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DETERMINATION OF PARTICULAR RELATIVE REDUCTION IN COLD ROLLING OF THIN AND EXTRA THIN STRIPS TO IMPLEMENT THE PROCESS WITH THE LEAST FORCE

Introduction. *It has been theoretically established and experimentally confirmed that the elastic deformations of rolls and strips in cold rolling have a significant and, in the case of thin rod rolling, a crucial effect on all process parameters.*

Problem Statement. *The influence of the elastic-plastic interaction of a thin strip with rolls, the tension, the temperature and rate of deformation, and the strength of strip material shall be taken into account for developing a modern theory of longitudinal cold rolling.*

Purpose. *Modeling and forecasting the parameters of cold rolling of thin and extra thin strips.*

Materials and Methods. *To solve this problem, the conditions of rolling strips made of 08kp steel with different degrees of preliminary metal hardening, which reflected the features and regularities of hardening the strip material in the multicellular state line, have been modeled. The partial relative reductions vary within 0.02—0.35, with the initial data corresponding to the most characteristic conditions of cold rolling of thin and extra thin steel strips on operating mills taken.*

Results. *The quantitative data on the influence of the strip thickness, at the entrance to the deformation zone, partial and preliminary relative reduction during cold rolling on the process conditions with the least force. For the first time, the conditions and range of partial relative reductions for the cold rolling process of thin and extra thin strips with the least force have been determined. It has been established that in the case of cold rolling of thin and extra thin strips made of unriveted and pre-hardened steel, varying partial relative reductions within the range from 0.1 to 0.30—0.35 provides the realization of process with the least force.*

Conclusions. *The implementation of cold rolling process with the least force is advantageous in terms of energy saving and manufacturability, as it allows reducing the specific consumption of electricity and expanding the range of cold rolling mills for smaller thicknesses of rolling strips and indicates the need to determine conditions for such a process.*

Keywords: cold rolling, process modeling, molding processes, plastic deformation, extrusion.

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Mass production of thin hot-rolled steel strips with a thickness of 1.2—1.5 mm or less, up to 0.8—1.0 mm, which, due to cheaper price, in many cases, are used instead of cold-rolled products of similar thickness [1], has been mastered in recent years. However, thin and extra thin cold-rolled steel strips with a thickness of less than 0.8—1.5 mm up to 0.25—0.4 mm [2—6] and tinplate with a thickness of 0.12—0.20 mm [4, 7—9], due to high quality indicators at a relatively low price, continue to remain one of the most effective and demanded types of metal products, with their stock expanding and output increasing [2, 3, 8, 10]. The technology for the production of thin and extra thin cold-rolled strips is distinguished by its multistage and long technological cycle, high level of technological loads, and high specific consumption of electrical energy caused by a high yield strength of the deformable metal and the features of elastic-plastic interaction of a thin strip with rolls, as well as by unresolved problems in this regard. All these factors limit the stock of products, reduce the breakdown capacity of the working stands and the efficiency of the rolling equipment [4, 7—9, 11—12]. Particularly, the regularities have not been studied yet at the moment and the quantitative relationship between the force that acts on the rolls, the total and particular relative reductions, and the thickness of the strip, which ensures the implementation of the cold rolling process of thin and extra thin strips with the least force has not been determined. This fact causes the relevance and feasibility of this research [8, 9, 11, 12]. The goal has been achieved with the use of the apparatus of modern theory of lengthwise rolling.

