Influence of temperature regime of the combined process of casting and rolling of strips from high-alloy aluminium alloys

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In aluminum foil production, challenges arise in the real-time monitoring and control of technological parameters and temperature control during casting and rolling, leading to significant raw material and energy losses. Malfunctions and disruptions in the thermal conditions of the caster-roller cause a reduction in continuous casting billet quality. This paper proposes elements of a specialized system for data analysis and process monitoring of continuous casting for high-strength aluminum alloys grades 8011 and 8006, presented as a universal architecture of the industrial process based on the thermal field modeling of caster-rollers. Existing automated control systems for continuous casting of aluminum strips either lack the appropriate software or rely heavily on imported solutions. This study lays the groundwork for developing an automated control system for the continuous casting. Initial matrices were obtained to build a mathematical model of strip deformation in the “metal-roller” contact zone and the “bushing-roller” zone, based on the thermal field data for caster-rollers during the casting and rolling of aluminum alloys 8011 and 8006. The research results and proposed approaches will be beneficial for practical applications in industry and for use in other secondary metallurgy processes, including aluminum foil production in Vietnam.

Key words: aluminum foil, continuous casting-direct rolling process, twin-roll casting, parameter control, temperature field, casting and rolling

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Introduction

Issues of energy and resource conservation in the mineral and raw materials sector are of primary importance for any country [1, 2]. In this regard, efficient process management through high-tech equipment and instrumentation determines the further development of the national economy [3, 4]. In the production of metals and high-tech products under multi-stage process management, new automated control systems are essential [5, 6]. In aluminum foil production, particularly in the manufacture of billets during continuous casting-direct rolling process (CC-DR) on twin-roll casting units, much identical equipment is used, necessitating sequential and ongoing control and regulation of technological parameters along the production line [7, 8]. Challenges in the automated control of the thermal regime in continuous rolling of high-alloy aluminum strips stem from inadequate thermal field monitoring of crystallizer rollers, currently performed intermittently via manual contact thermocouple measurements. Discrepancies (such as melt overheating or partial crystallization) across all stages of the technological process are not accounted for. Thus, in the manufacturing of products in high-temperature, chemically aggressive environments associated with duplex and triplex processes integrated into the equipment’s technological chain, real-time monitoring of technological parameters is complicated, leading to substantial losses of raw materials and energy [9, 10]. Continuous thermal regime control, particularly in the casting and rolling area (within the crystallizer rollers gap) while considering the specific aluminum alloy being cast, is of scientific and practical interest.

Vietnam’s secondary metallurgy industry is currently expanding. For improved product quality from alloyed scrap and metallized waste, stricter control over melt preparation parameters for casting is necessary [11, 12]. Modern Vietnamese aluminum foil manufacturing focuses on producing finished products from high-alloy aluminum alloys using a combined casting and rolling method. However, difficulties in process and thermal regime control have arisen with this shift. Existing technologies exhibit specific shortcomings, in particularly regarding parameter monitoring and control [13, 14]. Several studies propose advanced solutions to this problem by collecting additional informational process parameters [15–18]. The development of a comprehensive, multi-level automation system for reliable temperature regime control, facilitating effective management of continuous rolling (CR) process for aluminum strips – a combined casting and rolling process – is scientifically and practically relevant [19, 20]. The model serves as the foundation for creating a database for a digital twin with temperature control at all stages of foil billet production. This approach allows to create a predictive model for technological conditions during alloy transitions in casting and rolling, enabling temperature adjustments when changing the melt's chemical composition within the crystallizer rollers gap. The proposed thermal field control system can be implemented in the computer-aided process control system (CAPCS) of the VIET NHAT plant — Cau Kien Industrial Park, Hai Phong, Vietnam, where a control system is practically absent, and measurements are taken manually at intervals after the metal is poured into the mixer using contact thermocouples.

Thermal regime calculations for continuous rolling

The productivity of CR units and the speed parameters of the continuous rolling process are determined by the thermophysical properties of the metal, the material of the stamp rolls, or the cooling system [21, 22]. Other parameters, such as strip compression ratio, pressure, and roll surface temperature in the deformation zone, are considered dependent variables [23, 24].

