DOI 10.1007/s11015-020-01045-1
Metallurgist, Vol. 64, Nos. 7-8, November, 2020 (Russian Original Nos. 7-8, July–August, 2020)

INFLUENCE OF OUTER PARTS OF A STRIP ON THE DEFORMATION AND FORCE PARAMETERS OF THIN-SHEET ROLLING

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UDC 621.771.01

We present the results of experimental investigations of the distribution of deformation indicators and rolling forces along the length of brass (L63) strips in a 150 × 235 two-roll mill equipped with a microcontroller system for high-precision measurements of loads acting upon the rolls. The results of the quantitative analyses of changes in the sizes of strips and rolling forces on stationary and nonstationary sections along the strip length are presented. A significant effect of the outer parts of the strip on the rolling force and the pressure of the metal upon the rolls is established. On the basis of the experimental results, we propose an equation for the evaluation of the influence of the outer parts of the strip on the rolling force and pressure. The equation for the mean pressure of the metal upon the rolls is improved with regard for the influence of the outer parts and the stiffness of the strip on the site of deformation in the process of thin-sheet rolling. It is shown that the proposed equations make it possible to increase the accuracy of evaluation of pressure and determination of rolling forces along the length of thin strips.

Keywords: deformation indicators, rolling force, evaluation of the mean pressure, outer parts and the stiffness of the strip, 150 × 235 rolling mill, L63 brass, measurement of rolling forces along the length of the strip, microcontroller system for measuring forces.

The metallurgical and machine-building plants are equipped with sheet mills of various types and purposes in which the deformation of metals along the length is realized under various conditions. In the process of rolling of strips, it is necessary to guarantee not only the production of large amounts of sheet metals but also its high quality along the entire length [1–4].

The presence of contact friction between a strip and the rolls guarantees the possibility of seizure and realization of the steady process of rolling. Independently of the conditions of contact deformation observed in the course of rolling of the end sections of sheets, strips, and bands, we can assume that the neighboring vertical sections of the semifinished rolled metal in the zone of deformation are in the state of pure plastic compression. Then the pressure required for the plastic deformation of the end sections is practically equal to the true yield limit of a sheet or a strip under the conditions of plane deformation at the beginning and at the end of the zone of deformation. In the case of plastic compression of the other vertical sections along the length of the sheet (strip), the compressive stresses or the pressure of the metal upon the roll are higher than in the end parts. In the steady-state period of rolling, in the process of deformation of the middle cross sections, a part of the metal should be shifted toward the entry or toward the exit against the action of friction forces acting in the contact of the metal with the roll, as well as against the action of stresses caused by the outer parts of the strip. Therefore, as the strip elongates from the entry or exit of the deformation zone, the level of pressure required for its plastic deformation increases.

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Translated from Metallurg, Vol. 64, No. 7, pp. 77–84, July, 2020. Original article submitted March 5, 2020.

The effects of the levels of strains and stresses formed in the course of rolling of various metals on the formation of thickness and width along the strip length are different, which requires additional experimental investigations. Despite a significant number of works [5–14] devoted to the study of the conditions of formation of sizes, shapes, and force indicators of sheet, graded, and screw rolling, the deformation and force indicators of the process in nonstationary zones require additional experimental studies and theoretical analyses.

Independently of the type of a mill, the process of rolling of sheets, strips, or pipes is realized under stationary or nonstationary conditions of plastic deformation of metals or alloys [15]. The end parts of the metal are rolled either without tension or under the conditions of unilateral tension under nonstationary conditions. The remaining parts of the strips and sheets are deformed under quasistationary conditions. In [16, 17], it was shown that different conditions of deformation of the metal lead to the nonuniform distributions of rolling forces along the length of the strips.

It is known that the decisive influence on the formation of rolling forces is exerted, parallel with the area of contact surface of the metal with the rolls, by the contact pressure, which depends on the deformation resistance of the metal and the stressed state of the strip. In the course of fundamental theoretical and experimental investigations [6–10], it was established that the stressed state of the strip is affected by the mean stress intensity factor in the zone of deformation n_{m}, by the coefficient of influence of the out-of-contact zones on the zone of deformation n_{σ}, and by the coefficient of influence of tension σ_{t}. In a series of experimental works [6–8, 18], it was shown that the stressed state of the strip in the zone of deformation and, hence, the level of pressure and rolling forces are strongly affected by the outer parts of the rolled metal at the entry and at the exit of the mill. This also requires additional investigations with regard for the variations of stiffness and the sizes of the semi-finished rolled metal. In addition, the influence of the out-of-contact zones in the course of thin-sheet rolling in the presence of a long zone of deformation (for which the coefficient characterizing its shape, i.e., $l_{\mathrm{d}}/h_{\mathrm{av}}$, is larger than 1) is also poorly investigated.

