DOI:
UDC 621.771.014

O.P. Maksymenko[1], Doctor of Engineering sciences, full professor, Head of the Department of Metal Processing
V.M. Samokhval[1], Candidate of Engineering Sciences (Ph. D), docent, associate professor, volsamokhval@gmail.com
A.Y. Orobtsev [2], Candidate of Engineering Sciences (Ph. D), Head of Technical Department
K.K. Marchenko[1], Postgraduate Student, marchenokk@gmail.com
[1]Dniprovsk State Technical University, Kamianske, Ukraine
[2]Dneprovsky Integrated Iron and Steel Works, Kamianske, Ukraine

MODELING THE INFLUENCE OF ROLL WEAR ON THE ROLLING PARAMETERS IN A WIRE ROD BLOCK

A mathematical model of the rolling process in a wire rod block with the determination of the average resultant force of the internal longitudinal forces of the metal in the roll bite deformation is proposed, as a criterion for the rolling process stability, and the analysis of the limits of the process self-regulation from perturbations arising from the wear of the rolls of one of the modules. The influence of the wear of the gauge roll of one of the modules on the rolling parameters in all subsequent modules is revealed, which is manifested in the gradual increase of tension stresses between the modules. Such an increase in tension within the self-regulating equilibrium conditions in the deformation roll bite of the fifth and all subsequent modules leads to a decrease in the rolling moments in these modules and in general for the block. The model allows to determine the maximum wear of the calibers, which maintains the stability of the rolling process, which is estimated by the value of the average resulting longitudinal forces.

***Keywords**: roll wear; interstand tension; process stability; torque rolling; average resultant longitudinal forces.*

Запропонована математична модель процесу прокатування в дротовому блоці з визначенням середньої результуючої сили внутрішніх подовжніх сил металу в осередку деформації, в якості критерію сталості процесу прокатування, та виконано аналіз меж саморегулювання процесу від збурювань, що виникають від зношення валків одного з модулів. Виявлено вплив зношення калібру одного з модулів на параметри прокатування у всіх наступних модулях, який проявляється в поступовому збільшенні напружень натяжіння між модулями. Таке збільшення натяжіння в межах саморегулювання умов рівноваги в осередках деформації п'ятого і всіх наступних модулів призводить до зменшення моментів прокатування в цих модулях і в цілому для блоку. Модель дозволяє визначити граничний знос калібрів, за якого зберігається сталість процесу прокатування, яка оцінюється за значенням середньої результуючої подовжніх сил.

***Ключові слова**: знос валків; міжклітьове натяжіння; сталість процесу; момент прокатування; середня результуюча подовжніх сил.*

Formulation of the problem

The development of technology and the improvement of equipment for the production of wire rod allowed to improve the geometric indicators of quality, increase productivity and improve the mechanical properties of rolled products. The results of numerous theoretical and experimental studies of the rolling process in a wire block are given in [1—3]. In these works, the results of the analysis of the geometry and kinematics of the rolling process of the wire rod, the temperature and force conditions in the deformation zone, taking into account the mass forces, are presented.

The modern wire rod block is a 10-module unit, the continuous rolling process in which is carried out with a minimum tension at a speed of up to 120 m/s. Despite the fact that the rolls of the block are made of high-strength carbide material, during the campaign, the grooves of gauges are subject to significant wear [4, 5]. Given the high cost of such rolls, their wear and downtime associated with change rolls, negatively affect the productivity and cost of production. In addition, as the rolls wear, the shape of the groove gradually changes, which leads to a redistribution of the reductions and the corresponding deviations of other technological parameters. In the conditions of wire rod blocks having a group drive, such deviations can reach critical values, leading to violations of the stability of the rolling process.

Analysis of recent research and publications

It is well known that in the deformation zone during rolling, external disturbances, to a certain extent, are compensated by the redistribution of friction forces. Such a redistribution of friction forces manifests itself in a change in the position of the neutral section of the deformation roll bite, which is numerically determined through the angle γ. The dependences of the angle γ, as a regulator of the equilibrium conditions in the deformation zone, on the rolling parameters are considered in detail in [6].

