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SIMULATION THE INFLUENCE OF INERTIA FORCES ON THE PARAMETERS OF HIGH-SPEED ROLLING IN A WIRE BLOCK

High-speed rolling is becoming more and more widespread in the manufacturing of both flat and profile products. However, there are a number of unsolved problems in the theory of high-speed rolling. A scheme and method for calculating inertia forces, taking into account the displacement and acceleration of the center mass the mechanical system made of particles the deformation zone, have been developed to refine the mathematical model of the high-speed rolling process. Using a refined model of the high-speed rolling process, the mass forces, the energy-power and kinematic parameters, as well as on the longitudinal stability the rolling process in the stands of the wire block were calculated when rolling a wire rod with a diameter of 5.5 mm.
***Keywords**: high-speed rolling; inertia force; energy-power and kinematic parameters.*

Високошвидкісна прокатка набуває все більшого поширення у виробництві як плоских, так і профільних виробів. Однак у теорії швидкісного прокатування існує ряд невирішених проблем. Для вдосконалення математичної моделі процесу високошвидкісного прокатування розроблено схему та метод розрахунку сил інерції, що враховують зміщення та прискорення центру мас механічної системи з частинок в зоні деформації. За допомогою вдосконаленої моделі процесу швидкісного прокатування розраховували масові сили, 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; сила інерції; енергосилові та кінематичні параметри.*

Problem's Formulation

High-speed rolling is becoming more and more widespread in the manufacturing of both flat and profile products. The highest kinematic parameters have been achieved on wire rod production lines, where speeds of 100—110 m/s are common, and in some cases the speed reaches 125 m/s. To achieve such high rolling speeds required solutions to a set of technical and technological problems, the effectiveness of which has a scientific basis. However, there are a number of unsolved problems in the theory of high-speed rolling, one of which is taking into account the influence of inertia forces on the process parameters.

The actualization of taking into account the influence of inertial forces in the process of rolling was pointed out in the works of A.I. Tselikov in the 60s of the last century [1]. In the works of other authors [2—4], the assumption is considered that the inertial forces can have a significant effect on the power parameters, the kinematics of the process and the longitudinal stresses in the inter-stand intervals. The result of the action of mass forces, in particular, the inertial forces, from the point of view of general mechanics, are presented in the publications of L.I. Sedov [5], S.M. Targ [6] and other authors.

Based on the general ideas about the dynamics of mechanical systems, in [7], a model was proposed for accounting for mass forces during high-speed rolling. The authors proceeded from the joint solution of the differential equilibrium equation identified in the deformation zone of the elementary volume, the plasticity equation taking into account the inertial forces acting on the metal particles. However, in this model, the conditions of equilibrium of a thin section (element of the deformation zone) and the entire zone deformation are not divided enough.

In particular, taking into account the inertial force of the elementary volume in the deformation zone

$$F_{m\text{-}ev} = \rho \cdot F_x \cdot d_x \cdot d\left(\frac{V_1 \cdot F_1}{F_x}\right) \cdot \frac{1}{dt},$$

an expression was obtained for the inertial force, which is required "to accelerate the metal in the deformation zone from the input speed V_0 to the output speed V_1" [7, p. 91]

$$F_m = \rho \cdot F_1 \cdot V_1^2 \cdot \left(\frac{\mu+1}{2\mu}\right) \cdot \ln(\mu),$$

where ρ is the density of the rolled metal; F_x — the current value of the cross-sectional area of the strip; F_1 is the cross-sectional area of the strip at the exit from the deformation zone; V_0 and V_1 — and — the speed of rolling at the entrance to the deformation zone and at the exit from it; μ is the coefficient of elongation.

In this case, the average acceleration of the metal is determined using an approximate estimate of the value for simplified kinematic considerations, using the average speed over the deformation zone and the time of movement of the material particle in it

$$a_{cp=}\frac{\nu_1^2 + \nu_0^2}{2l_d},$$

where l_d is the length of the deformation zone.

According to the above formula for rolling a wire rod with a diameter of 5.5 mm in the last stand of a wire block at a rolling speed of 100 m/s, the acceleration reaches 1.2·105 m/s^2, and the inertia forces are 350 N [7, p. 91].

