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Effect of Moulding Sand Thermal Capacity on Morphology of Carbide Phase in High-Chromium Cast Iron

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The paper gives mathematical description of relationships between some selected stereological parameters of carbide phase in ferritic high-chromium cast iron containing 2.2 % C and 22 % Cr and the thermal capacity C of moulding sands [J/m^{3}K]. It has been observed that the degree to which changes in the thermophysical parameters of moulding sand affect structure of the examined alloy depends strongly on the casting wall thickness.

Keywords: carbides morphology, quantitative analysis, thermal capacity.

1. INTRODUCTION

High-chromium cast irons are widely used for all those applications where the main requirement is material resistance to abrasive wear [1, 2]. These alloys are a good example of heterogeneous materials whose structure, and hence also the type, shape and properties of the individual constituents, decide, among others, about the abrasion resistance under given operating conditions [3, 4].

In as-cast condition, the microstructure of high-chromium cast iron is composed of hard, brittle and combined with each other precipitates of eutectic carbides of an M_7C_3 type, embedded in a ferritic, martensitic, or austenitic matrix. When solidified, the eutectic carbides are relatively stable during heat treatment, contrary to the matrix, which is prone to transformations with precipitation of fine, secondary carbides inside the dendrites of former austenite [5 – 7]. The rate of heat transfer during solidification and cooling of casting exerts an important effect on the type and morphology of the precipitating phases. The main source stimulating the rate of these processes is, besides the casting wall thickness, the type of moulding sand, and more exactly its thermo-physical parameters.

The study presented here mainly aims at providing an analysis of the effect of thermal capacity C on some selected stereological parameters of carbides present in high-chromium cast iron of certain chemical composition. An effect of the casting wall thickness has been taken into consideration as well.

2. TEST MATERIAL

In sand moulds with different content of micro-chills, plates of the thickness amounting to 6, 18 and 30 mm were cast. The compositions of the test moulding sands are given in Table 1. It has been decided to use moulding sand of this specific type, since homogeneous sands of mineral origin are not capable of achieving the thermophysical parameters sufficiently high to induce some important changes in the morphology of structural constituents of an alloy. A research on this particular subject was carried out some years ago by Zenon Ignaszak [8].

Table 1. Moulding sand compositions (CO_2 hardened)

Moulding sand M_1	100 % silica sand, 6 % water-glass
Moulding sand M_2	75 % silica sand, 25 % cast iron shot, 6 % water-glass
Moulding sand M_3	45 % silica sand, 55 % cast iron shot, 6 % water-glass

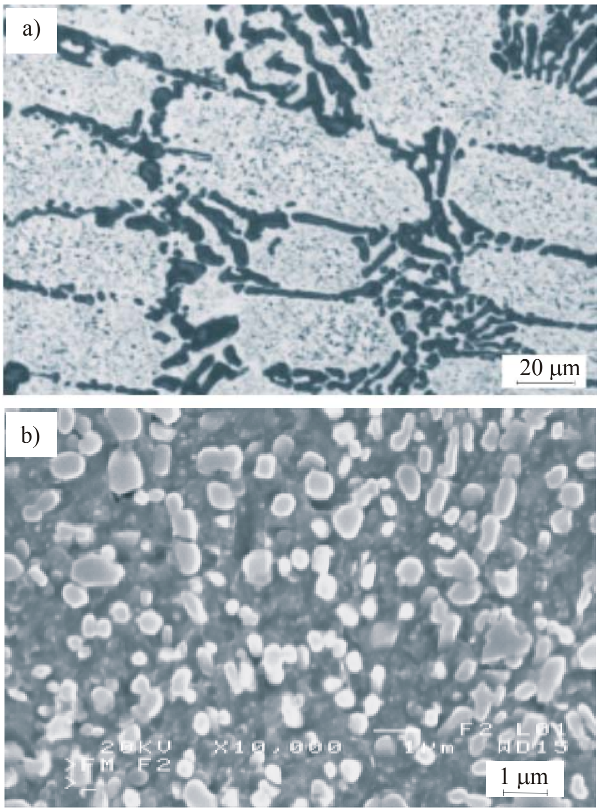

Fig. 1. Microstructure of tested alloy after annealing: a – general view; b – secondary carbides

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Homogeneous mould materials, characterised by the cooling capacity much higher than, e.g. chromite sand, perform their function much more effectively when used together with base silica sand mixture [9].

