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Influence of Electromagnetic Stirring of Steel in the Mold on Solidification Processes of Billets 150 × 150 mm

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The experimental studies and analytical calculations on determining the mass of solidified skin and its thickness at the exit from the mold during casting steel 3сп with and without electromagnetic stirring in the mold are performed. It is established that electromagnetic stirring can significantly increase the mass of solidified metal, what improves the speed of continuous casting in 10-15%.

Keywords: STEEL, CCM, EMS, SOLIDIFICATION

Introduction

One way to improve the quality of continuous cast steel billets and increasing productivity of CCM is the use of external influences on liquid and crystallizing metal, in particular, of rotating magnetic field in the liquid phase of the ingot [1].

Electromagnetic stirring is carried out in different parts of a billet during its formation in the CCM: in the mold, secondary cooling zone and at the end of the liquid cup [2]. Electromagnetic stirring in continuous casting mold is one of the most effective methods of physical influence on the liquid metal, providing the formation of high-quality surface and internal structure of the ingot, increase of the yield, improving productivity of the CCM and flexibility of steel industry [3]. The choice of optimal method of electromagnetic stirring for each case is determined by the grade of steel, superheating of the metal supplied to the casting, the rate of extraction, billet section [4].

This paper presents the results of experimental studies of the influence of electromagnetic stirring in of the CCM mold on solidification of a billet 150 × 150 mm of steel 3сп.

Results and Discussion

A six-groove CCM (Danieli) designed for casting billets from carbon, low-alloyed, siliceous and bearing steels operates at PSC "Donetsk metallurgical plant". Tubular molds are used in the curvilinear CCM for billets with cross section, mm: 100 × 100, 120 × 120, 125 × 125, 130 × 130, 150 × 150, with wall thickness 9 and 12.

General view of the CCM mold equipped in the lower part of EMS is shown in **Figure 1**. Danieli Rotelec stirrer is fixed on a support, which is part of the oscillation table independent of the mold table. It is powered from the power source of low frequency to increase the magnetic field penetration depth into the liquid phase of the crystallizing ingot. **Table 1** shows the parameters of EMS.

Continuous casting of billets 150 × 150 mm of steel 3сп was performed on a curvilinear CCM with tubular molds 1000 mm high at a speed of 2.7-3.2 m/min. Water consumption for cooling of the mold was 1800-2000 l/min. The temperature of the metal in the pouring basket was 1545-1560 ° C. In the process of casting metal in the mold went into the azimuthal motion under the influence of the rotating magnetic field of EMS. The values of the currents in three-phase windings of EMS were set different for each of the six CCM grooves.

For comparison we selected a series of 27 melts, casted without stirring in the CCM of PSC "Donetsk metallurgical plant" and PJSC "Yenakiieve Iron and Steel Works". Grade of steel and sections of billets were similar.

Data obtained by CCM automated process control system from the melt reports on the casting speed, water consumption for cooling the mold, the

Table 1. EMS parameters.

Parameter	Quantity
Number of poles	2
Number of phases	3
Phase current in operation, A	150-500
Frequency, Hz	3-6
Intensity between the phase and neutral at the frequency 6 Hz, V	158
Maximum total power, kVA	380
Calculated magnetic field induction, T	0.04
Nominal water consumption, m^3/h	22
Bore diameter, mm	480
Height, mm	530

cooling water temperature differential between inlet and outlet of the mold, the temperature of steel in the tundish ladle were selected for each of the six grooves. According to these data the mass of the formed in the mold solid phase and thickness of the hardened crust at the outlet of the mold were determined.

Figure 1. Six-groove CCM mold 6-strand, equipped with the EMS

The amount of abstracted heat from the mold by cooling water is determined from the following expression

$$Q_m = c_w \cdot G_w \cdot \Delta t_w \cdot \tau_m, \qquad (1)$$

where c_w – specific heat of water, kcal/kg·K; G_w – consumption of water for cooling the mold, l/min; Δt_w – temperature of water heating, which cools the mold, °C; τ_m – residence time of metal in the mold when it moves from the meniscus to the lower cutoff, min;

$$\tau_m = \frac{h_a}{v_c}, \qquad (2)$$

h_a – active height of the mold (the distance from the meniscus to the lower cutoff of the mold), m; v_c -casting speed, m/min.

