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PREPARATION OF CONTINUOUSLY CAST HIGHLY-ALLOYED STEEL SLAB BILLETS

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A description is provided for a new patented design of a slab crystallizer and its cooling system with calculation results and identified shortcomings obtained previously. In the work using Autodesk Simulation CFD software, heat transfer is simulated in slab molds of two designs with different wall materials and cooling systems. Melt is supplied to the crystallizer through a submersible deep-bottom nozzle with two outlets. Results of heat transfer modeling using the program are presented in the form of temperature distribution along the length of the mold wide wall. Workpiece crust thickness is considered according to previous calculation results. Maximum values of wall temperatures obtained are comparable with calculations performed previously. Based on results of the color images shown in pictures of the wall surface temperature maximum and minimum values, temperature differences along the length of the walls are established, which are compared for various mold designs, cooling systems, and wall materials. Use of the new slab crystallizer permits an increase in wall working surface temperature up to 300 °C and a reduction in temperature drop along the length of the wide wall by a factor of 4–5 compared with the existing copper design of the slab crystallizer. The result obtained points to the possibility of preparing highly-alloyed steel slab billets with a better surface.

Keywords: slab crystallizer, wall material, cooling system, heat transfer modeling, wall surface temperature, temperature difference at the surface.

Questions of improving continuously-cast billet surface quality and structure, and expansion of the range of steels developed with the aim of achieving a competitive product are important for metallurgical enterprises both within our country and overseas.

Introduction

Results are provide within an article [1] for calculating heat exchange within a slab copper crystallizer No. 1 and in a slab crystallizer No. 2 with nickel walls [2] with an average value of heat flow removal of 2 MW, from which it follows that the average temperature at the wall working surface of crystallizers Nos. 1 and 2 is respectively 167 and 284 °C. In this case billet skin thickness at the outlet from crystallizers Nos. 1 and 2 is correspondingly 17.2 and 16.4 mm, i.e., the divergence is 5%. In this case it is not considered that in crystallizer No. 1 the depth of folds at a billet surface, within which stresses are concentrated, may exceed 1–2 mm. Therefore, at the outlet from crystallizer No. 2 there is formation of a stronger billet skin. No data have been provided in [1] about temperature distribution over the wall thickness of crystallizers Nos. 1 and 2 and about the temperature drop Δt over the wall perimeter, which govern stresses arising within the workpiece skin and its tendency towards cracking.

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Results have been provided [3] for structural calculation of slab crystallizer cooling within a new evaporation-condensation cooling system, with walls of new materials differing from copper and its alloys. The possibility has been demonstrated of utilizing a high potential heat carrier for production requirements. A disadvantage of the work includes the comparatively greater size of the steam condensers and the inconvenience of their location.

In [4] in order to improve continuously-cast billet quality it was proposed to use a new technology and submersible pouring nozzle with eccentric openings. Calculations demonstrated that up to 38% of steel heating is removed in the upper part of a crystallizer. With an increase in crystallization rate the amount of equiaxed crystals within a metal structure increases by several factors. Test-industrial approval of the improved CBCM crystallizer during pouring low-carbon and low-alloy steels has demonstrated an increase in strength sand impact toughness of the hot-rolled metal obtained. Prediction of the ultimate strength and elongation for sheet low-alloy steel was performed by means of well-known equations. A study of rolled steel quality was conducted on slabs selected from eight melts.

A. S. Él'darkhanov and coworkers [5] have noted that in order to provide competitive continuously-cast billet it is necessary to obtain them at minimum cost with high quality. According the authors' opinion this may be achieved by intensifying the heat transfer process from poured metal into cooling water within a crystallizer. The authors consider intensification of heat removal by using artificial roughening of the heat exchange surface. On the basis research conducted by the authors it has been established that the amount of heat removed within a crystallizer may be increased by up to 29%. For comparison there is use of ribbed surfaces to increase the amount heat removed in a crystallizer overall by 6–11%.

In [6] A. V. Kuklev with colleagues proposed an equation for steel crystallization in a continuous billet casting machine of considerable cross section by means of cooling cores, removing melt heat within a crystallizer. On the basis of a proposed mathematical model and calculations for temperature distribution and steel skin growth within a continuously-cast billet it has been established that overall heat removal from molten steel within a crystallizer is comparable with intense electromagnetic mixing of a melt within a crystallizer. It has been established that the overall ingot solidification time is reduced by 10% compared with traditional steel casting technology.

