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Sereda Borys[1], doctor of technicals ciences, professor, Head Department of automobiles and transport and logistics systems
Середа Б.П., доктор технічних наук, професор, завідувач кафедри автомобілів та транспортно-логістичних систем
ORCID: 0000-0002-9518-381X
e-mail: seredabp@ukr.net

Belokon' Yuriy[2], doctor of technical sciences, professor
Бєлоконь Ю.О., доктор технічних наук, професор, завідувач кафедри металургійних технологій, екології та техногенної безпеки
ORCID: 0000-0002-9327-5219
e-mail: belokon.zp@gmail.com

Kruglyak Irina[1], Doctor of Technical Sciences, Professor, Head Department of industrial engineering
Кругляк І.В., доктор технічних наук, професор, завідувач кафедри галузевого машинобудування
ORCID: 0000-0002-9518-381X
e-mail: krugly@ukr.net

Kruglyak Dmytro[2], candidate of technical sciences, assistant professor
Кругляк Д.О., кандидат технічних наук, доцент, доцент кафедри металургійних технологій, екології та техногенної безпеки
ORCID: 0000-0001-7812-8360
e-mail: krugly@ukr.net

[1]Dniprovsky State Technical University, Kamianske
Дніпровський державний технічних університет, Кам'янське
[2]Zaporizhzhia National University, Zaporizhzhia
Запорізький національний університет, Запоріжжя

MODELING OF STRIP SHAPE INDICATORS DURING ROLLING IN NON-CONTROLLED MILLS

МОДЕЛЮВАННЯ ПОКАЗНИКІВ ФОРМИ ШТАБИ ПРИ ПРОКАТЦІ У НЕРЕГУЛЬОВАНИХ КЛІТЯХ

In the theoretical work, it is proposed to define the indicators of the shape of sheet samples before and after rolling, and to establish equations describing the change in shape during rolling, along with determining the coefficients of shape alignment. The obtained equations for shape change and the coefficients of shape alignment can be utilized for optimizing the shape of the active forming area between the roll gap and the squeezing modes to obtain flat sheets or slabs in non-adjustable rolling mills. We will establish the relationship between the obtained shape indicator $Ф_л$ *and the indicator used for quality control of sheet shape in industrial conditions. For automatic control of flatness and slab shape during rolling, the indicators* $Ф_л$ *and* $K_{в.ф}$ *characterize the controlled object and are used as control signals for the control system of the strip rolling process SAAPF.*

Keywords*: rolling, shape indicator, strip, elongation coefficient, alignment coefficient, flatness, automatic regulation.*

Основна проблема при прокатці штаби правильного профілю в поперечному перерізі полягає в забезпеченні в процесі роботи правильної форми позіху валків, тобто в збереженні прямолінійності та взаємної паралельності утворюючих валків в осьовій площині. З метою автоматичного регулювання форми штаб показник форми повинен характеризувати пласкість прокатуваного металу в цілому, тобто він повинен бути функцією усіх розмірів штаби, *що змінюються під час прокатування. У роботі теоретично визначити показники форми листових зразків до і після прокатування та встановлені рівняння зміни форми під час прокатування та знайдено коефіцієнти вирівнювання форми. Отримані рівняння зміни форми штаби і величини коефіцієнта вирівнювання форми листа можуть використовуватися для оптимізації форми активної твірної поміж валкового розхилу та режимів обтиску з метою отримання пласких листів або штаб в нерегульованих прокатних клітях. Визначимо зв'язок поміж отриманим показником форми* $Ф_л$ *та показником, яким користуються для контролю якості форми листів в промислових умовах. Встановлено, що показник форми листа* $Ф_л$ *буде позитивним для коробчатого, від'ємним для хвилястого і дорівнюватиме нулю для плаского листа. Для автоматичного регулювання величини показників* $Ф_{л0}$ *і* $Ф_{л1}$ *повинні визначатися за витяжкою листового металу під час його прокатування. За автоматичного регулювання пласкості і форми штаб під час прокатування показники* $Ф_л$ *і* $К_{в.ф}$ *характеризують об'єкт регулювання і їх використовують як керуючі сигнали регулятора САРПФ штаби. За оцінкою авторів, використання САРПФ на базі створеної методики регулювання дозволяє підвищити площинність прокатуваних штаб на 5—10 % і забезпечити її стабільність на 95 % довжини штаби завдяки безперервному коректуванню профілю міжвалкового зазору в автоматичному режимі.*

