The Character of the Solidification Structure of Massive Ductile Cast-Iron Castings and its Prediction

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Abstrakt This paper deals with the simulation of solidification and cooling of a massive casting, with various ways of accelerated cooling using steel chills in order to reduce the heterogeneity of the pouring temperature field and to increase the rate of cooling of the casting. The results of the simulation of the temperature field are compared with experimentally measured temperatures. It seems that numerically controlled cooling enables the optimization of the technology of pouring of massive ductile cast-iron castings with spheroidal graphite. The relationships among four characteristic parameters and the corresponding local solidification times were determined in the series of samples that had been selected from defined positions of the massive casting.

1 Introduction

The problem of optimization of the properties and production technology for the casting of massive ductile cast-iron (spheroidal graphite) castings had been investigated in the past few years. During the investigations, the centre of focus was the verification of the possibility of applying two original models – the 3D model of transient solidification and the cooling of a massive cast-iron casting and the model of chemical and structural heterogeneity. Both models have been applied to describing the temperature field, the control of crystallization and the cooling of continually cast steel slabs, to the descriptions of their chemical heterogeneity and to determining the basic characteristics of their microstructure [1,4]. In describing the crystallization of the steel, the time for which the metal remains at a temperature between the liquidus and solidus is called the local solidification time, and the volume of metal corresponding to this time is determined by the sizes of the dendrites. When describing the solidification of cast-iron, including cast-iron with spheroidal graphite, the term ‘local solidification time’ is not generally used, despite the fact that the eutectic crystallization of grey cast-iron always runs within a certain temperature interval and naturally even a time solidification interval.

2 Numerical Model of the Temperature Field

The Fourier equation for a casting must be adapted so as to describe the temperature field of a casting in all its three phases: in the melt, in the mushy zone and in the solid phase. Here it is necessary to introduce the specific volume enthalpy $h_v = c.\rho.T$, which is dependent on temperature. The thermodynamic enthalpy function includes latent heat of phase or structural changes . The equation then takes on the form

$$\frac{\partial h_v}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial t}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial t}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial t}{\partial z}\right) \quad (1)$$

The specific heat capacity *c*, density ρ and heat conductivity *k* are also functions of temperature. The temperature of the general nodal point of the casting is obtained from the enthalpy-temperature dependence, which must be known for the relevant ductile cast-iron. The software pack ANSYS had been chosen for this investigation because it enables the application of the most convenient method of numerical simulation of the release of latent heat of phase and structural changes using the thermodynamic enthalpy function [3]. A real 500×1000×500 mm ductile cast-iron block with 15 chills on one side (No.1) had been used for the numerical calculation and the experiment (**Fig. 1a**).

The iso-zones, calculated in castings No. 1, No. 2 (with chills on three sides) and in its chills in various parts after casting, are illustrated in **Fig. 1b**. The comparison of the iso-zones, including the mushy zone in castings No. 1 and No.2 shows that this time is, relatively, not very much influenced by the increase in the number of chills or by the increase in the number of walls on which the chills are mounted. The total solidification time of casting No. 1 is 5:08:10 hours and 4:33:35 hours of casting No. 2.

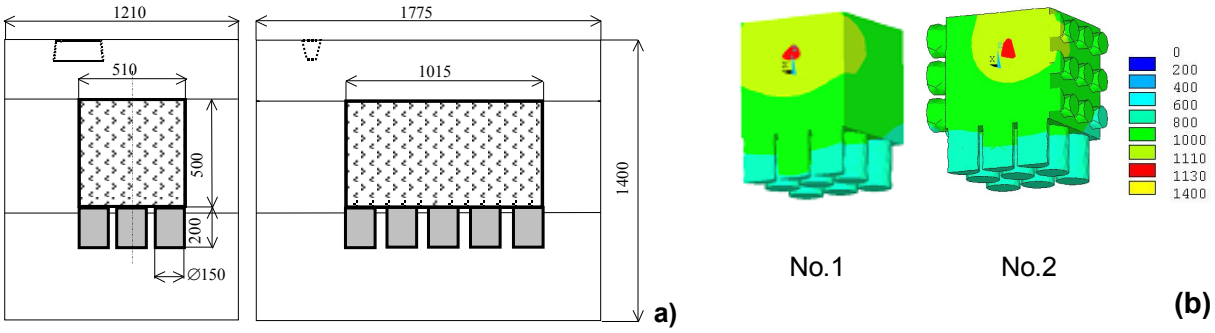

Fig. 1 a) The forming of casting No. 1 with chills on one side **b**) The calculated iso-zones in casting No. 1(5 hours) and No 2 (4.5 hours) and in its chills

3 The Relation between the Model of the Temperature Field and the Model of Structural and Chemical Heterogeneity

The aim was to verify the extent to which the revealed differences in the local solidification times affect the following parameters: a) The average size of the spheroidal graphite particles; b) The average density of the spheroidal graphite particles; c) The average dimensions of the graphite cells, and d) The chemical heterogeneity of the elements in the cross-sections of individual graphite cells. The relationships – among the given four parameters and the corresponding local solidification times – were determined in the series of samples that had been selected from defined positions of the massive casting. The casting No. 1 was selected from a series of three castings. The average chemical composition of the cast-iron before casting is given in **Tab. 1**. A 500×500×40 mm plate had been mechanically cut out of the middle of the length by two parallel transversal cuts. Then, further samples were taken from exactly defined points and tested in terms of their structural parameters and chemical heterogeneity. Samples in the form of testing test-samples for ductility testing, with threaded ends, were taken from the bottom part of the casting (A), from the middle part (C) and from the upper part (G). The 15 mm in diameter

and 12 mm high cylindrical samples served the actual measurements in order to determine the structural parameters and chemical heterogeneity.