The Aim of the Present Work is to estimate the influence of the characteristics of the outer parts of the metal and the conditions of deformation on the pressure and the forces acting along the length of a thin strip in the process of rolling.

Materials and Experimental Procedure

We carried out our investigations on a laboratory 150×235 two-roll mill with an actual diameter of rolls equal to 141.6 mm mounted in the laboratory of the "Pressure Treatment of Materials and Additive Technologies" (PTM AT) Chair at the Moscow Polytechnic University (Fig. 1). As billets for experimental rolling, we used specimens ≈ 2 mm in thickness, ≈ 20 mm in width, and ≈ 200 mm in length cut out from the strips of L63 brass taken from commercial batches. The strips were rolled with a speed of 0.249 m/sec. The laboratory mill was equipped with a domestic microcontroller system aimed at measuring rolling forces (with an accuracy of ± 0.01 kN) [15] along the strip length under the left and right pressing screws with periods of 0.1–0.0125 sec. This system makes it possible to compute the total value of forces, to reproduce it in the displays of devices, to transmit the accumulated data to the input of a computer, to form a report about the sequence of rollings, and to printout the results of measurements. The system of monitoring of the rolling forces was developed in cooperation with the "KROS" firm. It was adjusted prior to the realization of pilot rolling for the inquiry of the force gauges with periods of 0.0125 sec corresponding to the length of strip segments equal to 3.113 mm.

For our investigations, we selected nine specimens made of L63 brass. Prior to and after rolling, we measured the thickness and width of each specimen at three points along its length with an accuracy of ± 0.01 mm: at the beginning of the strip (1), in the middle of the strip (2), and at its end (3). We also measured the lengths of

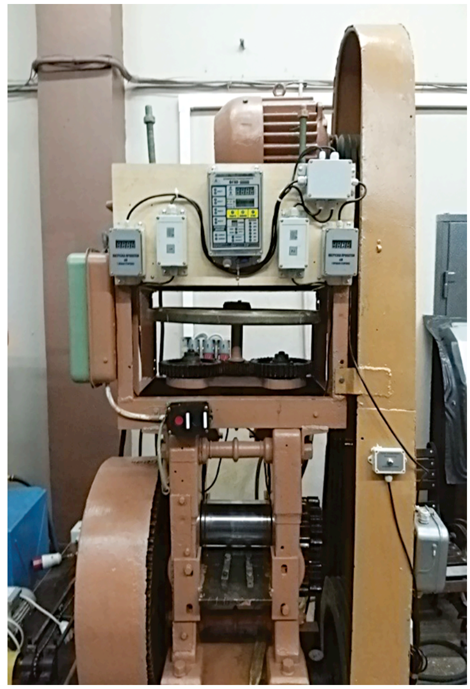

Fig. 1. A 150×235 two-roll mill in the laboratory of the "PTM AT" Chair equipped with a microcontroller system of measuring of the rolling forces.

all specimens l. The procedure of rolling was performed with three reductions: $\varepsilon \approx 10, 20,$ and 30% (three specimens for each adjustment of the rolling mill).

In the process of rolling of the strips, we automatically measured the rolling force P_f along the length of three segments of the strips with steps $\Delta l = 3.113$ mm and with an accuracy of ± 0.01 kN. The averaged indicators of measurements of the sizes of strips prior to and after rolling and reduction ε are presented in Table 1.

After deformation, we recorded the obtained data by the recorders of rolling forces. Then, as a result of computer processing of these data, we obtained the plots of distribution of the forces along the length of the strips in the process of rolling in the 150×235 mill.

Results of Experimental Studies and Their Discussion

The averaged results of experimental investigations are given in Table 1, where we present the following parameters and indicators of pilot rollings: h_0 and b_0 are, respectively the thickness and width along the length of the strips prior to rolling; h_1 and b_1 are, respectively the thickness and width along the length of the strips after rolling at the beginning of each strip (1), in the middle of the strip (2), and at its end (3); l_0 and l_1 are the lengths of the strip prior to and after rolling; Δh is the absolute reduction; ε is the relative reduction; Δb is the absolute widening; P_f are the values of the total rolling force measured by the gauges under the left and right pressing screws under the conditions of deformation; ε is the computed value of the relative reduction along the strip length, and P_{comp} is the computed value of the rolling force.

