Research of Radial Flattening of Rolls in the Deformation Zone during Sheet Rolling

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Abstract. The radial flattening of the rolls in the deformation zone is one of the reasons leading to the appearance of a strip minimum thickness during sheet rolling. Working rolls come into contact at the barrels edges as a result of pressing the strip into their core. At the same time, the rolling force increases significantly during rolling, reaching limit values for the rolling mill. A further reduction in thickness is not possible for this reason. Therefore, an accurate determination of the rolls radial flattening is necessary for developing modes of belt deformation. The rolls radial deformation during the rolling of the belts in various modes was investigated, the existing methods for determining it in the work for the symmetric process and asymmetric rolling processes with different peripheral speeds of the work rolls were tested at the DUO-200 KhPL SUSU (NRU) experimental mill.

1. Introduction
In theory and practice of rolling production, it is known that one of the reasons leading to the appearance of a strip minimum thickness during rolling is the rolls radial flattening in the deformation zone. The work rolls cores come into contact at the bodies edges as a result of indentation of the strip in them. In this case, for example, during ordinary (symmetrical, SR) rolling, the rolling force increases significantly, and in asymmetric rolling with different peripheral speeds of the work rolls, particular during the rolling-drawing process (RD) [1, 2], the rolls contact at the bodies edges heat rolls, thermal stresses and chip rolls. There is such a specific defect as ribbing, which makes it impossible to further rolling due to deterioration in product quality.

2. Methods
The work aim is to study the rolls radial deformation in the deformation zone during sheet rolling using symmetric and asymmetric rolling, assessment of existing methods for its determination.

Two methods are used in the practical experimental study of rolls radial deformation at present. The essence of the first method is that during the deformation of the strip in the rolls, small lead “pilot” strips are simultaneously rolled [3]. The difference in the thickness of the strip and the "pilot" determine the total radial rolls deformation in the deformation zone. The second research method is based on a change in the electrical resistance of a wire isolated from the roll core located in a small diametrical hole in the work roll [4]. The electrical resistance of the wire changes when its length changes.
The advantage of this method is the ability to obtain changes in radial deformation along the length of the deformation zone. However, to certain disadvantages of this method can be attributed the complexity of the work roll design, the violation of its continuity.

Rolling “pilots” near the strip does not cause difficulties. In order to minimize the effect on the experimental study results of the rolls elastic deformation during the rolling of “pilots”, it is necessary to select the initial “pilots” thickness such that it does not exceed the strip thickness at the exit from the deformation zone in 1.1–1.2 times. In this case, the elastic deformation of the rolls in contact with the “pilots” is close to zero, as the experimental rolling shows. The use of micrometers for measuring the strip and “pilots” thickness with an accuracy of 0.5 μm allows for high measurement results accuracy.

The research technique and processing of experimental data was as follows.

Annealed strips 40 mm wide of CuZn36 brass, 040A10 and 321S31 steels were rolled with front and rear tension at the Duo-200 mill of SPSU SUSU (NRU) with front and rear tension. The initial strips thickness: brass CuZn36 and steel 321S31 – 0.5 mm, steel 040A10 – 0.33 and 0.5 mm. Hardness of rolls is 59–61 HRz.

Strip with different draws in the aisle were rolled in the SR and RD modes. During rolling, peripheral roll rotation speeds ratio (Kv) was changing from 1 to K = (λ is the ratio of the strip thicknesses to (h0) and after rolling (h1), K = V1i/Vr0, V1i, Vr0 are the peripheral speeds of the rolls, V1i > Vr0).

The following parameters were recorded during rolling: the rolling force (P), the forward creep of the strips, their thicknesses before and after rolling. The rolling force was measured by dynamometer mounted under the mill screws. Measurement of the strips forward creep (i1, i0) relative to the rolls was carried out according to the punch method [5, 6] (here i1, i0 is the lead on the leading V1i and driven Vr0 rolls, respectively).

The strips thickness in the middle and the “pilots” was measured using a measuring bracket with a type “LIZ” GOST 10197 indicator with a 1 μm scale division.