The material used for castings was selected basing on the results obtained in former investigations. This was high-chromium cast iron of the following chemical composition; 2.2 % C, 22 % Cr, 0.3 % Si, 0.01 % Al, 0.028 % P, 0.023 % S. The microstructure of tested alloy after heat treatment consists of large eutectic carbides on grain boundaries and small secondary carbides within the matrix (Fig. 1).

From the investigations it followed that alloy of this composition, when attacked by an abrasive material projected at an angle of 37°, should offer the highest abrasion resistance under predetermined operating conditions.

3. RESULTS OF TESTS

The value of the thermal capacity C for silica sand-based moulding mixtures containing micro-chills (cast iron shot) was determined from the following equation:

$$C = c \times \rho \, , \ [\mathrm{J/m^3K}] \, , \qquad (1)$$

where C is the thermal capactiy, c is the specific heat, ρ is the density of moulding sand.

The obtained values are compiled in Table 2.

Table 2. Thermal capacity C [J/m^{3}K] of moulding sand

Moulding sand	M_1	M_2	M_3
Thermal capacity C	1.58e6	1.81e6	2.22e6

The stereological parameters of carbides, like shape factor (W_m), volume content of carbides in as-cast state (U_s) and after heat treatment (U_w), which in this particular case was isothermal annealing, were determined by means of a Visilog 4 computer program. The results of the measurements are compiled in Table 3.

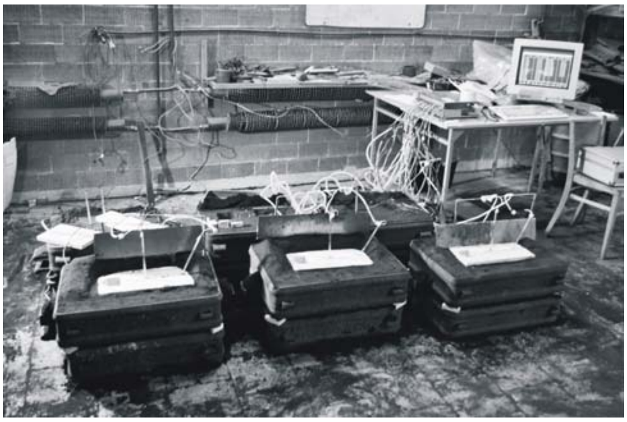

Fig.2. The test stand for measuring of thermophysical properties of moulding sand

The thermal capacity C was determined for the three types of moulding sands and for the three different casting wall thicknesses. Altogether, nine different conditions of the casting cooling and solidification were obtained. The view of casting mould with apparatus for measurement of thermophysical properties of moulding sand is shown in Fig. 2. The test stand consist of three forms with a set of 10 thermo-couples placed in each of form and connected with computer. The experimental procedure was described in [10].

3.1. Mathematical description of relationships between the morphology of carbide phase and thermal capacity of moulding sands

Thermal capacity of moulding sands was related to the shape factor, volume content of carbides, casting wall thickness, and content of micro-chills in moulding sand. Quantitative relationships were derived, applying the method of association and rejection [11]. To the equations were associated the coefficients of statistical estimation: R – coefficients of multiple regression, F – the value of F-Snedecor test. The simulations were carried out on standardised values from <0.5 – 1.5> interval according to the relation:

$$X = [(X_i - X_{min}) \, / \, (X_{max} - X_{min})] + 0.5 \, . \qquad (2)$$

3.2. Median of the shape factor of eutectic carbides – W_m

$$W_m = 1.03 + 0.236 \times X_{gr} + 0.07/\mathrm{C}; \ R = 0.917; \ F = 4, \qquad (3)$$

where W_m is the median of the shape factor of eutectic carbides, X_{gr} is the casting wall thickness, C is the thermal capacity.

From the diagram plotted in Fig. 3 it follows that the effect of thermal capacity on the shape factor of eutectic carbides in specimens after heat treatment is independent of the casting wall thickness, and its increase results in decrease of the shape factor value. This means that the precipitates of less developed surface are formed.

3.3. Volume content of carbides – U_w

$$U_w = 31 + 6.05 \times {X_{gr}}^2 + 2.16 \, / \, (X_{gr} \times X_C); \ R = 0.937; \ F = 3. \qquad (4)$$

An increase in the thermal capacity of moulding sand causes, within the whole range of the varying casting wall thicknesses, a decrease in volume content of the precipitated carbides (Fig. 4). At the same time, an increase in the casting wall thickness results in an increase of the carbides content in alloy. Since the examined materials are all in heat treated condition, and the task of the heat treatment is to make the structure approach a near-equilibrium state, a more or less the same volume content of carbides in all the specimens should be expected, as the content of carbides present in the cast material after annealing is said to depend on the chemical composition of alloy. In terms of this approach it is necessary to check once again if the examined parameter has been determined correctly (U_w).

