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MODEL STUDY OF THE EFFECT OF METAL FILLER PARTICLES ON LIQUID METAL TEMPERATURE DISTRIBUTION DURING CASTING BY GASIFIED MODELS

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A mathematical model is developed for calculating the temperature field established in liquid alloy after filling a lost foam casting mold when filler metal particles are placed in a expanded foam polystyrene model. The effect of a stepwise drop in temperature of the cast alloy caused by thermal destruction of foam polystyrene and heat exchange with filler particles is observed. The dependence of this effect on filler volume fraction in the area of its location and ratio of thermophysical properties of the basic alloy and filler material is established.

Keywords: casting in gasified models, mathematical modeling, temperature effect, filler volume fraction.

This work is devoted to development of physical bases for preparing components of cast composite materials for pipeline fittings, pumps, and other objects [1]. An effective method for improving the operating capacity of components is provision of special properties to an object operating under conditions of especially severe external action [2]. For cast components this is accomplished by using composite materials, local modification, and alloying with introduction into molten metal of a small amount of dispersed filler particles [3, 5].

During casting by a gasified model additional possibilities are provided in view of the simplicity of placing nanofiller (fine platelets, small pieces of metal, micro- and nano-particles of metal powder) within a prescribed part of a gasified model) made of foam polystyrene [5] within closed model cavities, at the surface of a model [6], at the surface foam polystyrene granules [7], and within foam polystyrene granules [8].

The aim of the present work is to study the interaction on molten basic alloy with metal fillers introduced into the foam plastic during casting by a gasified model based on a mathematical model of this process taking account of kinetics for mold filling and the effect of thermal decomposition of foam polystyrene during casting.

A gasified model of casting (Fig. 1) made of foam polystyrene with density ρ_{P0} has the shape of a parallelepiped with height H, horizontal section area S, perimeter in this section Π, and volume V.

In the upper part of a gasified model volume V_E, located at a height h from the feeder, metal filler inclusions are placed with an overall volume of kV_E, where $k << 1$ is the volume fraction of filler in the upper part of the model. Nanofiller material properties: ρ_{E0}, ρ_{E1} are density in solid and liquid conditions; c_{E0}, c_{E1} are heat content in solid and liquid states; Λ_E is melting specific heat. Filler particles are distributed uniformly throughout the volume of the upper part of a model so that the average filler density throughout the volume equals $k\rho_{E0}$. The initial filler temperature T_{E0} = 300 K. It is taken in calculations that the metal filler particles are heated to the temperature of the cast metal and melt within it, remaining in the areas of initial location.

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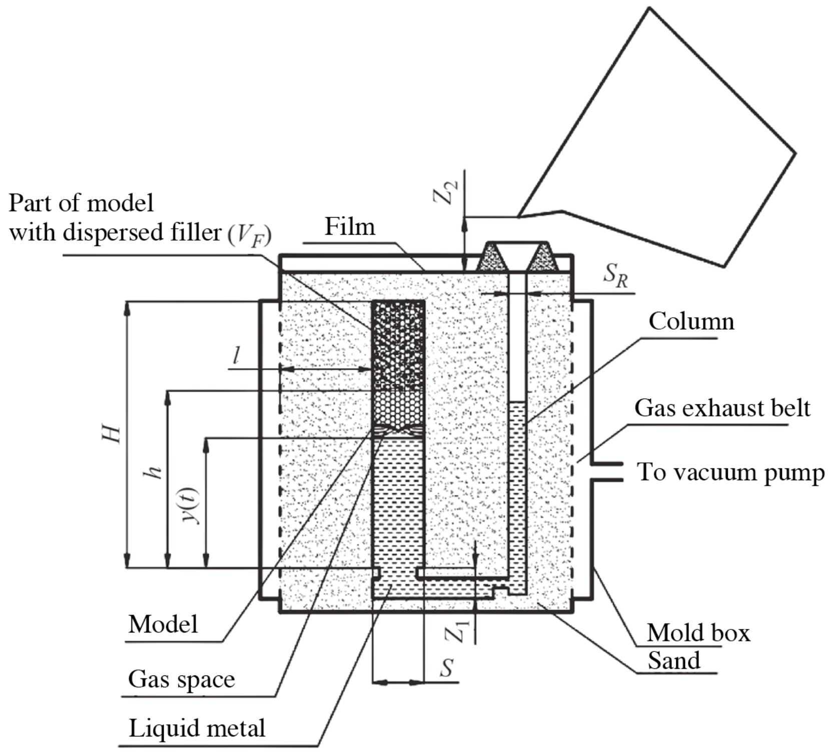

Fig. 1. Diagram of casting mold using gasified model partly filled with fine metal filler.

