DOI:
UDC 621.771.2

**O. Maksimenko**, Doctor of Tech. Sc., Professor, O.maks1940@gmail.com.
**A. Nikulin**, Cand. of Tech. Sc., Associate Professor, av_nikulin@ukr.net
**A. Pryimak**, specialist, personalrav_@ukr.net
**V. Krivov**, graduate student, vlad krivov91161@ukr.net
Dniprovsk State Technical University, Kam'yanske

# MODELING THE INFLUENCE OF FRICTION ON THE STABILITY THE PROCESS AND FORCE PARAMETERS WHEN ROLLING IN A MODERN WIRE BLOCK

*Rolling of round billet in wire blocks is the main method of wire rod production in the conditions of modern metallurgical manufacturing. However, in the theory of high-speed rolling there are a number of unsolved problems. To improve the mathematical model of the high-speed rolling process, a scheme and method for calculating the longitudinal stability of the process have been developed. Using an improved process model, the power and kinematic parameters were calculated, as well as the longitudinal stability of the rolling process in the cages of the wire block when rolling wire rod with a diameter of 5.5 mm.*

***Keywords**: high-speed rolling; friction coefficient; longitudinal stability; energy-power and kinematic parameters.*

*Прокатка круглої заготовки у дротяних блоках є основним методом виробництва катанки в умовах сучасного металургійного виробництва. Однак у теорії високошвидкісного прокатування існує ряд невирішених проблем. Для вдосконалення математичної моделі процесу високошвидкісного прокатування розроблено схему та метод розрахунку поздовжньої сталості процесу. За допомогою вдосконаленої моделі процесу розраховували енергосилові та кінематичні параметри, а також подовжню стійкість процесу прокатки в клітях дротяного блоку при прокатуванні катанки діаметром 5,5 мм.*

***Ключові слова**: високошвидкісне прокатування; коефіцієнт тертя; поздовжня сталість; енергосилові та кінематичні параметри.*

## Problem's Formulation

Contact friction in the deformation zone during rolling plays an extremely important role, since it realizes the steady and stability of the process. The friction conditions in the roll — strip pair are largely determined by the value the friction coefficient. Theoretical and experimental studies [1—4] show which factors and parameters have a significant effect on $f_y$ — the coefficient of friction in a steady process of hot rolling. It should be noted that the experimental data for determining $f_y$ refer to a relatively narrow range of rolling speed variation (0—15 m/s). However, wire rod production in a modern wire block is characterized by a high-speed mode with output speeds of 110—120 m/s, and sometimes up to 150 m/s. In the absence of experimental data on the value of $f_y$ for the above production conditions, the values of the friction coefficient are often taken insufficiently substantiated.

## Analysis of recent research and publications

In work [5], the calculated value of the friction coefficient in the steady mode varies from 0.14 to 0.06, and in the study [6] it is 0.45. In other publications [7, 8], $f_y$ values are taken in the range 0.25—0.35. At the same time, it is well known that a sufficiently accurate determination of the friction coefficient makes it possible to significantly bring the model closer to the real process. In this case, special attention should be paid to the assessment of the limiting conditions of rolling and the longitudinal stability of the rolled work in rolls. It is important to know at what minimum value of $f_y$ the rolling process of wire rod is stable without partial or complete slippage.

## Formulation of the study purpose

Accordingly, a model study of the limiting conditions for rolling wire rod with a diameter of 5.5 mm in the wire block of the 400/200 mill of PJSC DMK is proposed, as well as the determination of the minimum value the friction coefficient at which the process will be carried out stably without braking the metal in the rolls. In addition, the paper provides an assessment of the effect of friction conditions in the contact of the metal with the rolls on the tension along the entire line of the wire block.

## Presenting main material

The theoretical solution of the problem is based on the use of the average resultant longitudinal internal forces $Q^*_{cp\,np}$ of a plastically deformed metal [9, 10], which in a dimensionless form is determined by the formula

$$Q^*_{cp\,np} = \frac{1}{l_d} \int_0^{\alpha_y} Q^*_{x\,np} \, R \, d\varphi \, .$$

The current value of the longitudinal internal force can be calculated based on its definition

$$Q_{x\,np} = \sigma_x \, h_x \, b_{cp} \, ,$$

where the normal stress $\sigma_x$ is found using the plasticity condition, proceeding from the solution of the differential equation of T. Karman [2].

