

INNOVATION IN METALLURGICAL
INDUSTRIAL AND LABORATORY EQUIPMENT,
TECHNOLOGIES AND MATERIALS

ИННОВАЦИИ В МЕТАЛЛУРГИЧЕСКОМ
ПРОМЫШЛЕННОМ И ЛАБОРАТОРНОМ
ОБОРУДОВАНИИ, ТЕХНОЛОГИЯХ И МАТЕРИАЛАХ



UDC 539.5, 621.74.045

DOI 10.17073/0368-0797-2025-6-613-620



Original article

Оригинальная статья

EFFECT OF ANNULAR SEAMS ON STRESS-STRAIN STATE IN CYLINDRICAL CERAMIC SHELL MOLD DURING SOLIDIFICATION OF A STEEL CASTING IN IT

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Abstract. During the crystallization of liquid metal in a shell casting mold, significant normal stresses occur on its surfaces. On the inner – compressive, on the outer – tensile. They are especially pronounced at the initial moment of cooling time. This can lead to damage to the casting mold, and hence damage to the crystallizing metal casting. It is possible to reduce the level of stress-strain state in the surface layers by applying special annular (temperature) recesses (seams) to the outer and inner surfaces. In this paper, the problem of the influence of temperature seams in inner and outer layers of a shell mold (SM) on the level of its stress-strain state (SSS) during crystallization of a steel casting was formulated and solved. The normal stresses σ_{22} , σ_{33} , which occur both on the inner and outer surfaces of SM at the initial moment of metal casting and cooling of the steel casting, are accepted as a parameter of SM resistance to cracking. An axisymmetric problem for a cylindrical ceramic SM is considered. Based on the formulated objective function, the paper presents an algorithm for solving the problem using the equations of the linear theory of elasticity, the equation of thermal conductivity and the proven numerical method. As a result of solving the problem, the minimum number and locations of recesses on the inner and outer surfaces of SM, ensuring a decrease in normal stresses, were determined. The results of solving the problem are presented in the form of stress plots across the sections of the considered area. The authors analyzed the obtained results of SM resistance to cracking and gave recommendations on the use of the obtained results in various scientific and technical fields.

Keywords: investment casting, shell mold, stress state, temperature seam, crack resistance, stresses detection algorithm

Acknowledgements: The research was supported by the Russian Science Foundation, grant No. 24-29-00214, <https://rscf.ru/project/24-29-00214/>.

For citation: Evstigneev A.I., Odínokov V.I., Chernyshova D.V., Evstigneeva A.A., Dmitriev E.A. Effect of annular seams on stress-strain state in cylindrical ceramic shell mold during solidification of a steel casting in it. *Izvestiya. Ferrous Metallurgy*. 2025;68(6):613–620. <https://doi.org/10.17073/0368-0797-2025-6-613-620>

ВЛИЯНИЕ КОЛЬЦЕВЫХ ШВОВ НА НАПРЯЖЕННО-ДЕФОРМИРОВАННОЕ СОСТОЯНИЕ В ЦИЛИНДРИЧЕСКОЙ КЕРАМИЧЕСКОЙ ОБОЛОЧКОВОЙ ФОРМЕ ПРИ ЗАТВЕРДЕВАНИИ В НЕЙ СТАЛЬНОЙ ОТЛИВКИ

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Аннотация. При кристаллизации жидкого металла в оболочковой литейной форме на ее поверхностях возникают значительные нормальные напряжения: на внутренней – сжимающие, на наружной – растягивающие. Особенно ярко они проявляются в начальный момент времени охлаждения. Это может привести к повреждению литейной формы, а значит, и к повреждению кристаллизующейся металлической отливки. Снизить уровень напряженно-деформированного состояния в поверхностных слоях можно с помощью нанесения на внешнюю и внутреннюю поверхности специальных кольцевых (температурных) выточек (швов). В настоящей работе сформулирована и решена задача по влиянию температурных швов во внутренних и внешних слоях оболочковой формы (ОФ) на уровень её напряженно-деформированного состояния (НДС) при кристаллизации стальной отливки. В качестве параметра стойкости ОФ к трещинообразованию приняты нормальные напряжения σ_{22} , σ_{33} , возникающие как на внутренней, так и внешней поверхностях ОФ в начальный момент заливки металла и охлаждения стальной отливки. Рассматривается осесимметричная задача для цилиндрической керамической ОФ. На основе сформулированной целевой функции приведен алгоритм решения задачи с использованием уравнений линейной теории упругости, уравнения теплопроводности и апробированного численного метода. В результате решения задачи определено минимальное количество и места расположения выточек на внутренней и внешней поверхности ОФ, обеспечивающих уменьшение нормальных напряжений. Результаты решения задачи представлены в виде эпюр напряжений по сечениям рассматриваемой области. Дан анализ полученных результатов стойкости ОФ к трещинообразованию. Даны рекомендации по использованию результатов работы в различных научно-технических областях.

