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Analysis of the influence parameters on steel strip defects in continuous roll casting-rolling

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Problems. *The casting-rolling process is currently one of the most effective and promising processes used for the production of steel sheets. The advantages of this process include the small dimensions of the unit and a significant reduction in energy resources. This occurs due to a combination of technological operations and absence of the intermediate heating of the metal. At the same time, there is the challenge of a sustainable industrial process for producing high quality steel sheets.*
Objective. *Companies developing direct melt strip processes using twin-roll crystallizers report a number of challenges they face. Among such problems are defects on the surface of the cast strip. Currently, there is no generally accepted classification of surface defects, such as surface cracks, wrinkles, namely, depressions, and transverse deformation bands. At the moment, there is also no justification for the reasons for the appearance of surface defects during the rolling process.*
Methods. *Based on the research results, a hypothesis was proposed about the causes of defects on the surface of the cast strip and ways to prevent them. During the operation of two-roll crystallizers, a combination of metal hardening processes and its subsequent plastic deformation occurs. The metal moves sequentially through areas of crystallization and deformation. During the research, the authors calculated the process of roll casting-rolling.*
Conclusions. *Based on the research results, we believe that when casting steel using twin-roll casting-rolling, it is necessary to reduce the compression to a minimum value. This recommendation will ensure welding of defects on the surface. The use of this proposal will allow the casting process to be carried out at high speed and little force to be applied to squeeze the rolls. We propose to carry out the process of forming a cast strip with the necessary quality parameters at the following stages of rolling.*

Keywords: *roll casting-rolling, casting, rolling, squeeze, reverse speed, rolling effort.*

Introduction

The most promising and efficient process for producing steel sheets is roll casting-rolling. Among the advantages of this method of producing steel sheets, it is important to note the significant energy savings, which reaches up to ninety percent, and the compactness of the installation. Why is this happening. When using the casting-rolling method, the number of operations is reduced. In addition, due to the absence of the need for intermediate heating of the metal, the need for energy resources is also reduced, which is very important today. But even with the introduction of the twin-roll casting method into production, the problem of sustainable industrial production of high-quality steel sheets does not disappear. Many Japanese companies and firms use twin-roll crystallizer to produce liquid steel strips. These companies and firms note the appearance of specific defects on the surface of the strips that are cast in twin-roll crystallizer. And although there is no clear and accurate classification of surface defects in this process, the most characteristic of them can still be identified. These include transverse deformation bands, transverse deformation depressions, surface cracks, wrinkles and namely.

State of the issue

One of the characteristic features of two-roll crystallizers is the joint crystallization of liquid metal and its subsequent plastic deformation in the zone between the rolls rotating towards each other. The metal, falling between the

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rolls, alternately passes through various zones of crystallization and deformation. In Fig. 1. shows the relative position of the crystallization and deformation zones during continuous rolling.

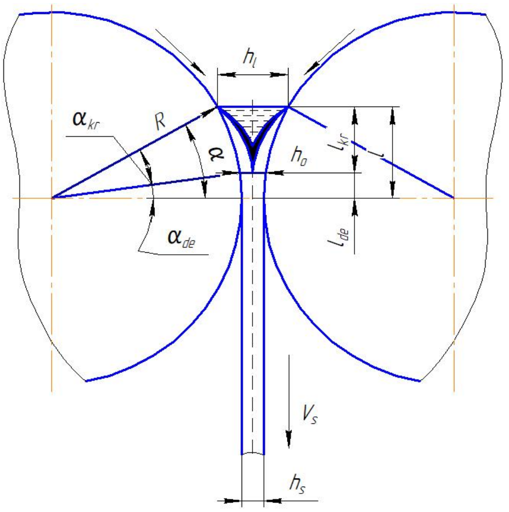


Fig. 1. Scheme presenting cross-section of continuous roll casting-rolling: R – outer radius of the roll; ℓ – total length of the crystallization-deformation zone; α – angle of contact between the metal and the roll; ℓ_{kr} – length of the crystallization zone; α_{kr} – angle of the crystallization zone; ℓ_{de} – length of the deformation zone; α_{de} – angle of the deformation zone (rolling section); h_l – cross-section size of the liquid metal bath; h_0 – strip thickness at the beginning of the deformation zone; h_n – strip thickness at the roll exit; V_n – strip exit velocity from the rolls

