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Additional effect on the deformation zone during plastic metal flow

Valeriy Chigirinsky[a] and Irina Volokitina[b*]

[a]Candidate of Technical Sciences, Department of Metallurgy and Mining Engineering, Rudny Industrial Institute, 50 let Oktyabrya str. 38, 111500 Rudny, Kazakhstan
[b]PhD., Department of Metallurgy and materials science, Karaganda Industrial University, 30 Republic Ave., 101400 Temirtau, Kazakhstan

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In the article, on the basis of previously conducted theoretical and experimental studies, a phys-ical model of the process of additional impact on the basis of non-uniform plastic deformation is developed and investigated. On the basis of the physical model, a mathematical model of the additional impact is developed, the generalizing factor of which in the case of asymmetric de-formation is the external moment from the side lines.

1. Introduction

At the present stage of science and technology development the directions that allow controlling fundamental processes in nature and technology are considered promising. In continuum mechanics where the theory of plasticity is in many respects the determining direction, it is especially important because such processes provide an opportunity to optimize the modes of shaping. Preliminary analysis shows that control schemes are possible due to additional effect on the deformation zone, with simultaneous realization of the main force parameters of the process (Mutiev, 1955).

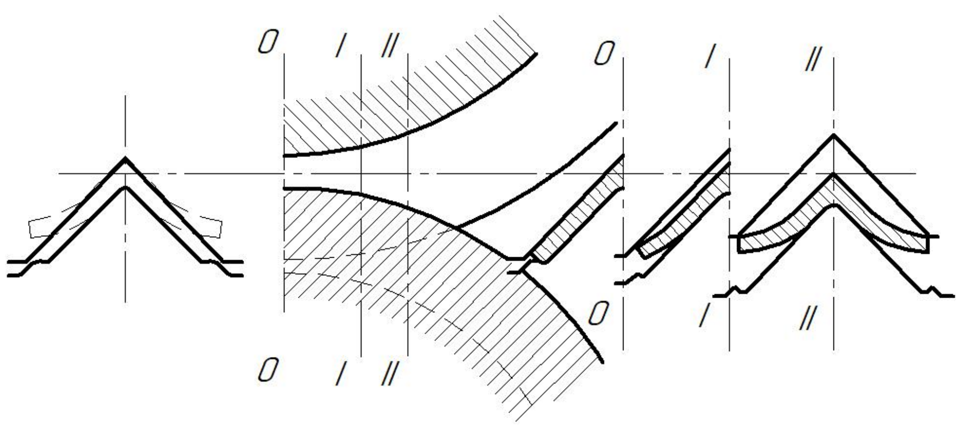

Fig. 1. Sequence of inlet, bending and reduction of strip in the finishing gauge during angle steel rolling

* Corresponding author.
E-mail addresses: irinka.vav@mail.ru (I. Volokitina)

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Various physical manifestations can meet such criteria, including processes related to non-uniformity of plastic processing. The resulting longitudinal interaction in the reduction zone causes additional stresses (Gubkin, 1960) which can change the stressed and strained state of the metal in the desired direction under certain conditions. The combination of different effects in the deformation zone can be interpolated as one main and the other auxiliary or supplementary ones. Fig.1 shows the straightening of the angle flanges in the finishing gauge with simultaneous thickness reduction of the flanges (Naizabekov et al., 2004; Bakhtinov et al., 1983). It is of interest to evaluate the unbending loading versus the main loading determined by the flanges straining. In paper (Levanov et al., 1976), at reduction of a cylindrical billet at simultaneous rotation of the upper striker an intensive shear deformation in the transverse direction is realized. This reduces the specific pressures on the tool. Fig. 2 shows additional rotational effect on the contact specific pressures.

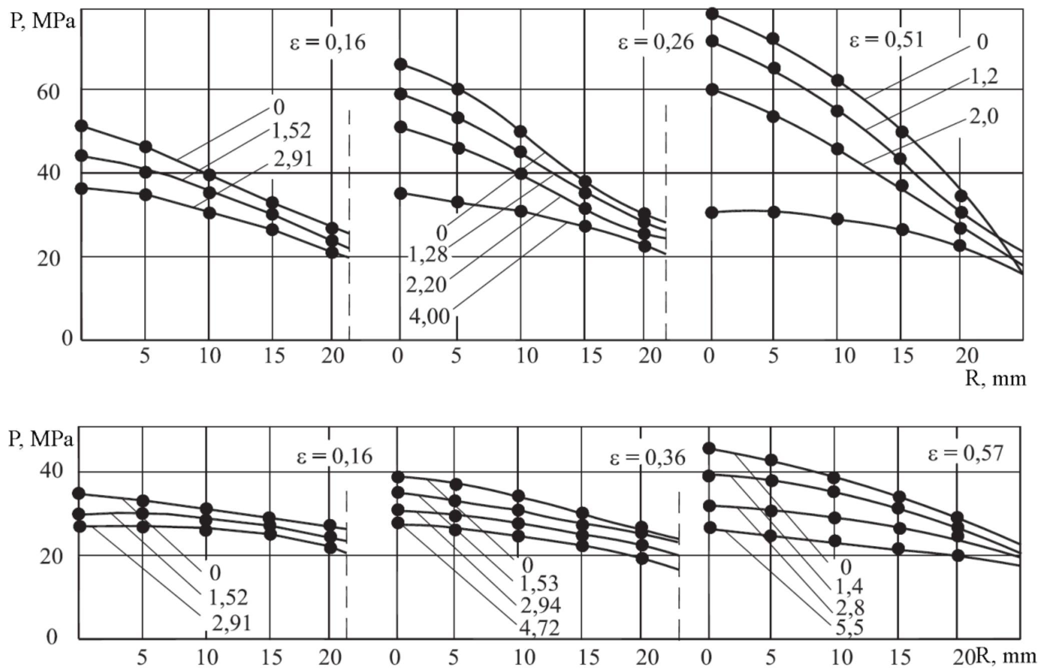


Fig. 2. Contact stress diagrams for torsional upsetting

Rotational action on the deformation zone is defined here as an additional control loading.
Experimental studies presented in paper (Chekmarev et al., 1962) show that the additional loading is determined not only by the controlling active action of contact friction forces (Levanov et al., 1976), but also by such a factor as non-uniformity of plastic straining. The rolling process of a symmetrical stepped sample, Fig. 3, with different strain rates across its width was studied. The figure shows contact stress measurement points along the length of the deformation zone. A physical model scheme is proposed. Different reduction on the tool side is represented as an additional effect on the main rolling process. The last mode is characterized as straining determined by plastic shape change of the entire workpiece. The stress state of different sections of the strip was represented by experimental stress state ratios depending on the additional stresses caused by non-uniform reduction in the cross-section of the rolled strip.

