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EFFECT OF NONCONTACT ZONES ON THE DEFORMING FORCES IN METAL-SHAPING OPERATIONS

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The mechanism responsible for the effect of noncontact zones in metal-shaping operations is examined. A theoretical relation is derived to determine the magnitude of thrusting stresses that are formed, and a comparison is made between results obtained by calculation. An algorithm is developed to calculate the energy-force parameters of the process with allowance for the effect of nonuniform plastic deformation caused by the presence of noncontact zones.

Keywords: *noncontact zones, metal-shaping, rolling in grooves, nonuniformity of deformation, calculation of energy-force parameters.*

In some of the loading schemes used in metal-shaping operations, the noncontact zones which are formed end up being adjacent to a local deformation zone. Such a situation is encountered in the longitudinal rolling of shapes and tubes and the helical rolling of solid and hollow shapes. Figure 1 shows examples of the presence of noncontact zones (the hatched regions) during the deformation of metal.

In the upsetting of tall cylinders ($h > 3d$) with $\varepsilon = 5–10\%$, the maximum strains are formed only in the surface layers [1]. Frictional forces on the contact surface impede deformation, with the interior mass of metal tending to move laterally and forming barrel-shaped convexities next to the ends of the semifinished product. When a thick bar is being drawn, the internal part of the bar's cross section should undergo the same degree of elongation as the upper layers near the contact zone. According to Tomlenov [2], tensile stresses reaching the value of σ_s form in the central part of bar when the ratio of the length of the arc of contact l during the rolling operation to the thickness of the bar $l/h < 1$. Lengthening of the noncontact zones creates a thrusting force over the area F_0 of the compressed part of the bar's cross section. It can be approximately assumed that the entire volume of metal that is displaced goes into elongating the bar and that the actual amount of elongation depends on the contact length l and the depth of deformation h_d. The value of h_d was determined by S. I. Gubkin, A. I. Tselikov, V. A. Livanov, P. S. Istomin, and A. I. Kolpashnikov.

With a certain degree of approximation, we can take $h_d = 1.2l$ based on experiments performed by the authors of [3].

The effect of noncontact zones on the rolling force was examined in [4].

The diagram that is used to describe the rolling and upsetting of cross-shaped specimens was chosen to represent the stress-strain state of the semifinished product in the present study (Fig. 2). With a certain degree of approximation, the main principles and methods used in analytical calculations performed in accordance with the cross-shaped cross section

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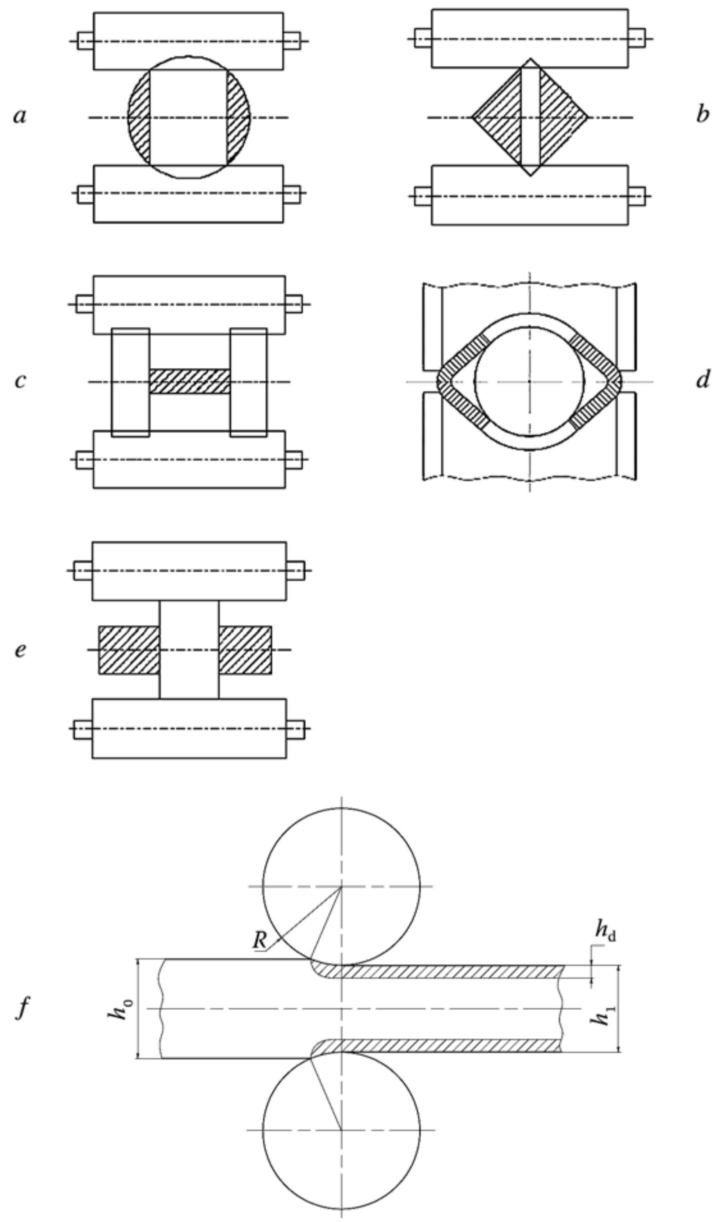

