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Sleeve Deformation in a Three-Roller Screw-Rolling Mill

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Abstract—The screw rolling of steel pipe in a three-roller mill is considered. Given the differences in the unit-force distribution within the deformation region, a method is developed for calculating the deformation parameters in sleeve rolling on a long mandrel. A method is presented for calculating the reduction and contact surface area of the metal and the roller, in the region where the diameter of the sleeve is reduced and in the region where the wall thickness is reduced. Account is taken of the tangential flow of metal into the gaps between the rollers, which is characteristic of the rolling of thin-walled pipe when the ratio of the diameter and the wall thickness is $D_{pi}/S_{pi} > 8$. The results are intended for industrial use in the production of pipe with $D_{pi}/S_{pi} = 8–15$, when the tolerances are ±6% on the wall thickness and ±0.5% on the diameter. The results provide a better understanding of the production of thin-walled pipe on screw-rolling mills.

Keywords: screw rolling, steel pipe, contact surface, pipe diameter, wall thickness, reduction increment, reduction zone, thinning zone, unit force, input section, three-roller mill

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Screw rolling is used to produce high-precision pipe for the manufacture of bearings, couplings, races, and other components from moderate- and high-alloy ball-bearing steel (ШХ15, 20Х, 50Х, 32Г2С, etc.).

A long floating mandrel is used in rolling. In Fig. 1a, we show the deformation region for a three-roller mill with supply angle β (in the horizontal plane) to ensure axial displacement of the blank and with rolling angle γ (in the vertical plane). The deformation region consists of four basic sections: the input cone, consisting of the initial reducing zone (where the diameter is reduced and the mandrel is inserted in the sleeve) and the preliminary thinning zone; the primary thinning section corresponding to intense reduction by the shoulder; the calibration section; and the output section.

In rolling, when the metal makes contact with the roller, the first stage is reduction of the diameter; the next is reduction in the wall thickness (thinning). The unit force in these sections is different. As an example, we may note the broaching process, where a piercing section is followed by a sleeve-rolling section. The unit force at the rollers is greater in the piercing section [1–7]. That corresponds to the thinning zone in the rolling mill. In the sleeve-rolling section, the unit force in the broaching force is 70–75% of that in the piercing section. That corresponds to the zone where the diameter is reduced in the three-roller mill. Therefore, we need to consider the two zones of metal–roller contact separately.

In Fig. 1b, we show the deformation region of the rolling mill. The radius R of the metal in the gap between the rollers is measured at point A, which corresponds to the onset of metal–roller contact. The metal radius r corresponds to point B, where the metal leaves the roller. Point C corresponds to the transition from the reduction zone, where the overall pipe diameter is decreased, to the thinning zone, where the wall thickness is decreased. The metal is in contact with the roller over arc ACB. The total width b of the contact surface is equal to the chord AB, which may be determined from the formula [5, 8]

$$b = \sqrt{\frac{2R_{ro}r}{R + r}\Delta S}, \qquad (1)$$

where R_{ro} is the roller radius, mm; r is the radius of the metal strip, mm; b is the width of the metal blank, mm; ΔS is the reduction increment.

In fact, the reduction increment ΔS is the total increment denoted by ΔS_Σ in Fig. 1b, which is the sum of the reduction increment ΔS_d for the diameter and the reduction increment ΔS_w for the wall thickness.