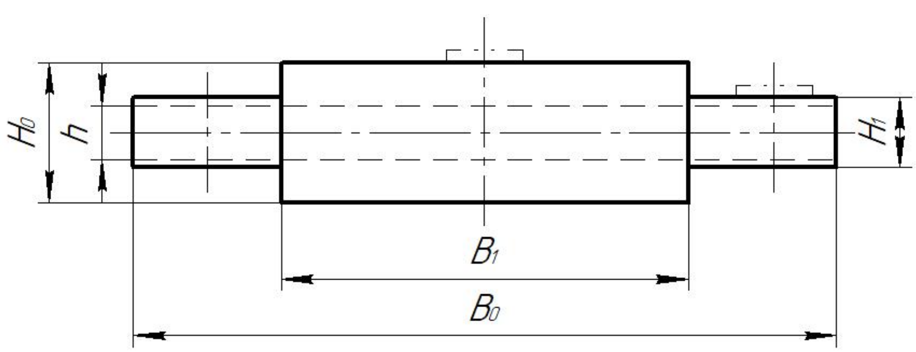


Fig. 3. Symmetrical stepped sample with plotted contact stress measurement points

The expressions for the average specific pressures for the sections with different reductions were calculated after processing the experimental data and determining the average specific pressures for the elements:

$$p_1 = n_1 \cdot p\,, \quad p_2 = n_2 \cdot p, \tag{1}$$

where p_1, p_2 − average specific pressures in elements with greater and lower reduction; p − average specific pressure at rolling of the whole stepped sample of equal cross-sectional area; n_1, n_2 − stress state ratios of elements taking into account the effect of additional backing and tensile stresses in the elements with different reduction. Such a physical model of the process is promising because it provides an opportunity to estimate the additional effect as a controlling factor of plastic shape change.

Different reduction across the width of the workpiece shapes the geometry of the finished product, which causes strain non-uniformity. This changes not only the stress state but also the flow of metal in different directions. Fig. 4 shows the template of the cross-section of the rolled product after reduction in the roughing pass with "witnesses". Such rolling scheme is further used to produce thin-walled profiles of reduced metal intensity for truck wheel rims (Chigirinsky et al., 2023). Local plastic strains unrelated to the drawing capabilities of roughing gauges significantly change the metal flow streams in the transverse direction (Chigirinsky, Volokitina, 2023). Metal moves from areas of higher reduction to areas of lower reduction. This is clearly seen in Fig. 5, where circles show the centers of the "witnesses" before and after rolling. The lower part of Fig. 5 shows a plot of the distribution of reduction ratios across the strip width. This characterizes the strain as highly non-uniform.

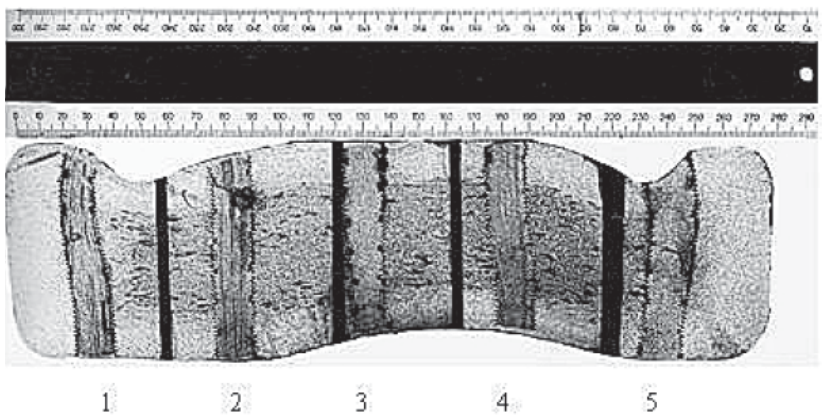


Fig. 4. Location of "witnesses" after the 1st pass

Displacements of witness centers show the flows of plastic flow of the medium in the transverse direction. Local (additional) strains associated with non-uniform reduction are those controlling influences, which form plastic flows of metal on the basis of the drawing ability of the gauge.

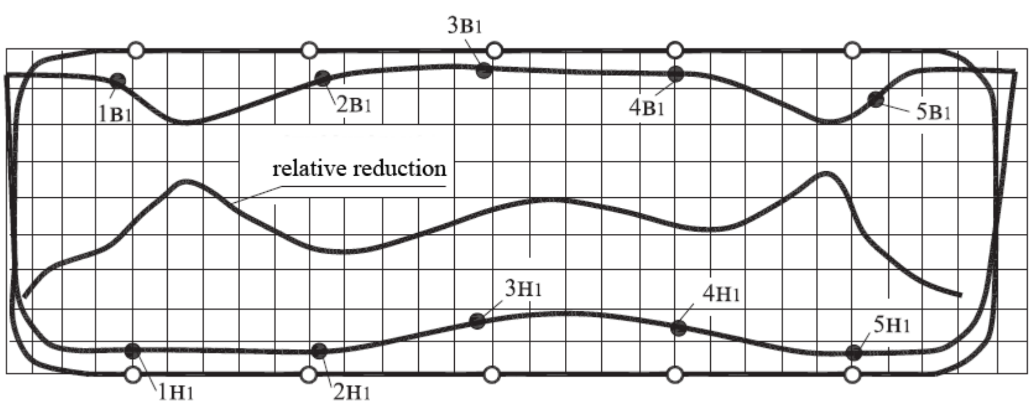


Fig. 5. Transverse movement of the screws after the 1st pass

The external backing and strip tension, as an additional external influence on the deformation zone, in the inter-stand gap of continuous mill significantly affects the con-tact stresses in the deformation zone. This is widely used in the adjustment of the rolling process of continuous mills.

Chigirinsky et al. (2014) present experimental studies of the process of asymmetric rolling of stepped samples, Fig. 6.

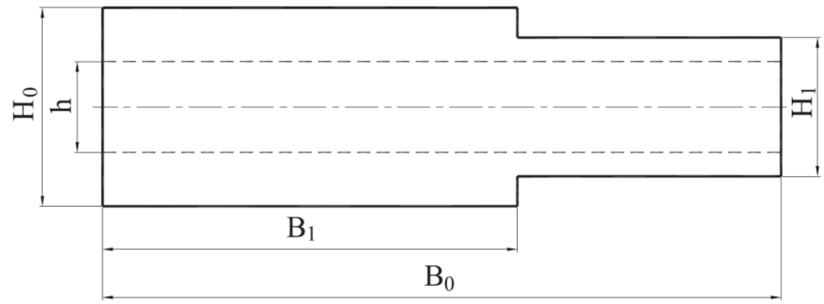


Fig. 6. Unsymmetrical stepped sample

Such deformation modes are characteristic for rolling of sections of complex asymmetrical shape. Their peculiarity is that the rolled strip tends to sickle in the horizontal plane at the inlet and outlet of the deformation zone. Lateral guides are used to ensure straight strip movement in the rolls. In this case, the physical model of the process becomes more complicated and the impact of non-uniform strain on the rolling parameters is realized when there is a simultaneous impact of external lateral forces on the deformation zone from the side of the guides. This raises some features of the process that require more detailed analysis. Strain asymmetry leads to bending of the strip at the inlet and outlet of the deformation zone due to different draws across the width of the rolled product. Interaction between different sections of the strip in the longitudinal direction does not occur fully. When the guides affect the outer zones, the strip starts to move straight, the extensions across the width are aligned, there are longitudinal interactions in the deformation zone, and additional stresses appear. A certain correspondence is established between the lateral forces on the guide side and the non-uniform strain parameters, which is necessary to know. In this case, the lateral forces can act as generalized characteristics of the additional effect on the deformation zone, according to the non-uniformity that takes place in the deformation zone. This correspondence was shown in the presented work.

