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Research Article

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Abstract

The results of a numerical analysis of unsteady heat transfer in the "metal-mold-environment" system during continuous combined casting and extrusion of an aluminum alloy in an installation with a horizontal carousel mold are presented. The heat engineering zones characterized by different intensity of heat transfer between the melt and the surface of the mold have been determined. A quantitative assessment of the influence of the rate of heating of the crystallizer on the temperature-time characteristics during the period of the transient thermal process is given. It is shown that an increase in the productivity of the installation reduces the duration of the transient thermal process when starting the installation from a cold state until it reaches a stationary thermal regime. The dependence of the time at which the installation reaches the stationary thermal regime on the rotation speed of the crystallizer wheel has been obtained.

***Keywords**: Installation, Continuous combined casting-extrusion, Horizontal mold, Computer model, Numerical analysis, Heat transfer, Transient process, Aluminum alloy, Productivity.*

1 Introduction

The development of technologies for foundry and metal forming is directed towards the unification of several technological stages in one installation [1-8]. These include, for example, a horizontal semi-continuous casting machine (HSCCM) [9]. It should also be noted the improved process of Extrolling of the combination of rolling and extrusion in one deformation zone [10, 21] implemented in the CCRE-2.5 pilot unit.

Widespread, especially in non-ferrous metallurgy, are the Super Caster units of the Italian company Fata-Hunter, a distinctive feature of which are large diameters of crystallizer rolls, which are individually driven by an electric motor through a planetary gearbox [11, 12]. The ingot rolling technology used here is characterized by low capital intensity and low operating costs. However, this technology has a number of disadvantages due to the difficulty of supplying and retaining the metal in the rolls during reductions [13].

The process of discrete extrusion of non-ferrous metal alloys is complex and energy-consuming with the release of a large amount of heat generated by the action of frictional forces and plastic deformation. With an increase in the extruding speed the temperature of the deformed metal increases intensively, and when critical temperatures are reached its destruction occurs [14].

As studies of the methods of continuous extrusion of metals have shown [15-24], their use significantly increases the efficiency of the production of profiles from non-ferrous metals. One of the promising directions in the development of these technologies is the combination of continuous casting with extrusion on a Conform installation with a horizontal carousel mold [21-26]. During the operation of the installation, the metal melt is fed through the batcher into the annular groove of the rotating mold wheel and solidifies to contact with the stationary part of the container, formed at the interface of the groove with the arcuate segment (Fig. 1). The solidified metal is extruded into the die hole in the segment in the form of a press product. The supply of liquid metal into the groove, its solidification and extrusion proceed in a continuous mode [27].

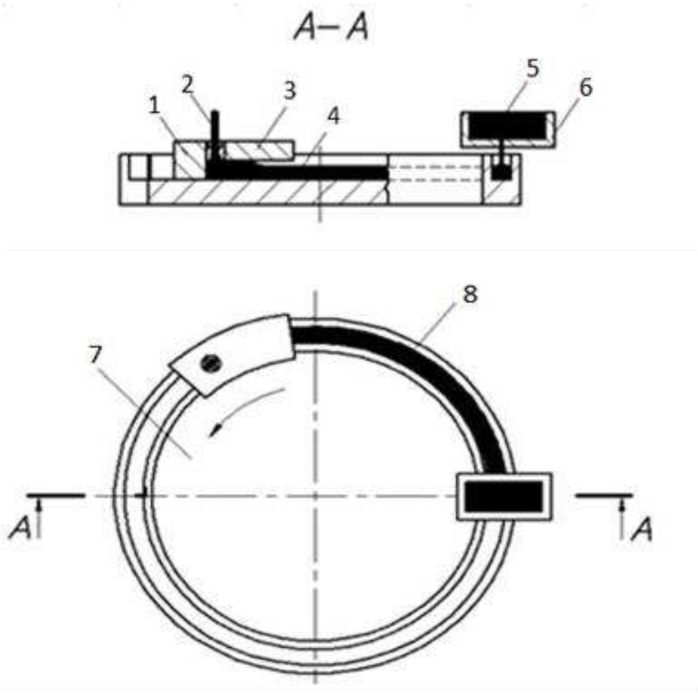


Fig 1. Installation scheme of continuous casting and extrusion with horizontal carousel mold: 1 – die stopper; 2 – press product; 3 – stationary arcuate segment; 4 – solidified ingot; 5 – metal melt; 6 – dispenser; 7 – crystallizer wheel; 8 – annular groove

A necessary condition for combining continuous casting and extrusion of metal is the observance of such thermal conditions in the "metal-crystallizer-environment" system, which ensures the solidification of the melt and stabilization of its temperature in the section in front of the container [28-30]. An analysis of the thermal regimes of continuous casting before extrusion of aluminum alloys carried out on the basis of the method proposed in [31, 32] that confirmed this statement.

Further studies of the nature of the dependence of the thermal operation of the "metal-crystallizer-environment" system on the parameters of the technological process showed that in an unstable transient mode the crystallizer wheel gradually warms up with each round from the initial temperature until a stationary thermal state is reached. At the same time on the basis of computer simulation it was found that the degree and rate of heating of the crystallizer in the initial period of operation of the installation have the main effect on the nature of unsteady heat transfer and changes in the enthalpy of the melt [33, 34]. As a result, operational and design solutions were proposed that ensure rational temperature-time conditions for the installation at a fixed design rotational speed of the mold (the productivity of the installation in terms of the mass flow rate of the melt poured in) in a long-term stable period of its operation [29, 30].

The purpose of this work was to theoretically study unsteady heat transfer to determine the temperature-time conditions of the elements of the system "metal-horizontal crystallizer-environment" in transient thermal modes of operation of the Conform installation with combined casting-extrusion of an aluminum alloy.

2 Materials and method of carrying out research

The analysis of the dynamics of heat transfer in the transient operating mode of the installation was carried out in three calculated sections passing through the volume of the metal and the material of the mold solidifying in the groove. The sections are formed by a vertical cutting plane located at a distance from the pouring point of the melt *P* at angles $\varphi_1 = 30°$, $\varphi_2 = 120°$ and $\varphi_3 = 210°$ (Fig. 2). As can be seen, the central angles φi of the circular arc of the mold groove with radius R_k = 0.175 m are located between the polar axis OP (segment $OP = R_k$) and the rays connecting the pole O with the design sections. The φ_i reading is taken in a clockwise direction.

In accordance with the technological conditions in the control section φ_3, located at an angular distance $\Delta\varphi = 15°$ from the beginning of the extruding zone (stationary arcuate segment) a temperature range must be provided over the metal section the maximum value of which is 3-5 °C lower than the solidification temperature aluminum melt [35].

