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Quantitative Estimation of Formation of Shrinkage Porosity by the Niyama Criterion

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Abstract—Critical values of the Niyama criterion were determined for castings from alloy ML10 on the basis of a computational experiment. It was shown that the Niyama criterion is suitable only for qualitative evaluation of the possibility of porosity formation. One of the options of constructing an unambiguous dependence and scale of porosity by the values of the temperature gradient and solidification rate was proposed.

Keywords: Niyama criterion, porosity, simulation, magnesium alloy ML10, PoligonSoft

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INTRODUCTION

Modern gating systems for casting various machine engineering parts are designed using methods of computer-aided simulation; at the same time, forecasting of the occurrence and location of gas and shrinkage porosity is important. Besides direct simulation, various criteria for estimating formation of shrinkage porosity based on computation of thermophysical parameters of the solidification process are frequently used. The most widespread forecast of porosity formation is realized when using the Niyama criterion [1]:

$$Ny = G/\sqrt{\dot{T}}, \quad (1)$$

where G is the temperature gradient and $\dot{T}$ is the cooling rate. All the values are taken near the solidus temperature.

The probability of porosity formation increases with decrease in Ny. If the Niyama criterion is lower than the critical value, then formation of porosity is guaranteed.

The difficulties of application of the Niyama criterion are connected with the fact that there is no single critical value for this criterion for different alloys and conditions (technologies) of obtaining of castings.

For low-alloy steels, the critical value was determined by the author of work [1]. In [2], critical values of the Niyama criterion were determined on the basis of radiographic research for casting steel plates. Work [3] presents critical values of the Niyama criterion for some nickel alloys and high-alloy steels. In [4], the critical value of the Niyama criterion was determined for castings of titanium alloy Ti–46Al–8Nb obtained by the method of casting into an inclined mold (tilt-casting).

The Niyama criterion is the main tool for forecasting shrinkage porosity in the MAGMA software package for simulating molding processes [5].

It is shown in [6] that formation of porosity depends not only on the temperature-time parameters of the technology of obtaining casting but also on its geometry. The feeding conditions of the mushy zone during solidification of the inner and outer corner will be different, since the solidification front in the first case will be convex toward the liquid phase, and in the second case, concave. This circumstance leads to formation of a different pattern of porosity at close values of the Niyama criterion.

Search for a universal criterion for obtaining qualitative castings is one the main research directions. Work [7] suggests a dimensionless Niyama criterion for direct forecasting of shrinkage porosity. The dimensionless criterion accounts for thermal parameters of solidification, physical and casting properties of an alloy and does not require determination of critical values. However, the proposed method has not yet received sufficient experimental confirmation.

In this work, we made an attempt to determine a quantitative relationship between shrinkage porosity in a cast plate of magnesium alloy ML10 and solidification conditions in the form of the Niyama criterion.

EXPERIMENTAL

The mechanisms of formation of shrinkage porosity in castings are well presented in mathematical models of modern software packages. Long-term experience of application of the system of computer-aided simulation of molding processes PoligonSoft [8] shows that, at the appropriate settings, the model of

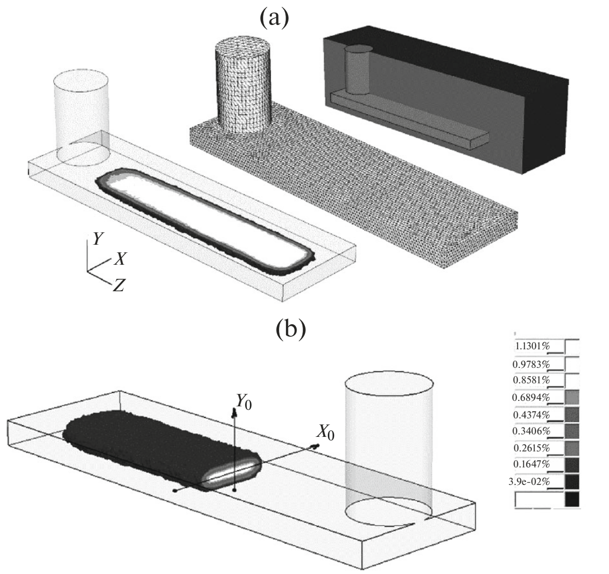

Fig. 1. Appearance of casting and chill mold, finite-element model of the casting and porosity in the central (a) and transverse (b) sections of the plate. Central lines X_0 and Y_0 start on the surface of the casting.

porosity formation demonstrates a high degree of adequacy for simulation results [9, 10].