The monograph (Chigirinsky et al., 2014) also shows the control effect of non-uniformity of plastic deformation across the width of the strip on the force parameters of the process and its practical use. Figure 7 shows samples with different configurations of the central highly reduced part of the finished profile.

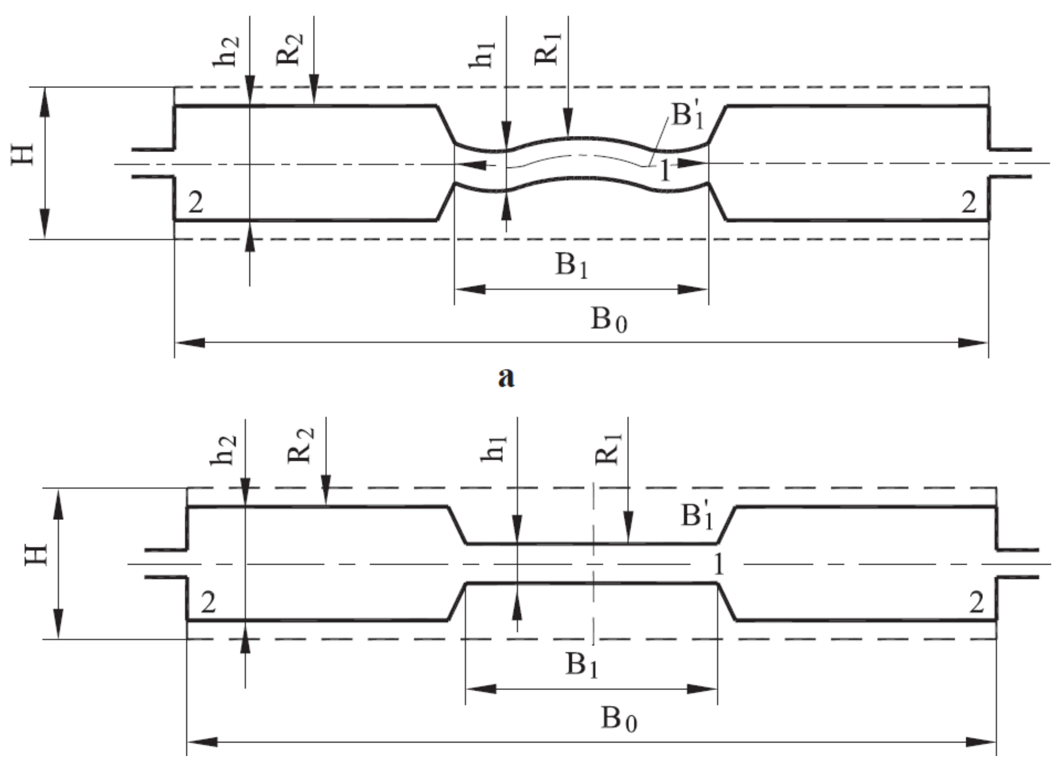


Fig. 7. Thickness profiles with wavy center part (a) and flat center part (b)

In one case, the central part is made with a rectilinear cross-sectional surface, in the other case it is made with a wave surface. Such width straining modes are used for rolling sections with a thin-walled center section. Changing the shape of the profile makes it possible to influence by non-uniform reduction the process of forming a thin-walled section of the profile with reduced metal consumption. There is an additional effect factor on the deformation zone in both deformation schemes shown in the figure, but it is different. In case with the wavy surface of the center part, the longitudinal interaction of differently reduced elements is smaller due to the formation of a larger width of the strongly reduced element. According to the volume constancy law, as the transverse strain increases, the drawing capacity at this section decreases, the strain irregularity decreases, and the longitudinal interaction in the deformation zone decreases, the longitudinal backing decreases, or the sign of the longitudinal additional stress changes. There is a change in the physical process associated with non-uniformity of strain due to the geometry of the central highly reduced part of the profile. Figure 8 shows the alignment of the finishing and pre-finishing gauge templates in the last pass when rolling a truck wheel rim profile. In this case, a technology of rolling a particularly thin-walled profile in the central part is realized by means of a control action characterized by a corrected shape (wave-shaped) of a strongly reduced section (Chigirinsky et al., 2014).

Fig. 8. Finishing and pre-finishing templates when rolling a rim with center wavy part

It should be noted that the paper (Chigirinsky et al., 2014) summarizes theoretical and experimental studies, provides evidence of the high-efficient rolled sections implementation.
Plastic strain non-uniformity is present in all metal forming processes, which negatively affects the manufacturing processes of products. This influence is obvious. For example, the flow of metal in the longitudinal direction in the deformation zone across the width of rolled product at the moment of capture and at steady-state process is different. At the beginning of rolling the widening is not restricted by anything; it is maximum. This is explained by the stress state where there are no tensile additional stresses along the lateral edges of the strip. During the steady process, additional tensile stresses appear at the edges of the strip due to the aligning action of the drawings across the rolled product width. These tensile stresses are able to ensure its tightening before entering the deformation zone. The widening is reduced, but a "broken" front and back end of the strip remains that has to be removed, thereby increasing metal consumption.

When rolling high strips, plastic deformation does not penetrate the entire height of the rolled product. Uneven tendency of separate layers of metal in the drawing along the height of the workpiece occurs. This causes longitudinal interaction, which results in additional compressive stresses in the near-contact layers and tensile stresses in the central layers. There is transverse tightening of the central layers and forced widening of the contact layers. The cross-section of the rolled product has a double convex shape. It can be seen from the above that physical processes associated with inhomogeneity and non-uniformity of straining during rolling have an impact on the deformation zone, cause the effects of plastic shape change, change the stress-strain state of the metal, have a regulating effect on the flow parameters of the medium. There is a need for theoretical and experimental justification of these phenomena, qualitative and quantitative assessment of additional influences, and identification of features and effects of plastic shape change.

The purpose of this study is theoretical and experimental justification of the effects of additional effect on the deformation zone under non-uniform reduction conditions.