Improving existing and developing new units requires precise selection of design parameters and operating modes to ensure efficient heat transfer, optimal casting speed, and high-quality billets [25, 26]. Such selection is possible through the use of mathematical process models. Successfully addressing this task requires a comprehensive set of studies:

– development of mathematical models of thermal fields in crystallizer rollers;

– examination of the energy characteristics of the equipment;

– carrying out modelling of the process to identify the most promising improvements for CR units.

The crystallization mode of the billet in the active casting and rolling zone of the aluminum strip, as well as the required mechanical properties of the strip, are defined by mathematical models of the temperature field in the cast strip and crystallizer rollers [27, 28]. The strip's temperature field is formed using a general thermal balance model and experimental data obtained by freezing thermocouples under known boundary conditions in the "melt-roll" contact zone.

Experimental methodology

The experiment's methodology was as follows. The temperature across the section of the crystallizing strip was measured using chromel-alumel thermocouples with electrode diameters of 1.2 mm, protected by asbestos sheaths. These thermocouples were placed in open slots of the casting nozzle at intervals of 45–50 mm, allowing precise temperature measurements at various points along the strip. One thermocouple was positioned in the central part of the nozzle, while others were placed 1–8 mm from the nozzle edge. This distribution of thermocouples provided temperature data both at the center and along the edges of the strip, which is essential for understanding crystallization uniformity. The thermocouple length from the junction to the plane of the crystallizer rolls was 160 mm, ensuring sufficient length for accurate temperature measurement in the crystallization zone. During the casting process, the thermocouples were embedded in the metal, enabling the capture of temperature changes over time. The cold ends of the thermocouples were isolated and connected to a high-speed potentiometer KSP-4. Measurement accuracy was ±5 °C, which is a relatively high precision for such processes.

The obtained data allowed determination of the cast strip's temperature field and the depth of the liquid phase at the initial casting moment. This information is crucial for ensuring the final product's quality, as it provides insight into temperature distribution across the strip and enables process adjustments to achieve optimal crystallization conditions. The temperature of the crystallizer roller surfaces at various points was measured using contact thermocouples. Roll temperature control is essential, as excessive or insufficient temperature can adversely affect the crystallization process and strip quality. Contact thermocouples provided precise data on the roll surface temperature, enabling timely process adjustments.

The combination of these measurements creates a detailed picture of the temperature field during the combined casting and rolling process. Understanding the temperature distribution and its dynamics over time enhances control over the melt casting and rolling process, ensures uniform cooling and metal crystallization in the roller gap, and prevents billet defects. Complex measurement methods allow process optimization to achieve the desired mechanical and physical properties of aluminum strips.

The phenomenon of rolling ahead of the solidified part of the billet in the deformation zone, as well as changes in the cross-section of the cast strip, affected the temperature field. The thermal conductivity of the band material causes heat transfer along the strip axis and around the roller circumference. Due to the predominant heat transfer through thermal conductivity, the problem can be considered in a one-dimensional formulation. The need to solve problems using nonlinear equations arises from the complex shape of the cast strip in the active heat exchange zone, as well as the presence of phase transitions involving the release of latent crystallization heat.

Fig. 1 presents the coordinate schemes for discretizing the problem used in the combined casting and rolling process. One of the key features of this process is