The model of porosity formation implemented in the PoligonSoft system describes two mechanisms of shrinkage defects. The first considers flow of the melt under gravitational forces during the pipe formation. The second mechanism considers filtration flow of the melt in a dendritic framework. The melt flows in the mushy zone of casting under the impact of a pressure gradient, which appears because of shrinkage of the solidified melt. Microporosity, which is the subject of the work, is formed at this stage of solidification. The model of filtration flow realized in PoligonSoft is fully described in [11–14].

Table 1. Thermophysical properties of alloy ML10 and chill mold

Name	Value
Alloy ML10	
Density at solidus temperature, kg/m^3	1673
Specific heat capacity, kJ/kg^{-1} K^{-1}	1.256
Crystallization heat, kJ/kg^{-1}	331.2
Solidus temperature, °C	609
Liquidus temperature, °C	649
Thermal conductivity coefficient, W/m^{-1} K^{-1} (solidus)	69
Thermal conductivity coefficient, W/m^{-1} K^{-1} (liquidus)	39
Chill mold	
Heat capacity, kJ/kg^{-1} m^{-3}	4000
Thermal conductivity coefficient, W/m^{-1} K^{-1}	40

Filtration flow of the melt in the dendritic framework in PoligonSoft is described by the Darcy equation:

$$f_L v_L = -\frac{K}{\mu}[\mathrm{grad}P - \rho_L g], \quad (2)$$

where f_L is the fraction of the liquid phase, v_L is the flow velocity of the melt, P is the pressure, ρ_L is the density of the melt, μ is the dynamic viscosity, K is the permeability of the dendritic framework, and g is the acceleration of gravity.

Integration of Eq. (2) in a one-dimensional approximation provides a drop of pressure over the depth of mushy zone in the form [6, 7]

$$\Delta P = A[\dot{T}/G^2] = A(Ny)^{-2}, \quad (3)$$

where A is a constant determined by chemical composition of the alloy and state diagram. It can be seen that the less the Ny value, the higher the pressure drop in the mushy zone and the higher the risk of porosity formation. This result is well known as the theoretical substantiation of the empirical Niyama criterion.

The aim of this work is to determine a quantitative relationship between porosity computed by direct simulation based on the Darcy equation and thermal solidification conditions in the form of the Ny criterion.

A plate with dimensions of 480 × 140 × 25 mm of magnesium alloy ML10 of the composition Mg–0.9Zr–0.4Zn–2.5Nd was selected as the object of the computational experiment. Figure 1 presents the appearance of the plate with end rise with diameter of 75 and height of 115 mm. A similar casting was used in works [3, 15–17], where the Niyama criterion was applied as a tool for development of a new methodology of computing the feeding length of casting of low-alloy and high-alloy steels. The casting feeding length is a parameter which characterizes the efficiency of the risers during solidification of steel castings.

In this work, we simulated the process of solidification of a casting in a steel chill mold. A series of computations for various chill mold temperatures of 200, 300, 400, and 500°C was carried out. It was assumed that, in the initial state the melt was already cast into the mold and had temperature of 720°C. Solidification occurred in the air at temperature of 20°C. The thermophysical properties of the chill mold are presented in Table 1.

The obtained distributions of temperature were used for computing the values of Niyama criterion Ny, temperature gradient G, local solidification time t_f, and cooling rate $\dot{T}$ for all the nodes of the mesh model in the module Kriterion-3D of the PoligonSoft system. The temperature gradient and cooling rate were computed for isotherm θ slightly higher than temperature of solidus: $\theta = T_S + 0.1\ (T_L - T_S)$, where T_L and T_S are the liquidus and solidus temperatures of the alloy, respectively.