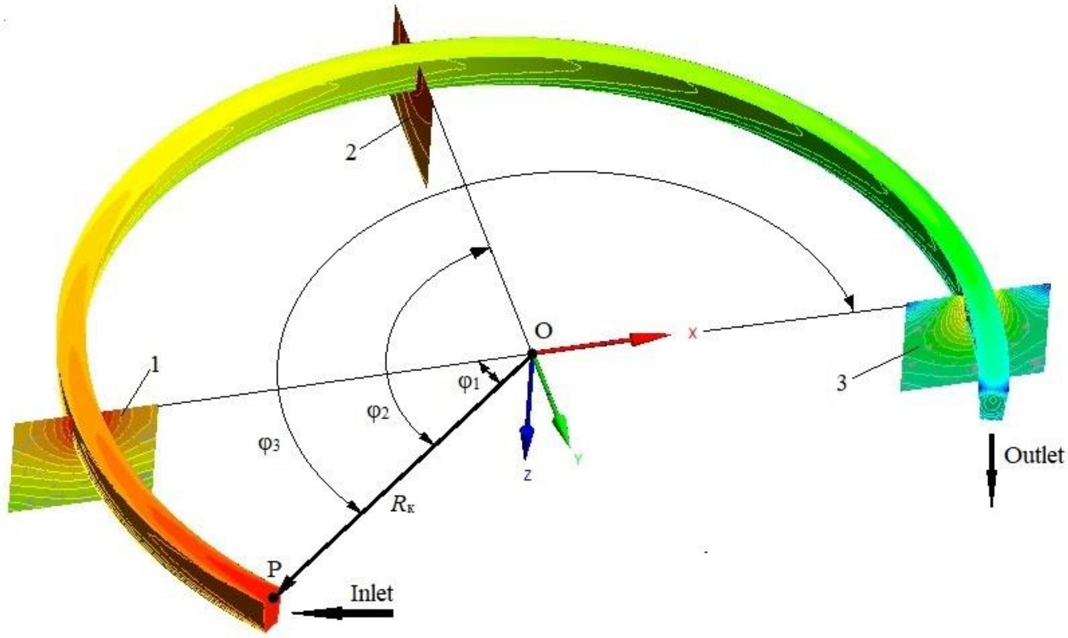


Fig. 2. The layout of the design sections in the body of the horizontal mold from the place of pouring the melt P: 1, 2 and 3 – design sections, at central angles $\varphi_1 = 30°$, $\varphi_2 = 120°$ and $\varphi_3 = 210°$

Numerical studies were carried out on a previously developed three-dimensional computer model of heat transfer in a pilot plant implemented on the basis of software [35-37] SolidWorks (2017) and Ansys CFX 17.1.

Nonlinear differential equations for the conservation of energy for the processed melt and the elements of the installation were written in the form of a substantial derivative:

$$\rho_i c_i(t)\frac{Dt_i}{d\tau} = \rho_i c_i(t)\frac{\partial t_i}{d\tau} + \rho_i c_i(t)\mathrm{div}(w_i t_i) = \lambda_i \nabla^2 t_i + q_{vi}, \tag{1}$$

where t_i is the temperature field in the i-th element; ρ_i, c_i and λ_i – density, volumetric heat capacity and thermal conductivity of the i-th element; w_i is the vector of the angular velocity of motion of the i-th element in the body of the mold and the melt; q_{vi} is a function characterizing heat sources (internal heat release during phase transition and metal pressing) in the i-th element [38]:

$$q_{vi} = S_h' + S_h'', \tag{2}$$

where S_h' – internal heat release during phase transition; S_h'' – heat release from the forces of contact friction and deformation forces of the metal being processed.

In the mathematical model a cylindrical coordinate system was used (Fig. 2), where the divergence and Laplace operator included in the system of differential equations (1) had the following form:

$$\mathrm{div} = \frac{\partial}{\partial R} + \frac{1}{R} + \frac{1}{R}\frac{\partial}{\partial \varphi} + \frac{\partial}{\partial z}\,; \tag{3}$$

$$\nabla^2 t_i = \left\{ \frac{\partial^2 t_i}{\partial R_i^2} + \frac{1}{R_i}\frac{\partial t_i}{\partial R_i} + \frac{1}{R_i^2}\frac{\partial^2 t_i}{\partial \varphi_i^2} + \frac{\partial^2 t_i}{\partial z_i^2} \right\}. \tag{4}$$

Equation (1) was supplemented by the boundary conditions:

$$t_i = t_0\,(R, z, \varphi, \tau = 0);\ w_i = (R, z, \varphi, \tau) = \text{const};\ \lambda \frac{\partial t}{\partial n}\Big|_{\Gamma_i} = \pm q_i\,. \tag{5}$$

Here q_i – function characterizing the conditions of radiation-convective heat transfer at the boundary of the surface of the i-th element Γ_i ($q_i > 0$ – heat flux is directed inside the element).

In the boundary conditions (5) the angular velocity of movement of the installation elements w_i relative to the Z axis of the system will change: the mold wheel with the melt solidifying in its groove, the other elements of the design model are stationary ($w_i = 0$). The enthalpy of the melt poured into the groove of the crystallizer is calculated based on the accepted initial values of its temperature and flow rate which is functionally related to the value of w_i.

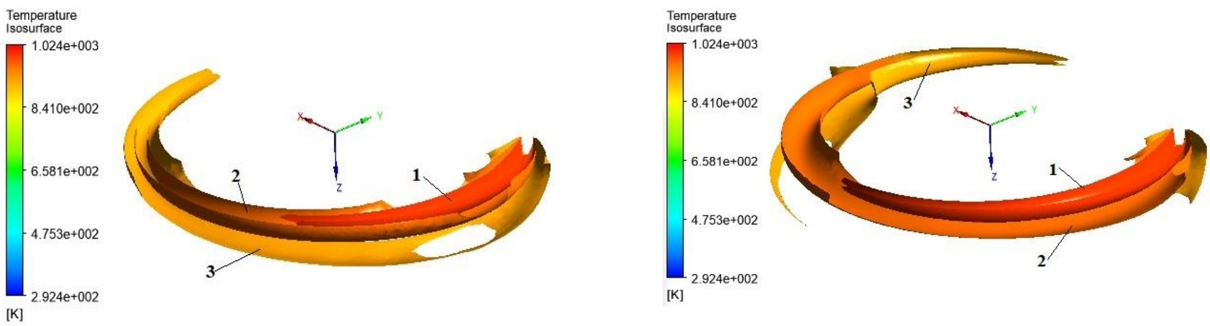
3 Results and discussion

A numerical study of the process of continuous combined casting-extrusion was carried out for the eutectic aluminum alloy Al12Si with a melting (solidification) temperature of 580 °C. When analyzing the temperature-time characteristics of the transient thermal process the speed of rotation of the crystallizer wheel w_c was taken as the operating parameter, the range of which varied within 1-3 rpm. The temperature t_p of the metal melt poured into the groove was taken equal to 750 °C, the ambient temperature was 20 °C.