Carrying out an analysis of the available research and development of industrial models of two-roll continuous casting machines, we can conclude that the issue of the quality of the products manufactured on them is acute. First of all, this relates to the quality of the sheet surface, as well as defects on its surface. According to previous studies, it can be concluded that defects in the form of a crack can occur if the local tensile strength of the material is less than the internal stresses in the solid layer. In the process of continuous casting of blanks on a two-roll machine, such stress sources can be associated with the process of forming the sheet that is cast.

When two layers of metal come into contact, which are formed during the crystallization of the metal and the formation of the solid phase, stresses arise at their junction. Thus, in this area one can observe the effect of "rolling" the sheet, which in turn generates additional deformations and stresses.

By analyzing the causes of surface defects in cast strips and ways to prevent them, several assumptions can be made. One of the first assumptions states that any change or wave formation on the surface of liquid steel during crystallization will manifest itself in the form of a surface crack defect [9]. Therefore, in order to guarantee the high surface quality of the steel strip, the continuous rolling-casting crystallization process must be constantly monitored, and its parameters must be stable.

In addition, cracks on the surface of liquid metal can appear as a result of the formation of waves on the surface or as a result of turbulent flows on the surface of the liquid metal [7-10]. To ensure a constant thickness of the resulting sheet of metal and the absence of cracks on its surface, it is necessary to ensure that there is no waviness on the surface of the liquid metal, and also to monitor the level of liquid steel in the mold, which should be at a constant level. The difference in steel level in the mold should not exceed two millimeters.

The next assumption for the reason for the occurrence of surface defects in cast strips is that this method is used, as a rule, for stainless steels. As noted above, the issue of the appearance of surface defects is decisive, including for low-alloy steels. As practice shows, it is difficult to obtain a high-quality surface without defects for sheets made of low-alloy steels. In this case, the problem of ensuring the quality of the sheet surface can be solved by adding a small amount of alloying elements to low-alloy steel. Thus, a slight addition of titanium at the level of eighty-eight thousandths of a percent ensures the absence of these defects on the surface of the strip [11].

An interesting assumption about the reason for the appearance of low-speed and high-speed defects on the surface of the strips [12]. High-speed defects can appear when a crust forms at the bottom of the casting bath under conditions of high steel casting speeds. Since there is slippage between the roller at the top of the casting bath and the liquid metal, the molten steel that is fed cannot keep up with the rotating surfaces of the rollers.

In this case, transverse deformation bands appear on the surface of the strip. It was experimentally shown [12] that a "crocodile skin" defect appears during cooling and crystallization, which is explained by the simultaneous solidification of various phases of the melt. Since phases γ and σ have different strength characteristics and different thermal conductivity, this can lead to local deformation of the metal strip, and in turn to the formation of a "crocodile skin" defect. At the same time, at low casting speeds, slow-speed defects occur. At low casting speeds, the top ball of molten steel cools quickly and a crust appears on the surface. During subsequent operation of the rolls, this surface crust is tightened, which leads to the appearance of defects in the strip.

The assumption of the appearance of transverse cracks on the surface of the steel strip is also worthy of attention. Transverse cracks form when the mechanical properties of steel differ in the longitudinal and transverse directions. As a result, when rolling sheets in rolls, cracks may appear in the longitudinal direction [2]. On the other hand, the process of transverse opening of longitudinal cracks is practically absent.

Various cracking processes occur in the heated and cooled zones of the strip. Since there is an oxide film on the metal surface between the mold and the outer surface of the workpiece, irregularities in the hard crust of the cast workpiece appear.

The difference in the thickness of the resulting sheet is critical.

