New Solutions in Pipe Billet Production

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Received: 29 July 2024 | Revised: 22 August 2024 | Accepted: 8 September 2024

 DOI: https://doi.org/10.48084/etasr.8554

ABSTRACT

This paper proposes a method for determining the speed of hollow steel billet casting to produce seamless oil and gas pipes. At the same time, the use of hollow billet excludes, in the technological process of pipe production, the piercing of the billet. The results of industrial production modeling were recalculated into natural quantities according to the Fourier number similarity criterion. The calculations determined that the optimal drawing speed and casting speed of a billet with a diameter of 210 mm are 2.01 m/min and 0.273 t/min, respectively. At the same time, productivity increased by 16%, compared to the one when casting a solid billet. To ensure the homogeneity of structure and mechanical properties over the entire cross-section of the hollow billet, the optimum ratio of coolant flow rates into the inner cavity and outside the billet in the secondary cooling zone was determined, considering the area of the cooled surface, which is equal to 1.46.

Keywords-hollow billet; casting speed; secondary cooling zone

I. INTRODUCTION

In any production method, continuous cast steel billets are characterized by composition non-uniformity . The larger the original cross-section of the billet, the greater the degree of chemical heterogeneity across the entire cross-section. Large solid continuous-cast billets entering the rolling process usually contain a high content of carbon and other impurities in the central zone. Therefore, it is recommended to remove metal from the central zone of the billet [1-5]. Furthermore, there are many known options for forming an axial cavity in a billet for subsequent rolling, e.g. drilling of cast solid billet, piercing of solid billet on cross-helical rolling mills, press piercing of solid billet on a hydraulic press, centrifugal casting and casting of hollow billet son continuous casting machines through crystallizers with mandrels. Removal of the defective axial zone from an initially solid billet by drilling or press piercing is ineffective due to the low productivity and high consumption of expensive cutting or deforming tools, which makes them unsuitable for mass production. Also, it is necessary to take into account the presence of surface defects after drilling and after pressing piercing [6, 7]. Highly productive methods for producing hollow billets include helical rolling. As a result of intense alternating deformation of the section and the action of high diametrical tensile stresses, the metal of the axial zone is destroyed [8]. In this case, on piercing mills the metal of the axial zone is not removed, but is pushed from the center into the inner surface layer of the sleeve together with defects.

A promising method is obtaining hollow cast billets directly from the melt, the main ones being made with centrifugal casting or casting with a mandrel. Despite the relevance of centrifugal casting, obtaining centrifugally hollow cast billets will not solve the problem of obtaining high-quality hollow billets due to a number of disadvantages. The supply of liquid metal into a rotating mold from an intermediate dispensing ladle through a tray is carried out by an open stream, which leads to oxidation of the metal, which either lies on the inner surface or is located in layers in the depth of the cast billet [9]. The production of hollow cast billets on continuous casting machines using a mandrel is a fairly productive method that ensures high quality metal, since the two-sided heat removal from the crystallization zone through a water-cooled crystallizer and mandrel ensures rapid cooling of the melt and suppression of the liquation processes. In addition, the absence of blank axial zone eliminates such defects as central porosity and axial liquation [10]. Thus, the most preferable method is to produce hollow blanks on continuous casting machines using a mandrel. However, to the best of our knowledge, there are practically no published works on the calculation of hollow steel billets casting process technological parameters, which is a problem in the design and implementation of the production technology development. As a consequence, the purpose of this work is to develop a methodology for determining the basic parameters of hollow pipe billet casting [11-16].

II. RESEARCH METHOD

The object of the current research is a billet for the pipe production made of 25CrMnV steel with an outer diameter of 210 mm manufactured by LLP KSP Steel. For the calculations, the data of the LLP KSP Steel and the data acquired from the Toraighyrov Uuniversity were considered (Table I). To determine the optimal parameters of the hollow steel billet casting process, aluminum casting was performed at the laboratory facility of the Toraighyrov Uuniversity in accordance with the theory of similarity [17].

TABLE I. INITIAL DATA

Parameter	**LLP KSP Steel**	**Toraighyrov University**
Crystallizer diameter, mm	210	50
Crystallizer height, mm	800	30
Crystallizer material	Copper	Copper
Diameter of mandrel, mm	-	30
Material of billet	25CrMnV (alloy steel)	A5 (primary aluminum)
Thermal diffusivity, W/m·K	80	230
Density, t/m^3	7.85	2.989
Temperature of material in secondary cooling zone (SCZ), °C	950	500
The coefficient of linear expansion, 1/deg	$1.45 \cdot 10^{-5}$	$2.22 \cdot 10^{-5}$