2. Development of a physical model of additional effect on the deformation zone as a controlling factor of the plastic deformation process

If the impact occurs against the main loading, then additional effects are literally on the surface of the phenomenon. There is convincing simple experimental confirmation of this thesis. Indeed, during rolling, the outgoing end of the strip can be freely strained by a slight force from the hand, but this becomes impossible when the rolling process is stopped for a jammed strip in the rolls. In this case, it is necessary to overcome the resistance of the entire deformation zone and the outer end of the strip. In engineering, such impact is realized not by hand, but by longitudinal and transverse external forces, non-uniformity of plastic deformation, combined impact of the tool on the processed metal. Thus, the additional effect on the deformation zone should occur at loads less than the main deformation shaping. This statement should be determinant in the development of a physical and mathematical model of this phenomenon. This statement needs to be substantiated and proven to ensure the validity of the result.

We present the following physical model of non-uniform strain and the possibility of its effect on the processes of plastic processing of metals. At non-uniform strain, as a result of different reduction in width and height of the profile, there is a different tendency of metal in these zones to move in length (Chigirinsky et al., 1999; Gubkin, 1947). Since the metal is an integral substance, longitudinal interactions occur between its individual elements in the deformation zone (Chekmarev et al., 1967). Without destroying the plastic medium, the interaction causes partial averaging of the longitudinal strain. This keeps the possibility to deform in zone and to move in a certain way along the rolling process. The kinematics of metal flow in the reduction zone is changed during the front outer zone formation. The drawing is finally averaged and becomes uniform for the whole deformation zone, despite the fact that the reductions along the section of the profile are different (Chekmarev et al., 1967). Longitudinal additional backing and tensile stresses appear. These stresses change the physical process and, under certain conditions, can have an additional effect on the deformation zone.

A theoretical solution to this problem is considered. More general case of non-uniform impact on the deformation zone is analyzed both from deformation non-uniform reduction and from external forces. This can be done by considering the equilibrium of the outer zone when rolling a sample with asymmetric non-uniform loading. The outer zone equilibrium will be ensured if the strip at the outlet or inlet will move straight (without sickling or twisting) and without acceleration, which is characteristic of the steady-state part of the rolling process. Let us use the method of sections at the inlet to the deformation zone, (Brovman et al., 1991) and replace the action of the rejected defloration zone by longitudinal forces caused by non-uniform reduction along the strip width. It is assumed that the rectilinear motion of the strip is provided by the lateral guides. Let's replace the guide act at the inlet by the transverse force P or torque M_{iny}, Fig. 9.

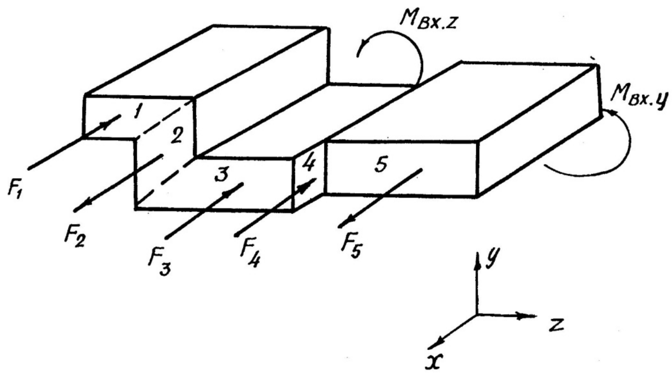


Fig. 9. Outer zone equilibrium of a complex profile

Equations of equilibrium have the form:

$$\sum F_{ix} = 0 \quad \sum M_y = 0, \tag{2}$$

The first equation of equilibrium defines the sum of projections of forces on the x-axis caused by non-uniform reduction at the inlet to the deformation zone. The second equation of equilibrium defines the sum of torques of the same forces with respect to the vertical axis y. Further analysis shows that the first equation of equilibrium allows to determine theoretically the coefficient of average drawing, the second one allows to justify additional effects on the deformation zone.
From the second equation of equilibrium (2) it can be written:

$$\sum M_y = \sum(\sigma_{0I} F_{0i} y_{0i})_i + M_{iny} = 0, \tag{3}$$

where σ_{0I} – additional stress caused by non-uniform plastic deformation; F_{0i} – i-th element area; y_{0i} – position of i-th element's center of gravity where the force is applied; M_{in} – external torque acting on the strip from the lateral force side at the inlet to the deformation zone. By knowing the additional stresses σ_{0I} from Eq. (3) we can determine the torque acting from the guide side M_{in}. Additional stresses as a result of interaction of differently reduced elements under non-uniform strain conditions are determined either theoretically (Chigirinsky et al., 2014) or experimentally (Chekmarev et al., 1962). According to paper (Chigirinsky et al., 2014):

$$\sigma_0 = 2\frac{\sigma_i}{\varepsilon_i} \cdot \frac{a_i}{1+a_i} \cdot ln\frac{\mu_{av}}{\mu_i} \qquad \sigma_1 = 2\frac{\sigma_i}{\varepsilon_i} \cdot \frac{1}{1+a_i} \cdot ln\frac{\mu_{av}}{\mu_i} \tag{4}$$

where σ_0 , σ_1 – additional stresses at the inlet and outlet of deformation zone for the $i-th$ element; σ_i – normal stress rate; ε_i – strain rate; a_i – coefficient determining the ratio between additional stresses at the inlet and outlet of the deformation zone; $ln\frac{\mu_{av}}{\mu_i}$ – longitudinal interaction strain between adjacent strip sections with different reductions; μ_{av} – average drawing in the deformation zone when rolling a profile with different width strains; μ_i – partial draw of the $i-th$ strip element.

Additional stresses based on experimental data of the work (Chekmarev et al., 1962):

$$\sigma_0 = \beta\sigma_u(k_1 - 1) \qquad \sigma_1 = \beta\sigma_u(1 - k_2) \tag{5}$$

where $k_1 = n_1 -$ metal experimental stress state ratio of the strongly reduced element (1), (backpressure); $k_2 = n_2 -$ metal experimental stress state ratio of the weakly reduced element (1), (tensile). Substituting expressions (4), (5) into the equilibrium Eq. (2) for the torques, we obtain the following expressions for the deformation zone inlet and outlet:

$$M_{in} = \sum 2\frac{\sigma_i}{\varepsilon_i}\cdot\frac{a_i}{1+a_i}\cdot ln\frac{\mu_{av}}{\mu_i}F_{0i}y_{0i} \qquad M_{out} = \sum 2\frac{\sigma_i}{\varepsilon_i}\cdot\frac{1}{1+a_i}\cdot ln\frac{\mu_{av}}{\mu_i}F_{1i}y_{1i}, \tag{6}$$

From expressions (6) we can see what factors determine the torques of additional stresses in non-uniform reduction conditions. One of the main ones is the longitudinal interaction of zones with different width reduction $ln\frac{\mu_{av}}{\mu_i}$, then the areas of elements, positions of additional forces, Fig. 9. Expressions (6) are difficult to use in calculations because there is non-linearity of relations σ_i/ε_i in the structure of additional stresses (4), (5) and in expressions for torques (6). Obviously the torque (6) needs to be experimentally worked out as functions of:

$$M_{in} = f\left(\sum 2\frac{\sigma_i}{\varepsilon_i}\cdot\frac{a_i}{1+a_i}\cdot ln\frac{\mu_{av}}{\mu_i}F_{0i}y_{0i}\right) \tag{7}$$

$$M_{out} = f\left(\sum 2\frac{\sigma_i}{\varepsilon_i}\cdot\frac{1}{1+a_i}\cdot ln\frac{\mu_{av}}{\mu_i}F_{1i}y_{1i}\right), \tag{8}$$