The analysis of indicators presented in Table 1 enables us to establish the quantitative regularities of the distributions of thickness and width along the length of the strips after the rollings with different reductions. The results of our studies confirm the well-known facts that the thickness of the strips decreases at the ends of

Table 1
Sizes and the Deformation and Force Indicators of Rolling Along the Length of Brass Strips in the 150 × 235 Mill

No. of the specimen	Part of the strip	h_0, mm	b_0, mm	l_0, mm	h_1, mm	b_1, mm	l_1, mm	Δh, mm	Δb, mm	ε_m, %	P_f, kN	P_{comp}, kN
1	1(b)	2.03	20.3	200.5	1.81	20.5	223.0	0.22	0.2	10.84	22.0	23.95
	2(m)	2.02	20.0		1.82	20.1		0.20	0.1	9.90	33.81	31.37
	3(e)	2.04	20.1		1.82	20.5		0.22	0.4	10.78	17.00	19.55
2	1(b)	2.03	20.1	199.0	1.63	20.5	241.5	0.40	0.4	19.70	9.03	10.38
	2(m)	2.03	20.0		1.64	20.3		0.39	0.3	19.21	53.18	61.16
	3(e)	2.04	20.0		1.64	21.0		0.76	1.0	19.61	8.50	9.78
3	1(b)	2.01	20.3	202.0	1.44	21.0	277.0	0.57	0.7	28.36	10.51	12.09
	2(m)	2.01	20.3		1.45	20.7		0.56	0.4	27.86	72.17	83.00
	3(e)	2.01	20.2		1.41	21.2		0.60	1.0	30.35	10.50	12.08

the strip as compared with its middle part and that the widening of the metal in the end parts of the strip increases as compared with its values in the middle part. The thicknesses and widths of the strips vary within the ranges 0.01–0.04 and 0.1–0.7 mm, respectively, depending on the deformation conditions of rolling. The data of measurements indicate that the rolling forces observed in the course of deformation of the end sections of the strips are 2–7 times lower than in the middle part of the rolled metal.

In Figs. 2 and 3, we present the distributions of rolling forces along the length of brass strips rolled in the 150 × 235 two-roll mill with reductions of ≈ 10 and 30%.

The distribution of the rolling force along the strip length is strongly nonuniform. In the case of rolling of the end sections, the force takes its minimum value and increases from the time of biting of the strip by the rolls up to the attainment of the steady process of rolling. On the contrary, the force decreases from the steady process of rolling of the main part of the strip toward the end part of the strip. The distribution of forces along the length of the rolled strips is, most likely, determined by the conditions of deformation and by the influence of outer parts of the strip on the zone of deformation and weakly quantitatively correlates with the distribution of reduction of the metal and the thickness of the strips at the exit of the rolling mill (see Table 1). Thus, in the case of rolling of the front end of the strip (Specimen 3), the degree of reduction was equal to 28.36% and the rolling force to 10.51 kN. In the case of deformation of the middle part of the semifinished rolled metal, the degree of reduction decreases by 0.5% ($\varepsilon = 27.86\%$). At the same time, in this case, the rolling force, on the contrary, becomes almost seven times higher and equal to 72.17 kN.

For the nonstationary conditions of deformation of the end sections almost equal to the width of the strip, the rolling force varies from the minimum value (at the onset of rolling) to the maximum value attained after biting of the strip by the rolls and, conversely, decreases from the maximum value to the minimum value prior to the exit of the strip from the rolls.