Ключевые слова: литье по выплавляемым моделям, оболочковая форма, напряженное состояние, температурный шов, трещиностойкость, алгоритм определения напряжений

Благодарности: Исследование выполнено за счет гранта Российского научного фонда № 24-29-00214, <https://rscf.ru/project/24-29-00214/>.

Для цитирования: Евстигнеев А.И., Одинокое В.И., Чернышова Д.В., Евстигнеева А.А., Дмитриев Э.А. Влияние кольцевых швов на напряженно-деформированное состояние в цилиндрической керамической оболочковой форме при затвердевании в ней стальной отливки. *Известия вузов. Черная металлургия*. 2025;68(6):613–620. <https://doi.org/10.17073/0368-0797-2025-6-613-620>

INTRODUCTION

Investment casting is widely used to produce geometrically complex castings while maintaining dimensional accuracy.

However, this process is characterized by a relatively high rejection rate of shell molds (SMs), primarily due to micro- and macrocracking as well as partial or complete mold failure during shape formation and, most critically, during key technological operations such as firing and metal pouring, especially at the early stage of cooling. These failures result from nonuniform heating across the thickness of the shell mold. Consequently, the limited durability of SMs is mainly associated with elevated stress–strain state (SSS) levels within the mold. To mitigate these effects, a range of technological solutions is applied in industrial practice.

The stress–strain state of multilayer shell casting molds has been extensively studied by both domestic and international researchers. In particular, studies [1; 2] examined the influence of shell mold shape and geometry; works [3; 4] focused on wall thickness; investiga-

tions [5; 6] addressed the properties of mold materials; and publications [7 – 9] analyzed the influence of casting geometry. Domestic studies dedicated to this problem are presented in [10 – 13]. Similar issues have also been investigated in relation to permanent mold casting [14; 15].

The present study continues the authors' research on the crack resistance of ceramic SMs used in investment casting. In earlier work, the SSS of cylindrical SMs during pouring with liquid metal was investigated using mathematical modeling. The theoretical analysis identified optimal physical parameters of the SM material and its morphological structure as key factors governing crack resistance. These results formed the basis for the development of new SM designs and configurations, for which several Russian Federation patents for inventions have been granted (including Nos. 2743439 and 2763359).

The theoretical investigations are based on a numerical method [16] applied to the following problem: liquid metal is poured into a multilayer SM, where it solidifies to form a casting; during subsequent cooling, the temperature field and stress–strain state in the cross-sections of the SM are determined.

At the initial stage of the study, the analysis was performed for a casting in the form of a cylinder with a spherical rounding at the lower part, which simulates a riser-type casting model within a shell mold.

Further theoretical investigations of cylindrical SMs focused on quantifying how the force interaction with the supporting filler (SF) and the interlayer friction parameters within the shell mold affect its stress–strain state (SSS) [17; 18]. These results also led to the granting of Russian Federation patents (Nos. 2769192 and 2788296).

As shown by industrial monitoring of casting-mold durability, the most unpredictable casting geometry is spherical (ball-shaped). For spherical SMs, the optimal supporting-filler (SF) coverage angle and its effect on the stress–strain state (SSS) of the SM were determined in [19].

Foreign studies [20 – 22] present numerical-method-based mathematical modeling of these processes, whereas works [23; 24] address modeling of the SSS in a solidifying casting.

The search for technological solutions to reduce critical SSS levels in SMs led to a new ceramic SM design [25]. The proposed design builds on a well-known approach for reducing thermal stresses in castings by introducing so-called stiffening ribs [26].

It was shown that the durability of spherical SMs increases when annular (temperature) seams, or recesses, are introduced on the inner surface of the mold. A similar durability increase associated with such seams has also been reported for metal casting molds.