Due to the abstracted heat from the mold the solidifying billet crust, the mass of which is determined from the expression, is formed [9]

$$m_c = \frac{Q_m}{q_c + q_{ph} + c_s(t_{tl} - t_c) + c_s(t_s - t_{ph})}, \qquad (3)$$

where q_{hc} – the latent heat of crystallization, kcal/kg; q_{ph} – heat of phase transformations of solid and liquid phases, kcal/kg; c_l, c_s – specific heat capacity of liquid and solid phases of the solidifying billet, kcal/kg·°C; t_{tl}, t_s, t_{sp} – steel temperature in the tundish ladle, the solidus temperature, the average temperature of the solidified phase, respectively, °C.

Figure 2 shows a histogram of the crust mass distribution among the grooves of six-groove CCM without and with electromagnetic stirring.

During the residence of the molten metal in the mold the crust shell is formed. The volume of the solidified crust in the mold is determined from the expression

$$V_c = \frac{m_c}{\rho}, \qquad (4)$$

where ρ – crust density kg/dm^3.

The average cross-sectional area of the crust shell is determined by the following expression

$$S_{av} = \frac{V_c}{h_a}, \qquad (5)$$

We find the cross sectional area

$$S_{av} = 2a \cdot \delta_{av} + 2(a - 2\delta_{av})\delta_{av}, \qquad (6)$$

where a – length of the billet, mm; δ_{av} – average thickness of the crust, mm.

Taking into account (1-6), we obtain a quadratic equation for determining the average crust thickness

$$4\delta_{av}^{2} - 4a\delta_{av} + S_{av} = 0, \qquad (7)$$

where $S_{av} = \frac{m_c}{\rho h_a}$.