3.4. Volume content of carbides in untreated alloy – U_s

$$U_s = \exp(3.301 + 0.467 \times X_\lambda - 0.173 \times {X_\lambda}^2 - \\ - 1.262 \times X_{gr} \times C + 1.156 \times X_{gr} \times X_b);$$

$$R = 0.937; \ F = 36; \qquad (5)$$

Table 3. The results of the measurements of stereological parameters (designations are explained in the text)

Moulding sand	Casting wall thickness X_{gr}								
	6	18	30	6	18	30	6	18	30
	W_m			U_w [%]			U_s [%]		
M_1	1.3	1.4	1.6	40.2	43.2	48.0	33.0	33.1	32.2
M_2	1.2	1.3	1.5	39.4	37.5	44.6	32.8	31.6	29.9
M_3	1.3	1.3	1.4	35.4	38.2	47.6	34.8	31.0	29.7

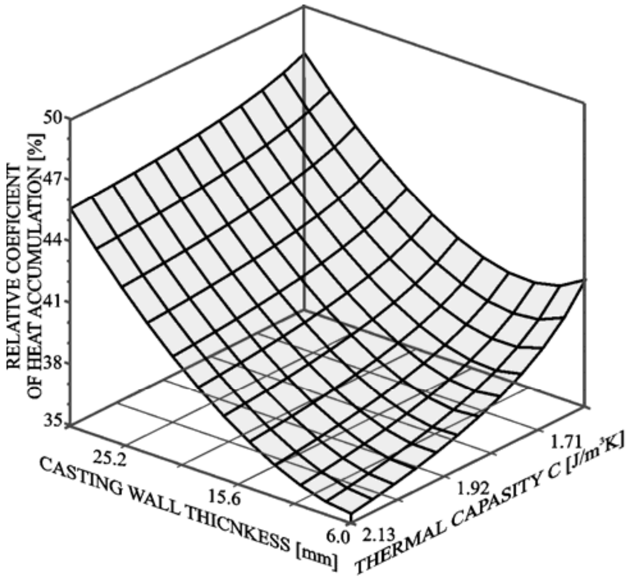

Fig. 3. Relationship between the shape factor of eutectic carbides (W_m) in heat treated specimens, the casting wall thickness X_{gr} and thermal capacity C of moulding sand

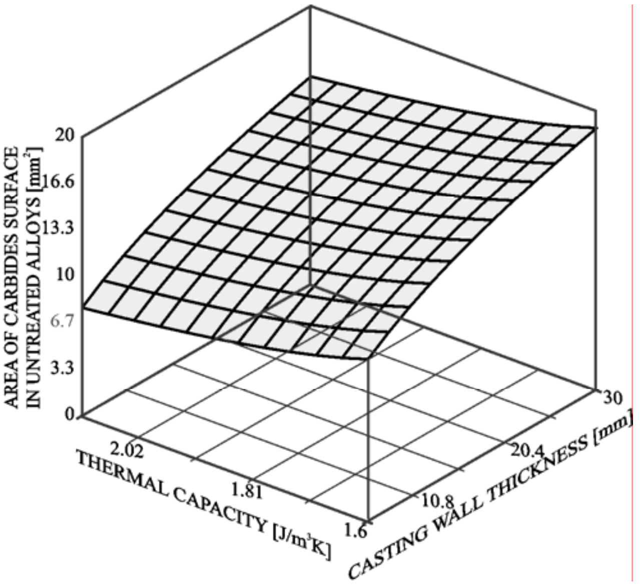

Fig. 4. Volume content of carbides U_w, %, in alloys after annealing in function of the casting wall thickness X_{gr}, mm, and thermal capacity C of moulding sand, J/m^{3}K