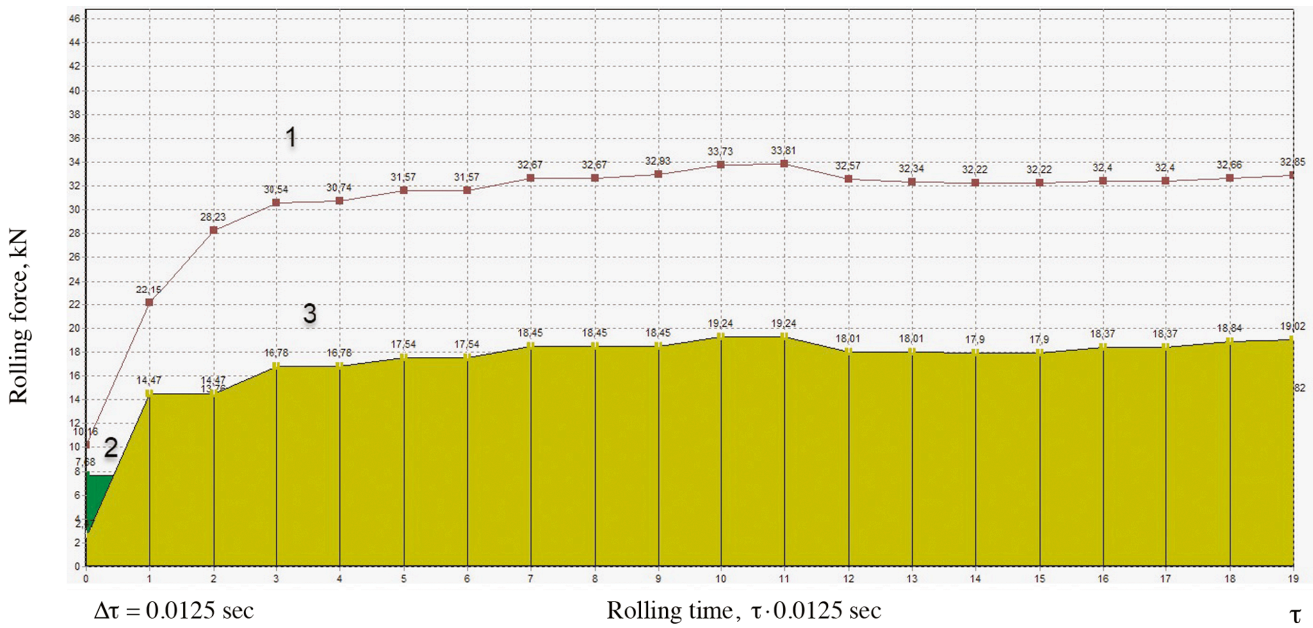

Fig. 2. Distribution of rolling forces along the length of a brass strip with a reduction of 10% (Specimen 1) measured in the 150 × 235 mill: *1* — total force; *2* and *3* — rolling forces under the left and right pressing screws, respectively.

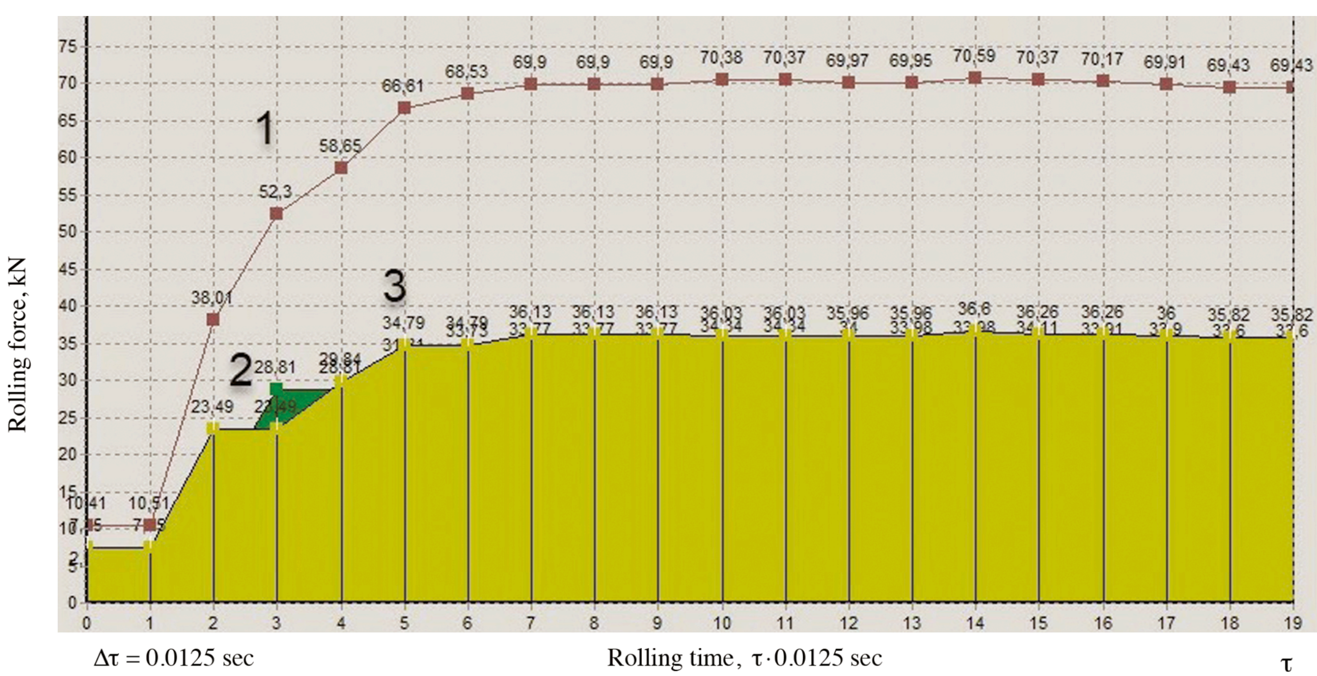

Fig. 3. Distribution of rolling forces along the length of a brass strip for a reduction of 30% (Specimen 3) measured on the 150 × 235 mill: *1* — total force; *2* and *3* — rolling forces under the left and right pressing screws, respectively.

