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COMPUTATIONAL SIMULATION OF REDUCTION MODES IN WIRE ROD ROLLING

РОЗРАХУНКОВЕ МОДЕЛЮВАННЯ РЕЖИМІВ ОБТИСНЕНЬ ПРИ ПРОКАТЦІ КАТАНКИ

The stability of the long rolling process, as well as the quality of the finished product, largely depend on the accepted roll pass design and the accuracy of determining the deformation parameters. When changing conditions or clarifying results, it is often necessary to make adjustments "in the metal", that is, to use a new gauges of rolls or modification of equipment. To reduce costs, it can be recommended to improve the calculation methods. The aim of the work is to develop a new method for calculating the parameters of deformation during rolling, taking into account the law of constancy of seconds volumes, the conditions of metal equilibrium in the rolls of each pass, the front and back tension of the sample, the longitudinal stability of the metal, as well as the equality of the angles of the neutral cross-section. The simulation method is presented on the example of a study the manufacturing of wire rod with a diameter of 8 mm in the conditions of a continuous wire block the 400/200 rolling mill of PJSC KAMET-STAL. Analyzing the results of calculations, the deformation modes by new and previously used methods, it can be seen that in this case the data do not differ significantly. The results of the simulation confirm the adequacy of the proposed method for calculating the deformation regime during wire rod rolling. The chosen model of calculations the long-length rolling process includes a large number of factors determined by the rolling theory, and more fully characterizes the stress-strain state of the metal in the deformation zones of the wire block, this can be crucial for the efficiency of mastering or improving the production technology.

***Keywords**: calculation methodology, deformation parameters, wire block, wire rod.*

Стабільність процесу довгомірної прокатки, а також якість готового виробу багато в чому залежать від прийнятого калібрування валків і точності визначення параметрів деформації. При зміні умов або уточненні результатів часто доводиться вносити корективи «в метал», тобто використовувати нове калібрування валків або модифікацію обладнання. Для зниження витрат можна порекомендувати вдосконалити методи розрахунку. Метою роботи є розробка нової методики розрахунку параметрів деформації при прокатці з урахуванням закону сталості секундних об'ємів, умов рівноваги металу в валках кожної кліті, переднього і *заднього натягу зразка, поздовжньої стійкості металу, а також рівності кутів нейтрального поперечного перерізу. Метод моделювання представлений на прикладі дослідження при прокатці катанки діаметром 8 мм в умовах безперервного дротового блоку стану 400/200 ПАТ «КАМЕТ-СТАЛЬ». При прокатці катанки в безперервному дротяному блоці використовується система «кругло-овальних» калібрів і чергуються з поворотом на 90⍰ валків зазори в послідовності клітей. При прокатці катанки діаметром 8 мм в блок дроту входить кругла заготовка діаметром 19,8 мм. Дотримуючись послідовністі розрахунків, що виконуються при моделюванні режимів прокатування в 10—8 клітях, можна визначити геометричні, кінематичні та силові параметри по всій лінії дротяного блоку при прокатці відповідної смуги.*

Аналізуючи результати розрахунків режимів деформацій за новими і раніше використовуваними методами, видно, що в розглянутому випадку дані істотно не відрізняються. Результати моделювання підтверджують адекватність запропонованого методу розрахунку режиму деформацій при прокатці катанки. Обрана модель розрахунків процесу довгомірної прокатки включає більшу кількість факторів, що визначаються теорією прокатки, і більш повно характеризує напружено-деформований стан металу в зонах деформації дротового блоку, це може мати вирішальне значення для ефективності освоєння або вдосконалення технології виробництва.

Ключові слова: *методика розрахунку, параметри деформації, дротовий блок, катанка.*

Problem's Formulation

The stability of the long rolling process, as well as the quality of the finished product, largely depend on the accepted roll pass design and the accuracy of determining deformation parameters. The reduction mode in the design must be selected in accordance with the basic principles of the rolling theory. To date, the solution of this problem by the method of successive approximations on the basis of experimental data has been widespread, which gives partial solutions in specific conditions. When conditions change or the results are refined, it is often necessary to make adjustments "in the metal", i.e. new calibration of the rolls or modifying the equipment. To reduce costs, it can be recommended to improve the calculation methods.