In [7] A. A. Vopneruk and co-authors noted that within domestic metallurgy there is a steady reduction profitability. The main reason for concerns active competition from the direction of Chinese metal product producers. It is emphasized in the work that an attempt to increase crystallizer life is made by actual improvement of crystallizer structure, and also development of energy-efficient protective coatings at a working surface. Coatings (Ni, Co–Ni, Fe-Ni) have been checked making it possible to achieve crystallizer plate life up to 3984 melts (637,440 tons of poured steel).

In [8] preparation of continuously-cast slab billets of alloyed and highly-alloyed steels (07Kh25n13, Kh23N18, etc.) has been considered in the Hammer and Sycle Plant of comparatively small cross sections 140×300, 140×400 mm, etc. At the basis of the steel-pouring technology [8] is a method for obtaining workpieces [9] and a method for treating steels with low production ductility [10] has been proposed. In [9] a version of a billet controlled cooling system has been proposed within which metal is not cooled uniformly and slowly, but interrupted with alternation of periods of short-term rapid supercooling with periods of heating (method of pulsed-continuous crystallization). In view of the low production ductility of the steel developed and also the billet skin formed within a crystallizer preference is given to controlling cooling in a crystallizer. Drawbacks of pulsed cooling; the possibility of using pulsed-continuous cooling method [9, 10] in order to prepare slab a section workpieces of comparatively small cross section (140×140–160×160 mm; 140×300 and 140×400 mm) and cooling water consumption up to 50 m^3/h. Short-term shutdown of cooling water fed to a crystallizer leads to a requirement for using an additional automatic process control system.

Questions of the effect of crystallizer cooling, connected with pouring rates, properties of the slag-forming mixture (SFM) in order to provide "mild" cooling, crystallizer oscillation, electromagnetic mixing, CBCM reconstruction, on continuously-cast billet quality are analyzed in [11–20].

In [11, 12] consideration is given to questions of metal cooling during continuous casting d heat exchange within a crystallizer with pouring rates not more than 7 m/min.

"Mild" metal cooling with SFM selection is considered in [13–15].

M. Hanao and H. Kania with co-authors note [13, 14] that one of the main reasons for development of longitudinal cracks within the surface of a continuously-cast billet is its nonuniform solidification within a crystallizer. With the aim of preventing this "mild cooling" is very important for the crystallizing skin beneath a meniscus within a section of length of several tens of millimeters. In the authors opinion this is possible by selection of the SFM.

In [15] improvement is considered for slab surface quality with thickness 250 and 300 mm with a steady-state pouring regime and improvement of internal slab structure in the stage for the end of pouring. For this in [15] a new SFM has been developed, added to a crystallizer, and in the period at the end of pouring there is use of a method of billet withdrawal at a constant rate. Use of the SFM developed provides preparation of a "mild cooling" effect for metal. As a result of this the non-equilibrium shell growth index was reduced, which as a result led to a reduction in billet metal damage by longitudinal cracks and an improvement in slab surface quality. The method of withdrawing an ingot at a constant rate has been developed with the aim of improving the quality of slabs 1400–2300 mm thick in the section for the end of pouring. Attention is accentuated in the work on the fact that during casting a slab of considerable cross section at a rate of 0.7–1.4 m/min it is difficult to prevent "extrusion" of molten steel as a result of binding ("inversion") within the slab shell in the central part of its width. In order to prevent this the authors [15] have suggested a reduction in water cooling intensity. According to results of completed work the damage index by internal defects for thick slabs was reduced from 1.0 to 0.1.

Consideration is given in [16] to the effect of production factors on formation of a steel ingot shell within a CBCM crystallizer by means of a mathematical model. There is interest in the work in variation of temperature and heat flow during a continuous casting "steady state regime". Notable variations are observed both with respect to thermocouple readings within the crystallizer condition monitoring system, and also from results of developed numerical model. A mathematical model has been proposed by the authors [16] making it possible to predict high-frequency variation of heat flow. It has been established from results of mathematical modeling that a consequence of heat flow variation within a crystallizer is the cyclic nature of ingot shell growth. As a result of this a shell along the internal surface acquires "waviness". In the opinion of the authors the problem of ingot shell nonuniformity with a crystallizer should be at the enter of attention of producers. Traces of crystal twisting serve as areas for crack generation. With an increase the depth of twisting traces there is an increase in the probability of forming transverse cracks with skin breakage and metal extrusion. In addition, within the area of a "trace" unfavorable heat transfer conditions are created with a comparatively slow metal solidification rate and inadequate shell thickness.