The generally accepted (conventional) theory of lengthwise rolling [14, 15] was developed based on the understanding that the strip is rigid-plastic, and the rolls are ideally rigid bodies, i.e. without taking into account the influence of elastic deformations of rolls and strip, which excludes the possibility of its use for predicting the parameters of the cold lengthwise rolling process [12, 13]. Cold rolling of thin and extra thin strips is made with small absolute reductions Δh (Δh ≤ 0.005—0.5 mm), for large values of the parameter R/h_0 ($R/h_0 \geq 300$—3000, where R, h_0 are the work roll radius and the strip thickness at the entrance to the deformation zone, respectively), and with high average contact normal stresses ($p_{cpc} \geq 500$—1500 N/mm^2). Under these rolling conditions, the radial elastic compression of the work rolls takes values that are comparable to plastic deformation (reduction) of the strip and the actual length of contact of the strip with the rolls l_c, i.e. the length of the elastic-plastic deformation zone increases, because it is already determined not only by the plastic deformation of the strip ($l = \sqrt{R\Delta h}$), but also by elastic radial compression of work rolls [9, 12, 16]. The elastic compression and elastic recovery of the strip also have a significant effect on the length of the elastic-plastic deformation zone l_c. [12]. Therefore, the ratio l_c/l is always greater than unity and, depending on the specific rolling conditions, may reach 2—4 and more [12, 13].

Nowadays, it has been theoretically established and experimentally confirmed that elastic deformations of rolls and strips during cold rolling have a great influence on all parameters of the process, and in the case of rolling the thin strips, this effect becomes decisive [7, 9, 12, 13, 16]. The modern theory of lengthwise cold rolling [13] has been developed given the influence of the features of the elastic-plastic interaction of a thin strip with rolls, tension, temperature-rate conditions of deformation and strength properties of the strip material. On the basis of this theory, the parameters of cold rolling of thin and extra thin strips have been modelled and predicted in this research. This theory [13, 17, 18], the accuracy and reliability of which have been experimentally confirmed [12, 19], is based on the following models:

the length of the elastic-plastic deformation zone [12, 13, 17]:

$$l_c = x_1 + \sqrt{R\Delta h + x_1^2}, \tag{1}$$

where

$$x = x_{1n} + 6\,\theta_{в} p_{cpc} R\left(1 - 2\frac{x_{1n}}{l_c}\right)\left[4\frac{x_{1n}}{l_c}\left(1 - \frac{x_{1n}}{l_c}\right) + 1\right]; \tag{2}$$

$$\theta_{в} = \frac{1 - v_{в}^{2}}{\pi E_{в}}; \quad (3)$$

$$\frac{x_{1n}}{l_{c}} = \frac{1}{1 + \sqrt{1 + \left(\frac{\varepsilon}{1 - \varepsilon}\right)\frac{E_{n}}{1.15\sigma_{T1}\xi_{1}}}}; \quad (4)$$

$$\xi_{1} = 1 - \frac{q_{1}}{1.15\sigma_{T1}}; \quad (5)$$

the average contact normal stress [13, 18]

$$p_{cpc} = \frac{1.15}{2(1 - v_{n}^{2})}\left(\sigma_{T0}\xi_{0}\frac{x_{0n}}{l_{c}} + \sigma_{T1}\xi_{1}\frac{x_{1n}}{l_{c}}\right) + \frac{1.15\sigma_{Tcp}\xi_{cp}}{1 - v_{n}^{2}}\left\{1 + \frac{fl_{в}}{3h_{cp}}\left[1 + \left(\frac{fl_{в}}{3h_{cp}}\right)^{2}\right]\right\}\frac{l_{в}}{l_{c}}; \quad (6)$$

where

$$\frac{x_{0n}}{l_{c}} = \left(1 - \frac{x_{1n}}{l_{c}}\right)\left[1 - \sqrt{1\frac{\beta\sigma_{T0}\xi_{0}}{\varepsilon E_{n} + \beta\sigma_{T1}\xi_{1}(1 - \varepsilon)}}\right]; \quad (7)$$

$$\xi_{1} = 1 - \frac{q_{0}}{1.15\sigma_{T0}}; \quad (8)$$

$$\xi_{cp} = \xi_{0} + (\xi_{1} - \xi_{0})\left(\frac{\gamma_{c}}{\alpha_{c}} + \frac{x_{1}}{l_{c}}\right); \quad (9)$$

