Numerical analysis of the non-stationary thermal state of the tool in the combined casting and extrusion of aluminum alloy

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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 Horizontal mold · Aluminum alloy · Casting · Extrusion · Numerical model · Non-stationary heat transfer

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, 11] implementen 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 [12, 13]. 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 [14].

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 [15].

As studies of the methods of continuous extrusion of metals have shown [11, 16–24], 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 [11, 22–26]. 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 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 at angles \( \varphi_1 = 30^\circ \), \( \varphi_2 = 120^\circ \), and \( \varphi_3 = 210^\circ \) (Fig. 2). As can be seen, the central angles \( \varphi_i \) 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 \( \varphi \) reading is taken in a clockwise direction.

In accordance with the technological conditions in the control section \( \varphi_3 \), located at an angular distance \( \Delta \varphi = 15^\circ \) 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 \( 3–5^\circ \)C lower than the solidification temperature aluminum melt [35].

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.

To create a computational grid, the installation is divided into 8 domains: CORPUS, consisting of 181 088 elements; CRISTALLYZER, consisting of 1 899 260 items; INSULATOR, consisting of 38 217 elements; DIE, consisting of 1 074 651 elements and (GROOVE) — the area of the metal being processed, located under the arcuate segment (extrusion zone) and consisting of 185 461 items. The mesh size in the final calculation of the entire model was 3.7 million cells. The mesh is built automatically according to the following rules: between domains within the computational domain, the nodes are joined according to the “node-to-node” rule. The cell size inside the domains “GROOVE” and “GROOVE 2” containing the liquid phase is 0.8 mm. The parietal layer is placed using 10 cells at a distance of 2 mm from the wall with a growth factor of 1.2. The configuration of the grid inside the domain with the liquid phase was selected

The form of a press product. The supply of liquid metal into the groove, its solidification, and extrusion proceed in a continuous mode [27].

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].

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.
to be minimal. In other areas, the cell size is not fixed. On all surfaces, a boundary layer of three cells is set at a distance of 1 mm from the wall. In the domain of the mold, the mesh thickening is set at the point of contact with the metal being processed. Based on the resulting mesh model, a computational model is created by imposing boundary and initial conditions and parameters of the simulated processes and setting the solver settings.

The domain “GROOVE” and “GROOVE 2” are described using the model of an incompressible fluid; the system of Navier-Stokes equations for the laminar fluid flow and the heat conduction equation are solved. Moreover, in the volume of the “GROOVE 2” domain, the release of a volumetric heat source is set depending on the temperature of the alloy being processed (heat released from plastic deformation). On the surface of the “GROOVE 2” domain, a surface heat source is specified (heat released from friction against the walls of the mold and the arcuate segment).

The model additionally sets functions that determine the thermophysical characteristics of the processed melt depending on its current temperature: thermal conductivity, heat capacity, density, and surface tension coefficient. In this case, the functional dependence takes into account the change in the heat capacity and thermal conductivity of the melt during the release of the latent heat of its phase transformation.

The rotating mold transports the solidified melt to an arcuate segment with a die. To simulate this process, the rotation of the metal being processed is set in a computer model. In this case, the model of a movable wall is used, by taking into account in each wall cell, the velocity vector corresponding to the rate of rotation. For the crystallizer and the insulating layer, a velocity vector similar in magnitude and direction was set, thus simulating their rotation.

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:

$$\rho_i c_i \frac{DT_i}{d\tau} = \rho_i c_i T_i \frac{d}{d\tau} + \rho_i c_i \text{div}(w_i T_i) = \lambda_i \nabla^2 T_i + q_{vi} \quad (1)$$

where $T_i$ is the temperature field in the $i$th element; $\rho_i$, $c_i$, and $\lambda_i$ are the 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; and $q_{vi}$ is a function characterizing heat sources (internal heat release during phase transition and metal pressing) in the $i$th element [38]:

$$q_{vi} = S_{h'} + S_{h''} \quad (2)$$

where $S_{h'}$ is internal heat release during phase transition and $S_{h''}$ is 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:

$$\text{div} = \frac{\partial}{\partial R} + \frac{1}{R} \frac{\partial}{\partial \phi} + \frac{\partial}{\partial z} \quad (3)$$

$$\nabla^2 T_i = \left\{ \frac{\partial^2 T_i}{\partial R_i^2} + \frac{1}{R_i} \frac{\partial T_i}{\partial R_i} + \frac{1}{R_i^2} \frac{\partial^2 T_i}{\partial \phi_i^2} + \frac{\partial^2 T_i}{\partial z_i^2} \right\} \quad (4)$$
Equation (1) was supplemented by the boundary conditions:

\[ T_i = T_0 (r, \varphi, \tau = 0); \quad \frac{\partial T}{\partial n} |_{r_i} = \pm q_i \]

