Numerical Analysis of Influence of the Mold Material on the Distribution of Shrinkage Cavities

R. Dyja

Institute of Computer and Information Sciences, Czestochowa University of Technology,
ul. J. Dąbrowskiego 73, 42-201 Czestochowa, Poland
Corresponding author. E-mail address: robert.dyja@icis.pcz.pl

Abstract

Production of castings, like any other field of technology is aimed at providing high-quality product, free from defects. One of the main causes of defects in castings is the phenomenon of shrinkage of the casting. This phenomenon causes the formation of shrinkage cavities and porosity in the casting. The major preventive measure is supplementing a shortage of liquid metal. For supplement to be effective, it is necessary to use risers in proper shapes. Usually, the risers are selected on the basis of determination the place of formation of hot-spots in the castings. Although in these places the shrinkage defects are most likely to occur, shape and size of these defects are also affected by other factors. The article describes the original program setting out the shape and location of possible cavities in the casting. In the program is also taken into account the effect of temperature on the change in volume of liquid metal and the resultant differences in the shape and size of formed shrinkage cavities. The aim of the article is to describe the influence that have material properties of the mold on the simulation results.

Keywords: Application of Information Technology to the Foundry Industry, Castings Defects, Macroshrinkage, Solidification Process, Finite Element Method

1. Introduction

A shrinkage cavity is an open or enclosed area inside the casting, which is not filled with casting material when the solidification ends. Its elimination is impossible. Usually the aim is to ensure that the cavity arose in the places foreseen by the designer of mold. Such a procedure requires that the separate parts of the casting solidify in the correct order, because the solidified as the last are particularly vulnerable to the occurrence of shrinkage cavities. Another solution is using the risers, which act as reservoirs supplying the casting with liquid metal.

The phenomenon of the shrinkage cavities in castings, is mainly due to the difference in density of the liquid and solid phase of material of the casting. Simulations of temperature distribution in the solidifying casting are able to provide some indication about a possible location of the cavities in the casting. However, the location of the cavities is also affected by a number of other factors which should be considered in simulations, such as the existence of channels through which the liquid metal can flow. This topic was also undertaken in the work of other authors [1, 2]. The proposed program takes into account these effects in calculation and presents the results of the simulation in the form of easy to interpret the distributions of the casting area degree of filling.

Although usually the largest change of the casting material

density occurs at the transition from the liquid phase into the solid phase, it should be remembered that due to temperature decrease there is also a change in volume of these phases. Change of the liquid phase volume, although it is usually not large and relates to the moment when there is no problem with the flow of liquid metal, may have some impact on the final shape of the shrinkage cavities. This influence on the simulation results is also reflected in presented paper.

2. Description of developed method

2.1. Finite element method

Presented algorithm is based on the results of previous calculations of solidification model. The required results are time depended temperature change and solid phase fraction distribution. Numerical simulations of solidification are based on heat transfer equation with heat source term:

$$\nabla \cdot \left(\lambda \nabla T\right) + \dot{q} = c\rho \frac{\partial T}{\partial t} \tag{1}$$

where λ is heat conductivity, T is temperature, c is specific heat, ρ is density, t is time and q is heat source term, which in the case of solidification is related to the phase change phenomena.

Solution of equation (1) is obtained numerically with use of the finite element method [3]. In presented paper time discretization was done with the use of two-step time discretization scheme, represented by Dupont II scheme. The amount of solid phase which grows in solidifying casting was calculated according to intermediate model. The intermediate model assumes full solute diffusion in liquid phase and finite solute diffusion in solid phase. The numerical model uses two types of boundary conditions, namely Newton boundary condition (III type boundary condition) and heat exchange between two regions (IV type boundary condition).

2.2. A determination of the position and size of shrinkage cavities

The author's algorithm used in this paper is an extension of the method presented in [5]. In this method is assumed to have the results of simulation of temperature distribution during the casting solidification obtained using the finite element method. Algorithm also relies on the assumption that the casting area is divided into elements corresponding to triangular finite elements.