***Ключові слова**: прокатка, показник форми, штаба, коефіцієнт витяжки, коефіцієнт вирівнювання, площинність, автоматичне регулювання.*

Problem's Formulation

The task of sheet rolling, together with leveling and straightening processes, aims to produce strip and sheets of flat shape, without «waviness» and «camber» defects. In industrial conditions, the shape of sheets is characterized by the ratio of flatness deviation a to the established length L, at which this deviation is measured. However, this ratio does not indicate whether the sheet or strip section is wavy, flat, or camber, nor does it consider the width of the strip. For the purpose of automatic regulation of strip shape, the shape indicator should characterize the flatness of the rolled metal as a whole. That is, it should be a function of all dimensions of the strip that change during rolling.

Analysis of recent research and publications

The main problem in rolling of strips of correct profile in cross-section lies in ensuring the correct shape of the roller pass during operation, i.e., in maintaining the straightness and mutual parallelism of the forming rollers in the axial plane. In the case of absolutely rigid roller installation, their uniform heating and wear, this condition could ideally be satisfied. However, since any real system has finite rigidity, the task arises primarily to compensate for the deformations to which the rollers are subjected under the action of rolling forces. Furthermore, it is necessary to compensate for the instability over time and along the length of the roll (width of the strip) of factors affecting the shape of the roller pass.

Therefore, three main factors can be distinguished, significantly different in their nature and methods of compensation, which cause a change in the shape of the roller pass [1, 2]. These are the pressure of the metal on the rollers, the heating of the rollers, and their wear. Let's consider the nature of the influence of these factors in more detail.

The pressure of the metal on the rollers, in turn, is determined, under other equal conditions, by such basic parameters as compression and deformation resistance. In continuous rolling, the tension of the strip also plays an important role.

All three parameters can be unstable over time and along the width of the strip. For convenience of analysis, each factor can be considered as a sum of a constant mean value and a variable deviation from this mean value (in terms of two variables: time and coordinate across the width).

The most important parameter among those mentioned can be considered as the compression [3]. This parameter is a function of the initial thickness of the strip and the gap between the rollers. Disturbance to this parameter can arise from the initial thickness variation of the strip. If this is longitudinal thickness variation, it causes longitudinal compression instability (at a given gap). Transverse initial thickness variation causes uneven compression across the width of the strip (even with correct roller pass shape). What happens in this case?

Unstable compression over time leads to fluctuations in the pressure of the metal on the rollers and, consequently, to fluctuations in the gap between the rollers and the shape of the roller pass. The latter, in turn, affects the magnitude of compression, but now in the direction of its stabilization. Thus, in the presence of a system with positive feedback, the system is stable.

The uneven compression across the width of the strip poses a more complex challenge. Similar to the above, this non-uniformity affects only one of the components of the deformation of the forming metal — elastic flattening, which is proportional to the rolling force along the strip length (and thus, under equal conditions, to the specific compression across the width of the strip). The second and most important component of deformation — the deflection of the roll during its elastic bending — is not as directly related to the nature of its loading along the strip length. In other words, the elastic curve of the roll during bending is not similar (or equidistant) to the distribution of load on it. Consequently, regulation becomes significantly more complicated.

It is pertinent to note that the profile of the strip is not influenced by the parallel displacement of the rolls caused by the deformation of supports, pressure mechanisms, or stands. However, these deformations are significant for longitudinal thickness variation of the strip. From the above, it should not be assumed that longitudinal and transverse thickness variations are independent factors. Clearly, any type of deformation (bending, stretching, flattening) within the elastic limit is a consequence of the same force — the rolling force. Hence, the problems of their compensation, especially when dealing with the variable component of the rolling force, are interdependent.

The second parameter affecting the pressure of the metal on the rollers is the deformation resistance, or essentially, the rolling temperature [4, 5]. This parameter is more inertial over time than the previous one, and if it changes, it does so monotonically and predictably. This allows for extrapolation of the temperature function and anticipation (prediction) of regulatory influence based on it. The most characteristic influence on the strip profile is the temperature gradient (linear) across the width of the strip, causing its camber. Another typical case is the lower temperature at the edges of the bar compared to its center.