It should be noted that numerical differentiation of temperature fields in order to compute local values of the temperature gradient and cooling rate significantly depends on errors of numerical solution of nonlinear thermal conductivity equation. To reduce the error of computation of the temperature gradient, solidification was simulated with step of 0.25 s on a sufficiently fine mesh. The cooling rate of the melt was computed as an average value per solidification time of the melt in the mushy zone: $\dot{T} = (T_L - T_S)/t_f$. Local solidification time t_f was computed as the difference of times of reaching the solidus and liquidus temperatures in a mesh node: $t_f = \tau_S - \tau_L$. The following dimensions are accepted in the work: $[\tau]$ = min, $[G]$ = K m^{-1}, $[\dot{T}]$ = K min^{-1}, $[Ny]$ = K$^{1/2}$ min$^{-1/2}$ cm$^{-1/2}$.

Figure 1a shows a general view of the casting in the chill mold, the finite-element casting model used in computations, and the porosity in the central section of the plate (a) at the chill mold temperature of 300°. Porosity below 0.05% is not shown.

Research was carried out on a transverse section approximately in the middle of the plate, which is shown in Fig. 1b. Nodes located as close as possible to this section and grouped along the lines X_0 and Y_0 were selected from the array of data obtained in the computation. To perform this operation, a program allowing extracting from PolygonSoft files the data related to the nodes of our interests was developed.

RESULTS AND DISCUSSION

Figure 2 shows the change in temperature gradient in transverse section of the plate along X_0 (Fig. 2a) and Y_0 (Fig. 2b). Markers on the graphs show the values obtained as a result of computation in the module Kriterion-3D of the PoligonSoft system.

The temperature gradients in the isotherm θ (on conventional boundary of solid and liquid phases) decreases as the isotherm moves toward the center of the plate (X = 70 mm), where for reasons of symmetry it must be equal to zero.

According to known analytic solutions, the temperature gradient on the lateral side of the casting (X = 0) must be maximal. Some drop of temperature gradient neat the casting surface (see Fig. 2a) is associated with the error of numerical differentiation of the temperature field near the boundary of the mesh model. Solid lines in this figure, which approximate the results of computation, are plotted with allowance for the requirements of the theory. According to the sym-

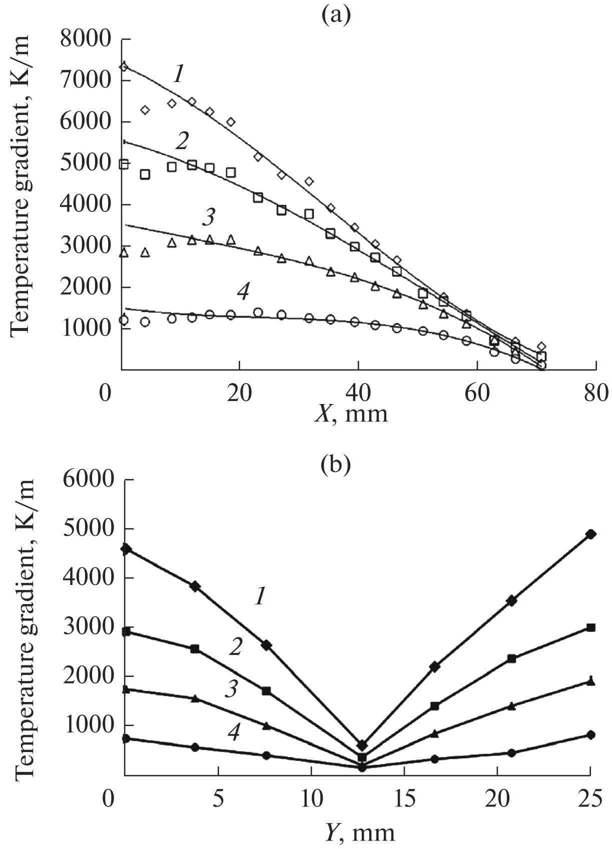

Fig. 2. Change in the temperature gradient in transverse section of the plate along X_0 (a) and Y_0 (b) at chill mold temperature: (*1*) 200; (*2*) 300; (*3*) 400; (*4*) 500°C.

metry condition, the temperature gradient on the lines X_0 and Y_0 must be equal to zero. The value of temperature gradient at points X = 70 mm and Y = 12.5 mm apparently correspond to the error of determination of the temperature gradient.