In dimensionless form, the quantities are:

$$\frac{\sigma_x}{2k_{cp}} = \frac{p_x}{2k_{cp}} - 1 ; \tag{1}$$

$$Q^*_{x\,np} = \frac{\sigma_x}{2k_{cp}} \cdot \left( \frac{h_1}{R} + \varphi^2 \right) ; \tag{2}$$

$$Q^*_{cp\,np} = \frac{1}{\alpha_y} \int_0^{\alpha_y} Q^*_{x\,np} \, d\varphi \, . \tag{3}$$

where $2k_{cp}$ is the average resistance to deformation; $p_x$ — normal pressure in the deformation zone; $h_1$ is the thickness of the strip at the exit of the metal from the rolls; $R$ is the radius of the rolls; $\varphi$ is the current angle of capture; $\alpha_y$ is the capture angle in the steady state.

It should be noted that the current internal force $Q^*_{x\,np}$ along the length of the deformation zone changes qualitatively like the longitudinal stress $\sigma_x$. When rolling under conditions when $f_y > \alpha_y$, in each section of the deformation zone, it is compressive and directed in opposite to the movement of the strip. In cases when $f_y < \alpha_y$ this force in some sections of the deformation zone is tensile, and in others, closer to the exit of the metal from the rolls, compressing, which leads to the multidirectional of its action.

If $f_y = 2\alpha_y$, then the current internal force of the plastically deformed metal along the entire length of the deformation zone becomes tensile. In accordance with the above, the average resultant of the longitudinal internal forces $Q^*_{cp\,np}$, depending on the rolling conditions, may have different signs.

However, given that $Q^*_{cp\,np}$ is physically a resistance force and cannot play an active role in the process of plastic deformation of the metal, it is oppositely directed with respect to the movement of the strip. Therefore, as long as $Q^*_{cp\,np} < 0$ the rolling of the strip in the rolls will be carried out stably without partial or complete slippage. With a positive value of this force, the process is impossible. Then the limiting conditions for steady-state rolling are determined by the following relationship:

$$Q^*_{cp\,np} = 0 \, . \tag{4}$$

This condition is more stringent than the boundary case of rolling in a steady state known in the theory:

$$\alpha_y^{\max} = 2 f_y \, .$$

Calculations [10] show that when using the boundary condition (4), the limiting angle of capture $\alpha_y^{\max} = (1,4...1,5) f_y$ does not exceed, which is more consistent with the results of experiments [3]. In addition, when analyzing using the limiting condition (4), it becomes clear the possible loss of stability of the strip in the rolls with subsequent slipping in the presence of an advance zone ($\gamma > 0$, positive angle of the neutral section), which is confirmed experimentally [11, 12].

The limiting condition (4) was obtained on the basis of a logical analysis of the nature of internal forces and their action on the strip. In this case, it is possible to establish the physical picture of the change in the limiting pull-in and push-out contact forces in the deformation zone when the sign of the internal force $Q^*_{cp\ np}$ changes. For this, let us analyze the equilibrium conditions for the selected current volume of metal in the deformation zone with an average strip width $b_{cp}$ (Fig. 1).

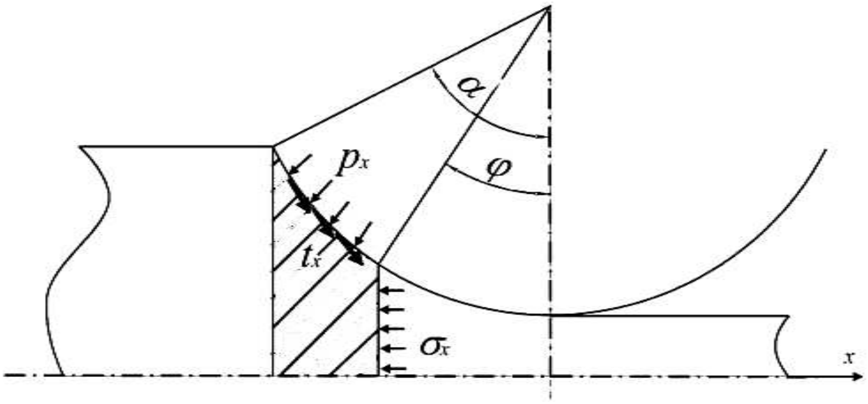

*Fig. 1.* To the equilibrium of the current volume of the metal in the deformation zone

Equating the longitudinal components of the forces due to stresses $\sigma_x$, $p_x$, $t_x$, we arrive at the equation

$$2\int_{\varphi}^{\alpha_н}\left(\frac{t_x}{2k_{cp}}\cos\varphi-\frac{p_x}{2k_{cp}}\sin\varphi\right)d\varphi=\frac{\sigma_x}{2k_{cp}}\left(\frac{h_x}{R}+\varphi^2\right). \tag{5}$$

Let us find the average values of these forces for the entire deformation zone, taking into account (2) and (3). Considering the balance between contact and internal longitudinal forces in the deformation zone, we arrive at the equation

$$\frac{1}{\alpha_y}\int_0^{\alpha_y}\left[2\int_{\varphi}^{\alpha_y}\left(\frac{t_x}{2k_{cp}}\cos s-\frac{p_x}{2k_{cp}}\sin s\right)ds\right]d\varphi+\left(-Q^*_{cp\,np}\right)=0. \tag{6}$$

It follows from the above equation that a change in the sign of the average resultant force $Q^*_{cp\ np}$ will lead to a redistribution of the pull-in and push-out forces in favor of the latter, which entails deceleration of the metal and, subsequently, the stop of the strip in the rolls. Thus, the analysis performed confirmed the validity of the limiting condition (4) from the point of view of the physics of the process.