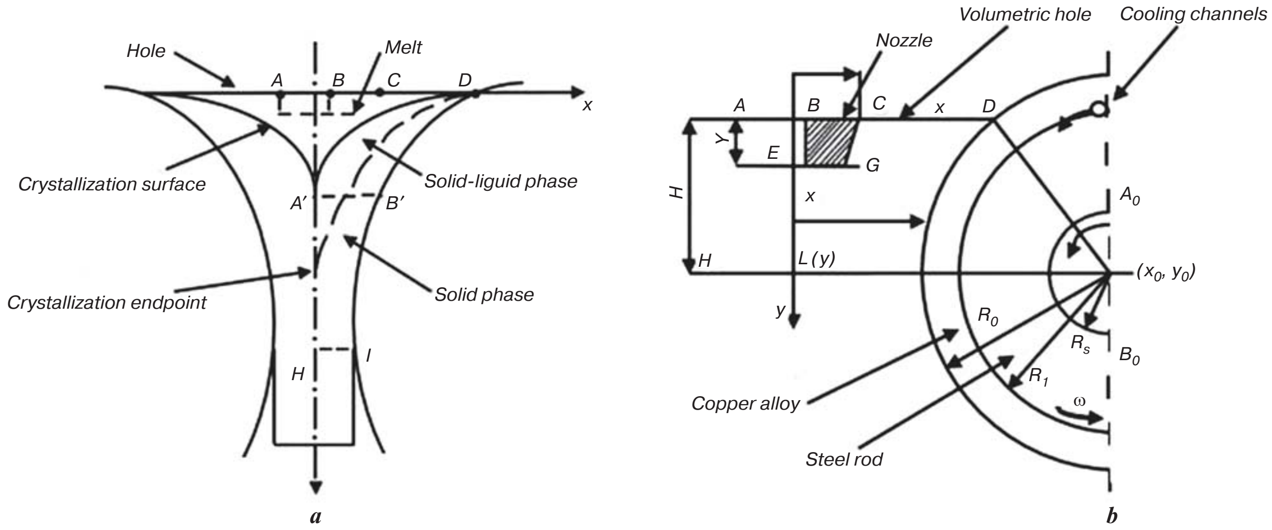

Fig. 1. Coordinate schemes in the strip deformation area:
a – "metal-roller" contact zone; *b* – "nozzle-roll" contact zone (*compiled by the authors*)

the similarity of dimensionless fields for like quantities, meaning that the absolute values of these quantities differ only in scale. In other words, in two analogous processes, values of like quantities at certain points in space and time differ by a constant factor. The complexity of this task lies in the need to account for the sharp changes in the temperature field in the active zone, caused by the change in strip geometry. In the active zone, where metal crystallization and deformation occur, the temperature field undergoes the most significant changes. These changes are associated with the non-uniform cooling of the strip and the complex dynamics of heat transfer between the metal and the crystallizer rollers. Temperature gradients in this zone can be very high, requiring precise modeling and control.

Accounting for discrepancies from thermal field equilibrium is another important aspect. In real conditions, heat transfer is uneven due to various factors, such as cooling rate, thermal conductivity of the material, and heat exchange conditions at the metal-roll interface. These factors can significantly affect the crystallization process and the subsequent deformation of the metal. Heat transfer conditions in different process zones also play a crucial role. In the crystallization zone, where the metal transitions from a liquid to a solid state, heat transfer is intense. In the deformation zone, where the already solidified metal is rolled, heat transfer is also important but has a different nature due to plastic deformation and friction. Accounting for these differences is necessary for precise process modeling and achieving optimal casting and rolling conditions.

Plastic deformation with changes in the geometric dimensions of the casting also is yet another critical aspect. During rolling, the metal undergoes significant mechanical loads, leading to changes in its structural geometry. Similarity criteria can be used to assess and optimize these complex processes.

The Nusselt criterion (*Nu*) is used to assess heat transfer in the active zone within the crystallizer roller gap:

$$Nu = \frac{l \cdot \alpha_T}{\lambda} \qquad (1)$$

where: l – characteristic length, m; α_T – heat transfer coefficient, W/(m^2·K); λ – thermal conductivity coefficient, W/(m·K).

The Prandtl-Reuss flow equation evaluates plastic and elastic deformations during the combined casting and rolling process:

$$\varepsilon_\chi = \frac{3}{2}\frac{\varepsilon_e}{\sigma_e}(\sigma_\chi - \sigma_0) \qquad (2)$$

where: ε_χ – deformation rate along the axis; ε_e – deformation intensity; σ_e – stress intensity; σ_χ – normal stress; σ_0 – yield stress.

Turbulent flow in the mold arises from the penetration of various spectra of pulsations from the melt flow region. Turbulent transport in the viscous layer is characterized by the Prandtl similarity criterion Pr. Reynolds determined that the transition of the liquid flow regime occurs at a specific value of the Reynolds criterion *Re*. When the stability of the melt flow is disrupted, the critical Reynolds number becomes key.

External influences on the liquid and solidifying metal significantly impact the casting process's efficiency [29]. Modern foil production methods are highly complex and require significant time and material costs, often resulting in metal losses and insufficient product quality. During strip formation on the CR unit, various thermal processes occur, including metal movement inside the gating system, the formation of turbulent and convective flows in the gap between crystallizer rollers, both contact and non-contact heat exchange, supercooling of the melt, crystal formation and growth, impurity diffusion, formation of new phases and non-metallic inclusions, as well as shrinkage [30, 31]. These processes usually occur under the influence of gravity alone. In the future development of the twin-roll casting method, the focus is on the use of thermal-force effects, such as pressure, electromagnetic fields, vibration, and others. The following aspects are important to consider:

– when increasing external pressure on the melt within the gating system, cavitation phenomena in the stirred metal are absent;

– modification of the metal feed scheme to the nozzle will influence the level of turbulent mixing of the metal in the roll gap;

– applying vibration combined with an effective cooling system in a special reservoir enhances the intensity of convective heat exchange and changes the parameters;

– the intensity of the impurity redistribution process during alloy crystallization can be controlled by adjusting the diffusion boundary layer thickness;

– the crystallization rate can be increased by enhancing the temperature gradient at the solidification boundary, which is due to the influence of vibration and melt stirring;

– the shape and placement of dendrites in the structure depend on various factors, including the thickness of the diffusion boundary layer, the direction of convective flow, heat dissipation, and the influence of gravitational or external forces. If gravitational effects are not considered, the alloy crystallization process is determined by the surface tension effect of the melt;

– control over the purity of interdendritic spaces from liquating impurities is achieved by increasing the metal feed rate and creating negative pressure at the alloy solidification boundary;

– applying vibration improves the casting density, flowability, and crack resistance, while also reducing shrinkage defects and the reject rate;

– regulating the melt flow rate along the solidification boundary allows to control over the crystallization rate and the orientation angle of dendrites in the casting;

– for achieving higher quenching pressures necessary for crystal fragmentation and forming additional crystallization centers, degassing and refining processes of treated alloys are used. Additionally, applying vibration within the temperature range between the liquidus and solidus helps reduce the alloy crystallization time;

– stirring during inert gas purging (argon) enhances heat transfer, promoting faster crystallization, structure refinement, and reducing the tendency toward physical heterogeneity.

Plane-strain condition models are often used to calculate various metal processing processes [32, 33]. This model includes the equilibrium equation for plasticity conditions, incompressibility conditions, and the relationship between stresses and displacements [34, 35]. At the "melt-nozzle-roller" contact point, the following mathematical equations can be formulated.

Position of entry contact point of crystallizer rollers [HI]:

$$u = 0,\ v = v_{in},\ dT/dy = 0 \tag{3}$$

Position of distribution nozzle contact with crystallizer rolls [AB], [EG], [CG]:

$$u = 0,\ v = v_m,\ T = T_m \text{ in } \overline{\mathrm{AB}} \tag{4}$$

$$u = v = 0,\ T = T_m \text{ in } \overline{\mathrm{EG}} \tag{5}$$

$$u = v = 0,\ T = T_m \text{ in } \overline{\mathrm{CG}} \tag{6}$$

where: T_m – melt temperature, °C.

Position of melt pool contact [CD]:

$$du/dy = 0,\ v = 0,\ dT/dy = 0 \tag{7}$$

where: u – horizontal distance from the central roll axis to the entry contact point, mm; v – vertical distance from the baseline to the entry contact point, mm.

Contact zone between melt pool and roll surface [DI]:

$$u = (y - y_0)\omega,\ v = -(x - x_0)\omega \tag{8}$$

$$-k\frac{dT}{dn} = h_c(T - T_c) \tag{9}$$

where: k – thermal conductivity of roll material, W/(m·K); h_c – heat transfer coefficient, W/(m^2·K); T_c – roller surface temperature in the contact zone with the melt, °C; ω – roller rotation speed, rpm.

The control modes and settings in a CR unit affect the rotation speed of the crystallizer rollers. Roll advance plays a key role in these calculations, as it defines the boundary conditions in the contact zone. The heat transfer coefficient h_c reflects changes in thermal conditions in this zone and it is used in the respective calculations. The melt temperature during casting and rolling of alloy 8011 is 690 °C, and for alloy 8006, it is 710 °C. The water temperature in the roll core channels of the crystallizer remains constant at both the inlet and outlet, with a balanced input and output of thermal energy.

The application of radial and convective cooling conditions to estimate the temperature of rollers surfaces that do not come into contact with the melt is expressed as follows:

$$-k\frac{dT}{dn} = h_w(T - T_w) \tag{10}$$

$$dT/dn = 0,\ 0 \le \varphi \le 2\pi \tag{11}$$

where: T_w – temperature of the rollers surfaces, °C; n – normal to the contact surface; h_w – heat transfer coefficient from the rollers, W/(m^2·K).