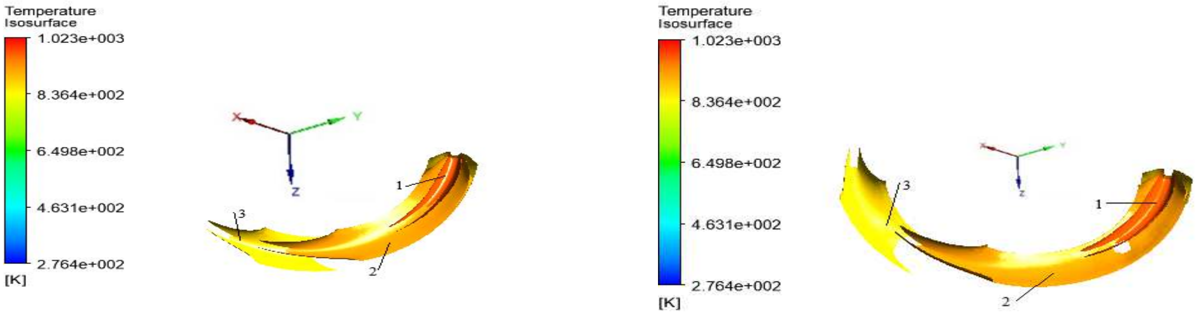
In accordance with the specified value w_k and the dimensions of the section of the mold groove 10×10 mm, the mass flow rate of the melt (unit productivity) G_p took values 0.27-0.81 kg/min. Note that in proportion to the value of G_p in equation (1) the amount of heat supplied with the poured metal to the elements of the installation also changed.

The results of modeling the dynamics of heat transfer in a transient thermal process indicate a significant effect of the rotation speed of the horizontal mold wheel on the rate of its heating and, as a consequence, on the nature of the temperature field in the tool body and solidifying melt.

Fig. 3 shows the isotherms t_1, t_2, and t_3 calculated during the transient thermal process corresponding to the temperature value over the cross section of the mold body 700, 650, and 600 ºC, at t_p = 750 °C and the rotation speed of the mold wheel w_c = 1 and 3 rpm.



a *b*



c *d*

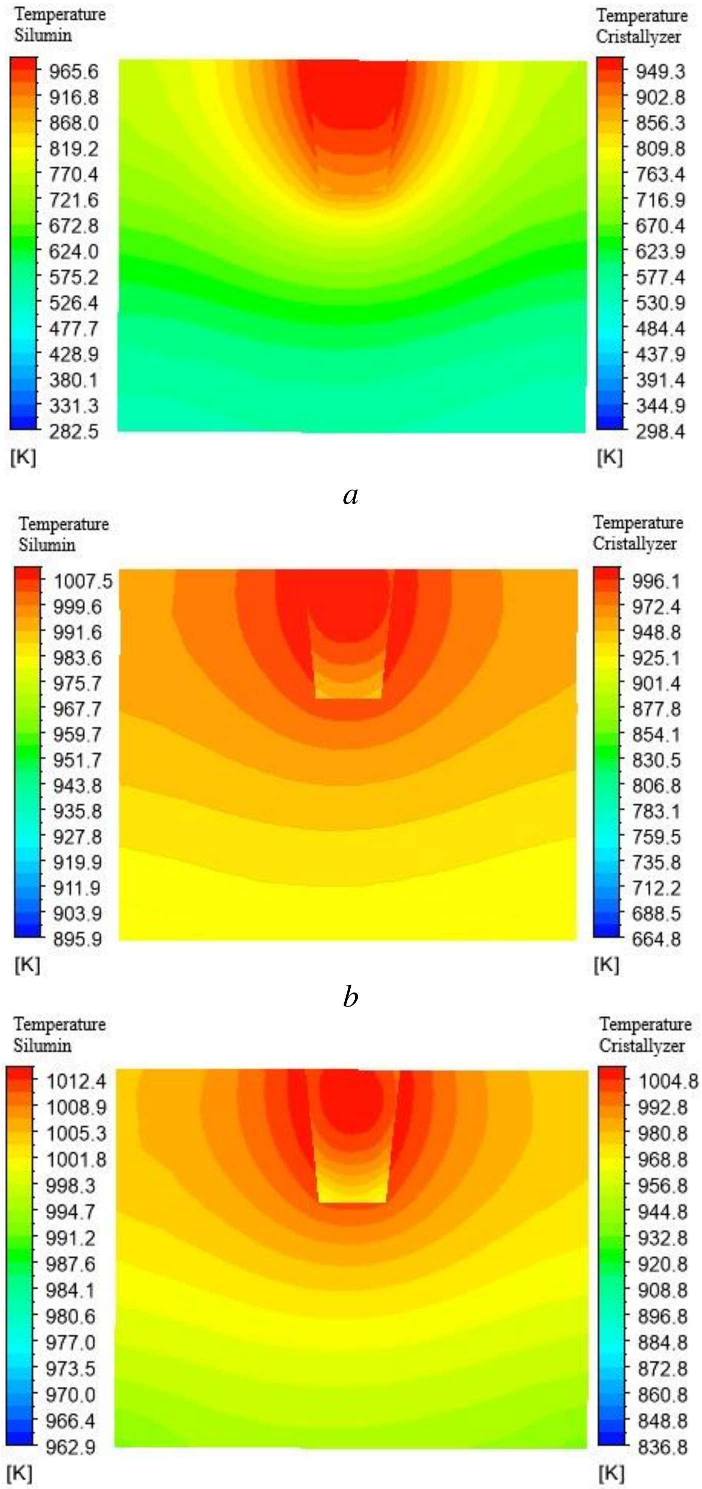
Fig. 3. The values of the isotherms t_i in the body of the mold in the transient thermal process at t_p = 750 ºC:
1 – t_1 = 700 ºC; 2 – t_2 = 650 ºC; 3 – t_3 = 600 ºC;
a – τ_{ex} = 320 s, w_k = 3 rpm; *b* – τ_{ex} = 840 s, w_k = 3 rpm;
c – τ_{ex} = 320 s, w_k = 1 rpm; *d* – τ_{ex} = 840 s, w_k = 1 rpm

As can be seen, during the transient thermal process τ_{ex} the location of the considered isotherms changes, associated with a different rate of heating of the mold. So, for example, an isotherm with a temperature of t_1 = 700 °C during periods of time τ_{ex} = 320 and 840 s, at a mold rotation speed $w_к$ = 3 rpm, the length of an arc segment $\Delta\varphi_i$ from the pouring point of the melt *P* (Fig. 2) equal to 0.066 and 0.115 m respectively. At $w_к$ = 1 rpm the arc distance $\Delta\ \varphi_i$ changes significantly and the length of the arc segments for the considered time periods τ_{ex} decreases to 0.025 and 0.045 m respectively.