When steel is poured into a spherical shell mold, the internal normal stresses across the cross-section are fully compressive and reach relatively high values. Accordingly, the theoretical analysis focused on conditions that reduce the absolute magnitude of these stresses. The most effective solution was a shell mold design incorporating annular seams in the inner layer (lining) [25]. In contrast, for cylindrical shell molds, the greatest risk is associated with tensile normal stresses at the mold–SF contact surface.

In the present study, we consider a ceramic shell mold with a cylindrical section and theoretically analyze the effect of temperature seams not only in the outer layer of the shell mold but also on its inner surface. A “rigid” mold configuration is examined, namely a single-layer ceramic mold with a constant shear modulus.

MATHEMATICAL FORMULATION OF THE PROBLEM

An axisymmetric body of revolution is considered (Fig. 1), comprising a liquid phase (metal) (*I*), a solidifying shell (*II*), a shell mold (*III*), a supporting filler (*IV*), circular recesses a_i on the surface of the lining (surface S_2), and circular recesses b_i on the contact surface between the mold (*III*) and the supporting filler (*IV*) (surface S_3).

Let A be a finite set of circular recesses a_i on surface S_2 ; $A = \{a_i, i = 1, \dots, n\}$; and let B be a finite set of circu-

lar recesses b_i on surface S_3 ; $B = \{b_k, k = 1, \dots, m\}$. Let $C = A \cup B$. As follows from the authors’ numerous studies, the critical stresses during steel pouring into a shell mold are σ_{22} and σ_{33} . Moreover, during steel cooling in a SM with cylindrical sections, the hazardous stresses are the tensile stresses σ_{22} on surface S_3 , whereas during steel cooling in a shell mold of spherical configuration, the hazardous stresses are the compressive stresses σ_{33} on surface S_2 .

Problem statement. Determine the minimum number and placement of recesses A on surface S_2 of the shell mold and the number of recesses B on surface S_3 , as well as their geometric arrangement, such that during metal cooling in the casting mold the maximum (absolute) stresses in the domain Q at $\tau = \tau^*$ remain within prescribed limits for the axisymmetric problem:

$$\begin{aligned} |\sigma_{33}| &< 55 \text{ MPa}; \\ \sigma_{22} &< 20 \text{ MPa}, \end{aligned} \quad (1)$$

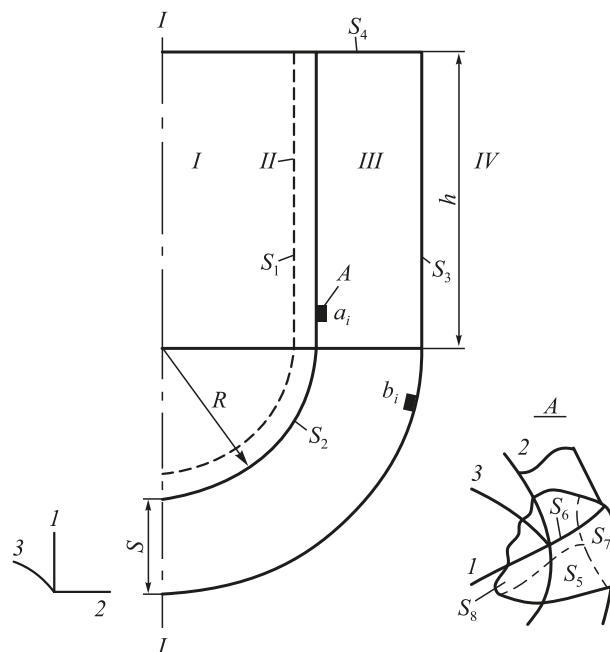


Fig. 1. Calculation scheme of the system with indication of the surface to the problem boundary conditions:

- S_1 – inner contact surface of liquid and solidified metal;
- S_2 – inner contact surface of solidified metal and ceramic mold;
- S_3 – outer contact surface of ceramic mold and supporting filler;
- I – liquid metal; II – crust of solidified metal;
- III – shell mold (SM); IV – supporting filler;
- R – radius of SM spherical part; h – height of SM cylindrical part

Рис. 1. Расчетная схема системы с указанием поверхности к граничным условиям задачи:

- S_1 – поверхность контакта жидкого и затвердевшего металла;
- S_2 – внутренняя поверхность контакта затвердевшего металла и керамической формы;
- S_3 – внешняя поверхность контакта керамической формы с опорным наполнителем;
- I – жидкий металл; II – корочка затвердевшего металла;
- III – оболочковая форма; IV – опорный наполнитель; R – радиус сферической части ОФ; h – высота цилиндрической части ОФ

here Q is the meridional cross-section domain; τ^* is the maximum cooling time after which the temperature over the domain Q begins to equalize and the normal stresses σ_{22} and σ_{33} start to decrease in absolute value.