In our opinion, the proposed approach to the assessment of mass forces contains the methodical inaccuracy, consisting in the simultaneous use of two different estimates of the same value — the average acceleration, which casts doubt on the adequacy of the results obtained.

Formulation of the study purpose

The purpose of this work is to improve the mathematical model of high-speed rolling, when, along with the acceleration of metal particles in the deformation zone, the corresponding movement of the center mass of the system would be taken into account, as well as to refine the calculation of the mass forces in each stand of the wire block and their effect on the stability of the rolling process.

Presenting main material

To refine the model of high-speed rolling, due to a more definite consideration of the influence of inertia forces, it is proposed to switch to using the theorem on the change in the momentum of the system (equivalent to the theorem on the motion of the center mass) by stages of its motion, when the accelerations of the center mass are determined more accurately.

Analyzing the steady rolling process, let us single out the metal volumes V_1 and V_2 bordering on the deformation zone (Fig. 1), subject to the condition $V_1 = V_{оч} = V_2$ ($V_{оч}$ — is the volume of the plastic deformation zone).

Let at some moment of the steady rolling process the centers mass m_1, $m_{оч}$, and m_2 of these volumes are in sections A_1, $A_{оч}$, A_2 with the corresponding speeds $V_0, \frac{V_1 + V_0}{2}$ and v_1. Further, in the process of deformation, the particles of the volume of the metal V_1 begin to pass into the zone of plastic flow and at a certain moment fill the volume $V_{оч}$. In this case, the center of mass m_1 reaches the section $A_{оч}$ and acquires speed $\frac{V_1 + V_0}{2}$.

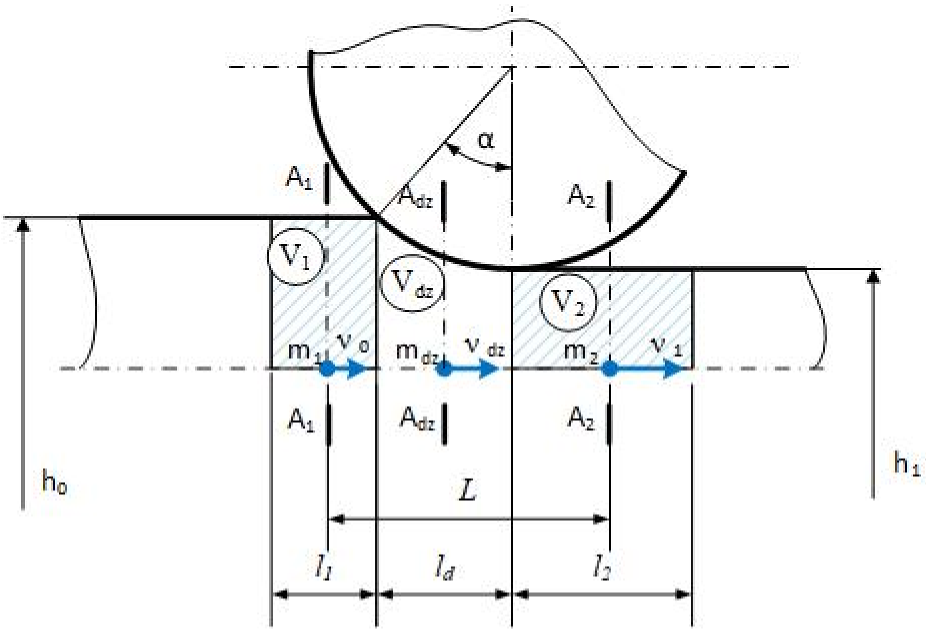

Fig. 1. Diagram of the deformation zone with highlighted domains and their centers of mass

Accordingly, with the volume V_1 the volume $V_{оч}$, also moves, as a result, the center of its mass $m_{оч}$ occupies a position corresponding to the section A_2 and reaches the speed of movement v_1. Continuing the reasoning, we note that as a result of the passage the selected phases of motion, the volume of metal V_1 should take the position V_2 and increase the speed to v_1.

