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Numerical Simulation of the Solidification Process with the Convective Movement of the Liquid Phase and the Formation of Shrinkage Cavity

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The presented work is devoted to the numerical modeling of the solidification process, taking into account the natural convection of the liquid phase as well as the shrinkage cavity formation process. The formation of the internal macroscopic cavities due to material shrinkage during the casting process is a frequent and serious concern that should be predicted numerically before the real process. In the paper, the main assumptions of the mathematical and numerical model are presented. The mathematical model is based on the partial differential equations of momentum, continuity, and heat transport with the convective term. The numerical description of the considered problem is based on the finite element method. The algorithm of the shrinkage cavity creation process is described. The influence of the motion of the liquid phase on the shape and localization of the shrinkage cavity is considered. Using the numerical model, an original computer program was developed. A computer simulation was done to obtain the temporary distributions of the temperature and velocity of the liquid phase in the casting, as well as the position and shape of the shrinkage cavity. The numerically obtained location and shape of the macroscopic defect were compared to the shrinkage cavity in the real casting.

topics: solidification, natural convection, shrinkage cavity, finite element method

1. Introduction

Defects of casting are various abnormalities of size, weight, internal structure, external appearance, mechanical and physical properties. The full register of casting defects contains about eighty types of failures. One of the most important and commonly observed defects are macroscopic voids appearing due to contraction of the material in the solidification process. These defects are called shrinkage cavities and are often discussed in the literature [1–8].

The contraction of the material takes place in three main steps. As the temperature drops, the first noticeable contraction is the shrinkage of the liquid phase. The volume of liquid metal decreases linearly with temperature change. The effects of this stage of contraction are usually not significant.

The most important stage of contraction takes place during the liquid–solid phase transition. This is caused by the greater density of the solid phase compared to that of the liquid. The loss of material volume is responsible for the creation of shrinkage cavities.

The last stage of contraction occurs during the cooling process in the solid state. This process leads to stresses appearing in the particular regions of the casting and may cause cracking.

The presented paper focuses on the investigation of the effects of the second stage of contraction. The impact of natural convection of the liquid phase on the formation of shrinkage cavities was included.

2. Mathematical model

The considered region consists of domains that are characterized by a different amount of liquid, solid and air phases (Fig. 1). The basic domains in the casting are: solid region Ω_S, liquid region Ω_L

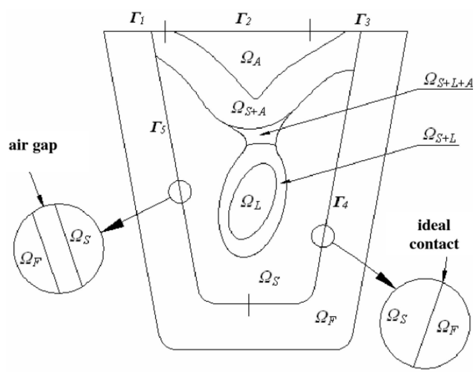

Fig. 1. Mould and casting consisted of regions filled with mixture of solid, liquid and air.

and air filled region Ω_A. Beside these, mixture of the basic phases are also considered. During solidification, the solid–liquid area Ω_{S+L} is observed, as well as the mixture of solid and air Ω_{S+A} or the three-phase composition Ω_{S+L+A}. The shrinkage of material causes the air to appear in a thin layer near the top boundary. Because of the small size of that region, it is neglected in Fig. 1. The mould region Ω_F is omitted during the calculation, however its influence on the cooling process is taken into account by the appropriate boundary conditions.

The basis of the mathematical model are the partial differential equations of heat transfer with convective term, the momentum equation, and the continuity equation, given respectively as

$$\rho c_{eff}\left(\frac{\partial T}{\partial t}+u_i T_{,i}\right)=\left(\lambda T_{,i}\right)_{,i}, \tag{1}$$

$$\frac{\mu}{\rho}u_{i,jj}-u_j u_{i,j}-\frac{1}{\rho}p_{,i}-g_i\beta(T-T_{rf})=\frac{\partial u_i}{\partial t}, \tag{2}$$

and

$$u_{i,i}=0. \tag{3}$$

The notation type ',i' reads as a derivative of the spatial coordinate i. Now, (1)–(3) are supplemented by the appropriate boundary conditions

$$\begin{aligned} &\boldsymbol{x}\in\Gamma_{1-5}:\ -\lambda\,\boldsymbol{n}\cdot\nabla T=\alpha\left(T-T_\infty\right),\\ &\boldsymbol{x}\in\Gamma_{1-5}:\ u_i=0. \end{aligned} \tag{4}$$

and the initial condition

$$t=0:\ T|_{\Omega_L}=T_0,\quad u_i|_{\Omega_L}=0. \tag{5}$$

The effective heat [9] is used to model the latent heat releasing during solidification when the temperature of the material is between liquidus and solidus

$$c_{eff}=c+\frac{L}{T_L-T_S}. \tag{6}$$

Thermal conductivity, density, specific heat, dynamic viscosity are functions of solid, liquid, and gas content. These functions are given respectively as

$$\begin{aligned} \lambda&=f_s\lambda_s+f_l\lambda_l+f_a\lambda_a,\\ \rho&=f_s\rho_s+f_l\rho_l+f_a\rho_a,\\ c&=f_s c_s+f_l c_l+f_a c_a,\\ \mu&=f_s\mu_s+f_l\mu_l+f_a\mu_a, \end{aligned} \tag{7}$$

and all parameters indirectly depend on temperature. Further, (7) shows a way for averaging these quantities. On the other hand, the way the amount of a particular phase is calculated is an important part of the shrinkage cavity formation algorithm.