To assess the degree of influence of external influences on the equilibrium conditions in the deformation zone, the average resulting longitudinal force index proposed in [7—9] can be used. The rolling process model using this indicator is based on using dependencies

$$Q_{ср.пр} = \frac{1}{\alpha} \cdot \int_0^{\alpha} Q_{x\_пр} d\varphi\,; \tag{1}$$

$$Q_{x\_пр} = \sigma_x \cdot h_x \cdot b_x\,, \tag{2}$$

or in dimensionless form

$$Q^*_{ср.пр} = \frac{1}{\alpha} \cdot \int_0^{\alpha} Q^*_{x\_пр} d\varphi\,;$$

$$Q^*_{x\_пр} = \frac{Q_{x\_пр}}{2K_{ср} \cdot R \cdot b_x} = \frac{\sigma_x}{2K_{ср}} \left(\frac{h_1}{R} + \varphi^2 \right),$$

where α — is the angle of contact (angle of bite) in the steady state process; $Q_{x\_пр}$ — current longitudinal force from plasticity stresses of the deformable body in the deformation zone; $2K_{ср}$ — average deformation resistance; φ — current capture angle along the deformation zone; h_x и b_x — current thickness and width of the roll along the deformation zone; R_k — roll radius.

The average resultant force $Q_{\text{ср.пр}}$ is the resistance force of the metal to deformation, prevents the longitudinal flow of the metal and, therefore, cannot contribute to the rolling process. The direction of the vector of this force is opposite to the movement of the metal in the focus. Accordingly, as shown in [7, 8], at negative values of this force $Q_{ср.пр} < 0$, the rolling process remains stable. When $Q_{ср.пр} = 0$ there are extreme rolling conditions. If this force takes positive values, the rolling process is impossible.

The proposed stability criterion for the rolling process is more stringent in comparison with the well-known condition $\gamma = 0$.

Research goal statement

The aim of the work is to simulate rolling in a wire block using the average resulting longitudinal forces as a criterion for the stability of the process and analysis of the limits of the process self-regulation from disturbances introduced by the wear of the rolls.

Statement of the main material

When developing a model of the rolling process in a wire block, we proceeded from the solution of the differential equilibrium equation of *T*. Karman using the friction model

$$t_x = f_y \cdot p_x\,,$$

where f_y — steady-state friction coefficient; p_x — current values of metal pressure on rolls.

To determine the rolling parameters in gauges, the model provides for the use of the corresponding strip method and the law of constancy of second volumes. A feature of the model is the account of the tensions arising between the unit modules.

The sequence of calculations in the developed model includes the following steps. First, we determine the sizes of the corresponding strip for each of the passes, along which we calculate the usual geometric and deformation parameters.

Kinematic parameters are determined taking into account the tension between the modules. In this case, taking into account the recommendations of the studies [2], the specific tension for the first pass is assigned as minimum.

For the first pass, the width of the workpiece on exit from the roll bite is calculated according to the method described in [10], setting a certain value of the coefficient of friction. To a first approximation, a value of 0.26 was used. Then we determine the forward slip by the known dependence

$$S = \frac{R_k \cdot \gamma^2}{h_1} + \frac{\dfrac{\sigma_1}{2K_{cp}} \cdot \dfrac{h_1}{R_k} \cdot \dfrac{b_1}{b_{cp}} - \dfrac{\sigma_0}{2K_{cp}} \cdot \dfrac{h_0}{R_k} \cdot \dfrac{b_0}{b_{cp}}}{4 \cdot \dfrac{p_{cp}}{2K_{cp}} \cdot f_y}, \qquad (3)$$

where γ — neutral plane angle; σ_0, σ_1 — front (exit) and rear (entry, back) specific tension of the roll (as the ratio of the tension force to the cross-sectional area of the workpiece); b_{cp} — average width workpiece over the deformation zone.