Strips rolling was carried out simultaneously with the rolling of four “pilots”. Two “pilots” rolled at a distance of 5 mm from the strip edges, and two “pilots” at the roll body edges. “Pilots” fedded in the rolls by the wires. Rolling four “pilots” allows you to control the roll gap shape, i.e. possible crossings and deflection of the rolls.

3. Results

The results were processed as follows. The rolls radial deformation was determined as the arithmetic mean of the left and right edges of the strip by the equation:

$$\Delta R_r = 0.5(\Delta R_{right} + \Delta R_{left})$$  \hspace{1cm} (1)

where $\Delta R_{right}$, $\Delta R_{left}$ - roll radial deformation at the right and left edges, respectively.

The radial deformation at each edge of the strip was determined by the equation:

$$\Delta R_{right} = 0.5(h_1-h_{pr}), \Delta R_{left} = 0.5(h_1-h_{pl})$$  \hspace{1cm} (2)

where $h_{pr}$, $h_{pl}$ are the “pilots” thicknesses at the right and left edges.

As is known, in indirect measurements, the measured quantity A is related to the measured parameters $a_i$ by the dependence:

$$A = f(a_1...a_m)$$  \hspace{1cm} (3)

The parameters values $a_1...a_m$ are usually obtained by direct measurements.

In this case, the radial deformation target value of the rolls is found from expressions (1) and (2).

The measured parameters (arguments) are changed randomly, with indirect measurements. In this regard, a special method is used to process the results – the reduction method, in which the results of indirect measurements lead to a number of direct consistent measurements. Statistical processing of experimental data was performed according to the method described in [7].
The result of indirect measurement and calculated by the equation:

\[ \bar{A} = \frac{\sum_{k=1}^{n} A_k}{n} \]  

(4)

where \( n \) is the number of individual values of the measured, \( A_k \) is the individual value of the measurand obtained by substituting the \( k \)th combination of consistent measurement results.

The root-mean-square deviation of the indirect measurement result is found by the equation:

\[ S(\bar{A}) = \sqrt{\frac{\sum_{k=1}^{n} (A_k - \bar{A})^2}{n(n-1)}} \]  

(5)

Confidence limits of measurement result random error are calculated by the equation:

\[ \varepsilon(p) = tS(\bar{A}) \]  

(6)

where \( t \) is the Student’s distribution coefficient.

Empirical regression lines are plotted in Figure 1–3 based on the statistical processing results. Subsequently, the experimental data on the study of rolls radial flattening were processed using the least squares method, the parameters of the theoretical regression line were determined, and its correlation analysis was performed.

Analysis of the results and conclusions:

1. The table shows the influence of rolling process technological parameters on the rolling force and the rolls radial deformation (Figures 1–3). The presented results confirm the theoretical and experimental laws on the influence of the mismatch of the rolls rotation speeds, the strip drawing in the passage, its strength characteristics on the rolling force.

The rolling force, for example, for brass CuZn36 decreases by more than 2 times (Figure 1) with a change in the parameter \( K_v = 1 \) to \( K_v = \lambda \) (condition RD, \( i_1 = 0, i_0 = 33\% \)). The same trend is observed for other materials (table 1).

2. The nature of the change in the radial deformation of the rolls almost corresponds to the nature of the change in the rolling force. A close relationship between the rolls radial deformation is characteristic of both SR and any asymmetric rolling process.

With an increase in the parameter \( K_v \) (Figure 3), the radial flattening of the rolls decreases almost by the same amount as the rolling force decreases during RD compared with SR.
Similarly, the rolls radial deformation increases in the case of both RD and SR with an increase in drawing. It can be seen from the information shown in Figure 2 that for small drawing (up to $\lambda = 1.1$), the radial deformation of the rolls differs slightly ($R_{sr}/R_{dr} = 1.17 \ldots 1.3$, $R_{sr}/R_{dr} = 1.16 \ldots 1.35$). The radial deformations in case of a RD are, usually, 2.5 to 3 times less than in case of a SR with drawing $\lambda > 1.3$, which corresponds to a decrease in rolling force during RD as compared to SR.