Thermal changes within the roll are expressed as follows:

$$-kr\frac{dT}{dn} = h_c(T - T_x) + h_r \tag{12}$$

$$(T - T_x),\ \pi/2 \le \varphi \le (\pi - \varphi_1) \tag{13}$$

where: r – roll diameter, m; φ – roll tilt angle relative to the horizon, degrees; h_r – heat dissipation coefficient during roll rotation, W/(m^2·K).

The roll surface temperature in the contact zone with the melt in the mold is calculated by the following relation:

$$-k\frac{dT}{dn} = h_c(T_c - T),\ (\varphi_1 \le \varphi \le \pi/2) \tag{14}$$

In the roll contact zone with the melt, the water cooling flow can be considered turbulent. This allows an evaluation of how water exchanges heat with the melt in the flow, using the heat transfer coefficient (J).

The relationship between the similarity criterion *Nu* and the heat transfer coefficient is expressed as follows:

$$Nu = \frac{(f/8)RePr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)} = \frac{h_w D_w}{k_w} \tag{15}$$

$$f = (1.821\log_{10}Re - 1.64)^{-2} \tag{16}$$

$$Re = \rho_w U D_h/\mu_w \tag{17}$$

$$Pr = \mu_w C_w/k_w \tag{18}$$

where: D_w – characteristic length size, m; k_w – thermal conductivity of the melt, W/(m · K); Pr – Prandtl number; f – hydraulic friction coefficient; U – characteristic speed, m/s; D_h – hydraulic diameter, m; C_w – specific heat capacity of the medium, J/(kg · K); μ_w – dynamic viscosity of the medium, kg/(m · s); ρ_w – density of the medium, kg/m^3; Re – Reynolds number.

Measurement results of temperature fields

Fig. 2 shows the temperature field of crystallizer rolls, constructed based on practical measurement results taken directly during the casting and rolling of aluminum alloys 8011 and 8006. These results were obtained by measuring with contact thermocouples and by freezing thermocouples into the gap between the rollers before stopping the unit after a batch of billets.

In solving these problems, it is essential to consider the sharp temperature field variations caused by melting temperature changes, alloy type, and strip shape changes in the active zone of the crystallizer rollers. To account for these changes, attention should be paid to the following aspects:

– in fully solidified sections, deformation spreads evenly across the entire height of the section, accompanied by corresponding changes in the temperature field;

– in sections of the semi-solid phase, deformation occurs exclusively due to the extrusion of the liquid phase, while maintaining a constant shell thickness;

– the rolling process is characterized by slippage between the strip and roller surfaces, which appears after crystallization completes at point A. This is considered by introducing a variable speed ω_x determined by the constant volume flow rate law, allowing for both geometric and temporal characteristics of the deformation zone.

To improve the temperature field model and evaluate changes in related quantities at several control points,

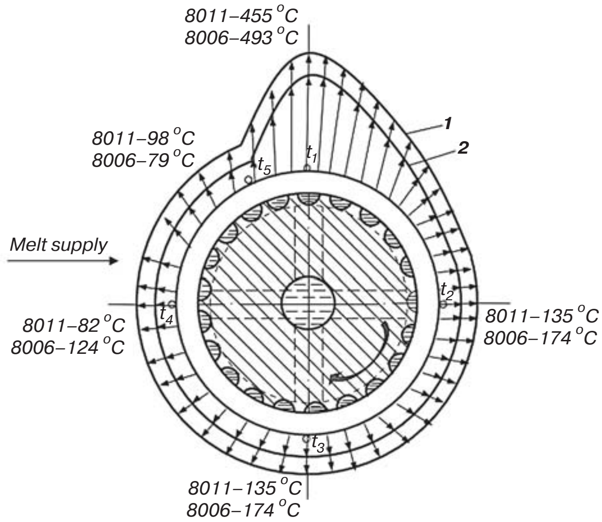

Fig. 2. Temperature fields of crystallizer rollers for aluminum alloys: *1* – for alloy 8011; *2* – for alloy 8006 (compiled by the authors)

a comparison of calculated and experimental temperature data was conducted. This was done within the combined casting and rolling process using alloys 8011 and 8006.

Through mathematical process modeling on CR unit equipment, temperature fields for both the strip and the crystallizer roll's jacket can be obtained for various combinations of technological and design parameters. When analyzing the change in jacket surface temperature throughout a single roll rotation, the following features can be distinguished:

– when in contact with the melt, the roll surface temperature peaks between 475–510 °C;

– after rotating 90°, the temperature drops to 130–155 °C;

– at the point where contact with the gating system begins, the minimum temperature is recorded, ranging from 95–135 °C.