Because even with small deviations in thickness, only sections of the sheet of greater thickness are cooled and rolled out on rollers. Therefore, there is a separation of cold and hot zones. This is due to different mechanical properties in the transverse and longitudinal directions of the hot and cold zones of the sheet. As a result, stresses arise in the sheet, causing cracks to appear. To combat these processes and obtain a sheet without defects, it is proposed [1-6] to use a special microrelief on the surface of the rolls and select a coating material for the rolls, the process of continuous rolling casting is carried out in a protective atmosphere, which will reduce the stress in the sheet, as well as reduce the pressure on the rollers.

The proposed hypothesis

The unique aspect of two-roll crystallizers lies in the fusion of metal solidification and subsequent plastic deformation within the space between two rotating rolls. Metal within this inter-roll space sequentially transitions through zones of crystallization and deformation, following a conceptual framework that delineates three distinct zones within the inter-roll space (refer to Fig. 1). Zone 1 encompasses the initial phase of the process, where intense heat transfer occurs from the liquid melt to the crystallizer rolls, which are actively cooled by water. Within the initial section of this zone, as the cooled rolls make contact with the superheated melt exceeding the liquidus temperature, no solidified metal layer forms on their surface. This subzone is distinguished by its limited extent and maximal cooling rate values along the length of the crystallization-deformation zone. Zone 2 follows the formation of a continuous crust of solidified material on the roll's surface, initiating a phase where growth occurs on both rolls' sides. Within this subzone, there's a reduction in the heat flux value at the metal-roll boundary until it reaches a minimum. Additionally, a semi-liquid state of metal characterizes a sub-zone within zone 2, with metal temperature ranging between the liquidus and solidus temperatures. Columnar dendrites emerge and grow towards each other, connecting to determine the length of the crystallization zone. Contact between these dendrites results in increased pressure at the metal-roll contact point, intensifying heat removal to the crystallizer rolls.

In the deformation zone (corresponding to the central rolling angle α), the liquid phase is completely absent. Here, by analogy with the process of hot rolling of sheets, plastic deformation of the metal is carried out between the rotating rolls. During forming, the displaced volume of metal is forced to move forward (advance S_1) and backward (lag S_0) relative to the surface of the crystallizer roll. Thus, in the deformation zone, two sections with different kinematics are realized – the advance zone, in which the metal flow velocity is higher than the circumferential speed of the crystallizer roll, and the lagging zone, in which the metal flow velocity is lower than the circumferential speed of the crystallizer roll. These zones are separated by the so-called "neutral section" in rolling theory. The position of this section is characterized by the value of the neutral angle. The ratio of the circumferential speed of the roll V_r and the metal of the strip V_m is shown in Fig. 2.

As a result of plastic deformation, the metal in the rolling zone is forced to move relative to the roll surface both forward and backward. This creates two zones with different kinematics. The first lagging area (lag speed ΔV_2), where the metal flow speed is less than the peripheral speed of the mold roller. The second advance area (advance speed ΔV_1), where the metal flow speed is higher than the peripheral speed of the mold roller. These areas are separated by a neutral area. The position of the neutral section is described by the value of the central angle γ. A similar effect is called the "rolling effect" in the plastic deformation of hardened layers in rolls.