$$h_{cp} = 0.5\,(h_{0} + h_{1}); \quad (10)$$

$$\frac{l_{в}}{l_{c}} = 1 - \frac{x_{0n}}{l_{c}} - \frac{x_{1n}}{l_{c}}; \quad (11)$$

$$l_{в} = l_{c}\,(1 - \frac{x_{0n}}{l_{c}} - \frac{x_{1n}}{l_{c}}); \quad (12)$$

the rolling forces [6]

$$P_{c} = p_{cpc} l_{c} b. \quad (13)$$

In formulas (2)—(14) the following designations are used: index «*c*» means that this parameter is calculated given the combined effect of elastic deformations of the rolls and the strip; l_c, $l_в$ are the length of the elastic-plastic deformation zone and the length of the plastic section of the contact of the strip with the rolls during the rolling ($l_c = x_{0n} + l_в + x_{1n}$), mm, respectively; x_{0n}, x_{1n} are the lengths of the sections of elastic contact of the strip with the rolls, which are determined by elastic compression and elastic recovery of the latter, respectively, mm; R, b, Δh are the radius of the work roll, the width of the strip and the particular absolute reduction of the strip during the rolling, mm, respectively; h_0, h_1, h_{cp} are the thickness of the strip at the entrance and at the exit from the deformation zone and its average value in the zone, respectively; $v_в$, v_n, $E_в$, E_n are Poisson's ratio and elastic modulus (N/mm^2) of the material of the work rolls and the strip, respectively; σ_{T0}, σ_{T1}, σ_{Tcp} are the yield stress of the strip material at the entrance to and the exit from the deformation zone and the average value of the yield stress of the strip material in the deformation zone, as calculated given the influence of the degree, temperature, and rate of deformation during the rolling, N/nn^2; q_0, q_1 are absolute values of back and front pull, N/mm^2; β, f, ε are the Lode coefficient, the friction coefficient, and the particular relative reduction during the rolling (dimensionless values); p_{cpc}, γ_c, α_c are the average contact normal stress (N/mm^2), the neutral angle, and the angle of contact of the strip with the roll during the rolling (rad); P_c is the rolling force, MN.

Earlier, we found [7, 9, 12] that as a result of the peculiarities of the elastic-plastic force interaction of a thin strip with rolls during the cold rolling, there was always a strip thickness at the entrance to the deformation zone h_0, at which the rolling process is carried out with the least linear force P_c/b. This condition, the validity of which has been confirmed experimentally and by new data on the modeling of the cold rolling process, with the use of models (1)—(13), is written in the form [9, 12]:

$$\frac{\delta P_{снм}}{\delta p_{0нм}} = 0. \quad (14)$$

The implementation of the cold rolling process with the least linear force is advantageous in terms of energy saving and manufacturability since it helps to reduce energy consumption, increases the compressing capacity of the working stands, and expands the stock of cold rolling mills towards smaller thicknesses, which is important [5—7, 9, 11, 12].

Based on the foregoing, we have judged the technological and energy efficiency of the cold rolling process of thin and extra thin strips from the nature of changes in the linear rolling force dependences plotted given $P_c/b = \varphi(h_0)$ (curve *1*) and without taking into account the effect of

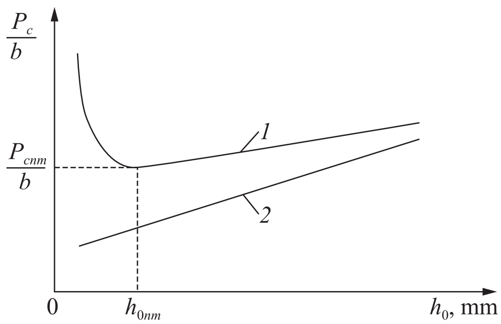

Fig. 1. Qualitative dependences P_c/b = φ (h_0) during cold rolling, calculated with taking into account (curve *1*) and without taking into account (curve *2*) the influence of elastic deformations of rolls and strip

elastic deformations of the rolls and strip P/b = = φ (h_0) (curve *2*), the qualitative view of which is shown in Fig. 1. The difference between the ordinates of curves *1* and *2* at h_0=const is numerically equal to an increase in the linear rolling force caused by the influence of elastic deformations of the rolls and the strip (shown by shading in Fig. 1). The letters $P_{снм}/b$ and $h_{0нм}$ in Fig. 1 indicate the values of the linear rolling force and the strip thickness at the entrance to the deformation zone, which correspond to the condition of the process with the least force.

