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MODELING OF A CONTINUOUSLY CAST BILLET CENTRAL POROSITY REDUCING PROCESSES

The results of studies aimed at solving the actual problem of improving the quality of continuously cast billets are presented. Technical solutions have been developed to improve the crystallization process by means of pulsating metal blowing with an inert gas in the mold and shear reduction of the billet in the secondary cooling zone of a continuous casting machine (CCM). Physical modeling of shear reduction of continuously cast billets in the secondary cooling zone of CCM on model ingots has been carried out. The resulting macrostructures of model ingots were studied, indicating the absence of internal cracks in the central zone of the billet at a degree of deformation of up to 5 % and small shear angles (≤ 15–18°), and at a degree of deformation of more than 5 % and shear angles of about 18°, cracks develop periodically, emerging on the surface of the ingot. With pulsating blowing and shear «soft» compression in the final period of solidification, their positive effect on reducing the zone of columnar crystals and reducing the central porosity was established.

Keywords: continuously cast billet, central porosity, CCM, crystallization, crack.

Introduction

The development of central porosity in continuously cast billets is mainly due to the presence of a deep liquid hole, a developed columnar structure, which makes it difficult to feed the billet during shrinkage, and also prevents non-metallic inclusions from floating during the casting process. A promising way to reduce the central porosity in a continuously cast billet is the «soft» reduction of the ingot in the secondary cooling zone of the CCM [1].

The wide use of this method is limited, since it is impossible to use large degrees of reduction due to the risk of developing cracks in the workpiece. Therefore, for its implementation, dynamic compression systems are used [2, 3].

The purpose of this work is to simulate the processes of producing continuously cast billets using soft reduction of continuously cast billets.

Materials and methods of research

Analysis of the quality of continuously cast billets of square and round sections, produced at the enterprises of PB LLP «Casting» and PB LLP «KSP steel» from 2006 to 2010 showed that in billets with a developed columnar structure, the size of pores and shrinkage cavities has a higher value. Therefore, with a decrease in the proportion of columnar crystals in a continuously cast billet, the value of axial porosity will be smaller, which will reduce the required total degree of compression of the continuously cast billet in the process of soft reduction. In [4], it is noted that the process of workpiece reduction can be intensified by using shear deformations.

Based on the foregoing, the authors proposed a comprehensive method for improving the quality of a steel continuously cast billet by pulsating metal blowing with an inert gas in the mold and shear reduction of the ingot at the end of the secondary cooling zone of the CCM [5]. The method of pulsating blowing is proposed to be used to reduce the proportion of the columnar structure in the workpiece. It can be implemented with no suction of the melt into the dip tube before supplying pressurized inert gas in each cycle and with vacuum suction of the melt.

Theoretical analysis showed that the implementation of pulsating blowing in the CCM mold is possible at an argon flow rate of up to 5 l/min, a pulsation frequency of up to 16 Hz, and an amplitude of gas pressure fluctuations in the system from 0.08 to 0.15 MPa. At high values of these parameters, a perturbation may occur on the metal surface in the mold and the quality of the workpiece surface may deteriorate.

Experimental studies of the formation of the macrostructure of a continuously cast billet during pulsed blowing were carried out on a laboratory CCM for the cross section of the mold 30×30 mm and ingot pulling speed 1 m/min. The casting temperature of the model lead-based alloy is 350 °C. Pulsation purge was carried out with vacuum suction through a tube dia. 5 mm at an immersion depth of 15 mm with a pulsation frequency of 0–5 Hz, an inert gas flow rate of 0–5 l/min. The pressure in the dip tube was in the range of 0.08–0.12 MPa. To analyze the microstructure, longitudinal templates were cut out from the obtained workpieces, ground, polished, and etched in a solution of the following composition: 42 g M_oO_2, 29 ml HNO_3, 100 ml H_2O.

The macrostructure was studied on an MPB-2 instrument (×24). The width of the zone of columnar crystals was measured. It was revealed that at a gas flow rate of 4–5 l/min, waves are observed on the «mirror» of metal in the mold. An analysis of the macrostructure of the obtained samples showed that pulsating mixing has an effect on the length of the structural zones of the ingot. The zone of frozen crystals slightly increased, the zone of columnar dendrites decreased. The width of the zone of equiaxed macrograins increased. This allows us to conclude that the pulsation effect contributes to an increase in the number of nuclei of solid particles in the melt due to the breaking off of dendrites and the washing out of crystal nuclei from the interface between the solid and liquid phases into the axial part of the forming ingot.