Fig. 1. Examples of rolling with noncontact zones in the case of: *a*) the flattening of wire; *b*) the planetary rolling of a bar of square cross section on its edge; *c*) a beam-shaped bar; *d*) the rolling of a tube on a mandrel; *e*) a bar with a cross-shaped cross section; *f*) the rolling of a thick bar.

scheme can also be used to analyze results from calculation of the forces for rolling in grooves (such as in the rolling of beams, channels, etc.), longitudinal and helical rolling, the piercing of tubular semifinished products, slab reduction, and other shaping operations.

By virtue of the continuity of the medium in question, the elongation of the part of the cross section that is undergoing compression – the area $F_0 = b_1 h_0$ (where b_1 is the final width of the bar, and h_0 is its initial thickness) – creates the tensile stress σ_t in the noncontact zones. This stress should in turn create the compressive stress σ_{cm} in the part of the cross section undergoing compression.

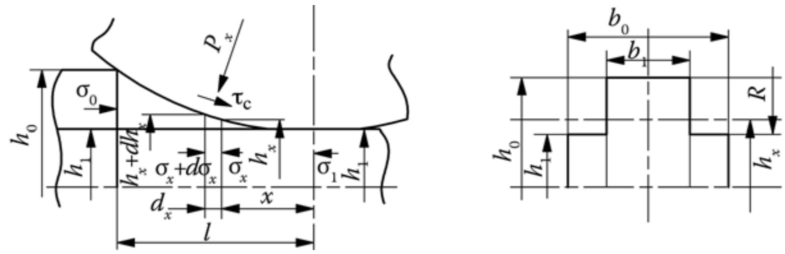

Fig. 2. Diagram of the deformation of a bar with a cross-shaped cross section.

In the deformation of a bar whose cross section is in the shape of a cross, the tensile forces in the lateral zones – in the area $F - F_0$ (where F is the total cross-sectional area) – can be estimated as follows:

$$\sigma_{cm} = \sigma^*,$$

where σ^* is the resistance of linear deformation in tension with allowance for the temperature, rate, and degree of deformation.

The condition of equality of the compressive and tensile forces in the zones F_0 and $(F - F_0)$ can be expressed by the following equation:

$$\sigma^*(F - F_0) = \sigma_{cm} F_0, \tag{1}$$

where σ_{cm} is the compressive stress in the zone in which the bar undergoes plastic compression – the thrusting stress that develops from the action of the noncontact zones. This compressive stress is equal to

$$\sigma_h = \sigma_{cm} = \sigma^*\left(\frac{F}{F_0} - 1\right). \tag{2}$$

The effect of the thrusting stress from the noncontact zones on the contact stress that develops during rolling can be determined using the coefficient n_h from the formula obtained by Hessenberg and Sims [6] (the formula was obtained from an analysis of diagrams of the contact stresses over the arc of contact during rolling):

$$n_h = 1 + (\sigma_0 + \sigma_1)/4k, \tag{3}$$

where σ_0 and σ_1 are, respectively, the thrusting stresses upon entry and exit, MPa; $k = 0.57\sigma_f$ (σ_f is the flow stress with allowance for the temperature, rate, and degree of deformation, MPa).