The presented algorithm should take into account the behavior of liquid metal consistent with physical laws. Therefore, it is assumed that: the movement of liquid takes place under the effect of gravity, fully solidified canals prevent the motion of liquid, there must be enough liquid metal to compensate for loss caused by the solidification. It is required that every element is described by: solidification time, area, the current amount of liquid metal and a list of adjacent elements. These elements must be sorted ascending according to solidification time. Operation of the proposed method consists of the following steps for each of the elements:

1. Determination the liquid metal loss A_C due to solidification, with the use of formula (2)
2. Finding elements that are not fully solidified and have a connection with the current element.
3. Subtracting amount of the liquid contained in the current element from the A_C.
4. Further subtraction from the A_C amount of the liquid contained in the elements that are connected with the current element [5]. As the first elements are chosen those that have the highest location. Condition of the feeding possibility is that the element that supplies liquid metal has higher location of geometrical center than the current element
5. If there is subtracting the amount of liquid from the A_C occurs updating the degree of filling the current element and element that provides liquid metal. The degree of filling is a ratio of amount of liquid metal in the element and the area of element.
6. The algorithm stops when the value of A_C drops to zero, or when there are no elements that could feed the current element.

The loss of liquid due to solidification is calculated by the following formula:

$$A_C = A_E \cdot \left(1 + \beta\right) \tag{2}$$

where A_C is the amount of liquid needed to supply the solidified finite element of given area A_E, and β is a value of volumetric shrinkage.

One of the improvements of this algorithm involves taking into account the volume change of the liquid phase caused by temperature. This requires an earlier determination of the degree of overheating of liquid metal and calculation on this basis the volume change of the liquid phase, which is called in the algorithm 1 liq_loss. Finding the level of the surface of liquid metal is done in accordance with the steps of the algorithm 1. Its input is a list of elements in the casting and the previously mentioned value of the volume change of the liquid phase. The resulting values are arrays containing the amount of liquid metal and the filling ratio of each element, as well as the variable that stores the total amount of liquid metal in the casting.

Algorithm 1 Procedure to determine the level of liquid metal surface taking into account volume changes of the liquid phase
Input: element_list, liq_loss
Output: liq_quant, fill_degree, liq_quant_cast
liq_quant_cast = cast_area
1. for each e from element_list:
    1.1. liq_quant[e] = area(e)
    1.2. fill_degree[e] = 1
2. for each e from element_list:
    2.1 if liq_loss – liq_quant[e] > 0 then:
        2.1.1. liq_loss = liq_loss – liq_quant[e]
        2.1.2. liq_quant_cast = liq_quant_cast – liq_quant[e]
        2.1.3. liq_quant[e] = 0, fill_degree[e] = 0
    2.2. else:
        2.2.1. liq_quant[e] = liq_quant[e] – liq_loss
        2.2.2. liq_quant_cast = liq_quant_cast – liq_loss
        2.2.3. fill_degree[e] = liq_quant[e]/area(e)
        2.2.4. liq_loss = 0
3. return liq_quant, fill_degree, liq_quant_cast

Moreover, an additional condition was introduced, which assumes preventing the flow of liquid metal through the finite elements that have at least 90% of the solid phase. This condition was introduced to model the resistance of flow of liquid metal caused by the solid phase growth. Taking into account this condition requires a modification of procedure tracing the neighborhood of solidified element. It is necessary to take into account the condition presented in the form of algorithm 2. The input for this algorithm is: an index of the solidified element, an index of the element for which the flow possibility is tested, the list of neighbors of the inspected element and the array that holds the solid phase fraction for all elements at a given moment of time.

Algorithm 2 Procedure to check if an element b makes possible the flow of liquid metal
Input: a, b, neighbor_list, solid_ratio
Output: flow
1. if solid_ratio[b] < 90% then:
    1.1. return flow = true
2. for each e from neighbor_list[e]:
    2.1. if e != a && solid_ratio[e] < solid_ratio[b] then:
        2.1.1. return flow = true
3. return flow = false

The character of this algorithm is based on the fact that the simple introduction of no-flow condition through the elements significantly filled with the solid phase would result in a lack of flow of liquid metal in most of the cast, since the fully solidified elements usually are surrounded by the elements with considerable amount of solid phase. The condition in which it is assumed that the metal can flow in the direction of decreasing the solid phase fraction can overcome this negative phenomenon in the simulation.