Tab. 1 Chemical composition of ductile cast-iron

Element	C	Mn	Si	P	S	Ti	Al	Cr	Ni	Mg
wt.%	3.75	0.12	2.15	0.039	0.004	0.01	0.013	0.07	0.03	0.045

In the points of the defined positions of the samples prepared in this way, the quantitative metallographic analysis was used to establish the structural parameters of cast-iron, the in-line point analysis to establish the chemical composition of selected elements and numerical calculation using the 3D model to establish the local solidification time. Quantitative analyses of the basic micro-structural parameters in the samples have been the subject of a special study [4]. The measurement of the size parameters of the graphite was conducted on the Olympus CUE4 picture analyser under standard conditions, i.e. with a magnification of 100× and on each sample a total number of 49 views were evaluated. On the basis of average values of these results the structural parameters of graphite, i.e. the radius of the spheroids of graphite – R_g, the distances between the edges of graphite particles – L_g and the radius of the graphite cells – R_c have been determined for each sample. These results are given in **Tab. 2**. The local solidification times Θ of the selected samples of known coordinates within the massive experimental casting were calculated by the 3D model.

Tab. 2 Graphite properties and local solidification time of ductile cast-iron

	Structural parameters [μm]			Local solidification time [s]	Sample coordinates [mm]		
Sample	R_g	R_c	L_g	Θ	x	y	z
A	28	83	110	48	190	50	507.5
C	36	104	136	2509	190	210	507.5
G	39	109	140	4542	190	450	507.5

It is obvious from the results in **Tab. 2** that in the vertical direction from the bottom of the massive casting (sample A: y = 50 mm) to the top (gradually samples C: y = 210 mm and G: y = 450 mm) the characteristic and significant relations are as follows:

The average size of the spheroids of graphite, the average size of the cells of graphite and also the average distance between the individual particles of the graphite are all increasing. This relation was confirmed by the quantitative metallographic analysis. The relationships between the structural characteristics of graphite in the casting and the local solidification time were expressed quantitatively using a semi-logarithmic dependence (equation 2, 3, 4). Despite the fact that, for the structural characteristics of graphite R_g, R_c and L_g, there are only three pairs of measured values, i.e. (R_g,Θ), (R_c,Θ) and (L_g,Θ), the given dependences can be considered significant due to the fact that the quantitative metallographic analysis covers 49 measured views (with a magnification of 100×) on each of the three 3D samples (**Fig.2**). This research can therefore be considered as statistically significant. The relationships between the structural characteristics of graphite and the local solidification time Θ had been found using the least-squares method. The testing indicates that the local solidification time Θ has significant influence on the ductility. The relationship between the ductility and the local solidification time (equation 5) indicates that the reduction in the ductility of cast-iron in the state immediately after

pouring is – in the first approximation – directly proportional to the square of the local solidification time.

$$R_g = 19.08 + 2.274 \ln \Theta \quad R_c = 61.33 + 5.567 \ln \Theta \quad L_g = 84.50 + 6.586 \ln \Theta \quad A_5 = 23.399 - 8.1703 \Theta^2 \quad (2,3,4,5)$$

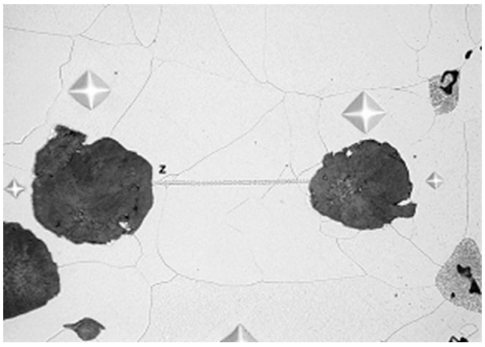

Fig. 2 Structural characteristics measurement of ductile cast-iron ($Z \equiv L_g$ = 165 μm)

4 Conclusion

It can be seen from previous experimentation and the evaluations of the results that – in the general case of the solidification of ductile cast-iron – there could be a dependence of the size of the spheroids of graphite, the size of the graphite cells and therefore even the distance among the graphite particles on the local solidification time, i.e. on the solidification time in which the considered point remains within the mushy zone. The described connection with the 3D model of a transient temperature field, which makes it possible to determine the local solidification time, seems to be the means via which it is possible to estimate the differences in structural characteristics of graphite in cast-iron and also the effect of the local solidification time on ductility in the poured casting.

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