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Dependence of Stretching Force on Conicity of Crystallizer

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ABSTRACT. At continuous casting, the quality of billet and stability of the process depend on the quality of contact between the walls of the crystallizer and the billet.

Conicity of a crystallizer is one of the effective methods to provide permanent contact between the crystallizer and the billet along the whole length of the crystallizer.

In the paper the influence of conicity of the crystallizer on the stretching force of the billet on the example of a round billet is shown. The results obtained are generalized to rectangular billets. *© 2011 Bull. Georg. Natl. Acad. Sci.*

Key words: *conicity of crystallizer, continuous casting.*

It is known that at continuous and semicontinuous casting, as a rule, there is a gap formed between the walls of the crystallizer and billet due to settling of the latter. As a result heat exchange sharply decreases which could be caused by the heating of the consolidated skin of the billet as well as by the occurrence of unfavourable thermal stresses. One of the most effective methods to provide full contact of the billet with crystallizer along the whole length is the application of a crystallizer with reverse conicity. In order to provide non-obstacle sliding of the shell of the forming billet by the working walls of the crystallizer and not allowing extra large stretching force it is necessary to make a theoretical evaluation of the dependence of the stretching force on the conicity of the crystalizer.

Let us consider the example with a round billet shown in Fig.1. Assume that the radius of the meniscus is equal to R_0 at the temperature of hardening t_0. Then while cooling, the given layer tends to have the size

$$R' = R_0[1-\alpha(t_0 - t_c)],$$

where $t_c = \frac{1}{2}(t_0 + t_n)$ is the average temperature of the billet skin, t_n is the temperature of the billet surface.

$$R' = R_0\left(1-\alpha t_0 + \frac{\alpha t_0}{2} + \frac{\alpha t_n}{2}\right) = R_0\left[1-\frac{\alpha(t_0 - t_n)}{2}\right].$$

In fact the profile of the crystallizer is defined by the function $R(x)$. If $R(x)>R_1$, then reduction does not occur. If there are parts on which $R(x)<R^2$, then plastic deformation occurs, as the pipe is drawn on these parts. The walls of the crystallizer serve as matrix.

Let us have n parts in the general case; on each at the beginning R_{0i}, and at the end R_{1i}. Then according to the general methods of the theory of plasticity, the force of drawing in the i-th part will be equal to (without friction) [1,2]:

$$T = 2K \ln\lambda \cdot 2\pi R_{1i}\delta_1, \qquad (1)$$

where $K = \frac{\sigma_s}{\sqrt{3}}$, σ_s is limit of the fluidity, δ - skin thickness, $\lambda = \frac{R_{0i}}{R_{1i}}$.

This formula is applied at small angles, as in the given case. Moreover, as the reduction is small

$$\ln n \approx \ln\left(1+\frac{R_{0i}}{R_{1i}}-1\right) \approx \frac{R_{0i}-R_{1i}}{R_{0i}}, \qquad (2)$$

$$T_i = \frac{2}{\sqrt{3}}\sigma_s \frac{\Delta R_i}{R_{0i}} 2\pi R_{0i}\sigma_i = 7.2\sigma_s \Delta R_i \delta_i .$$

To take into account friction force we add the value

$$\Delta T_i' \approx 2\pi R_{0i}\ell_i \mu P, \qquad (3)$$

where ℓ_i is the length of the given part, μ – friction coefficient, P – specific pressure, which is now defined not by ferrostatic pressure but by the process of plastic deformation.

At small angles the billet skin may be considered as a thin-walled pipe and accepted as

$$P = 2K \ln \frac{R_{0i}}{R_{0i}-\delta_i} \approx 2K \frac{\delta_i}{R_{0i}}.$$

Then full force

$$T_i + \Delta T_i = 7.2\sigma_s \Delta R_i \delta_i + 6.28 \cdot 1.15 \sigma_{si} \delta_i \ell_i \mu =$$

$$7.2\sigma_{si}\Delta R_i \delta_i + 7.2\sigma_{si}\delta_i \ell_i \mu = 7.2\sigma_{si}\delta_i(\Delta R_i + \mu \ell_i).$$