If we consider that $\sigma_f = \sigma_s$ – the resistance to deformation which develops during the action of the vertical force – and we allow for a certain degree of approximation (assuming that the contact pressure $n'_\sigma = 1$), we can determine the coefficient n_h from the expression

$$n_h = 1 + (\sigma_h/2\sigma_s). \tag{4}$$

With allowance for Eq. (2), Eq. (4) will have the form

$$n_h = 1 + \frac{\left(\frac{F}{F_0} - 1\right)\sigma_s^*}{2\sigma_s} \tag{5}$$

or

$$n_h = 1 + \left(\frac{F}{F_0} - 1\right)\frac{\sigma_s^*}{2\sigma_s}, \tag{6}$$

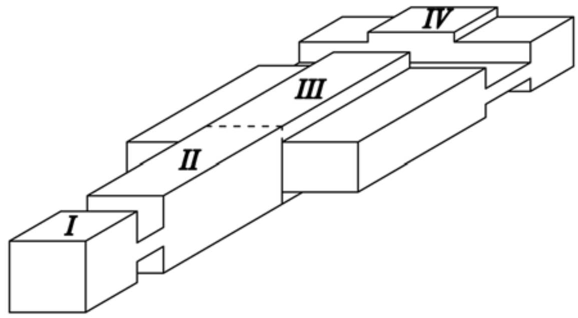

Fig. 3. Specimen for studying lateral noncontact zones.

TABLE 1. Results of Calculation of the Thrust Coefficient n_h with the Use of Eq. (6) and the Formula Obtained by Smirnov

Specimen parameters		Ratio l/h	n''_σ calculated from the formula	
n, mm	l, mm		of Smirnov	(6)
Lead				
30	30	1.0	1.0	1.0
	15	0.5	1.4	1.3
	10	0.333	1.6	1.6
	7.5	0.25	1.73	1.7
	5	0.167	2.3	2.8
22.5	10	0.444	1.42	1.4
	7.5	0.333	1.5	1.75
15	7.5	0.5	1.3	1.35
	5	0.333	1.52	1.53
	2.5	0.167	2.15	2.4
Steel				
30	15	0.5	1.37	1.3
	10	0.333	1.54	1.6

where σ_s^* is the stress created by linear tension with allowance for the horizontal displacement. The following empirical relation [5] was obtained from the experimental rolling of specimens of aluminum alloy D1 with noncontact lateral zones (Fig. 3):

$$n_h = 0.6 + 0.4F/F_0, \tag{7}$$

which can be obtained through transformations of Eqs. (6) with the ratio $\sigma^*/\sigma_s \approx 0.8$. The latter corresponds to values of yield strength ($\sigma_{0.2}$ = 180 MPa at ε = 10% and $\sigma_{0.2}$ = 150 MPa at ε = 8%) [3].

The effect of noncontact zones in the deformation of thick bars can be expressed by means of the method proposed by Smirnov and Tselikov [7]: “by the compression of rectangular specimens of the dimensions *l*, *b*, and *h* between parallel dies and by local compression of specimens of substantial length *L* on the section bounded by the length *l*.” The specimens being compared have the same thickness h and same width $b > 5l$ [7]. It is proposed that the effect of the "external zones" be accounted for by introducing the coefficient n''_σ:

$$n''_\sigma = (l/h_{av})^{-0.4}.$$

Having used this method to also conduct a study for lead specimens and having taken $h_d = 1.2l$, we used the above data and Eq. (6) to find a value of the coefficient n_h that accounts for the effect of thrust from the noncontact zones. The elongation of the bar was determined from the displaced volume (see Fig. 1f), while the area that was compressed was determined as $F_0 = h_d b$. Comparison of the results (see Table 1) showed satisfactory agreement between the experimental values of the coefficient n_h and the values calculated with the use of Eq. (6).

