The Simplifying the Calculation of the Strip Profile during Rolling in a Four-High Mill Stand

M I Rumyantsev, A N Kolybanov and O K Yesipova
Department of Materials Processing Technologies, Nosov Magnitogorsk State Technical University, 38, Lenin Street, Magnitogorsk, 455000, Russia
E-mail: mikhail.rumyantsev54@bk.ru

Abstract. The task of simplifying the calculation of deformation of the rolls and the strip profile during rolling in a four-high (quatro) stand has been formulated and stated in the article. The design and computer experiment results on the basis of which nonlinear approximations have been obtained for simplified calculation of the transverse rigidity moduli of the roller unit of the quatro finishing stand of the wide - strip hot mill 2500 have been described. The calculation of the transverse rigidity moduli of the roller unit of the quatro finishing stand is performed depending on the rolling force and the regulating force.

1. Introduction
The main element of the system “Four-High Mill Stand” is a roll unit (roll system). Elastic deformations of the roll system affect the cross-sectional shape (profile) of the strip and can cause “transverse thickness variation” and “nonflatness” defects [1–4]. The task of calculating the deformation of the rolls for prediction of strip profile is important for controlling the rolling process. In the most general formulation, it is necessary to consider the joint description of the stress-strain state (SSS) of both the roll system and the rolled strip using the three-dimensional theory of elasticity and plasticity. There are various methods for calculating roll deformation [5–11]. But the calculations by simple methods [5–6] give a noticeable error, and the calculations by more accurate methods [7–11] are, as a rule, labor-consuming.

A model of deformation of a quarto roller unit under symmetric loading was created and developed by the scientists: Salganik V.M., Melzer V.V., Poletskov P.P. and Omelchenko B.Ya. at the Metal Forming Department of Nosov MSTU in 1970–2009 [12–14]. Good results were obtained with its use in solving a number of problems [14–16]. The essence of the task of simplifying the calculation is to replace the complex of analytical dependencies that make up this model with two approximations, which are obtained from the results of computer simulation performed according to the experimental designing procedure [17].

2. Features of the roll unit deformation model
The transverse thickness variation (profile) of the strip at the exit of the rolls:

\[ \delta h = \frac{K_c - K}{K_c} \cdot (w_{p1} + w_{p2} - z_{p1} - z_{p2}) + \frac{K_c}{K_c} \cdot \delta H, \]

where \( w_{p1} \) and \( w_{p2} \) are the deflections of the axes of the upper and lower work rolls; \( z_{p1} \) and \( z_{p2} \) are the current profiles of the upper and lower work rolls; \( \delta H \) is transverse thickness variation of the strip at the entrance to the rolls; \( K_c \) is coefficient of elastic compliance of the work rolls.
\[ K_e = \frac{\pi}{2 \cdot 1 - v_p^2} \cdot \ln \left( \frac{3.04 \cdot D_{ww} \cdot E_p}{P_w \cdot (1 - v_p^2)} \right) \]

where \( v_p \) and \( E_p \) are Poisson's ratio and Young's modulus for compressing the material of the work roll. For example, for a steel forged roll \( v_p = 0.3 \) and \( E_p = 20.59 \cdot 10^4 \) MPa. For the alloyed cast-iron roll of a two-layer casting \( E_p = 14.71 \cdot 10^4 \) MPa and \( v_p = 0.27 \); DWR is the diameter of the barrel of the work roll; \( P_{ww} = P/W \) is the rolling force related to the strip width; \( K_e \) is the effective coefficient:

\[ K_e = \frac{K_{bh} \cdot K_c}{K_{bh} + K_c}. \tag{3} \]

\( K_{bh} = P/\Delta h \) is the coefficient of the strip compliance.

The profiles of the work rolls \( z_{p1} \) and \( z_{p2} \), and also necessary for other calculations, the profiles of the support rolls \( z_{o1} \) and \( z_{o2} \) are the initial data. The deflections of the work rolls \( w_{p1} \) and \( w_{p2} \) are determined taking into account the deflections of the support rolls \( w_{o1} \) and \( w_{o2} \) and the sinking of the work rolls as the beams on an elastic base. And the loading of the roll unit not only by the rolling force \( P \), but also by the regulating force of the anti-bending (+\( Q \)) or the additional bending (-\( Q \)) of the work rolls is displayed. In general, the model includes 11 equations and is implemented by using the matrix method, which requires the application of a special computer program.