It seems likely that the variations of the rolling forces in the nonstationary sections of the strips are caused by the changes in the stressed state in the process of deformation. Both at the entry into the mill and at the exit of strips from the rolls, the plane stressed state of the metal is predominant. In this state, one of the principal stresses acting along the rolling axis and opposing plastic deformation is almost absent. The metal is deformed in three directions: its thickness decreases, its width increases, and the strip becomes longer. Moreover, the processes of widening and elongation of the end sections of the strip are more intense than in the case of rolling of the middle part. Thus, in the case of rolling of brass strips with a degree of reduction $\varepsilon \approx 10\%$, the values of widening Δb_1 and Δb_3 of the end parts constitute 0.2 and 0.4 mm, respectively. At the same time, in the middle part of the strip, we have $\Delta b_2 = 0.1$ mm, which is much smaller. In this case, the rolling force in the process of deformation of the middle part of the strip (Specimen 1) is as high as 30–34 kN. At the same time, in the middle of the end sections, we get $P_0 = 17$–22 kN, which is 1.5–2 times lower.

In the case of rolling performed with a reduction of about 30% (Specimen 3), the value of widening in the middle of the strip $\Delta b_2 = 0.4$ mm. At the same time, in the end sections, it is equal to 0.7–1.0 mm, i.e., higher, on the average, by 100%. In this case, the rolling forces under the conditions of deformation in the middle section of the strip constitute 71–73 kN. In the middle of the end sections, they are equal to 37–38 kN, i.e., twice lower (see Fig. 3).

The variations of the conditions of deformation of the end sections of the strips depend on the stressed state of the metal in the course of its transformation from the plane state into the 3D state and result both in the inhomogeneous reduction along the strip length and in the formation of longitudinal variations of thickness and width of the rolled metal. Depending on the degree of deformation, the longitudinal variations of thickness were equal to 0.01–0.04 mm per ≈ 250 mm of strip length, which is significant in the case of rolling of relatively short strips of this kind. The measured rolling forces at the beginning of the end sections and in the middle part of the strips exhibit more than a 2–3-fold difference, which should be taken into account in regulating the thickness of the end sections of the strips and bands according to the signals of the gauges of rolling forces. In addition, the design and initial adjustment of the sheet mill to the rolling of precise strips suppose the availability of an adequate mathematical model of the pressure of metal upon the rolls and, hence, of the rolling forces. The application of the experimental data for the high-precision evaluation of the distribution of rolling forces along the length of the strips performed with high periodicity requires the analysis and improvement of the model both of the pressure of metal upon the rolls and of the corresponding rolling forces.

Results of Analytic Investigations and Discussion

The rolling forces P acting in different sections of deformed strips depend on the mean pressure P_{av} of the metal upon the rolls and on the contact area F_c. In applied calculations, the rolling force acting in a section of the strip is found by using the following well-known equation:

$$P = P_m F_c. \tag{1}$$

The area F_c of contact of the metal with the roll is determined by the length and width b_m of the zone of deformation and depends on the absolute reduction Δh, the radius of the rolls R, and the widths of the strip at the entry, b_0, and at the exit, b_1, of the zone of deformation:

$$F_c = \sqrt{\Delta h R}\, b_m = l_b b_m, \tag{2}$$

where l_b is the length of the arc of biting obtained without taking into account the elastic compression of the rolls, mm; R is the radius of working rolls, mm; $b_m = \dfrac{(b_0 + b_1)}{2}$ is the mean width of a strip in the zone of deformation, mm, and b_0 and b_1 are, respectively, the widths of the strip at the entry and at the exit from the rolls, mm.

The analysis of the works [6–10, 18–20] makes it possible to determine the main factors affecting the pressure of the metal upon the rolls in the process of rolling, namely, the deformation resistance of the metal σ_s (actual yield limit), the stress intensity factor n_{m}, the coefficient of influence of the out-of-contact zones on the zone of deformation n_σ, and the coefficient of influence of tension n_{t}, which is equal to 1 in the case of rolling of sheets and strips without tension. The mean pressure of the metal upon the rolls with regard for the influence of the above-mentioned factors is given by the formula

$$P_{\mathrm{m}} = 1.15\sigma_{s\mathrm{m}} n_{\mathrm{m}} n_\sigma n_{\mathrm{t}}, \tag{3}$$

where $\sigma_{s\mathrm{m}}$ is the mean value of the deformation resistance of the metal at the entry σ_{s0} and at the exit from the rolls σ_{s1}.