Analysis shows that at the initial moment of time after the start-up of the installation in the "melt - tool" system, the bulk of the heat goes to heating the mold (Fig. 3). In this case, the more heat is supplied with the melt the faster the crystallizer heats up and, accordingly, the time for reaching the stationary thermal mode of operation of the installation as a whole decreases. It has been determined that when the rotation speed of the mold changes from 1 to 3 rpm, the time to reach the stationary thermal regime (τ_{st}) decreases almost three times (from 46 to 15 minutes).

It was found that in the transient thermal process, the crystallizer has two temperature-time heating zones the characteristics of which depend on the productivity of the installation.

In the first zone intense heat exchange occurs between the metal melt and the walls of the mold wheel. The analysis shows that at tp = 750 ºC and G_p = 0.81 kg/min ($w_к$ = 3 rpm), the time interval from the start of the installation to the passage of this zone $\Delta\tau_{ex}$ is 320 s. In this case the rate of change of the average temperature of the mold in the first design section along its rotation (φ_1) $\Delta\bar{t}_k / \Delta\tau_{ex}$ = 15.3 ºC/min and the maximum temperature gradient between the wall of the mold and the peripheral layer of the melt in the groove gradt_{mold} = 87 ºC/mm (Fig. 4)



c

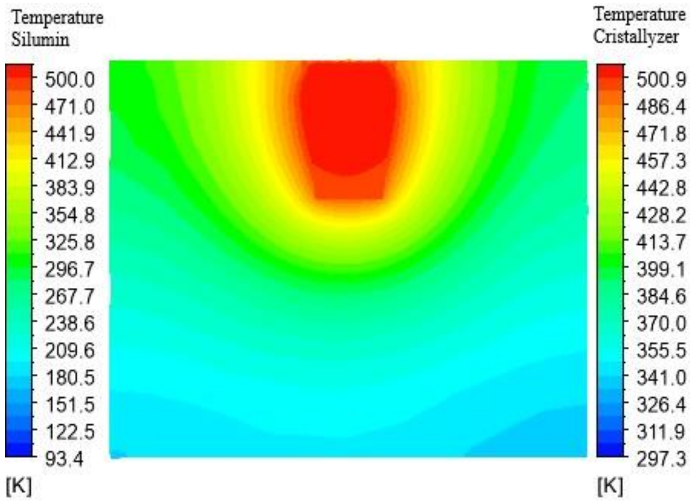
Fig. 4. Temperature field (K) in the design section of the metal and the mold $\varphi_1 = 30°$ at $t_p = 750$ °C, $w_k = 3$ rpm:
a – $\tau_{ex} = 60$ s; b – $\tau_{ex} = 320$ s; c – stationary thermal regime

Calculations have shown that a decrease in the productivity of the installation to $G_p = 0.27$ kg/min ($w_k = 1$ rpm) increases the duration of the first temperature-time zone $\Delta\tau_{ex}$ to 450 s. At the same time the value of the parameters $\Delta \bar{t}_k / \Delta\tau_{ex}$ and gradt_{mold} noticeably decrease the values of which in the section φ_1 are 4.78 ºC/min and 23 ºC/mm respectively (Fig. 5).

In the second zone, the rate of heat removal from the melt to the mold decreases, and the length of the arc of solidification of the melt increases. So, in the considered section φ_1 at $w_k = 3$ rpm, the values and $\Delta \bar{t}_k / \Delta \tau_{ex}$ gradt_{mold} decrease to 4.5 ºC/min and 2.3 ºC/mm respectively. At $w_k =$ 1 rpm, these values take the corresponding values of 1.82 ºC/min and 4.2 ºC/mm.

Fig. 6 shows the generalized temperature-time dependences obtained during the period of the transient thermal process at different productivity of the installation in the calculated sections φ_i of the crystallizer body and the solidifying melt.

It can be seen that the nature of the temperature field of the mold and the metal changes both during $\Delta\tau_{ex}$ from the start of the installation until it reaches a stationary thermal regime and in the course of their movement from the pouring point to the pressing zone. With an increase in the productivity of the installation the temperature of the mold and the alloy being processed increases in the design sections φ_i which is associated with an increase in the heat supplied to the casting-extrusion process with the poured melt.

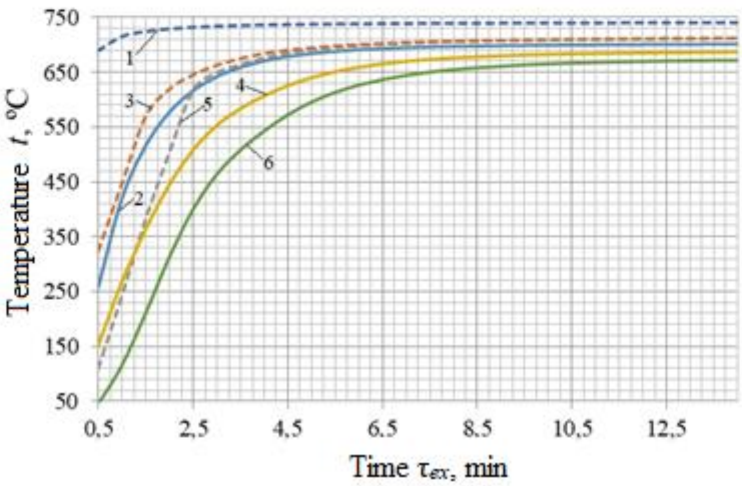


a

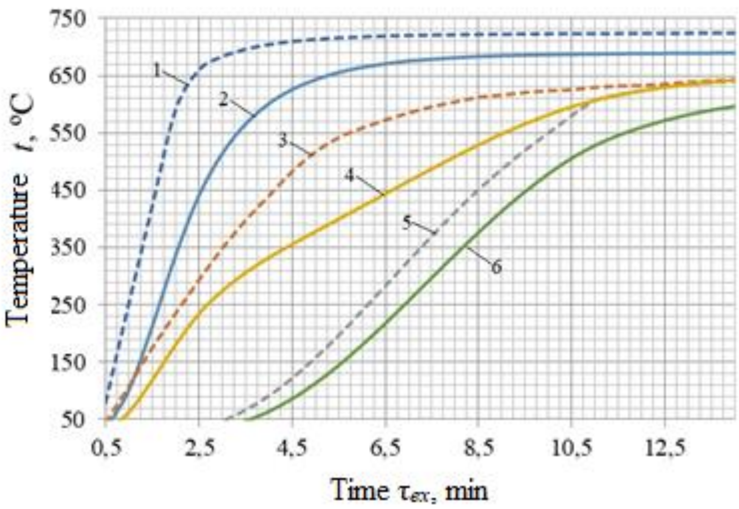
b

c

Fig. 5. Temperature field (K) in the design section of the metal and the mold $\varphi_1 = 30°$ at $t_p = 750$ °C, $w_k = 1$ rpm:
a – $\tau_{ex} = 60$ s; *b* – $\tau_{ex} = 450$ s; *c* – stationary thermal regime