Analysis of recent research and publications

When rolling wire rod in a continuous wire block, a system of "round-oval" gauges and alternating with a 90° rotation of rolls clearances in a sequence of stands [1—4] are used. This system ensures a smooth transition from one cross-section of the specimen to another and allows for a good quality of the wire rod surface. Its disadvantage is a comparatively low coefficient of metal drawing per pass (м = 1.2... 1,4), as well as certain difficulties associated with the stability of the roll in the rolls [5,6]. Rolling in the wire block is carried out continuously with front and rear strip tension. Specific metal tensions: rear $q_0 = \frac{\sigma_0}{2k_{cp}}$ and front $q_1 = \frac{\sigma_1}{2k_{cp}}$ do not exceed 0.03... 0.04 in relation to the average resistance to deformation of the metal at the deformation zone [7,8]. To determine the deformation regime of metal during rolling in a wire block, experimental data and empirical formulas for calculating the coefficients of longitudinal and transverse deformation are usually used [9].

Formulation of the research goal

The purpose of this work is to develop a new method for calculating the parameters of deformation at rolling with taking the law of constancy of seconds volumes, the conditions of metal equilibrium in the rolls of each stands, the front and rear tension of the specimen, the longitudinal stability of the metal, as well as the equality of the angles of the neutral cross-section, obtained from the condition of equilibrium the forces in the zones of deformation $\text{г}_{\text{р}}$ and based on the kinematics of the process г_{c}:

$$\gamma_К = \sqrt{\frac{S \cdot h_1}{R}}, \tag{1}$$

where S is the advancing of the metal in a given pass; h_1 is the thickness of the strip at the outlet of the rolls; R is the rolling radius of the roll.

The studies were also based on the method of corresponding band [10].

Presenting main material

The simulation method is presented on the example of a study at rolling wire rod with a diameter of 8 mm under the conditions of a continuous wire block of Mill 400/200 of PJSC KAMETSTEEL. When rolling wire rod with a diameter of 8 mm, a round billet with a diameter of 19.8 mm enters in the wire block. Moreover, the first two stands do not reduction the metal, so the initial diameter at the entrance to the third stand is 19.8 mm.

It should be noted that the longitudinal stability of the rolling was estimated by the value of the average resulting internal longitudinal forces of the plastically deformable metal $Q^*_{ср\ пр}$ [11, 12]. In accordance with the physical sense, this force is directed opposite to the motion of the rolling specimen in the zone of deformation, which determines the negative numerical values of the magnitude. Its maximum possible value is $Q^*_{ср\ пр} = 0$.

Theoretically, the equilibrium of forces in the zone of deformation was ensured by using the solutions of the differential equation of T. Kármán [13] in the Coulomb model of the distribution of specific frictional forces. In accordance with [14], the value of the coefficient of friction over the entire group of the wire block was taken to be equal to $f_y = 0,26$.

Let's determine the reduction mode in the last tenth stand of the block. To do this, let's take the initial advancing value to be $S_{10} = 0,03$. Then, with the linear speed of the rolls $v_{в10} = 95,0$ m/s according to the factory instructions, the speed of the strip at the exit of this cage will be $v_{110} = 99,75$ m/s. In this case, the kinematic angle of the neutral section (1) is:

$$\gamma_{к10} = \sqrt{\frac{0,03 \cdot 7,18}{103,4}} = 0,0456 \text{ rad.}$$

With entering angle $\alpha_{y10} = 0,2$ rad that provides the expected productivity of the tenth stand with rolling parameters $f_y = 0,26$, $h_1 = 7,18$ mm, $R_к = 103,4$ mm at specific roll tensions $q_{010} = 0,02$ and $q_{110} = 0,0$, the condition of metal equilibrium in the rolls is observed at $\gamma_{p\ 10} = 0,06$ rad (Fig. 1). This found value of the angle is significantly higher than the previously accepted kinematic value, which requires (1) an increase in the advancing. This found value of the angle is significantly higher than the previously accepted kinematic value, which requires on base (1) an increase of the advancing value. Note that Fig. 1 shows in a dimensionless form the distribution of the normal pressure of the metal on the rolls $\frac{p_x}{2k_{ср}}$, the change in the specific forces of friction $\frac{t_x}{2k_{ср}}$, as well as a diagram of the internal longitudinal normal stress of the plastically deformed metal $\frac{\sigma_x}{2k_{ср}}$ and the internal longitudinal force $Q^*_{српр} = \frac{\sigma_x h_x b}{2k_{ср} R_p b}$. In addition, the same figure shows the values of the mean resultant force $Q^*_{ср\,пр}$, the average metal pressure on the rolls $\frac{p_{ср}}{2k_{ср}}$, the dimensionless rolling moment $M_{пр}$ and the dimensionless friction forces in the lagging $T_{отс}$ and advancing zones $T_{оп}$, as well as the angle of the neutral cross-section γ_p . In the next approximation, taking into account the upward trend $S_{10} = 0,07$. The new value is $\gamma_{к10} == 0,0697$ rad. In the solution of the Kármán equation, increasing the entering angle to $\alpha_{y10} = 0,26$ rad, the angle of the neutral cross-section increases slightly to $\gamma_{p\ 10} = 0,065$ rad, which is not enough.

A further increase in the gripping angle due to the appearance of longitudinal tensile stresses in the metal will lead to a decrease in the longitudinal stability of the rolling in the zone of deformation up to its loss.