The cooling rate curve (Fig. 3) are much smoother, since they are the average values over the mushy zone, which are obtained directly from temperature fields without operation of numerical differentiation. The cooling rate is maximal on the surface of the casting and rapidly decreases with movement of mushy zone toward the center of the casting. A significant part of the plate is solidified at an almost constant cooling rate, the value of which depends only on chill mold temperature. The higher the chill mold temperature, the large the domain of the casting where cooling rate can be considered constant.

At relatively small values of X (up to 20–30 mm), the rate is significantly higher than in the center of the plate. This is the effect of additional heat transfer through the lateral surface X = 0 mm. In the central part of the plate (X > 40 mm), edge effects disappear and heat transfer becomes unidirectional. Figure 4 shows the change in the volume fraction of pores f_P com-

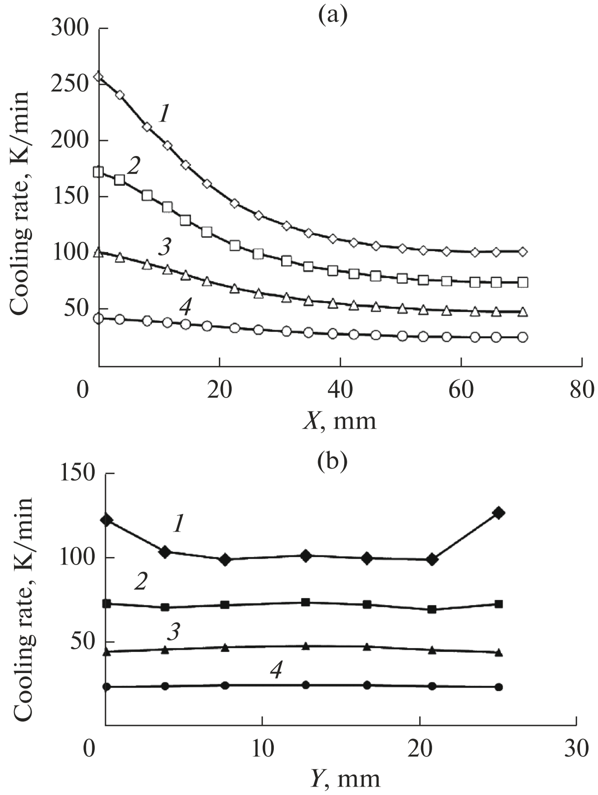

Fig. 3. Change in the cooling rate of the melt in transverse section of the plate along X_0 (a) and Y_0 (b) at chill mold temperatures: (*1*) 200; (*2*) 300; (*3*) 400; (*4*) 500°C.