Calculation of slag properties for use in models of the steel continuous casting process is provided in [17].

The mechanism of the effect of steel pouring parameters containing carbon less than 0.03% on surface quality of a continuously-cast slab billet and also a study of the effect of pouring rate and heating temperature in the intermediate ladle on quality, size, and composition of surface macro-inclusions are considered in [18]. The authors of the work have studied in detail the structure of the zone located close to the slab broad side where there is "turning" of scale, caused by operation of the crystallizer oscillation mechanism. It has been demonstrated that the depth of skin "rotation" decreases linearly with an increase in pouring rate. The authors of [18] explain the reason for an increase in temperature within a crystallizer, including close to the meniscus. As a result of this solid phase growth is suppressed and a slag "overhang" floats, located over the perimeter of a crystallizer and its upper part, and the depth of "inversion" is reduced. In concluding the work the authors noted that with a reduction in depth of turning its capacity for trapping inclusions floating towards the meniscus, and as a result a reduction is observed in the amount of macro-inclusions within a slab surface. Supply of melt to a crystallizer with a high degree of heating above the liquidus temperature also makes it possible to reduce the amount of subsurface nonmetallic inclusions.

Production of slabs with a high aluminum content is considered in [19]. During planning steel casting the main attention of the authors is devoted to the following questions: cooling regime and crystallizer conicity; specifications for an SFM and its selection; recommended pouring rate. The pouring rate was increased gradually in the work to 0.75, 0.9, 1.0, and 1.15 m/min. During evaluation of quality for the slabs obtained significant attention was devoted surface quality and slab suitability for cleaning. At the surface of cast slabs fine longitudinal depressions were observed in the form cavity-depressions, and longitudinal cracks in the wide side. The location density of depressions increased in the course of pouring with their predominant location within the center of the broad side. Within the depth of depressions longitudinal cracks were observed mainly 25–50 mm longa and 4–7 mm deep. Depression formation is connected by the authors with inadequately good SFM operation. Cleaned billets after longitudinal cutting were rolled in a strip mill into strip 2.6 mm thick with the required quality.

An improvement in continuously-cast steel quality and slab quality dictates a requirement for studying friction within a crystallizer [20]. In this case the authors of the work noted that with a normal sinusoidal rule for crystallizer oscillation pouring at fast rates may be accompanied by low SFM supply to the slab and crystallizer contact zone, increasing friction and worsening surface quality. With a slab pouring rate of 1.66 m/min and oscillation frequency of 158.4 cycles/min with an amplitude of ±5 mm the rate of crystallizer and slab oscillation cycle by a sinusoidal rule is: maximum 0.0392 m/sec and minimum 0.0499 m/sec; with sinusoidal oscillation the rate changes from 0.0452 to 0.0467 m/sec. The authors of [20] have established that work completed by a compressive force with non-sinusoidal oscillation is two times greater, and the value of crystallizer advance is 40% higher than with sinusoidal oscillation. The advantages noted facilitate better "sealing" of surface cracks and better separation of the ingot shell from the crystallizer, a reduced tendency towards crack formation and propagation, and as a result improved cast billet surface quality.

On the basis of these data it is possible to separate the main paths to solution of the problem of improving continuously-cast biller quality;

1. "Mild" metal workpiece cooling in a crystallizer and provision of solidified billet uniformity within it that is achieved to a different extent by increasing wall temperature, changing wall material [1], a reduction in water cooling intensity [15], SFM selection [13–15], and supply to a crystallizer of melt with a higher degree of heating [18];

2. Correct selection of crystallizer parameters and oscillation rule, a reduction in billet working surface friction with a crystallizer wall [20];

3. Heat removal from melt within the upper part of a crystallizer [5, 6].

The Aim of the Work: modeling heat exchange within slab crystallizer No. 2 of new construction with cross section 250×1850 mm with a double-contour cooling system, and also copper walls of existing slab crystallizer No. 1 with cross section 250×1850 mm.