As is evident from Fig. 1b, the reduction in diameter proceeds over arc AC, while the reduction in wall thickness proceeds over arc CB. The width of the section where the diameter is reduced is determined by the chord b'_d, while the width of the section where the wall thickness is reduced is determined by the chord b'_w. We need to determine the corresponding widths for chord AB. Dropping the perpendicular to chord AB from points C and N, we obtain the segments AN and

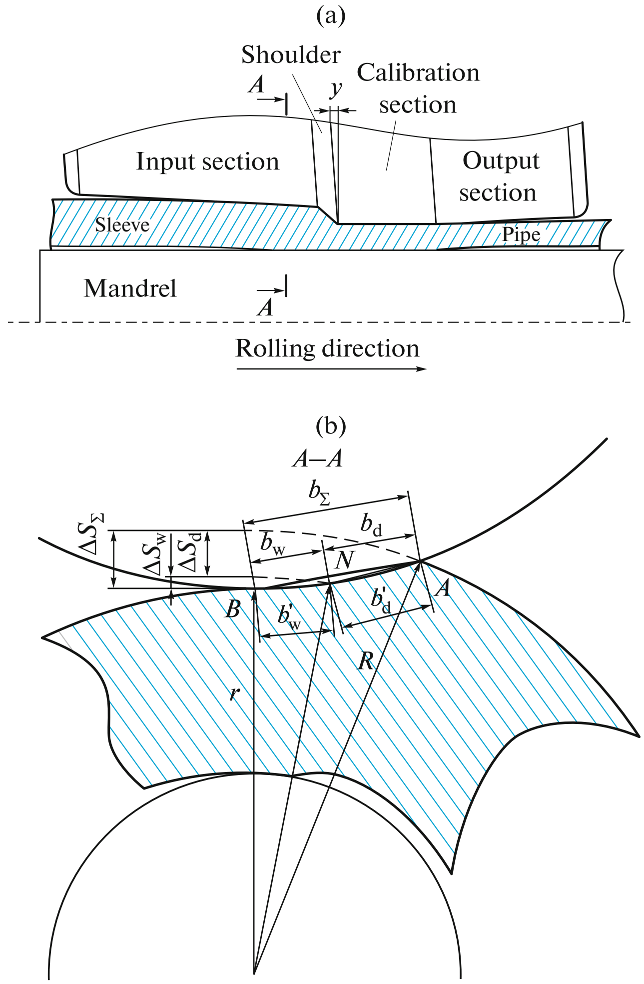

Fig. 1. Deformation region of rolling mill (a) and determination of the contact-surface width in cross section *A–A* (b).

NB, which are equal to the projections of b_d' and b_w', respectively. We denote AN and NB by b_d and b_w. Then b_d is the width corresponding to decrease in the diameter and b_w is the width corresponding to decrease in the wall thickness.

Considering the two triangles ANC and BNC, we obtain formulas for the contact-surface widths b_d and b_w

$$b_d = \left(\sqrt{\frac{2R_{ro}r}{(R+r)\Delta S_\Sigma}}\right)\Delta S_d,$$

$$b_w = \left(\sqrt{\frac{2R_{ro}r}{(R+r)\Delta S_\Sigma}}\right)\Delta S_w. \quad (2)$$

On the basis of Eq. (2), we may determine the width of the metal–roller contact surface in the sections corresponding to decrease in the diameter and decrease in the wall thickness.

In Fig. 2, we show the reduction in wall thickness in the regions of the mill close to the shoulder, where most of the deformation occurs [9]. To calculate b_d

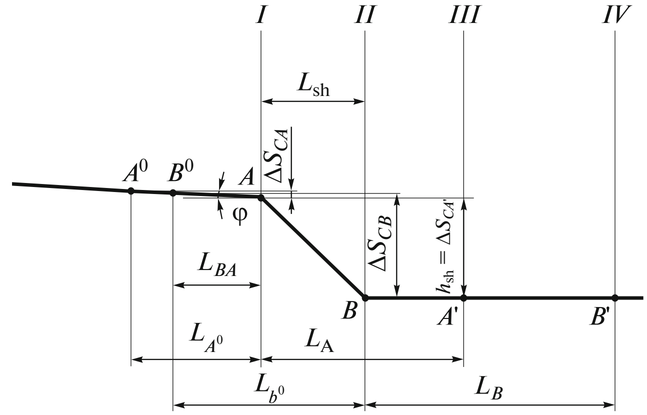

Fig. 2. Calculating the reduction increment ΔS_{CA} in the wall thickness at the shoulder in the longitudinal cross section of the deformation region.

and b_w, we need to select several characteristic cross sections and points of the deformation region and determine the reduction increments ΔS_d and ΔS_w.