When performing specific calculations of the force and other parameters of rolling a wire rod with the diameter 5.5 mm from a circle of 17.3 mm, we used the technique published in [14]. The calculation results are shown in tabl. 1 for the case when the coefficient of friction in the contact between the strip and the rolls of all stands in the wire block is $f_y = 0.22$. The graphs in Fig. 2—4 show the results of calculations depending on different values of the friction coefficient.

*Table 1.* Parameters of deformation and longitudinal stability of the rolling process the wire rod with a diameter of 5.5 mm with $f_y = 0.22$

| Real geometric dimensions of specimens and other parameters | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| № | $h_0$, mm | $h_1$, mm | $\Delta h$, mm | $b_0$, mm | $b_1$, mm | $v_0$, m/s | $v_в$. m/s | $v_1$, m/s | $F_0$, mm$^2$ | $F_1$, mm$^2$ | $R_k$, mm | $B_k$, mm | $h_{вр}$, mm | $t$, mm |
| 1 | 17,3 | 11,0 | 6,3 | 17,3 | 21,1 | 10,5 | 12,9 | 13,5 | 234,9 | 181,8 | 102,6 | 23,7 | 4,6 | 1,80 |
| 2 | 21,1 | 13,8 | 7,3 | 11,0 | 13,8 | 13,5 | 16,0 | 16,5 | 181,8 | 149 | 101,7 | 13,83 | 6,14 | 1,50 |
| 3 | 13,8 | 9,1 | 4,7 | 13,8 | 16,6 | 16,5 | 19,9 | 20,8 | 149 | 118,6 | 103,3 | 18,89 | 3,5 | 2,10 |
| 4 | 16,6 | 11,0 | 5,6 | 9,1 | 11,0 | 20,8 | 25,1 | 26,1 | 118,6 | 94,37 | 102,5 | 11,45 | 4,95 | 1,06 |
| 5 | 11,0 | 6,5 | 4,4 | 11,0 | 14,3 | 26,1 | 31,6 | 33,6 | 94,37 | 73,35 | 104 | 16,85 | 2,7 | 1,12 |
| 6 | 14,3 | 8,6 | 5,7 | 6,5 | 8,6 | 33,6 | 40,0 | 42,1 | 73,35 | 58,41 | 103,3 | 8,97 | 3,7 | 1,27 |
| 7 | 8,6 | 5,5 | 3,1 | 8,6 | 10,8 | 42,1 | 49,9 | 53,0 | 58,41 | 46,48 | 104,4 | 13,56 | 2,1 | 1,30 |
| 8 | 10,8 | 6,9 | 3,9 | 5,5 | 6,9 | 53,0 | 63,2 | 66,7 | 46,48 | 36,88 | 103,9 | 7,27 | 2,92 | 1,01 |
| 9 | 6,9 | 4,4 | 2,5 | 6,9 | 8,5 | 66,7 | 79,6 | 84,6 | 36,88 | 29,09 | 104,7 | 10,24 | 1,6 | 1,16 |
| 10 | 8,5 | 5,5 | 3,0 | 4,4 | 5,5 | 84,6 | 98,0 | 103,8 | 29,09 | 23,72 | 104,4 | 5,76 | 2,18 | 1,14 |