(5)

Here, \( q_i \) is the function characterizing the conditions of radiation-convective heat transfer at the boundary of the surface of the \( i \)-th element \( \Gamma_i \) \((q_i > 0)—heat \ flux \ is \ directed \ inside \ the \ element)\). In the boundary conditions (5), the angular velocity of movement of the installation elements \( \omega_i \) 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 \((\omega_i = 0)\). 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 \( w_c \).

In Eq. (2), the value of internal heat release during the phase transition \( S_h' \) is taken into account when solving the heat conduction equation in the domains “GROOVE” and “GROOVE 2”\); heat release from the forces of contact friction and deformation forces of the processed metal \( S_h' \) is taken into account when solving the heat conduction equation in domain “GROOVE 2”\).

In general, the value of \( S_h' \) is determined by the equation:

\[ S_h' = \int c_p(T) dT + L \]

(6)

In the model, the heat of solidification \( L \) was not taken into account separately, but was included in the value of the effective heat capacity. This value is a discontinuous energy characteristic of thermal processes with phase transitions, depending on the fraction of the solid phase in the crystallizing zone.

Heat release from the forces of contact friction and deformation forces of the processed metal \( S_h' \) was taken into account in the model by adding a volumetric heat source [10]:

\[ S_h'' = q_{fr} + q_d \]

(7)

Here, \( q_{fr} \) is the heat release from overcoming the forces of contact friction with the stationary tool and the walls of the mold (surface source of heat release); \( q_d \) is the heat release from the work of plastic deformation (volumetric source of heat release for extrusion with lateral outflow of the deformed metal). These values were determined by the following relationships:

\[ q_d = \sigma_s(T, \epsilon, \xi)(1, 45\lambda + 0, 8)b^2\lambda v_0 \]

(8)

\[ q_{fr} = 4b\sigma_s(T, \epsilon, \xi)\mu R\varphi v_0 \]

(9)

where \( \lambda \) is the draw ratio; \( b \) is the wheel groove width; \( v_0 \) is the speed of feeding the billet into the container; \( \sigma_s(T, \epsilon, \xi) \) is the resistance to deformation of the billet material; \( R \) is the average radius over the width of the mold wheel groove; and \( \mu \) is the coefficient of friction.

3 Results and discussion

A numerical study of the process of continuous combined casting-extrusion was carried out for the eutectic aluminum alloy A112Si with a melting (solidification) temperature of 853 K. 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 1023 K, the ambient temperature was 293 K.

In accordance with the specified value \( w_c \) and the dimensions of the section of the mold groove \( 10 \times 10 \) 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 Eq. (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.

Figure 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 973, 923 and 873 K, at \( T_p = 1023 \) K and the rotation speed of the mold wheel \( w_c = 1 \) and 3 rpm.

As can be seen, during the transient thermal process \( \tau_{ex} \), 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 \( T_1 = 973 \) K during periods of time \( \tau_{ex} = 320 \) and 840 s, at a mold rotation speed \( w_c = 3 \) 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 \( w_c = 1 \) rpm, the arc distance \( \Delta \varphi_{i} \) changes significantly and the length of the arc segments for the considered time periods \( \tau_{ex} \) 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 (\(\tau_{st}\)) 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 \(T_p = 1023\) K and \(G_p = 0.81\) kg/min (\(w_k = 3\) 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 (\(\varphi_1\)) \(\Delta T_k/\Delta \tau_{ex} = 15.3\) K/min and the maximum temperature gradient between the wall of the mold and the peripheral layer of the melt in the groove \(\text{grad} T_{mold} = 87\) K/mm (Fig. 4).

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 values of the parameters \(\Delta T_k/\Delta \tau_{ex}\) and \(\text{grad} T_{mold}\) noticeably decrease the values of which in the section \(\varphi_1\) are 4.78 K/min and 23 K/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 \(\varphi_1\) at \(w_k = 3\) rpm, the values and \(\Delta T_k/\Delta \tau_{ex}\) \(\text{grad} T_{mold}\) decrease to 4.5 K/min and 2.3 K/mm, respectively. At \(w_k = 1\) rpm, these values take the corresponding values of 1.82 K/min and 4.2 K/mm.

