Metallurgy

Continuous Casting of Hollow Iron Billets and the Method of Casting Process Automation

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ABSTRACT. Theoretical calculations of optimal drawing force of hollow billet out of crystallizer is elaborated. Design of automation process device for hollow billets continuous casting is presented.

Key words: *continuous casting method, hollow iron billets, pipe.*

Recently, the casting of iron pipes by the semi-continuous casting method is well mastered and it is successfully applied in foundry industry. As regards the casting of hollow iron billets with wall thickness δ=25-45 mm at relatively minor diameters (150-350 mm), its range of application is a lot more in machine building hence it is poorly studied. In order to understand the difficulty of casting of such thick-walled billets, let us consider the formation process of hollow foundry in water-cooled metallic crystallizers.

In casting hollow ingots from metal characterized by preshrink expansion, the profile of the internal crystallizer (mandrel) consists of two zones - cylindrical and conical. The cylindrical zone corresponds to the process of preshrink ingot expansion and the conical to metal setting [1,2]. At the same time, the angle of cone slope should maximally coincide with the rate and value of linear shrinkage of drawn casting . Unlike thin-walled pipes (δ=8-16 mm), whose temperature is in the range 1000°C and shrinkage not more than 0.2% [3] on crystallizer output, billets with wall thickness δ=25-45 mm (at external diameter of billet 150-350mm) have temperature in the range of 850-900°C. By this time the value of shrinkage reaches 0.35-0.4% and probability of the capture of internal crystallizer dramatically increases. Taking into consideration that iron has some plasticity at 1000°C and 0.2% shrinkages cannot strongly affect the force of drawing the ingot out of the crystallizer, whereas, the crust of the ingot is sufficiently stable at 900°C, devoid of any plasticity and the ingot can become wedged in the cavity of the crystallizer at 0.4% linear shrinkage under wrong selection of the profile of the internal crystallizer (mandrel).

An optimum alternative of the casting process of hollow ingots is the case when the internal surface of the stretched ingot fits closely to the surface of mandrel (maximum heat exchange takes place). At the same time, the extraction from the cavity of the crystallizer is effected without considerable force, i.e. despite the shrinkage phenomena of capture of internal crystallizer by casting ingots due to correct selection of profile of mandrel.

Taking into account the circumstance that at such sizes (δ=25-45 mm) at the exit from the stabilizer, the billet is fully solidified and has a liquid core there is practically no extrusion influence of the outer crust on the force of stretching, and the more so on the capture of mandrel from the part of the hollow billet. Therefore, it is safe to say that the stability of the casting process depends entirely on the conditions of formation of the internal surface of the hollow billet. This, in turn, is controlled by the force of extrusion of the hollow billet out of the internal crystallizer.

Proceeding precisely from this consideration, the authors set themselves the goal in the proposed paper to establish a correlation between the drawing ingot force and design sizes of separate zones of mandrel (cylindrical, conical, and the angle of cone slope) and main technological parameters of casting (the rate of ingot extraction, metal temperature, the crystallization coefficient).

Let us consider in more detail the formation process of a hollow billet on the part of internal crystallizer (mandrel) and the degree of impact of the formed crust on the surface of the mandrel as a result of shrinkage phenomena (Fig. 1).

In the solidification process, the newly formed crust tries to have the following length:

$$l_o=\pi d_o(1-\alpha t_o+\alpha t) \quad (1)$$

but practically its length is equal to:

$$l=\pi d_{(x)}, \quad (2)$$

where l_o is length of crust; d_o - diameter of billet (internal) at meniscus; α - coefficient of linear expansion; t_o - temperature of solidification; t - temperature of crust (fluid); $d_{(x)}$ - diameter of crust (fluid).

The extension totals:

$$l_o=\pi [d_{(x)} - d_o\alpha (t_o-t)]; \quad (3)$$

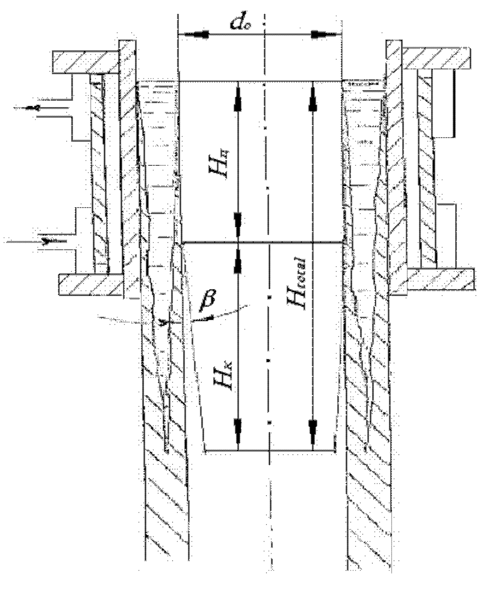

Fig. 1. Contact zones of hollow ingot with crystallizer (mandrel)

$$\varepsilon = \frac{\Delta\ell}{\ell_o} = \frac{d_{(x)} - d_o + \alpha(t_o - t)d_o}{d_o}. \quad (4)$$