3. Description of numerical analysis

The purpose of the analysis was to examine the impact of the mold material on the results obtained from the numerical simulation of the formation of shrinkage cavities.
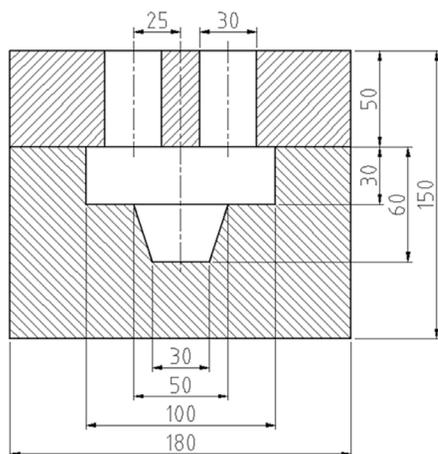

Fig. 1. The shape of the casting used in the simulations

Two variants of the simulation were performed. During the first variant the casting solidifies in the metal mold, while in the second one - in the sand mold. The tests were performed for the shape of the casting shown in Figure. 1.

Numerical simulations of temperature distribution and the solid phase fraction, which are the input to my own program, were carried out in the NuscaS system [6]. This system solves the heat conduction problem using the finite element method. The number of finite elements, which participated in the FEM calculations is equal to 34 529, regardless of the task variant. Simulation of the degree of filling of elements uses the same mesh.

As a material of casting was adopted the alloy of aluminum with addition of 2% copper. This alloy is characterized by a relatively high value of the volumetric shrinkage [9], which value was equal to 6%. Change in the volume of the liquid phase due to temperature decrease was equal to 0.1% for every 10 K, this value was estimated from data for pure aluminum [7]. Other physical properties for this alloy are collected in Table 1.

Table 1.
The physical properties of cast material

Quantity	Unit symbol	Value Liquid phase	Value Solid phase
Thermal conductivity coefficient	W/mK	104	262
Density	kg/m^3	2498	2824
Specific heat	J/kgK	1275	1077
Solidus temperature	K		877
Liquidus temperature	K		926
Melting temperature of pure metal	K		933
Latent heat of solidification	J/kgK		390000

In Table 2 the physical properties of mold materials used in the simulations are summarized. Data concerning sand mold parameters are taken from [8], and the properties of the metal mold from [4].

The temperature of the liquid metal at the beginning of the simulation was equal to 1150 K. It is assumed that the metal mold was heated to 600 K, while the sand mold had a temperature equal to ambient temperature, ie 300 K.

Table 2.
The physical properties of mold materials

Quantity	Unit symbol	Value Metal mold	Value Sand mold
Thermal conductivity coefficient	W/mK	24	0.66
Density	kg/m^3	7200	1590
Specific heat	J/kgK	600	1135

For both variants of the calculations the parameters of boundary conditions have the same values. On the upper and side surfaces of the mold the occurrence of Newton boundary condition was assumed, which simulated the heat exchange with the environment, taking into account the heat exchange coefficient of 200 W/m^{2}K. On the lower surface of the mold, due to difficulty of heat exchange, the value of this coefficient was reduced to 50 W/m^{2}K. The same value of the heat exchange coefficient was also used for the upper surface of the open risers due to the presumed use of an insulating layer of powder. The value of the ambient temperature was equal 300 K. Heat exchange between casting and mold including boundary condition assumes the heat exchange through the insulation layer of conductivity coefficient of separating layer equal to 1000 W/m^{2}K.
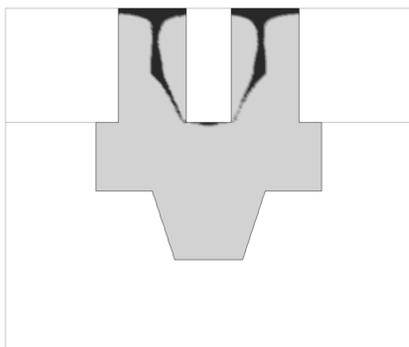