The second term in dependence (3), taking into account the influence of front and rear tension, was denoted as $\varphi(q_0, q_1)$.

Using the forward slip value in the first pass, we determine the velocity of metal exit from the deformation zone V_1 and the rolling constant $C = h_1 \cdot b_1 \cdot V_1$. The rolling constant, determined by the parameters of the first pass, remains unchanged for all the others.

Further, using pressure distribution diagrams $\frac{p_x}{2K_{cp}}$ and plasticity conditions, we obtain the values of normal longitudinal stresses $q = \frac{\sigma_x}{2K_{cp}}$ and the average resulting longitudinal force of the plastically deformable metal $Q^*_{x\_np}$.

For the second pass, using the iterative procedure, the values of the metal exit velocity from the rolls and the cross-sectional area are selected that satisfy the rolling constant. In each of the iterations, the definition of the width of the workpiece at the exit, the front tension, the forward slip, and other intermediate parameters is provided. Similarly, we perform parameter calculations for all subsequent modules of the wire rod block.

We use the obtained rolling parameters for the block modules to calculate the rolling moment in the usual and dimensionless form $M^*_{np} = M_{np} \cdot \frac{1}{2K_{cp} \cdot R_k^2 \cdot b_{cp}}$. A condition check $B_k \geq b_1$ is also performed to prevent overflow of gauge.

Using the developed model, we performed parameter calculations for the real case of rolling a wire rod with a diameter of 5.5 mm in the conditions of mill 400/200 of the Dnieper Metallurgical Plant. The main parameters of rolling according to the existing technology are shown in table 1. In this case, the friction coefficient was taken $f_y = 0.26$.

The calculated rolling parameters are summarized in tabl. 2.

As follows from the data obtained, the rolling process is carried out with minimal tension between the modules and is characterized by sufficient stability. This is confirmed by the calculated values of the average resulting longitudinal force — negative values of approximately the same order were obtained for all modules, from –0.009 to –0.016.

To analyze the possible limits of self-regulation of the process from disturbances introduced by the wear of the rolls, the rolling parameters were calculated for the case when there is wear in one of the modules that exceeds the wear on the other modules. From the results of measuring the actual wear of several sets of rolls of the block, it was found that the maximum wear is observed in the fifth module. During the campaign, “draft” modules gauges (No. 1 — No. 7) provide rolling of approximately 2500 tons of wire rod. Moreover, the maximum wear of the fifth module rolls is 1.0—1.2 mm. For other "draft" modules, the amount of wear varies between 0.4—0.6 mm. Therefore, using the developed model of the rolling process in the wire block, we performed the simulation of the perturbing effect of the wear of the rolls of the fifth module on the rolling parameters of the entire block.

Table 1. Rolling parameters in a wire block of wire rod with a diameter of 5.5 mm according to existing technology and the dimensions of the corresponding strip

№ module	Gauge Parameters, mm				Workpiece Parameters				Dimentions of the corresponding strip				
	width	groove depth	gap	radius	height	width	cross-sectional area	elongation coef.	thickness		corresponding reduction	wigth	
									input	output		input	output
	$B_к$	$h_{вр}$	g	R_k	h_i	b_i	A_i	λ	$h_{0пр}$	$h_{1пр}$	$\Delta h_{пр}$	$b_{0пр}$	$b_{1пр}$
0					17,3	17,3	234,9						
1	23,65	4,6	1,8	102,6	11	21,05	181,8	1,2924	15,33	9,75	5,58	15,33	18,65
2	13,83	6,14	1,5	101,7	13,78	13,78	149	1,2202	18,65	12,21	6,45	9,75	12,21
3	18,89	3,5	2,1	103,3	9,1	16,57	118,4	1,2585	12,21	8,06	4,14	12,21	14,68
4	11,45	4,95	1,06	102,5	10,96	10,96	94,37	1,2544	14,68	9,72	4,97	8,06	9,71
5	16,85	2,7	1,9	103,9	6,5	14,43	73,62	1,2819	9,71	5,76	3,95	9,71	12,78
6	8,97	3,7	1,29	103,3	8,69	8,69	59,25	1,2425	12,78	7,7	5,09	5,76	7,7
7	13,56	2,1	1,9	104,3	6,1	9,75	46,7	1,2687	7,7	5,41	2,29	7,7	8,64
8	7,27	2,92	1,01	103,9	6,85	6,85	36,84	1,2676	8,64	6,07	2,57	5,41	6,07
9	10,24	1,6	1,3	104,7	4,5	8,31	29,34	1,2556	6,07	3,99	2,08	6,07	7,36
10	5,76	2,18	1,16	104,4	5,52	5,52	23,92	1,2266	7,36	4,89	2,47	3,99	4,89