Stress at elastic deformation:

$$\sigma = E\varepsilon = \frac{E}{d_o}[d_{(x)} - d_o + \alpha(t_o - t)d_o], \quad (5)$$

where E is average modulus of crust strain. Besides:

$$\rho = \frac{\sigma \cdot \delta}{R_o}, \quad (6)$$

where R_o is radius of internal cavity of billet; d - thickness of billet crust.

The specific pressure of billet crust on the surface of mandrel is obtained by insertion of the value s in equation (6):

$$\rho = \frac{E\delta}{R_o d_o}[d_{(x)} - d_o + \alpha(t_o - t)d_o]. \quad (7)$$

The mandrel profile can be presented in the following way:

$$d_{(x)} = d_o\,[1-\varphi_{(x)}]. \quad (8)$$

$$\varphi_{(x)} = \begin{cases} 0_1 & 0 \le x \le H_{cyl} \\ \varphi_{1(x)} & H_{cyl} \le x \le H_{cyl} + H_{con} \end{cases},$$

$$\rho_{(x)} = 1 - \frac{d_{(x)}}{d_o},$$

$$t = t_o - m\,x,$$

$$\rho_{(x)} = \frac{EK_2\sqrt{x}}{R_o\sqrt{v}}[-\varphi_{(x)} + \alpha(t_o - t)], \quad (9)$$

where K_2 is coefficient of solidification on the part of the mandrel; V – rate of casting; X – coordinate; $\delta=K\left(\frac{x}{v}\right)^{1/2}$ - crust thickness.

The profile of internal crystallizer (mandrel) is ideally selected, when P=0, i.e. when

$$\varphi_{(x)}=\alpha(t_o-t).$$

Let us present the function $t_{(x)}$ in the following way:

$$t=t_o-mx, \quad (10)$$

where $x=H_{con}+H_{cyl}=H_{total.}\ t_1=t_o-m\,H_{total.}$

$$m = \frac{t_o - t_1}{H_{total}};$$

$$t = t_o - \frac{t_o - t_1}{H_{total}} \cdot x;$$

by inserting the value m in equation (10), we obtain:

$$t = t_o - \frac{(t_o - t_1)}{H_{total}} \cdot x, \qquad (11)$$

where t_1 is the temperature of billet crust at its exit from the crystallizer. By inserting the value t in equation (9) we obtain:

$$P_{(x)} = \frac{EK_2\sqrt{x}}{R_o\sqrt{v}} \cdot \left[-\varphi_{(x)} + \frac{\alpha(t_o - t_1)}{H_{total}} \cdot x \right]; \qquad (12)$$

$$d_{(x)} = \begin{cases} d_o; & 0 \le x \le H_{cyl} \\ d_{1(x)}; & H_{cyl} \le x \le H_{cyl} + H_{con} = H_{total} \end{cases}$$

$$d_{(H_{total})} = d_{1(H_{total})} = d_1;$$

$$d_{1(x)} = d_o - cx;$$

$$d_{1(x)} = d_o - cH_{total} \qquad c = \frac{d_o - d_1}{H_{total}};$$

$$d_{1(x)} = d_o \left[1 - \frac{(d_o - d_1)x}{d_o H_{total}} \right]; \qquad (13)$$

$$d_{(x)} = \begin{cases} d_o; & 0 \le x \le H_{cyl} \\ d_o \left[1 - \frac{(d_o - d_1)x}{d_o H_{total}} \right]; & H_{cyl} \le x \le H_{total} \end{cases} \qquad (14)$$

$$\varphi_{(x)} = \begin{cases} 0; & 0 \le x \le H_{cyl} \\ \frac{(d_o - d_1)}{d_o H_{total}} x; & H_{cyl} \le x \le H_{total} \end{cases}$$

$$\frac{(d_o - d_1)}{2} = H_\kappa \cdot tg\beta$$

$$\varphi_{(x)} = \begin{cases} 0; & 0 \le x \le H_{cyl} \\ \frac{2H_{con} tg\beta \cdot x}{d_o H_{total}}; & H_{cyl} \le x \le H_{total} \end{cases}. \qquad (15)$$