For this the weight and size of metal particles should be much less than the weight of liquid metal and dimensions of the upper part of the model.

A gasified model is filled by molten metal with a temperature (in a ladle) T_0 by a siphon method through the casting system with column cross section S_R (see Fig. 1). Designations are introduced: $y(t)$ is the level of molten metal in a mold at some instant of time t from the start of casting; t_0 is time of metal ascent to the casting height H (i.e., the time for mold filling); t_1 is rime for liquid metal to reach the start of the zone of dispersed filler particle location; q is molten metal consumption in a ladle; μ is consumption hydraulic coefficient. Molten metal properties: c_{M1} is heat content; ρ_{M1} is density; a_{M1} is thermal conductivity. During ascent of molten metal in a casting with rate $v(t)$ there is thermal destruction of foam polystyrene. The temperature of molten metal ascending in the mold $T_1(y,t)$ up to reaction with filler is not constant since molten metal is cooled upwards by foam polystyrene thermal destruction products [9].

The rate of metal ascent $T_1(y,t)$ mainly depends on processes of foam polystyrene thermal product removal with density $\rho_{P1}(t)$ from the so-called “gas space” between the molten metal surface and foam polystyrene (see Fig. 1) [10]. The following factors affect parameters of the thermal destruction removal process from the “gas space”:

– casting dimensions and production factors (rate of molten metal feed into a mold, molten metal temperature, column dimensions);

– excess pressure in the “gas space” (determined by the metal stream pressure, depending on height z_2 of ladle ascent above the casting funnel, (i.e., the mouth of the column) and the degree of rarefaction in the mold box p_V, i.e., the difference between atmospheric pressure and absolute pressure in the mold box);

– mold box gas permeability, determining: distance from the model to the rarefaction belt l; overall coefficient of foam polystyrene thermal destruction product properties D (with molten metal temperature); gas permeability of the refractory pigment and sand in the mold box b.

Gaseous products of foam polystyrene destruction are removed from the gas space under action of excess pressure in the gas space and rarefaction in the mold box; vapor products to a considerable extent condense in the sand and may be subject to secondary thermal destruction; carbon (in the form of soot) is cooled at the inner surface of the refractory pigment or partly dissolves in molten metal.

A mathematical model of the process for reaction of molten basic metal with metal filler inclusions introduced into the gasified model is a set of equations describing the processes occurring during casting. Solutions of this set of equations are functional correlations of gasified model parameters, physical properties of the materials used, and thermodynamic parameters of the mold filling process.

An equation for calculating the molten metal temperature over the vertical axis (from $y = 0$ to $y = H$) has been provided in [9]:

$$\Delta T(y,t,k) = T_1(y,t) - T(y,t,k)$$

$$= \frac{T_1(y,t) - T_2(y,t,k)}{2} - \frac{T_1(y,t) - T_2(y,t,k)}{\sqrt{\pi}} \int\limits_0^{\frac{y-h}{2\sqrt{a_{M1}(t-t_1)}}} e^{-x^2}\, dx\,. \tag{1}$$

The value of $T_1(y,t)$ is determined by an equation [16]:

$$T_1(y,t) = T_0 - \frac{AT_0 + B}{c_{M1}\rho_{M1}\sqrt{\pi a_{M1}}} \int\limits_0^t \frac{v(t)\rho_{E1}(t)}{\sqrt{t-\theta}}\, e^{-\frac{y^2}{4a_{M1}(t-t_1)}} d\theta\,, \tag{2}$$

where θ is integration variable; A = 4032 J/(kg·K), B = 3773 J/kg are coefficients in the equation for calculating the foam polystyrene thermal destruction energy $(W = AT + B)$ [9].