The temperature field changing are influenced by various factors, such as process temperature, thermal properties of the roll jacket material, alloy characteristics (including crystallization range), cooling system, and the design and diameter of the rolls. In the CC-DR process, heat exchange parameters depend on multiple factors, including billet thickness, crystal structure, surface quality, defect presence, and process stability [36, 37].

In continuous rolling, it is necessary to control metal overheating, especially for aluminum alloys, where this parameter is limited to a range of 15–35 °C. In the quasi-stationary casting mode, the crystallizer roll surface temperature is maintained in the range of 65–110 °C before immersion in the melt. When the temperature falls below 65 °C, billet formation becomes difficult, and the casting process becomes unstable. Typically, the strip temperature as it exits the crystallizer rolls corresponds to the solidus temperature.

Proper selection of technological and design parameters in the combined casting and rolling process significantly enhances the thermal properties of roll jackets. This leads to improved quality of the foil billet and a substantial increase in the productivity of continuous rolling units. The complex processes of heat transfer and deformation are multidimensional, necessitating a deeper analysis of nonlinear effects using three-dimensional modeling methods to comprehensively account for the factors affecting temperature field changes. In this context, the obtained data can be adapted with the results of finite element analysis (FEA) modeling of similar processes under equal conditions in modern simulation software such as ANSYS.

Conclusion

Modern casting and rolling technologies for aluminum alloys, especially in high-temperature and chemically aggressive environments, face challenges in real-time monitoring of technological parameters, leading to significant losses of raw materials and energy. Accurate calculations and thermal field models, as well as the temperature regime in continuous rolling, enable improvements to existing units and the development of new ones, providing efficient heat exchange, optimal casting speed, and high quality of produced billets. This includes accounting for the thermal conductivity of materials, controlling the surface temperature of rolls, and using advanced temperature measurement methods. Preconditions have been established for the creation and development of automated control over the continuous rolling process. Primary matrices have been obtained for constructing a mathematical model in the strip deformation area in the "metal-roller" contact zone and the "nozzle-roller" zone, based on thermal field data collected for crystallizer rolls during the casting and rolling of aluminum alloys 8011 and 8006. Modeling and experimental data make it possible to define optimal crystallization and rolling conditions, significantly improving product quality. The proposed temperature field control system could be highly beneficial for the VIET NHAT plant's computer-aided process control system (CAPCS) — Cau Kien Industrial Park, Hai Phong, Vietnam, when integrated into the industrial process architecture and adapted to the conditions at VIET NHAT for producing high-quality foil billets.

References

1. Litvinenko V. S., Petrov E. I., Vasilevskaya D. V., Yakovenko A. V., Naumov I. A., Ratnikov M. A. Assessment of the Role of the State in the Management of Mineral Resources. *Journal of Mining Institute*. 2023. Vol. 259. pp. 95–111.

2. Nguyen M. P., Ponomarenko T., Nguyen N. Energy Transition in Vietnam: A Strategic Analysis and Forecast. *Sustainability*. 2024. Vol. 16, Iss. 5. 1969.

3. Litvinenko V., Bowbrick I., Naumov I., Zaitseva Z. Global Guidelines and Requirements for Professional Competencies of Natural Resource Extraction Engineers: Implications for ESG Principles and Sustainable Development Goals. *Journal of Cleaner Production*. 2022. Vol. 338. 130530.

4. Kinzyaulatova G. I., Elkina L. G. Ensuring Balanced Development of Innovation and Investment Processes in the Russian Federation. *CITISE*. 2022. Vol. 31, Iss. 1. pp. 91–107.

5. Safiullin R. N., Afanasyev A. S., Reznychenko V. V. The Concept of Development of Monitoring and Control Systems for Intelligent Technical Complexes. *Journal of Mining Institute*. 2019. Vol. 237. pp. 322–330.

6. Aramja A., Kamach Q., Elmeziane R. Companies' Perception Toward Manufacturing Execution Systems. *International Journal of Electrical and Computer Engineering (IJECE)*. 2021. Vol. 11, Iss. 4. pp. 3347–3355.

7. Shestakov A. K., Sadykov R. M., Petrov P. A. Multifunctional Crust Breaker for Automatic Alumina Feeding System of Aluminum Reduction Cell. *E3S Web of Conferences*. 2021. Vol. 266. 09002.