*Table 1 continuation*

| Geometric dimensions, reduced to the corresponding strip and other parameters | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| № | $h_0$ | $h_1$,mm | | $b_0$,mm | $b_1$,mm | $\alpha$, rad | $Q^*_{ср.\ пр}$ | $p_{cp}/2k_{cp}$ | $\gamma$ | $M_{кр}$ | $q_0$ | $q_1$ | $R\gamma^2/h_1$ |
| 1 | 15,33 | 9,75 | 5,58 | 15,33 | 18,65 | 0,233 | -0,0092 | 1,0904 | 0,0567 | 0,0575 | 0 | 0,025 | 0,0338 |
| 2 | 18,65 | 12,21 | 6,45 | 9,75 | 12,21 | 0,252 | -0,0037 | 1,0323 | 0,0514 | 0,0677 | 0,025 | 0,027 | 0,0220 |
| 3 | 12,21 | 8,06 | 4,14 | 12,21 | 14,71 | 0,200 | -0,0084 | 1,1021 | 0,0527 | 0,0452 | 0,027 | 0,021 | 0,0355 |
| 4 | 14,71 | 9,72 | 4,99 | 8,06 | 9,71 | 0,221 | -0,0077 | 1,0774 | 0,0532 | 0,0536 | 0,021 | 0,022 | 0,0299 |
| 5 | 9,71 | 5,78 | 3,94 | 9,71 | 12,70 | 0,195 | -0,0101 | 1,1667 | 0,0528 | 0,0445 | 0,022 | 0,027 | 0,0502 |
| 6 | 12,70 | 7,64 | 5,06 | 5,78 | 7,64 | 0,221 | -0,0071 | 1,0903 | 0,0549 | 0,0525 | 0,027 | 0,052 | 0,0407 |
| 7 | 7,64 | 4,87 | 2,77 | 7,64 | 9,54 | 0,163 | -0,0088 | 1,1727 | 0,0491 | 0,0324 | 0,052 | 0,053 | 0,0517 |
| 8 | 9,54 | 6,07 | 3,46 | 4,87 | 6,07 | 0,183 | -0,0073 | 1,1162 | 0,0515 | 0,0382 | 0,053 | 0,063 | 0,0454 |
| 9 | 6,07 | 3,86 | 2,21 | 6,07 | 7,53 | 0,145 | -0,0094 | 1,2345 | 0,0447 | 0,0293 | 0,063 | 0,024 | 0,0542 |
| 10 | 7,53 | 4,87 | 2,66 | 3,86 | 4,87 | 0,160 | -0,0113 | 1,2234 | 0,0482 | 0,0331 | 0,024 | 0 | 0,0497 |

*Notes*: $h_0$ and $h_1$ — the thickness of the specimen at the entrance and exit of the deformation zone; $\Delta h$ — absolute reduction; $v_0$ and $v_1$ — rolling speed at the entrance and exit of the deformation zone; $v_в$ — the speed of the surface of the rolls; $F_0$ and $F_1$ — cross-sectional area of the specimen before and after the passage; $R_k$ — rolling radius of the roll; $B_k$ — width of caliber; $h_{vr}$ — depth of cut of caliber; $t$ — gap; $\varphi$ is the angle of contact of the metal with the rolls; $\gamma$ is the angle of the neutral section; $q_0 = \sigma_0\ /\ (2k_{cp})$ and $q_1 = \sigma_1\ /\ (2k_{cp})$ — dimensionless rear and front specific tensions; $M_{PR}$ — rolling torque

The numerical value of the force $Q^*_{cp\ np}$ makes it possible to evaluate the longitudinal stability of the process under different rolling conditions [3]. In cases when $Q^*_{cp\,np} < 0$, and in modulus is hundredths of a unit, rolling is performed steadily with a significant margin of stability. With a modulus of this value in thousandths, the process is performed steadily, but with slightly less stability. With the further approach of the modulus of this force to zero, rolling is performed under conditions close to the limiting ones.

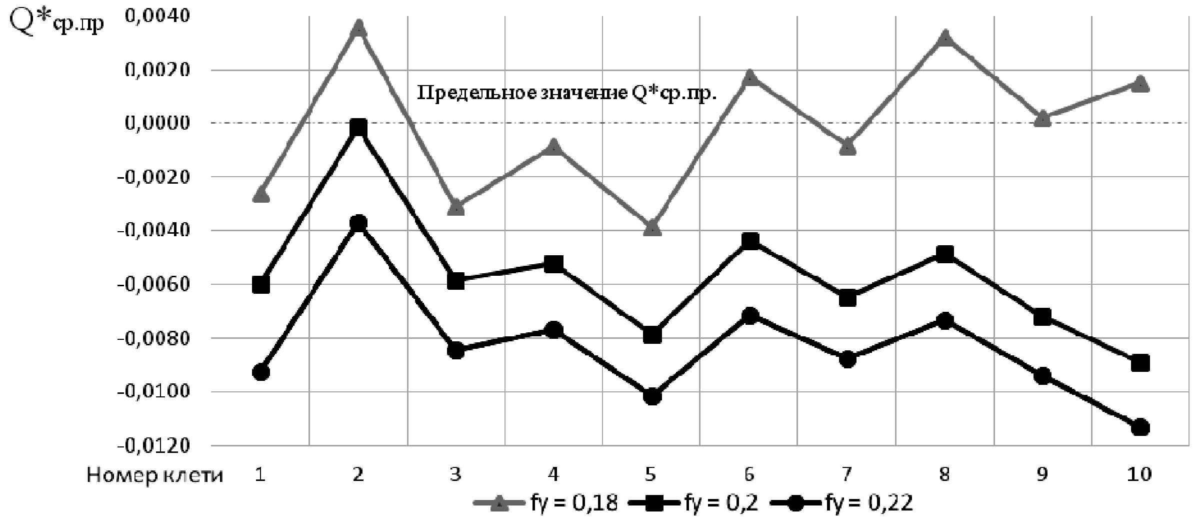

*Fig. 2.* Dependence of the resulting force $Q^*_{ср.\ пр}$ from the friction coefficient along the stands of the wire block