b, мм	1
$R_к$, мм	103,4
$h_{1,\,мм}$	7,18
f_y	0,26
αy, р	0,2
Q0/2k	0,02
Q1/2k	0

$Q^*_{ср\,пр}$	-0,0159
$p_{ср}/2K_{ср}$	1,2097079

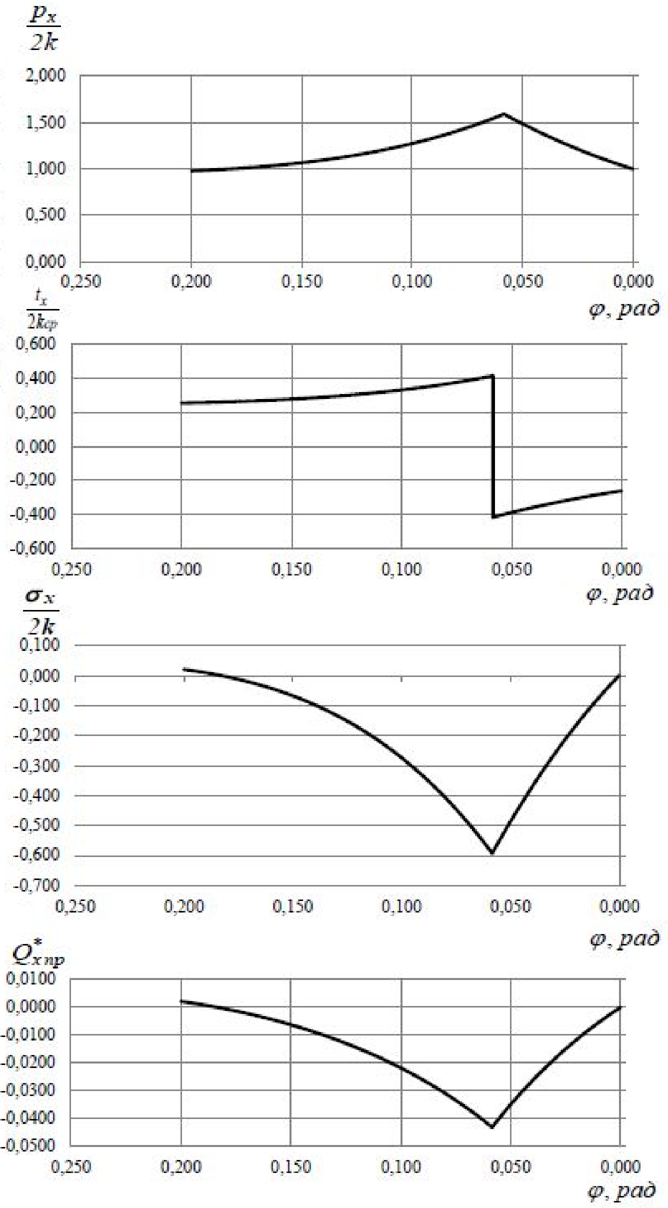

Fig. 1. Distribution of contact and internal stresses and current longitudinal force in the deformation zone of the tenth stand

In order to achieve the equality (approximate) of the kinematic and equilibrium values of the neutral angles, the advance value is reduced (fork method). At $S_{10} = 0{,}05$, the speed of the strip $v_{110} = 99{,}75$ m/s we have

$$\gamma_{\kappa 10} = \sqrt{\frac{0{,}05 \cdot 7{,}18}{103{,}4}} = 0{,}0589 \text{ rad.}$$

In the case when $\alpha_{y10} = 0{,}21$ rad in solving the boundary value problem of the rolling theory for the parameters corresponding to the data of Fig. 1, we get $\gamma_{p10} = 0{,}059$ rad, i.e. $\gamma_{p10} \approx \gamma_{\kappa 10}$. As a result, it can be assumed that for a gripping angle of 0.21 rad, the absolute reduction is $\Delta h_{10} = 103{,}4 \cdot 0{,}21^2 = 4{,}56$ mm, and the initial thickness of the metal is $h_{0\,10} = 7{,}18 + 4{,}56 = 11{,}74$

mm. Next, the seconds volume of the metal is determined, which is constant for all deformation zones of the block

$$V_{сек} = v_{1\,10}\cdot h_{1\,10}\cdot b_{1\,10} = 99,75\cdot 7,18\cdot 7,18 = 5142,35 \text{ m/s·mm}^2.$$

It should be noted that for these data, plots similar to those shown in Fig. 1.

With the dimensions of the strip $h_{0\,10}, h_{1\,10}, b_{1\,10}$ already known for the 10th stand, it remains to determine $b_{0\,10}$.

Let's find the final dimensions of the 8 stand roll using the law of constancy the seconds volumes:

$$h_{1\,8} = b_{1\,8} = \sqrt{\frac{V_{сек}}{(1+S_8)\cdot v_{в8}}}. \tag{2}$$

Corresponding to the values of advancing S_8, we find the values of h_{18} and $\gamma_{к8}$. When solving the boundary value problem with the T. Kármán equation, the values of $\gamma_{p\,8}$ is found. The real value is S_8, at which equality $\gamma_{p\,8} = \gamma_{к\,8}$ is observed. In the specific conditions at the rolling mill for the 8th stand of the block, this condition was fulfilled when: $s_8 = 0,05$; $v_{1\,8} = 63,89$ m/s; $h_1 = 8,97$ mm; $\gamma_{p\,8} = \gamma_{к\,8} = 0,066$ rad; $\alpha_{y8} = 0,245$ rad; $\Delta h_8 = 6,16$ mm; $h_{08} = 15,13$ mm at $q_{0\,8} = 0,015$, $q_{18} = 0,03$. Note that the final width of the specimen is $b_{1\,8} = 8,97$ mm. As in the case of determining the initial width of the roll in 10 stand of the block, the size of specimen mark $b_{0\,8}$.