Obviously, in this case, the center of mass m_1, moving, will reach the section A_2 and increase its speed to v_1. Note that for the center mass m_1 of the volume V_1 to increase its speed from v_0 to v_1 it needs to overcome the distance L (see Fig. 1). Let us determine the time T of passing this path:

$$T = \frac{l_1}{2v_0} + \frac{2l_d}{v_0 + v_1} + \frac{l_2}{2v_1},$$

where l_1 and l_2 — are the lengths of the domains V_1 and V_2.

Based on the equality of the volumes the domains under consideration, the values of these lengths can be calculated:

$$l_1 = \frac{1}{2}\left(1 + \frac{h_1}{h_2}\right) l_d \cdot \frac{b_{cp}}{b_0};$$

$$l_2 = \frac{1}{2}\left(1 + \frac{h_0}{h_1}\right) l_d \cdot \frac{b_{cp}}{b_1},$$

where h_0 and h_1 are the strip thickness before and after the pass; b_0 and b_1 — strip width before and after pass; b_{cp} is the average width of the metal strip in the deformation zone.

Having determined the time T, it is easy to find the average acceleration of the volume of the metal and its center of mass when the section moves from A_1 to A_2:

$$\mathrm{a_{cp}} = \frac{\mathrm{v_1 - v_0}}{\mathrm{T}}$$

and then calculate the force of inertia

$$\mathrm{F_m = m_{оч} a_{cp}}.$$

In accordance with the proposed scheme, the values of metal acceleration and mass force in the deformation zone of each of the stands of a typical wire block of the mill were calculated when rolling a wire rod with a diameter of 5.5 mm. Real modes of deformation of this profile and the corresponding strip are given in the article [8]. The calculation results and rolling parameters based on the given data taking into account the rolling speeds are presented in tabl. 1.

Анализ табличных данных показывает, что ускорение металла возрастает от первой клети к последней. В десятой клети оно достигает величины 50 000 м/с^2.

Table 1. Geometric, kinematic and power parameters of rolling in a wire block

№ stand.	$\frac{h_0}{h_1}$	$\frac{b_{cp}}{b_0}$	$\frac{b_{cp}}{b_1}$	l_d, mm	l_1, mm	l_2, mm	T, 10^{-3} s	a_{cp}, 10^{-3} m/s^2	$m_{оч}$, 10^{-3} kg	F_m, N	σ_1'	q_1
1	1,570	1,108	0,910	23,91	17,65	27,96	3,86	0,79	40,75	32,3	0,178	$9\cdot10^{-4}$
2	1,527	1,126	0,899	25,68	23,88	29,11	3,46	0,86	34,67	30,0	0,20	0,001
3	1,515	1,102	0,915	20,66	18,90	23,77	2,25	1,88	22,54	42,4	0,36	0,0018
4	1,513	1,102	0,916	22,65	20,72	26,07	1,97	2,71	19,68	53,3	0,57	0,0028
5	1,680	1,153	0,882	20,28	18,65	23,97	1,39	5,38	14,07	75,7	1,03	0,0052
6	1,660	1,161	0,878	22,83	21,25	26,66	1,24	6,94	12,46	86,4	1,48	0,0074
7	1,570	1,124	0,900	17,02	15,66	19,68	0,73	14,8	7,31	108,4	2,33	0,0117
8	1,572	1,123	0,901	19,01	17,46	23,08	0,65	21,3	6,49	138,3	3,75	0,019
9	1,573	1,120	0,903	15,18	13,91	18,36	0,41	43,3	4,1	178	6,12	0,031
10	1,546	1,132	0,897	16,7	15,80	19,07	0,36	53,0	3,62	192	8,1	0,041

Note: b_0 and b_1 — strip width before and after the pass; b_{cp} is the width of the strip in the deformation zone; $\sigma_1' = \frac{F_m}{h_1 b_1}$ — dimensional value; $q_1' = \frac{\sigma_1'}{2k_{cp}}$ — in dimensionless form.

Analysis of the tabular data shows that the acceleration of the metal increases in the direction from the first stand to the last. In the tenth stand, it reaches a value of 5·104 m/s^2.