We consider four characteristic cross sections (Fig. 2): (*I–I*) at the base of the shoulder; (*II–II*) at the top of the shoulder; (*III–III*) at a distance from the base of the shoulder equal to a third of the subsequent supply increment; (*IV–IV*) at a distance from the top of the shoulder equal to a third of the subsequent supply increment. These cross sections correspond to points A, B, A', B', respectively. The distance of points A^0 and B^0 from points A and B is a third of the previous supply increment. We may determine L_{A^0}, which is a third of the previous supply increment (the distance between points A^0 and A), from the formula [6, 10–12]

$$L_{A^0} = \frac{1}{3}\pi D_{pi}\tan(\beta)\frac{\mu_I}{\mu_\Sigma}\frac{\eta_{ax}'}{\eta_{ta}'}, \quad (3)$$

where D_{pi} is the diameter of the final pipe; β is the supply angle of the rollers in the mill; μ_I is the extension coefficient in the given cross section; μ_Σ is the total extension coefficient; η_{ax}' and η_{ta}' are the axial and tangential speeds, respectively.

The reduction increment ΔS_{CA} in the wall thickness may be determined from the formula [13]

$$\Delta S_{CA} = L_{A^0}\tan(\varphi), \quad (4)$$

where φ is the inclination of the input section to the rolling axis.

Taking account of the definition of the extension coefficient in cross-section *II–II*, we now determine L_{B^0}, which is a third of the previous supply increment (the distance between points B^0 and B), from the formula

$$L_{B^0} = \frac{1}{3}\pi D_{pi}\tan(\beta)\sqrt[3]{\frac{\mu_I^3}{\mu_\Sigma^2}\frac{\eta_{ax}'}{\eta_{ta}'}}. \quad (5)$$

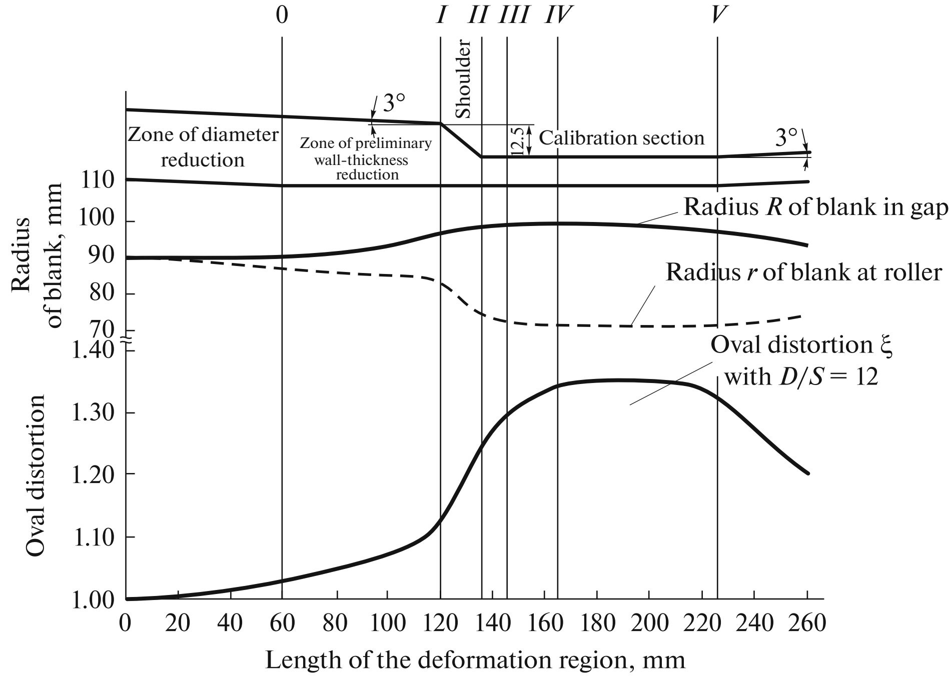

Fig. 3. Distribution of the radius of the blank and the oval distortion over the length of the deformation region.