Full force should be defined summing these values in all the parts, on which $R < R'$

$$F = 7.2\sum_{i=1}^{n} \sigma_{si}\delta_i(\Delta R_i + \mu\ell_i). \qquad (4)$$

In the simplest case we take that R' and R are changed linearly

$$t_n = t_{no} - (t_{no} - t_{n1})\frac{x}{\ell},$$

where t_{n0} is the meniscus's primary temperature, t_{n1} surface temperature on the outlet from crystallizer at the length equaled to ℓ.

$$R' = R_0\left\{1-\frac{\alpha}{2}[t_0 - t_{n0} + (t_{n0}-t_1)]\frac{x}{\ell}\right\},$$

and at $t_{n0} = t_0$

$$R' = R_0\left[1-\frac{\alpha}{2}(t_0-t_1)\frac{x}{\ell}\right],$$

at $x = \ell$

$$R_1' = R_o\left[1-\frac{\alpha}{2}(t_o - t_1)\right].$$

Let the crystallizer be fulfilled with conicity and

$$R_1 = R_o - (R_o - R_1)\frac{x}{\ell}.$$

Here R_1 is a radius on the outlet of the crystallizer.

At $R_1 < R_1'$ plastic deformation will take place and its force according to (4) will be:

$$F = 7.2\sigma_s\delta\left[(R_1 - R_1') + \mu\ell_i\right] =$$

$$7.2\sigma_s\delta\left[R_0 - \frac{R_0\alpha}{2}(t_0-t_1) - R_0 + (R_0 - R_i) + \mu\ell\right] =$$

$$= 7.2\sigma_s\delta\left[\mu\ell + R_0 - R_1 - \frac{R_0\alpha}{2}(t_0-t_1)\right] \qquad (5)$$

It is essential that the dependence $F(\mu)$ is linear.

$$R_0 - R_1 \geq R_0\frac{\alpha}{2}(t_0 - t_1).$$

At R_0 = 20 cm, $a = 10^{-5}$ 1/grad, t_0 = 1500 °C, t_1 = 1100 °C.

$$R_0 - R_1 \geq \frac{20}{2}10^{-5}\cdot 400 = 0.04\text{cm} = 0.4\text{mm}.$$

Deformation of the "drawing" type will take place already at conicity more than 0.4 mm per radius or 0.8 mm per diameter. In practice even higher values of conicity are used.

Taking the average thickness of the billet's skin at $x = \frac{\ell}{2}$

$$\delta_{\text{aver}} = K\sqrt{\frac{\ell}{2v}},$$

where v is the pouring rate and σ_{sc} = 765-0.51t_c [3].

$$t_c = \frac{t_c + t_{nc}}{2}, \text{ at } x = \frac{\ell}{2},\ t_n = t_{nc}.$$

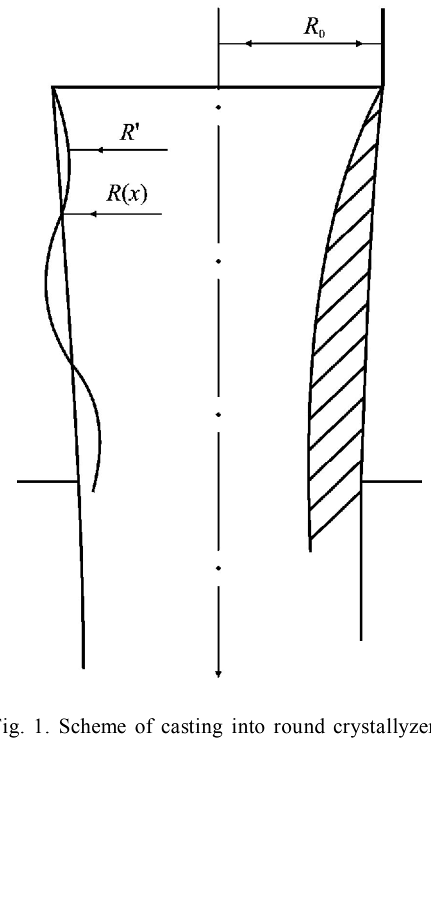

Fig. 1. Scheme of casting into round crystallyzer.