Description of slab crystallizer construction and their cooling systems: No. 1 is an existing slab copper crystallizer with section dimensions 250×1850 mm, cooled with cold water with wall thickness $\delta = 0.03$ m, channel diameter $d = 0.02$ m, water cooling temperature $t_w = 20\,°C$, water weight second consumption $M = 47.3$ kg/sec,

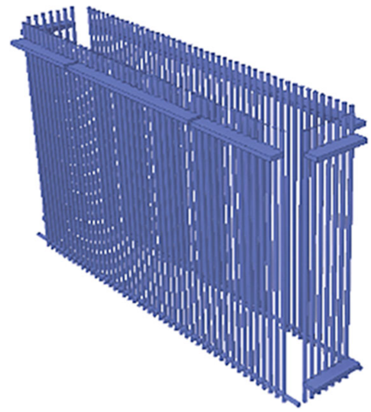

Fig. 1. Crystallizer cooling system 3D-model.

water velocity in the channel $\omega_c = 7.1$ m/sec, wall internal surface temperature $t_2 = 45°C$, temperature at the wall working surface $t_1 = 167–172°C$; No. 2 with a nickel working walls with a two-contour cooling system: section size 250×1850 mm, wall thickness $\delta = 5$ mm, channel size 5×13 mm, water cooling rate in channel $w_w = 8.2$ m/sec, temperature at the wall inner surface $t_2 = 186°C$, temperature at the wall working surface $t_1 = 279–284°C$, cooling water temperature $t_w = 150°C$.

The new crystallizer construction with nickel working walls [2] includes a closed water circulation route with a heat exchanger. A slab crystallizer and its cooling system consists of four longitudinal working walls arranged in pairs with support and working parts, vertical channels for cooling water, a thermocouple, connections to a crystallizer automatic control system, a water pump within a closed circuit for pumping hot water, an electric heater, and a heat exchanger with slotted channels for hot and cold water. A previously closed circuit, including a crystallizer, a heat exchanger with pipelines and water pumps is filled with clean water. The electric heater and water circulation pump are switched on. After reaching a prescribed water heating temperature the electric heater with the automatic control system is switched off. Then simultaneously there is pouring of molten metal into the crystallizer and there is supply of cold water from a circulation route to the heat exchanger. Water passing within crystallizer channels and the heat exchanger, removes heat correspondingly from poured metal and cold water. The circulation temperature in the first hot water circuit and cold in the second circuit is controlled according to thermocouple readings.

Research Analysis and Results

In order to avoid the disadvantages of work [1] in the present work heat exchange in crystallizers Nos. 1 and 2 is additionally modelled by using an Autodesk Simulation CFD program. A billet skin thickness is adopted according to calculated data [1]. Starting data for modeling has been provided during description of the construction of crystallizers Nos. 1 and 2, and also work in [1]. Physical parameters of the heat carrier (water) are prescribed automatically by a program and are tabulated values [21].

A crystallizer cooling system (3D-model) is provided in Fig. 1. The crystallizer model is four broad and narrow walls arranged in pairs made of nickel, which are tightened by a steel support base with cut grooves, within which there is heat carrier circulation. Steel supply to the crystallizer is accomplished through an unsupported pouring nozzle with two outlets in the form of an ellipse with sizes 60×90 mm. The steel selected for pouring was high-alloy steel Kh23N18 with prescribed pouring rate consumption up to 1 m/min.

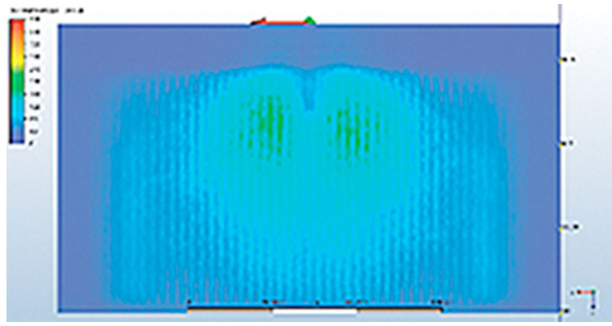

Fig. 2. Temperature distribution at copper crystallizer No. 1 wide wall surface.

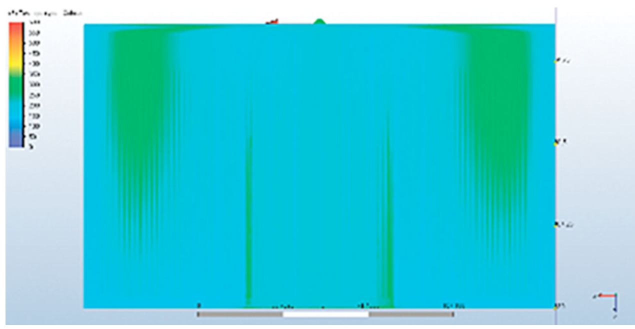

Fig. 3. Temperature distribution at surface of crystallizer No. 2 wide nickel wall with a looped cooling system.