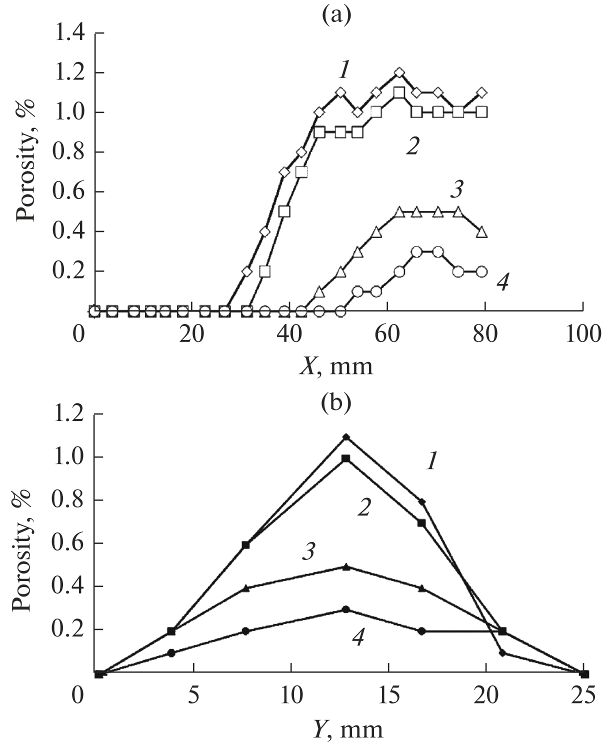

Fig. 4. Computed volume fraction of pores in transverse section of the plate along X_0 (a) and Y_0 (b) at chill mold temperatures: (*1*) 200; (*2*) 300; (*3*) 400; (*4*) 500°C.

puted in PoligonSoft along the lines X_0 (*a*) and Y_0 (*b*) in transverse section of the plate. The coordinate of the section *X* where first pores appear and the value of maximum porosity depend on chill mold temperature.

There are insufficient points in Fig. 4b to show the change in porosity near the casting surface. However, it can be seen in Fig. 1b that porosity is absent near the casting surface.

Increase in the chill mold temperature leads to decrease in the cooling rate of the melt, which has a positive effect on feeding of the central part of the casting. At the same time, increase in the chill mold temperature leads to decrease in the temperature gradient and as a result to increase in the width of the mushy zone, which complicates feeding of mushy zone of the casting.

It is assumed that the multidirectional influence of the parameters *G* and $\dot{T}$ on the formation of porosity is taken into account by the Niyama criterion.

Figure 5 presents the dependences of the pores volume fraction computed from the Darcy equation in the porosity model of the PoligonSoft system on the Niyama criteria computed by data of Figs. 2 and 3.

Each technological process (chill mold temperature) is presented in Fig. 5 by two noncoinciding curves plotted along X_0 and Y_0. The dotted line plotted by the mesh nodes along Y_0 characterizes solidification in conditions of unidirectional heat transfer as in an infinite flat wall. The solid curve for nodes along the line X_0 is related to formation of porosity in the case of a concave growth front. Analysis of these curves implies that it is impossible to obtain an unam-

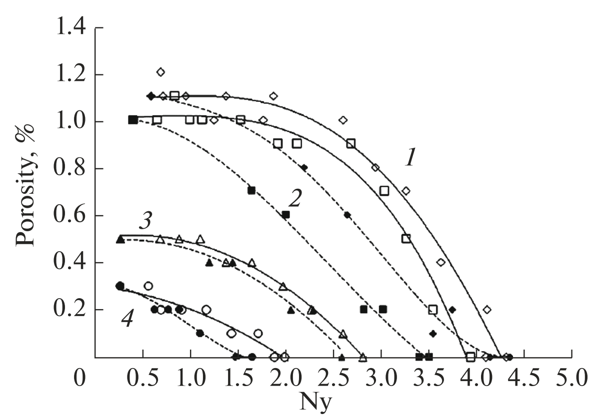

Fig. 5. Volume fraction of pores depending on the value of the Niyama criterion during casting of the given plate into chill mold at temperatures: (*1*) 200; (*2*) 300; (*3*) 400; (*4*) 500°C. Solid lines—for nodes along the line X_0; dashed lines—for nodes along the line Y_0.

Table 2. Critical values of the Niyama criterion for alloy ML10 during casting into steel chill mold

Chill mold temperature, °C	200	300	400	500
Ny_{crit}*	$\frac{4.1}{4.35}$	$\frac{3.5}{3.9}$	$\frac{2.6}{2.75}$	$\frac{15}{19}$

* Numerator—unidirectional heat transfer; denominator—concave growth front.

biguous quantitative dependence between the conditions of solidification of the casting and porosity using only the Niyama criterion. Besides the thermal conditions of solidification (G and $\dot{T}$), the value of porosity at the given point depends on technological factors (in this case the chill mold temperature) and on the curvature of the isotherm θ, i.e., geometry of the casting.