III. RESULTS AND DISCUSSION

The casting speed $q_{st.h}$ for a hollow billet with a diameter of 210 mm was determined by [11]:

$$q_{st.h} = \rho_{st} S_{st.h} v_{st.h} \quad (1)$$

where ρ_{st} is the hardened steel density (t/m^3), $S_{st.h}$ is the cross-sectional area of the hollow billet (m^2), and $v_{st.h}$ is the drawing speed of a steel hollow billet (m/min). The density of the hardened steel is:

$$\rho_{st} = \frac{\rho_{0st}}{1+3\alpha_{st} t_{stSCZ}} = \frac{7,85}{1+3 \cdot 1.45 \cdot 950} = 7.54 \text{ t/m}^3 \quad (2)$$

where ρ_{0st} is the steel density at 0 °C (t/m^3), α_{st} is the linear expansion coefficient of steel (m^2), and t_{stSCZ} is the steel temperature at the end of the SCZ (°C). The cross sectional area of a hollow billet is found by:

$$S_{st.h} = \pi(R_{st}^2 - r_{st}^2) =$$
$$3.14(0.105^2 - 0.072^2) = 183.4 \cdot 10^{-4} \text{m}^2 \quad (3)$$

where R_{st} and r_{st} are the external and internal radii of a steel hollow billet (m). The internal radius of the hollow billet corresponds to the internal radius of the sleeve obtained on the piercing mill. As a result, the casting speed is:

$$q_{st.h} = 7.54 \cdot 183.4 \cdot 10^{-4} v_{st.h} = 0.136 v_{st.h}. \quad (4)$$

The speed of drawing a hollow billet at a continuous casting machine was determined from the condition of equality of the Fourier numbers [17], based on experiments on casting an aluminum hollow billet. The optimal drawing speed of an aluminum billet with a diameter of 50 mm depends on the thickness of the crust formed in the crystallizer, which must withstand the static pressure of the metal and friction against the walls of the crystallizer. The growth of the metal crust, in turn, depends on the residence time of the metal in the crystallizer:

$$\tau_{Al} = \frac{h_{Al}}{v_{Al}} \quad (5)$$

where τ_{Al} is the optimal residence time of aluminum in the crystallizer (min), h_{Al} is the working height of the crystallizer equal to the difference between the total height of the crystallizer and the underfilling (m), and v_{Al} is the drawing speed of the aluminum billet (m/min). The drawing speed of a hollow aluminum billet was determined empirically in the laboratory for continuous casting of Toraighyrov University as can be seen in Figure 1. To do this, the drawing speed increased with fixed maximum time with the condition of maintaining the integrity of the metal crust when leaving the crystallizer. The casting of the aluminum billet was carried out three times at each drawing speed. The average results are shown in Table II.

TABLE II. EXPERIMENTAL DATA FOR CASTING ALUMINUM BILLETS

Drawing speed/ m/min	**Calculated metal residence time in the crystallizer/ min**	**Rupture of the metal crust at the exit of the crystallizer**		
2.0	125×10^{-4}	no	no	no
2.5	100×10^{-4}	no	no	no
3.0	83×10^{-4}	no	no	no
3.5	71×10^{-4}	no	yes	no
4.0	63×10^{-4}	no	yes	yes
4.5	56×10^{-4}	yes	yes	yes

Fig. 1. Facility for continuous casting of billets at the laboratory of Toraighyrov University and hollow aluminum billet.

Analysis of the experimental results determined that the maximum drawing speed of the aluminum billet, with the conditions that the metal crust was not broken, was 3 m/min. From the equality condition of the Fourier numbers, the optimal residence time of a steel billet with a diameter of 210 mm in a crystallizer with a working height of $h_{st} = 700$ mm was determined:

$$\tau_{st.h} = \tau_{Al} \cdot \frac{\beta_{Al} \cdot S_{st.h}}{\beta_{st} \cdot S_{Al}} \quad (6)$$

where $\tau_{st.h}$ is the optimal residence time of a steel in the crystallizer (min), β_{Al}, β_{st} represent the thermal diffusivity of aluminum and steel, respectively (W/m.K), S_{Al} is the cross-sectional area of the aluminum billet (m^2), and $S_{st.h}$ is the cross-sectional area of the steel hollow billet (m^2). The sectional area of the aluminum billet is:

$$S_{Al} = \pi(R_{Al}^2 - r_{Al}^2) =$$
$$3.14(0.025^2 - 0.015^2) = 12.56 \cdot 10^{-4}\ m^2 \quad (7)$$

where R_{Al} and r_{Al} are the external and internal radii of the aluminum hollow billet (m). The optimal residence time of the steel in the crystallizer is:

$$\tau_{st.h} = 83 \cdot 10^{-4} \cdot \frac{230 \cdot 183.4 \cdot 10^{-4}}{80 \cdot 12.56 \cdot 10^{-4}} = 0.348 \text{ min} \quad (8)$$

The speed of drawing a steel hollow billet is:

$$v_{st.h} = {}^{h_{st}}/_{\tau_{st.h}} = {}^{0.7}/_{0.348} = 2.01 \text{ m/min} \quad (9)$$

As a result, the speed of casting a hollow steel billet is:

$$q_{st.h} = 0.136 \cdot 2.01 = 0.273 \text{ t/min} \quad (10)$$

Comparing the values of the casting parameters of solid billet cast on a PB LLP KSP Steel and a hollow steel billet as it can be seen in Table III, it is seen that the drawing and casting speeds of the hollow billet are higher.