The process with the least force creates the most favorable technological conditions for rolling a thinner strip $h_{1нм}$, i.e. a strip with the least thickness, given the rigidity of the working stands of the mill [9, 11]:

$$h_{1нм} = \frac{P_{снм} + P_з - P_{пр}}{М_{кл}}, \qquad (15)$$

where $P_з$, $P_{пр}$ are the force of the “bottoming” of the end sections of the work rolls during the rolling and the force of preliminary pressing (“bottoming”) of the work rolls before the rolling, MN, respectively; $М_{кл}$ is the stiffness modulus of the working stand, MN/mm.

From formula (15) it follows that the lesser the force $P_{снм}$, the lesser the final (least) strip thickness rolled on a particular mill. This is also facilitated by the fact that with a decrease in the force P_c, the forces $P_з$ and $P_{пр}$ decrease as well [9, 11]. Therefore, the implementation of the rolling process on a specific mill with the least force $P_{снм}$ or with a force close to it, contributes to the expansion of its range towards smaller thicknesses, which is important for cold rolling of thin and extra thin strips.

Carrying out the rolling process at $h_0 = h_{0нм}$ and in the range of thicknesses to the right of the minimum on curve *1* (Fig. 1) is also advantageous in terms of energy consumption, since in this case, the negative effect of elastic deformations of rolls and strip on the rolling force and on the torque decreases, as a result of which the process efficiency increases [9]. Rolling in the thickness range to the left of the minimum on curve *1* (Fig. 1) is possible, but it is characterized by an excessive increase in force P_c due to the increased influence of friction stresses on this parameter, which indicates the inexpediency of its use.

The above analysis of the features and regularities of the elastic-plastic interaction of a thin strip with rolls during cold rolling has shown that at each specific mill there is a range of strip thicknesses at the entrance to the deformation zone, which provides the possibility of implementing the process with the highest technological and energy efficiency, including the least rolling force. In this research, this approach to solving the problem of increasing the efficiency of the cold rolling process of thin and extra thin strips has been proposed for the first time.

The purpose of this research is to study the effect of thickness, partial and total relative reductions on the force parameters of the process during the cold rolling of thin and extra thin strips, given the peculiarities of the elastic-plastic interaction of a thin strip with rolls and to determine the optimal range of partial relative reductions that ensure the implementation of the cold rolling process with the least force.

The theoretical determination of the strip thickness at the entrance to the deformation zone $h_{0нм}$ for the implementation of the cold rolling process with the least force involves solving equation (14). The solution of this equation in an explicit form has been found impossible, and the use of other methods for its solution is impractical. The point is that the solution to equation (14) makes sense only for cold rolling of thin and extra thin strips, i.e. for the case of rolling, when the main factor determining the level and nature of changes in function $P_c/b = \varphi(h_0)$ is the elastic deformations of the rolls and the strip, more precisely the ratio between them, which depends primarily on the particular relative reduction and the strength properties (yield stress) of the strip material. The rest of the parameters of the cold rolling of thin and extra thin strips at each specific mill (roll radius, friction coefficient, rolling speed, tension modes, etc.) differ in relative stability of values, or varies within narrow limits and their effect on the position of the minimum of function $P_c/b = \varphi(h_0)$ is not so important. Therefore, in this research, as a parameter for determining and influencing the coordinate of the minimum of function $P_c/b = \varphi(h_0)$, we use the partial relative reduction during cold rolling, the value of which, as one of the main parameters of the technology on operating mills, is fixed continuously and, if necessary, may be changed in the desired direction [19].