The results obtained in [6–8], as well as the results of our experiments demonstrate that the pressure of the metal upon the rolls and, hence, the rolling forces are also affected by the outer parts of the strip (sheet). Moreover, the coefficient of influence of the outer parts of the strip n_b on the zone of deformation increases with the level of stiffness and the thickness of rolled strip. This should be taken into account in finding the mean pressure. Therefore, in order to improve the method used for the evaluation of the mean pressure of the metal upon the rolls, it is recommended to take into account the coefficient n_b of influence of the outer parts of the strip on the zone of deformation. Thus, the level of pressure exerted in the course of rolling with tension should be found by using the relation

$$P_{\mathrm{m}} = 1.15\sigma_{s\mathrm{m}} n_{\mathrm{m}} (n_\sigma n_b)^{0.5} n_{\mathrm{t}}. \tag{4}$$

In the case of rolling of strips (sheets) without tension (the coefficient $n_{\mathrm{t}} = 1$), the mean pressure is given by the formula

$$P_{\mathrm{m}} = 1.15\sigma_{s\mathrm{m}} n_{\mathrm{m}} (n_\sigma n_b)^{0.5}. \tag{5}$$

On the basis of the analysis of experimental data, the coefficient of influence of the level of stiffness and the outer parts of the strip in the steady period of rolling n_b can be found, in the first approximation, by using the equation

$$n_b = \frac{\sigma_{s1}}{\sigma_{s\mathrm{m}}} \frac{h_1}{h_{\mathrm{m}}}. \tag{6}$$

In the course of rolling of the end sections of the strip during the nonstationary process, the coefficient n_b varies from 1 to the value given by Eq. (6) and is equal to $(0.7–0.8)n_b$ in the middle part of this section.

The influence of the out-of-contact zones on the stressed state of the strip in the case of short zone of deformation with $l_{\mathrm{b}}/h_{\mathrm{m}} \le 1.0$ is well studied. Moreover, the relations for the evaluation of the coefficient n_σ were obtained in the case of rolling of thick strips. In [7, 21], it was shown that, as the ratio $l_{\mathrm{b}}/h_{\mathrm{m}}$ increases from 0.1 to 1.0, the coefficient n_σ decreases from 3 down to 1 and then smoothly increases for $l_{\mathrm{b}}/h_{\mathrm{m}} > 1$.

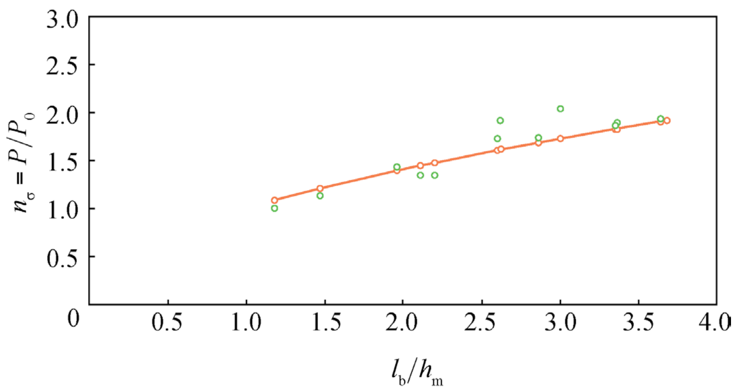

Fig. 4. Dependence of the stress intensity factor n_σ on the parameter of shape of the zone of deformation l_b/h_m in the case of rolling of thin strips.

In [7], on the basis of these results, it was shown that the influence of external friction on the growth of the coefficient $n_\sigma = P/1.15\sigma_s$ is significant for $l_b/h_m > 1$ and that the effect of the outer (out-of-contact) zones on the zone of deformation in the case of thin-sheet rolling is weak.

On the basis of the results of pilot rollings of thin strips made of copper, brass, and bronze with variable degrees of reduction and measuring of the rolling forces along the length of the strips with steps of ≈ 3 mm, we plotted the dependence of the coefficient $n_\sigma = P/P_0$ of influence of the out-of-contact zones on the stressed state of deformed metal on the shape (l_b/h_m) of the long zone of deformation (Fig. 4).

The curve (see Fig. 4) plotted with a sufficiently high accuracy for the coefficient of determinacy equal to 0.89 can be approximated by the following relation:

$$n_0 = P/P_0 \approx P/1.15\sigma_s = (l_b/h_m)^{0.5} \tag{7}$$

for $1 \le l_b/h_m \le 4$.