a



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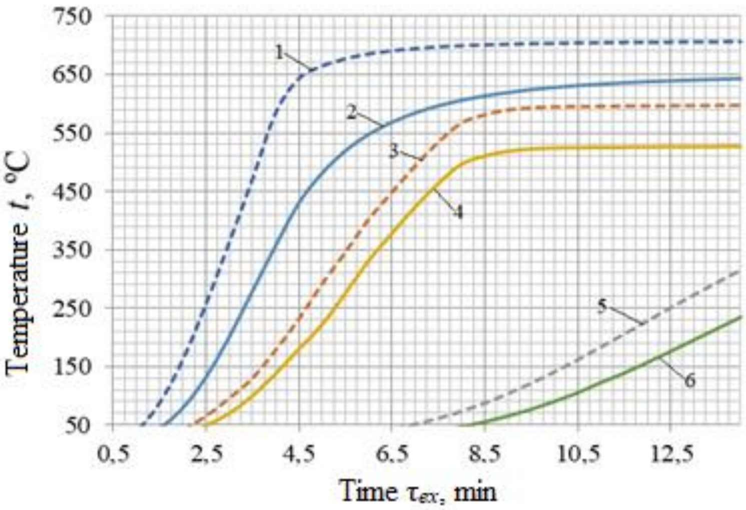

c

Fig. 6. Temperature change in the body of the mold and metal in the design sections φ_i in transient thermal mode:
1, 2 – temperature of metal and mold at w_k = 3 rpm;
3, 4 – temperature of metal and mold at w_k = 2 rpm;
5, 6 – temperature of metal and mold at w_k = 1 rpm;
a – $\varphi_1 = 30°$; b – $\varphi_2 = 120°$; c – $\varphi_3 = 210°$

With an increase in the rotational speed of the mold up to 3 rpm during the period of the transient process, the asymmetry of the temperature field in the calculated sections of the metal φ_2 and φ_3 increases. The region with the maximum temperature is shifted to the surface layers of the metal in contact with the environment. When the speed decreases to 1 rpm the shift of the temperature field with the maximum temperature over the metal cross section is insignificant. In the design sections φ_2 and φ_3 the region with the maximum temperature shifts towards their central part.

It should be noted that at $w_k \leq 1.75$ rpm the design of the installation upon reaching a stationary thermal regime provides in the third control section φ_3 in front of the extrusion zone the temperature of the solidifying melt below the point of its phase transition due to sufficient heat removal into the environment.

4 Summary

1. A numerical study of unsteady heat transfer during continuous combined casting-extrusion of an aluminum eutectic alloy Al12Si was carried out, on the basis of which two temperature-time zones were determined in transient thermal modes of operation of the Conform installation.

2. The dependence of the time at which the installation reaches a stationary thermal regime on the rotation speed of the crystallizer wheel w_k at start-up from a cold state has been obtained.

3. It was found that during the transient thermal process the character of the temperature field in the body of the tool and the solidifying melt is significantly affected by the value of w_k. So, with its increase, an increase in the asymmetry of the temperature distribution in the calculated sections of the metal near the extruding zone is observed with a shift of the region of maximum values to its surface layers.

4. It is shown that an increase in the productivity of the installation in terms of the mass flow rate of the poured melt is accompanied by an almost linear reduction in the time of the transient thermal process from the start-up of the installation to its stationary mode of operation.

Declarations

Ethical Approval

The work contains no libelous or unlawful statements, does not infringe on the rights of others, or contain material or instructions that might cause harm or injury.

Consent to Participate

The authors consent to participate.

Consent to Publish

The authors consent to publish.

Authors Contributions

The authors declare that they are all participants in the work and none of them performed only administrative functions.

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Competing Interests

The authors declare about the absence of competing interests.

Availability of data and materials

Not applicable.

