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Influence of Basic Physical Phenomena of the Casting-Riser System Solidification Process on Defects Formation in The Casting

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Knowledge about the complex physical phenomena used in the casting process simulation requires continuous, complementary research and the improvement in mathematical modeling. The basic mathematical model taking into account only thermal phenomena often turns out to be insufficient to analyze the process of metal solidification, therefore more complex models are formulated that include coupled thermal and flow phenomena. The mathematical description then consists of the system of Navier–Stokes differential equations, the equations of the continuity of flow and energy. The finite element method was used to numerically model this problem. Numerical simulations of the formation of a steel casting were made, starting from the moment of filling the mould cavity with molten metal and ending with complete solidification. During pouring, the forced movement of the molten metal dominates, and after filling of the mould cavity, mainly natural convective movements occur. In computer simulations, the impact of liquid metal movements on the process of solidification of the alloy in the casting-riser system was assessed, which was the aim of this work. In order to obtain a casting without defects, an appropriate selection of the shape of the riser was made. Also, the locations of possible shrinkage defects were pointed out, trying to ensure right supply conditions, so that the casting was free from these defects, which is important for foundry practice.

topics: numerical simulations, Navier–Stokes equations, casting defect, solidification

1. Introduction

Today, the production of high-quality castings without foundry defects requires continuous improvement of casting methods. Any research on real objects aimed at achieving this goal is significantly difficult by the lack of visibility and high temperatures occurring there. On the other hand, computer simulations allow for a fairly trouble-free improvement of the casting process and provide indications for its proper conduct [1–6].

In this article, the process of casting solidification is analysed, considering the phenomena of heat exchange and fluid flow (complex model [2, 3, 5, 6]), starting from the moment of filling the metal mould by molten metal and ending with complete solidification of the casting. For comparison, the solidification of the casting was analysed by taking into account only thermal phenomena (basic model [4]). In this way, we assessed the effect of considering or ignoring the movements of the liquid metal on the process of making a casting without shrinkage defects, which was the aim of this work. The shape of the solidus line was observed, assessing whether it has been enclosed in the casting area. Such a situation would mean no supply of liquid metal from the riser to this area and the formation of defects in this place of the casting, which we try to avoid.

2. Mathematical description

The mathematical model of the casting solidification process taking into account the liquid metal movements (complex model) is based on the solution of the following system of equations (the Navier–Stokes equations (1), the continuity equation (2), the heat conductivity equation with the convection term (3), the first order pure advection equation (4)) in a cylindrical, axial-symmetrical coordinate system [2–6]

$$\begin{cases} \mu\left(\frac{\partial^2 v_r}{\partial r^2}+\frac{1}{r}\frac{\partial v_r}{\partial r}+\frac{\partial^2 v_r}{\partial z^2}-\frac{v_r}{r^2}\right)-\frac{\partial p}{\partial r}+\rho g_r+\rho g_r\beta\left(T-T_\infty\right)_r=\rho\frac{\mathrm{d}v_r}{\mathrm{d}t}, \\ \mu\left(\frac{\partial^2 v_z}{\partial r^2}+\frac{1}{r}\frac{\partial v_z}{\partial r}+\frac{\partial^2 v_z}{\partial z^2}\right)-\frac{\partial p}{\partial z}+\rho g_z+\rho g_z\beta\left(T-T_\infty\right)_z=\rho\frac{\mathrm{d}v_z}{\mathrm{d}t}, \end{cases} \tag{1}$$

$$\frac{\partial v_r}{\partial r} + \frac{v_r}{r} + \frac{\partial v_z}{\partial z} = 0, \tag{2}$$

$$\frac{\lambda}{r}\frac{\partial T}{\partial r} + \frac{\partial}{\partial r}\left(\lambda\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right) = \rho\, C_{ef}\left(\frac{\partial T}{\partial t} + v_r\frac{\partial T}{\partial r} + v_z\frac{\partial T}{\partial z}\right), \tag{3}$$

$$\frac{\partial F}{\partial t} + v_r\frac{\partial F}{\partial r} + v_z\frac{\partial F}{\partial z} = 0 \tag{4}$$

where λ — thermal conductivity coefficient [W/(m K)]; $\mu(T)$ — dynamical viscosity coefficient [kg/(m s)]; $\rho{=}\rho(T)$ — density [kg/m^3]; v_r and v_z — r- and z-component of velocity [m/s], respectively; T — temperature [K]; $C_{ef} = c + L/(T_L{-}T_S)$ — effective specific heat of a mushy zone [J/(kg K)]; L — latent heat of solidification [J/kg]; T_L and T_S — respective liquidus and solidus temperatures [K] of the analyzed alloy; g_r and g_z — r- and z-component of the gravitational acceleration [m/s^2], respectively; p — pressure [N/m^2]; β — volume coefficient of thermal expansion [1/K]; t — time [s]; c — specific heat [J/(kg K)]; r — radius [m]; T_∞ — reference temperature ($T_\infty{=}T_{in}$) [K]; and F — pseudo-concentration function across elements lying on a free surface.