Figure 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 \(\varphi_i\) 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 increase in the design sections \(\varphi_i\) which is associated with an increase in the heat supplied to the casting-extrusion process with the poured melt.
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 $\phi_2$ and $\phi_3$ 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 $\phi_2$ and $\phi_3$, the region with the maximum temperature shifts towards their central part.

The results obtained in the numerical study of complex heat transfer in the unit (Fig. 6) are in good agreement with the experimental data. Thus, Table 1 shows the values of temperatures measured during the experiment on the surface of the mold. The temperature of the metal and the surface of the mold wheel were monitored with a Testo 835-T2 optical

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![Fig. 4](image_url) **Fig. 4** Temperature field (K) in the design section of the metal and the mold. $\varphi_1 = 30^\circ$ at $T_p = 1023$ K, $w_k = 3$ rpm: a $\tau_{ex} = 60$ s; b $\tau_{ex} = 320$ s; c stationary thermal regime

![Fig. 5](image_url) **Fig. 5** Temperature field (K) in the design section of the metal and the mold. $\varphi_1 = 30^\circ$ at $T_p = 1023$ K, $w_k = 1$ rpm: a $\tau_{ex} = 60$ s; b $\tau_{ex} = 450$ s; c stationary thermal regime
pyrometer. Operating parameters of the unit during the experiment: \( w_k = 2 \text{ rpm} \) \( T_p = 1023 \text{ K} \). In each section, measurements were made near the groove of the mold wheel. The discrepancy in the measured points was no more than 10%, which confirms the adequacy of the computer model and the possibility of working out engineering solutions on it.

It should be noted that at \( w_k \leq 1.75 \text{ rpm} \), the design of the installation upon reaching a stationary thermal regime provides in the third control section \( \varphi_3 \) 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.

#### Author contribution

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

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Declarations

Ethical approval  The work contains no libelous or unlawful statements and 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.

Competing interests  The authors declare no competing interests.

Data availability  Not applicable.