3. The experimental results presented in Figures 1–3 and in the table are described by the linear regression equation using the least squares method. For the conditions of the experimental mill Duo-200, the equation is:

$$\Delta R_r = 2.32 + 0.008P / B$$

where $P$ is the rolling force (kN), $B$ is the strip width (m).

The correlation analysis [8] of expression (7) confirmed the close relationship between $\Delta R_r$ and $P$ ($r \Delta R_rP = 1$), which indicates the possibility of using this expression to calculate the rolls radial deformation for the Duo–200 mill when designing deformation modes [9–11].

4. The experimental data obtained in this work make evaluate using known methods for engineering calculations possible for determining the radial flattening of rolls. This is especially important for designing rolling thin strips and foils deformation modes because, the rolling process should be carried out without the rolls contact at the bodies’ edges in asymmetric rolling.

Mostly, the calculation methods for determining the rolls radial flattening are based on the Hertz problem solution of compressing two cylinders whose axes are parallel, and normal contact stresses on the roll contact area are distributed according to an elliptic dependence.

Kovalsky B. S. obtained the equation, using the Hertz method [12, 13]:
\[ \Delta R_r = 2\theta_r \frac{P}{B} \left( \ln \frac{2R}{a} + 0.407 \right) \]  

(8)

where \( \theta_r = \frac{1-v_r^2}{\pi E_r} \) (\( v_r, E_r \) - Poisson’s ratio and the roll material modulus of elasticity), \( a \) – half width of the cylinder contact area.

It is fundamental to determine the half-width of the rolls contact area or the deformation zone half-length (\( a = 0.5 \) \( l_c \)) in the equation (8). The Hertz problem of two cylinders did not imply the presence of a plastically deformed strip between the rolls. In addition, there are zones of elastic compression and strip restoration when sheet cold rolling at the entrance and exit of the deformation zone. This case, as is known, affects the width of the contact area, i.e. the length of the deformation zone.

Nevertheless, methods for calculating the length of the deformation zone in symmetric sheet rolling have been developed, approximating real diagrams of normal contact stresses by elliptic distribution. However, it can be assumed that for any method of sheet rolling (SR, AR, DR), the distribution of normal contact stresses along the length of the deformation zone can also be approximated by an elliptic distribution.

In this case, we use known equations to determine the deformation zone length.

So, according to Tselikov-Hitchcock [14, 15], without the strip elastic deformation we have:

\[ l_c = (R\Delta h(1+16q\theta_r / \Delta h))^{1/2} \]  

(9)

where \( \Delta h \) is the draught of the strip, \( q=P/B \).

The equation [16] is proposed by Dinnik A. A.:

\[ l_c = (R(1+16q\theta_r(1+\frac{\theta_p}{\theta_r})))^{1/2} \]  

(10)

where \( \theta_p = \frac{1-v_p^2}{\pi E_p} \) (here \( v_p, E_p \) - Poisson’s ratio and elastic modulus of the strip material, respectively).

To determine the length of the deformation zone, we use the expression [12, 13] obtained by Polukhin V.P.:

\[ l_c = (R\Delta h + C_i (\theta_r + \theta_p ) R q)^{1/2} \]  

(11)

where \( C_i = 8 + 4\left( \frac{\Delta h}{\theta_r q(1+n)} \right)^{1/2}, n = \frac{\theta_r}{\theta_p} \).

An equation (12) for calculating the rolls radial flattening is obtained using expressions (8, 9) in [17, 18]:

\[ \Delta R_r = \theta_r q(\ln R + \frac{32}{16\theta_r q + \Delta h} + \frac{32}{16\theta_r q + \Delta h} + 1,587) \]  

(12)

The working roll radial deformation was calculated for various kinematic variants and deformation modes (see table). An analysis of the calculated and experimental data shows that the closest calculated results compared with the experimental ones were obtained using the Grigorjan-Zheleznoy method equation (12). The largest deviation of various materials, processes and deformation modes is 25%. Other methods, in particular according to expression (11), give a deviation from experimental data up to 67%.