Table 2. Design parameters for the developed model

Calculation parameters													
№	$b_{ср}$	α	γ	$R\gamma^2 / h_1$	$\varphi\,(q_0 q_1)$	S	V_0	$V_В$	V_1	q_i	$Q_{ср}$*	$p_{ср}/2k$	$M_{пр}$
1	16,99	0,233	0,0655	0,0452	0,0022	0,047	10,48	12,93	13,54	0,025	-0,016	1,1517	0,061
2	10,98	0,252	0,0623	0,0323	-0,0007	0,032	13,54	16,01	16,52	0,025	-0,011	1,0856	0,072
3	13,44	0,200	0,0597	0,0457	0,0013	0,047	16,52	19,86	20,79	0,05	-0,014	1,1696	0,048
4	8,89	0,220	0,0617	0,0402	0,0002	0,04	20,79	25,08	26,08	0,065	-0,009	1,0914	0,054
5	11,25	0,195	0,0569	0,0585	-0,0014	0,057	26,08	31,63	33,43	0,055	-0,012	1,1975	0,049
6	6,73	0,222	0,0562	0,0424	-0,0045	0,038	33,43	40,02	41,54	0,005	-0,011	1,1460	0,064
7	8,17	0,148	0,0537	0,0556	0,0012	0,057	41,54	49,87	52,71	0,035	-0,016	1,2738	0,026
8	5,74	0,157	0,0567	0,055	0,0023	0,057	52,71	63,21	66,81	0,09	-0,013	1,1915	0,027
9	6,72	0,141	0,0463	0,0564	-0,0027	0,054	66,81	79,60	83,90	0,025	-0,012	1,2940	0,032
10	4,44	0,154	0,0515	0,0567	-0,0012	0,056	83,9	98,00	103,49	0	-0,016	1,3085	0,034
												Σ=	0,467

The wear value was modeled at the levels of 0.4 mm, 0.6 mm and 0.8 mm, assigning the thickness of the roll at the exit of the fifth module, respectively 6.9 mm, 7.1 mm and 7.3 mm. The calculation results, in comparison with the parameters of the basic schedule according to the existing technology, are shown in Fig. 1—4.

Fig. 1 shows the dynamics of the change in the front specific tension as the wear in the module 5 changes. From the data obtained it follows that the change in the gauge of the 5th module leads to an increasing tension increase for all subsequent modules. In this case, as the wear increases, the tension also increases. As a result, when wear the gauge of the 5th module is 0.8 mm, the maximum value of the front tension is observed for the ninth module.. Such features of tension change are associated with self-regulation processes in each of the deformation zones for module 5 and all subsequent ones to maintain a balance of forces and ensure that the conditions for the constancy of second volumes are satisfied.