In the general case, ΔS_{CB} is the sum of the reduction in wall thickness by the shoulder h_{sh} and the reduction increment ΔS_{CB^0A} on section B^0A of the deformation region

$$\Delta S_{CB} = \Delta S_{CB^0A} + h_{sh}. \quad (6)$$

We see in Fig. 2 that

$$\Delta S_{CB^0A} = L_{B^0A}\tan(\varphi). \quad (7)$$

We may determine L_{B^0A} as the difference between L_B and L_{sh}. Then

$$\Delta S_{CB} = (L_B - L_{sh})\tan(\varphi) + h_{sh}. \quad (8)$$

Consider cross section *III–III*, which corresponds to point *A*'. This cross section is in the calibration section of the deformation region at a distance $L_{A'}$ (equal to a third of the subsequent supply increment) from point *A*. Here

$$L_A = L_{A^0}\left(\frac{\eta_\Sigma}{\eta_I}\right)^{2/3}. \quad (9)$$

It is evident from Fig. 3 that $\Delta S_{CA'}$, the reduction increment in the wall thickness in cross section *III–III*, is equal to the shoulder height h_{sh}.

We next consider cross section *IV–IV* through point *B*' at a distance $L_{B'}$ from cross section *III–III*, where $L_{B'}$ is a third of the subsequent supply increment from point *B*. In this cross section, there is no reduction increment in the wall thickness. Over the whole perimeter, its wall thickness is equal to that of the final pipe. Accordingly, in this cross section, there is no zone corresponding to reduction in wall thickness. However, as a result of the considerable metal flow into the gaps between the rollers, there is some reduction in diameter of the blank.

The reduction increment ΔS_d in the diameter depends entirely on the metal flow into the gaps between the rollers. The oval distortion ξ may be calculated as the ratio of the radius *R* of the metal in the blank to the radius *r* of the blank at the roller (Fig. 1), according to [14].

DEFORM software is used for computer simulation of the rolling of a sleeve ($D_{sl} \times S_{sl}$ = 181 × 28 mm) to the final pipe ($D_{pi} \times S_{pi}$ = 150 × 12.5 mm) [15]. The deformation region is formed by rollers inclined at a supply angle 10° and a rolling angle 4°, with a shoulder. The input section has 3° taper with respect to the rolling axis; the taper of the shoulder is 42° and its height h_{sh} = 12.5 mm [9]. The calibration section is parallel to the rolling axis; its length is 90 mm. The output section has 3° taper with respect to the rolling axis. Rolling is simulated with an initial temperature of 1160°C. The simulation is verified for the rolling process in [14]. We find that the geometric discrepancy between the simulation and the rolling process in the 130T mill at Moscow Institute of Steel and Alloys is no more than 10%. In simulation, the radii of the blank under the roller and in the gap between the rollers are measured (Fig. 3). On that basis, the oval distortion ξ is determined.

Table 1. Partial reductions at the wall of breakdown bar and partial reducing at diameter in sections

Cross section	Reduction increments in the diameter and wall thickness within the deformation region for the rolling of a sleeve ($D_{sl} \times S_{sl} = 181 \times 28$ mm) to the final pipe ($D_{pi} \times S_{pi} = 150 \times 12.5$ mm)		
	ΔS_d, mm	ΔS_w, mm	ΔS_Σ, mm
0–0	2.6	0.0	2.6
I–I	9.7	0.9	10.6
II–II	5.1	12.9	18.0
III–III	12.0	12.5	24.5
IV–IV	23.1	0.0	23.1