3. A possible approach to simplify the calculation of roll deformation and strip profile

In order to simplify the calculation of the transverse strip thickness variation, the method of approximation of the roll deflection dependence on the dimensions features of the roll unit and the loading conditions can be applied. With this approach, a multiple regression analysis will produce an equation that, given the current characteristics of the roll unit, the strip width, the effort values \( P \) and \( Q \), will allow the value \( \delta h \) to be determined by a simple calculation using the formula. Such approach was used, for example, in [6] for calculating the deformation of the roll unit of the cold rolling quarto-mill 1700.

In a more general form, the indicated simplifying approach can be applied if the dependence for calculating the modulus of the transverse rigidity of the roll system will be constructed. The transverse strip thickness variation is expressed in terms of the moduli of the transverse rigidity of the roller system from the rolling force \( M_{ww}^p \) and the regulating force \( M_{ww}^q \) as follows [18–19]:

\[ \delta h = \frac{P}{M_{ww}^p} - \frac{Q}{M_{ww}^q}. \tag{4} \]

The stiffness moduli are numerically equal to the inverse of the change in the transverse strip thickness variation from a single increment of the rolling force \( \delta h_P \) and the regulating force \( \delta h_Q \) according to the following formulas:

\[ M_{ww}^p = \frac{1}{\delta h_P} = \frac{P' - P}{\delta h(P') - \delta h(P')}, \tag{5} \]

\[ M_{ww}^q = \frac{1}{\delta h_Q} = \frac{Q' - Q}{\delta h(Q') - \delta h(Q')} \tag{6} \]

where, \( \delta h(P') \), \( \delta h(P'') \) and \( \delta h(Q') \), \( \delta h(Q'') \), are the values of the transverse thickness variation of the strip at different values of the rolling force \( P' > P'' \) and the regulating force \( Q' > Q'' \), respectively, and all other conditions being equal.
Thus, to simplify the calculation of the deformation of the roll unit and the profile of the strip during rolling in the quarto stand, it is necessary to find the dependence of the modulus of the transverse rigidity of the roller system on the influencing factors $x_1; x_2; x_3 \ldots x_n$:

$$M_W = f(x_1; x_2; x_3 \ldots x_n).$$

(7)

4. Experiment design

The experiment was carried out by means of a computer program in MS EXCEL, and a mathematical model [12–14] was implemented. The finishing stand of the wide – strip hot mill 2500 of the PJSC “MMK” was selected as the subject of the study. The goal of the experiment was to replace the above model with a polynomial dependency.

According to the experimental designing technique [17], a second-order symmetric composite rotatable design was chosen. And since four influencing factors had been chosen, the design was four-factor. In total, 25 experiments were conducted, 16 of which correspond to the full factorial experiment (“core” of the design), 8 experiments with “star” points and one experiment in the middle of the design. The range of the factors change was chosen according to the possible change of these factors at the wide - strip hot mill 2500. The rolling force at the points of the design was assumed to be 16 MN, and the regulating force was 0.2 MN. The levels of variation of the factors were presented in table 1.

Table 1. Levels of factors variation.

| Factors          | $W$ [mm] | $l_{OR}$ [mm] | $D_{WR}$ [mm] | $K_{\Delta h}$ [MPa] |
|------------------|---------|--------------|---------------|----------------------|
| Main level, (0)  | 1625    | 2200         | 690           | 20460                |
| Variation interval | 187     | 100          | 10            | 8120                 |
| Upper level, (+1)| 1812    | 2300         | 700           | 28580                |
| Lower level, (-1)| 1438    | 2100         | 680           | 12340                |
| Star point, (+2) | 2000    | 2400         | 710           | 36700                |
| Star point, (-2) | 1250    | 2000         | 670           | 4220                 |

5. Experimental results

After the regression equations had been obtained according to the method [17], and the transition from them to polynomials with natural factors had been made, two equations for the roll stiffness moduli from the rolling force $M_w^p$ and the regulating force $M_w^\theta$ had been got:

$$M_w^p = -26465 + 3.227 \cdot W + 2.918 \cdot l_{OR} + 62.39 \cdot D_{WR} + 1.45 \cdot K_{\Delta h} - 0.018405 \cdot W \cdot l_{OR} + 0.00666 \cdot W \cdot D_{WR} + 0.0011846 \cdot W \cdot K_{\Delta h} - 0.02412 \cdot l_{OR} \cdot D_{WR} - 0.001767 \cdot l_{OR} \cdot K_{\Delta h} + 0.002833 \cdot D_{WR} \cdot K_{\Delta h} + 0.010365 \cdot W^2 + 0.009477 \cdot l_{OR}^2 - 0.00975 \cdot D_{WR}^2 - 0.000007 \cdot K_{\Delta h}^2$$