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Figures

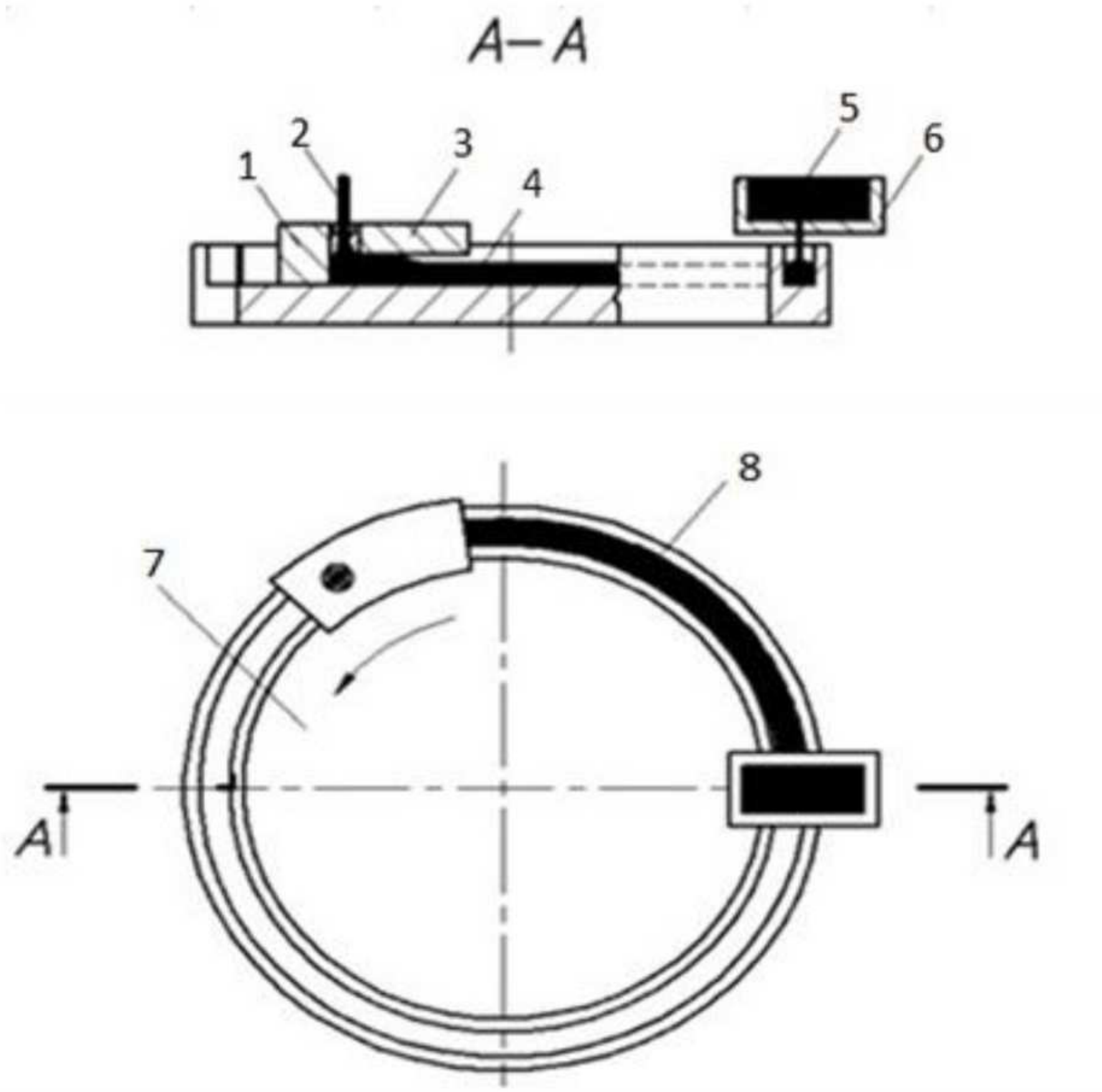

Figure 1

Installation scheme of continuous casting and extrusion with horizontal carousel mold: 1 – die stopper; 2 – press product; 3 – stationary arcuate segment; 4 – solidified ingot; 5 – metal melt; 6 – dispenser; 7 – crystallizer wheel; 8 – annular groove

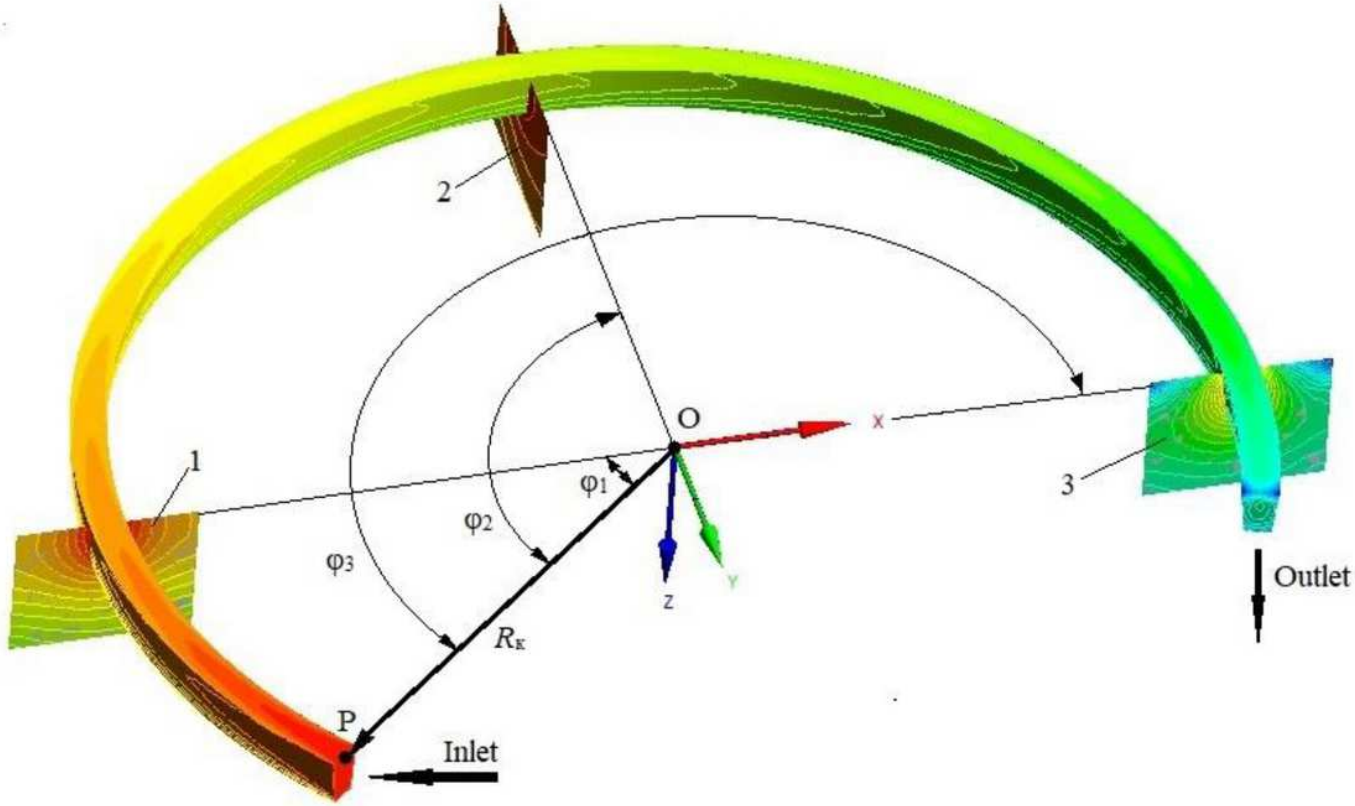

Figure 2

The layout of the design sections in the body of the horizontal mold from the place of pouring the melt P: 1, 2 and 3 – design sections, at central angles φ1 = 30°, φ2 = 120° and φ3 = 210°