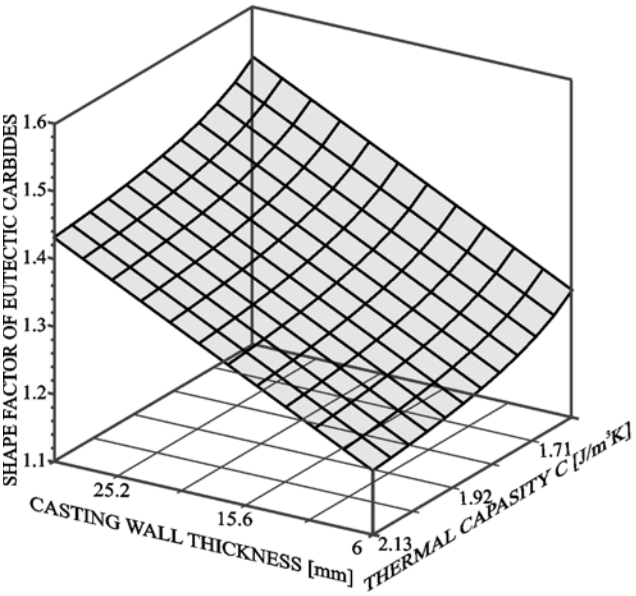

Fig. 5. Volume content of carbides U_s in function of the plate thickness X_{gr} and thermophysical parameters of moulding sand in untreated alloy

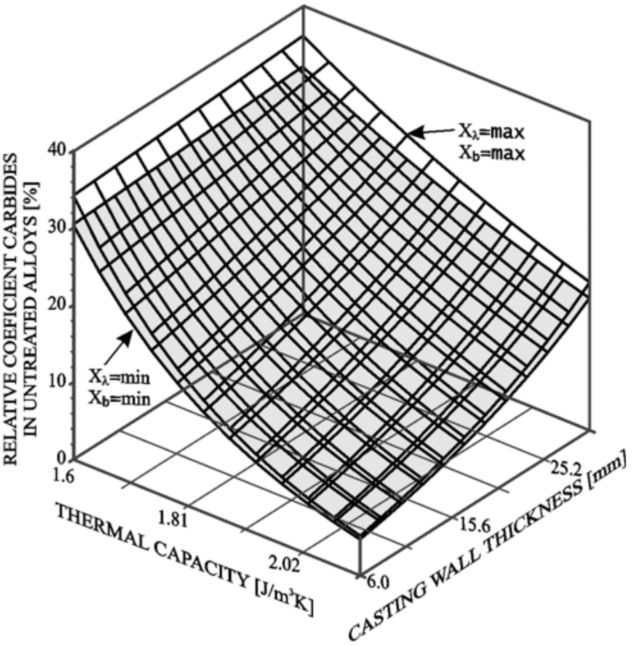

Fig. 6. In untreated alloys: area of carbides surface D_s in function of the casting wall thickness X_{gr} and thermal capacity C of moulding sand

Average size of carbides in untreated alloy – D_s :

$$D_s = 13.5 + 6.5 \times ln\ (X_{gr}) - 3{,}5 \times ln\ (C);$$

$$R = 0.912;\ \ F = 47, \qquad (6)$$

where X_λ is the thermal conductivity; X_b is the relative coefficient of heat accumulation.

The equation which describes the volume content of carbides in specimens before heat treatment allows for all the investigated thermophysical parameters and casting wall thickness. The least significant effect on the content of the forming carbide phase has the thermal conductivity λ [W/m^{2}K] (Fig. 5), which seems to be a result quite unexpected. An increase of the thermal capacity causes the greater drop in the content of carbides, the smaller is the casting wall thickness. On the other hand, increasing of the casting wall thickness strongly affects a similar increase in carbide content, but this only when the thermal capacity of moulding sand is high; it is of no significance when the capacity is low.

An average size of carbides D_s , represented in the case under discussion by a mean area of the precipitates surface, strongly depends on the casting wall thickness, being practically independent of the thermal capacity of moulding sand. On the other hand, an increase in the thermal capacity within the whole range of the varying plate thicknesses is uniform and causes only very small decrease in the mean size of carbide precipitates (Fig. 6).

4. CONCLUSIONS

The mathematical descriptions specified in this study have proved a significant effect of the thermal capacity of moulding sands on the morphology of carbides in alloys before heat treatment and on eutectic carbides in alloys after annealing.

– An increase in the volume content of the carbide phase U_s in untreated alloy (from 5 to 30 %) is very obvious, while the value of the thermal capacity C is decreasing (from 2.13 to 1.6 J/m^{3}K).
– The same change of the thermal capacity in the case of castings after annealing also causes an increase in the volume content of eutectic carbides.

Applying this mathematical description together with mathematical descriptions of other thermophysical parameters of moulding sands enables forecasting the structure characteristics of ferritic high-chromium alloys in function of the thermophysical parameters for a given casting wall thickness.

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