Modeling of mould cavity filling process with cast iron in Lost Foam method

Part 1. Mathematical model – rate of pattern gasification

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Abstract

In this work a mathematical model of mould cavity filling process with cast iron for lost foam method was shown, enclosing phenomena connected with gasification of foamed polystyrene pattern. For its description the thermal balance equation was used, which together with pouring rate equations (part 2) and pressure change equations (part 3) enabled determination of permeability, refractory coating thickness and foam pattern density influence on pouring rate, gas pressure in gas gap and its size. In this work authors showed results of numerical simulation concerning rate of pattern gasification and gas gap size, based on developed mathematical model. Presented studies indicated, that with decrease in coating permeability and increase in its thickness the gas gap size increased causing the decrease of foamed polystyrene pattern gasification rate.

Keywords: Metal casting, Lost foam process, Foamed polystyrene pattern

1. Introduction

Lost foam method, in which patterns made of high-molecular materials was introduced by H.F. Shroyer. In 1958 he patented the technology, in which foamed polystyrene patterns were placed in classic moulding sand [1]. Solution proposed by T.R. Smith in 1964 [2], in which moulding sand was replaced by dry sand without clay addition caused development of this method. Casting technology for lost foam method starts with pattern preparation from floated polystyrene. Such pattern can be prepared with use of a matrix or contour thermal saw. Next, pattern is joined with gating system, also prepared from floated polystyrene by gluing or welding. On such prepared pattern equipment a refractory coating is applied, often by immersing and then dried. Coated pattern is placed in a moulding box and covered by dry sand, which is vibratory compacted. Such mould is then poured with liquid metal. During pouring polystyrene pattern is gasified and liquid metal can fill resulting cavity.

This technology is characterized by low investment and manufacturing costs. There is no need for cores, joint faces, drafts, what results in higher precision of castings. Dry sand application eliminates moisture influence on casting flaws, moreover sand reclamation of moulding sands is cheaper. This technology can be applied for small production, because patterns can be prepared with use of thermal cutting plotters or matrices manufactured with use of rapid prototyping techniques [3].

Character of mould cavity filling is mainly dependent on polymer gasification process [4]. Quantity of gases resulting from liquid metal and foamed polystyrene pattern depends on liquid metal temperature and pattern density. For iron-based alloys the gas quantity is almost three times of that for aluminum alloys. Gas
can be removed from the mould cavity only through refractory coating and sand bed. Presented in this work mathematical model describes these phenomena.

2. Mathematical model

2.1. Assumptions

Pattern gasification rate was determined with following assumptions:
- no heat flow to the environment,
- liquid metal temperature (pouring temperature) and ambient temperature during pouring process is constant,
- foamed polystyrene pattern gasification proceeds only from solid state with negligence of liquid state.

Scheme of physical model of gas gap with the most important factors taken into account in mathematical model is shown in fig. 1.

![Diagram of physical model for gas gap](image)

Fig. 1. Scheme of physical model for gas gap with parameters taken into account in mathematical model

2.2. Foamed polystyrene pattern gasification rate

For determination of gasification rate thermal balance was applied, in which in stationary state a heat amount is transferred from liquid metal to the pattern by heat conduction $Q_{prz}$ and radiation $Q_{pro}$ and should be equal to the heat amount needed for pattern gasification $Q_{roz}$. Considering heat flow during mould cavity filling with cast iron, one can write the heat balance equation as follows:

$$Q_{roz} = Q_{prz} + Q_{pro}$$  

(1)

Heat transferred by conduction from liquid metal to the pattern is proportional to the temperature difference between these two materials, thermal conductivity coefficient for gases in gas gap and heat flow surface, equal to area of pattern cross-section $A_{mod}$ (assumed that the liquid metal surface and the gasified front are flat). This heat can be expressed with relation:

$$Q_{prz} = \frac{\kappa \cdot (T_{met} - T_{mod})}{y_{mod} - y_{met}} \cdot A_{mod}$$  

(2)

where:
- $\kappa$ - thermal conductivity coefficient of steam-gas mixture.

This coefficient can be expressed as a sum of thermal conductivities of particular components of the mixture, with proportion to its quantity and can be found e.g. in [5]. The actual composition of the mixture is not known and can be only evaluated, what was shown in work [6], in which also the thermal conductivity coefficient was studied in function of temperature and pressure.

Heat transferred by radiation to the pattern can be calculated according to the Stefan – Boltzmann law:

$$Q_{pro} = \frac{\sigma}{1 + \frac{1}{\varepsilon_{met} + \varepsilon_{mod}}} \cdot (T_{met}^4 - T_{mod}^4) \cdot A_{mod}$$  

(3)

Heat radiation is determined by emissivity $\varepsilon_{met}$ for $\varepsilon_{mod}$ particular surfaces. Degrees of emission depend mainly on material surface quality and can change in wide range. Surface of floated polystyrene pattern can be white and glossy with emissivity of $\varepsilon_{mod} = 0.01$ or black, when it is covered with soot – $\varepsilon_{mod} = 1$ (body full radiator). In the first case, the radiation heat is two rows lower than conduction heat (for assumed 5 mm gas gap). In the second case the radiation heat is lower but comparable with conduction heat.