Thus, it is advisable to calculate the rolls radial deformation in the deformation zone using equation (12) for symmetric and asymmetric rolling processes, including DR.
Table 1. Experimental and calculated radial data rolls flattening during rolling at the mill Duo – 200.

| Material  | $h_0$ mm | $\lambda$ | Process | $K_r$ | $q$ kN mm | $\Delta R_r^q$ $\mu$m | $\Delta R_r^1$ $\mu$m | $\Delta R_r^2$ $\mu$m | $\Delta R_r^3$ $\mu$m | $\Delta R_r^4$ $\mu$m |
|-----------|----------|-----------|---------|-------|-----------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| CuZn36   | 0.5      | 1.07      | DR      | 1.07  | 60        | 6.0                   | 1.18                  | 1.12                  | 1.39                  | 1.14                  |
| CuZn36   | 0.5      | 1.18      | DR      | 1.18  | 100       | 12.8                  | 0.84                  | 0.8                   | 1.0                   | 0.8                   |
| CuZn36   | 0.5      | 1.5       | DR      | 1.5   | 150       | 16.2                  | 0.93                  | 0.89                  | 1.12                  | 0.82                  |
| 040A10    | 0.5      | 1.07      | DR      | 1.07  | 70        | 7.0                   | 0.86                  | 1.12                  | 1.41                  | 1.14                  |
| 040A10    | 0.5      | 1.18      | DR      | 1.18  | 115       | 9.0                   | 0.75                  | 1.33                  | 1.67                  | 1.25                  |
| 040A10    | 0.5      | 1.5       | DR      | 1.5   | 175       | 14.0                  | 0.83                  | 1.2                   | 1.3                   | 1.12                  |
| 321S31    | 0.5      | 1.07      | SR      | 1.0   | 135       | 17.5                  | 0.86                  | 0.83                  | 1.05                  | 0.88                  |
| 321S31    | 0.5      | 1.18      | SR      | 1.18  | 200       | 20.5                  | 1.01                  | 0.98                  | 1.23                  | 0.91                  |
| 321S31    | 0.5      | 1.5       | SR      | 1.5   | 400       | 33.0                  | 0.86                  | 1.21                  | 1.43                  | 1.1                   |
| 321S31    | 0.5      | 1.07      | AR      | 1.0   | 600       | 58.0                  | 1.22                  | 1.19                  | 1.2                   | 1.0                   |
| CuZn36   | 0.3      | 1.5       | AR      | 1.0   | 275       | 23.0                  | 1.22                  | 1.13                  | 1.43                  | 1.1                   |
| CuZn36   | 0.3      | 1.5       | DR      | 1.5   | 120       | 12.0                  | 1.1                   | 1.0                   | 1.23                  | 1.05                  |

$^1\Delta R_r$ – $l_r$ according to Tselikov–Hitchcock, $\Delta R_r$ – according to Kovalsky B. S.

$^2\Delta R_r$ – $l_r$ according to Dinnik A. A., $\Delta R_r$ – according to Kovalsky B. S.

$^3\Delta R_r$ – $l_r$ according to Polukhin V. P., $\Delta R_r$ – according to Kovalsky B. S.

$^4\Delta R_r$ – according to Grigoryan–Zheleznov

4. Conclusion

The rolls radial flattening during symmetric and asymmetric rolling, including PV, was experimentally studied for various materials and deformation modes using the “pilots” method.

The lowest rolls radial deformation in compare with symmetric process appears during DR (in 2-3 times).

The nature of the change in the rolls radial deformation is almost proportional to the change in the rolling force.

A comparison of different calculation methods and experimental data on the rolls radial deformation during asymmetric and symmetric rolling indicates the possibility of using the Grigoryan - Zheleznov method in designing the deformation modes for sheet rolling.

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