In (1)–(7), T, T_0, T_∞, T_{rf}, T_L, and T_S [K] denote the temperatures: initial, ambient, reference, liquidus, and solidus, respectively; t [s] represents time; u_i [m/s] — velocity component; g_i [m/s^2] — gravitational acceleration component; p — pressure [Pa]; c and c_{eff} [J/(kg K)] — specific and effective heat, respectively; ρ [kg/m^3] — density; λ [J/(s m K)] — thermal conductivity; μ [kg/(m s)] — dynamical viscosity; α [J/(s m^2 K)] — heat transfer coefficient; β [K^{-1}] — volumetric expansion coefficient; L [J/kg] — latent heat; $\boldsymbol{n}$ — vector normal to the boundary; f_l, f_s, f_a [-] — the amount of liquid, solid, air phase.

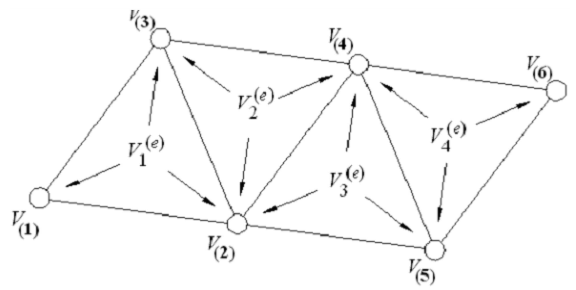

Fig. 2. Recalculation of elemental volumes to nodal volumes.

3. Shrinkage cavity formation

Shrinkage cavity calculation process is based on a sorted list of nodes which have a non-zero liquid content. First the nodes are sorted according to decreasing vertical coordinate starting from the top of the casting to its bottom.

In the second step, the nodal volumes for all nodes in the finite mesh are calculated (Fig. 2). The casting is initially filled with liquid phase of a volume equal to the total volume of the casting V, while the amount of the solid and air is 0. This is expressed as

$$\sum_{i=1}^{n}V_{l(i)}=V,\quad \sum_{i=1}^{n}V_{s(i)}=0,\quad \sum_{i=1}^{n}V_{a(i)}=0 \tag{8}$$

The solid fraction f_s is calculated in the following way

$$f_s=\begin{cases}1, & \text{if } T<T_S,\\ \frac{T_L-T}{T_L-T_S}, & \text{if } T_S\le T\le T_L,\\ 0, & \text{if } T>T_L.\end{cases} \tag{9}$$

During the cooling process of the casting, the temperature is checked in the nodes with a non-zero liquid content at each time step. If the temperature in any node decreases below T_L, the procedure of introducing air into the forming shrinkage cavity starts. The progression of the shrinkage cavity is calculated using the contraction coefficient S_h. Taking f_s from the previous step t and f_s from the current step $t+\Delta t$, the volumetric increment of the solid phase in the node i is calculated

$$\Delta V_{s(i)}=\left[f_{s(i)}\left(t+\Delta t\right)-f_{s(i)}\left(t\right)\right]V_{l(i)}\left(t\right). \tag{10}$$

Then, the current volume of the solid phase in the i node can be determined with

$$V_{s(i)}\left(t+\Delta t\right)=V_{s(i)}\left(t\right)+\Delta V_{s(i)}. \tag{11}$$

In the next step, the total increment of the solid phase in the casting is obtained in the following way

$$\Delta V_s = \sum_{i=1}^{n} \Delta V_{s(i)}. \tag{12}$$

The volume of the liquid phase in each node is calculated as

$$V_{l(i)}\,(t + \Delta t) = V_{l(i)}\,(t) - \Delta V_{s(i)}. \tag{13}$$

The new amount of the solid in the i node is obtained by using the following formula

$$f_{s(i)}\,(t + \Delta t) = \frac{V_{s(i)}\,(t + \Delta t)}{V_{(i)}}. \tag{14}$$

The global increment in air volume V_a at current time step (progression of the shrinkage cavity) is determined as a result of multiplication ΔV_s by the contraction coefficient S_h. Thus,

$$\Delta V_a = \Delta V_s\, S_h. \tag{15}$$

4. Results of numerical simulation

The geometry of the casting with the raiser together with the boundary and initial conditions used in the calculations are shown in Fig. 3a and b.

The material properties of steel with 0.55% of carbon as well as the air parameters are shown in Table I.