The mathematical model of the solidification process of the casting without taking into account the movements of liquid metal (basic model) is reduced only to the solution of the heat conductivity equation (3) without the convection term [4].

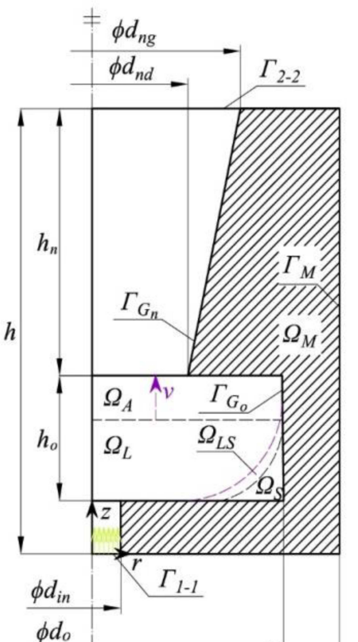

Fig. 1. Scheme and identification of subregions of the considered region.

In the case of (1)–(4), they are completed by appropriate boundary conditions and initial conditions. The initial conditions for temperature and velocity fields are given, respectively, as [3–5]

$$\boldsymbol{v}(r,z,t_0) = \boldsymbol{v}_0(r,z) = v_{in}\big|_{\Gamma_{1-1}}, \tag{5}$$

and

$$T(r,z,t_0) = T_0(r,z) = \begin{cases} T_{in} & \text{on } \Gamma_{1-1}, \\ T_A & \text{in } \Omega_A, \\ T_M & \text{in } \Omega_M. \end{cases} \tag{6}$$

The boundary conditions, specified in the considered problem, on the indicated surfaces (Fig. 1), were as follows:

- for velocity [3, 5]

$$\begin{aligned} & v_n\big|_{\Gamma_{1-1}} = v_{in}, \quad \frac{\partial v_t}{\partial n}\big|_{r=0} = 0, \\ & v_t\big|_{\Gamma_{1-1}} = v_t\big|_{\Gamma_{2-2}} = v_n\big|_{\Gamma_{2-2}} = 0, \\ & v_n, v_t\big|_{\Gamma_G} = 0, \quad v_n\big|_{r=0} = 0, \end{aligned} \tag{7}$$

- for temperature [3–5]

$$\begin{aligned} & T\big|_{\Gamma_{1-1}} = T_{in}, \\ & \lambda_M\frac{\partial T_M}{\partial n}\big|_{\Gamma_M} = -\alpha_M\left(T_M\big|_{\Gamma_M} - T_a\right), \\ & \frac{\partial T}{\partial n}\big|_{\Gamma_{2-2}} = 0, \quad \lambda_S\frac{\partial T_S}{\partial n}\big|_{\Gamma_{G-}} = \lambda_G\frac{\partial T_G}{\partial n}\big|_{\Gamma_{G-}}, \\ & \frac{\partial T}{\partial n}\big|_{r=0} = 0, \quad \lambda_G\frac{\partial T_G}{\partial n}\big|_{\Gamma_{G+}} = \lambda_M\frac{\partial T_M}{\partial n}\big|_{\Gamma_{G+}}, \end{aligned} \tag{8}$$

where T_a — ambient temperature [K]; α_M — heat transfer coefficient between the ambient and the mould [W/(m^2 K)]; T_A — temperature of air inside the mould cavity in the initial state [K]; T_{in} — initial temperature [K]; T_M, T_G and T_S — mould, gap (protective coating) and solid phase temperatures [K], respectively; v_{in} — initial velocity [m/s]; λ_M, λ_S and λ_G — thermal conductivity coefficient of the mould, solid phase and gap [W/(m K)], respectively; v_t and v_n — tangential and normal component of the velocity vector [m/s], respectively; n — outward unit normal surface vector [m].

This problem was solved using the FEM in the weighted residuals formulation [3–5].

3. Results of numerical calculations

The influence of liquid metal movements on the solidification process of the casting was analysed in the following casting-conical riser-mould system shown schematically in Fig. 1.

The outside dimensions of the mold are $d = 0.320$ m and $h = 0.280$ m, whereas the dimensions of the mould cavity are $d_o = 0.200$ m, $h_o = 0.070$ m, $h_n = 0.150$ m, $d_{nd} = 0.080$ m, $d_{ng} = 0.100$ m, and $d_{in} = 0.020$ m. The internal surface of the steel mould is covered with

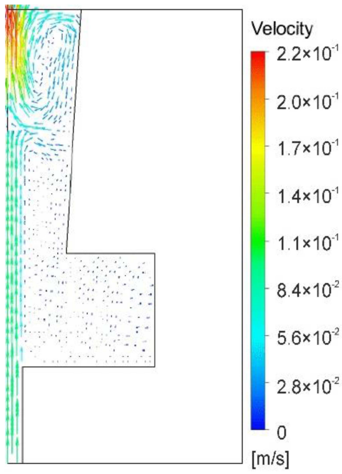

Fig. 2. Velocity vectors at $t = 86$ s, I variant.