The equation of the specific pressure of billet crust on the surface of the mandrel has the following form:

$$P_{(x)} = \begin{cases} \frac{EK_2\sqrt{x}}{R_o\sqrt{v}} \cdot \frac{\alpha(t_o - t_1)}{H_{total}} \cdot x; & 0 \le x \le H_{cyl} \\ \frac{EK_2\sqrt{x}}{R_o\sqrt{v}} \cdot \left[\frac{\alpha(t_o - t_1) \cdot x}{H_{total}} - \frac{2H_{con} tg\beta \cdot x}{d_o H_{total}} \right]; & H_{cyl} \le x \le H_{total} \end{cases} \qquad (16)$$

The strain of friction amplification on a given surface will be equal to:

$$\tau_{(total)} = \mu P_{(x)} = \begin{cases} \frac{2\mu EK_2 x^{1,5}}{R_o\sqrt{v}} \cdot \frac{\alpha(t_o - t_1)}{H_{total}}; & 0 \le x \le H_{cyl} \\ \frac{2\mu EK_2 x^{1,5}}{d_o\sqrt{v}} \cdot \left[\frac{\alpha(t_o - t_1)}{H_{total}} - \frac{2H_{con} tg\beta}{d_o H_{total}} \right]; & H_{cyl} \le x \le H_{total} \end{cases}.$$

The friction amplification is equal to:

$$dT = 2\pi\tau_n \frac{d_o}{2} dx = \pi d_o \tau_n dx;$$

the integral friction amplification:

$$T_{(t)} = \int_0^x \pi d_o \tau_{total} dx = \begin{cases} \pi \frac{2\mu EK_2 x^{5/2}}{5/2 \sqrt{v}} \cdot \frac{\alpha(t_o - t_1)}{H_{total}}; & 0 \le x \le H_{cyl} \\ \frac{4\pi\mu K_2 x^{5/2}}{5\sqrt{v}} \cdot \left[\frac{\alpha(t_o - t_1)}{H_{total}} - \frac{2H_{con} tg\beta}{d_o H_{total}} \right]; & H_{cyl} \le x \le H_{total} \end{cases}$$

Therefore, to the full height of crystallizer (mandrel), the friction amplification of crust against mandrel (at the expense of the mandrel) is equal to:

$$T_{(H_{total.})} = \frac{4\pi\mu EK_2 H_{total}^{3/2}}{5\sqrt{v}} \cdot \left[\frac{\alpha(t_o - t_1)}{1} - \frac{2H_{con} tg\beta}{d_o} \right]; \qquad (17)$$

Taking into account the crust effect on the surface of the internal crystallizer at the expense of the ferrostatic pressure of liquid metal of billet:

$$T_{(f\cdot st.)} = \int_0^{H_{total.}} \mu\gamma S_1 x \, dx = \frac{\mu\gamma}{2} S_1 H^2_{total}. \qquad (18)$$

$$T_{(f.st.)} = 1.57 \mu \gamma d_o H^2_{total}. \quad (19)$$

Therefore, the total drawing ingot force from the mandrel is equal to:

$$T_{(total)} = \frac{4\pi \mu E K_2 H_{total}^{3/2}}{5\sqrt{v}} \cdot \left[\alpha(t_o - t_1) - \frac{2H_{con} tg\beta}{d_o} \right] + + 1.57 \mu \gamma d_o H^2_{total}. \quad (20)$$

With the knowledge of interconnection between the main technological casting parameters and the design parameters of mandrels (the profile of mandrel), the stability of the continuous casting process of hollow billets cannot be a difficult task. However, as further experimental investigations have shown, this is far from sufficient for ensuring the complete safety of the casting process, especially, in industrial conditions. The point is that the stability of the continuous casting process of hollow castings completely depends on the formation conditions of the internal surface of casting. The control of the casting process is effected only by shrinkage force of hollow billet from mandrel. Moreover, as is seen in expression 20, a direct relation exists between the duration of the contact zone (H_{con}+H_{cyl}) of hollow casting with the internal crystallizer and drawing force. The slightest deviation from the technological regime of casting to any side direction is fraught with serious consequences. Naturally enough, the contact zone duration of a hollow ingot is easily regulated by the liquid metal level in the cavity of the crystallizer. It should be noted that a hollow billet has a fluid mandrel in its exit from the crystallizer, i.e. the formation of internal and external sides of billets occurs practically independently up to that time. Excessive or insufficient cooling of the internal crust is by no means related to the external one, but under the available designs of crystallizer units, when both crystallizers are rigidly fixed on common frame, their displacement independently of one another relatively to the level of liquid metal (meniscus) is impossible.