The value of $T_2(y,t,k)$ is determined from heat exchange conditions for molten alloy and dispersed particles(i.e., particle heating conditions):

$$T_2(y,t) = \frac{c_{M1}m_M T_1(y,t) + 2c_{E0}m_E T_0 - (c_{E0}m_E - c_{E1}m_E)T_{E1} - \Lambda_E m_E}{(c_{M1}m_M + c_{E1}m_E)}$$

$$= \frac{c_{M1}\rho_M T_1(y,t) + 2c_{E0}\rho_{E0}kT_0 - (c_{E0} - c_{E1})\rho_E kT_L - \Lambda\rho_E k}{(c_{M1}\rho_M + c_{M1}\rho_M k)}. \tag{3}$$

In the majority of cases during heating of filler particles there is melting of them with subsequent filler heating by melt that is considered in the following expression for calculating the rate of molten metal ascent in a mold [9]:

$$v(t) = \frac{d}{dt}y(t) = y(t) = \begin{cases} u_1(t) & \text{for} \quad t \le \tau, \\ u_1(\tau) + u_2(t) - u_2(\tau) & \text{for} \quad t > \tau, \end{cases} \tag{4}$$

where $u_1(t)$, $u_2(t)$ are subsidiary functions; τ is time for filling the lower part of a mold and casting system from 0 to z_1 (see Fig. 1),

$$\tau = \frac{(S+S_R)z_1}{q\mu}. \tag{5}$$

The index for pressure in the zone of foam polystyrene thermal destruction P in units of molten metal column height is calculated by an equation

$$P = z_2 + \frac{p_V}{\rho_{M1}g} \tag{6}$$

(g is free fall acceleration).

The density of thermal destruction products in the "gas space" is determined by an equation:

$$\rho_{P1}(t) = \frac{p(t)S}{Dbq\mu t_L T_0} = \frac{S}{Dbq\mu t_L T_0}\begin{cases} \rho_{M1}g\left[\dfrac{q\mu}{S_{\text{av}}}t - \dfrac{S+S_R}{S_{\text{av}}}u_1(t)\right] & \text{for} \quad t < \tau, \\ \rho_{M1}g\left[\dfrac{q\mu}{S_R}t - \dfrac{S+S_R}{S_R}[u_1(\tau)+u_2(t)-u_2(\tau)]\right] & \text{for} \quad t \ge \tau, \end{cases} \tag{7}$$

where t_L is delay time for filling a mold, during which there is formation of a thermal destruction zone (gas space).

With application of the expressions obtained values have been calculated for the reduction in temperature for a number of alloys after thermal destruction of a foam polystyrene model and mixing with different solid metal particle fillers. It is taken in calculations that metal filler inclusions are not carried from the area of the initial location in a gasified model V_E, nor by the flow of foam polystyrene thermal destruction products (since the density of these products is low comrade with that of filler density), nor the flow of the main molten metal (the rate of which is slow).

Calculations for steel 35ML (GOST 977–88) melt temperature after filling the zone of a gasified model with nanofiller of carbon steel St3 (GOST 380–2005) powder were conducted for a gasified model in the form of a parallelepiped (base area $S = 0.06$ m^2, height $H = 0.4$ m). The filler was located in the upper part of a model (at a height of $h = 0.3$ m from the model base) (see Fig. 1). Results of calculations are given in Fig. 2.

Calculations for a mathematical model of mold filling [9] have established: $t_0 = 25.3$ sec; $t_1 = 20.7$ sec. Production parameters were the following: mold box dimensions $800 \times 800 \times 600$ mm; $p_V = -30$ kPa; $l = 0.35$ m; $S_R = 1.30 \cdot 10^{-3}$ m^2; $z = 0.06$ m; $D = 4.5 \cdot 10^9$ kg/(m$^2 \cdot$ sec$^3 \cdot$ K) [14]; $h_K = 0.1$ m; $\rho_{P0} = 25$ kg/m^3; $T_0 = 1880$ K; $q = 0.25 \cdot 10^{-3}$ m^3/sec; $\mu = 0.65$. Thermophysical properties of the material are taken from publications [11, 12].

During casting by a gasified model without use of filler (see Fig. 2, curve 3) the metal temperature decreases along the vertical axis of a casting only as a result of foam polystyrene thermal destruction.