Finally, the third, most difficult to regulate parameter is tension [6]. The tension between stands depends on the force applied to the strip by the tension regulator, the ratio of rolling speeds in adjacent stands, and the ratio of compressions in the same stands. Naturally, one would expect this parameter to be the least stable among those considered: since fluctuations in each of the mentioned influences cause fluctuations in tension. Fluctuations in tension cause changes in compression, which in turn affects tension. Thus, here too, there is a complex feedback control system. The most unpleasant aspect is the uneven tension across the width of the strip, causing uneven compression, and consequently, uneven stretching across the width of the strip. As we have already noted, such deviations from the rolling regime immediately affect its flatness.

Thus, of the three parameters considered that determine the pressure of the metal on the rollers, two (compression and tension) are interdependent, while the third — deformation resistance (rolling temperature) — is autonomous and significantly more inertial [7].

Two other factors that affect the profile of the roller pass are thermal deformation of the rollers and wear of the rollers.

The non-uniformity of thermal deformation of the rollers is caused by different contact conditions with the strip along different sections of the barrel length, as well as by different cooling conditions.

Finally, roller wear is the least predictable and irreversible (unlike all previously mentioned) cause of changes in the roller pass profile.

To conclude this section, it is necessary to emphasize that the flatness of the strip is related to the uniformity of compression across its width, but uniform compression is not a necessary condition for achieving the correct profile of the strip [8, 9]. Therefore, the most important factor in simultaneously addressing both tasks is the profile indicator of the strip. In the case of significant starting thickness, flatness is not an issue, and in such conditions, the profile can be effectively regulated.

Formulation of the study purpose

The aim of the study is to theoretically determine the shape indices of sheet samples before and after rolling, formulate equations describing the change in shape during rolling, and find coefficients for shape correction.

Presenting main material

To obtain a generalized measure of form (see Fig. 1), let's consider two transverse sections of the sheet. If we measure the length of longitudinal sections between the cuts at the edges and in the middle of the sheet, we will find that for a flat sheet, these lengths will be the same, while for a non-flat one, they will be different. Moreover, the greater the difference in these lengths, the greater the deviation of the sheet's form from flat. The deviation of the sheet's form from flat, given the same relative difference in lengths, increases as the width of the sheets b decreases. Therefore, the form of the sheets $\Phi_{л}$ can be estimated by the ratio of the difference in lengths in the middle l_c and at the edges of the sheet $l_к$ to the average length l and the width of the sheet b on sections between the cuts of the sheet, i.e.:

$$\Phi_{Л} = \frac{l_C - l_R}{b \cdot l}; \tag{1}$$

$$l = \frac{l_C - l_K}{2}. \tag{2}$$

Thus, the form index of the sheet $\Phi_{л}$ will be positive for camber, negative for wavy, and equal to zero for flat sheet.

Let's establish the relationship between the obtained $\Phi_{л}$ form factor and the indicator used for quality control of sheet forms in industrial conditions. To do this, let's consider a section of a sheet of camber shape, marking the length at half the defect wave as L (Fig. 1). For $b > L$, the form of the section of the sheet, represented by the amount of non-flatness relative to the length at which it is measured, will be equal to a/L. To determine the $\Phi_{л}$ form factor on the highlighted section of the sheet, we calculate the length of two half-waves $l_к$, using the length of its horizontal projection $l_к$ and the non-flatness magnitude a, replacing the curve that reflects the camber sheet through its middle with two segments BO and OC.

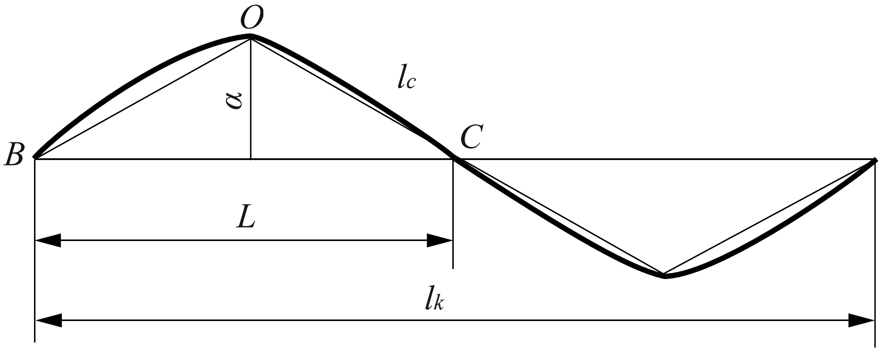

Fig. 1. The section of the sheet has a camber shape

Taking into account that in $a/b << l$ and assuming $l_K \approx l$, and using expression (2), we obtain:

$$l_C = l_K \cdot \sqrt{1 + \left(\frac{2a}{L}\right)^2} \approx 1 \cdot \left(1 + 2\frac{a^2}{L^2}\right) \tag{3}$$

substituting l_c from (3) into (1) and replacing $l_к$ with l in the latter, we obtain:

$$\Phi_{Л} = \frac{2 \cdot a^2}{b \cdot L^2}. \tag{4}$$

According to equation (1), the form factor before rolling is:

$$\Phi_{Л_0} = \frac{l_{C_0} - l_{K_0}}{B_0 \cdot L_0}. \tag{5}$$

After rolling:

$$\Phi_{Л_1} = \frac{l_{C_1} - l_{K_1}}{B_1 \cdot L_1}. \tag{6}$$

The form factor indices according to (5) and (6) cannot be used in SAAPF because continuous measurement of the edge and center lengths of the slab metal directly during rolling is not possible. Therefore, for automatic adjustment of the indices $\Phi_{л0}$ and $\Phi_{л1}$, they are determined based on the extraction of sheet metal during rolling. The distribution of extraction across the width is obtained using the values of the generalized (average) extraction λ and the non-uniformity of extraction across the width of the sheet $\Delta\ \lambda$. We express the generalized extraction as the semi-sum of the extraction at the center λ_c and at the edges of the sheet $\lambda_к$, i.e.:

$$\lambda = \frac{\lambda_C + \lambda_K}{2} \tag{7}$$

the non-uniformity of the distribution of extractions is defined as their difference, represented by:

$$\Delta\lambda_y = \lambda_C - \lambda_K, \tag{8}$$

where λ_c and $\lambda_к$ — are the extraction at the center and edge of the sheet, respectively, which will be equal to:

$$\lambda_C = \frac{l_{C_1}}{l_{C_0}}; \tag{9}$$

$$\lambda_C = \frac{l_{K_1}}{l_{K_0}}. \tag{10}$$

Considering that $l_{C_0}/l_0 \approx l_{K_0}/l_0 \approx 1$, we obtain:

$$\frac{l_{C_1} - l_{K_1}}{l_1} - \frac{l_{C_0} - l_{K_0}}{l_0} = \frac{\Delta\lambda_y}{\lambda}. \tag{11}$$

From here, we obtain the general equation for the change in the form of the sheet during rolling:

$$b_1 \cdot \Phi_{Л_1} = b_0 \cdot \Phi_{Л_0} + \frac{\Delta\lambda_y}{\lambda}. \tag{12}$$

In the case of cold rolling without sheet expansion, i.e., when $b_1 = B_0$, we will have:

$$\Phi_{Л_1} = \Phi_{Л_0} + \frac{\Delta\lambda_y}{\lambda \cdot b}. \tag{13}$$

The ratio of the form factors of the sheet after rolling to before rolling is nothing but the form alignment coefficient $K_{в.ф}$. We obtain the $K_{в.ф}$ coefficient by dividing both sides of equation (13) by $\Phi_{л0}$.

$$K_{в.ф} = \frac{\Phi_{Л_1}}{\Phi_{Л_0}} = 1 + \frac{\Delta\lambda_y}{\lambda \cdot b \cdot \Phi_{Л_0}}. \tag{14}$$

As a result of conducting an active experiment, the following results were obtained (Tabl. 1). Material: strip 0.91x100x117 mm of grade A5M aluminum (ultimate tensile strength — 7.8 kgf/mm^2, elongation — 40.7 %).

Table 1. The results of the experiment

№	Thickness before rolling, mm	Thickness after rolling		
		left edge	middle	right edge
1	0,91	0,74	0,73	0,73
2		0,66	0,68	0,70
3		0,59	0,63	0,62
4		0,56	0,57	0,58
5		0,59	0,62	0,64

Calculations of profile and cross-section parameters, as well as determining the magnitudes of controlling influences on the profile and form, can be conducted using the formulas obtained from the previously provided methodology (Tabl. 2, 3).