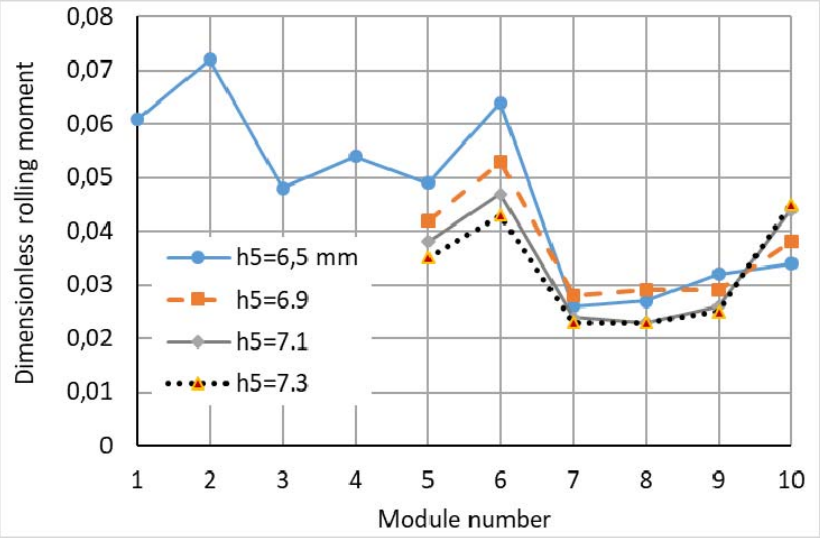

Fig. 1. Dependences of the distribution of the front specific tension on the block modules when the wear in the gauge of the fifth module changes

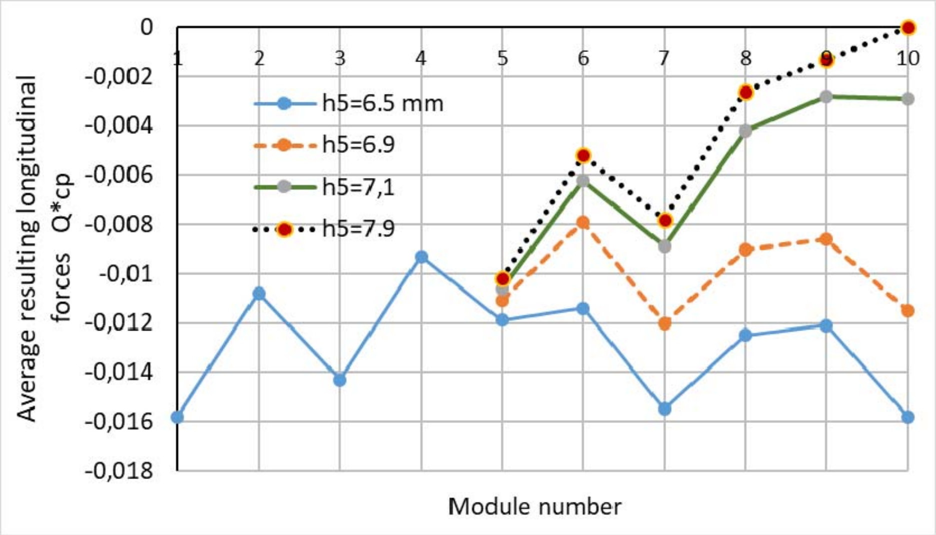

Fig. 2. The effect of wear of the rolls of the fifth module on the average resulting longitudinal forces of plastically deformable metal

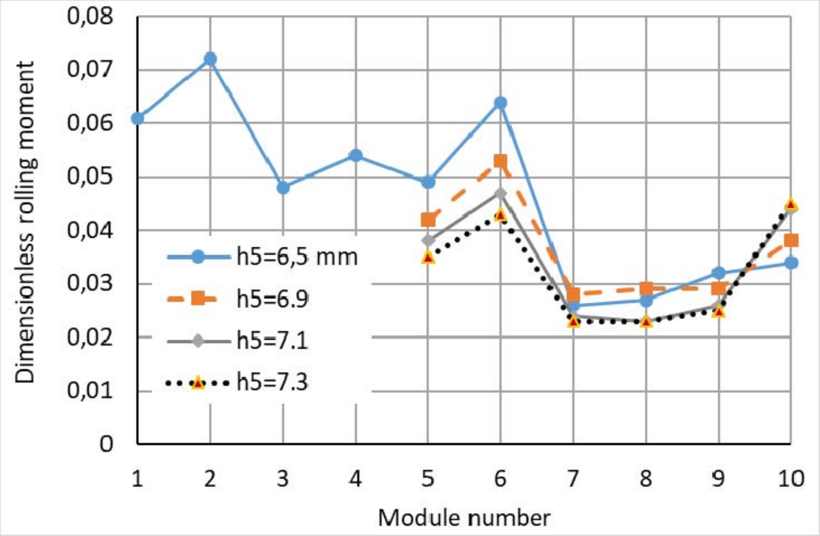

Fig. 3. Change in dimensionless rolling moment depending on the wear of the rolls of the 5th module