The slight disagreement that is seen is due to the need to account for spreading in the contact zone. It would probably be best to also take into account other factors, such as the friction coefficient and the geometric factor l/h.

The differential equation that describes the contact stresses p_x of an isolated element in the region in which the cross-shaped bar undergoes compression (Fig. 2) has the form:

$$dp_x = \mp 4\mu k \frac{dx}{h}, \tag{8}$$

where the sign "+" corresponds to the sign of the thrusting stresses and the sign "–" corresponds to the tensile stress.

After integration of the equation, we obtain:

$$p_x = 4\mu k \frac{x}{h} + C_0, \tag{9}$$

where μ is the friction coefficient; C_0 is a constant.

The boundary conditions at $x = 0$

$$\sigma_x = \sigma_{cm}; \quad p_0 - \sigma_{cm} = 2k \to p_0 = 2k + \sigma_{cm}.$$

From this, we find the value of the arbitrary constant:

$$C_0 = 2k + \sigma_{cm}.$$

Solving system (8)–(9) with the assigned boundary conditions and with $x = 0.5l$, we find that in the absence of noncontact zones the average contact stress will be equal to

$$p_{av} = 2k\left(1 + \frac{\mu l}{2h}\right). \tag{10}$$

Equation (10) makes it possible to find the value of the coefficient that characterizes the effect of the noncontact zones

$$n_h = 1 + \left(\frac{F}{F_0} - 1\right)\sigma_{cm} \Big/ 2\left(1 + \frac{\mu l}{2h}\right)\sigma_s. \tag{11}$$

The effects of μ and the ratio l/h are clearly negligible for thick bars and a friction coefficient within the range 0.4–0.1.

The method proposed here can be used to determine how the nonuniformity of deformation of a rolled bar over its width affects the average contact stress when equalization of the natural elongations gives rise to compressive stresses (thrust) in the regions with large reductions and to tensile stresses in the regions with small reductions. The magnitude of these stresses can be determined with allowance for the average elongation factor by using the formulas found by Chekmarev and Mutiev [8].