*Table 2.*Transition from a wavy to a flat sheet

№	l_{C0}, мм	l_{K0}, мм	l_{C1}, мм	l_{K1}, мм	λ_C	λ_K	λ	$\Delta\lambda_y$	$\Phi_{Л0}$	$\Phi_{Л1}$	$K_{в.ф}$
1	110	112	117	117	1,06	1,04	1,05	0,02	0,0002	-0,0000095	0,0475
2	105	107			1,11	1,09	1,10			-0,0000182	0,091
3	102	104			1,15	1,13	1,14			-0,0000246	0,123
4	98	100			1,19	1,17	1,18			-0,0000305	0,1525
5	95	97			1,23	1,21	1,22			-0,0000361	0,1805

*Table 3.*Transition from a camber to a flat sheet

№	l_{C0}, мм	l_{K0}, мм	l_{C1}, мм	l_{K1}, мм	λ_C	λ_K	λ	$\Delta\lambda_y$	$\Phi_{Л0}$	$\Phi_{Л1}$	$K_{в.ф}$
1	112	110	117	117	1,04	1,06	1,05	0,02	0,0002	0,0000095	0,0475
2	107	105			1,09	1,11	1,10			0,0000182	0,091
3	104	102			1,13	1,15	1,14			0,0000246	0,123
4	100	98			1,17	1,19	1,18			0,0000305	0,1525
5	97	95			1,21	1,23	1,22			0,0000361	0,1805

The coefficient of shape alignment of the sheet during rolling in an unregulated mill can take the following values (Fig. 2):

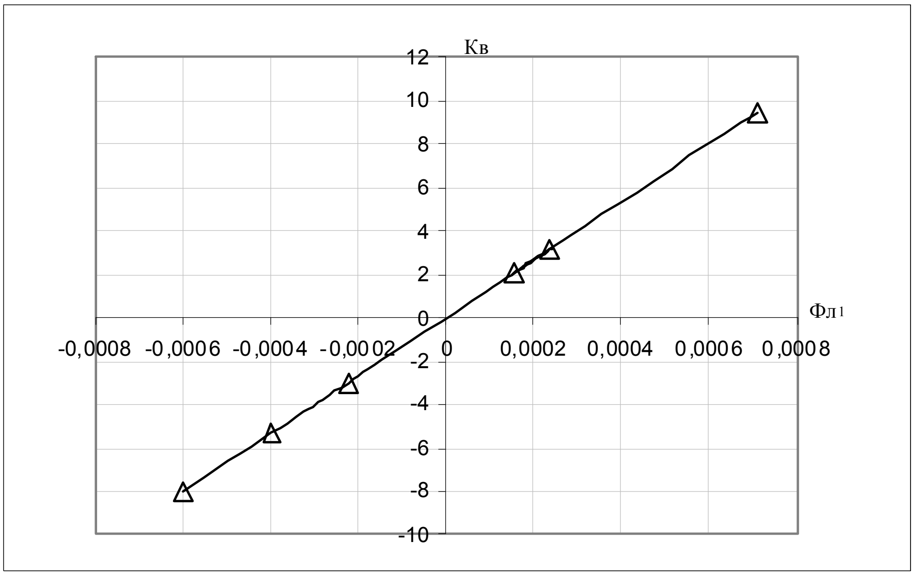

Fig. 2. The dependence of the shape alignment coefficient $K_в$ on the profile shape factor after rolling

$K_{в.ф} > 1$ — the flatness of the sheet deteriorates;

$K_{в.ф} = 1$ — the flatness of the sheet does not change;

$K_{в.ф} < 1$ — the flatness of the sheet improves.

The utilization of the System Automatic Adjustment Shape and Form (SAAPF) based on the developed regulation methodology will enable an increase in the flatness of rolled strips by 5—10 %

and ensure its stability over 95 % of the length of the strip by continuously adjusting the profile within the inter-roll gap in automatic mode.

Conclusions

The obtained equations for changing the shape of the strip and the magnitude of the shape alignment coefficient can be used to optimize the shape of the active forming zone between the roll gap and the compression modes in order to obtain flat sheets or strips in unregulated rolling mills. During automatic adjustment of flatness and shape of the strip during rolling, the indices $Ф_{л}$ and $К_{в.ф}$ characterize the controlled object, and they are used as control signals for the SAAPF strip regulator.

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