The value of τ^* is determined from the function

$$F = \max |\sigma_{33}(\tau, Q)|, \quad (2)$$

under the constraint $\tau \leq 60$ s.

To compute F , we write the governing equations in a Cartesian coordinate system for each subdomain (Fig. 1) using linear elasticity theory:

– domain I :

$$\begin{aligned} \sigma_{11} = \sigma_{22} = \sigma_{33} = \sigma = P; \\ P_1 = -\gamma h; \quad \dot{\theta} = a_1 \Delta \theta; \end{aligned} \quad (3)$$

– domain II, III :

$$\begin{cases} \sigma_{ij,j} = 0, \quad i, j = 1, 2, 3; \\ s_{ij} - \sigma \delta_{ij} = 2G_p \varepsilon_{ij}^*; \quad \varepsilon_{ij}^* = \varepsilon_{ij} - \frac{1}{3} \varepsilon \delta_{ij}; \quad \varepsilon = \varepsilon_{ii}; \\ \varepsilon_{ii} = 3k_p \sigma + 3\alpha_p (\theta - \theta_p^*); \quad \varepsilon_{ij} = 0,5 (U_{i,j} + U_{j,i}); \\ C_p \gamma \frac{\partial \theta}{\partial \tau} = \text{div}(\lambda \text{grad} \theta), \end{cases} \quad (4)$$

where σ_{ij} are the components of the stress tensor; σ is the hydrostatic stress; ε_{ij} are the components of the elastic strain tensor; h is the height of the liquid metal column;

$k_p = \frac{1-2\mu}{E}$ is the bulk compression coefficient; μ is Poisson's ratio; E is Young's modulus; $G_p(\theta)$ is the shear modulus in domain p ($p = II, III$); α_p is the linear thermal expansion coefficient; a_1 is the thermal diffusivity coefficient in domain (I); τ is time; θ is temperature; C_p is the specific heat capacity in domain (p); γ is the specific weight; θ_p^* is the initial temperature in domain (p); $\lambda = \lambda(\theta)$ is the thermal conductivity coefficient; summation over repeated indices is implied.

During the cooling of liquid metal, under the condition that the metal temperature $\theta_m \leq \theta_c$ (where θ_c is the crystallization temperature), the thickness of the solidified layer Δ_i is determined from the solution of the phase-transition equation.

Initial conditions:

$$\begin{aligned} \Delta|_{\tau=0} &= 0 - \text{absence of solid phase;} \\ \theta_I^*|_{\tau=0} &= \theta_m^* - \text{temperature of the poured liquid metal;} \\ \theta_{III}^*|_{\tau=0} &= \theta^* - \text{initial mold temperature.} \end{aligned}$$

Boundary conditions of the problem in orthogonal coordinates (Fig. 1):

– for the axisymmetric problem

$$\begin{aligned} U_3 = 0; \quad \sigma_{31} = \sigma_{32} = 0; \quad \varepsilon_{13} = \varepsilon_{23} = 0; \\ \frac{\partial u_i}{\partial x_3} = 0; \quad \frac{\partial \sigma_{3i}}{\partial x_3} = 0, \quad i = 1, 2, 3; \end{aligned} \quad (5)$$

– on the axis of symmetry

$$U_2 = 0; \quad \sigma_{21} = 0; \quad q_n = 0; \quad \theta = \theta_m;$$

– on surfaces S_1, S_3, S_4

$$\begin{aligned} \sigma_{11}|_{S_1} = -P; \quad \sigma_{12}|_{S_1} = 0; \quad U_1|_{S_3} = 0; \quad \sigma_{21}|_{S_4} = 0; \\ \sigma_{22}|_{S_4} = 0; \quad \sigma_{11}|_{S_3} = 0; \\ \sigma_{12}|_{S_3} = -\psi \frac{U_{sl}}{U^*} \tau_s \cos(n_1 x_1); \\ \theta|_{S_3} = \theta^*; \quad \theta|_{S_2} = \theta_m, \end{aligned} \quad (6)$$

where U_{sl} is the displacement of the mold material during sliding relative to the SF (sand), U^* is the normalizing displacement; ψ is the friction coefficient between the mold and the supporting filler; τ_s is the conditional yield limit in shear; q_n is the heat flux.

