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FEATURES OF THE COLD-ROLLING OF TUBES ON TANDEM MILLS WITH A FOUR-HIGH STAND

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Aspects of rolling on tandem four-high cold-rolling tube mills are studied. The article examines how the gear ratio of the diagonal transmission of the stand is related to the axial force on the semifinished product and loss of stability by the tube. An improved method is developed for designing the rolls so that the deformation process is divided between a pair of breakdown rolls and a pair of sizing rolls. The study is performed using an expert automated system developed to design technologies for the cold periodic rolling of tubes. The laws that govern the accumulation of damage resulting from the effects of the main process parameters are described and technical recommendations are made on mastering the use of the given type of mill.

Keywords: *cold-deformed tubes, cold periodic rolling of tubes, four-high stand of the mill, damage content of the metal, design of the mill rolls.*

On the tandem cold-rolling tube mills [1, 2, etc.] developed at the All-Union Research Institute of the Pipe Industry (in Dnepropetrovsk) under the direction of M. V. Popov, the tube is deformed simultaneously by two successive pairs of rolls of the same size. This scheme makes it possible to increase the draft during the rolling operation by a factor of 1.5–2. The first pair of rolls, which initiates the deformation of the incoming semifinished product, is usually referred to as the breakdown pair. The second pair of rolls is called the sizing pair. These mills are difficult to operate because of the complicated adjustments that must be made to their equipment and the distinctive features of the process of deformation in two pairs of rolls simultaneously. These features should be reflected in the design of the equipment. Tandem cold-rolling tube mills are being used with success in Ukraine, but problems have been encountered with the mills at plants in the Urals. Most of these problems are related to the fact that the specific features of the rolling operation on these mills have not been adequately taken into account.

This article examines certain aspects of the rolling conditions on tandem cold-rolling tube mills. Allowing for these conditions will facilitate the practical use of such mills.

One of the most important features of the type of mill being discussed is that rotation is transferred from the breakdown pair of rolls to the sizing pair through a unilateral diagonal transmission with the gear ratio $D_{g2}/D_{g1} = 1.03–1.06$. As on a conventional mill, the rolls of the breakdown pair are brought into rotation by drive pinions with a pitch-circle diameter D_{p1}. The nominal diameter of the drive pinion of the second (sizing) roll pair is determined by the gear ratio

$$D_{p2} = \frac{D_{g2}}{D_{g1}} D_{p1}, \tag{1}$$

where D_{g2} and D_{g1} are the pitch-circle diameters of the gear wheels on the breakdown and sizing rolls, respectively.

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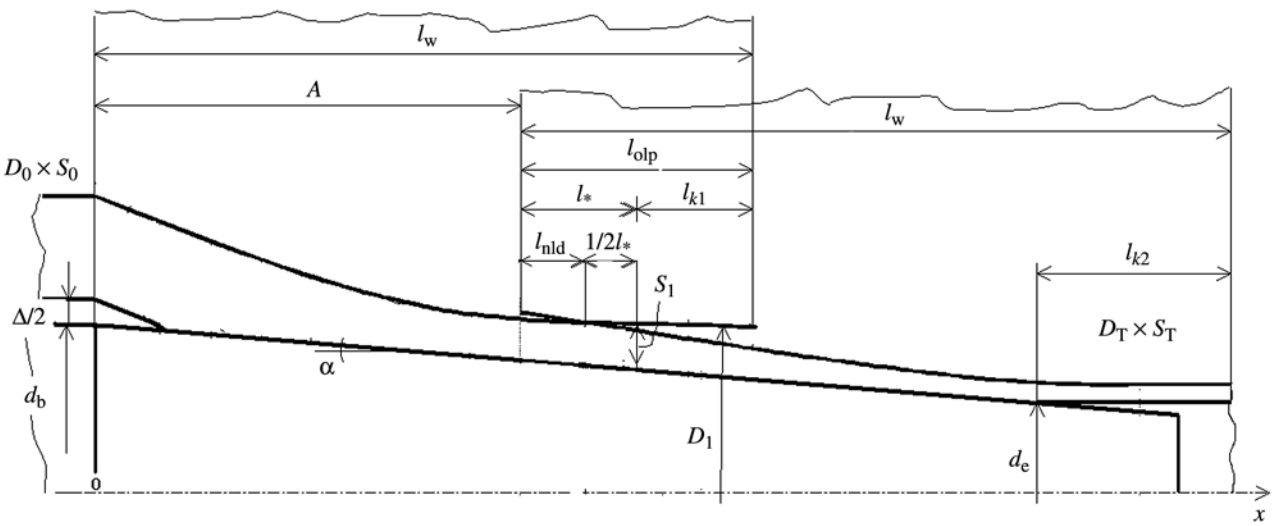

Fig. 1. Dimensions of the working cone in rolling on a tandem cold-rolling tube mill: $D_1 \times S_1$ – tube diameter and wall, rolled by the first pair of rolls; α – apex angle of the mandrel; d_b, d_e – diameter of the mandrel at the beginning and end of the working cone; Δ – clearance for mandrel insertion; the remaining notation is explained in the text.

