Peculiarities of calculations of formation of extended sections of steel castings in disposable moulds with functional coating of definite microrelief

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Abstract. In the present article are considered the issues of influence of the microrelief of the working cavity surface of the sand-and-clay mould on the intensity of heat exchange and formation of the structure in the surface area of the metal blank, for prevention of hot cracks formation.

The development of technological means for struggle against hot cracks in steel castings obtained in disposable, including sand-and-clay, moulds remains actual at the present time [1–5]. As one of the measures for preventing such defects during formation of steel castings, it is possible to use a special relief coating 4-5 mm thick of the inside surface of the mould. Such coating, as the research shows, creates additional obstacles to formation of hot cracks (HC) on account of formation in the surface zone of a solidifying alloy of stronger structure - a “reinforced” layer, dispersal of stresses in the casting in the period of its crystallization, as well as reduces heat expansion of the mould base.

During making a definite microrelief on the surface of the mould working cavity the chromite sand of fractions 0,2 and 0,4 has been suggested. The use of a functional coating based on the chromite sand of definite fractions forms a microrelief on the surface of the casting mould working cavity, which changes conditions of its heat exchange with the melt of the alloy. As a result, morphology of dendrite crystals in the surface zone of the casting is changed. In this connection, it is suggested to use the method of calculation of intensity of heat exchange of the metal blank being formed, with a combined shape, which allows to determine the value of the effective coefficient of heat accumulation of the mould with a functional coating, during solidification of the steel casting. This method is also used in the calculations of duration of solidification of steel castings sections, and their linear rates of crystallization.

The extent of the coating relief is considered by the coefficient of the mould $K_f$, which is determined from the expression:

$$K_f = \frac{S_{cov}}{S_{cov0}},$$

where $S_{cov}$ - actual surface area, $S_{cov0}$ - geometrical surface area, m².
The actual surface area of the casting mould working cavity with a functional coating was determined by a 3d model of this surface, obtained by the method of volume reconstruction. Two layers of the casting mould are suggested to be considered on account of application of the effective coefficient of the mould heat accumulation \( b_{ef} \) \[6\]. Considering a relief surface of the mould the following expression was received for calculation of the value \( b_{ef} \), and adequacy of it was checked in CSS "PoligonSoft":

\[ b_{ef} = \left\{ 1 + 2 \sum_{n=1}^{\infty} (-1)^n \left( \frac{1-K_b}{1+K_p} \right)^n \exp\left( \frac{-n^2}{F_0} \right) \right\} b_{cov}, \]  

(2)

where \( K_b = \frac{b_m}{b_{cov}} \); \( F_0 = \frac{a_{cov}^2}{\delta_{cov}^2} \), \( \delta_{cov} = K_f \delta_{cov} \); \( b_{ef} \) - efficient coefficient of the mould heat accumulation, W·s\(^{1/2}\)/(m\(^2\)·K); \( b_m, b_{cov} \) - coefficient of heat accumulation of the mould and coating, accordingly, \( a_{cov} \) - thermal diffusivity of the coating, m\(^2\)/s; \( \tau \) - time, s; \( \delta_{cov} \) - coating thickness, m.

According to expression (2) \( b_{ef} \) is the function of time. Its magnitude, dependent on the value of Fourier criterion \( F_0 \), is in the limits from \( b_{cov} \) to \( b_m \). Calculation of time of the casting section solidification \( \tau_s \) is determined from the equation of its heat balance by the iteration method, because it is a function of the effective coefficient of the combined mould heat accumulation \( b_{ef} \) and its initial temperature. Thus, for extended elements of the casting \( \tau_s \) blank is calculated according to the formula:

\[ \tau_s = \left( \frac{C}{B} \right)^2 / \psi, \]  

(3)

where \( C = \rho q_{eq} X_c / K_f \) and \( B = \frac{2}{\sqrt{\pi}} b_{ef} (T_p - T_{mi}) \) - complexes in the equation of heat balance, considering \( K_f \); \( \psi \) - calculated coefficient considering irregularity of a temperature field along the mould section during its solidification; \( \rho \) - density of the alloy, kg/m\(^3\); \( X_c \) - adjusted dimension, m; \( T_p \) - mean calculated temperature of the casting in the process of its solidification, K; \( T_{mi} \) - initial temperature of the mould, K.