When comparing the results obtained with the data of [8], it can be concluded that the proposed method provides the values of the considered parameters 1.5—2.0 times less (Fig. 2). Similar conclusions can be drawn regarding the F_m mass forces. As you know, these forces are directed oppositely to the movement of the roll and therefore, at the exit from the deformation zone, each of the stands have a supporting effect.

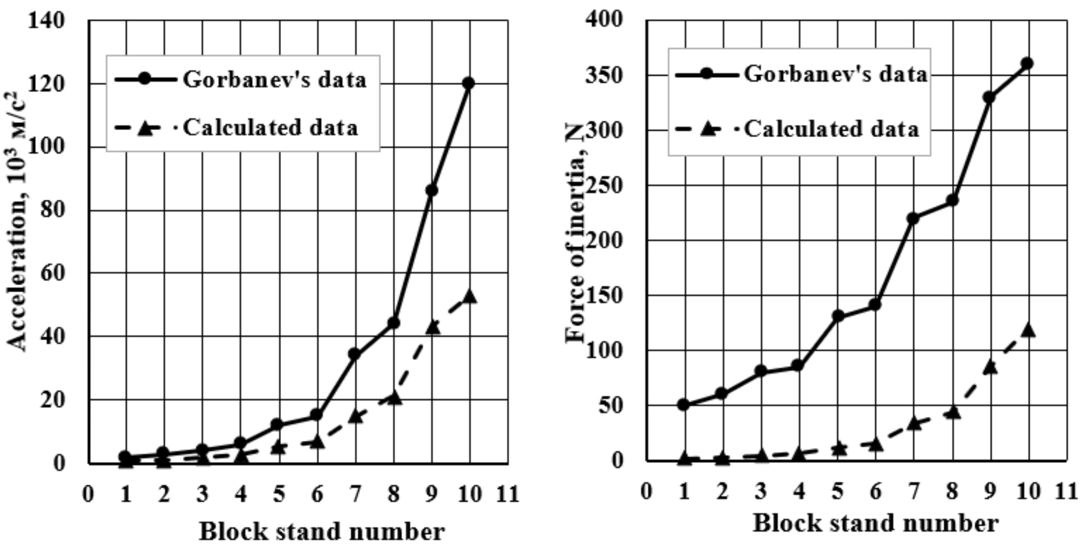

Fig. 2. Comparison of calculated data

It should be noted that in the first six stands they are insignificant and constitute thousandths of the average metal deformation resistance $2k_{cp}$. Therefore, these stresses cannot significantly affect the energy-force and kinematic parameters of the deformation zone in these stands. In the rest of the stands, especially in the last one, the supporting stresses from the action of mass forces can have a more significant effect on the specified parameters and the longitudinal stability of the rolling process. Let us analyze this influence on the example of rolling wire rod in the last stand of the wire block. The supporting normal stresses from the action of mass forces in the outlet section of the deformation zone are $q_1' = -0{,}041$ (the minus sign indicates that they act in the direction opposite to the movement of the strip). The evaluation of the longitudinal stability of the process is carried out when determining the average resultant longitudinal forces of the plastically deformed metal according to the method described in [8, 9]. Longitudinal stability characterizes the boundaries of variation of the parameters at which the forces pulling the metal into the rolls are sufficient to ensure the stationarity of the process.

The average resulting force is found from the expression

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

$$Q^*_{x\,np.} = \frac{Q_{x\,np.}}{2k_{cp} R b_{cp}} ; Q_{x\,np.} = \sigma_x h_x b_{cp} ,$$

where $Q^*_{x\,np.}$ and $Q_{x\,np}$ are the current dimensionless and dimensional internal forces; σ_x — longitudinal normal stress of plastically deformed metal.

When solving the differential equilibrium equation, it was assumed that the friction conditions in the deformation zone obey the Coulomb model with a friction coefficient f_y = 0,26. The calculation results are shown in tabl. 2, which compares the obtained rolling parameters with allowance for mass forces ($q_1' = -0{,}041$) and with deformation without taking into account inertial forces ($q_1' = 0$).