To solve this problem, we have studied the influence of the partial relative reduction, thickness, and degree of preliminary reduction (yield point of the strip materials) on the level, nature of the change, and the position of the minimum of dependence $P_c/b = \varphi(h_0)$ during the cold rolling. The quantitative data on the parameters of the cold rolling process, given the peculiarities of the elastic-plastic interaction of a thin strip with rolls, have been obtained with the use of models (1)—(13). For this purpose, an appropriate technique and an algorithm for its implementation have been developed. In the course of the study, the conditions for rolling of strips made of 08kp steel [$\sigma_T = 230 + 34.6\,(100\varepsilon_\Sigma)^{0,6}$] have been simulated with a different degree of pre-hardening of the strip metal ($\varepsilon_{пр} = 0$—0.9), which reflects the features and regularities of strengthening the strip material in the line of a multi-stand mill. The partial relative reductions vary within the range of 0.02—0.35 and the following initial data corresponding to the most typical conditions for cold rolling of thin and extra thin strips of steel on operating mills are taken: R = 300 mm; $f = 0.03$—0.07; $h_0 = 0.05$—$1{,}0$ mm; $q_0 = q_1 = 0$. Based on the simulation results, dependences $P_c/b = \varphi(h_0)$ and $l_c = \varphi(h_0)$ at ε = const and f = const have been plotted and the thickness of the strip at the entrance to the deformation zone has been determined for the rolling with the least force.

3. RESULTS. Fig. 2 shows dependences $P_c/b = \varphi(h_0)$ and $l_c = \varphi(h_0)$ for two different values of the preliminary reduction of the strip at $f = 0.05$ and ε = var, as example. The dependences $P_c/b = \varphi(h_0)$ and $l_c = \varphi(h_0)$, which have a similar shape, have been obtained by simulating the cold rolling process with other values of the coefficient of friction.

Figure 2 shows that, regardless of the degree of partial relative reduction ε and the degree of pre-hardening of the strip $\varepsilon_{пр}$, the dependences $P_c/b = \varphi(h_0)$ and $l_c = \varphi(h_0)$ have the same qualitative character of change. They differ from each other only quantitatively, and as ε and $\varepsilon_{пр}$ grow, the absolute values of the linear rolling force and the length of the deformation zone increase, which is a consequence of an increase in the yield stress of the strip material. In this sense, the most valuable and somewhat unexpected data are the data on the effect of the partial relative reduction on the strip thickness at the entrance to the deformation zone, which ensures the rolling process with the least force. They are marked with points on curves $P_c/b = \varphi(h_0)$. In the case of the rolling of unriveted ($\varepsilon_{пр} = 0$) steel (Fig. 2, *a*), there is an increase in the partial relative reduction from 0.02 to 0.1 due to low yield point. The strip materials have practically no effect on the strip thickness, which ensures that the process is carried out with the least force ($h_{0нм} \approx 0.275$ mm). A further increase in the partial relative reduction causes an increase in the thickness of the strip $h_{0нм}$ along a linear relationship, the value of which at $\varepsilon = 0.35$ reaches 0.4 mm. A completely different and practically identical qualitative picture of the change in strip thickness $h_{0нм}$ is observed during