For the thermal analysis, we used Dirichlet (first-kind) boundary conditions. To determine $\theta_m(\tau)$ and $\theta^*(\tau)$, the data from Ref. [27] were adopted:

$$\begin{aligned} \theta_m = \theta_m^* - \frac{\tau}{\tau_1} \theta_1; \\ 0 < \tau < 60 \text{ s}; \\ \theta^* = \theta_0 \left(1 + \sqrt{\frac{\tau}{\tau_2}} \right), \end{aligned} \quad (7)$$

here τ is the cooling time, s; $\theta_m^* = 1550$ °C; $\theta_1 = 100$ °C; $\theta_0 = 20$ °C; θ^* is the temperature on surface S_3 ; $\tau_1 = 60$ s; $\tau_2 = 1$ s.

The time τ does not exceed 60 s, since for $\tau \geq 60$ s the stresses in the SM do not pose a risk of failure.

The shear modulus of the SM is taken as

$$G_{\text{mold}} = 2960 \text{ kg/mm}^2. \quad (8)$$

The algorithm for solving system (4) under boundary conditions (5) – (7) is described in detail in Ref. [27].

The calculation yielded the following results:

$$F = -65.6 \text{ MPa}; \quad \tau^* = 21.65 \text{ s}. \quad (9)$$

The solution results are presented in Fig. 2 in the form of stress plots along the cross-section of the shell under consideration. The stresses σ_{22} and σ_{33} are highly significant. In the lining, σ_{22} and σ_{33} are negative and reach large magnitudes in the cylindrical part of the SM, with $|\sigma_{33}|$ being approximately 1.5 times greater than $|\sigma_{22}|$. In the spherical part, the difference between σ_{22} and σ_{33} is smaller; however, as the stresses approach the cylindrical region, the difference becomes pronounced. In the outer layer (at the contact with the supporting filler), the stresses σ_{22} are positive. In the spherical part, they are approximately equal in magnitude, whereas in the cylindrical part they increase

toward the upper portion of the mold. The stresses σ_{33} on this surface (surface S_3) are comparable to σ_{22} in the spherical region and are practically zero in the cylindrical region. Fig. 2 shows that the stresses σ_{33} and σ_{22} arising during steel pouring into the ceramic shell mold significantly exceed (in absolute value) the limits specified in (1).

Having determined the value of τ^* from (9), we proceed to solving the formulated problem. The process of steel cooling in a ceramic SM with temperature seams (annular recesses) is considered. In contrast to the previous problem, the cross-section Q represents a multiply connected domain. The initial and boundary conditions largely coincide with those of the previous problem. Boundary conditions (6) are supplemented as shown in Fig. 1):

$$(\sigma_{22} = \sigma_{21})|_{S_i} = 0, i = 5, 6; (\sigma_{11} = \sigma_{12})|_{S_i} = 0, i = 7, 8; (10)$$

Relationship (7) is also satisfied for the adopted value of the shear modulus given in (8).