Table 2. The influence of mass forces on the parameters of the rolling process in the tenth and of the wire block

Rolling type	$Q^*_{cp\,np}$	$\frac{p_{cp}}{2k_{cp}}$	γ	M^*_{np}	q_0	q_1
Rolling with account the inertia forces	0,0173	1,337	0,0512	0,039	0,02	– 0,041
Rolling without account the inertia forces	0,0164	1,320	0,0529	0,036	0,02	0
Difference in parameters, %	5,2	1,270	3,21	7,69	–	–

Note: γ is the angle of the neutral section; $M^*_{np} = \frac{M_{np}}{2k_{cp} R b_{cp}}$ — is the moment of rolling in dimensionless form; R — is the radius of the rolls; q_0, q_1 is front and rear specific tension in dimensionless form $q_i = \frac{\sigma_i}{2k_{cp}}$; p_{cp} — is the average normal stress in the deformation zone.

Data analysis tabl. 2 shows that at the maximum value of inertial forces in the case of rolling a wire rod with a diameter of 5.5 mm (tenth stand), the effect of their effect on the parameters of the deformation zone is ambiguous. The average normalized stress $\frac{p_{cp}}{2k_{cp}}$ increased by about 1.3 %, and the γ angle increased by 3 %. The torque value increased by 7,7 %, and the average resulting force — by 5 %. The increase of $Q^{*}_{cp\,np}$ during rolling taking into account the mass force is explained by the growth of the lagging zone in the deformation zone.

Conclusions

A scheme and method for calculating mass forces, taking into account the displacement and acceleration of the center of mass the mechanical system made of particles the deformation zone, have been developed to refine the mathematical model of the high-speed rolling process.

Using a refined model of the high-speed rolling process, the mass forces in the stands of the wire block were calculated when rolling a wire rod with a diameter of 5.5 mm. The influence of the supporting normal stresses from the action of inertial forces on the energy-power and kinematic parameters, as well as on the longitudinal stability the rolling process, is determined. The analysis the calculated data shows that under the operating modes of the rolling mill, the effect the influence of mass forces on the technological parameters will not be critical.

The refined model of the high-speed rolling process, taking into account the longitudinal stability, can be used to determine the technological parameters on the existing mills and for a more reasonable choice of parameters when designing new wire blocks.

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МОДЕЛЮВАННЯ ВПЛИВУ СИЛ ІНЕРЦІЇ НА ПАРАМЕТРИ ВИСОКОШВИДКІСНОЇ ПРОКАТКИ В ДРОТОВОМУ БЛОЦІ

Максименко О.П., Самохвал В.М., Нікулін О.В., Лобойко Д.І., Марченко К.К.

Реферат

Високошвидкісна прокатка набуває все більшого поширення при виготовленні як плоских, так і профільних виробів. Для досягнення високих показників використані рішення комплексу технічних і технологічних проблем, в основі яких знаходилось наукове обґрунтування. Однак у теорії прокатування існує ряд проблем, одна з яких враховує вплив сил інерції на параметри процесу та недостатньо розв'язана. При дослідженні впливу цих сил виходили зі спільного розв'язання диференціального рівняння рівноваги виділеного в осередку деформації елементарного об'єму, рівняння пластичності з урахуванням масових сил, що діють на частинки металу. Як відомо, ці сили спрямовані протилежно напрямку руху смуги і тому на виході з осередку деформації кожної з клітей діють підпираючи переміщення частинок матеріалу. Для вдосконалення математичної моделі процесу високошвидкісного прокатування розроблено схему та метод розрахунку сил інерції з урахуванням переміщення та прискорення центру мас механічної системи з частинок осередку деформації. За допомогою вдосконаленої моделі швидкісного процесу прокатки були розраховані сили інерції в клітях дротяного блоку при прокатуванні катанки діаметром 5,5 мм. Визначено вплив поздовжніх нормальних напружень від дії інерційних сил на енергосилові та кінематичні параметри, а також на поздовжню стійкість процесу прокатування. Аналіз даних розрахунків показує, що за прийнятих режимів роботи обраного прокатного стану вплив масових сил на технологічні параметри не буде критичним. Уточнена модель процесу високошвидкісного прокатування, враховуюча поздовжню стійкість, може бути використана для визначення технологічних параметрів на існуючих дротових станах та при раціональному виборі параметрів при проектуванні нових дротових блоків.

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