To a large extent, Eq. (1) determines the deformation conditions and the axial forces transmitted by the second pair of rolls. Thus, it is possible to choose an efficient ratio (1) for rolling with substantial drafts while avoiding having the tube become unstable due to large axial forces.

The deformation conditions in the breakdown pair of rolls differ from a conventional mill in that the metal is subjected to an additional load (tension or thrust) from the sizing roll pair, depending on the direction of the axial forces. Thus, the axial force in the *i*th instantaneous deformation zone (IDZ) is determined with allowance for the axial force in the corresponding IDZ of the second roll pair; the distance between the latter IDZ and the first IDZ is equal to the distance *A* between the two pairs of rolls. To illustrate:

$$Q_{1i} = Q_{1i} + Q_{2j}, \tag{2}$$

where i is the number of the IDZ with the coordinate x under the first pair of rolls; j is the number of the IDZ with the coordinate $x + A$ under the second pair of rolls.

The additional axial load calculated from Eq. (2) has a substantial effect on the stress state of the metal, its cumulative damage content, and the degree to which any variation in the thickness of the wall of the tube can be corrected.

The next noteworthy feature of the rolling operation on the given type of mill is the fact that the tube in the second pair of rolls is rolled with a continuous feed of metal from the first pair

$$m_{2i} = m_1\mu_i, \tag{3}$$

where m_1 is the feed of metal into the first roll pair; μ_i is the running draft in the ith cross section of the first pair.

Condition (3) should be taken into account when designing the second roll pair, especially in regard to the determination of its width. Also, the amount of metal rolled during the reverse stroke in the sizing stand is greater than the amount rolled in a conventional mill because the linear displacement during the forward stroke in the first pair is equal to $0.7m_1\mu_1$, where μ_1 is the draft in the first roll pair. It can thus be assumed that the draft during the reverse stroke of the second pair will be 0.5, rather than the value 0.3 for conventional stands.

The above features were taken into account in developing an improved method of designing the rolls for the prescribed rolling schedule $D_0 \times S_0 \rightarrow D_T \times S_T$. The method includes the following stages.

The first stage entails calculating the lengths of the parts of the working cone that have two working sections l_w – with a certain overlap l_{olp} – and the sizing section of the second pair l_{k2} (Fig. 1):

$$l_w = L_{st} - L_{feed} - L_{rtn};$$

$$l_{olp} = l_w - A;$$

$$l_{k2} = k_{n2} m_1 \mu_\Sigma,$$

where L_{st}, L_{feed}, and L_{rtn} are the respective values for the travel of the stand: total travel, travel during the feed period, and travel during the return period; μ_Σ is the total reduction; k_{n2} = 2–3 is the polishing coefficient for the second roll pair; the remaining notation is explained in the text.

The section on which the deformation cones overlap consists of the sizing section of the first pair l_{k1}, the no-load section l_{nld}, and the beginning of the compression zone of the second pair $0.5l_*$:

$$l_{olp} = l_{nld} + 0.5l_* + l_{k1}.$$

The introduction of the coefficient k_2 is significant. It makes it possible to distribute the reduction between the two pairs of rolls and determines the thickness of the wall of the tube rolled in the first pair:

$$s_1 = k_2 d_1 \Bigg/ \left(\frac{D_T}{s_T} - (1 + k_2) \right).$$

Now let us proceed with the improved method and use the below formula to specify the regime for the true relative reductions in wall thickness [3]:

$$\frac{\Delta s_i}{s_i} = B\left(\frac{x}{l} - 1\right) e^{Ax/l}, \tag{4}$$

where l is the length of the compression zone of the corresponding roll pair; the coefficient B is determined from the boundary condition; the coefficient $A < 0$ varies and is determined based on the condition of minimizing the load near the sizing section in order to minimize either the longitudinal variation in the thickness of the tube wall or the damage content of the tube.

Wall thickness, the diameter of the mandrel, and the diameter of the tube in each control section are calculated in accordance with regime (4). The depth of the pass is calculated from the formula $h_i = (D_i - \Delta_i)/2$, where Δ_i is the gap between the collars of the passes in the given control section. The distribution of the gaps along the rolling cone is determined by the rigidity of the working stand according to experimental data and depends on the distribution of the rolling forces. Meanwhile, the total spreading force acting on the stand is comprised of the vertical forces under the first and second pairs of rolls: $P_\Sigma = P_1 + P_2$. For annular passes, we can adopt a dome-shaped distribution of Δ_i in accordance with the distribution of the vertical forces P_i and with allowance for the stand's stiffness coefficient.

