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## **Mechanisms of plastic deformation in case of production of thin-walled rolled stock of the special purpose**

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**Abstract**

The effects of plastic deformation changing the metal stress-state parameters in separate sites of complex thin-walled profiles are experimentally shown. Additional influence on the metal can be implemented in the form of uneven deformation on strip cross section. The kinematic impact on the deformation zone is implemented by cross shifts of profile thin-walled part and metal yielding in the planned direction. Change of a metal stressed state changes the force of rolling, production possibilities of thin-walled rolled stock of a special purpose.

Key words: ADDITIONAL INFLUENCE, KINEMATIC INFLUENCE, DEFORMATION ZONE, ROLLING FORCE, SHEAR DEFORMATION.

Identification of the plastic deformation mechanisms of a thin-walled rolled stock allows to use them for influencing the products formation process, changes in the stress-strain state of the metal, obtaining the required quality and to have the technological ability to its production, which is very important.

According to works [1-5] the process of plastic deformation can be represented in the forms of basic and additional load. Additional - (control), as well as the basic, is implemented by external influence on the deformation zone. An example is the external tension or backing, bending, twisting or leveling action of rulers, guides on the strip during the rolling, etc.

The experimental data show that the additional load on the deformation zone is realized with the forces and moments significantly lower than basic [1, 2]. This feature of plastic deformation is differing from the load in an elastic zone.

Under combined action of different formative loads in the elastic area the total strain is represented as the sum of individual strains (superposition method), i.e., without the effect of the additional loading. While in the plastic region the additional tension creates favorable conditions for the combining of the technological operations during processing. For example, cobbing and bending, combination of longitudinal and transverse bending at cold straightening, etc.

The additional stresses and leveling action of external zones, which causes the stress-strain state

changing in the local areas of the deformation zone arises if the unevenness of plastic deformation is used as additional load.

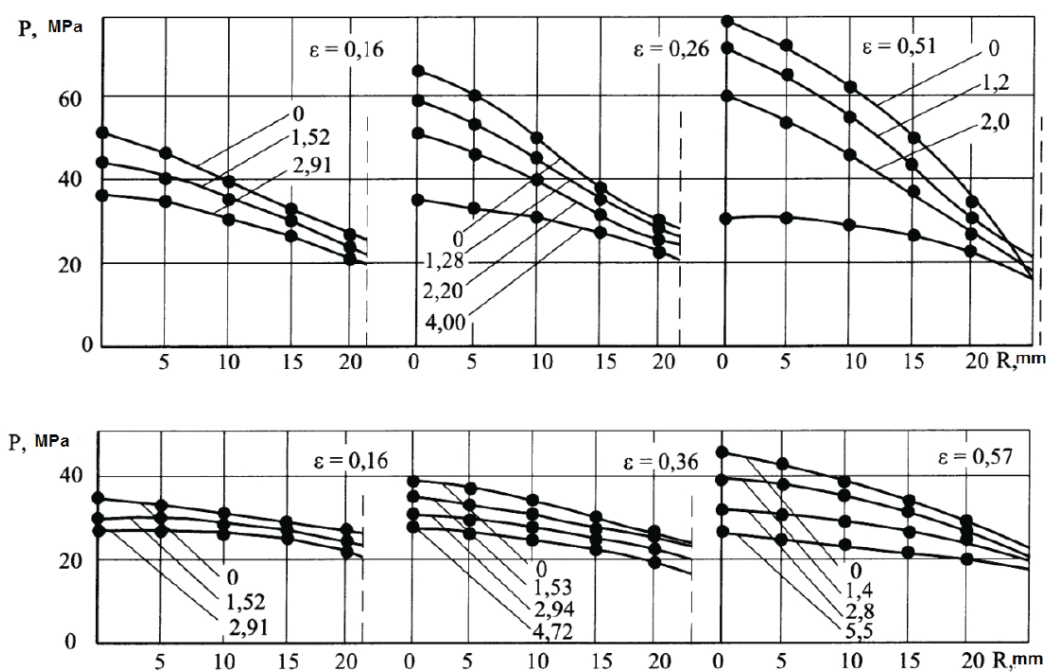
The appearance of such load local zones and material yielding can be used as a regulatory factor in the whole process of form changing.