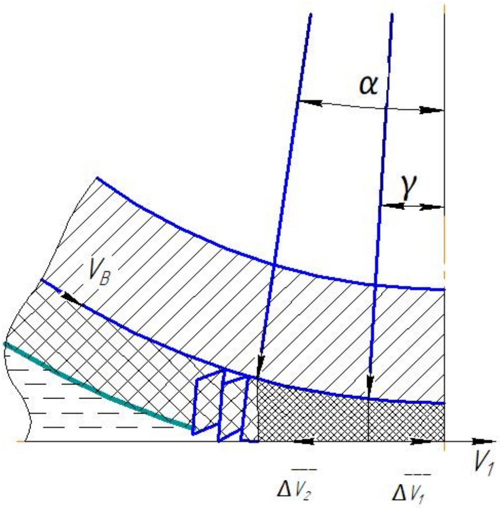


Fig. 2. Layer destruction scheme

The metal crust in the crystallization zone is affected by the reverse movement of the metal from the deformation zone. Therefore, the metal crust is affected by compressive deformation in the tangential direction, and in the radial direction it pushes it away from the surface of the roll. Therefore, the metal crust is susceptible to destruction before entering the deformation zone. The hardened metal crust peels off and comes off the surface of the roll under the influence of the stresses that arise Fig. 2. At this moment, voids are formed between the solid metal and the roll. These voids are filled with liquid melt. And a mixture of semi-liquid or liquid melt and solid fragments of the crust appears. Under the action of tensile stresses in the leading area, the outer layers of the strip are deformed. Therefore, they can take on the appearance of "crocodile skin".

The transition of low-alloy and carbon steels from a ductile to a brittle state occurs at temperatures close to "solidus" [13]. Microalloying with calcium and titanium increases the technological ductility of continuously cast billets from low-alloy and carbon steels. Changes in ductility were not found in austenitic stainless steels. This indicates a potential correlation with the processability of direct cast stainless steel strips.

Kinematics of metal in the rolling zone. The importance of information about the position and length of the deformation area is key when studying the process of sheet formation in a two-roll crystallizer, however, the difficulty of establishing the boundary between two characteristic sections of the crystallization-deformation zone forces us to turn to mathematical modeling.

The growth of the crust thickness can be described with a sufficient degree of reliability by the function of the square root:

$$\delta = k\sqrt{\tau}\,, \tag{1}$$

where k – crystallization coefficient, mm/s^{0,5};
τ – time, s.

Further calculations were performed in the following sequence, using engineering techniques for flat rolling [14].

First, the transverse size of the liquid metal bath h_p was calculated based on the known values of the radius of the rolls R, the height of the melt pour ℓ and the final thickness of the strip h_n based on the following relationship:

$$h_p = h_n + 2\sqrt{R^2 + l^2} - 2R\,. \tag{2}$$

and the contact angle of the metal with the roll was determined:

$$\alpha = 2\arcsin\left(\frac{1}{2}\sqrt{\left(h_p - h_n\right)/R}\right). \tag{3}$$

Having chosen N divisions of the contact angle, we determine the step along the contact angle $\Delta\alpha=\alpha/N$. For the i-th step of moving the metal into the gap between the rolls, the value of τ_i is determined by the ratio of the length of the crystallization arc ℓ_i to the linear speed of the roll rotation V_r.

$$\tau_i = l_i / V_r\,, \tag{4}$$

where: $l_i = \alpha_i R$, $\alpha_i = \Delta\alpha_i$.

Then we check the ratio

$$2\delta_i \geq h_i \tag{5}$$

As it is performed, we fix the angle of the deformation zone α_{np}.

Based on the calculated value of the angle of the deformation zone α_{np} and the known strip thickness h_1 at the exit from the crystallizer rolls, we determine the strip thickness when closing the metal solid crusts on the rolls h_0:

$$h_0 = h_1 + \alpha_{np}^2 R\,. \tag{6}$$

Next, we determine the kinematic parameters of the deformation zone according to the formulas adopted in the simplified theory of flat longitudinal rolling of thin strips (D/h_1 >>1). According to this theory, the neutral angle γ was calculated from the formula:

$$\gamma = \frac{\alpha}{2}\left(1 - \frac{\alpha}{2f}\right), \tag{7}$$

where f – coefficient of friction,
q_0, q_1 – back and front tension;
p_{avg} – average contact stresses.

The advance $S_1 = \left(V_1 - V_r\right)/V_r$ was calculated according to the formula:

$$S_1 = \frac{R\gamma^2}{h_1}\,. \tag{8}$$

The lag $S_0 = \left(V_0 - V_r\right)/V_r$ was calculated according to the formula:

$$S_0 = 1 - \frac{1 - S_1}{\cos\alpha}\frac{h_1}{h_0}\,, \tag{9}$$

while $V_0 = V_r\left(1 - S_0\right)$.