As follows from the tabl. 1 and fig. 2, when rolling with $f_y = 0.22$, the values of the longitudinal force are negative along the deformation zones of all ten stands. Consequently, the deformation of the metal as a whole in the block is stable, the process is stable, although in the second stand, where $Q^*_{ср.пр} = -0{,}0037$ the probability of transition to the limiting rolling conditions is somewhat higher than in the others. When rolling with $f_y = 0.2$ in the same stand $Q^*_{ср.пр} = -0{,}0002$, the process is close to the limiting one.

With fluctuations of external factors in this stand, slippage of the strip in the rolls is possible, if the longitudinal forces of the next stand do not support the process. Analysis of the values of the average longitudinal internal force during rolling with $f_y = 0.18$ shows that under these conditions the stability of the process is impossible, since these forces in the second, sixth, eighth and tenth stands are positive. At the same time, in the centers of deformation of the said stands, the push-out longitudinal contact forces exceed the pull-in ones. Analysis of the graphs in Fig. 2 showed that the coefficient of friction during rolling of wire rod with a diameter of 5.5 mm cannot be lower than $f_y = 0.22$.

Continuing the analysis of the research results, let us turn to the data presented in Fig. 3 and fig. 4.

The graphs presented show that, according to the theory, the rolling process should not be interrupted in any of the indicated cases, since the angle of the neutral section $\gamma > 0$ and the ratio $\frac{f_y}{\alpha_y} > 0{,}5$, which contradicts the above arguments. Let's pay attention to the fact that in the considered rolling cases the interstand tensions $q_0$ and $q_1$ do not exceed the value of 0.063 (see Tabl. 1), although with a decrease in the friction coefficient they somewhat increase.

More clearly, the dependence of the specific tension of the strip $\sigma_1/2k_{cp}$ is shown by broken lines in Fig. 5, where the friction conditions at the contact of the metal with the rolls along all the stands of the wire block are determined by the values of $f_y$.

As follows from the given graphs, in stands № 1 and № 2, with an increase in $f_y$, a slight decrease in the specific tension is observed. In the next two stands, $\sigma_1/2k_{cp}$ decreases with increasing friction coefficient. Further, from the fifth to the eighth stand inclusive, the inter-stand specific tension increases and then decreases again. Moreover, with an increase in $f_y$ in these stands, the value of $\sigma_1/2k_{cp}$ decreases. Summarizing the results obtained, it should be noted that with an increase in the friction coefficient, the distribution of specific tensions in the inter-stand spaces becomes more uniform.

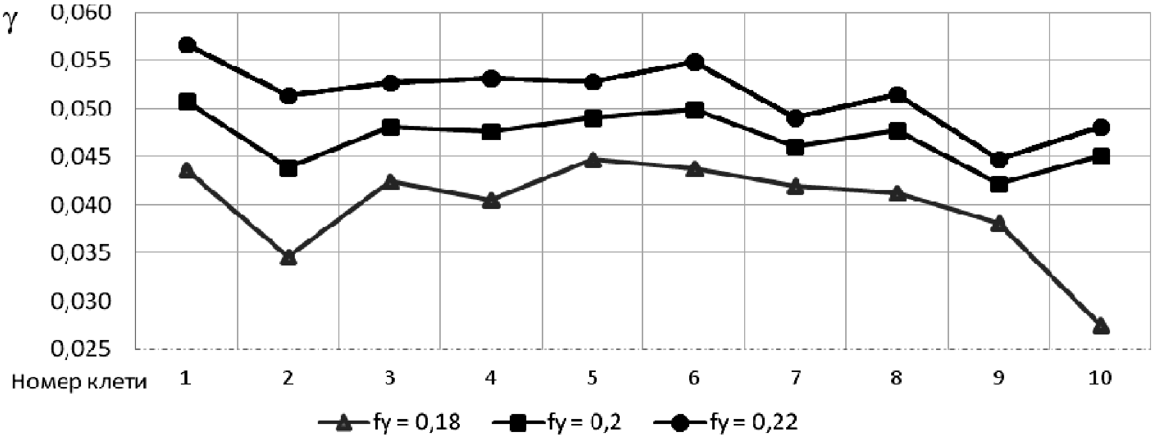

*Fig. 3.* Change in the angle of the neutral section γ along the stands depending on the coefficient of friction