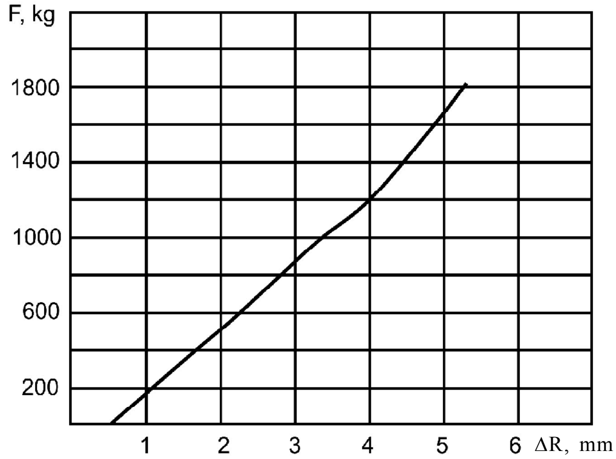

Fig. 2. Dependence of the force on conicity at circle casting Ø400 mm.

$$t_{nc} = t_0 - \frac{(t_0 - t_1)}{2} = \frac{t_0 + t_1}{2};\quad t_c = \frac{t_0}{2} + \frac{t_0}{4} + \frac{t_1}{4} = \frac{3t_0 + t_1}{4};$$

$$\sigma_{sc} \approx 765 - 0.13(3t_0 + t_1)$$

At $K = 2.8$ cm/min$^{0.5}$, $v = 30$ cm/min, $\ell = 100$ cm.

$$\delta = 2.8\sqrt{\frac{100}{2 \cdot 30}} = 3.6\,\text{cm},$$

$$\sigma = 765 - 0.13(3.1500 + 1100) = 40\,\text{kg/cm}^2.$$

Formula at small values of conicity exceeds the force, as the pressure $2K \ln \dfrac{R_0}{R_0 - \delta}$ requires considerable deformation.

Not taking friction force into account, we have

$$F = 7.26\sigma_s\delta\left[R_0 - R_1 - R_0\frac{\alpha}{2}(t_0 - t_1)\right]. \tag{6}$$

Taking into account σ and t_c in the cross-section on the outlet from crystallizer, i.e.

$$\delta = K\sqrt{\frac{\ell}{v}};\ t_c = \frac{t_0 + t_{ni}}{2};\ \sigma_s = 765 - 0.26(t_0 - t_{n1}),$$

then at the given parameters

$$\delta = 2.8\sqrt{\frac{100}{30}} = 5.1\,\text{cm};$$

$$\sigma_s = 765 - 0.26 \cdot 2600 = 90\,\text{kg/cm}^2,$$

$$A = 7.2 \cdot 90 \cdot 5.1\left(20 - R_1 - \frac{20}{2}10^{-5} \cdot 400\right) =$$

$$= 3300(20 - R_1 - 0.04).$$

At $R_1 = 19.9$ cm, $F = 200$ kg. At $R_1 = 19.8$ cm, $F = 530$ kg.

Dependence F on $\Delta R = R_0 - R_1$ is shown in Fig.2.

It is seen that conicity strongly influences the force. At deterioration conicity is destroyed, causing a sharp decrease of the effort, i.e. the so-called "run-in" occurs.

We must note that in the parts in which "blowing" of the billet instead of compression occurs the proof of the skin should be taken into account. At the distance of x from the meniscus the pressure is equal to $f(x)$, and

$$fx - \sigma_s \ln\frac{R}{R - \delta} \approx fx - \sigma_s\frac{\delta}{R}.$$

While casting into square (rectangular) crystallizer we can use the same formulae, changing by the sides of the square one half, if there is the same conicity on all the four facets.

$$F = 4.6\sigma_s\delta\left[a_0 - a_1 - a_0\frac{\alpha}{2}(t_0 - t_1)\right]. \tag{7}$$

If conicity is equal to a_0-a_1 on two facets with the size axb and on the other two facets with the size b_0-b_1 then

$$F = 2.3\sigma_s\delta\left[a_0 - a_1 - a_0\frac{\alpha}{2}(t_0 - t_1)\right] +$$

$$+ 2.3\sigma_s\delta\left[b_0 - b_1 - b_0\frac{\alpha}{2}(t_0 - t_1)\right]. \tag{8}$$

The obtained formulae allow to calculate the optimal conicity of crystallizers at given technological regimes.

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