In the context of our hypothesis, it is necessary to determine the amount of metal movement in the lag zone and its effect on the crust in the solidification zone.

The speed of the return movement of the metal ΔV along the surface of the roll from the entrance to the deformation zone to the crystallization zone is:

$$\Delta V = V_0 - V_r\,. \tag{10}$$

Table 1 shows the calculated values of the kinematic parameters of the deformation zone for different spill velocities and, accordingly, degrees of deformation. Calculations are given for the coefficient of friction f = 0,5.

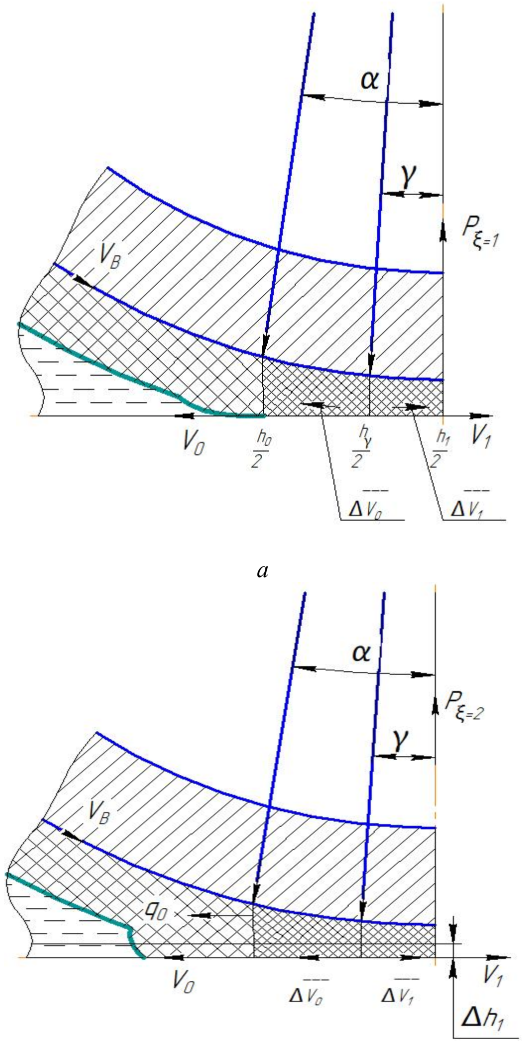
From the data given in [15], it follows that the speed of reverse movement ΔV of the hardened metal from the deformation zone along the surface of the crystallizer roll can reach 13.5 m/min at a pouring speed of 900 m/min and compression in the deformation zone of 33.5% (pouring mode 5). In pouring mode 1 (5.3% forming), the return speed is 3.8 m/min.

The backward movement of the metal from the deformation zone, affecting the metal crust in the crystallization zone, should lead to compression deformation in the tangential direction and its peeling in the radial direction. That is, prerequisites are created for the destruction of the metal crust before entering the deformation zone. The destruction can be brittle, because according to known experimental data [13], the transition of carbon and low-alloy steels from a viscous to a brittle state occurs at temperatures close to solidus. In this case, the crust of the hardened metal will break into separate fragments, the size of which will depend on the magnitude of the movement and the properties of the steel (Fig. 2). In the case when brittle failure does not occur, the crust under the action of radial component stress can peel off from the surface of the roll. In both cases, liquid steel will penetrate into the cracks and voids that have formed. The resulting solid-liquid mixture of metal during rolling in the deformation zone can initiate a defect of the “crocodile skin” type.