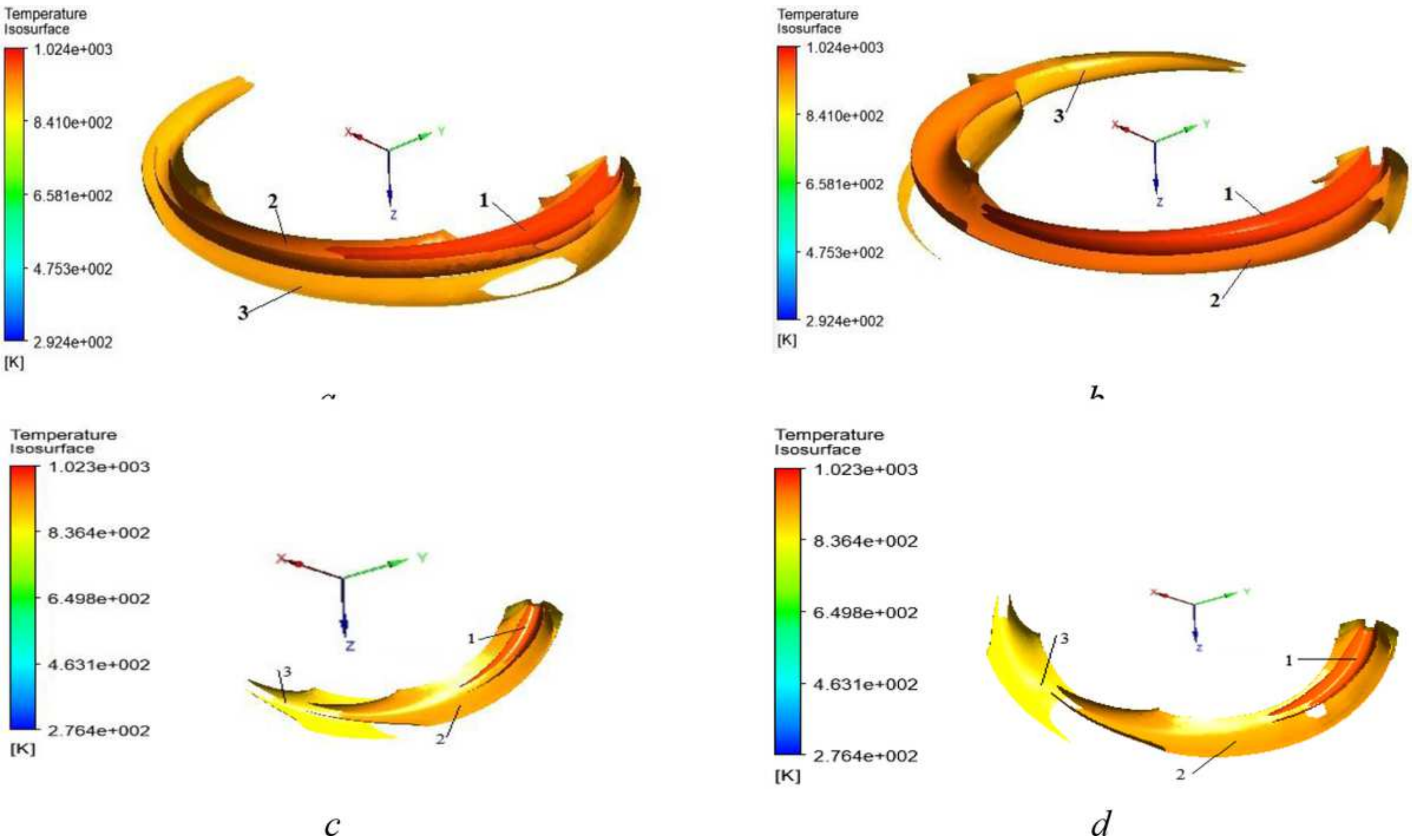

Figure 3

The values of the isotherms ti in the body of the mold in the transient thermal process at tp = 750 ºC: 1 – t1 = 700 ºC; 2 – t2 = 650 ºC; 3 – t3 = 600 ºC; a – τex = 320 s, wk = 3 rpm; b – τex = 840 s, wk = 3 rpm; c – τex = 320 s, wk = 1 rpm; d – τex = 840 s, wk = 1 rpm

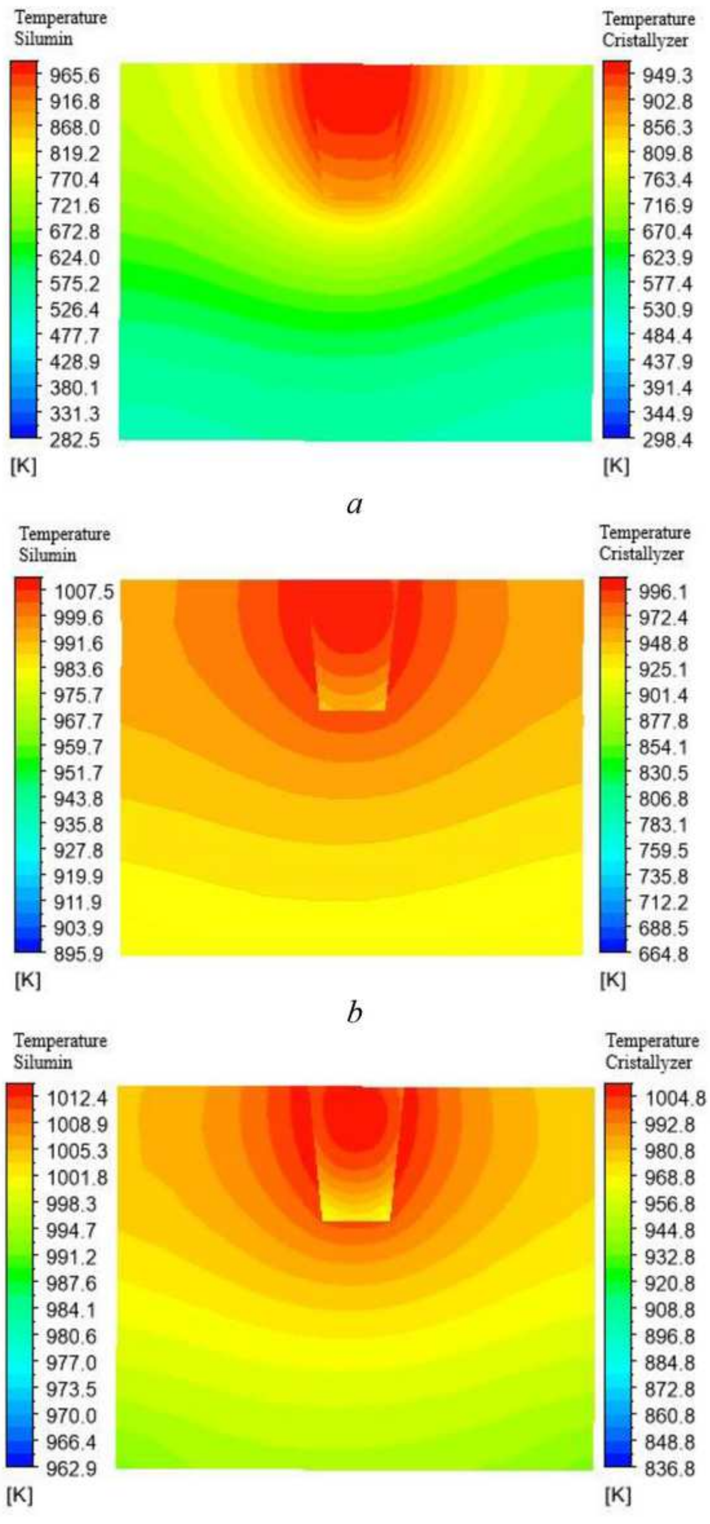

Figure 4

Temperature field (K) in the design section of the metal and the mold φ1 = 30° at tp = 750 °C, wk = 3 rpm: a – τex = 60 s; b – τex = 320 s; c – stationary thermal regime