Let's determine the parameters in the 9th stand of the block. Rolling radius of rolls is $R_{к\,9} = 104,5$ mm; roll dimensions $h_{0\,9} = b_{18} = 8,97$ mm; $b_{09} = h_{18} = 8,97$ mm; $b_{19} = h_{010} = 11,74$ mm; specific tension of the roll $q_{09} = 0,03$, $q_{19} = 0,02$. At $S_8 = 0,065$; $v_{в\,9} = 77,65$ m/s; $v_{1\,9} = 82,7$ m/s, as before, we find the final thickness of the roll. It should be noted in advance that $h_{1\,9} = \dfrac{V_{сек}}{v_{19}\cdot b_{19}}$, after substituting values

$$h_{1\,9} = \frac{5142}{82,7\cdot 11,74} = 5,3 \text{ mm}. \tag{3}$$

Next, we will find the reduction of the metal $\Delta h_9 = 8,97 - 5,3 = 3,67$ mm and the entering angle $\alpha_{y9} = \sqrt{\dfrac{3,67}{104,5}} = 0,187$ rad.

When solving a boundary value problem with the Kármán equation for the values of the parameters $R_{к9} = 104,5$ mm; $h_{1\,9} = 5,3$ mm; $f_y = 0,26$; $\alpha_{y9} = 0,0187$ rad, $q_{09} = 0,03$, $q_{19} = 0,02$ the angle is $\gamma_{p\,9} = 0,057$ rad.

Kinematic angle of neutral section in this pass

$$\gamma_{к\,9} = \sqrt{\frac{0,065\cdot 5,3}{104,5}} = 0,0574 \text{ rad}.$$

As you can see, the angles $\gamma_{p\,9}$ and $\gamma_{к\,9}$ found are very close ($\delta\gamma_9 \approx 0,7\%$). Therefore, the found dimensions of the 9 stand of the block are accepted. We also note that the initial width of the roll is 10 square $b_{010} = h_{19} = 5,3$ mm.

Thus, based on the equality of the seconds volumes of the metal, the solution of the boundary value problem with the Kármán equation and the fulfillment of the conditions for the equilibrium of forces in the zone of deformation, and the correspondence to the kinematic parameters of the process, the geometric dimensions and indicators of the corresponding strip in the 9th and 10th stands of the block were obtained (Tabl. 1). Taking into account that $b_{08} = h_{17}$, when determining the specified width of the rolled metal, it is necessary to know the required kinematic and geometric parameters of rolling in the seventh stand. For the adopted algorithm of calculations in compliance with the sequence of actions corresponding to rolling in the ninth cage, this is not difficult to achieve. The result is $b_{08} = h_{17} = 6{,}38$ mm and Tabl. 1 is supplemented by geometrical parameters when rolling the rolled sheet in the 8th stand of the block.

Table 1. Geometric parameters of the corresponding stripes for the final stands of the block

Stand number	h_0, mm	h_1, mm	b_0, mm	b_1, mm	α_y, rad	Δh, mm	Δb, mm
8	15,13	8,97	6,38	8,97	0,245	6,16	2,59
9	8,97	5,3	8,97	11,74	0,187	3,67	2,77
10	11,74	7,18	5,3	7,18	0,21	4,56	1,78

Observing the sequence of calculations performed at the simulating the reduction modes in 10—8 stands, it is possible to determine the geometric, kinematic and force parameters along the entire line of the wire block when rolling the corresponding strip. The results of the calculations are given in Tabl. 2.

Table 2. Geometric, kinematic and force parameters of rolling the corresponding strip