On the other hand, the resistance of the crust to the backward movement creates a force support of the metal at the entrance to the deformation zone. This effect leads to a change in the stress state of the metal in the deformation zone, an increase in the contact stress p and, in general, an increase in the force P affecting the rolls. An increase in advance will lead to an increase in the manifestation of the “crocodile skin” defect. An increase in the rolling force ΔP leads to elastic deformation of the elements of the roll system and a change in the size of the inter-roll gap, and therefore to an increase in the thickness of the strip Δh_1 at the exit from the crystallizer rolls:

$$\Delta h_i = \Delta P / c_к ,$$

where $c_к$ – modulus of elasticity of the roll system, MN/mm.



a

b

Fig. 3. Scheme of the formation of the defect “ribbedness” of the strip during roll casting-rolling due to the support of the metal crust at the entrance to the rolling zone: *a* – without support; *b* – with support

Under the action of the rear support in the deformation zone, the advance S_1 and, accordingly, the speed V_1 of the strip at the exit from the rolls increases. Due to the increase in metal consumption $\Delta Q = \Delta h_1 \cdot \Delta V_1$ (Fig. 3) the power support at the entrance to the deformation zone weakens, the rolling force decreases and the thickness of the strip returns to its original size h1. At the next time segment Δτi+1 the situation repeats itself. The length of the temporary segment Δτ is inversely dependent on the speed of roll pouring. As a result of the described cyclic effects, the strip may acquire a “ribbed” defect, and the pouring process may undergo “vibration”.

Calculation of kinematic and power parameters of roll pouring – rolling of the steel strip

The rolling force P is defined as the product of the average contact stress p_{avg} and the contact area of the roll with the deforming metal $F_к$:

$$P = p_{avg} F_к \tag{12}$$

where $F_к = BR$; B – strip width.

In engineering practice, p_{avg} is determined by the dependence on the deformation resistance of the metal σ_{avg} and the stress state coefficient η, which takes into account the conditions of deformation during rolling.

Variants of the Tselikov method were used to calculate p_{avg}, as in the work of [Vasylev]:

$$p_{avg} = \sigma_{avg} \xi_{avg} \frac{2h_1}{\Delta h(\delta-1)} \frac{h_\gamma}{h_1} \left(\left(\frac{h_\gamma}{h_1} \right)^{\delta} - 1 \right) \tag{13}$$

and in the work of Konovalov [14]:

$$p_{avg} = \frac{2{,}3}{\Delta h} \times$$

$$\times \sigma_{avg} \left[\!\left[\xi_0 \frac{h_0}{\delta-2} \left\{ \left(\frac{h_0}{h_\gamma} \right)^{\delta-2} - 1 \right\} + \frac{h_1}{\delta+2} \left\{ \left(\frac{h_0}{h_\gamma} \right)^{\delta+2} - 1 \right\} \right]\!\right] \tag{14}$$

where σ_{avg} – average value of deformation resistance;

$$\xi_0 = 1 + q_0 / \sigma_{avg} \text{ – support factor;} \tag{15}$$

q_0 – back support;