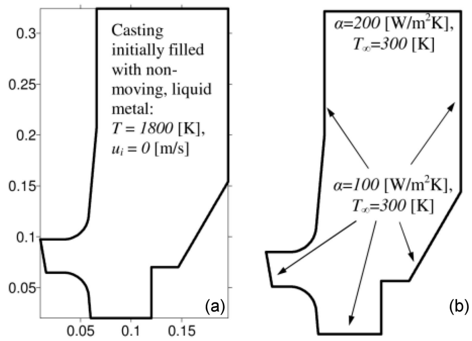

Fig. 3. Geometry of the casting with (a) initial conditions, (b) boundary conditions.

TABLE I

Material properties used in calculation.

Material property	Liquid phase	Solid phase	Air
λ	23	35	0.027
ρ	6915	7800	1.1
c	837	644	1000
μ	0.00087	∞ (non-movable)	∞ (non-movable)
β	0.00027	0 (non-movable)	0 (non-movable)
Parameter of solidification	Value		
L	270000		
T_L	1766		
T_S	1701		
S_h	0.0575		

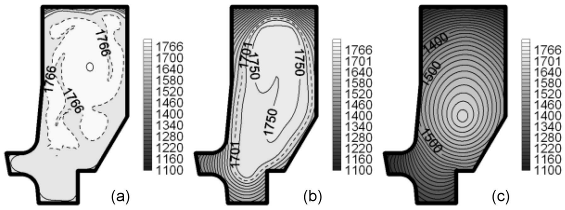

Fig. 4. Temperature of the solidifying material [K] after (a) 17, (b) 70, (c) 170 s. Note that T_S and T_L are marked with dashed curves.

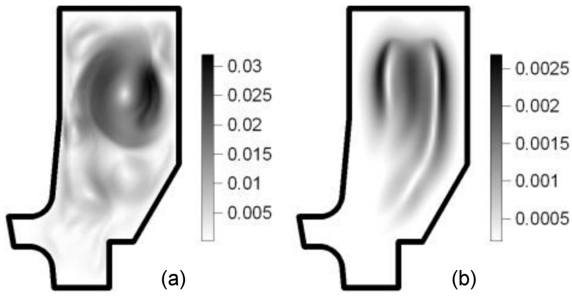

Fig. 5. Magnitude of velocity [m/s] in the casting after (a) 17 and (b) 70 s.

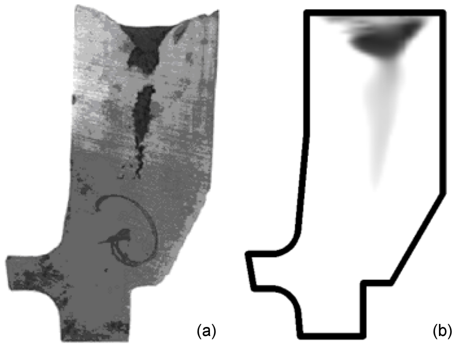

Fig. 6. Comparison of (a) the real shrinkage cavity with (b) the results of simulation.

The casting was discretized into triangular finite elements with a total number of nodes equal to 37025. The calculation was made with a variable time step until the entire material became solid. It happened after 170 s.

The positions of liquidus and solidus isolines are presented in Fig. 4. The effect of natural convection on the localization of the liquidus temperature is clearly visible. The magnitude of convection is showed in Fig. 5. At the beginning of the process, a set of convection cells is noticeable.

Volumetric contraction of the material during solidification causes the air penetration into the casting (Fig. 6). The shrinkage cavity consists of the upper, large "bubble" surrounded by the solid phase, and the lower, narrow section penetrating the raiser. There is a good agreement between the real defect and the results of simulation.

5. Conclusions

The presented results of the numerical simulation show that the implemented model allows to predict the localization and shape of shrinkage cavities, which often appear during the casting process. Appropriate choice of cooling parameters in connection with the analysis of the results obtained from computer simulation may be helpful in choosing the optimal parameters of the process. Control of the casting process will result in a better localization of the potential defect and its shape, which is highly desired from a technological point of view.

References

[1] M.C. Flemings, *The solidification processing*, Mc Graw-Hill, New York, 1974.

[2] C.J. Kim, S.T. Ro, *J. Heat. Trans.* **115**, 1078 (1993).

[3] C. Pequet, M. Rappaz, M. Gremaud, *Metall. Mater. Trans. A* **33**, 2095 (2002).

[4] J. Campbell, *Castings* 2nd ed., Butterworth-Heinemann, Oxford 2003.

[5] C. Zhang, Y. Bao, M. Wang, L. Zhang, *Arch. Foundry Eng.* **16**, 27 (2016).

[6] J. Hajkowski, P. Roquet, M. Khamashta, E. Codina, Z. Ignaszak, *Arch. Foundry Eng.* **17**, 57 (2017).

[7] A.S. Jabur, F.M. Kushnaw, *J. Appl. Computat. Math.* **6**, 7 (2017).

[8] M. Wu, A. Ludwig, A. Kharicha, *Appl. Math. Model.* **41**, 102 (2017).

[9] B. Mochnacki, J.S. Suchy, *Numerical Methods in Computations of Foundry Processes*, Polish Foundrymen's Technical Association, Kraków 1993.