On the basis of experimental and theoretical studies the effects and mechanisms of plastic deformation, which determine the stress - strain state of the metal in the process of thin-walled products rolling are shown.

In [4, 5] the additional influence on the deformation zone in the form of the upsetting sample twisting is shown. The results of contact stresses measurements are presented in Fig. 1. Reducing of contact stresses occurs with increasing of form factor  $D_0/H_0$ , deformation degree of  $\varepsilon$  and parameter of  $\eta_\Phi = \varphi_\Phi/\varepsilon$ , where  $\varphi_\Phi$  - the angle of striker rotation. The rotation increases the shear deformations in different directions. This increases the intensity of the strain  $\Lambda$ .

To evaluate the effect of additional influence at rolling [6] the experimental laboratory studies defining the forces and moments from the outer strip portions, which are acting on the deformation zone have been carried out.

This was achieved by asymmetric cobbing across the strip width (Fig.2), and the leveling action of the lateral ruler, in which the force measuring installation was mounted (Fig.3).



**Figure 1.** Diagrams of contact stresses at the sediment with torsion. At the top-  $D_0/H_0 = 4$  at the bottom  $D_0/H_0 = 2$ ; the figures in curves - are the values of  $\eta_\Phi$

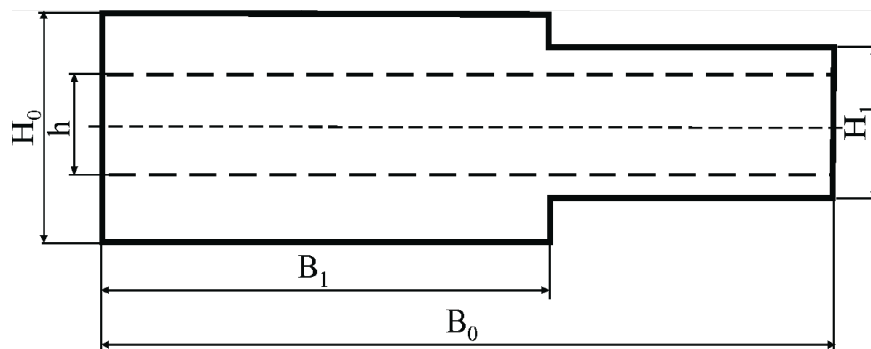


Figure 2. Asymmetric step sample

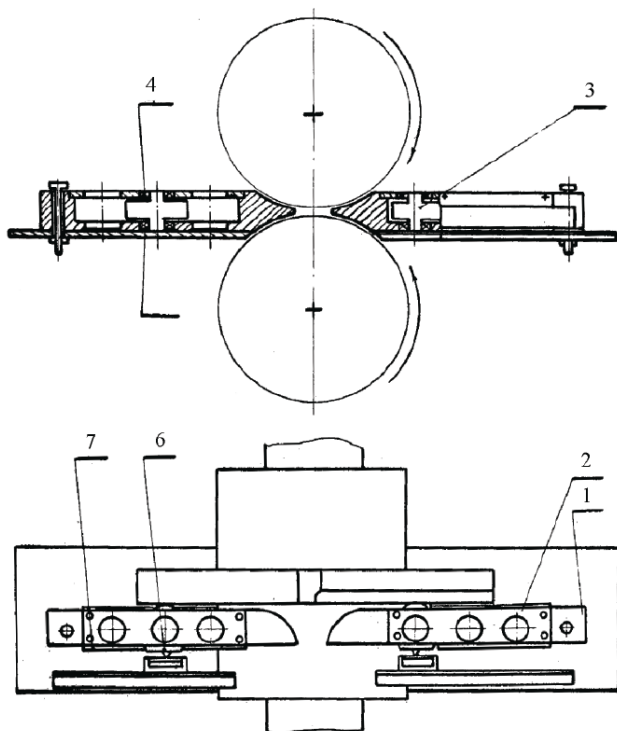


Figure 3. Scheme of setup for measuring of pressures on the ruler

A typical oscillogram of pressures on the strip lateral rulers from the side of the deformation zone input and output is presented in Figure 4. The experimental data on the forces measurement are shown in Table 1.

The forces acting on the rulers from the input side, are larger than the forces on the output side and are in range of 480,0 ... 1952,0 N and 212,0 ... 838,0 N, respectively. The force moments are in the range of 40,5... 162,0 Nm on the input side and 30,5... 120,9 Nm on the output side.