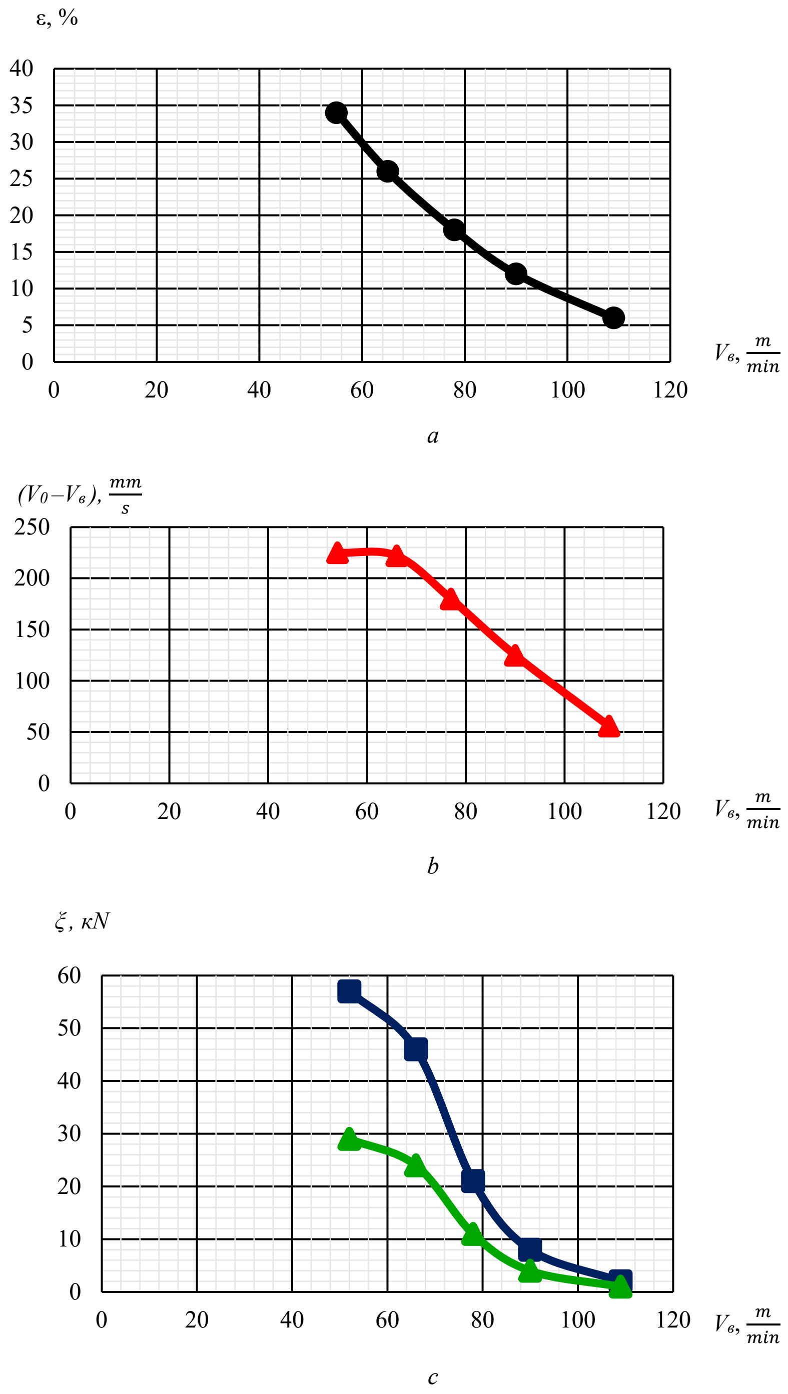
$$\delta = f / tg(\alpha/2) \tag{16}$$

$$\Delta h = h_0 - h_1 \tag{17}$$

$$h_\gamma = h_1 \gamma^2 R \tag{18}$$

The dependence was applied to determine the deformation resistance:

$$\sigma_{avg} = S\sigma_{dz} \dot{\varepsilon}^{a} (10\varepsilon)^{b} (T/1000)^{c} , \tag{19}$$



a

b

c

Fig. 4. Dependence of forming (a) dependence of pouring speed on relative deformation (b) Dependence of pouring speed on reverse speed (c) Dependence of pouring speed on rolling force: ▲ – without support; ■ – with support

where: $\dot{\varepsilon}$, ε, T – average values of speed, degree and temperature of the metal in the deformation zone;

$$\varepsilon = \Delta h / h_0 \qquad (20)$$

$$\dot{\varepsilon} = V_1 \varepsilon / (R \sin \alpha) \qquad (21)$$

$$V_1 = V_\text{в} (1 + S_1) \qquad (22)$$

$S\sigma_{dz}$, a, b, c – numbers determined for each brand of steel by its chemical composition.

The parameters of the deformation resistance studies for the construction of dependence (19) were in the range $\dot{\varepsilon}$ = 0,01–150 s^{-1}; ε = 0,05–0,3; T = 800–1300 °C.