The experimental results were processed by regression analysis in Microsoft Office Excel. Taking the argon flow rate (l/min) as x1 and the pulsation frequency (Hz) as x_2, we obtained the regression equation (1) to determine the width of the zone of the columnar structure (y, %) of a model lead alloy ingot:

$$y = 48{,}07 - 4{,}56x_1 - 0{,}67x_2 \qquad (1)$$

Calculated correlation coefficient (R^2 = 0,71), which showed good convergence of results; the adequacy of the model was carried out. Fisher's design criterion F_p 0,41 less $F_{табл}$.

The hydrodynamics of continuous casting was modeled on the experimental setup, which was a model of a CCM mold made of Plexiglas. To obtain a fluid motion similar to the motion of molten steel in the liquid core of a hardening workpiece, the equalities of the Reynolds, Froude and Weber criteria were observed. Experimental studies on hydraulic modeling of pulsating blowing in the CCM mold were carried out for the section 125×125 mm. Water consumption (Q' = 10 l/min) corresponded to the drawing speed of the steel billet of 2.5 m/min, water was supplied through a channel dia. 9 mm (a real pouring nozzle has a diameter of 14.5 mm, which corresponds to a scale of M = 0.6). As bubbling gas, air was used, which was supplied through a tube with a diameter of 5 mm, lowered into the mold under the liquid level to a depth of 90 mm. The gas flow rate varied from 1 to 5 m/min. To create a vacuum, a separate channel was connected to the tube by means of a pulsator, through which the gas was pumped out..

Results and discussion

A series of experiments were carried out with liquid pouring with an open jet and a submerged jet through a submerged nozzle: without purge, with purge, with pulsating purge without vacuum suction into a dip tube, with pulsating purge with vacuum suction into a dip tube. It has been established that the most intense movement in the liquid is provided by pulsating blowing of the liquid hole with vacuum suction of the liquid into the dip tube, which should eventually stimulate the processes of nucleation due to the destruction of growing dendrites during solidification of the workpiece and prevent the development of a columnar structure.

Shear soft reduction of the continuously cast billet in the secondary cooling zone of the continuous casting machine is provided by a pull-straightening device due to the installation of pairs of conical and cylindrical rolls. Also, vertical supporting rollers should be additionally provided, which will ensure the rigid position of the workpiece along the CCM production line. The process of shear reduction of continuously cast billets at the end of the solidification period was modeled in a number of experiments. The degree of healing of the central porosity was compared with different reduction schemes, as well as the maximum degree of reduction before the appearance of cracks in the workpiece at the end of the solidification period.

To determine the degree of healing of the axial defect, laboratory studies were carried out to simulate the reduction of continuously cast billets from lead alloys. The reduction was simulated in cylindrical and conical rolls at different degrees of reduction and shear angles. Tapered rolls implemented a shear reduction scheme. For modeling, we used the Pb – Bi alloy, from which ingots with a cross section were made 17×17 mm. Holes dia. 2 mm for modeling central porosity.

The model ingot was reduced in two passes. In the first pass, the ingot was compressed with a shift and the cross section of the model ingot was obtained in the form of a parallelogram; in the second pass, the geometry of the model ingot was restored, its dimensions after compression were measured with a caliper, the dimensions of the hole were measured using an MPB-2 microscope with a division value of 0.05 mm.

The behavior of an artificial defect was described using the hole closure ratio ψ, which is the product of the elongation factor and the ratio of the cross-sectional areas of the hole before and after deformation (2):

$$\psi = \mu F'_{\text{отв}} / F^{0}_{\text{отв}}, \tag{2}$$

where $F'_{\text{отв}}$ and $F^{o}_{\text{отв}}$ – hole area before and after total reduction; ɵ – drawing ratio.

Coefficient ψ shows the relationship between the reduction in cross-sectional areas of the defect and the workpiece; at $\psi > 1$ the cross-sectional area of the defect decreases less intensively compared to the cross-sectional area of the workpiece, and the elimination of discontinuities is unattainable. Corresponds to complete healing $\psi = 0$.