8. Dmitrieva V. V., Avkhadiev I. F., Sizin P. E. Application of Modern Software and Hardware Complexes for Automation of Conveyor Lines. *Mining Informational and Analytical Bulletin*. 2021. No. 2. pp. 150–163.

9. Ugolnikov A. V., Makarov N. V. Application of Automation Systems for Monitoring and Energy Efficiency Accounting Indicators of Mining Enterprises Compressor Facility Operation. *Journal of Mining Institute*. 2019. Vol. 236. pp. 245–248.

10. Opalev S. A., Alekseeva S. A. Methodological Substantiation of the Choice for Optimal Modes of Equipment Operation During the Stage-Wise Concentrate Removal in Iron Ores Beneficiation. *Journal of Mining Institute*. 2022. Vol. 256. pp. 593–602.

11. Zabaykin Yu. V., Anisimov P. F., Zaernyuk V. M., Lyutyagin D. V., Davshan A. S. Reproduction of the Russian Mineral Resource Base: Trends and Development Prospects. Moscow: National Research, 2020. 340 p.

12. Nazarova Z. M., Kosyanov V. A., Zabaykin Y. V., Kulikov V. V., Zaernyuk V. M., Goldman E. L., Kharlamov M. F., Yashin V. P., Yashina V. I. Economic Prerequisites and Prospects for the Reproduction of the Russian Mineral Resource Base. Moscow: National Research, 2020. 388 p.

13. Leonova M. S., Timofeeva S. S. Environmental and Economic Damage from the Dust Waste Formation in the Silicon Production. *IOP Conference Series Earth and Environmental Science*. 2019. Vol. 229. 012022.

14. Yolkin K. S., Yolkin D. K., Kolosov A. D., Shtayger M. G. Technologies, which Allow to Reduce an Impact of Metal Silicon Production on the Environment. *IOP Conference Series Materials Science and Engineering*. 2018. Vol. 411, Iss. 1. 012028.

15. Oksengoyt E. A., Kunitsky N. A., Petrov P. A., Shestakov A. K. Modern Equipment by Soyuztsvetmetavtomatika for Detecting Aerosols and Spills of Harmful Pollutants. *Tsvetnye Metally*. 2023. No. 4. pp. 61–65.

16. Bazhin V. Yu., Masko O. N., Nguyen Huy H. Increasing the Speed of Information Transfer and Operational Decision-Making in Metallurgical Industry Through an Industrial Bot. *Non-ferrous Metals*. 2023. No. 1. pp. 62–67.

17. Sverguzova S. V., Sapronova Z. A., Zubkova O. S., Svyatchenko A. V., Shaikhieva K. I., Voronina Y. S. Electric Steelmaking Dust as a Raw Material for Coagulant Production. *Journal of Mining Institute*. 2023. Vol. 260. pp. 279–288.

18. Shestakov A. K., Petrov P. A., Nikolaev M. Yu. Automatic System for Detecting Visible Emissions in a Potroom of Aluminum Plant Based on Technical Vision and a Neural Network. Metallurgist. 2023. Vol. 66. pp. 1308–1319.

19. Anufriev A. S., Lebedik E. A., Smirnov A. A. Automated Ball Charge Control System for Grinding Units. *Obogashchenie Rud*. 2024. No. 1. pp. 3–9.

20. Rozs R., Ando M. Collaborative Systems, Operation and Task of the Manufacturing Execution Systems in the 21st Century Industry. *Periodica Polytechnica Mechanical Engineering*. 2020. Vol. 64, Iss. 1. pp. 51–66.

21. Kulchitskiy A. A., Mansurova O. K., Nikolaev M. Yu. Recognition of Defects in Hoisting Ropes of Metallurgical Equipment by an Optical Method Using Neural Networks. *Chernye Metally*. 2023. No. 3. pp. 81–88.

22. Makarov S. S., Alies M. Yu. Mathematical Model and Numerical Simulation of Conjugate Heat Transfer During Cooling of a High-Temperature Metal Body by a Gas-Liquid Medium Flow. *Chemical Physics and Mesoscopy*. 2022. Vol. 24, Iss. 3. pp. 287–295.