This paper presents calculations of force and kinematic parameters in the deformation region during rolling

Table 1. Calculation of roll casting-rolling parameters

Technical characteristics	Values				
Pouring mode, No.	1	2	3	4	5
Pouring speed, m/min	108	90	78	66	54
Metal forming $(h_0–h_1)/h_0$, %	5.3	11.2	18.3	25.9	33.5
Reverse speed $(V_0–V_r)$, mm/s	63	126	184	222	225
Rolling effort without support ($\xi_{avg} = 1$), MH	1084	3947	10862	23616	29409
Rolling effort with support ($\xi_0 = 2$), MN	1990	7513	21066	46196	56795

of low-carbon steel C10E with a thickness of 2 mm. In Fig. 4 it can be seen that the relative compression of the solidified metal increases from five to thirty-three percent, and the length of the deformation zone increases three times with a decrease in speed. But at this moment the lag of the metal from the rolling speed increases, and the reverse speed ΔV of the deformed metal also increases. These processes contribute to the appearance of pressure on the hardened crust. At the same moment, a force support appears in the deformation area. This in turn leads to an increase in the deformation force of the strip in the rolling zone. During the increase in force support, the accumulated mass of displaced metal is drawn into the area between the rolls and is subsequently subjected to forming.

Based on the above, we can summarize that the calculated rolling force, taking into account the support, increases to 57 MN. This is a fairly large value, so it cannot always be achieved under real conditions. As observed in Fig. 4., the relative compression in this case is fifteen percent.

Conclusions

Based on research results, we believe that when casting steel using the twin-roll casting method, it is necessary to reduce compression to a minimum value. To ensure welding of hardened edges when casting steel lists, it is necessary to reduce the compression to a minimum value. This recommendation will ensure that defects on the surface are welded. Using this proposal will allow you to carry out the casting process at high speed and apply little effort to compress the rolls. We propose to carry out the process of forming a cast strip with the necessary quality parameters at the following stages of rolling. We recommend that the formation of a cast strip with the specified geometry, metal structure and properties be carried out at the stages of both cold and hot rolling.

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Analysis of the influence parameters on steel strip defects in continuous roll casting-rolling

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Проблематика. *Процес розливки-прокатки на даний момент являється одним з найбільш ефективних та перспективних процесів, що застосовується для виробництва сталевого листа. Перевагами вказаного процесу можна вказати незначні габарити агрегату та значне зменшення енергоресурсів. Це відбувається завдяки поєднанню технологічних операцій та виключенню проміжного нагріву металу. В той же час стоїть задача сталого промислового процесу виробництва високої якості сталевого листа.*

Мета дослідження. *Компанії, що займаються розробкою процесу прямого отримання смуги з розплаву із застосуванням двохвалкових кристалізаторів вказують ряд проблем з якими стикаються. Серед таких проблем можна назвати дефекти на поверхні литої смуги. На даний час відсутня загальновизнана класифікація поверхневих дефектів, таких як тріщина (“surface cracks”), зморшки (“wrinkles”), нерівності (“namely”, “depressions”), поперечні смуги деформації. На даний момент також відсутнє обґрунтування причин появи поверхневих дефектів у процесі розливки-прокатки.*

Методика реалізації. *За результатами досліджень запропонована гіпотеза про причини появи дефектів на поверхні литої смуги та шляхи їх запобігання. Під час роботи двовалкових кристалізаторів відбувається поєднання процесів затвердіння металу та його подальшої пластичної деформації. Метал послідовно переміщається крізь області кристалізації і деформації. В процесі дослідження авторами проводився розрахунок процесу валкової розливки-прокатки.*

Висновки. *За результатами досліджень вважаємо, що при литті сталевої штаби із застосуванням двохвалкових кристалізаторів необхідно знижувати обтиснення до мінімального значення. Дана рекомендація забезпечить зварювання затверділих корок, що виникають на поверхні. Застосування даної пропозиції дозволить вести процес розливання на високій швидкості та застосовувати незначне зусилля притиснення валків. Пропонуємо процес формування литої смуги з необхідними параметрами якості виконувати на наступних етапах прокатки.*

Ключові слова: *валкова розливка-прокатка, розливка, прокатка, обтиснення, зворотна швидкість, зусилля прокатки.*