It is of interest to use experimental data of paper (Chekmarev et al., 1962), expressions (5) to determine the torques of forces from the outer zone side:

inlet side

$$M_{in} = \beta\sigma_u\cdot\frac{F_0}{2H}\cdot\frac{(k_1-1)\cdot(1-k_2)}{k_1-k_2} \tag{9}$$

outlet side

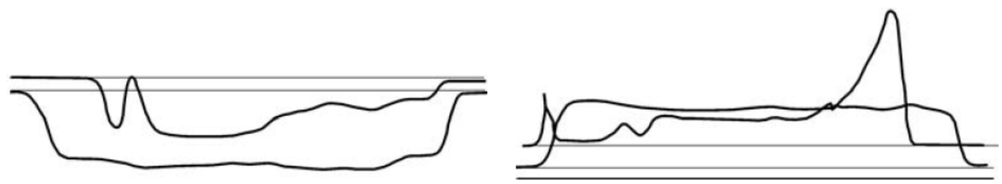
$$M_{out} = \beta\sigma_u\cdot\frac{F_1}{2h}\cdot\frac{(k_1-1)\cdot(1-k_2)}{k_1-k_2}, \tag{10}$$

Using expressions (7),(8) and (9),(10) and comparing the results of calculations strengthens the validity or otherwise of the physical and mathematical model used in solving the given problem. The calculations using the above formulas refer to different experiments, different authors and different approaches to study the non-uniformity of deformation (Chekmarev et al., 1962; Chigirinsky et al., 2014). It's a pretty fundamental issue in process studies. We shall focus on a more detailed analysis for the reliability of the result and its justification.

In paper (Chekmarev et al., 1962), a symmetrical sample was rolled, Fig. 3, no pressure measurements on the lateral guides were made. Straightness of the sample motion was ensured by the geometry of the initial workpiece, with symmetrical reduction along the rolled product width. Nevertheless, there were longitudinal interactions in the zone, additional stresses in the inlet and outlet planes of the deformation zone, the backing (reduction) and tensile forces acting on the outer zones of the strip were identified. There is no strip bend, but there is an interaction factor. Considering the interaction factor, known values of additional stresses (5), formulas for forces torques from these additional stresses (10), it became necessary to calculate the torques from the lateral guides that determine the possibility of strip curvature and the impact from the lateral guides. Physical and mathematical model of non-uniform strain through additional stresses was one for the works (Chekmarev et al., 1962; Chigirinsky et al., 2014).

It should be noted that work became necessary to substantiate the validity of the result (Chigirinsky et al., 2014). In this study, a similar sample was rolled with the difference that the shape of the sample was asymmetric, Figure 6. In the process of asymmetric deformation, the rolled product was curved at the inlet and outlet of the deformation zone. Special guides were used to ensure straightness of its motion, which were supported by collars on the load cells. Rolling forces in the deformation zone were measured at the same time. Typical oscillograms are shown in Fig. 10, from the inlet and outlet sides of the metal from the deformation zone. Oscillogram (b) shows the change in the value of lateral force P during strip rolling at the outlet of the deformation zone. There is a sharp increase in pressure on the guide while the front end of the strip is coming out of the rolls. Alignment of the curved short end of the strip occurs with high peak loads. At this point, the pressure on the guide at the inlet to the deformation zone follows an increasing pattern, and then a steady-state process occurs.

The comparison of the data shows that equalizing forces at the inlet to the deformation zone are larger than at the outlet from the deformation zone during the steady-state process.



a b

Fig. 10. Force oscillograms from the strip side to the lateral guides from the inlet side (a) and outlet side (b)

Thus, it was possible to link different papers (Chekmarev et al., 1962; Chigirinsky et al., 2014) through the strain non-uniformity to a common influence factor, which characterizes the additional impact on the deformation zone. Such a generalized factor, taking into account physical and mathematical modeling, is the external transverse forces or torques from lateral guides side. Two experiments data and calculated data are shown in the comparative Table 1.

Table 1. Calculated and experimental torque values

No. of samples in series	K_1	K_2	Data (9),(10) Nm		Data (7),(8) Nm		Inlet failure %	Outlet failure %
			Inlet	Outlet	Inlet	Outlet		
1	1,13	0,25	51,8	43,2	53,6	39,5	3,4	8,6
2	1.26	0,19	81,0	65,3	91,5	70,6	11,8	7,5
3	1,39	0,45	99,8	80,5	96,1	70,2	3,7	14,9
4	1,40	0,60	89,2	77,5	93,6	69,8	4,7	9,9
1	1,17	0	68,4	50,0	75,6	54,1	9,5	7,6
2	1,33	0,28	103,0	77,2	110,7	79,2	7,0	2,5
3	1,65	0	167,6	126,0	162,0	112,3	3,3	10,9
4	1,71	0,25	153,4	124,7	153,0	111,0	0,3	11,0
1	1,15	0,31	44,4	36,1	48,5	36,0	8,5	0,3
2	1,27	0,40	71,8	59,3	83,2	56,2	13,7	5,2
3	1,48	0,34	104,8	88,8	105,0	81,0	0,2	8,8
4	1,64	0,35	122,4	103,7	132,6	99,4	7,7	4,1
1	1,15	0	41,4	29,5	40,5	30,5	2.2	3,3
2	1,33	0,17	71,4	53,7	75,8	54,7	2,2	1,8
3	1,56	0,20	112,0	84.8	115,5	83,5	3,0	1,5
4	1,62	0,36	111,0	85,3	109,0	80,6	1,8	5,5
1	1,20	0	53,0	32,5	55,5	37,0	4,5	11,4
2	1,45	0	102,4	67,0	104,0	72,8	1,5	8,0
3	1,60	0	108,2	75,1	109,8	74,9	1,5	2,9
1	1,16	0	42,5	27,2	42,3	30,5	0,5	10,8
2	1,36	0,21	73,4	48,1	71,6	54,5	2,4	11,0
3	1,42	0,39	79,6	51.3	73,6	57,6	7.5	10,9
4	1,63	0,36	98,9	72,7	94,4	77,8	4,6	6,5
1	1,15	0,18	54,1	41,2	59,4	42,9	8,9	4,1
2	1.24	0,48	66,1	53,7	72,5	53,8	8,8	0,2
3	1,33	0,53	87,1	69,1	9,08	69,1	4,1	0
4	1,58	0,44	117,7	98,0	125,3	99,9	6,1	1,9

Comparison of the results of two experiments presented in Table 1 shows that they are practically the same within the failure limits. Thus, the validity of the physical model of additional effect on the deformation zone is confirmed. In this case, generalized factor of such influence is of interest. It consists of the torques acting from the guide side, characterizing the force longitudinal interaction in the deformation zone, and related to the non-uniformity of deformation in the zone of plastic metal forming.