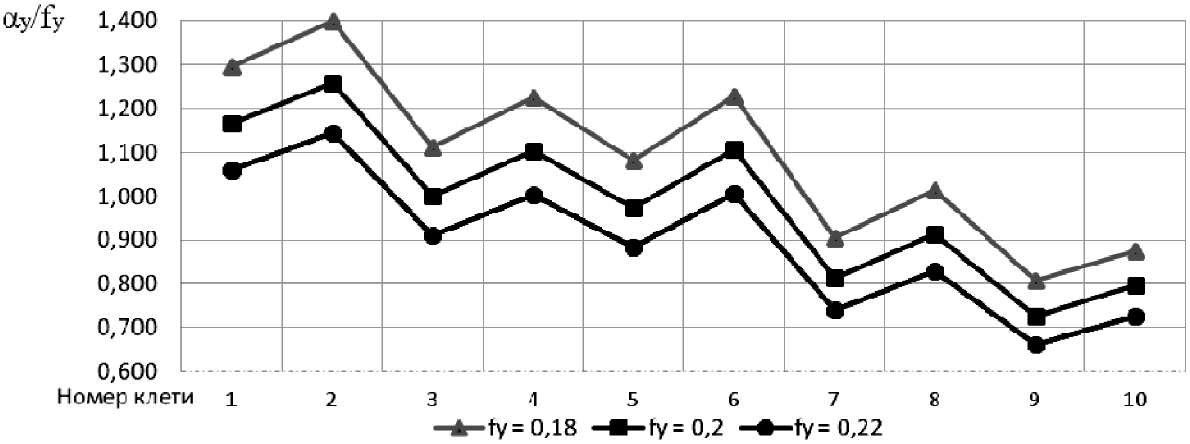

*Fig. 4.* Dependence of $\alpha_y/f_y$ on the coefficient of friction in the stands the wire block

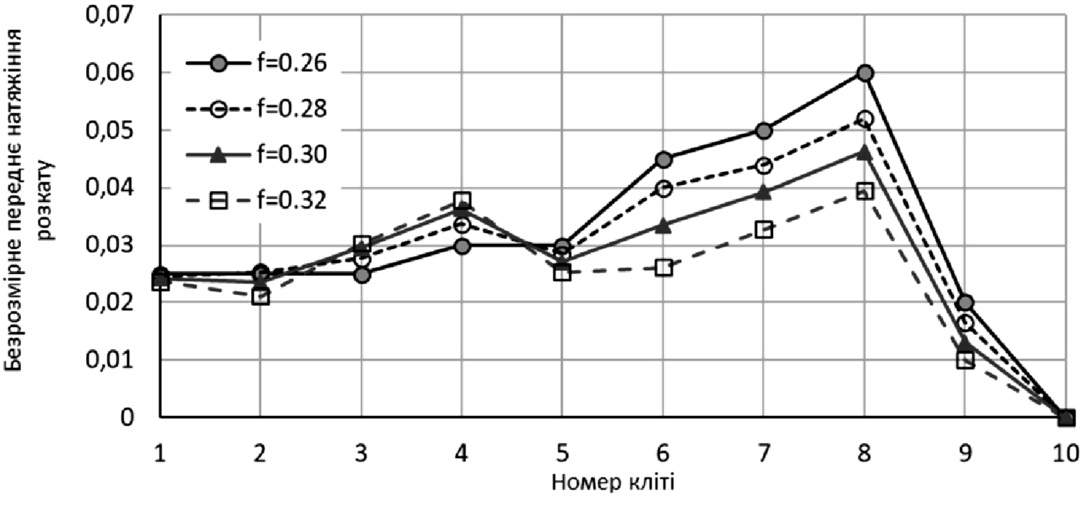

*Fig. 5.* The result influence of friction coefficient on the interstands tensions

With the wear of the surface of the rolls during the course of their operation, the stability of the strip in the deformation zone and the stability of the rolling process should increase due to a gradual increase in the friction coefficient up to the changing the working tool.

## Conclusions

New limit conditions for steady-state rolling have been developed and substantiated, which are more stringent than those known in the classical theory. As the coefficient of friction increases, the steady and stability of the rolling process increases along the entire line of the wire block. Model studies of the strip tension rolling process have been carried out. It is shown that the friction conditions for the contact of the tool with the metal of all ten stands of the wire block have a certain effect on the value of inter-stand tensions.

## References

[1] Grydev, A.P. (1973) *Vneshnee trenie pri prokatke [External rolling friction]* M.: Metallurgiya [in USSR].