In [7], as a result of averaging and integration of two branches of the distribution of contact pressure along the length of the zone of deformation, Tselikov deduced the formula for the evaluation of the mean pressure as a function of the mean stress intensity factor n_m without taking into account the influence of the out-of-contact zones and the outer parts of the strip on the zone of deformation:

$$P_m = 1.15\sigma_{sm} n_m. \tag{8}$$

The mean stress intensity factor n_m depends on the contact friction forces, shape, and sizes of the zone of deformation and is given by the formula [7]

$$n_m = \frac{2(1-\varepsilon)h_\gamma}{\varepsilon(\delta-1)h_1}\left(\left(\frac{h_\gamma}{h_1}\right)^\delta - 1\right), \tag{9}$$

where ε and Δh are the relative and absolute reductions of the strip, respectively; $\delta = \dfrac{2\mu l_b}{\Delta h}$; μ is the coefficient of contact friction; h_1 is the thickness of the strip at the exit from the rolls, mm; $h_\gamma = \sqrt{h_0 h_1}$ is the thickness of sheet in the neutral cross section of the zone of deformation in the first approximation, mm.

On the basis of the results of experimental investigations of the process of rolling of L63-brass strips with a reduction of 10%, we now perform the quantitative analysis of the accuracy of the available relations and adequacy of the proposed formulas for the evaluation of pressures and forces in the course of rolling of various sections along the length of the strip.

The pilot rolling of annealed strips (Specimen 1; middle section) with a thickness $h_0 = 2.02$ mm, width $b_0 = 20.0$ mm, and length $l_0 = 200.5$ mm was carried out with a reduction of 10.39% in the 150230 two-roll mill with dry working rolls with a radius $R_b = 70.8$ mm. At the exit of the mill, the mean thickness $h1$ = 1.82 mm, width $b_1 = 20.1$ mm, and length $l_1 = 223$ mm. Under these conditions of deformation, the length of the zone of deformation was equal to $l_b = 3.76$ mm and $l_b/h_m = 1.96$ mm. In the process of rolling, we measured the rolling force P_f along the length of the strip with an accuracy of ± 0.01 kN and a periodicity $\Delta\tau$ = 0.0125 sec corresponding to a segment of the strip of length $\Delta l = 3.113$ mm (see Fig. 2).

We now compute the mean pressures at the entry P_{m1} and at the exit P_{m3} in the case where the beginning and end of the brass strip are, in fact, located in the zone of deformation. Further, by using relation (1), we determine the rolling forces in the front, P_1, and rear, P_3, parts of the strip:

$$P_{m1} = 1.15\sigma_{sm} = 1.15\frac{150+275}{2} = 244.375 \text{ N/mm}^2.$$

Thus,

$$P_1 = P_m l_b b_m = 244.75 \cdot 3.76\left(\frac{20+20.1}{2}\right) = 18.42 \text{ kN}.$$

As compared with the measured quantity, the error is equal to 16.3%:

$$P_{m3} = 1.15\sigma'_s = 1.15 \cdot 275 = 316.25 \text{ N/mm}^2.$$

Then

$$P_3 = P_{m3} l_b b_1 = 316.25 \cdot 3.76 \cdot 20.5 = 24.38 \text{ kN}.$$

By comparing the computed value $P_3 = 24.38$ kN with the measured rolling force in the rear part of the strip $P_{f.r} = 17.0$ kN, we get the error equal to 43%. Note that the computed value of the rolling force in the front part of the strip is lower than the measured value. At the same time, in the rear part of the strip, the corresponding value turns out to be higher than the measured value. This requires additional investigations.

For the sake of comparison, we now compute the mean pressure P_m according to relation (8) in which the level of pressure depends on the deformation resistance of the metal σ_{sm} and the mean stress intensity factor n_m.

First, we find the coefficient n_m by using relation (9) with $\varepsilon = 0.099 \approx 0.1$ and computing:

$$\delta = \frac{2\mu l_b}{\Delta h} = \frac{2 \cdot 0.1 \cdot 3.76}{0.2} = 3.76, \quad h_\gamma = \sqrt{h_0 h_1} = \sqrt{2.02 \cdot 1.82} = 1.91 \text{ mm},$$

$$n_{\mathrm{m}} = \frac{2(1-\varepsilon)\,h_{\gamma}}{\varepsilon(\delta-1)\,h_1}\left(\left(\frac{h_{\gamma}}{h_1}\right)^{\delta}-1\right) = \frac{2\cdot(1-0.1)\cdot 1.91}{0.1\cdot(3.76-1)\cdot 1.82}\left(\left(\frac{1.91}{1.2}\right)^{3.76}-1\right) = 1.3.$$