# st.	h_1, mm	Δh, mm	b_1, mm	R_k, mm	α, rad	q_0	q_1	$v_в$, m/s	S	$\gamma_к$	$\gamma_р$	$p_{ср}^*$	$Q^*_{ср\ пр}$
3	12.57	5.0	20.7	101.8	0.222	0.0	0.015	19.1	0.035	0.065	0.065	1,095	-0,0125
4	14.43	6.27	14.4	100.4	0.25	0.015	0.06	23.97	0.043	0.066	0.065	1,08	-0,012
5	10.29	4.54	15.9	103.0	0.21	0.06	0.05	30.46	0.035	0.059	0.06	1,13	-0,0142
6	11.37	4.48	11.4	101.7	0.21	0.05	0.06	38.43	0.035	0.063	0.063	1,12	-0,0139
7	6.38	5.03	15.1	104.1	0.22	0.06	0.06	48.3	0.06	0.061	0.06	1,22	-0,0147
8	8.97	6.16	8.97	102.7	0.245	0.06	0.06	60.85	0.05	0.065	0.065	1,14	-0,0136
9	5.30	3.67	11.7	104.5	0.187	0.03	0.02	77.65	0.065	0.057	0.057	1,28	-0,0158
10	7,18	4,56	7,18	103,7	0,21	0,02	0,0	95,0	0,05	0,059	0,059	1,22	-0,0172

In accordance with [12] $Q^*_{ср\,пр} = \frac{1}{\alpha_y}\int_0^{\alpha_y}\left(\frac{p_x}{2k_{ср}}-1\right)\cdot\left(\frac{h_1}{R}+\phi^2\right)d\phi$, the value of which for each case of rolling was calculated in accordance with the plots given in Fig. 1 under the given conditions.

The analysis of the force $Q^*_{српр}$ values shows that the rolling process in all stands of the wire block is stable, since the values of the dimensionless average resulting longitudinal forces in absolute value are hundredths of a unit.

Preliminary calculations show that if $\left|Q^*_{ср\ пр}\right| > 0{,}001$, the rolling process will be stable. The specific tension of the roll along the entire line of the wire block does not exceed the permissible values. The relative reduction of the metal in all passes is noticeably less than 50% and all stands are loaded almost evenly. The entering angles in all stands are less than the friction angle. The advancing is within 0.03... 0.065, the dimensionless average metal pressure on the rolls for all stands is less than 1.3.

Let's compare the results of the study carried out to simulate the processes of deformation the rolled specimen in the stands of the wire block with the known factory data obtained on the basis of the results the DANIELI company for the production of wire rod. At the same time, the found dimensions of the corresponding strip in each pass are recalculated into the dimensions of the roll in accordance with the shape of the current gauge — a round or an oval. The equality of the cross-sectional areas and the same ratio of the transverse axes are taken into account. The results of the work performed for wire rod with a diameter of 8 mm are given in Tabl. 3 (lines of design values h_{1i} and b_{1i}).

Table 3. Factory and design modes for reduction at rolling the wire rod with a diameter of 8 mm

Reduction modes in zones of deformation, mm										
Number of stand		2	3	4	5	6	7	8	9	10
Factory Data	H_i	19,8	24,05	16,12	19,86	12,74	15,86	10,12	12,69	8,1
	V_i	19,8	13,21	16,12	10,36	12,72	7,91	10,12	6,18	8,1
Design values	h_i	19,8	14,19	16,28	11,61	12,83	7,20	10,12	5,98	8,1
	b_i	19,8	23,37	16,28	17,88	12,83	17,08	10,12	13,25	8,1

In the same tabl. 3 shows the factory data in the wire block for the same wire rod (lines of design values H_i and V_i).

Note that when comparing deformation modes, it is necessary to keep in mind that in the factory data for ovals, the size H_i refers to the width of the gauge, and the size V_i is taken from the cut of the gauge. For round gauges, the opposite is true. Therefore, when analyzing, it is necessary to compare the values from the strings H_i and b_i, as well as V_i and h_i.

Conclusions

Analyzing the results of calculations, the deformation modes by new and previously used methods, it can be seen that in this case the data do not differ significantly. The results of the simulation confirm the adequacy of the proposed method for calculating the deformation regime during wire rod rolling. In addition, the chosen model for calculating the long-length rolling process includes a larger number of factors determined by the rolling theory, and more fully characterizes the stress-strain state of the metal in the deformation zones of the wire block. For modern high-speed rolling processes, this can be crucial for the efficiency of designing or improving production technology.

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