Table 2. The width of the metal contact with the roll

Cross section	Width of metal–roller contact for the rolling of a sleeve ($D_{sl} \times S_{sl} = 181 \times 28$ mm) to the final pipe ($D_{pi} \times S_{pi} = 150 \times 12.5$ mm)		
	b_d	b_w	$b_d + b_w$
0–0	17.7	0.0	17.7
I–I	32.6	3.0	35.6
II–II	12.8	32.2	45.0
III–III	25.1	26.3	51.4
IV–IV	50.0	0.0	50.0

The distribution of ξ over the length of the deformation region is shown in Fig. 3. The horizontal coordinate 0 corresponds to the first contact of the sleeve with the roller (the beginning of the deformation region). Up to cross section 0–0, only the diameter is reduced; beyond cross section 0–0, both the diameter and the wall thickness are reduced. The cross sections from *I–I* to *IV–IV* correspond to those in Fig. 2. The pipe leaves the calibration section in cross section *V–V*.

Knowing ξ and ΔS_Σ, we may determine ΔS_d. It is evident from Fig. 1 that ΔS_Σ is the difference between the radius R of the metal in the gap between the rollers and the radius r of the blank at the roller. Then, taking account of the oval distortion, we may write

$$\Delta S_\Sigma = R - r = (\xi - 1). \quad (10)$$

On the basis of Eq. (4)

$$\Delta S_d = r(\xi - 1) - \Delta S_w. \quad (11)$$

Using Eq. (11), we may determine ΔS_d for any cross section of the deformation region. Thus, in cross section 0–0, at the beginning of the deformation region, there is no reduction of the sleeve wall (Fig. 3). The total width of the contact surface includes only the width b_d of the preliminary zone where the diameter is reduced, which may be determined by means of Eqs. (2) and (11). According to the graph, $\xi_{0-0} = 1.03$. Then $\Delta S_{d0-0} = 2.6$ mm and $b_{d0-0} = 17.7$ mm. Knowing the distribution of ξ, we may determine the decrease in diameter in the given cross sections using Eq. (1). Table 1 presents the calculated values of ΔS_d, ΔS_w, and ΔS_Σ in the basic cross sections of the deformation region.

From Eq. (2), we may determine b_d and b_w for those cross sections. The results are given in Table 2.

Knowing the width of metal–roller contact, the contact area of the metal surface with the roller may be determined. For the sake of simplicity, we represent this area in terms of elementary geometric forms: right-angled triangles and trapezia (Fig. 4). Up to cross section 0–0 and beyond cross section *IV–IV*, the contact area only includes the region where the diameter is reduced; it corresponds to a right-angled triangle. In cross section 0–0, the sleeve is fitted on the mandrel (Fig. 4) and reduction in wall thickness