[2] Tscelikov, A.I., Nikitin, G.S., Rokotyan, S.E. (1980) *Teoriya prodol'noi prokatki [Longitudinal rolling theory]* M.: Metallurgiya [in USSR].

[3] Grydev A.P. Zil'berg, U.V., Tilik, V.T. (1982) *Trenie i smazka pri obrabotke metallov davleniem [Friction and lubrication in metal forming]*: Spravochnik M.: Metallurgiya. [in USSR]

[4] Chekmarev A.P., Nefedov, A.A., Nikolaev V.A. (1965). *Teoriya prodol'noi prokatki [Longitudinal rolling theory]*. Kharkov: Izd-vo Kharkovskogo universiteta. [in USSR]

[5] Samokhval V.M. (2020) *Vyznachennya koeficientu tertya v procesi visokoshvydkisnogo prokatuvannya [Determination of the coefficient of friction in the process of high-speed rolling]*. Zbirnik naukovykh prats′ Dniprovs'kogo derzhavnogo tehnichnogo universitety (tehnichni nauky). – Kam'yans'ke: DDTU (Vyp. 2(37)), (pp. 46–52). [in Ukrainian]

[6] Byba, N.V., Shtoda, M.N., (2020) *Vliyanie perednego natyageniya na deformirovannoe sostoyanie kruglyh polos v oval'nom kalibre [Influence of front tension on the deformed state of round strips in oval caliber]*. Zbirnyk naukovyh prats' Dniprovs'kogo derzhavnogo tehnichnogo universitetu (tehnichni nauky). Kam'yans'ke: DDTU (Vyp. 2(37)), (pp. 17–22). [in Ukrainian]

[7] Gorbanev, A.A., Zhuchkov, S.M., & Filippov, V.V. et al. (2003). *Teoreticheskie i tekhlogicheskie osnovy vysokoskorostnoj prokatki katanki [Theoretical and technological foundations of high-speed rolling of wire rod]*. Mn.: Vyshcha shkola [in Belarus].

[8] Maksimenko, O.P., Samohval, V.M., Orobtsev, A.U., Nikylin, O.V., Marchenko, K.K. (2020) *Modelyuvannya protsesu prokatuvannya v klityah drotovogo bloku [Modeling of the rolling process in the cages of the wire block]*. Metalurgiyna ta girnychorudna promyslovist' (№ 3), (pp. 59–68). [in Ukrainian]

[9] Maksimenko, O.P., Loboyko, D.I., Romanyuk, R.Y. (2013) *Analiz silovogo vzaimodeystviya v ochage deformatsii pri prokatke [Analysis of force interaction in the deformation zone during rolling]*. Metallurgicheskaya i gornorudnaya promyshlennost' (№ 6) (pp. 47–49). [in Ukrainian]

[10] Maksimenko, O.P., Izmaylova, M.K., loboyko, D.I. (2016) *Prodol'naya ustoychivost' polosy v valkah s analizom kontaktnyh uslovyy: monografiya. [Longitudinal stability of the strip in rolls with the analysis of contact conditions: monograph]*. Dneprodzerzhynsk: DDTU. [in Ukrainian]

[11] Chekmarev, A.P., Prokof'ev, V. I., Galitskiy, V.P. i dr. (1967) *Eksperimental'noe issledovanie maksimal'nyh uglov zahvata pri ustanovivshemsya protsesse prokatki [Experimental study of maximum gripping angles in a steady rolling process]*. Obrabotka metallov davleniem: Nauch. trudy, DMetI. M. : Metallurgiya, (Vyp. LII), (pp. 79–88). [in USSR]

[12] Grudev, A.P. (1998) *Zahvatyvayushchaya sposobnost' prokatnyh valkov [Gripping power of the rolls]*. M.: "SP Intermet Inzhiniring".[in Ukrainian]

[13] Maksimenko, O.P., Nikulin, O.V., Samohval, V.M., Loboyko.,D.I. (2021) *Sistemnyy pidhid, metody doslidzhen' protsesiv prokatuvannya z analizom pozdovzhn'oyi stalosti: navch. posib. [Systematic approach, methods of research of rolling processes with the analysis of longitudinal constancy: textbook]*. Kam'yans'ke: DDTU.[in Ukrainian]

[14] Maksimenko, O.P.,& Kuz’min, E.V. (2017). *Samoregulirovanie processa s uchetom vnutrenih prodol’nyh sil pri prokatke v provolochnom bloke [Selfregulation of the process taking into account internal longitudinal forces during rolling in a wire block].* Metallurgicheskaya i gornorudnaya promyshlennost’ – Metallurgical and Mining Industry*, 6, 16–21* [in Ukrainian].