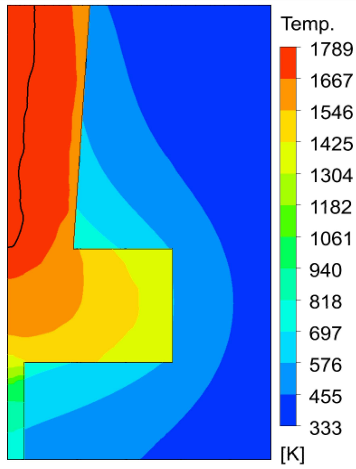

Fig. 4. Temperature field after solidification of the casting at $t = 562$ s, I variant.

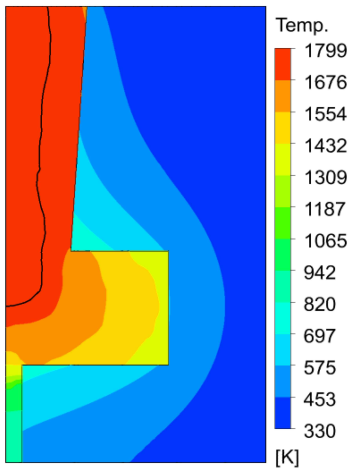

Fig. 3. Temperature distribution at $t = 488$ s, I variant.

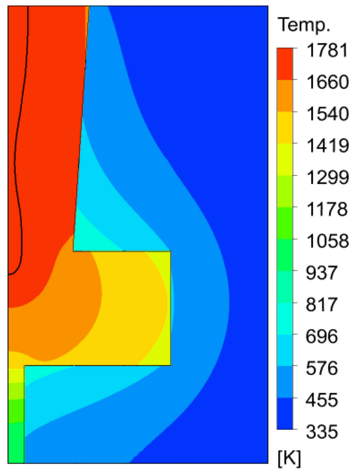

Fig. 5. Temperature field after solidification of the casting at $t = 488$ s, II variant.

a protective coating with a thickness of 2 mm. Numerical simulations were carried out for a casting made of low-carbon cast steel and a steel mould with thermophysical properties, which were taken from [5]. The overheated metal with the temperature of $T_{in} = 1845$ K was poured from the bottom with the velocity $v_{in} = 0.1$ m/s into the steel mould with the initial temperature $T_M = 345$ K. Other important temperatures were $T_A = 345$ K and $T_a = 300$ K. The heat transfer coefficient (α) between the ambient and the mould was equal to $\alpha_M = 200$ W/(m^2 K). The professional Fidap program was used to analyse the solidification process of the metal in the considered casting-riser system. The transient calculation process was interrupted when the temperature in the casting was lowered below the solidus temperature. The computation process was carried out on a computer with a 2.3 GHz IntelCore-i5 processor and lasted approximately 24 h when using the complex model or approximately 5 h when using the basic model. Such an extension of the computation time in the first case was due to the necessity to use a very small time step in the process of filling the mould cavity.

Numerical calculations of the solidification process of the casting-conical riser system were carried out with the use of two models, i.e., complex (I variant) and basic (II variant). Simulations of the casting formation were made, starting from the moment of filling the mould cavity with molten metal and ending with its complete solidification. The filling of the mould with liquid metal is shown in the form of velocity vectors for a selected moment of time (Fig. 2). Whereas, after filling, the temperature distribution is shown in Fig. 3, where a solidus line was drawn separating the solid–liquid area of the casting from its solid area.

Then, the temperature fields after the casting solidification for two calculation models were compared, observing the shape of the solidus line in the final solidification steps of the casting-riser system (Figs. 4 and 5). When the solidus line is closed in the casting, the area limited by it will not be fed with liquid metal from the riser and in this place, as a result of metal shrinkage, a shrinkage defect will occur (Fig. 5). However, we try to avoid such a situation and move such a defect to the riser, which can be achieved when using the complex model for calculations (Fig. 4).

4. Conclusions

In this paper, a mathematical model and numerical simulation results of the casting solidification were presented, taking into account the process of filling the mould cavity with liquid metal and convection movements after its completion. The influence of the molten metal motions on the solidification kinetics and the location of the end of the casting solidification were evaluated using the complex and basic models. It was observed that in the final solidification time of the casting-riser system, a closed solidus line is visible in the upper part of the casting when the calculations were carried out with the basic model (Fig. 5). This suggests the formation of shrinkage defects in this place. This situation was not observed if the calculations were carried out with the complex model (Fig. 4). In this case, the end of the solidification has taken place in the riser, which is desired since the riser is cut off and reprocessed. It also proves that the conical-shaped riser executed its task and the casting was made without casting defects.

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