Finally, we calculate the expansion and width of the pass in each section. The expansion of the first pair of rolls is calculated in accordance with standard rules, such as the rule developed by P. T. Emel'yanenko. The width of the pass of the second roll pair is calculated in accordance with the dimensions of the tube arriving from the first pair. In particular, on the section corresponding to the overlap zone $l_* + 0.5l_{k1}$ (see Fig. 1), the pass of the second roll pair should be wider than the pass of the first pair so that the part of the tube rolled in the first pair during the forward stroke can "pass through" the stand during the reverse stroke. The expansion should be minimal on the sizing section in order to ensure that the tube is rolled with the specified degree of accuracy.

In accordance with the methodology in [4], the damage accumulated during rolling in two pairs of rolls can be calculated from the formula

$$\omega = \omega_{r1} + \omega_{cr1} + \omega_{olp} + \omega_{r2} + \omega_{cr2}, \tag{5}$$

where ω_{r1} and ω_{r2} are the amounts of damage accumulated in the reducing zone under the first and second roll pairs, respectively; ω_{cr1} and ω_{cr2} are the same quantities in the compression zone; ω_{olp} is the same in the zone where the deformation cones of the first and second pairs of rolls overlap.

The components of Eq. (5) are calculated individually for each zone in relation to the number of stages of alternating deformation N [4]:

$$\omega = \sum_{j=1}^{N} \int_{0}^{\Lambda_j} \frac{a_j \Lambda^{a_j - 1}}{\Lambda_{p_j}^{a_j}} d\Lambda ,$$

where $a = f(\sigma/T)$ is an index that characterizes the reduction in the density of the material due to plastic deformation and $\Lambda_p = f(\sigma/T, \mu_\sigma]$ is the ductility of the metal determined from the empirical relations presented in [4]; σ/T is an index characterizing the stress state of the metal; μ_σ is the Lode coefficient.

In the course of calculating the axial forces in the *i*th IDZ, we evaluated the ratio of the advance and lag zones of the metal on the contact surface and used the following formula [5] to calculate the axial force with allowance for its sign:

$$Q_i = 2fp_i(F_{LGi} - F_{ADi}), \tag{6}$$

where $f = 0.1–0.3$ is the friction coefficient; p_i is the pressure of the metal on the rolls; F_{LGi} and F_{ADi} are, respectively, the areas of the lag and advance zones in the *i*th IDZ. These areas are determined from the formulas derived by Shevakin [6].

It is apparent from Eq. (6) that the compressive axial force will be negative in the case of high metal speeds and a large advance area $F_{LGi} < F_{ADi}$.

The possibility of the butt-joining of successive tubes – especially during the reverse stroke of the stand – and the potential for loss of stability by the tube in the form of harmonic vibration were checked on the basis of the condition

$$|Q_i^{\max}|/F_i \le 0.8\sigma_{0.2}, \tag{7}$$

where F_i is the cross-sectional area of the semifinished product being rolled, and $\sigma_{0.2}$ is the yield strength of the metal of the semifinished product.

Negative consequences can ensue if condition (7) is not satisfied.

The features discussed above were taken into account in developing an expert automated system to design technologies for the cold periodic rolling of tubes on Pilger-type mills [5, 7]. The system was used to study the laws that govern damage accumulation and changes in the force parameters and to develop recommendations on how to successfully introduce the use of a tandem cold-rolling tube mill at the Sinarsky Pipe Plant.

On the whole, the studies that were performed showed that with the use of properly designed rolls the amount of damage accumulated in stainless steels even with drafts of 7–8 will remain at or below the critical value $\omega_* = 0.3$ that corresponds to the formation of defects which cannot be removed by heat treatment. The reason for this is the favorable stress state that is created during rolling on the four-high tandem cold-rolling tube mill and the good ductility properties of the given grade of steel. The existing laws governing the effect of the rolling regime were again validated: damage content is increased by an increase in the feed, the expansion of the rolls, and the frequency with which particles enter the outlet region of the pass. It was determined that due to the axial load (2) the stress state is somewhat less severe during the reverse stroke than during the forward stroke. Considerably less damage is therefore accumulated in the reverse stroke, although this part of the rolling operation is accompanied by an increase the axial rolling forces. The feature just mentioned is in fact one of the reasons for the efficiency of rolling on a four-high tandem cold-rolling tube mill. The deformation in the pair of sizing rolls is roughly the same during the forward and reverse strokes. Thus, it is expedient to increase the percentage of deformation done in the breakdown rolls (satisfy Eq. (7)) while using the second pair as sizing rolls. In practice, the strain ratio is chosen experimentally by comparing several variants for the rolling operation. The design approach proposed here makes it possible to assign a certain ratio of deformation during the stand's forward stroke to deformation during its reverse stroke (in each pair of rolls).