Comparing the moments of a plastic bend on the input, 152,0 ... 234,2 Nm, and on the output 97,9 ... 197,5 Nm with experimental values, we are convinced that the latter is much less in size. This confirms the thesis about effect of additional influence at which the forces or the moments of additional influence forming are less than forces or the moments of the basic. Continuing the analysis it is possible to be convinced that the relative size  $M_{exp}/M_{pl}$  changes

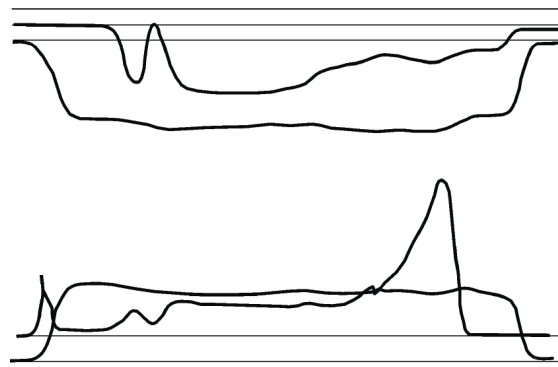


Figure 4. Oscillograms of pressures on lateral rulers

according to the parameter  $\delta$  (the relative moment of static deformation), which is connected with the deformation uneven across the width of the profile.

From the input and output sides they can be written as

in the input

$$\delta_{in} = \frac{\sum 2 \cdot S_{k0} \cdot z_k \cdot \frac{a_k}{1+a_k} \cdot \ln \frac{\mu_{med}}{\mu_k}}{W_{pl.in}}$$

in the output

$$\delta_{out} = \frac{\sum 2 \cdot S_{k1} \cdot z_k \cdot \frac{1}{1+a_k} \cdot \ln \frac{\mu_{med}}{\mu_k}}{W_{pl.out}}$$

where and  $S_{k0}$   $S_{k1}$  - are the cross-sectional areas of individual profile elements,  $\mu_{med}$  and  $\mu_k$  - are the coefficients of medium and particular drawings,  $z_k$  - are the coordinates of longitudinal forces application points in the planes of deformation zone input and output,  $a_k$  - is the coefficient determining the ratio of the additional stresses on the input and output of deformation zone,  $W$  - is the torque at the input and output of the deformation zone.

Following from the analysis the additional influence is connected with uneven deformation, as well the uneven deformation with secondary stresses,

which is determined by value  $h \frac{\mu_{med}}{\mu_k}$ .

**Table 1.** The forces and moments experimental values from the side of lateral rulers

№/№	$\frac{B_1}{B_0}$	$\frac{H_1}{H_0}$	The values of forces $P_{in}$ and $P_{out}$ , N		The values of forces moments $M_{in}$ and $M_{out}$ , N <sub>m</sub>		Relationships $\frac{P_{in}}{P_{out}}$	Relationships $\frac{M_{in}}{M_{out}}$
			Input	Output	Input	Output		
1	2	3	4	5	6	7	8	9
1	0,91	0,87	628,0	275,0	53,60	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	1225,0	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

For the confirmation of connection of additional influence with secondary stresses the experimental data of work were used [7]. By results of work the secondary stresses of a support and stretching through experimental coefficients  $k_1$  and  $k_2$ , support  $\sigma_n = \beta\sigma_u \cdot (k_1 - 1)$ , and stretching

$$\sigma_p = \beta\sigma_u \cdot (1 - k_2) \text{ were defined.}$$

From the equilibrium condition the moments values from side rulers are received

$$M_{in} = \beta\sigma_u \cdot \frac{S_0}{2 \cdot H} \cdot \frac{(k_1 - 1) \cdot (1 - k_2)}{k_1 - k_2},$$

$$M_{out} = \beta \sigma_u \cdot \frac{S_1}{2 \cdot h} \cdot \frac{(k_1 - 1) \cdot (1 - k_2)}{k_1 - k_2}$$

Definition of the moments from side rulers according to experimental data [6] by the expressions stated above shows that data deviation from the experimental don't exceed inherently of 5... 10%. Therefore, the tension nature of the main and additional influence – is different. If the bend represents the main loading, then the normal stresses of a bend have to reach the maximum value equal to yield point. If the strip in the course of rolling is leveled by rulers, then it is the additional influence, the moment of which is not defined by tensions equal to yield point anymore. For a strip or drawing curvature alignment, according to

the law of secondary stresses, there is an interaction of variously pressed out profile elements and external zones, which define the secondary stresses.