Investigations of the value of the mould heat accumulation coefficient with a functional coating based on the chromite sand, from the relationship of the coating thickness to the adjusted dimension of the casting, with consideration of the mould inside surface relief (figure 1) showed that the value \( b_{ef} \) increases with the rise of relationship of the coating thickness to the thickness of the casting wall.

**Figure 1.** Dependence of the value \( b_{ef} \) of the mould from relationship of coating thickness to adjusted dimension of the casting with consideration of \( K_f \).

From the graph in figure 1 also follows that coarsening of the chromite sand fraction for the functional coating results in a quicker growth of \( b_{ef} \), other things being equal, and can serve for explanation of
mechanism which is observed in the photos of microstructure of A352GrLCC steel (figure 2) crystallized at the surface of the casting, with different values of microrelief.

Namely, with crystallization on the mould surface with value $K_f = 1.22$ the mechanism of heterogeneous nucleus formation is realized directly on the peaks of chromite sand. The structure of the wall area of the mould, received on the surface with $K_f = 1.41$, in the area directly adjoining to the casting mould, is characterized by the presence of the zone of small “frozen” crystals, which goes to the zone of dendrite multidirectional crystals under the influence of temperature front due to the presence of microrelief.

According to [7], the rate of linear crystallization of steel in the sand-and-clay mould is found from the expression:

$$V_k = \frac{k_0 \left[1 + \frac{\Delta T}{K_f X_c}\right]^2}{2(x + 0.002 D \Delta T_m X_c)}.$$  \hspace{1cm} (4)

where $k_0$ – calculated coefficient of volume solidification; $\Delta T_m$ – overheating of steel higher than temperature of solidification, K; $D$ – a constant, $x$ – distance from the mould surface, m.

The coefficient of volume solidification $k_0$ is the function of time of solidification of the mould section being considered $\tau_s$, and of its adjusted dimension $X_c$, and can be found from the expression:

$$k_0 = \frac{X_c}{\sqrt{\tau_s}}.$$  \hspace{1cm} (5)

In the result of the fulfilled calculations the curves of linear rate of crystallization have been plotted for different values $K_f$ dependent on the distance to the boundary of the casting mould (figure 3).

It is known [7] that the increase of linear crystallization rate results in the increase of the volume crystallization rate, which, in turn, is confirmed with the results of microstructural analysis of the
mould surface zone, characteristic for the functional chromite coating based on fraction 0.4 mm. The received curves, according to the known relationships between the crystallization rate and the inter-axial distance of the dendrite structure [8], allow to evaluate dispersivity of the structure and to predict the level of mechanical properties of the melt, based on the mechanisms presented in works [9–11].

In figure 4 are presented photos of macrostructure of the mould sections subjected to formation of the defect HC (hot crack), made by different technologies. White lines drawn on the photos allow to trace the directions of growth of main axes of dendrites.

Figure 4. Photos of macrostructure of specimens from steel A352GrLCC: a) casting with HC, made by the usual technology; b) – casting without HC made with application of functional coating.

In castings made without application of the functional coating (figure 4, a), zone of columnar dendrites, main axes of which are oriented by the normal to the surface, adjoins directly to the mould surface. Such structure presented in the surface layer of the casting does not provide a sufficient level of mechanical properties in the temperature interval of crystallization, in order to resist the formation of HC. The application of a functional coating (figure 4, b), creates the microlief on the casting mould surface which contributes to deviation of the heat flow direction from the normal to the surface of contact. This changes the configuration of the temperature field, which, in the vicinity of the division surface, repeats the profile of microlief of the casting mould surface, which leads to the significantly more expressed manifestation of the mechanism of thinning of dendrites in the surface zone of the casting. As a result, a layer of multidirectional crystals of the casting surface zone is formed, which increases the strength of metal in solid-and-liquid condition, and in the process of solidification it prevents formation of surface HC.

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