References

1. de Sousa Rocha JR, de Souza EEB, Marcondes F, de Castro JA (2019) Modeling and computational simulation of fluid flow, heat transfer and inclusions trajectories in a tundish of a steel continuous casting machine. J Mater Res Technol 8(5):4209–4220. https://doi.org/10.1016/j.jmrt.2019.07.029
2. Jiang Y, Miao J, Luo AA (2019) Microstructure and mechanical property evolutions of CuNi10Fe1.8Mn1 alloy tube produced by HCCM horizontal continuous casting during drawing and its deformation mechanism. J Alloys Compd 771:905–913. https://doi.org/10.1016/j.jallcom.2018.09.041
3. Reznik PL, Ovsyannikov BV (2020) Influence of homogenization heat treatment and cooling modes on microstructure of AA7475 aluminum alloy ingot. Mater Sci Forum 989:335–340. https://doi.org/10.4028/www.scientific.net/MSF.989.335
4. Wang F, Ma Q, Meng W, Han Z (2017) Experimental study on the heat transfer behavior and contact pressure at the casting-mold interface in squeeze casting of aluminum alloy. Int J Heat Mass Transf 112:1032–1043. https://doi.org/10.1016/j.ijheatmasstransfer.2017.05.051
5. Luo Y, Zhang Z (2019) Numerical modeling of annular electromagnetic stirring with intercooling in direct chill casting of 7005 aluminum alloy billet. Progress in Natural Science: Materials International 29(1):81–87. https://doi.org/10.1016/j.pnsc.2019.01.007
6. Garg P, Jamwal A, Kumar D, Sadasivuni KK, Hussain CM, Gupta P (2019) Advance research progresses in aluminium matrixcomposites: manufacturing & applications. J Mater Res Technol 8(5):4924–4939. https://doi.org/10.1016/j.jmrt.2019.06.028
7. Cheng G, Lu Y, Cinklic E, Miao J, Luo AA (2019) Predicting grain structure in high pressure die casting of aluminum alloys: a coupled cellular automaton and process model. Comput Mater Sci 161:64–75. https://doi.org/10.1016/j.commatsci.2019.01.029
8. Dong X, Yang H, Zhu X, Ji S (2019) High strength and ductility aluminum alloy processed by high pressure die casting. J Alloys Compd 773:86–96. https://doi.org/10.1016/j.jallcom.2018.09.260
9. Kryukov IY, Naumova MG, Vdovin KN, Larina TP (2016) Development of mathematical model of thermal state of crystallizing blank rectangular in shape in horizontal semi-continuous casting machine. Fundamental Research 10(2):306–311. https://www.fundamental-research.ru/en/article/view?id=40850. Accessed 23 Jun 2021
10. Dovzenko NN, Sidelnikov SB, Belyaev SV, Soldatov SV, Bespalov VM, Leonov VV (2012) Improvement of construction of the pilot industrial plant SLIPP-2.5. J Sib Fed Univ Eng Technol 5(7):817–828. http://elib.sfu-kras.ru/bitstream/handle/2311/9537/16_Dovzenko.pdf;jsessionid=3650F3307F3529545C5A309BCEAAE91C?sequence=1. Accessed 23 Jun 2021
11. Sidelnikov SB, Galiev RI, Bersenev AS, Voroshilov DS (2018) Application and research twin roll casting-extruding process for production longish deformed semi-finished products from aluminum alloys. Mater Sci Forum 918:13–20. https://doi.org/10.4028/www.scientific.net/MSF.918.13
12. Rappaz M, Jarry P, Kurtuldu G, Zollinger J (2020) Solidification of metallic alloys: does the structure of the liquid matter? Metallurgical and materials transactions a: physical metallurgy and materials science 51:2621–2664. https://doi.org/10.1007/s11661-020-05770-9
13. Jarry P, Rappaz M (2018) Recent advances in the metallurgy of aluminum alloys. Part I: solidification and casting | Développements récents en métallurgie des alliages d'aluminium. Première partie : coulée et solidification. Comptes Rendus Physique 19(8):672–687. https://doi.org/10.1016/j.crhy.2018.09.003
14. Niinomi M (2019) Casting. Metals for biomedical devices (Second edition), 2019, 311–330. https://doi.org/10.1016/B978-0-08-102666-3.00011-0
15. Jensrud O (2012) High strength aluminium alloys extrusions - a review of the thermo-mechanical-process in high performance profile manufacturing. Key Eng Mater 491:11–18. https://doi.org/10.4028/www.scientific.net/KEM.491.11
16. Yun X-B, Yao M-L, Wu Y, Song B-Y (2011) Numerical simulation of continuous extrusion extending forming under the large expansion ratio for copper strip. Appl Mech Mater 80-81:91–95. https://doi.org/10.4028/www.scientific.net/AMM.80-81.91
17. Mitka M, Gawlik M, Bigaj M, Szymanski W (2014) Continuous rotary extrusion (CRE) of flat sections from 6063 alloy. Key Eng Mater 641:183–189. https://doi.org/10.4028/www.scientific.net/KEM.641.183
18. Popescu IN, Bratu V, Rosso M, Popescu C, Stoian EV (2013) Designing and continuous extrusion forming of Al-Mg-Si contact lines for electric railway. J Optoelectron Adv Mater 15(7-8):712–717
19. Zhao Y, Song B-Y, Yun X-B, Pei J-Y, Jia C-B, Yan Z-Y (2012) Effect of process parameters on sheath forming of continuous extrusion sheathing of aluminum. Transactions of Nonferrous Metals Society of China (English Edition) 22(12):3073–3080. https://doi.org/10.1016/S1003-6326(11)61573-2
20. Zhao D, Lü S, Li J, Guo W, Wu S (2021) A novel continuous squeeze casting-extrusion process for grain refinement and property improvement in AZ31 alloy. Mater Sci Eng A 808:140942. https://doi.org/10.1016/j.msea.2021.140942
21. Fastikovskiy AR, Selivanova EV, Fedorov AA, Peretyatko VN, Evtushee B, Efimov OY (2018) Improvement of continuous forming the “Conform” method. IOP Conference Series: Materials Science and Engineering 411(1):012082. https://doi.org/10.1088/1757-899X/411/1/012082
22. Ji C, Huang H (2020) A review of the twin-roll casting process for complex section products. ISIJ Int 60(10):2165–2175 https://www.jstage.jst.go.jp/article/isijinternational/60/10/60_ISIJINT-2020-149_article. Accessed 23 Jun 2021
23. Sidelnikov S, Sokolov R, Voroshilov D, Motkov M, Bespalov V, Voroshilova M, Sokolova S, Rudnitskiy E, Lebedeva O, Borisuk V (2020) Modeling the process of obtaining bars from aluminum alloy 0147 by combined rolling-extruding method with application of the deform-3D complex. Key Eng Mater 861:540–546. https://doi.org/10.4028/www.scientific.net/KEM.861.540
24. Sidelnikov SB, Voroshilov DS, Pervukhin MV, Motkov MM (2019) Development and research of technology for producing electrotechnical wire from alloys of the Al–REM system, obtained with the application of combined machining methods. Tsvetnye metally 9:63–68. https://www.rudmet.ru/journal/1853/article/31547/. Accessed 23 Jun 2021