TABLE III. TECHNOLOGICAL INDICATORS OF THE CASTING PROCESS FOR 210 mm BILLETS

Parameter	Solid billet*	Hollow billet
Drawing speed, m/min	0.8-0.9	2.01
Casting speed, t/min	0.235	0.273

*current data of the plant PB LLP KSP Steel

The productivity of PB LLP KSP Steel today is 350 thousand tons of round solid billets per year. Thus, in the case of a hollow billet use, the excess in tonnage compared to the solid will is at least 16% or 56 thousand tons. Moreover, as far as the economic expediency is concerned, the use of a hollow cast billet as the initial solution eliminates the need for a pierceing process, which in turn eliminates the excessive consumption of expensive tools from piercing mills, such as rolls and mandrels, guiding rulers and auxiliary tools, not counting labor. When casting a hollow billet, the technological parameters of cooling in the secondary cooling zone will differ from the parameters when cooling a solid billet, due to the difference in the cross section geometry. Because of this, to ensure a homogeneous structure and uniform mechanical properties over the cross section, it is necessary to determine the optimal cooling conditions for the hollow billet. Authors in [18, 19] proposed the use of an improved device for casting a hollow billet. However, a disadvantage of the device is the lack of cooling of the internal cavity of the hardened billet. To ensure uniform cooling of the hollow billet both from the inside and from the outside, it is necessary to determine the optimal ratio of the flow of the air-water mixture inside and outside the billet, respectively.

According to [20-21], water flow G is defined as:

$$G = gS \quad (11)$$

where g is the irrigation density, (m^3/(m^2·h)), and S is the irrigated surface area (m^2).

The irrigation density of the surface of the billet depends on the heat fluxes of the liquid core through the layer of hardened metal, radiation and convection from the surface of the billet. The heat flux depends only on the temperature of the metal and the environment, which are identical outside and inside the billet. The changing parameter is the area of the cooled surface of the billet. Authors in [22, 23] proved that the cooling uniformity depends on geometric parameters and provides more uniform mechanical properties over the cross section of the product. Therefore, the flow rate of the cooler should correspond to the area of the cooled surface:

$$\frac{G_o}{S_o} = \frac{G_i}{S_i} \quad (12)$$

where G_o,G_i represent the cooler consumption on the external and internal surfaces of the billet, respectively (m^3/(m^2·h)) and S_o, S_i represent the area of the cooled surface outside and inside, respectively (m^2).

$$\frac{G_o}{2\pi Rh} = \frac{G_i}{2\pi rh} \quad (13)$$

where R, r are the external and internal radii of the billet (m) and h is the length of the cooled surface (m). To ensure uniform cooling of the work piece and, accordingly, the growth of the metal crust with the same thickness during solidification, the ratio of the flow to the external and internal surfaces should be:

$$G_o = \frac{R}{r} \cdot G_i \quad (14)$$

According to the calculation results for a hollow billet with a diameter of 210 mm and an inner diameter of 144 mm, the flow rate of the cooler to the outer surface should be 1.46 times greater than with the inner. Subject to this cooling condition, the initial quality of the billet improves the final properties of the finished pipe and facilitates the production of high-strength pipes using appropriate heat treatment modes [24-27].

IV. CONCLUSIONS

This work proposes a method for determining the process parameters of hollow billet continuous casting, such as the drawing speed and the casting speed. Calculations of the process parameters for casting a hollow steel billet were performed using physical modeling of the hollow aluminum billet casting process based on the new Fourier similarity criteria. Calculations of the drawing speed and casting speed of a billet with a diameter of 210 mm determined that the optimal drawing speed is 2.01 m/min and the casting speed is 0.273 t/min. At the same time, productivity increases by 16%, compared to casting a solid billet. So, the feasibility of using the production of a hollow billet is substantiated, not only due to the improved quality, the absence of defects such as central porosity and axial liquation, but also due to increased productivity. The novel proposed optimal method for cooling a hollow billet in the secondary cooling zone consists of supplying coolant to the outer and inner surfaces of the billet depending on the area of the cooled surface. In the case of a billet with an outer diameter of 210 mm, the optimal ratio is 1.46. The results of the current work make a significant contribution to metallurgical production and in the production of seamless steel pipes. This research will allow the use of the proposed calculation methods when introducing hollow billet casting into production.

ACKNOWLEDGMENT

This research was supported by the Ministry of Education and Science of the Republic of Kazakhstan within the framework of grant funding of young scientists for scientific and (or) scientific and technical projects for 2022-2024 under the IRN AP14972971 project «Research the structure formation and mechanical properties of oil assortments pipes produced from cast hollow billets».

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