The relation of the moments  $M_{exp} / M_p$  is less than unity and fluctuates within 0.2 ... 0.8, which practically confirms the effect of additional influence. Thus the increase or reduction of this relation is in certain dependence on parameter  $\delta$ , which is the dimensionless quantity as well as the relation of the moments. Such compliance is confirmed by obtaining the experimental dependences presented in fig. 5,6.

Mathematical processing of experimental results by the least square method allowed the receiving the expressions: at the exit

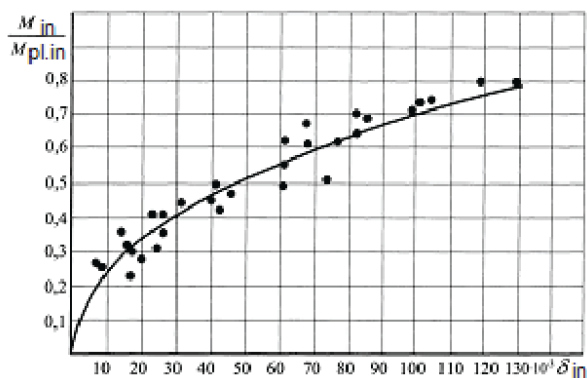
$$M_{out} = 1,827 \cdot M_{pl.out} \cdot \left[ \frac{\sum 2 \cdot S_{k1} \cdot z_k \cdot \frac{1}{1+a_k} \cdot \ln \frac{\mu_{med}}{\mu_k}}{W_{out}} \right]^{0,485} \quad (1)$$

in the input

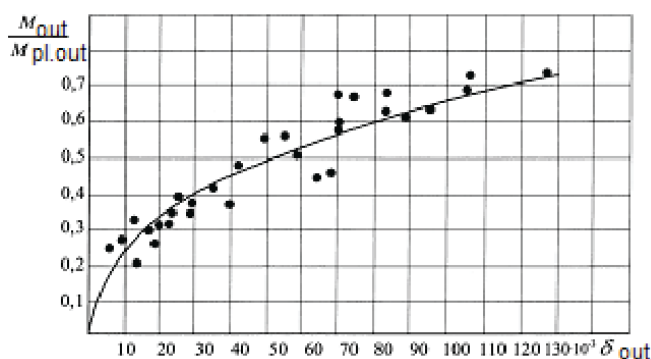
$$M_{in} = 1,938 \cdot M_{pl.in} \cdot \left[ \frac{\sum 2 \cdot S_{k0} \cdot z_k \cdot \frac{a_k}{1+a_k} \cdot \ln \frac{\mu_{med}}{\mu_k}}{W_{in}} \right]^{0,443} \quad (2)$$

where

$$a_k = 1,2995 - 0,1455 \cdot \left(\frac{l_d}{h_{med}}\right) - 0,1518 \cdot \left(\frac{l_d}{h_{med}}\right)^2 + 0,0643 \cdot \left(\frac{l_d}{h_{med}}\right)^3 - 0,0064 \cdot \left(\frac{l_d}{h_{med}}\right)^4$$



**Figure 5.** Dependence of the relation  $M_{in}/M_{pl.in}$  on parameter  $\delta_{in}$  in the input of the deformation zone



**Figure 6.** Dependence of the relation  $M_{out}/M_{pl.out}$  on parameter  $\delta_{out}$  in the output of the deformation zone