23. Zvyagina E. Y., Ogarkov N. N., Polyakova M. A., Sukhova M. D. Estimation of Depth and Degree of Mill Roll Surface Hardening During Grit Texturing. *Izvestiya. Ferrous Metallurgy*. 2020. Vol. 63, Iss. 9. pp. 735–741.

24. Antsupov A. V. (Jr.), Antsupov A. V., Antsupov V. P., Ryskina E. S. Methodology of Theoretical Assessment of Durability and Reliability of Operation of Rolls of Four-High Stands by Modeling Their Contact Interaction with Strips. *Bulletin of Nosov Magnitogorsk State Technical University*. 2023. Vol. 21, Iss. 3. pp. 97–113.

25. Negri E., Berardi S., Fumagalli L., Macchi M. MES-Integrated Digital Twin Frameworks. *Journal of Manufacturing Systems*. 2020. Vol. 56, Iss. 6. pp. 58–71.

26. Vertyanov D. V., Korobova N. E., Pogudkin A. V., Kravtsova V. D. Physical and Technological Characteristic Features of The Process of Installation of Dies Onto A Temporary Foundation in Internal Wiring Technology. *Journal of Technical Physics*. 2020. Vol. 90. pp. 1750–1757.

27. Ojeda Pardo F. R., Sánchez Figueredo R. P., Belette Fuentes O., Quiroz Cabascango V. E., Mosquera Urbano A. P. Metallographic Properties Evaluation of the Specimens Obtained by the Vibratory Method (Cast Iron ISO 400-12). *Journal of Physics Conference Series*. 2022. Vol. 2388, Iss. 1. 012058.

28. Zakirova G., Pshenin V., Tashbulatov R., Rozanova L. Modern Bitumen Oil Mixture Models in Ashalchinsky Field with Low-Viscosity Solvent at Various Temperatures and Solvent Concentrations. *Energies*. 2023. Vol. 16, Iss. 1. 395.

29. Chernyshov E. A., Baev I. V., Romanov A. D. Mechanical Properties and Structure of Castings at Different Ladle Processing of Liquid and Crystalizing Steel. *Izvestiya. Ferrous Metallurgy*. 2020. Vol. 63. pp. 644–650.

30. Kushchenko A. N., Syrkov A. G., Ngo Q.K. Inorganic Synthesis of Hghly Hydrophobic Metals Containing Surface Compounds with Electron Acceptor Modifiers: Process Features. *Tsvetnye Metally*. 2023. No. 8. pp. 62–72.

31. Pham Q. T., Syrkov A. G., Silivanov M. O., Ngo Q. K. Preparation of zinc nanooxide and its application for antibacterial coatings. *Tsvetnye Metally*. 2023. No. 9. pp. 51–56.

32. Kazyaev M. D., Samoilovich Yu. A., Kazyaev D. M., Vokhmyakov A. M., Spitchenko D. I. Study of the Temperature Field in Work Rolls of Cold Rolling Mills During Rapid Heating in a Chamber Furnace. *Modern Scientific Achievements in Metallurgical Heat Engineering and Their Industrial Implementation: Proceedings of the 2nd International Scientific-Practical Conference (Ekaterinburg, September 18–21, 2017)*. Ekaterinburg: UrFU, 2018. pp. 77–85

33. Podkustov V. P., Alekseev P. L. Mathematical Model of the Thermal Regime of Rolling. *Collection of Scientific Papers*. Moscow: MISIS, 1998. pp. 45–49

34. Akinlabi E. T., Dats E. P., Mahamood R. M., Murashkin E. V., Shatalov M. Y. On a Method of Temperature Stresses Computation in a Functionally Graded Elastoplastic Material. *Mechanics of Solids*. 2020. Vol. 55, Iss. 6. pp. 800–807.

35. Ospanova T. T., Sharipbaev A. A., Niyazova R. S. Algorithm of Numeral Modelling of Distribution of Temperature Field in Rolling Mill. *Fundamental Research*. 2015. No. 10-1. pp. 56–62.

36. Young Gun Ko. Microstructure Evolution and Mechanical Rroperties of Severely Deformed Al Alloy Processed by Differential Speed Rolling. *Journal of Alloys and Compounds*. 2012. Vol. 536. Suppl. 1. pp. S122–S125.

37. Elagin V. I. Ways of Developing High-Strength and High-Temperature Structural Aluminum Alloys in the 21st Century. *Metal Science and Heat Treatment*. 2007. Vol. 49. pp. 427–434. NFM