With placement in a gasified model of filler particles (see Fig. 2, curves 1, 2) the temperature of the molten basic alloy at the end of the casting process decreases stepwise in the region of filler location, and this reduction is superimposed on a reduction in temperature as a result of foam polystyrene thermal destruction.

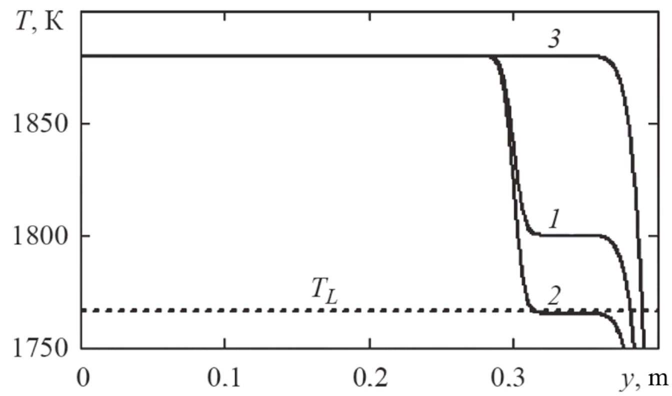

Fig. 2. Diagram of change in molten steel 35KhML (GOST 977–88) temperature over vertical axis y at instant of casting solidification with placement of filler (steel powder) in upper part of casting $(y > 0.3$ m): *1* — filler volume faction $k = 0.07$; *2* — filler volume faction $k = 0.11$; *3* — without filler ($k = 0$); - - - — steel 35KhML liquidus.

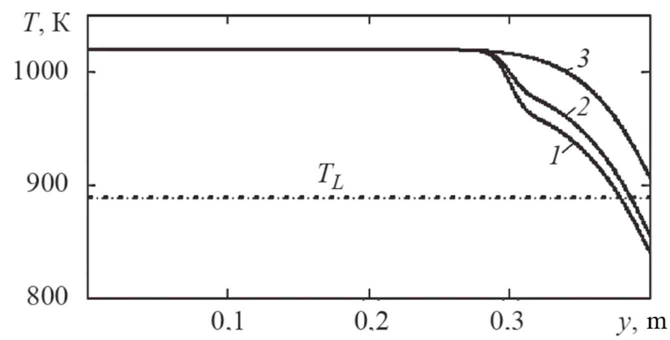

Fig. 3. Diagram of change in molten aluminum ally AK7 (GOST 1583–93) temperature over vertical axis y at instant of casting solidification: *1* — with placement of filler (aluminum powder) volume fraction $k = 0.05$ in the upper part of casting; *2* — with placement of filler (titanium powder) volume fraction $k = 0.05$ in the upper part of casting; *3* — without filler; -·-·- — AK7 alloy liquidus.

For casting aluminum alloy AK7 (GOST 1583–93) two calculations have been performed: with selection as a filler of AK7 alloy powder and titanium VT1-2 (GOST 19807–91). Parameters of the gasified model and mold box were the sane as with calculating steel casting (see Fig. 2).

Results of calculations are provided in Fig. 3.

For the basic aluminum alloy the time for reaching the zone of filler location $t_1 = 29.4$ sec, and the time for complete mold filling $t_0 = 31.8$ sec.

In the upper part of a casting with filler (as with steel casting, see Fig. 2) there is a stepwise reduction in molten metal temperature. However, due to the considerable effect of metal cooling under action of foam polystyrene thermal destruction in this part of the curve (with $y > 0.3$) for aluminum alloy no horizontal section is observed since the process of foam polystyrene thermal destruction has a greater effect on the temperature of the aluminum alloy than the steel temperature (since the density and temperature of aluminum are markedly lower). A stepwise change in molten aluminum temperature is superimposed on the flat reduction in temperature as a result of foam polystyrene thermal destruction.

From results of calculations of temperature fields for molten carbon steel and aluminum with different filler volume fractions it follows that the amount of reduction in molten metal temperature as a result of heat exchange with filler particles is proportional to the volume fraction of filler particles (Fig. 4).