Results are given in Fig. 2 for the temperature distribution at the surface of a copper crystallizer No. 1 wide wall from which it follows that the maximum value of temperature $t_{max\,1} = 200–220\,°C$ (in the vicinity of interaction of molten streams), and a minim value $t_{min\,1} = 60\,°C$. In the case the temperature drop over the length of the wide wall $\Delta t_1 = 140–160\,°C$.

Results are given in Fig. 3 for temperature distribution at the surface of a wide nickel wall for crystallizer No. 2 from which it follows that the maximum temperature value $t_{max\,2} = 300–320\,°C$ (in the region of interaction with a molten stream), and minimum value $t_{min\,2} = 220–230\,°C$. In this case the temperature drop over the length of the wide wall $\Delta t_2 = 80–90\,°C$.

Temperature distribution results at the surface wide nickel wall of crystallizer No. 2 are provided in Fig. 3, from which it follows that the maximum temperature value $t_{max\,2} = 300–320\,°C$ (in the region of interaction with molten streams), and a minimum value $t_{min\,2} = 220–230\,°C$. In this case the temperature drop over the length of the wide wall $\Delta t_2 = 80–90\,°C$. Comparison of Figs. 2 and 3 shows that $\Delta t_2 < \Delta t_1$ and that divergence is 60–70 °C. With the aim of a subsequent reduction in temperature drop over the wide wall length in crystallizer No. 2 a solution was adopted to use a direct cooling system for the crystallizer instead of a looped system. Results of heat exchange within the crystallizer are given in Fig. 4. It is seen that the maximum temperature value at the surface of the wide wall of nickel crystallizer No. 2: $t_{max\,2} = 270–280\,°C$, and $t_{min\,2} = 220–240\,°C$. In this case the temperature drop over the wide wall length of crystallizer No. 2 $\Delta t_2' = 30–40\,°C$, and the ratio $\Delta t_1 / \Delta t_2' = 4–5$ times. A higher average temperature at the wall surface of crystallizer No. 2 $t_2 = 260\,°C$ compared with the average temperature at the wall surface of crystallizer No. 1 at $t_1 = 140\,°C$ reduces supercooling of the continuously-cast billet skin and reduces the occurrence of stresses within it.

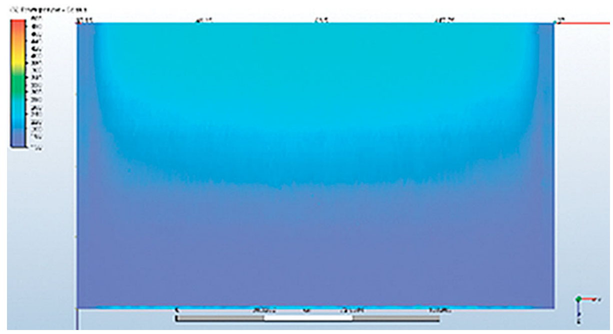

Fig. 4. Temperature distribution at surface of crystallizer No. 2 wide nickel wall with a straight-flow cooling system.

Results of modeling about the effect of higher average temperature values at the wide wall surface t_2 = 260°C for crystallizer No. 2 and lower temperature drops Δt_2 = 30–40°C over the length of crystallizer No. 2 on stresses and strains arising within a billet skin have been analyzed in [22]. A higher crystallizer wide wall temperature indicates that under stable uniform conditions there is a higher billet skin temperature in contact with a crystallizer wall. With an increase in skin temperature its deformation ε is reduced [2]. Therefore with t = 1400°C skin deformation $\varepsilon = 0.016$, and with t = 1350°C, $\varepsilon = 0.026$. With an increase in temperature drop Δt within the skin its deformation ε and stresses σ within it increase, and correspondingly the tendency of billet skin towards cracking also increases.

CONCLUSIONS

The results provided for calculating heat exchange and temperature distribution within the walls of a slab CBCM crystallizer expand ideas about the technology for preparing a continuously-cast billet and in particular new resource saving construction of a slab crystallizer with nickel walls. Higher temperature values at a wall surface (up to 300°C) and lower values of temperature drop over the nickel wall thickness Δt_2 = 30–40°C, compared with Δt_1 = 140–160°C within a copper slab crystallizer, provide the possibility of obtaining continuously-cast billets of highly alloyed steel with better surface quality and a minimum amount of cracks.

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