25. Gorokhov YV, Belyaev SV, Uskov IV, Konstantinov IL, Gubanov IY, Gorokhova TY, Hamtsov PA (2017) Application of combined casting–pressing for the fabrication of aluminum wire for soldering waveguides. Russ J Non-ferrous Metals 58(1):75–79. https://doi.org/10.3103/S1067821217010059

26. Zhang X, Guan R, Cui T, Zhou T (2011) Microstructure and mechanical properties of Al-Mg-Sc alloy processed by semi-solid continuous casting-extrusion. Adv Mater Res 299–300:139–142. https://doi.org/10.4028/www.scientific.net/AMR.299-300.139

27. Skuratov AP, Gorokhov YV, Potapenko AS, Belyaev SV, Gubanov IY, Ivanov AG (2018) Thermal control device for continuous casting and pressing of non-ferrous metals and alloys: Pat. 2657396 (RF)

28. Potapenko AS, Skuratov AP, Gorokhov YV (2017) Aluminum alloy solidification dynamics under transient heat mode of continuous casting and moulding equipment. Proceedings of Irkutsk State Technical University, 2017, 21(7), 109–118. http://journals.istu.edu/vestnik_irstu/journals/2017/07/articles/10. Accessed 23 Jun 2021

29. Skuratov AP, Potapenko AS, Gorokhov YV (2017) The research of thermal operations in the equipment of continual casting & aluminun extrusion in transitional mode. Journal of Siberian Federal University Engineering & Technologies 10(3):337–345/ http://elib.sfu-kras.ru/bitstream/handle/2311/32627/05_Skratov.pdf?sequence=1. Accessed 23 Jun 2021

30. Skuratov AP, Potapenko AS, Gorokhov YV, Popiyakova NP (2019) Numerical Investigation into the influence of overheating of aluminum melt on the heat exchange in the continuous combined casting and pressing. Russ J Non-ferrous Metals 60(3):225–231. https://doi.org/10.3103/S1067821219030143

31. Gorokhov YV, Skuratov AP, Belyaev SV, Gubanov IY, Uskov IV, Lesiv EM, Ivanov AG, Kirtk VI, Koptseva NP, Potapenko AS (2017) Analysis of combined metal casting thermal conditions: the pressing process during conform installation. ARPN Journal of Engineering and Applied Sciences 12(16):4742–4746 http://www.arpnjournals.org/jeas/research_papers/rp_2017/jeas_0817_6269.pdf. Accessed 23 Jun 2021

32. Stetsenko VY (2013) Mechanisms of the crystallization process of metals and alloys. Casting and Metallurgy 1:48–54

33. Semashko MY, Chigintsev PA (2016) A comprehensive study of the process of severe plastic deformation of aluminum alloy. Bulletin of the South Urals State University Ser Metallurgy 16(2):63–67. (in Russ.) https://doi.org/10.14529/met160209

34. Fomina EE, Zhiganov NK (2016) A modification of the simpler algorithm for solving the problem of modeling the process of continuous casting of non-ferrous metals. The Bulletin of Voronezh State Technical University 12(1):32–35 https://cchgeu.ru/science-nauchnye-izdaniya/vestnik-voronezhskogo-gosudarstvennogo-teknicheskogo-universiteta/-fayly/vypuski/12_1.pdf. Accessed 23 Jun 2021

35. Minakov AV, Pervukhin MV, Platonov DV, Khatsayuk MY (2015) Mathematical model and numerical simulation of aluminum casting and solidification in magnetic fields with allowance for free surface dynamics. Comput Math Math Phys 2066–2079:55. https://doi.org/10.1134/S096554251512009X

36. Torgovets AK, Pikalova IA, Yusupova YS (2016) Simulation in continuous casting processes. Karaganda State Industrial University 6(28):88–95

37. Ershov AA, Loginov YN (2018) Simulation of the conform-type pressing process by using the QFORM VX software complex. Metallurgist 62(3-4):207–211. https://doi.org/10.1007/s11015-018-0646-6

38. Gorokhov YV, Sherkunov VG, Dovzhenko NN et al (2013) Fundamentals of designing processes for continuous extrusion of metals: monograph. Krasnoyarsk: SibFU

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