Fig. 2. Cavities in the casting - results for a metal mold

Figure 2 and 3 show the filling of mold at the end of solidification. For the cast solidifying in the metal mold (Fig. 2) shortages in filling of elements appeared only in risers. It suggests that the size of the risers was selected correctly. Due to the fact, that the analyzed shape is symmetric, feeding the cast from both risers follows to the same extent. For this reason in both risers open shrinkage cavities appeared with shape and volume similar to each other.
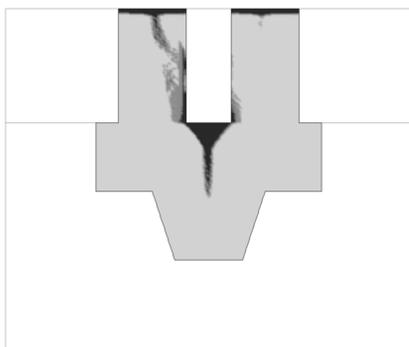

Fig. 3. Cavities in the casting - results for a sand mold

In the case of the sand mold the empty elements appeared in the mere cast. This suggests that for this case the risers in the real casting do not meet their role. This is probably related to the difficult heat dissipation by sand mold. For this reason, despite the use of powder that impede heat exchange between the surface of risers and environment, the casting solidified after its risers and cavities appeared in it.

4. Summary

In this paper the problems associated with determining the location of shrinkage cavities were presented. Simulations of distribution of the filling degree of elements were performed for the two variants of the physical properties of the mold material. These options reflected the case when the casting solidifies in the metal or sand mold. Analyzing the results can be seen a clear influence of conditions of heat dissipation by the casting on the shape and location of shrinkage cavities.

The program now takes into account the change in volume of the liquid phase, which causes a reduction in the level of metal in the risers in obtained results. However, the inclusion of this phenomenon proved to be irrelevant with regard to the possibility of emergence of defects in the casting, because change in the volume of the liquid phase occurs mainly when the casting does not have much solid phase and there are no significant obstacles to the flow of liquid metal.

Simulations also take into account a condition, in which the liquid metal can flow through the element that contains at most 90% of the solid phase. However, in the case of the analyzed shape of the casting, in which there were no narrow canals, it seems to have insignificant effect on the shrinkage cavities distribution.

References

[1] Skrzypczak, T. & Węgrzyn-Skrzypczak, E. (2010). Simulation of shrinkage cavity formation during solidification of binary alloy. *Archives of Foundry Engineering.* 10(1), 147-152.

[2] Sowa, L. (2002). Numerical simulation of the shrinkage cavity within solidifying steel casting. *Archives of Foundry.* 2(4), 245-250 (in Polish).

[3] Zienkiewicz, O.C. & Taylor, R.L. (2000). *The finite element method.* The Basis, Butterworth-Heinemann. Vol. 1, Oxford.

[4] Sczygiol, N. & Szwarc, G. (2000). Approaches to enthalpy approximation in numerical simulation of two-component alloy solidification. *CAMES.* 7, 717-734.

[5] Dyja, R. & Sczygiol, N. (2011). Method for determining the formation of shrinkage defects in the castings. *Archives of Foundry Engineering.* 11(4), 35-40.

[6] Sczygiol, N., Szwarc, G., Olas, T. & Nagórka A. (1997). Object-oriented analysis of solidification modelled by finite elements. *Solidification of Metals and Alloys.* 30, 233-242 (in Polish).

[7] Mutwil, J., Romankiewicz, A. & Romankiewicz R. (2003). Density investigations of liquid aluminium-silicon alloys. *Archives of Foundry.* 3(10), 53-60 (in Polish).

[8] Bokota, A. & Sowa L. (2001). Application of finite element method for modeling of fluidity test. *Archives of Foundry.* 1(1), 52-47 (in Polish).

[9] Stefanescu, D.M. (2009). Science and Engineering of Casting Solidification. Springer Science+Business Media, New York