For a billet 150 × 150 mm equation (7) takes the following form

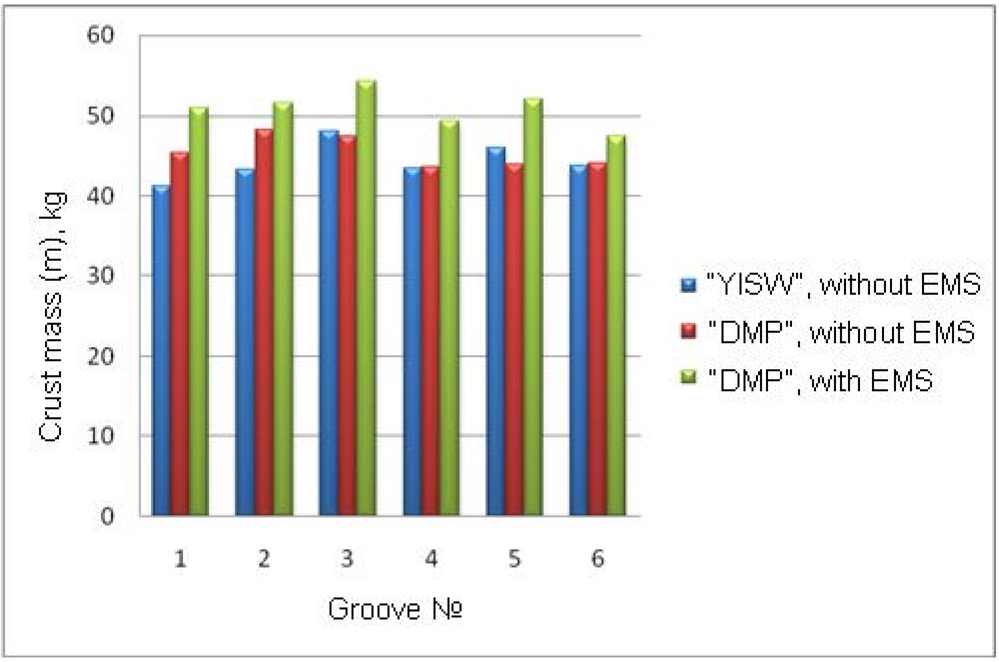

Figure 2. Mass distribution of the crust among the CCM grooves

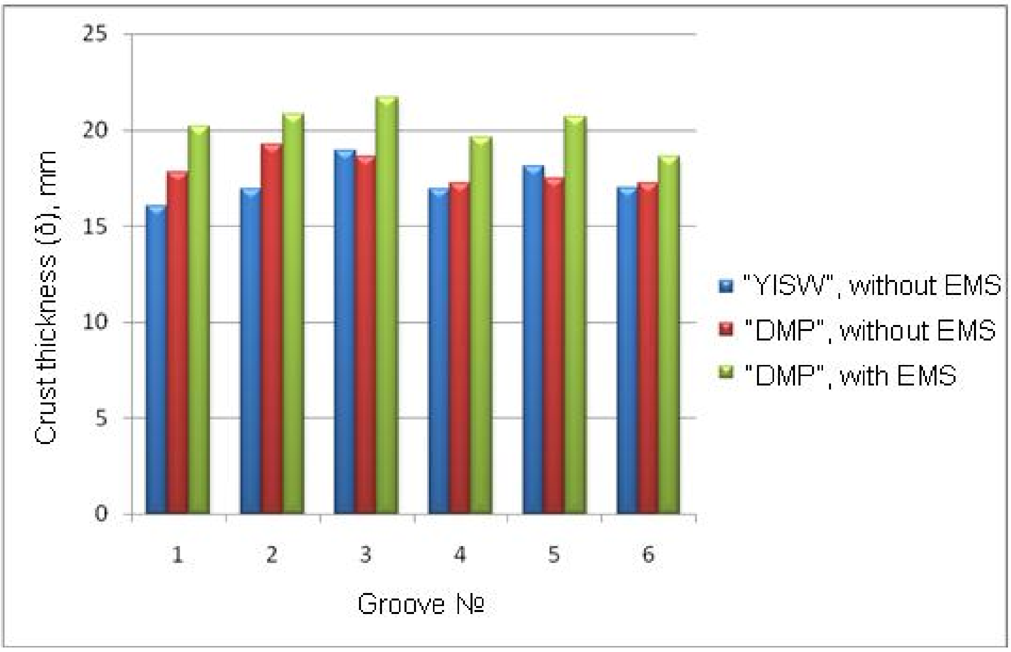

Figure 3. Distribution of crust thickness among the CCM grooves

$$4\delta_{av}^2 - 6\delta_{av} + \frac{m_c}{\rho h_a} = 0, \qquad (8)$$

where $\rho h_a = 69.35$ − for this case.

Using equation (8), we determine the average crust thickness at the outlet of the mold at each groove. Figure 4 shows the histogram of the crust thickness distribution among the CCM grooves without and with electromagnetic stirring.

For the calculation of the crust thickness distribution at the outlet of the CCM mold, according to the time, the following well-known dependence is used [4]

$$\delta = k\sqrt{\tau}, \qquad (9)$$

where k – solidification coefficient, cm/min^{0,5} (k = 2.6 cm/min $^{1/2}$ [6]).

Taking into account (9), the average thickness of the crust δav can be defined as the average integral value of the function (9) in the time range $[0, \tau_m]$

$$\delta_{av} = \frac{\kappa}{\tau_m}\int_0^{\tau_m} \tau^{1/2} d\tau = \frac{2}{3}k\sqrt{\tau_m}, \qquad (10)$$

From expression (10) it follows that the thickness of the crust at the outlet of the mold equals

$$\delta_m = \frac{3}{2}\delta_{av}, \qquad (11)$$

As follows from the data shown in **Figures 2** and **3**, the mass of hardened crust and its thickness are identical for the case of casting steel 3сп in six-groove CCM at PSC "Donetsk metallurgical plant" and PJSC "Yenakiieve Iron and Steel Works" without the use of electromagnetic stirring in the mold. At the same time, the use of electromagnetic stirring with current intensity 230-250 A in the winding of EMS contributes to a significant increase in mass of solidified metal in the mold and of the crust thickness of steel 3сп. It is connected with the fact that electromagnetic stirring increases the intensity of internal heat transfer in the metal bath in the mold.

Conclusions

The study shows that electromagnetic stirring in the CCM mold can significantly increase the mass of solidified metal, what improves the speed of continuous casting in 10-15%.

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Влияние электромагнитного перемешивания стали в кристаллизаторе МНЛЗ на процессы затвердевания заготовки сечением 150×150 мм

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Выполнены экспериментальные исследования и аналитические расчеты по определению массы затвердевшей корки и ее толщины на выходе из кристаллизатора при разливке стали марки 3сп без и с электромагнитным перемешиванием в кристаллизаторе. Установлено, что электромагнитное перемешивание позволяет существенно увеличивает массу затвердевшего металла, что позволяет повысить скорость непрерывной разливки на 10-15 %.