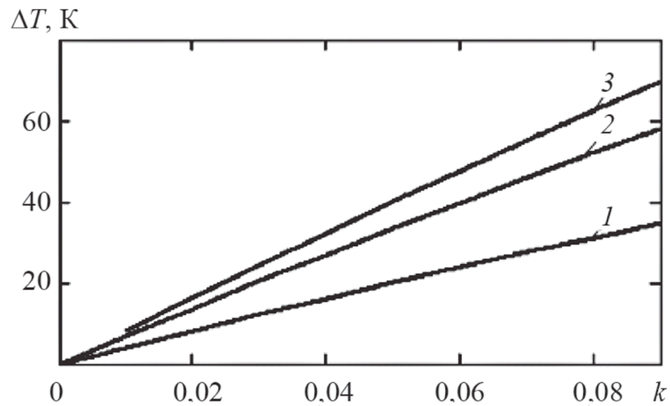

Fig. 4. Dependence of the magnitude of reduction in in molten steel (GOST 977–88) temperature in the area of steel powder placement in a model on volume fraction of fine filler particles: *1* — with $y = 0.30$ m (at start of zone with fine particles) ; *2* — with $y = 0.35$ m (in center of zone with fine particles); *3* — with $y = 0.40$ m (in upper point of casting).

In order to determine the effect of method for casting location in a mold box on molten metal cooling by filler a calculation was performed for casting gasified mold in the form of a parallelepiped with a size of $0.1 \times 0.1 \times 0.5$ m located vertically ($H = 0.5$ m) or horizontally ($H = 0.3$ m). Calculation was performed for casting steel 35L, the filler was carbon steel powder, and the gasified model was filled powder to one fifth of its height upwards. The rest of the parameters were the same as in previous calculations. Results of calculations showed that with vertical arrangement of a model the degree of alloy cooling is somewhat less than with a horizontal arrangement for a model ($\Delta T_1 < \Delta T_2$). This is connected with the fact that with horizontal arrangement for the model the cooling heat flow (which is proportional to the area of the model horizontal section) is greater than with a vertical arrangement, and therefore for more effective heating (or melting) it is more preferable to arrange the extent of the model horizontally.

Calculations have also been performed for the degree of molten metal (steel) cooling by filler, arranged in a gasified model with variation of the following production parameters: rate of metal feed into a mold, mold box rarefaction, and cross sectional area of the column. It has been established that these parameters hardly affect the reduction in molten metal temperature during interaction with filler and cannot be used for controlling the casting process.

After stepwise cooling of molten metal in the zone of filler particle location heat exchange commences for cooled metal with the supply downwards of molten metal with a higher temperature, and as a result there is gradual leveling of temperature in a casting.

Mathematical model (1)–(7) makes it possible to determine the maximum size of metal object (used for local cooling of casting material as a casting cooler) with which it is possible to melt this object with basic alloy. Melting of metal filler will be achieved if the temperature of the filler (which becomes equal to that of the basic metal) exceeds the filler material liquidus. In this case melting of the basic alloy and metal filler proceeds if the temperature of the basic alloy does not fall below the liquidus:

$$T(y_E, t_E, k) > T_L. \tag{8}$$

For filler of carbon steel (as an example) with a liquid phase temperature of the basic steel $T_0 = 1860$ K calculation showed that $T(0.35 \text{ m}; 25.3 \text{ sec}; 0.12) > T_L$, i.e., melting proceeds with $k < 0.12$. As applied to the extent of steel object (filler) this signifies that the maximum size of an object in the horizontal plane should not be greater than 0.12 (12%) of the minimum size of the casting horizontal cross section. If there are several

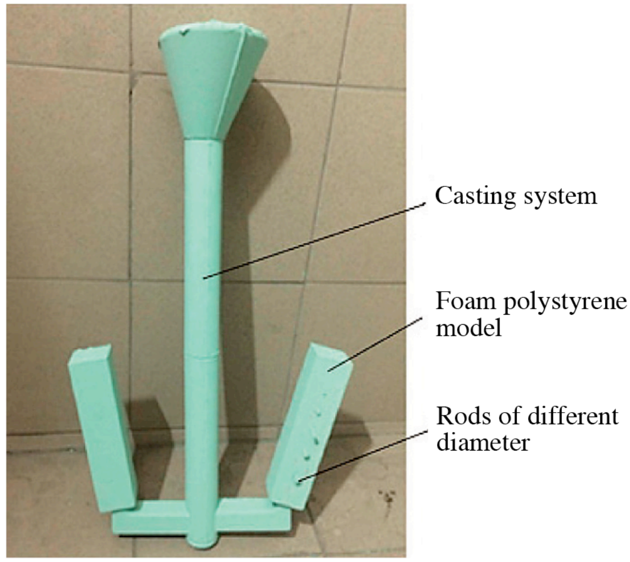

Fig. 5. Photo of "cluster" for casting specimens with rods.

objects in a horizontal section of a model, then the maximum overall size of objects should be less than 0.12 of the minimum size of the casting horizontal cross section in the area of object (filler) location.