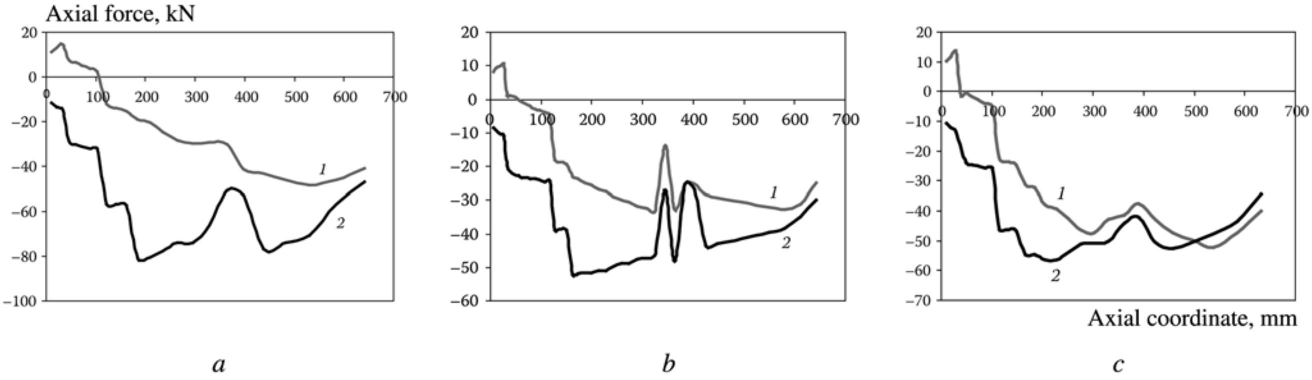

Fig. 2. Distribution of the axial forces in rolling on a KhPT-32-tandem mill with gear ratios of 1.057 (*a*), 1.032 (*b*), and 1.028 (*c*): *1*) forward stroke of the stand; *2*) reverse stroke of the stand.

The above method was used on a computer to design new rolls and analyze the rolling of steel 45 tubes on the KhPT-32-tandem mill at the Sinarsky Pipe Plant in accordance with the new schedule 45 × 3 → 25 × 1 mm. The draft was 5.25. It is apparent from the graphs in Fig. 2 that, in accordance with Eq. (2), the compressive axial forces increase more rapidly in the first pair of rolls (up to $x = 300$ mm). The axial forces decrease in the zone where the deformation cones overlap due to the low rate of compression. The forces exerted by the metal on the rolls in this zone decrease for the same reason. Because the amount of metal rolled in the sizing-roll pair during the reverse stroke of the stand is greater than in a normal mill, the forces on the rolls are greater during this stroke than during the forward stroke.

We subsequently studied the effect of the gear ratio of the diagonal transmission in Eq. (1), which determines the nominal diameter of the pinion of the second roll pair and the axial forces that the pair transmits. The gear ratio on the stand being discussed is 1.057, which led to high axial forces (see Fig. 2*a*), violation of condition (7), and destabilization of the tube. To lower the axial forces, it was proposed that the gear ratio be reduced to 1.032 by decreasing the diameter of the gear wheel of the second roll pair. A larger decrease in the gear ratio would be inadvisable, since it would increase the area of the lead zone and increase the axial compressive force created during the forward stroke of the stand (see Fig. 2*c*) in accordance with Eq. (6). This situation is illustrated by the below data:

Gear ratio	1.057	1.032	1.028
Maximum axial force, kN	79.8	52.1	56.2
Maximum relative stress based on Eq. (7)	0.92	0.70	0.76

The change in the gear ratio (see Fig. 2) lowered the axial forces by 32–37%, which makes it possible to avoid butt-joining of the ends of tubes. The change in gear ratio had almost no effect on the distribution of the forces on the rolls.

Conclusions. This investigation examined aspects the rolling of tubes on a tandem cold-rolling tube mill: the effect of the gear ratio of the diagonal transmission on the force conditions, the effect of the continuous feed of metal into the second pair of rolls, the subdivision of the strains between the two pairs of rolls, and calculation of cumulative damage. These factors were taken into account in developing an expert automated system to design a technology for the cold periodic rolling of tubes.

As for the KhPT-32-tandem mill, the improved method was used to design rolls for a new rolling schedule. To reduce the axial forces, it was recommended that the gear ratio be decreased from 1.057 to 1.032.

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