Heat used for pattern gasification can be determined with use of following relation:

$$Q_{roz} = H_{mod} \cdot m_{mod} = H_{mod} \cdot V_{mod} \cdot \rho_{mod} =$$

$$= H_{mod} \cdot V_{mod} \cdot A_{mod} \cdot \rho_{mod}$$  

(4)

In equation (4) $H_{mod}$ is the heat of decomposition for polystyrene, which according to [7] for density of 20 kg/m$^3$ is 912 kJ/kg. After substituting relations (2÷4) to thermal balance equation (1), transforming and simplifying, following relation was obtained:

$$\frac{\kappa \cdot (T_{met} - T_{mod})}{y_{mod} - y_{met}} + \frac{\sigma}{1 + \frac{1}{\varepsilon_{met} + \varepsilon_{mod}}} \cdot (T_{met}^4 - T_{mod}^4) \cdot A_{mod}$$

$$\frac{dv_{mod}}{dt} = \frac{-\frac{1}{\varepsilon_{mod}}}{H_{mod} \cdot \rho_{mod}}$$  

(5)
Relation (5) with equations describing mould cavity filling dynamics presented in part 2 and pressure changes in gas gap, presented in part 3 constitute mathematical model of lost foam process model for cast iron.

3. Numerical simulation studies

Numerical simulation studies was conducted for pattern with geometry shown in fig. 2. Moreover, following parameters were assumed:
- cast iron density $\rho_{\text{mod}} = 7200 \text{ kg/m}^3$,
- sand permeability $K_{\text{plasku}} = 8.5 \cdot 10^{-6} \text{ m}^2/\text{Pa}\cdot\text{s}$,
- sand bed thickness $L_{\text{plasku}} = 15 \text{ cm}$,
- temperature of liquid cast iron $T_{\text{met}} = 1573 \text{ K}$,
- pressure inside the mould $P_f = 100 \text{ kPa}$ (equal to atmospheric pressure).

 thermo-physical properties of polystyrene:
- heat of decomposition $H_{\text{mod}} = 912 \text{ kJ/kg}$,
- evaporation intensity $\epsilon_{\text{mod}} = 0.5 \text{ kg/m}^2/\text{s}$,
- thermal conductivity coefficient for steam-gas mixture $\kappa = 5 \text{ W/m}\cdot\text{K}$.

3.1. Range of numerical simulation studies

Conducted studies enclosed changing parameters, in range of:
- coating permeability $K_{\text{pok}} = 1 + 9.5 \cdot 10^{-9} \text{ m}^2/\text{Pa}\cdot\text{s}$,
- coating thickness $L_{\text{pok}} = 0.3 \pm 1.5 \text{ mm}$,
- polystyrene pattern density $\rho_{\text{mod}} = 10 \div 40 \text{ kg/m}^3$,

for evaluation of gas gap size, which determines the polystyrene pattern gasification kinetics.

In presented studies the changes in gasification rate and liquid metal flow rate were analyzed and their corresponding changes in position.

3.2. Analysis of numerical simulation results

In fig. 3 the character of changes in gasified pattern/liquid metal interface position in function of pouring time was shown. In fig. 4 the gasification rate in function of time together with liquid metal surface are illustrated. Difference between position of liquid metal and gasified pattern is the gas gap. From analysis of these diagrams on can conclude that in the initial state of pouring the gas gap is small, what results in high gasification rate of $14 \text{ cm/s}$, which next decreases with growing gas gap (causing decrease in heat quantity transferred from liquid cast iron to the pattern).

Surface of the liquid metal due to increase in pouring rate closes to gasified model interface and the gas gap size decreases. In result the gasification rate has to increase. Changes in rate are smaller and the process stabilizes. From fig. 4 one can see, that the rate of pattern gasification is slightly higher than the liquid metal flow rate what results in increase of gas gap size in function of time.

Fig. 2. Shape and dimensions of pattern modeled in numerical simulation
Conducted numerical simulations showed that the parameters of refractory coating applied on foamed polystyrene pattern have the strongest influence on gas gap size.

Changes in gas gap size in function of coating permeability were shown in fig. 5 and 6. For permeability $K_{pok}$ in range of $3.5 \times 9.5 \times 10^{-9}$ m²/(Pa·s), gap size in initial state of pouring is 1.5 to 3 mm and growing during pouring and at the end of the pouring process reaches value of 2.5 mm. In fig. 6 the influence of coating permeability $K_{pok}$ on average gas gap size is shown. For permeability of $1 \times 10^{-9}$ m²/Pa·s average gap size is equal to 12 mm. Similar experimental values was obtained by Shivkumar [8]. It must be pointed out, that average gap size for coatings with permeability above $K_{pok} = 5 \times 10^{-9}$ m²/ Pa·s stabilizes at value of 2 mm.

In fig. 7 and 8 influence of coating thickness on gas gap size is shown. Analyzing these diagrams on can see, that increasing coating thickness of about 0.3 mm results in increase of gas gap size of 1.2 mm. In fig. 8 relation of average gas gap size and refractory coating thickness is shown.
Another character of changes of gap size can be observed in relation to pattern density, shown in fig. 10. In this case for every analyzed pattern density the gap size at the beginning of pouring is almost identical and equals 3 mm, growing to 5 mm at the end of the pouring process. Obviously, for low densities of foamed polystyrene pattern the pouring process proceeds faster, what results in faster movement of gas gap. In fig. 11, where relation of average gas gap size and pattern density is shown, one can see, that the influence of pattern density on average gas gap size is small.

4. Summary

Numerical simulation studies presented in this work enabled analysis of major technological parameters influence on gas gap size, which determined the rate of pattern gasification in lost foam process. Studies have shown, that decrease in refractory coating permeability considerably increased the gas gap size and extended pouring time. Coatings with permeability higher than

\[ K_{pok} = 5 \cdot 10^{-9} \text{ m}^2/\text{Pa} \cdot \text{s} \]

drew only slightly influence on gas gap size, which value was then close to 2÷3 mm. Increase in coating thickness caused proportional increase in gas gap size. For studied foamed polystyrene pattern densities gas gap size reached values from range of 3÷5 mm.
References