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Reducing the Central Porosity of Continuous-Cast Billet by Modification of the Solidification Process

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Abstract—The quality of continuous-cast billet is considered. Means of improving billet solidification are developed, with the pulsed injection of inert gas into the metal in the mold and shear-enhanced mild compression of the billet in the secondary-cooling zone of the continuous-casting machine. These measures are found to shrink the columnar-crystal zone and reduce the central porosity.

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The development of central porosity in continuous-cast billet is mainly associated with the presence of a deep liquid crater and developed columnar crystalline structure. These factors interfere with blank shrinkage and prevent the ascent of nonmetallic inclusions in the course of casting. A promising means of reducing the central porosity in continuous-cast billet is mild compression of the billet in the secondary-cooling zone of the continuous-casting machine [1–3].

The adoption of this method has been constrained by the risk of cracking if the compression of the billet is too great. Therefore, a dynamic compression system is employed [4].

In the present work, we simulate the production of continuous-cast billet with mild compression.

Analysis of square and round continuous-cast billet produced at TOO Kasting and TOO KSP Steel from 2006 to 2010 shows that, in blanks with developed columnar crystalline structure, the size of the pores and shrinkage cavities has a considerable influence on billet quality. Hence, with decrease in the proportion of columnar crystals, the axial porosity in the continuous-cast billet will be reduced. Correspondingly, the total mild compression of the continuous-cast billet may be reduced. The compression of the continuous-cast billet in the continuous-casting machine may be intensified by using shear deformation, as noted in [5].

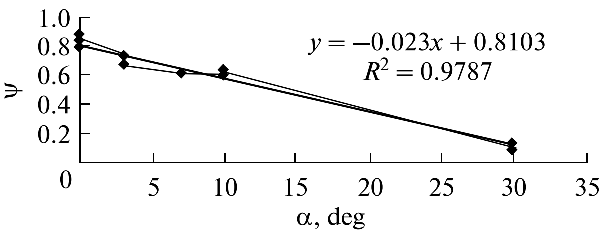
On that basis, we may propose a method of enhancing the quality of continuous-cast steel billet by pulsed injection of inert gas in the mold and shear-enhanced mild compression of the billet in the secondary-cooling zone of the continuous-casting machine [6]. Pulsed injection is used to reduce the columnar crystalline structure in the blank. It may be implemented without suction of the melt into the submerged tube prior to pressurized inert-gas supply in each cycle or with vacuum suction of the melt.

Theoretical analysis shows that pulsed injection of argon in the mold of the continuous-casting machine is possible at rates up to 5 L/min, with a pulsation frequency up to 16 Hz and amplitude of the gas-pressure fluctuations 0.08–0.15 MPa. Large parameter values may be associated with perturbations at the metal surface in the mold and deterioration in the billet surface.

Experiments on the macrostructure of continuous-cast billet with pulsed injection of inert gas are conducted on a laboratory continuous-casting machine (mold cross section 30 × 30 mm; ingot extrusion rate 1 m/min). The input temperature of the model lead alloy is 350°C. In pulsed injection, we employ vacuum suction through a tube (diameter 5 mm) at an immersion depth of 15 mm, with a pulsation frequency of 0–5 Hz and inert-gas consumption of 0–5 L/min. The pressure in the submerged tube is 0.08–0.12 MPa. For microstructure analysis, longitudinal templates are cut from the billet, ground, polished, and etched in a solution of the following composition: 42 g MoO_2, 29 mL HNO_3, and 100 mL H_2O.

The macrostructure is investigated on an MPB-2 instrument (×24). The width of the columnar-crystal zone is measured. It is found that, with gas injection at 4–5 L/min, waves are seen at the metal meniscus in the mold. Analysis of the sample microstructure shows that pulsed mixing affects the size of the structural zones in the ingot: the zone of frozen crystals is somewhat increased; and the zone of columnar dendrites is reduced. The width of the equiaxial-micrograin zone is increased. This indicates that pulsed injection increases the nucleation of solid particles in the melt on account of chipping of the dendrites and washing of the crystal nuclei from the solid–liquid boundary to the axial region of the ingot.

We use Microsoft Office Excel software for regression analysis of the experimental results. If the argon flow rate (L/min) is x_1 and the pulsation frequency



Dependence of the hole-closure coefficient ψ on the shear angle α of a model lead-alloy ingot when $\mu = 1.06$.

(Hz) is x_2, we obtain a regression equation for determining the width of the columnar-crystal zone (y, %) in the model lead-alloy ingot

$$y = 48.07 - 4.56x_1 - 0.67x_2. \quad (1)$$

The corresponding correlation coefficient $R^2 = 0.71$ indicates consistency of the results; the model is satisfactory. The Fisher statistic $F_{calc} = 0.41$, which is less than F_{table}.

We simulate the hydrodynamics of continuous casting on an organic-glass model of the mold in a continuous-casting machine. To obtain liquid motion resembling that in the liquid core of a solidifying steel ingot, we ensure agreement of the Reynolds, Froude, and Weber numbers. Experiments on the hydraulic modeling of pulsed injection in the mold of the continuous-casting machine is undertaken for a 125 × 125 mm cross section. The water flow rate ($Q' = 10$ L/min) corresponds to an extraction rate of 2.5 m/min for the steel billet. Water is supplied through a 9-mm channel, whereas the actual diameter of the casting nozzle is 14.5 mm; that corresponds to a scale $M = 0.6$. Air is injected through a 5-mm pipe immersed to a depth of 90 mm in the liquid within the mold. The gas flow rate is 1–5 m/min. To create vacuum in the tube, a separate channel is used to pump out the gas. The models used to simulate nonmetallic silicate inclusions (measuring 2–4 mm) are polypropylene powder particles (size 0.7 mm; density 0.9 g/cm^3).