SOLUTION ALGORITHM

1. The geometric dimensions of the domain, the final cooling time τ^* , the geometric dimensions of the recesses,

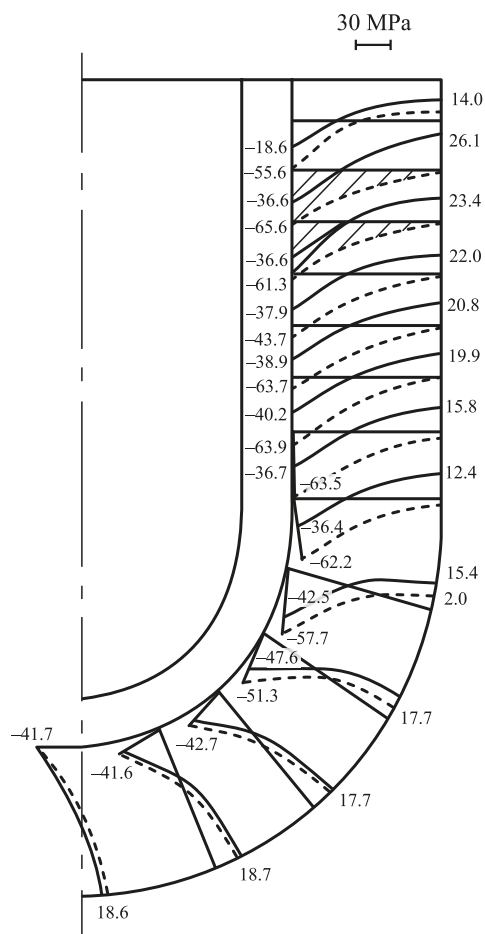


Fig. 2. Stress plots σ_{22} (—) and σ_{33} (---) along SM section

Рис. 2. Эпюры напряжений σ_{22} (—) и σ_{33} (---) по сечению ОФ

and their initial coordinates on surfaces S_2 and S_3 are specified: $a_i(0)$, $b_i(0)$. The cooling time τ^* is divided into a finite number of time steps: $\tau^* = \sum \Delta\tau_n$ (where n is the time-step index).

2. The investigated domain is divided into a finite number of elements by a system of orthogonal surfaces.

3. The arc lengths of the elements are calculated $S_{ij}^k(i, k = 1, 2, 3; i \neq k; j = 1, 2)$.

4. Initial and boundary conditions are specified for the elements forming the considered domain ((5), (6), (10)), as well as the constants of the physical and mechanical properties of the materials.

5. The temperature field at the time step $\Delta\tau_n$ is determined by a numerical solution of the heat conduction equation using an iterative scheme [27], taking into account the initial and boundary conditions at the given time step. The presence of recesses was not taken into account when solving the thermal problem.

6. If the condition $\theta|_{S_2} \leq \theta_c$ for domain (I) at surface S_2 , is satisfied, the thickness of the crystallized shell Δ_n is calculated.

7. System of equations (3) and (4) is solved taking in account boundary conditions (6) and (10), finite-difference analogs, and the developed methodology using the *Odyssey* software package¹. The stress fields σ_{ij} and displacement fields $U_i(i, j = 1, 2)$ are determined.

8. On surface S_3 , the mold-supporting contact is assessed for each element: if $\sigma_{11}|_{S_3} > 0 \Rightarrow \sigma_{11} = 0$, $\sigma_{12} = 0$, the boundary conditions are reassigned and operation **7** is performed.

9. A time step is performed. According to relations (7) the boundary conditions for solving the thermal problem are refined. If $\sum \Delta\tau_n < \tau^*$, operation **5** is performed. If $\sum \Delta\tau_n = \tau^*$, operation **10** is performed.

10. Over the domain Q , the values of σ_{33} and σ_{22} are analyzed, and the maximum values (in absolute magnitude) exceeding the constraints (1) are selected. Corresponding matrices are formed $[\bar{\sigma}_{22}]$, $[\bar{\sigma}_{33}]$. If constraints (1) are satisfied, operation **12** is performed.

11. From the matrices $[\bar{\sigma}_{22}]$, $[\bar{\sigma}_{33}]$ the maximum values are selected, and recesses are introduced in the corresponding cross-sections. Operation **7** is then performed.

12. The calculation process is completed.

RESULTS OF THE STUDY

Geometric parameters: $S = 5$ mm; $R = 20$ mm; $h = 50$ mm.

Time intervals $\Delta\tau_n$: 0.01, 0.02, 0.03, 0.04, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 2, 5, 5, 5, 3, 3, 5, 5, 5, 5 s.

The following physical parameters of the poured steel at $\theta > 1000$ °C ($\theta_m^* = 1550$ °C) [27]:

¹ Onikov V.I., Prokudin A.N., Sergeeva A.M., Sevastyanov G.M. ODYSSEY. Certificate of State Registration of a Computer Program No. 2012111389. Registered in the Register of Computer Programs on December 13, 2012.

$$G = 1000 \text{ kg/mm}^2; \alpha = 12 \cdot 10^{-6} \text{ deg}^{-1};$$

$$\lambda = 0.0298 \text{ W/(mm} \cdot ^\circ\text{C)};$$

$$L = 270 \cdot 10^3 \text{ J/kg (latent heat of fusion)};$$

$$C = 444 \text{ J/(kg} \cdot ^\circ\text{C)}; \gamma = 7.80 \cdot 10^{-6} \text{ kg/mm}^3; \theta_c = 1450 \text{ }^\circ\text{C}.$$

Physical properties of the ceramic shell mold:

$$G = 2960 \text{ kg/mm}^2; \alpha = 0.51 \cdot 10^{-6} \text{ deg}^{-1};$$

$$\lambda = 0.000812 \text{ W/(mm} \cdot ^\circ\text{C)};$$

$$C = 840 \text{ J/(kg} \cdot ^\circ\text{C)}; \gamma = 2.0 \cdot 10^{-6} \text{ kg/mm}^3.$$

Recess dimensions: $a_i = 1 \times 2 \text{ mm}$, $b_i = 1 \times 3 \text{ mm}$.