Expression (8), determining the limiting size of inclusions, is also valid for aluminum alloys. Therefore, conclusions drawn evaluating the dimensions of an object (filler) that guarantee melting in molten basic alloy of a casting are also valid the aluminum alloy AK7 with a temperature $T_0 = 1020$ K.

It should be noted that the conclusions and ratios obtained are only valid on condition that the melting temperature for filler is below that for basic alloy during casting. If this condition is not observed, then filler particles either remain solid or dissolve in the basic alloy as a result of diffusion processes.

In order to check the mathematical model and the basic melting conditions obtained based upon it for filler particles with basic alloy tests have been performed for casting steel for gasified models of foam polystyrene with installed rods of diameter 1, 2, 3, 4, and 5 mm of carbon steel St3 (GOST 380–2005). The distance between rods was from 40 to 30 mm.

Models with use of a feeder were installed in a collector to which a column was attached with funnel (Fig. 5). The "cluster" obtained win this way was painted with refractory paint. After drying the paint the "cluster" was placed in a mold box and filled with casting sand fraction 0.315 mm. Rarefaction in the mold box was up to $-8 \cdot 10^4$ MPa.

In order to prepare molten metal and induction furnace with a capacity of 450 kg was used. Casting was conducted with cast carbon steel 35L (GOST 977–88) from a ladle with a capacity of 250 kg, and the casting temperature was 1870 K. After cooling and cleaning the casting obtained it was cut over a vertical plane passing through the column. It follows from Fig. 6a that rods 5 mm in diameter are not melted by molten metal. Rods 4 mm in diameter and smaller were melted entirely in molten steel, i.e., no boundaries were observed in the casting cross section (see Fig. 6b).

Therefore, the maximum value for steel rod diameter with which rod melting is provided in a steel casting 40 mm thick is 4 mm. In this case the ratio of rod diameter to casting thickness (i.e., a value equal numerically to the volume fraction of filler inclusions) is $k = 0.100$. In this case rods 5 mm in diameter ($k = 0.125 > 0.12$) are not melted with basic cast metal. This agrees with calculations in the present work and points to the adequacy of the mathematical model developed.

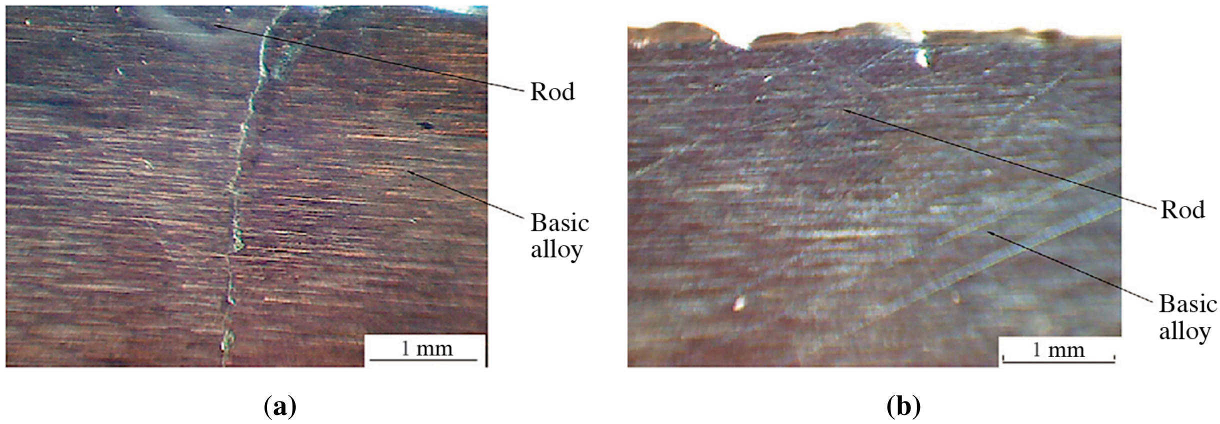

Fig. 6. Photo of specimens sections of carbon steel 35L prepare with casting by gasified models with steel rod inserts: (a) rod diameter 5 mm; (b) rod diameter 4 mm.