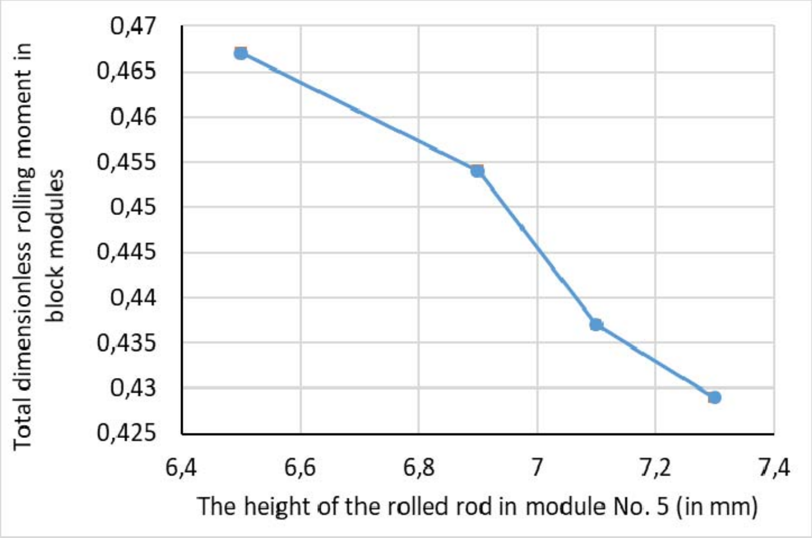

Fig. 4. The effect of roll wear on the 5th module on the total rolling moment

From an analysis of the dynamics of changes in the average resulting longitudinal forces of a plastically deformable body (Fig. 2), it follows that with increasing wear of the rolls of the 5th module, the value of this parameter decreases in absolute value, both for the 5th module and for all subsequent ones. Moreover, such a decrease has an increasing character for each subsequent module. As a result, when the caliber of the 5th module is worn down by 0.8 mm, the force value in $Q^*_{x\_np}$ the tenth module is obtained equal to zero, which indicates the achievement of the limit rolling conditions when slippage or stopping the rolling process are possible. Therefore, to prevent slippage, that is, violation of the stability of the rolling process, it is necessary to eliminate the causes that lead to loss of stability of the process. At the same time, actions to prevent or eliminate slippage should not be taken in the 10th module, but in the 5th. The most effective action to maintain the stability of the process will be the transshipment of the rolls of the block due to the achievement of the maximum allowable wear of the gauge of the 5th module.

Given that for the take value wear of 0.8 mm, which corresponds to the average wear around the perimeter of the caliber, the maximum wear for the most worn sections can reach somewhat larger values. This is confirmed by the results of measurements of actual gauge wear, according to which the maximum gauge wear of the 5th module, as mentioned earlier, reaches 1.0—1.2 mm. Thus, the theoretically substantiated, according to the criterion of the average resultant longitudinal forces, the need for change roll to the achievement of the maximum allowable wear, is confirmed by practical data.

According to the data shown in Figure 3, as wear in the 5th gauge increases and a corresponding increase in tension in subsequent modules leads to a decrease in rolling moment. The most significant torque reduction was obtained for modules 5 and 6. For subsequent modules, the effect of wear on the moment is weakened.

The exception is module No. 10, where the opposite nature of the moment change is obtained. This is due to the characteristics of the distribution of tension with increasing wear. The most significant increase in forward tension occurs in module No. 9, but for module No. 10, this tension is rearward. With a constant forward tension for module No. 10 equal to zero, an increase in the rear tension inevitably leads to a corresponding increase in torque.