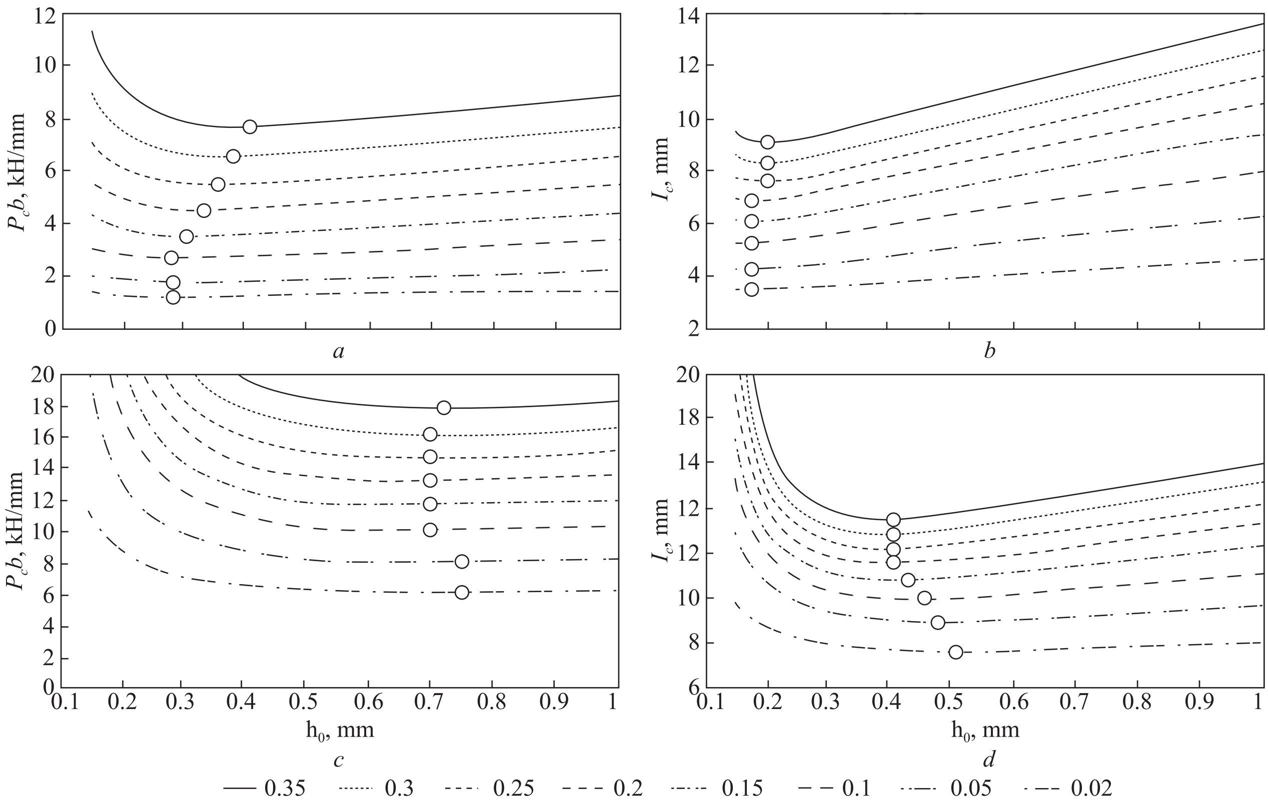

Fig. 2. Dependences $P_c/b = \varphi\ (h_0)$ and $l_c = \varphi\ (h_0)$, constructed from the results of modeling the parameters of cold rolling of non-riveted ($\varepsilon_{пр} = 0$) (*a*, *b*) and work-hardened ($\varepsilon_{пр} = 0.75$) (*c*, *d*) strips made of 08kp steel (R = 300 mm, $f = 0.05$; $q_0 = q_1 = 0$)