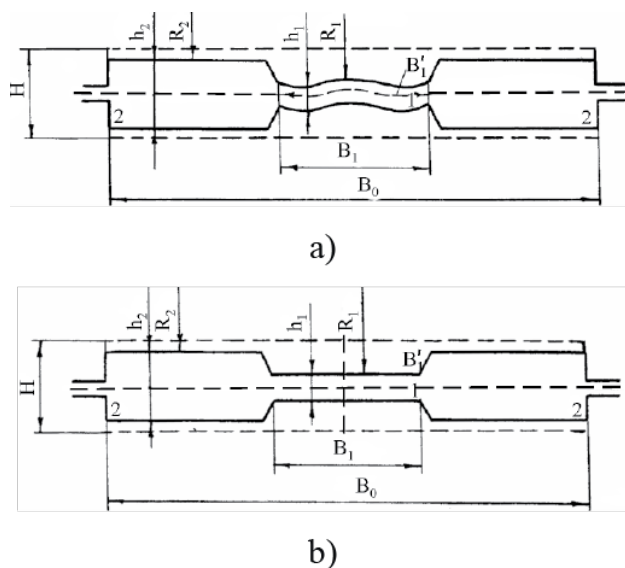
Expressions (3.1) and (3.2) allow not only to calculate the values of the moments from rulers during the difficult profiles rolling, but also to show visually the effect itself of additional influence within which the given regularity was designated above.

If the effect of additional influence takes place,

then is it possible to use it as the controlling mechanism allowing the regulation of a metal stressed state? It is possible by changing the longitudinal interaction of variously pressed out strip sites in the deformation zone. The longitudinal interaction is defined by ability of metal yielding in adjacent

elements of a profile. The longitudinal strain can be changed by changing the transverse deformation in each element. In thin-walled part of a profile the influence on transverse yielding in the last passes is problematic. The temperature is low, hence the plasticity, great coefficient of support, considerable longitudinal secondary stresses of compression take place. The kinematics of a metal yielding in thin-walled part of a profile has to be the "sparing", possessing the ability of combination of cobbing and transverse deformation in uniform process. The transverse plastic shear corresponds to such conditions. For confirmation of this situation in conditions of the rolling mill 210 the laboratory experiment with forming of thin-walled part in the form of a wavy surface (Fig. 7) was made. Strips in the conditions of uneven deformation by width were rolled. Thus, the rolling force was fixed. The different "waves" parameters determined the different width of the central element and, therefore, differ-

ent transverse deformation and hence, the different size of longitudinal interaction and force of rolling, Table 2.



**Figure 7.** Polythickness profiles with wavy and planar central parts

**Table 2.** Experimental values of relative roll pressure depending on transverse deformation coefficient.

Thickness, N mm	Relationship $S_1 / S_0$	Transverse deformation coefficient $B'_1 / B_1$			
		1,00	1,06	1,08	1,11
		Force relationship $P_1 / P_0$			
	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	0,93

Additional influence which is made by rulers or guides through external "ends" of a feed on the deformation zone causes the emergence of tensions, which are capable to level or change the drawings by height and a bandwidth. They determine kinematic and power parameters of a metal yielding, stressed

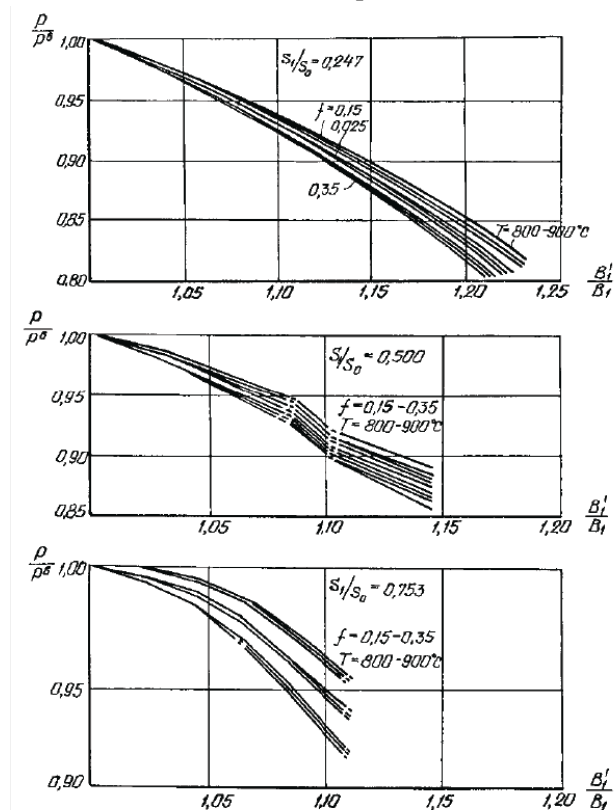
state of separate sites of a profile with increasing or reducing contact pressures [8, 9]. Also they change the rolling force.