The elongation ratio was determined by the formula (3):

$$\mu = F^{0}_{\text{сл}} / F'_{\text{сл}}, \tag{3}$$

where $F^{o}_{\text{сл}}$ and $F'_{\text{сл}}$ – ingot area before and after total reduction.

Further, the area, the elongation ratio of the model ingot, and the hole closing ratio were calculated from the obtained values.

An analysis of the experimental results showed that the complete closure of a hole with a diameter of 2 mm ($\psi = 0$) in the absence of shear reduction, it is achieved at an elongation ratio $\mu = 1{,}24$. With shear compression, the hole is completely closed at a lower elongation ratio (at $\alpha = 30°$, $\mu = 1{,}13$).

To process the simulation results, regression analysis was carried out in Microsoft Office Excel. Received the regression equation (4) to determine the coefficient of hole closure ψ from shear angle α model ingot and elongation ratio ɵ model ingot:

$$\psi = 5{,}26 - 0{,}02\alpha - 4{,}15\mu. \tag{4}$$

We determined the correlation coefficient R2 = 0,89 (Fisher's design criterion $F_{p} = 0{,}53$, which is less $F_{\text{табл}}$). For various draw ratios ɵ built graphs of dependence of the coefficient of closing the hole ψ on the shear angle α (figure 1). On the basis of the experiments carried out, it can be unambiguously concluded that shear soft reduction provides a more effective healing of the central porosity in workpieces compared to linear.

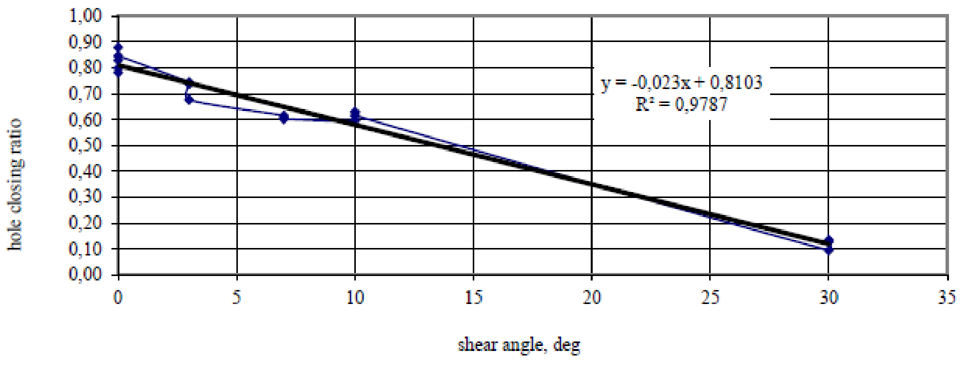

Figure 1 – Dependence of the coefficient of closing the hole ψ from shear angle α model ingot from lead alloys at = 1,06 μ

At the next stage of research, the maximum possible degree of shear reduction of a model ingot from an alloy of the Pb – Bi system was determined at the end of the period of solidification without the appearance of cracks. For comparison, ingots without reduction were obtained. For the experiment, a device was used to simulate the shear reduction of billets with a liquid core in the production of a continuously cast billet [6]. Dimensions of the metal mold 60×60×40 mm. The thickness of the moving plates is 5 mm. The thickness of the wedges during the experiment varied from 2 to 10 m, which provided different values of the shear angle. The use of a wedge 10 mm thick corresponded to a shear angle of 18°, 2 mm thick – shear angle 5°. The compression application time was determined using a Chromel-Copel thermocouple installed in the center of the mold. The reduction was carried out at 330 °C, which corresponded to the minimum overheating of the metal above the liquidus line and provided a liquid core in the ingot.

After the experiment, the macrostructure of the ingot was studied using microscopes MPB-2 (×24) and USB Micro. The study of the macrostructure of model ingots showed that there are no internal cracks in the central zone of the workpiece at a degree of deformation of up to 5 % and small shear angles ($\leq$ 15–18°). With a degree of deformation > 5 % and shear angles ~ 18° the development of cracks is periodically observed, emerging on the surface of the ingot, which can be explained by the loss of plasticity of the alloy.