In a series of experiments with casting of liquid by an open jet and a submerged jet in various conditions—without injection, with injection, and with pulsed injection in the presence or absence of vacuum suction into the submerged tube—we find that the motion in the liquid is most intense in the case of pulsed injection accompanied by vacuum suction into the submerged tube. These conditions stimulate nucleation on account of the disintegration of the growing dendrites on billet solidification and prevent the development of columnar structure.

We use a tractional and straightening system with added pairs of conical and cylindrical rollers for shear-enhanced mild compression of the billet in the secondary-cooling zone of the continuous-casting machine. In a series of experiments, we simulate shear-enhanced mild compression of the continuous-cast billet at the end of the solidification period. We compare the central porosity in different reduction conditions and with maximum reduction prior to cracking of the blank at the end of solidification.

To determine the decrease in the axial defect, we model the compression of continuous-cast lead-alloy billet. We model the compression in cylindrical and conical rollers with different degrees of reduction and shear angles. Conical rollers ensure compression with shear. We use Pb–Bi alloy, from which we produce 17 × 17 mm ingots. In the model billet, a hole (diameter 2 mm) is drilled to simulate central porosity.

The model ingot is reduced in two passes. In the first pass, shear is applied, and the cross section of the model ingot obtained takes the form of a parallelogram. In the second pass, the geometry of the model ingot is restored. Its dimensions after reduction are measured by means of a slide gage; the hole dimensions are measured using an MPB-2 microscope (scale division 0.05 mm).

The behavior of the artificial defect is estimated by means of the hole-closure coefficient ψ [8]

$$\psi = \mu F'_{ho}/F^0_{ho}, \quad (2)$$

where F'_{ho} and F^0_{ho} are the cross-sectional areas of the hole before and after deformation, respectively; μ is the extrusion coefficient.

We see that ψ expresses the ratio between the decrease in cross-sectional areas of the defect and the billet. When $\psi > 1$, the cross-sectional area of the defect does not decline as rapidly as the cross-sectional area of the billet, and the defect is not eliminated. Complete elimination of the defect corresponds to $\psi = 0$.

We may calculate μ from the formula

$$\mu = F^0_{in}/F'_{in}, \quad (3)$$

where F^0_{in} and F'_{in} are the areas of the ingot before and after total reduction. Then we calculate the area and extrusion coefficient of the model ingot and ψ.

Analysis of the experimental results shows that complete closure of a 2-mm hole ($\psi = 0$) without shear-enhanced reduction corresponds to $\mu = 1.24$. With shear-enhanced reduction, a smaller value of μ is required: $\mu = 1.13$ when $\alpha = 30°$.

Regression analysis of the results using Microsoft Office Excel software yields a regression relation between ψ and the ingot's shear angle α and extrusion coefficient μ

$$\psi = 5.26 - 0.02\alpha - 4.15\mu. \quad (4)$$

The correlation coefficient $R^2 = 0.89$. The Fisher statistic $F_{calc} = 0.53$, which is less than F_{table}. In the figure, we plot the dependence of ψ on α for different μ. On the basis of the experiments, we may confidently conclude that shear-enhanced mild compression of the billet improves the elimination of central porosity in the billet.

Next, we determine the maximum possible shear-enhanced reduction of the model Pb–Bi alloy ingot at the end of solidification to avoid cracking. For comparison, we obtain ingots without reduction. We use a system for modeling the shear-enhanced reduction of billet with a liquid core in the production of continuous-cast billet [7]. The dimensions of the metal mold are 60 × 60 × 40 mm. The thickness of the mobile plates is 5 mm. The taper thickness in the experiments is 2–10 mm, corresponding to different shear angles: 10 mm corresponds to 18°, and 2 mm to 5°. The time at which the reduction is applied is determined by means of a Chromel–Copel thermocouple at the center of the mold. The temperature in reduction is 330°C, which corresponds to the minimum temperature rise above the liquidus line and ensures a liquid core in the ingot.

After the experiment, we investigate the ingot's macrostructure by means of an MPB-2 microscope (×24) and a USB Micro instrument. We find that there are no internal cracks in the central zone with 5% reduction and small α ($\leq 15°$–$18°$). With >5% reduction and $\alpha \sim 18°$, cracks that reach the ingot surface are periodically observed. That may be attributed to loss of alloy plasticity.

CONCLUSIONS

(1) A comprehensive approach to improving the quality of continuous-cast steel billet has been proposed, on the basis of pulsed injection of inert gas into the metal in the mold of the continuous-casting machine and shear-enhanced mild compression of the billet in the secondary-cooling zone of the continuous-casting machine. This approach is covered by Kazakh patents RK 19409 and 21195.

(2) Physical modeling establishes the influence of pulsed injection of inert gas on the formation of the solidifying model and the dependence of the width of the columnar-crystal zone in the model billet on the inert-gas flow rate and pulsation frequency.

(3) Physical modeling of shear-enhanced reduction of continuous-cast billet in the secondary-cooling zone of the continuous-casting machine establishes the mechanism by which the central porosity is eliminated and indicates that the use of shear improves the defect elimination.

(4) Modeling shows that smaller degrees of axial porosity may be ensured by shear-enhanced reduction of continuous-cast billet with a liquid core, when the degree of reduction and shear angle are small.

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