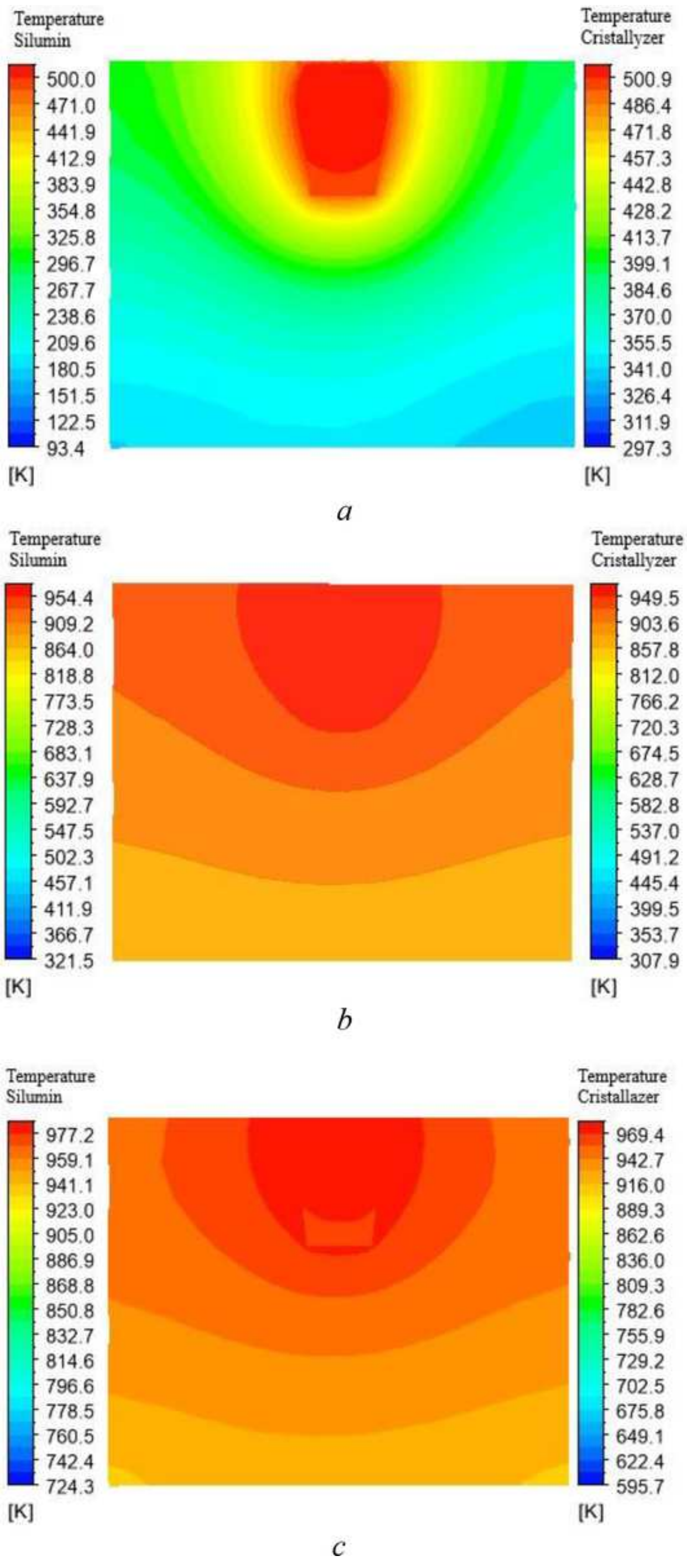

Figure 5

Temperature field (K) in the design section of the metal and the mold φ1 = 30° at tp = 750 °C, wk = 1 rpm: a – τex = 60 s; b – τex = 450 s; c – stationary thermal regime

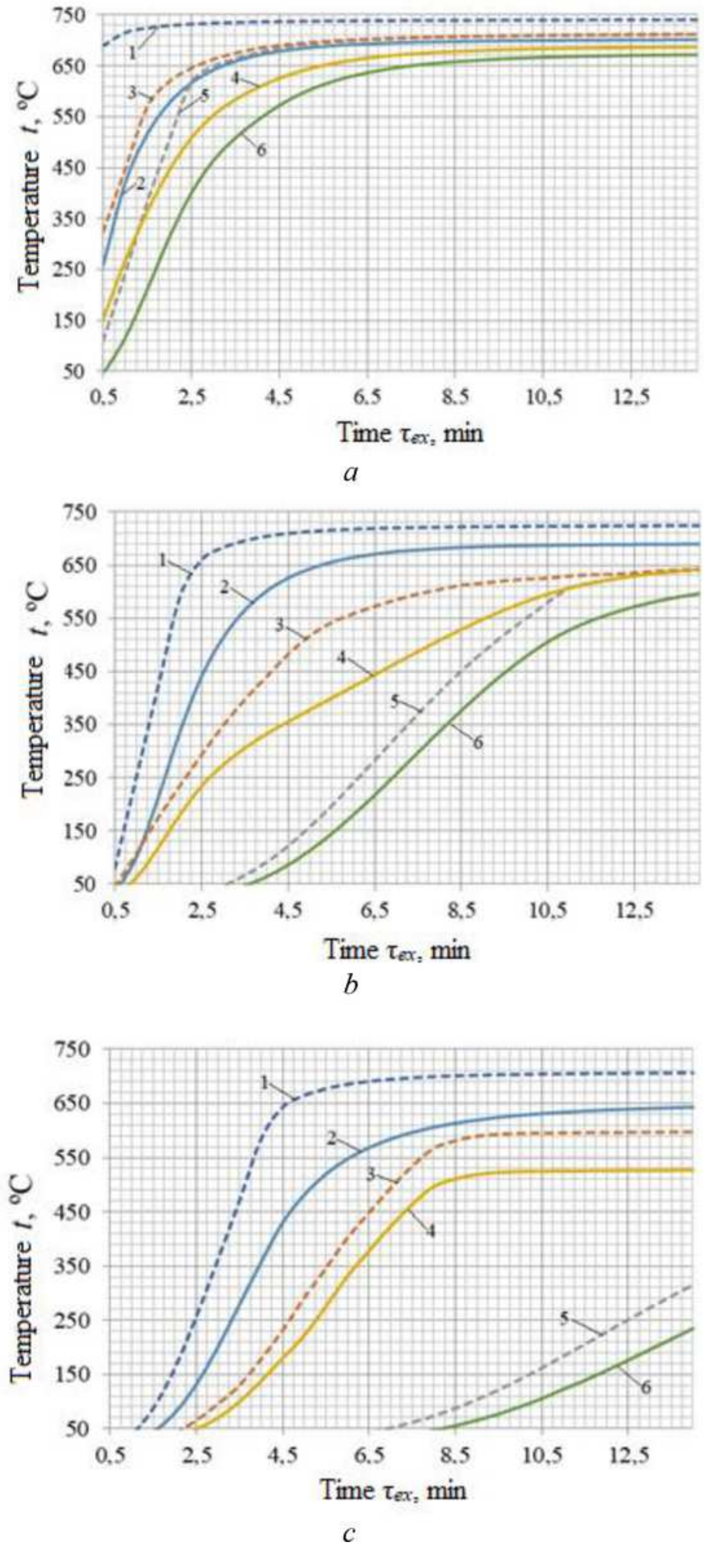

Figure 6

Temperature change in the body of the mold and metal in the design sections φi in transient thermal mode: 1, 2 – temperature of metal and mold at wk = 3 rpm; 3, 4 – temperature of metal and mold at wk = 2 rpm; 5, 6 – temperature of metal and mold at wk = 1 rpm; a – φ1 = 30º; b – φ2 = 120º; c – φ3 = 210º