Further on, the influence of strain non-uniformity can also reveal itself as a controlling influence. However, this increases the complexity of the physical process and the physical and mathematical reasoning behind it. In this regard, impact factors should be explored in more detail to strengthen the validity of the result and the feasibility of practical application (Chigirinsky et al., 1996).

3. Experimental evaluation of additional effect on the deformation zone

The evaluation of additional effect on the deformation zone is necessary in order to verify whether this loading is effective and capable to control the stress-strain state of the plastic medium. The efficiency of this effect will occur if it is shown that its implementation under force loading will be less than the main deformation effect. This is one of the main indicators of the controlling effect on the deformation zone.

In order to evaluate its effect, it shall be compared with the main one realizing plastic deformation. The mathematical model (7)...(10) of additional effect shows that its generalized characteristic is the forces or torques from lateral guides at realization of asymmetric strain along the strip width. In paper (Tselikov, 1962), it was assumed that the alignment of bending strip by guides occurs under plastic bending torque, i.e.:

$$M_{pl} = \beta\sigma_{и} \cdot W_{pl}, \tag{11}$$

where $\beta -$ stress state characteristic at the point; $\sigma_i -$ plastic yield stress; $W_{pl} -$ plastic resistance torque. If the stresses included in the torque are assumed to be equal to the plastic yield stresses, therefore, these stresses are maximum, and the loading from these torques is the main one. Further analysis and evaluation should be performed relative to this basic loading (11).

To confirm this fact, stepped asymmetrical samples were rolled on mill 150, Fig. 6, with different ratio of B_1/B_0 and H_1/H_0. Specially designed roller guides were used to measure the strip pressure on the guides, Fig. 11. Eight batches of lead samples were rolled with different workpiece dimensions B_1/B_0 and H_1/H_0, which were in the range of 0.5...0.93 and 0.65...0.91, respectively. Guide design consisted of a body 1, the lower part of which had three holes with a diameter of 30 mm, also there were covers 2 with the same holes. A roller 3 with rolling bearings 4 was inserted in the gap. The roller was protruding from the guide rail with its forming part. The guides were capable of rotating around a vertical axis, which was attached by nuts to the input and output tables. The second support was girder-type load cells. Table 2 summarizes the experimental data of force and torque measurements from lateral guides under non-uniform asymmetric reduction conditions.

Parameters H_1/H_0 and B_1/B_0 characterize to some extent the non-uniformity of plastic deformation across the width of the profile. Ratio H_1/H_0 quantifies the non-uniformity of deformation between two adjacent elements. Ratio B_1/B_0 represents the weighting of each element for non-uniform strain. Experimental data of lateral guide measurements are summarized in Table 2.

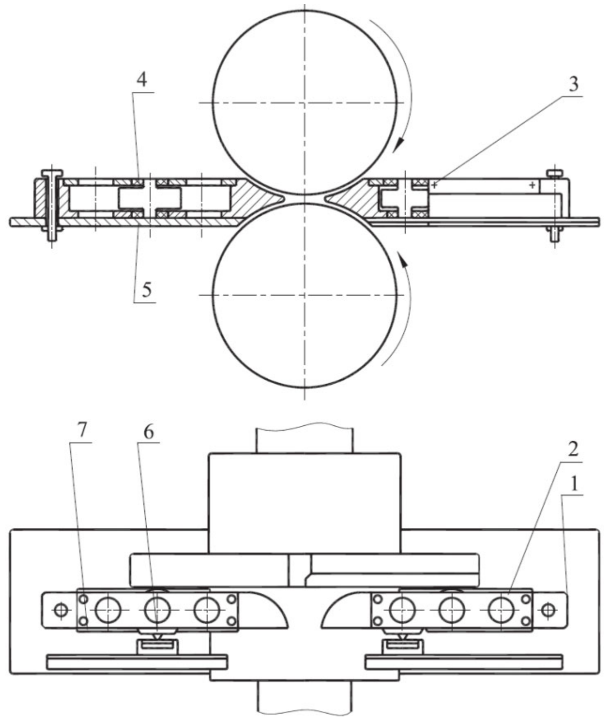


Fig. 11. Installation diagram for measuring the rolled product pressure on the lateral guides

Indeed, the greater the non-uniformity, Fig. 6, hence the smaller the ratio H_1/H_0 the greater the force on the guides. At values of $B_1/B_0 = 0.62$ and values of ratios $H_1/H_0 = 0.87$; 0.83;0.75;0.72 the torques on the inlet side increase respectively $M_{in} = 1115; 1210; 1805{,}0; 1952{,}0\ N$. on the outlet side from the deformation zone respectively $M_{out} = 487.0; 563.0; 786.0;\ 780.0\ N$. The closer the ratio B_1/B_0 is to unity, the straighter the strip comes out of the rolls, the less its tendency to warp, the less the force from guides side. At values of ratios H_1/H_0 =0.65…0.67 close to each other, and values of ratios $B_1/B_0 = 093; 0.77; 0.63$, force torques from the metal inlet side of rolls are equal to $M_{in} = 680.0; 1255.0; 1290.0$ N from the outlet side of the deformation zone respectively $M_{out} = 257.0; 505.0; 520.0\ N$.

The data analysis of Table 2 shows that the force torques on the guide side respond unambiguously to the change in strain non-uniformity. This allows us to state that the proposed physical model of additional effect on the deformation zone under non-uniform reduction across the strip width justifies itself on the one hand. And on the other hand the force torque on the guide side is generalized characteristics of asymmetric strain non-uniformity in the process of plastic processing of metal. Parameters B_1/B_0 and H_1/H_0 are able to estimate the non-uniformity process to a certain extent when the number of elements is minimum. However, they do not give a complete picture of loading asymmetry for profiles of complex design, Figure 8, 9, when their number is greater than two and with other qualitative indices.