cold rolling of strips of pre-hardened steel (Fig. 2, *c, d*). In this case, the linear rolling force and the strip thickness $h_{0нм}$ corresponding to the minimum on the curves $P_c/b = \varphi\ (h_0)$ increases as the total and partial relative reduction grows, since a further increase in the yield stress of the strip material occurs, but in a peculiar way. In the entire range of change in the degree of strip preliminary reduction ($\varepsilon_{пр}$<0.9) and $\varepsilon_{пр}$ = const and ε = var, the largest strip thickness $h_{0нм}$ is recorded when the cold rolling is carried out with small (ε = = 0.02—0.1) and large (ε≥0.3—0.35) partial relative reductions, and in all cases of the rolling, the maximum values of $h_{0нм}$ correspond to the smallest relative reductions (ε = 0.02) (Fig. 2, *c*). Within the range of partial relative reductions from 0.05—0.1 to 0.3 at $\varepsilon_{пр}$=const, the thickness $h_{0нм}$ is practically the smallest and remains the same. This means that the elastic deformations of the rolls and the strip in this range of partial relative reductions have the least effect on linear force $P_{снм}/b$ and strip thickness $h_{0нм}$. The increase in linear force $P_{снм}$ and in strip thickness $h_{0нм}$ within the range of small (ε < 0.05—0.1) and relatively large (ε > 0.3—0.35) partial relative reductions at $\varepsilon_{пр}$= const is explained by the prevailing negative effect of elastic deformations of the strip and the rolls. Therefore, the cold rolling process with small (ε < 0.05—0.1) and with large (ε > 0.3—0.35) partial relative reductions, especially at a high yield stress in the latter case, is energetically ineffective and impractical. In this sense, the most advantageous in terms of energy consumption and manufacturability for the cold rolling of thin and extra thin strips is the range of partial relative reductions from 0.1 to 0.3—0.35. Moreover, the large reductions are advisable to use when rolling unriveted steel, and the small ones, when rolling pre-hardened metal. The above considerations about the most favorable range of partial relative reductions during the cold rolling are more clearly shown in Fig. 3.

They indicate that during the cold rolling of unriveted steel strips (curve *1*), i.e. strips made of material with a low yield stress, linear forces $P_{снм}/b$ are the smallest and realized in the narrowest range of variation of strip thickness ($h_{0нм}$ = = 0.275—0.4 mm).

With an increase in the degree of pre-hardening (Fig. 3, curves *2—5*), i.e. with an increase in the yield stress of the strip material, the linear force $P_{снм}/b$ increases and the smallest strip thickness $h_{0нм}$ (Fig. 3, curves *2—5*), which ensures the implementation of the process with the least force, shifts to the region of large strip thicknesses at the entrance to the deformation zone. During the rolling with tension, as well as with a decrease in the coefficient of friction and the diameter of the work rolls, $P_{снм}/b$ decreases, and curves *2—5* in Fig. 3 shift to the region of smaller thicknesses $h_{0нм}$. However, the range of partial relative reductions, which guarantees the implementation of the rolling process with the least force, remains practically unchanged. Therefore, the range of partial relative reductions during the cold rolling of strips from 0.1 to 0.30—0.35 may be considered the most favorable for the implementation of the process with the least force, regardless of the degree of pre-hardening of the strip.

Conclusions

1. The influence of the peculiarities of elastic-plastic interaction of metal with tool on the nature of changes in linear rolling force $P_{c/b}$ depending on the strip thickness at the entrance to the deformation zone h_0 during the cold rolling of thin and extra thin strips has been studied. It has been shown that dependences $P_{c/b} = \varphi(h_0)$ during the cold rolling of thin and extra thin strips have a characteristic minimum in the range of small thicknesses of the rolled strips, which indicates that an increase in the linear rolling force caused by the combined effect of elastic deformations of

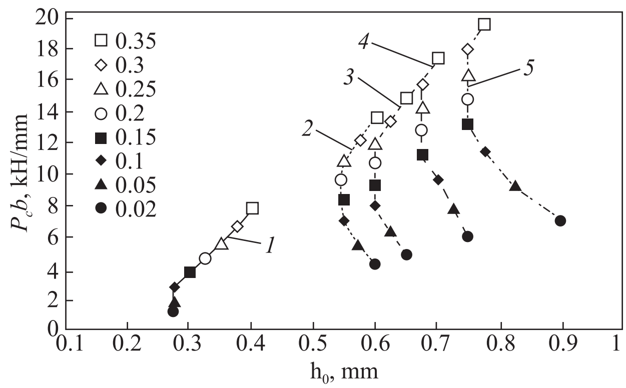

Fig. 3. Dependences $P_{снм}/b = \varphi(h_{0нм})$, constructed from the results of modeling the parameters of cold rolling of 08kp steel strips (R = 300 mm, f = 0,05; $q_0 = q_1 = 0$) with different degrees of preliminary work hardening: *1* — $\varepsilon_{пр} = 0$; *2* — $\varepsilon_{пр}$ = 0.4; *3* — the same 0.5; *4* — the same 0.7; *5* — the same 0.9

the metal and the tool in the rolling conditions takes the least value.