Conclusions

1 An integrated method is proposed to improve the quality of a steel continuously cast billet due to pulsating metal blowing with an inert gas and in the CCM mold and shear reduction of a continuously cast billet in the secondary cooling zone of the CCM, confirmed by innovative patents of the Republic of Kazakhstan No. 19409, No. 21195.

2 Physical modeling revealed the nature of the influence of pulsating metal blowing with an inert gas on the formation of crystallizing metal and established the dependence of the width of the columnar zone of crystals of a model workpiece on the flow rate and frequency of pulsations of an inert gas.

3 By physical modeling of shear reduction of continuously cast billets in the secondary cooling zone of CCM on model ingots, the mechanism of defect healing “central porosity” was revealed and it was found that the degree of defect healing during shear reduction is higher than during linear one.

4 On model billets, it has been established that the use of shear reduction of a continuously cast billet with a liquid core to reduce axial shrinkage porosity is possible at low degrees of reduction and shear angles.

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ҮЗДІКСІЗ ҚҰЙЫЛҒАН ДАЙЫНДАМАНЫҢ ОРТАЛЫҚ КЕУЕКТІЛІГІН ТӨМЕНДЕТУ ПРОЦЕСТЕРІН МОДЕЛЬДЕУ

Үздіксіз құйылған дайындамалардың сапасын арттырудың өзекті мәселесін шешуге бағытталған зерттеулердің нәтижелері келтірілген. Қалыпта инертті газбен пульсирленген металды үрлеу және дайындамаларды үздіксіз құю машинасының (ДҮҚМ) қайталама салқындату аймағында дайындаманың ығысуын азайту есебінен кристалдану процесін жақсарту үшін техникалық шешімдер әзірленді. Үздіксіз құйылған дайындамаларды үлгі құймалардағы ДҮҚМ қайталама салқындату аймағында ығысуды азайтудың физикалық моделі жүргізілді. Алынған үлгі құймалардың макроқұрылымдары зерттелді, бұл дайындаманың орталық аймағында 5 %-ға дейінгі деформация дәрежесінде және кіші ығысу бұрыштарында (≤ 15–18°) және деформация дәрежесінде ішкі жарықшақтардың жоқтығын көрсетеді. 5 %-дан астам және ығысу бұрыштары шамамен 18°, жарықтар периодты түрде дамып, құйма бетінде пайда болады. Пульсациялық үрлеу және ығысу «жұмсақ» сығымдау кезінде қатудың соңғы кезеңінде олардың бағаналы кристалдар аймағын азайтуға және орталық кеуектілікті азайтуға оң әсері анықталды.

Кілтті сөздер: үздіксіз құйылған дайындама, орталық кеуектілік, ДҮҚМ, кристалдану, жарықшақ.

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МОДЕЛИРОВАНИЕ ПРОЦЕССОВ СНИЖЕНИЯ ЦЕНТРАЛЬНОЙ ПОРИСТОСТИ НЕПРЕРЫВНОЛИТОЙ ЗАГОТОВКИ

Приведены результаты исследований, направленных на решение актуальной проблемы повышения качества непрерывнолитых заготовок. Разработаны технические решения по совершенствованию процесса кристаллизации за счет пульсационной продувки металла инертным газом в кристаллизаторе и сдвигового обжатия заготовки в зоне вторичного *охлаждения машины непрерывного литья заготовок (МНЛЗ). Осуществлено физическое моделирование сдвигового обжатия непрерывнолитых заготовок в зоне вторичного охлаждения МНЛЗ на модельных слитках. Исследованы полученные макроструктуры модельных слитков, указывающие на отсутствие внутренних трещин в центральной зоне заготовки при степени деформации до 5 % и малых углах сдвига (≤ 15 – 18°) и при степени деформации более 5 % и углах сдвига около 18° периодически наблюдается развитие трещин, выходящих на поверхность слитка. При пульсационной продувке и сдвиговом «мягком» обжатии в конечный период затвердевания установлено их положительное влияние на сокращение зоны столбчатых кристаллов и снижение центральной пористости.*

Ключевые слова: непрерывнолитая заготовка, центральная пористость, МНЛЗ, кристаллизация, трещина.

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