Table 2. Experimental values of forces and torques from lateral guide sides

№/№	B_1/B_0	H_1/H_0	Force values P_{in} and P_{out} N		Torque values M_{in} and M_{out} Nm		Force ratios P_{in}/P_{out}	Torque ratios M_{in}/M_{out}
			Inlet	Outlet	Inlet	Outlet		
1	0,91	0,87	628,0	275,0	53,6	39,5	2,3	1.4
2	0,78	0,83	1080,0	490,0	91,5	70,6	2,2	1,3
3	0,62	0,87	1115,0	487,0	96,1	70,2	2,3	1,4
4	0,52	0,91	1051,0	485,0	93,6	69,8	2,2	1,3
1	0,93	0,73	932.0	376,0	75,6	54,1	2,5	1,4
2	0,77	0,76	1340,0	550,0	110,7	79,2	2,5	1,4
3	0,62	0,72	1952,0	780,0	162,0	112,3	2,5	1,4
4	0,52	0,77	1783,0	770,0	153,0	111,0	2,3	1,4
1	0,92	0,88	564,0	250,0	48,5	36,0	2,3	1.3
2	0,77	0,88	955,0	390,0	83,2	56,2	2,5	1,5
3	0,62	0,83	1210,0	563,0	105,0	81,0	2,2	1,3
4	0,52	0,80	1500,0	689,0	132,6	99,4	2,2	1,3
1	0,92	0,76	772,0	319,0	62,4	46,5	2,4	1.4
2	0,77	0,75	1225,	478,0	100,2	69,0	2,6	1,5
3	0,62	0.75	1805,0	786,0	151.2	113,2	2,3	1,3
4	0,52	0,74	1860,0	838,0	157,5	120,9	2,2	1,3
1	0,93	0,82	480,0	212,0	40,5	30,5	2.3	1,3
2	0.78	0,83	888,0	380,0	75,8	54.7	2,3	1,4
3	0,63	0,79	1325,0	580,0	115,5	83,5	2,3	1,4
4	0,52	0,82	1250,0	559,0	109,0	80,6	2,2	1,5
1	0,93	0,66	680,0	257,0	55,5	37,0	2,6	1.5
2	0,77	0,65	1255,0	505,0	104,0	72.8	2,5	1,4
3	0,63	0,67	1290,0	520,0	109,8	74,9	2,5	1,4
1	0,91	0,80	502,0	212,0	42.3	30,5	2.4	1,4
2	0,75	0,83	840,0	378,0	71,6	54.5	2.2	1,3
3	0,62	0.87	870,0	403,0	73,6	57,6	2,2	1,3
4	0,53	0,82	1062,0	541,0	94,4	77,8	2,0	1.2
1	0,90	0,86	709,0	298,0	59,4	42,9	2,4	1,4
2	0,76	0,91	839,0	374,0	72,5	53,8	2,3	1,3
3	0,69	0.90	1068,0	479,0	90,8	69,1	2.2	1,3
4	0,50	0,84	1411,0	694,0	125,3	99,9	2,0	1,3

Fragments of such indices can be static moments of a given section, further factors taking into account longitudinal interaction in the deformation zone $ln\,\mu_{av}/\mu_i$, and so on. For more complete characterization of non-uniform strain parameters it is necessary to use mathematical model (7) and (8) reduced to dimensionless index, obtained on the basis of equations of equilibrium of external parts of the strip (2). Expressions in brackets, defining the torques from guide side, are shown by the parameters δ, from inlet and outlet sides:

Inlet

$$\delta_{in} = \frac{\sum 2 \cdot \frac{a_i}{1+a_i} \cdot ln\frac{\mu_{av}}{\mu_i} F_{0i} y_{0i}}{W_{pl,in}} \tag{12}$$

Outlet

$$\delta_{out} = \frac{\sum 2 \cdot \frac{1}{1+a_i} \cdot ln \frac{\mu_{cp}}{\mu_i} F_{1i} y_{1i}}{W_{pl,out}} \tag{13}$$

where W_{pl} $-$ plastic resistance torque at the inlet and outlet of the deformation zone.

In addition to dimensionless indices (12) and (13), it is recommended to use a dimensionless index for the torques on the guide side M_{exp}/M_{pl}. For this purpose, plastic bending moments were calculated for the sections used in the experiment within the limits, at the inlet -152.0...234.2 Nm, at the outlet - 97.9...197.5 Nm. Comparing the plastic torques with the data in Table 2, it can be seen that they are greater than the values obtained experimentally. The use of relative data for torques and parameters δ позволяет makes it possible to eliminate the influence of yield strength and absolute dimensions of the strip when building the mathematical model under asymmetric impact conditions.

Thus, at this stage of analysis, when comparing the results of measurement and calculation of torques, it can be seen that the additional effect is less than the main loading through strain non-uniformity. Torque ratio M_{exp}/M_{pl} is less than unity and varies within 0.2...0.8.

Taking into account expressions (12) and (13) according to the data of Table 2, the dependences of ratios M_{exp}/M_{pl} on parameters δ at the inlet and outlet of the deformation zone were plotted, Figure 12. The peculiarity of this structure is that the additional effect M_{exp}/M_{pl} is regulated by the parameter δ. It follows that all technological and design factors that change the parameter δ will affect the stress-strain state of the metal in the deformation zone. Such a structure leads to the conclusion that there is a possible effect of controlling influence on the plastic shaping of the strip.

Mathematical processing of experimental results by least squares method for the step function allowed to obtain expressions of the form:

inlet

$$M_{in} = 1{,}938 \cdot M_{pl,in} \cdot \left[\frac{\sum 2 \cdot \frac{a_i}{1+a_i} \cdot ln \frac{\mu_{cp}}{\mu_i} F_{0i} y_{0i}}{W_{pl,in}}\right]^{0\ 443} \tag{14}$$

outlet

$$M_{out} = 1{,}827 \cdot M_{pl,out} \cdot \left[\frac{\sum 2 \cdot \frac{1}{1+a_i} \cdot ln \frac{\mu_{cp}}{\mu_i} F_{1i} y_{1i}}{W_{pl,out}}\right]^{0\ 485}, \tag{15}$$

Correlation ratio of studied parameters is 0.946 and 0.937 for both the inlet and outlet, respectively. Expressions (14) and (15) allow calculating values of torques at asymmetric rolling of different profiles of any sizes and with any number of elements. It is necessary to pay attention to the difference of values of the main and additional loading, which can be explained by different physical processes occurring at plastic deformation. In plastic bending, the stresses of the latter reach maximum values equal to the yield strength, which characterizes the main loading. When rolling with non-uniform reduction, longitudinal interaction forces appear in the deformation zone, determined by additional stresses. The value of additional stresses, as it can be seen from the conducted studies, is less than the yield strength. It is characterized not by plastic loading, but by different stretches in the deformation zone, obeying the regularities of mathematical models (14),(15).