A special design construction of crystallizer unit was developed at the Institute of Metallurgy of the Georgian Academy of Sciences, allowing automation of the continuous casting process of hollow billets (Author's Certificate 1284652. The method of continuous casting of hollow billets and device for its realization [4], Fig. 2).

The method is based on the possibility of regulation of the magnitude of the contact ingot zone with mandrel at the expense of its movement along the height independently of the external crystallizer, i.e. at the expense of controlling the intensity by the shrinkage processes occurring in the ingot under formation. This device works at constant level of liquid metal in the cavity of the crystallizer, thereby allowing application of standard control schemes of liquid metal level in crystallizer, with the help of which the fluctuation of liquid metal can be regulated in the range ±5 mm [5].

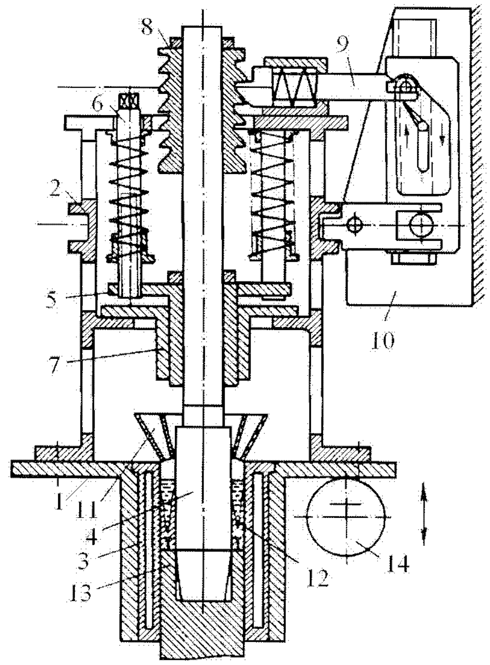

Fig. 2. Device for automation of the continuous casting process of hollow billets
1 – Body; 2 – Bearer frame; 3 – Crystallizer; 4 – Internal crystallizer (mandrel); 5 – Cup; 6 – Elastic elements; 7 – Guide cup; 8 – Ratchet; 9 – Stopper; 10 – System of reciprocative transportation of stopper; 11 – Casting funnel; 12 – Bar; 13 – Seed; 14 – Mechanism of reciprocative transportation of crystallizer.

The only condition of the effective work of the proposed device is to effect the downward movement of the crystallizer body in the process of swinging quicker than the rate of hollow billet drawing. In this case, effectiveness is higher when $V > V_1$.

The principle of the work of the device is the following. After the achievement by the liquid metal level of prescribed height, the ingot drawing begins simultaneously with the switch-on of the reciprotative mechanism-14. Initially, the stripping force is high (400-700 kg·p), but due to stopper 9, which is tightly pressed to ratchet 8, synchronized movement of crystallizer 3 and mandrel 4 is ensured. Subsequently, at every cycle of swinging, when the body of the crystallizer moves up, stopper 9 is in a pressed condition.

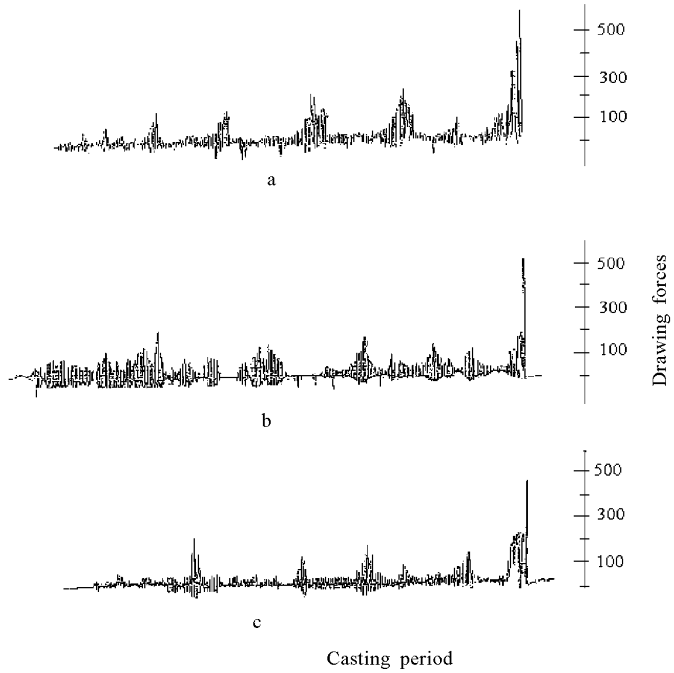

Fig. 3. Diagram of drawing forces of hollow billet from internal crystallizer

a – grey iron	∅ 240 mm	d - 32 mm
b – high-strength iron	∅ 240 mm	d - 32 mm
c –high-strength iron	∅ 150 mm	d - 24 mm