2. It has been established for the first time that in the conditions of cold rolling of thin and extra thin strips on the existing mills there is always a strip thickness at the entrance to the deformation zone, at which rolling is carried out with the least force. The implementation of the cold rolling process with the least force is advantageous in terms of energy saving and manufacturability, since it helps to reduce the specific consumption of electrical energy and to expand the range of cold rolling mills towards smaller thicknesses of rolled strips and indicates the need to determine the conditions for the implementation of such a process.

3. The quantitative data on the influence of the strip thickness at the entrance to the deformation zone, partial and preliminary relative reduction during the cold rolling on the conditions of the process with the least force have been obtained. It has been shown that the main factor for the implementation of the cold rolling process with the least force at the operating mills is partial relative reduction during the rolling.

4. For the first time, the conditions and the range of partial relative reductions for the implementation of the cold rolling of thin and extra thin strips with the least force have been deter-

mined. It has been found that during the cold rolling of thin and extra thin strips made of unriveted and pre-hardened steel, varying partial relative reductions within the range from 0.1 to 0.30—0.35 ensures the implementation of the process with the least force, which gives reason to consider it the optimal way, when developing deformation modes at cold strip rolling mills.

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ВИЗНАЧЕННЯ ЧАСТКОВОГО ВІДНОСНОГО ОБТИСКУ ПРИ ХОЛОДНІЙ ПРОКАТЦІ ТОНКИХ І ОСОБЛИВО ТОНКИХ ШТАБ ДЛЯ РЕАЛІЗАЦІЇ ПРОЦЕСУ З НАЙМЕНШОЮ СИЛОЮ

Вступ. Наразі теоретично встановлено й експериментально підтверджено, що пружні деформації валків і штаби при холодній прокатці мають суттєвий, а при прокатці тонких штаб — вирішальний вплив на всі параметри процесу.

Проблематика. Вплив особливостей пружно-пластичної взаємодії тонкої штаби з валками, натягу, температурно-швидкісних умов деформації та властивостей міцності матеріалу штаби необхідно обов'язково враховувати при розробці сучасної теорії поздовжньої холодної прокатки.

Мета. Моделювання та прогнозування параметрів процесу холодної прокатки тонких і особливо тонких штаб.

Матеріали й методи. Для вирішення поставленого завдання моделювали умови прокатки штаб зі сталі 08кп з різним ступенем попереднього наклепу металу, що відображало особливості та закономірності зміцнення матеріалу штаби в лінії многоклетевого стану. Значення часткових відносних обтиснень змінювали в діапазоні 0,02—0,35 і брали вихідні дані, відповідні найбільш характерним умовам холодної прокатки тонких і особливо тонких штаб зі сталі на діючих станах.

Результати. Отримано кількісні дані про вплив товщини штаби на вході в осередок деформації, часткового й попереднього відносного обтиску при холодній прокатці на умови ведення процесу з найменшою силою. Вперше визначено умови та діапазон часткових відносних обтиснень для здійснення процесу холодної прокатки тонких і особливо тонких штаб з найменшою силою. Встановлено, що при холодній прокатці тонких і особливо тонких штаб з ненаклепаної і попередньо зміцненої сталі зміна часткових відносних обтиснень в діапазоні від 0,1 до 0,30—0,35 забезпечує реалізацію процесу з найменшою силою.

Висновки. Реалізація процесу холодної прокатки з найменшою силою енергетично й технологічно вигідна, оскільки сприяє зменшенню питомої витрати електричної енергії та розширенню сортаменту станів холодної прокатки для менших товщин прокатних штаб і свідчить про необхідність визначення умов для реалізації такого процесу.

Ключові слова: холодна прокатка, моделювання процесу, процеси формовки, пластична деформація, екструзія.