As a result of the conducted pilot tests it became obvious that the width increase of strongly deformed site in the course of rolling changes the longitudinal

interaction of elements of a profile, and reduces the common roll pressure. So when rolling a strip with a thickness of 3 mm and the sectional area relation of elements  $B_1 / B_1$  within 0,42 ... 0,80, with transverse deformation coefficient increasing of the 1st element  $B_1 / B_1$  from 1,06 to 1,11, the relative roll pressure  $S_1 / S_0$  decreased from 0,94 to 0,89 (Tab. 2). Thus, the pressures changing are more on thin strips, than on thick strips. The roll pressure at  $S_1 / S_0 = 0,8$  changes in a little smaller degree. Attractive is an option when instead of additional compression there is a stretching.

The dependences of design values of relative pressure  $S_1 / S_0$  on coefficient of transverse deformation of an element with big cobbing are presented in fig. 8. At such yielding kinematics a decrease in relative roll pressure takes place.

For a rim profile in finishing passes the sectional areas relation of  $S_1 / S_0 = 0,25$  takes place. In this case the pressure decrease with the given transverse deformation is most noticeable. The new technological capabilities for influence on profile deformation process, including the receiving of rolled stock with the minimum thickness are represented.



**Figure 8.** Dependence of relative roll pressure on transverse deformation coefficient of strongly pressed out profile element

In fig. 9 and 10 the sections of finishing and prefinishing templates of rim profiles of a different design are represented. Such mode of a plastic deformation

defines a rim profile form in finishing pass. If the product form does not influence negatively on its utilization and strength properties, then the profile and its constructive decision is defined by deformation kinematic conditions.



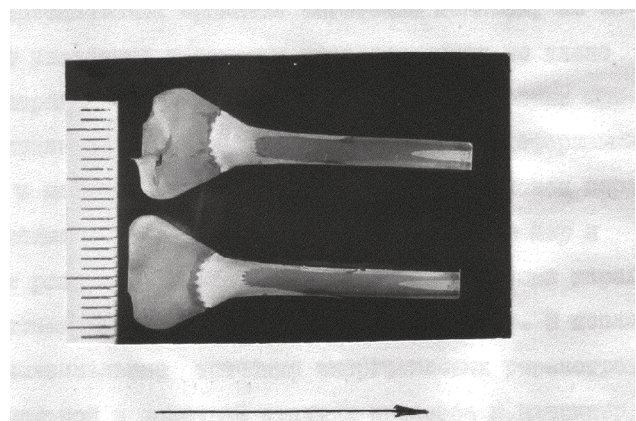
**Figure 9.** The rim rolling finishing and prefinishing templates with the central wavy part



**Figure 10.** The rim rolling finishing and prefinishing templates with a "rolling wave".

Implementation of this effect when profile thin-walled part forming allows to "squeeze out" the minimum thickness, provide the highly effective products production of reduced metal consumption.

The receiving of thin-walled products by periodic rolling has much in common with receiving of thin-walled products for trucks wheels rims. First of all, it is the presence of plastic deformation irregularity, but in different yielding directions. When rolling of compressor blades billets the longitudinal metal movement is implemented in the conditions of increase and decreases of cobbing longwise the deformation zone [10]. The contours of lag and advancing are formed. The metal yielding in thin-walled part of a profile is implemented not linear, but shearing deformations (Fig. 11). Forming of such yielding kinematics allowed the implementation of a thin-walled products production process from titanium alloys, providing the decrease of deformation force and flow coefficient, increasing the quality of finish products.



**Figure 11.** A transition site from lock to the pen part

Emergence of shearing deformations in this part of a profile needs to be coordinated with experimental data on measurement of forces and the moments of rolling longwise of a periodic feed. During the billet blades rolling with cobbing decrease, in thin-walled part of a profile there are longitudinal pulling stresses at the deformation zone, defining the force decrease effect, possibility of receiving thin-walled part of a product.

#### Conclusions.

1. The effects of plastic deformation at thin-walled profiles rolling are experimentally and theoretically shown.

2. Using of plastic yielding mechanisms at thin-walled profiles rolling allows to influence on process power and kinematic parameters, to provide a necessary thinner of walls and rolling quality.

3. Implementation of effects of deformation in finishing pass defines the new approaches of design of special purpose profiles.

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