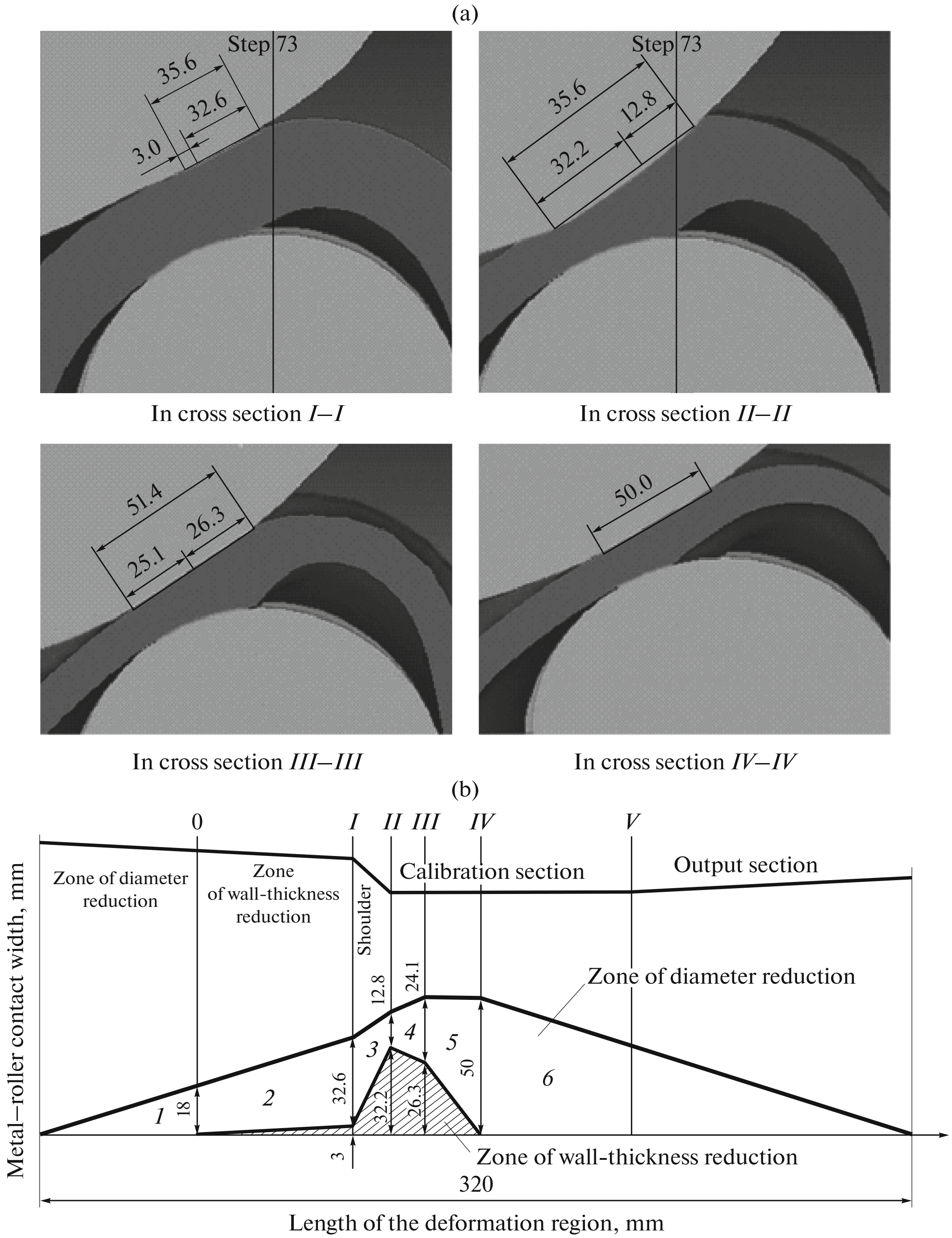

Fig. 4. Width of the contact surface in specific cross sections (a) and contact area in the zones where the diameter is reduced and the wall thickness is reduced (b).

begins. Accordingly, the contact area is divided into section F_d, where the diameter is reduced, and section F_w, where the wall thickness is reduced.

Between cross sections 0–0 and *I–I*, area F_w corresponds to a right-angled triangle. Area F_d corresponds to the trapezium between the given cross sections. Between cross sections *I–I* and *II–II*, areas F_w and F_d are determined as trapezia. Note that F_w is determined from b_w, and F_d from b_d.

CONCLUSIONS

When pipe is rolled on a three-roller screw-rolling mill, on account of the considerable oval distortion, the area of metal–roller contact consists of two zones: in the first, the diameter of the pipe is reduced; in the second, the wall thickness is reduced. On the basis of Eq. (5), the width of the contact surface in those zones may be determined. That permits more precise calculation of the force exerted on the rollers by the pipe blank.

Detailed analysis of the deformation at the roller's shoulder permits more precise calculation of the reduction increments in the wall thickness and the diameter, which are required in determining the contact width and contact area.

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