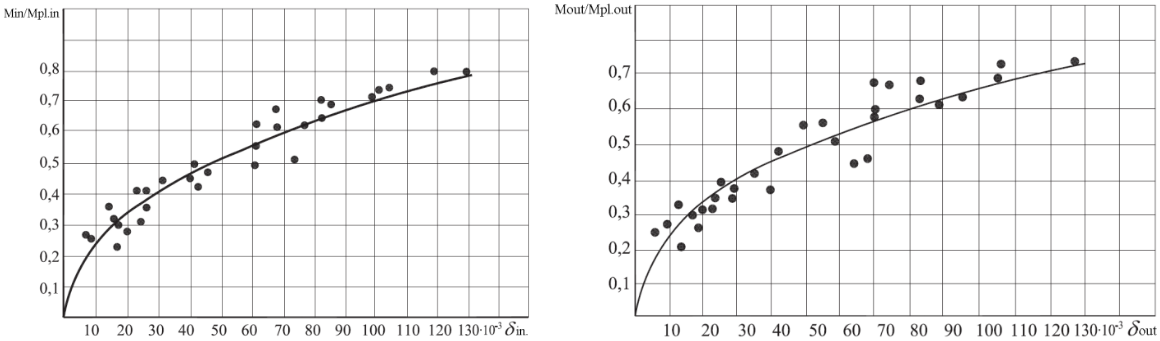


Fig. 12. Dependences of torque ratios M_{exp}/M_{pl} at the inlet and outlet of deformation zone on the parameters δ

In expressions (14), (15) there are some parameters that need to be known because they influence the additional effect and can change the nature of this effect. These include the ratio a_i and the average elongation at the deformation zone μ_{av}. The ratio of additional stresses at the inlet and outlet of the deformation zone can be determined using the experimental torque data, Table 2. An expression for calculating the factor is proposed a_i:

$$a_i = 1\ 300 - 0{,}146\left(\frac{l_d}{h_{av}}\right) - 0\ 152\left(\frac{l_d}{h_{av}}\right)^2 + 0\ 064\left(\frac{l_d}{h_{av}}\right)^3 - 0\ 006\left(\frac{l_d}{h_{av}}\right)^4 \qquad (16)$$

In some cases, in order to simplify (16) a_i can be taken equal to one. Using the equilibrium of external zones under external forces (2), from the inlet and outlet sides of the deformation zone, after transformations and simplifications we have the formula for determining the average stretching:

$$ln\mu_{av} = \sum_{i=1}^{i=n}\left[\frac{F_{0i}}{F_0} + \left(\frac{F_{1I}}{F_1} - \frac{F_{0i}}{F_0}\right)\frac{h_{0I} + h_{1I}}{h_{0I} + 3h_{1I}}\right] ln\mu_i, \qquad (17)$$

where F_{0i} and F_{1I} − areas of individual profile elements in the cross section at the inlet and outlet of the deformation zone; F_0 and F_1 cross-sectional areas of the profile at the inlet and outlet of the deformation zone; h_{0I}, h_{1I} − given heights of elements at the inlet and outlet of the deformation zone; μ_i − partial drawing of i −th element. Expression (17) takes into account the effect of non-uniform strain not only along the width of the profile, but also along the length of the deformation zone. Ratio of the areasF_{0i}/F_0 and F_{1I}/F_1 determines the effects of the partial drawing o i −th element on the value of the average drawing. The larger the ratio, the more significant this effect is. It should be added that the ratio F_{0i}/F_0 characterizes the effect of partial drawing which actually exists on the inlet side, the ratio F_{1I}/F_1 is the effect that is planned, and the average drawing itself characterizes what is obtained.

Table 3. Experimental values of relative rolling forces as a function of transverse strain ratio

Thickness N, mm	Ratio F_1/F_0	Transverse strain rate B_1'/B_1			
		1.00			1.00
		Force ratio P_1/P_0			
	0,42	1,00	0,94	0,92	0,90
2,0	0,50	1,00	0,95	0,94	0,90
	0,80	1,00	0,96	0,94	0,89
	0,42	1,00	0,94	0,93	0,89
3,0	0,50	1,00	0,94	0,93	0,90
	0,80	1,00	0,95	0,94	0,89
	0,42	1,00	0,96	0,94	0,91
4,0	0,50	1,00	0,97	0,96	0,90
	0,80	1,00	0,96	0,95	0,82
	0,42	1,00	0,96	0,95	0,92
5,0	0,50	1,00	0,97	0,97	0,91
	0,80	1,00	0,96	0,96	0,94
	0,42	1,00	0,97	0,95	0,92
6,0	0,50	1,00	0,98	0,97	0,92
	0,80	1,00	0,99	0,97	0,93
	0,42	1,00	0,96	0,94	0,92
7,0	0,50	1,00	0,98	0,97	0,92
	0,80	1,00	0,98	0,97	0,33

Additional influence effect as a controlling factor of the process realization was confirmed experimentally on the laboratory mill 210. The rolling force was measured from a rectangular initial workpiece with different geometry of the center part after the pass, Figure 7. Different parameters of the "wave" determined different widths of the center element and therefore different transverse strain causing different longitudinal interaction in the deformation zone, Table 3. The values P_0 and P_1 denote the metal pressure forces on the rolls which occur when rolling sections with different geometry of the central part (flat and wavy). The effect of factor F_1/F_0 is also shown, where in this experiment F_1 is the area of the strongly reduced element; F_0 is the area of the whole cross section of the profile. The experimental data analysis in Table 3 shows that for all the ratios of the outlet areas F_1/F_0 and thicknesses of initial workpiece the rolling force decreases with increasing transverse strain, in the wave-shaped central part zone where the maximum reduction is realized.

It follows that the effect of additional impact is shown for different implementation of non-uniform strain process across the width of the profile, Fig. 7 (flat central part and wavy). Rolling a sample with a wave-shaped central part reduces the longitudinal interaction in the deformation zone, the tendency of metal flow in the length in the central zone. The parameter $ln\mu_{av}/\mu_i$ is redistributed; the backing decreases, specific pressures decrease and the rolling force decreases. Physical process is corrected by the geometry of the center part of the strongly reduced element. Thus, non-uniform strain process becomes controllable and, importantly, efficient in terms of its implementation. An example of such an implementation could be the rolling of a thin-walled rim profile for truck wheels, Fig. 8. This circumstance emphasizes the fact that such a profile is problematic from the rolling point of view, since it is asymmetrical with respect to the horizontal and vertical axes (twisting, torsion).

There is a large variation in thickness across the width, hence large strain non-uniformity, especially in the thin-walled center section, including finishing passes. It has about 10 tolerances on the finished rolled product which limits the ability to adjust dimensions, especially of its lateral parts. As a result, the thin-walled central part of the profile is a constraining technological factor in the development of these profiles of reduced metal intensity. Indeed, the thin-walled part cools down quickly at the end of rolling, there is the non-uniform strain effect, and the maximum effect of contact friction is in this part of the strip. Adjustment of the process of non-uniform strain in finishing gauges made it possible to reduce the picking forces from the side of longitudinal additional stresses and even to change their sign. This allowed obtaining a profile of stable thickness of the product with reduced metal consumption in its central zone, Figure 7, (Chigirinsky et al., 1996).
The presented experimental investigations convincingly show the possibilities of additional effect on the deformation zone, besides it forms the controlling effects of this effect on the quality of rolled products and its implementation.

4. Conclusions

As a result of the conducted theoretical and experimental studies the following was established:

- examples of additional effects for metal forming processes, including rolling processes, are shown;
- physical model of the process of additional effect on the basis of non-uniform plastic shaping has been developed and investigated;
- mathematical model of the additional effect was developed on the basis of the physical model, the generalizing factor of which in the case of asymmetric strain was the external torque from lateral guides side;
- effect of additional effect on the deformation zone is shown and confirmed experimentally;
- possibilities of additional effect on the deformation zone, including its controlling factors, are shown.

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