## МОДЕЛЮВАННЯ ВПЛИВУ ТЕРТЯ НА СТІЙКІСТЬ ПРОЦЕСУ І СИЛОВІ ПАРАМЕТРИ ПРИ ПРОКАТУВАННІ В СУЧАСНОМУ ДРОТОВОМУ БЛОЦІ

**Максименко О.П., Нікулін О.В., Приймак А.Б., Кривов В.В.**

### Реферат

Високошвидкісна прокатка є основою при виготовленні катанки на сучасних металургійних підприємствах. Для досягнення необхідних показників користуються рішеннями виробничих технічних і технологічних проблем, в основу яких положено наукові аналіз та обґрунтування. Однак у теорії прокатування існує ряд проблем, які враховують вплив тертя на параметри процесу і знаходяться в стадії розв’язування. При дослідженні впливу дисипативних сил, які визначаються коефіцієнтом тертя, користувалися спільним розв’язанням диференціального рівняння рівноваги виділеного в осередку деформації елементарного об’єму і рівнянням пластичності зі знаходженням середньо інтегральної поздовжньої сили. Розроблено і обґрунтовано нові граничні умови прокатки при сталому режимі, які є більш жорсткими у порівнянні з відомими в класичній теорії. Проведено модельні дослідження процесу безперервної прокатки зі зміною коефіцієнту тертя та натягом смуги. За допомогою моделі високошвидкісного процесу прокатки були проаналізовані умови стійкого прокатування в клітях дротяного блоку сучасного сортового стану при виготовленні катанки діаметром 5,5 мм. Показано, що на величини міжклітьових натягів певний вплив мають умови тертя в контакті інструменту з металом всіх десяти клітей дротяного блоку. Доведено, що зі збільшенням коефіцієнта тертя стійкість і стабільність процесу прокатки зростають по всій лінії дротяного блоку.

### Література

1. Грудєв А.П. Зовнішне тертя при прокатці. М.: Металургія, 1973. 288 с.
2. Целиков А.І. та ін. Теорія поздовжньої прокатки. М.: Металургія, 1980. 320 с.
3. Грудєв А.П. та ін. Тертя і мастило при обробці металів тиском. М.: Металургія, 1982. 312 с.
4. Чекмарьов А.П., Нефьодов А.А., Ніколаєв В.А. Теорія поздовжньої прокатки. Харьков: Вид-во Харьковського університету, 1965. 212 с.
5. Самохвал В.М. Визначення коефіцієнту тертя в процесі високошвидкісного прокатування. Збірник наукових праць Дніпровського державного технічного університету (технічні науки). Кам’янське: ДДТУ, 2020. Вип. 2 (37). С. 46–52.
6. Биба Н.В., Штода М.М. Вплив переднього натягу на деформований стан круглих смуг в овальному калібрі. Збірник наукових праць Дніпровського державного технічного університету (технічні науки). Кам’янське: ДДТУ, 2020. Вип. 2 (37). С. 17–22.
7. Горбаньов А.А. та ін. Теоретичні та технологічні основи високошвидкісної прокатки катанки. Мн.: Вищ. шк., 2003. 267 с.
8. Максименко О.П., Самохвал В.М., Оробцев А.Ю., Нікулін О.В., Марченко К.К. Моделювання процесу прокатування в клітях дротового блоку. Металургійна та гірничорудна промисловість, 2020. № 3. С. 59–68.
9. Максименко О.П., Лобойко Д. І., Романюк Р.Я. Аналіз силової взаємодії в осередку деформації при прокатці. Металургійна та гірничорудна промисловість 2013. № 6. С. 47–49.
10. Максименко О.П., Ізмайлова М.К., Лобойко Д.І. Поздовжня стійкість смуги в валках з аналізом контактних умов: монографія . Дніпродзержинськ: ДДТУ, 2016. 213 с.

11. Чекмарьов А.П., Прокофьев В.І., Галицкий В.П. та ін. Експериментальне дослідження максимальних кутів захоплення при сталому процесі прокатки. Обробка металів тиском: Науч. труди, ДМетИ. М.: Металургія, 1967. (Вип. LII.) С. 79–88.
12. Грудєв А.П. Захоплююча здатність прокатних валків. М.: “СП Інтермет Інжинирінг”, 1998. 283 с.
13. Максименко О.П. та ін. Системний підхід, методи досліджень процесів прокатування з аналізом поздовжньої сталості. Кам’янське: ДДТУ, 2021, 347 с.
14. Максименко О.П., Кузьмин Є.В. Саморегулювання процесу з урахуванням внутрішніх поздовжніх сил при прокатці в дротовому блоці. Металургійна та горнорудна промисловість. 2017. № 6. С. 16–21