It is important to note that by reducing the rolling moment in modules No. 5 — No. 9, the total rolling moment of the block is reduced. The dependence of the change in the total rolling moment in the block on gauge wear in the 5th module is shown in Figure 4. This effect is manifested due to an increase in tension as the wear increases.

Conclusions

A model of the rolling process in a wire block has been developed, the distinguishing feature of which is the ability to determine the average resulting longitudinal forces of plastically deformable metal, which is used as a criterion for assessing the stability of the rolling process.

The effect of gauge wear on one of the module modules on rolling parameters in subsequent modules, which occurs as a result of self-regulation of equilibrium conditions in the deformation zones of these modules, is established. Most significantly, this effect manifests itself in the distribution of tension, which in turn leads to a decrease in the rolling moment in subsequent modules and the total rolling moment in the block.

The model allows you to determine the maximum allowable value of wear of the rolls according to the criterion of the average resulting longitudinal forces of the plastically deformable body, at which the stability of the rolling process in the wire rod block is maintained.

References

[1] Ivodytov A. N. & Horbanev A. A. (1989) *Razrabotka i osvoenye technolohyy proyzvodstva vysokokachestvennoi katanky [Development and mastering of high quality wire rod production technology]*. M. : Metallurhyia. [in Russian].

[2] Horbanev A. A., Zhuchkov S. M., Fylyppov V. V., Tymoshpolskyi V. I., Steblov A. B., Yunakov A. M., Tyshchenko V. A. (2003) *Teoretycheskye i technolohycheskye osnovy vysokoskorostnoi prokatky katanky [Theoretical and technological foundations of high-speed rolling wire rod]*. Mynsk : Vysshaia shkola. [in Russian].

[3] Kuhushyn A. A., Popov Yu. A. (1982) *Vysokoskorostnaia prokatka katanky [High speed rolling wire rod].* M. : Metallurhyia. [in Russian].

[4] Maksymeno O. P., Marchenko K. K. (2018) Metodyka y rezultaty issledovanyia iznosa kalybrov valkov pry prokatke katanky v provolochnom bloke [Methods and results of the study of wear gauge rolls when rolling rod in a wire block]. *Metallurhycheskaia i hornorudnaia promyshlennost*. [in Russian].

[5] Byon S. V., Lee Y. (2008) A study of roll gap adjustment due to roll wear in groove rolling: experiment and modeling. *JEM1065, Proc. JMechE Vol. 222 Part B: Engineering Manufacture*.

[6] Vydrin V. N. (1960) Dynamyka prokatnykh stanov [Rolling mill dynamics]. Sverdlovsk :Metallurhyzdat. [in Russian].

[7] Maksymenko O. P., Loboiko D. Y., Yzmailova M. K. (2016) Prodolnaia ustoichyvost polosy v valkakh s analyzom kontaktnykh uslovyi [Longitudinal stability of the strip in the rolls with the

analysis of contact conditions]. *Sbornyk nauchnykh rabot Dneprodzerzhynskoho hosudarstvenno-ho tekhnycheskoho unyversyteta (Tekhnycheskye nauky).* – Dneprodzerzhynsk: DDTU. [in Russian].

[8] Maksymenko O. P., Yzmailova M. K., Loboiko D. Y. (2015) Analyz prodolnoi ustoichyvosty protsessa prokatky s uchetom vnutrennykh sil i rezhyma natiazhenyi polosy [Analysis of the longitudinal stability of the rolling process, taking into account internal forces and strip tension mode]. *Metallurhycheskaia i hornorudnaia promyshlennost.* [in Russian].

[9] Maksymenko O. P., Loboiko D. Y., Romaniuk R. Ya. (2013) Analyz sylovoho vzaymodeistvyia v ochahe deformatsyy pry prokatke [Analysis of force interaction in the deformation zone during rolling]. *Metallurhycheskaia y hornorudnaia promyshlennost.* [in Russian].