The obtained results confirm qualitative interconnection between the Niyama criterion and the probability of porosity formation in the casting. With decrease in the Niyama criterion, the probability of porosity formation increases. It is possible to determine a critical value Ny_{crit} for castings of a certain type and identical sizes (in this case, it is a plate) obtained with the same technology below which porosity appears. The critical values of the Niyama criterion for flat and concave front of growth for a plate from alloy ML10 are presented in Table 2.

Since the cooling rate $\dot{T}$ is equal to the product of G and solidification rate W, the Niyama criterion can be denoted as $Ny = (G/W)^{-1/2}$. Work [11] suggested a new criterion of porosity formation taking into account curvature of the isotherm θ. This criterion is denoted as $F = kWG^{-1} < F_{crit}(M)$, where k is the curvature of the isotherm and M is a parameter accounting for the mold material. Possibly, the parameter k does solve the problem of the impact of the casting geometry, but since the proposed criterion is inversely proportional to Ny, the dependence $f_P(F)$ is still ambiguous. Obviously, an unambiguous quantitative dependence between porosity and solidification conditions $f_P = f(G, W)$ must be more complicated than the simplex $(G/W)^n$.

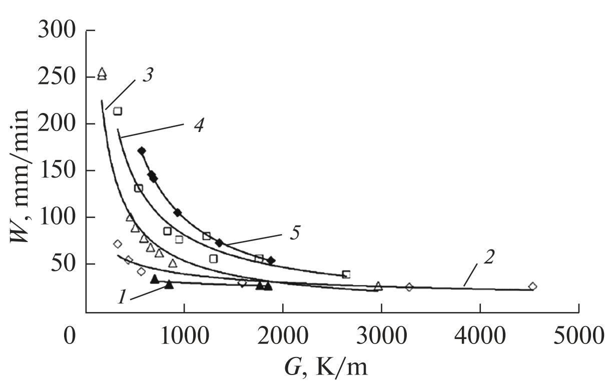

Fig. 6. Lines of constant porosity depending on the temperature gradient and crystallization rate: (*1*) P = 0.1; (*2*) 0.2; (*3*) 0.5; (*4*) 1.01; (*5*) 1.1%.

To find this dependence, nodes with values of porosity in a sufficiently narrow range were selected from the array of computed data. The obtained sets containe nodes with approximately identical porosity, but with various values of G and W and different chill mold temperature. Points corresponding to the selected nodes were plotted on the graph (Fig. 6) in coordinates (G, W). It can be seen that all the points lie on the lines of constant porosity, which never intersect. This means that the lines are on the surface $f_P = f(G, W)$, which unambiguously relates porosity to solidification conditions. By virtue of the accepted rules of selection of nodes, this dependence is valid for any temperature of the chill mold in the range investigated.

A scale for quantitative estimation of porosity according to the values of G and W can be constructed on the basis of the dependence $f_P = f(G, W)$. This scale will be suitable for computing the porosity during solidification with predominantly unidirectional heat transfer—in extended thin walls of shaped castings or during directional solidification. With lateral cooling of rod-type castings and cylindrical walls with large curvature, the error in calculating the porosity will be significantly greater.

CONCLUSIONS

(1) The results of a computational experiment substantiate the qualitative interconnection between the Niyama criterion and the probability of formation of porosity in the casting: the probability of formation of pores grows with decrease in the Niyama criterion.

(2) The Niyama criterion does not allow unambiguous determination of the quantitative relationship between solidification conditions and the casting porosity. Besides thermal conditions of solidification (temperature gradient and cooling rate), the volume fraction of pores at the given point of a casting depends on the curvature of the solidus isotherm as well as on technological parametres (chill mold temperature and chill mold material).

(3) Unambiguous dependence $f_P = f(G, W)$, which relates porosity P to solidification conditions (temperature gradient G and solidification rate W) and is valid for any temperature of the chill mold in the range investigated, was obtained.

(4) The dependence $f_P = f(G, W)$ for quantitative estimation allows constructing a porosity scale according to the values of G and W. This scale will be suitable for computing porosity where there is a predominantly unidirectional heat transfer—in extended thin walls of shaped castings or at directional solidification.

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