Calculations performed using the above algorithm yielded the following results: $F = 5$; $a_i = 2$; $b_i = 3$. The geometric locations of the recesses (a_i , b_i) and the temperature distribution in the cross-section ($x_2 = 0$) are shown in Fig. 3. The resulting stresses σ_{33} and σ_{22} are presented in Fig. 4.

As shown in Fig. 4, all maximum values of the stresses σ_{33} (in absolute magnitude) and the tensile stresses σ_{22} satisfy the specified constraints (1), although in some cross-sections they are very close to the limiting values.

CONCLUSIONS

An axisymmetric problem was formulated and solved to optimize the cooling of a steel casting in a ceramic

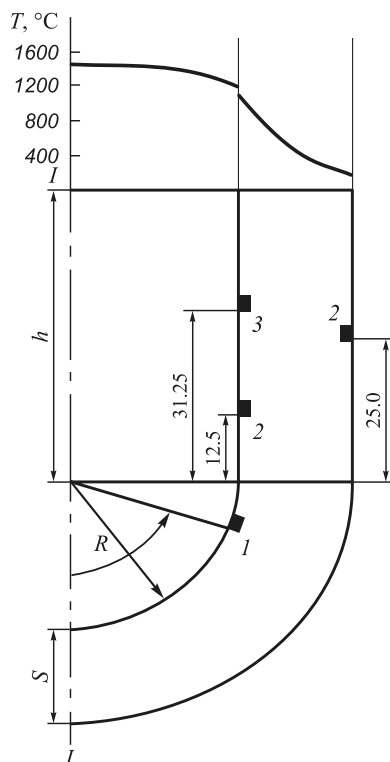


Fig. 3. Calculation scheme of the system with a group of recesses on the lining and outer layers of SM

Рис. 3. Расчетная схема системы с группой выточек на облицовочном и наружном слоях ОФ

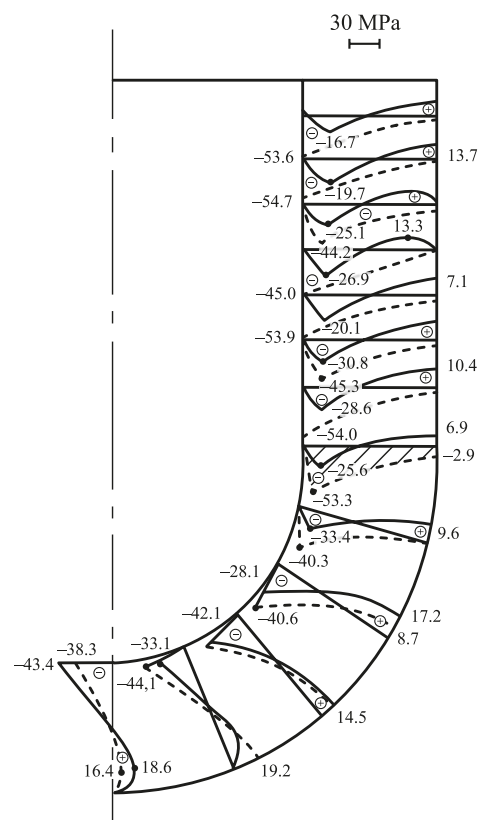


Fig. 4. Stress plots σ_{22} (—) and σ_{33} (---) along SM section

Рис. 4. Эпюры напряжений σ_{22} (—) и σ_{33} (---) по сечению ОФ

shell mold with cylindrical and spherical sections and annular temperature recesses.

The effectiveness of introducing annular recesses on the outer and inner mold surfaces in contact with the cooling metal was demonstrated.

The results can be used to analyze related processes, perform strength calculations, and support optimization studies.

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Received 03.12.2024

Revised 01.09.2025

Accepted 10.09.2025

Поступила в редакцию 03.12.2024

После доработки 01.09.2025

Принята к публикации 10.09.2025