CONCLUSIONS

1. A mathematical model has been developed for interaction of molten metal with metal filler objects in a polystyrene gasified model during casting. In the mathematical model kinetics are considered for mold filling, the effect of thermal destruction of foam polystyrene, heat exchange of the basic alloy and filler material. Use of a mathematical model makes it possible to predict the main features providing preparation of high quality cast components, to control processes of modification and local alloying, and also casting solidification.

2. Filler location in a gasified model made of foam polystyrene causes a local stepwise reduction in temperature of the basic alloy in the area of filler location, which it is important to consider in order to use metal inclusions as coolers and for effective modification of the basic alloy. The amount of local reduction in temperature of the basic alloy is proportional to the ratio of thermal properties of the basic alloy and filler material, and also the volumetric fraction of filler.

3. With horizontal arrangement of the extent of a casting the amount of local reduction in temperature of the basic alloy in the area of filler particle location is greater than with a vertical casting arrangement.

4. Melting of filler with molten basic alloy occurs with a volume fraction of filler less than the calculated critical value. For example, for carbon steel with a filler of steel particles and a casting temperature $T_0 = 1860$ K the critical volume fraction of filler is 0.12.

5. Calculated data for the reduction in basic alloy temperature in relation to filler volume fraction for cast carbon steels and cast aluminum alloys may be used as reference material during practical application of casting technology by a gasified model containing metal fillers

REFERENCES

1. S. G. Babaev and V. I. Kerimov, "Increase in the operating capacity of fountain fitting bolts based on studying the wear mechanism for a slide valve-saddle pair," *Khim. Neft. Mashin.*, No. 8, 15–17 (2015).
2. S. S. Zatulovskii, *Suspended Casting* [in Russian], Naukova Dumka, Kiev (1981).
3. M. Szucki, T. Goraj, J. Lelito, and J. S. Suchy, "Numerical analysis of solid particles flow in liquid metal," *Archives of Foundry Eng.*, **13**, Special Issue 3, 161–166 (2013).

4. P. Rohatgi, B. Schuitz, N. Gupta, and A. Daoud, *Solidification During Casting of Metal-Matrix Composites. ASM Handbook,* Casting. ASM International, **15**, 390–397 (1992).
5. L. P. Vishnyakova, O. I. Shinskii, and I. N. Morgun, "Study of features of foam polystyrene model destruction with implantation of metal fillers," *Porotsessy Lit'ya,* No. 4, 51–56 (2002).
6. N. V. Nesterov and A. G. Ermilov, *RF Patent 2391177,* MKI B22C 3/00. Method for Modifying a Vesting Surface.
7. A. Yu. Leshchev, A. M. Lipanov, P. G. Ovcharenko, and V. B. Dement'ev, *RF Patent 2427442,* MKI B22C 7/02. Method for Modifying Castings During Casting by Gasified Models.
8. N. V. Nesterov and B. S. Vorontsov, *RF Patent 2633806,* MKI B22C 7/02. Method for Modifying Castings During Casting by Gasified Models.
9. N. V. Nesterov and B. S. Vorontsov, "Mathematical model for liquid metal cooling during casting by gasified model," *Liteishchik Rossii,* No. 8, 24–29 (2014).
10. V. S. Shulyak, S. A. Rybakov, and K. A. Grigoryan, *Production of Castings by Gasified Models* [in Russian], MGIU, Moscow (2001).
11. P. F. Vasilevskii, A. E. Demakov, P. N. Plekhanov, et al., *Casting Handbook. Shaped Steel Castings* [in Russian], State Sci.-Tech. Publ. Eng. Lit., (1962).
12. N. M. Galdin, D. F. Chernega, D. F. Ivanchuk, et al., *Nonferrous Casting* [in Russian], Mashinostroenie, Moscow (1989).