000157\ \Delta T_c^3; \quad mm. \tag{33}$$

The correlation coefficient these equations is very high R = 0,99 and the standard deviation very low can be used in foundry practice. From these investigations results that at direct measurements of the ΔT_c Eq. (25) for the total chill can be used in foundry practice.

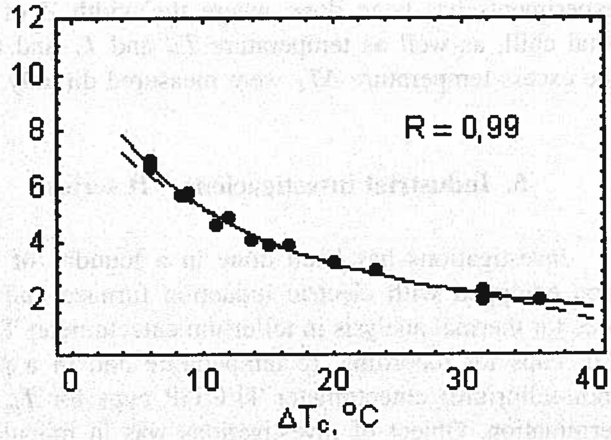


Fig. 10. Influence of the excess temperature ΔT_c in reference casting on the width Z of chill of wedge
——— Eq. (32), - - - - - - Eq. (33) • experimental data

6. Concluding remarks

1. On the base theoretical analysis of solidification of cast iron the analitical equation (25) were found between the excess of temperature range, ΔT_c and the chill width, Z in wedge shaped castings.
2. It has been shown that regression equation (4) is one variant of analitical equation (25) so it can be concluded that the problem of the "black box" associated with the regression equations has been resolved by providing a physical meaning to this expression.
3. In the case direct measurements of the excess of temperature ΔT_c Eq. (25) for the total chill Z can be used in foundry practice.

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