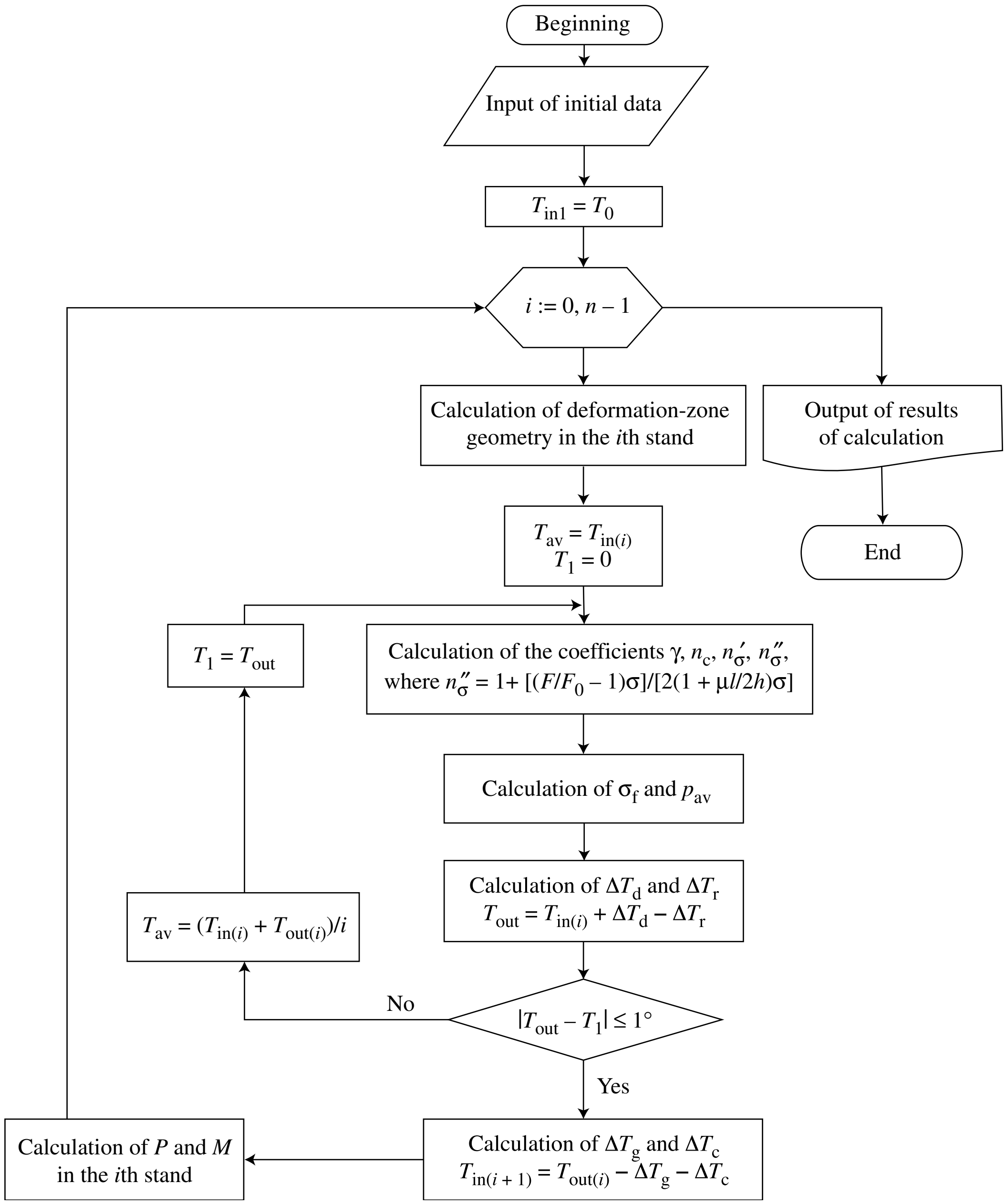

Fig. 4. Algorithm for calculating the energy-force parameters of hot rolling.

Above-derived Eq. (11) can also be used in practical calculations of the energy-force parameters that characterize plastic deformation during hot-rolling in passes. In this case, the expression used to determine the average contact stress takes the form

$$p_{av} = \gamma\, n_c n'_\sigma n''_\sigma \sigma_f = \gamma\, n_c n'_\sigma \left(1 + \frac{0.4(F/F_0 - 1)}{(1 + \mu l/2h)}\right)\sigma_f. \tag{12}$$

To automate these calculations, we developed a program with the algorithm shown in Fig. 4. The algorithm is based on the well-known algorithm in [4] that is used to calculate energy-force parameters. The algorithm makes it possible to calculate the temperature of a bar in the deformation zone with a high degree of accuracy. The innovation introduced here consists of modifications that were made to the block which analyzes the geometric parameters of the deformation zone (checks for the presence of noncontact zones) and the block that calculates the coefficients of the stress state (to make them consistent with the proposed methodology).

Conclusions

1. The transverse and longitudinal noncontact regions that are formed during various metal-shaping operations impede the movement of metal from the compression zone to the contact surface, which in turn increases the acting contact stresses due to the creation of compressive stresses associated with thrusting forces (studies by S. I. Gubkin, I. M. Pavlov, M. V. Storozhev, E. A. Popov, N. I. Gromov, A. I. Tselikov, and V. V. Smirnov).

2. The increase in the average contact stress p_{av} depends on the ratio of the area of the compression zone F_0 to the cross-sectional area of the specimen F.

3. The results obtained here can be used to solve many different practical problems that involve determining rolling forces and moments.

4. For the rolling of bars of rectangular cross section, when $b > 5l$ the area of the compressed part $F_0 = h_d b$. Here, $h_d = 1.2l$ – the (average) depth of penetration of the strain.

5. The increase in the average contact stress p_{av} depends on the friction coefficient μ and the ratio l/h and is found from Eq. (11).

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