[10] Hrudev A. A. (1988) *Teoryia prokatky [Rolling theory].* M. : Metallurhyia. [in Russian].

МОДЕЛЮВАННЯ ВПЛИВУ ЗНОСУ ВАЛКІВ НА ПАРАМЕТРИ ПРОКАТУВАННЯ В ДРОТОВОМУ БЛОЦІ

Максименко О.П., Самохвал В.М., Оробцев А.Ю., Марченко К.К.

Реферат

Дослідження впливу зносу валків на параметри прокатування були і залишаються актуальними для всіх типів станів. Однак, для дротових блоків такі дослідження особливо актуальні, як з огляду на зменшення зносу валків, так і для забезпечення сталості процесу прокатування.

Метою роботи є моделювання прокатування в дротовому блоці з використанням середньої результуючої подовжніх сил пластично деформованого тіла в якості критерію сталості процесу та аналіз меж саморегулювання процесу при збуреннях, викликаних зносом валків.

Розроблена математична модель процесу прокатування в дротовому блоці, з використанням середньої результуючої подовжніх сил в якості критерію сталості процесу, дозволила виконати аналіз меж саморегулювання процесу при збуреннях, які виникають від зносу валків одного з модулів блоку. На основі практичних даних виконано моделювання впливу зносу валків модуля №5. Величину зносу варіювали на чотирьох рівнях, які відповідали реальним значенням, отриманим для одного з комплектів валків блоку. Виявлено вплив зносу калібрів валків 5-го модуля на параметри прокатування в наступних модулях, що проявляється в наростаючому збільшенні натяжіння розкату між модулями та збільшенні середньої результуючої подовжніх сил. Збільшення натяжіння в межах саморегулювання умов рівноваги в осередках деформування модулю, що розглядається, та всіх наступних, призводить до зменшення моментів прокатування для цих модулів та в цілому для блоку.

Модель дозволяє визначити граничний знос калібрів валків, до якого зберігається сталість процесу прокатування в дротовому блоці, яка оцінюється за критерієм середньої результуючої подовжніх сил пластично деформованого тіла. Модель також може бути використана для уточнення технологічних параметрів, для забезпечення мінімізації зносу при збереженні оптимальних значень критерію сталості процесу прокатування.

Література

1. Иводитов А. Н., Горбанев А. А. Разработка и освоение технологии производства высококачественной катанки. М. : Металлургия, 1989. 256 с.
2. Теоретические и технологические основы высокоскоростной прокатки катанки / А. А. Горбанев и др. Минск : Высшая школа, 2003. 287 с.
3. Кугушин А. А., Попов Ю. А. Высокоскоростная прокатка катанки. М. : Металлургия, 1982. 220 с.
4. Максимено О. П., Марченко К. К. Методика и результаты исследования износа калибров валков при прокатке катанки в проволочном блоке. *Металлургическая и горнорудная промышленность*. 2018. № 2. С. 20–24.

5. ByonS. M., Lee Y. A study of roll gap adjustment due to roll wear in groove rolling: experiment and modelling. *JEM1065, Proc. JMechE Vol. 222 Part B: Engineering Manufacture*. 2008. P. 875–885.
6. Выдрин В. Н. Динамика прокатных станов. Свердловск : Металлургиздат, 1960. 255 с.
7. Сборник научных работ Днепродзержинского государственного технического университета (Технические науки). Днепродзержинск: Изд-во ДДТУ, 2016. 212 с.
8. Максименко О. П., Измайлова М. К., Лобойко Д. И. Анализ продольной устойчивости процесса прокатки с учетом внутренних сил и режима натяжений полосы. *Металлургическая и горнорудная промышленность*. 2015. № 1. С. 59–62.
9. Максименко О. П. Лобойко Д. И., Романюк Р. Я. Анализ силового взаимодействия в очаге деформации при прокатке. *Металлургическая и горнорудная промышленность*. 2013. № 6. С. 47–49.
10. Грудев А. А. Теория прокатки: Учебник для вузов. М. Металлургия, 1988. 240 с.