At the moment of the moving of crystallizer 3 and mandrel 4 down, at the reverse step of swinging, the system of reciprocative motion of stopper 10 disengages stopper 9 from meshing with the teeth of ratchet 8. Therefore, the springs of elastic elements are released and have the opportunity to develop a vertical force, corresponding to the pre-established optimal value of frictional forces between mandrel and billet. In emergency conditions, when the main technological parameters break down for some reason, billet shrinkage occurs with unforseen intensity and the drawing force does not correspond to the forces provided for in advance in the springs of elastic elements; the mechanism of mandrel reciprotative motion in the vertical direction begins to operate.

At slowed billet shrinkage, the elastic elements generate a pre-set force, allowing the mandrel to go down to the necessary distance per one cycle of swinging.

At acceleration of the billet shrinkage, a shrinkage friction between mandrel and billet at a lower depth is compensated by the force of springs, and mandrel goes down to the billet cavity at a lower depth. At the same time, in contrast to the above-described, when the required area of contact is set for one cycle of swinging, in the given case, the change of the depth of mandrel descendig is limited. At each swinging cycle, the device allows reduction of the contact area by the value h-h_1 (due to the difference in the moving rate of crystallizer and hollow billet), where h is the run of crystallizer, h_1 is the run of ingot during descending of the crystallizer. For the purpose of more operative alteration of the contact area, the oscillation frequency can be temporarily increased to maximum allowable value before the process of stabilization.

Let us consider the effectiveness of the proposed design on the example. Fig. 3 (a, b, c).

Fig. 3a shows the diagrams of alteration of the drawing forces of a hollow billet from internal crystallizer at continuous casting of a hollow billet of grey iron with diameter 240 mm and thickness d=32 mm. The swinging frequency of the crystallizer body is equal to 90 swing./min and amplitude - 15 mm. The rate of extension is 0.5 m/min. At the given regime of swinging each cycle runs for 0.66 sec. As is seen from the diagrams, the drawing forces increased and decreased several times during the proposed casting period.

Judging by the quantity of swinging, in the case of an increase of the drawing force, the proposed device completely corrected the drawing force over 6-7 cycles of swinging (4-4.5 sec). As regards the cases of decreasing of the drawing force, as mentioned above, correction takes place for one cycle of swinging.

მეტალურგია

თუჯის ღრუტანიანი ნამზადების უწყვეტი ჩამოსხმა და ჩამოსხმის პროცესის ავტომატიზაცია

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თუჯის ღრუტანიანი ნამზადების უწყვეტი ჩამოსხმის პროცესის სტაბილურობა ბევრად არის დამოკიდებული შიგნითა კრისტალიზატორის (დორნის) პროფილის სწორად შერჩევაზე. ჩამოსხმის პროცესის კონტროლი და ამავე დროს მართვა სწორედ სხმულის კრისტალიზატორიდან გამოწევის ძალის საშუალებით ხორციელდება. თეორიული გაანგარიშებების საფუძველზე მიღებულია ემპირიული ფორმულა, სადაც ასახულია ჩამოსხმის ძირითადი ტექნოლოგიური პარამეტრებისა და დორნის კონსტრუქციული პარამეტრების გავლენა სხმულის კრისტალიზატორიდან გამოწევის ძალებზე. მიღებული გამოსახულების ანალიზი, ისევე როგორც შემდგომი ექსპერიმენტული კვლევები, ცხადყოფს, რომ ჩამოსხმის პროცესი იმდენად მგრძნობიარეა თითოეული ამ პარამეტრის მიმართ, რომ ოპერატორის მხრიდან პრაქტიკულად შეუძლებელია (მით უმეტეს წარმოების პირობებში) პროცესის დარღვევის შემთხვევაში დროული რეაგირება. ამიტომ აუცილებელია ჩამოსხმის პროცესის ავტომატიზაცია.

ნაშრომში წარმოდგენილია ჩამოსხმის პროცესის ავტომატიზაციის ორიგინალური მოწყობილობა, განხილულია მისი ფუნქციონერების პრინციპი. მოყვანილია გამოწევის ძალის ცვლილებების ამსახველი დიაგრამები საიდანაც ნათლად ჩანს, რამდენად ოპერატიულად ახდენს რეაგირებას ავტომატიზაციის მოწყობილობა ოპტიმალური რეჟიმიდან გადაცდომის შემთხვევაში.

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