In view of relation (8), we find

$$P_{\mathrm{m}} = 1.15\sigma_{sm}n_{\mathrm{m}} = 1.15\cdot\frac{150+275}{2}\cdot 1.3 = 317.69\ \mathrm{N/mm^2(MPa)}.$$

By using P_{m} and the conditions of deformation of the brass strip ($\varepsilon = 10\%$), we determine the rolling force according to relation (8):

$$P_{P1} = P_{\mathrm{m}1}l_{\mathrm{b}}b_{\mathrm{m}} = 317.69\cdot 3.76\cdot 20.05 = 23.95\ \mathrm{kN}.$$

The indicated force given by relation (8), i.e., $P_{P1} = 23.95$ kN, corresponds to measured value of force almost in the middle part of the nonsteady section of the rolled strip and is much (by 30%) lower than the rolling force $P_{\mathrm{f}} = 34$ kN measured in the section of steady deformation (see Fig. 2).

For the steady period of rolling, we now compute the mean pressure by using relation (5) that takes into account the influence of the out-of-contact zones of the strip on the zone of deformation. First, we compute the coefficients n_{σ} and n_{b}.

We find the coefficient n_{σ} from relation (7):

$$n_{\sigma} = \left(\frac{l_{\mathrm{b}}}{h_{\mathrm{m}}}\right)^{0.5} = \left(\frac{3.76}{1.92}\right)^{0.5} = 1.40\cdot$$

Further, we determine the coefficient n_{b} by using relation (6):

$$n_b = \frac{\sigma_{s1}}{\sigma_{\mathrm{m}}}\cdot\frac{h_1}{h_{\mathrm{m}}} = \frac{275}{212.5}\cdot\frac{1.82}{1.92} = 1.22.$$

From relation (5), we get:

$$P_{\mathrm{m}} = 1.15\sigma_{sm}n_{\mathrm{m}}(n_{\sigma}n_b)^{0.5} = 1.15\cdot 212.5\cdot 1.3\cdot(1.40\cdot 1.22)^{0.5} = 416.17\ \mathrm{N/mm^2}.$$

By using P_{m}, we find the value of the rolling force:

$$P_{P2} = P_{\mathrm{m}2}l_{\mathrm{b}}b_{\mathrm{m}} = 416.17\cdot 3.76\cdot 20.05 = 31.37\ \mathrm{kN}.$$

The rolling force $P_{P2} = 31.37$ kN computed according to relation (5) taking into account the influence of the main factors affecting the pressure of the metal upon the rolls corresponds to the measured value of force $P_{\mathrm{f}} = 34$ kN with an error of 7.7%.

The analysis of the influence of the out-of-contact zones and the outer parts of the strip on the zone of deformation enables us to improve the applied model and the relation used to compute the level of pressure of the metal upon the rolls in the course of rolling of sheets. The application of the proposed relations (7) and (6) for the determination of the coefficient n_σ taking into account the influence of the out-of-contact zones and the coefficient n_b reflecting the influence of stiffness of the outer parts of the strip on the zone of deformation makes it possible to increase the accuracy of evaluation of forces in the case of thin-sheet rolling. The use of the improved dependences for the determination of force indicators enables us to get reliable estimates and determine the design-basis characteristics of the rolling equipment, as well as to increase the accuracy of initial adjustment of the mill and the operation of the system of automatic thickness control with regard for the characteristics of the outer parts of the strip.

CONCLUSIONS

1. We experimentally established a strongly nonuniform distribution of rolling forces over the length of brass strips. Under the conditions of deformation of the end sections of the strips, the rolling forces are 2–3 times lower than in the steady period of rolling.

2. We establish the quantitative regularities of the influence of out-of-contact zones and the outer parts of the strip on the pressure and rolling forces in the case of thin strips. It is shown that the out-of-contact zones and the outer parts of the strip increase the pressure and the rolling forces in the nonstationary and stationary parts of the deformed metal.

3. We improve the relations used for the evaluation of the mean pressure in the course of rolling of thin strips and taking into account the influence of the out-of-contact zones and the stiffness of the outer parts of the strip. This guarantees an increase in the accuracy of evaluation of the rolling forces along the length of the rolled metal.

4. In the adjustment of the mill for the purposes of rolling of high-precision (along the entire length) strips and bands, it is necessary to take into account the established regularities of changes in the deformation and force indicators of rolling of the end sections of the strips. The results of our investigations can be used for the design and adjustment of the systems of automatic thickness control within the periods of rolling of the end sections of bands and strips.

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