(8)

$$M_w^\theta = 1990 + 0.732 \cdot W - 1.3359 \cdot l_{OR} - 3.6758 \cdot D_{WR} + 0.387 \cdot K_{\Delta h} - 0.001243 \cdot W \cdot l_{OR} - 0.0030986 \cdot W \cdot D_{WR} - 0.0002147 \cdot W \cdot K_{\Delta h} + 0.00081 \cdot l_{OR} \cdot D_{WR} - 0.000261 \cdot l_{OR} \cdot K_{\Delta h} + 0.0006084 \cdot D_{WR} \cdot K_{\Delta h} + 0.00111014 \cdot W^2 + 0.000747 \cdot l_{OR}^2 + 0.006 \cdot D_{WR}^2 - 0.00000023 \cdot K_{\Delta h}^2$$

(9)

After the calculation by equations (equation 1, equation 2), the value $K_{\Delta h}$ should have the dimension kg/mm².

Figure 1–2 presents the diagrams of correspondence of the rolls stiffness modules from the rolling force and the regulating force, respectively, calculated with the use of the model [12–14] and the obtained equations (8–9). Table 2 shows the relative $\delta$ and absolute errors $\Delta$, the coefficient of determination (degree of conformity) $R^2$ and the effectiveness [20] $E_\delta$ of the obtained mathematical
model with $|\delta|$ no more than 5%. The indicated quality estimates of the model show that its compliance with the experimental results can be considered excellent.

![Figure 1. Correspondence diagram of the stiffness modulus from the rolling force.](image1)

![Figure 2. Correspondence diagram of the stiffness modulus from the regulatory force.](image2)

**Table 2.** Estimated characteristics of the mathematical model.

|                      | $\delta$, [%] | $\Delta_2$, [%] | $\Delta$, [kN/mm] | $\Delta_3$, [kN/mm] | $R^2$ | $E_5$, [%] |
|----------------------|---------------|-----------------|-------------------|---------------------|-------|-----------|
| **Roller stiffness modulus from the rolling force** | -3.74…6.55    | 0.16            | -1.80…2.32       | 0.06                | 0.99  | 96        |
|                      | -6.98…0.79    | -1.73           | -0.71…0.12       | -0.15               | 0.99  | 92        |

The dependences of the rolls stiffness moduli on the width of the strip under the operating rolling force and the regulating force at the maximum, average and minimum values of the influencing factors are shown in figure 3. From figure 3 it can be seen that the greater the length of the inter-roll contact $l_{OR}$ is the greater the stiffness moduli are. But if the modulus $M_{W}^O$ is monotonously decreasing with the strip width increase, then the modulus $M_{W}^R$ has the minimum, the position of which depends on the width. With an increase in the length of the inter-roll contact, the indicated minimum shifts to the region of large widths.

6. Conclusion

The calculation task of the rolls elastic deformation of the strip rolling mill is important not only for assessing the rigidity of the working stand, but also for calculating the transverse profile of the strip. The solution of this problem with the use of simple methods has a noticeable error, and the calculations by more accurate methods are laborious. In order to simplify the calculation of the transverse strip thickness variation, it is possible to use the method of approximation of the calculation results of roll deformations by using exact methods in a wide range of variation of the roll unit features and loading conditions. In this case, it is advisable to take the moduli of the transverse rigidity of the roller unit from the rolling force and from the regulating force as the approximated value, and the actual approximation should be non-linear.
When the method of the experiment designing is used, second-degree polynomials are obtained, which makes it possible to simplify the calculation of the transverse rigidity moduli from the rolling effort and from the regulating force for the roll unit of the finishing stand of the wide-strip hot mill 2500 of the PJSC MMK. The effectiveness of the mathematical model in the form of these polynomials with an admissible error of 5% is 96% for the modulus of rigidity from the rolling force and 92% from the regulating force. The calculation according to these expressions is made in a short time, which is a significant advantage for production conditions.

Figure 3. Dependence of the rolls stiffness moduli on the width of the strip with the variation of the rolling force (a) and the regulating force (b): 1- \( l_{OR} = 2400 \) mm, \( D_{WR} = 710 \) mm, \( K_{th} = 36700 \) MPa; 2- \( l_{OR} = 2200 \) mm, \( D_{WR} = 690 \) mm, \( K_{th} = 20460 \) MPa; 3- \( l_{OR} = 2000 \) mm, \( D_{WR} = 670 \) mm, \( K_{th} = 4220 \) MPa.

References

[1] Shatalov R L 2004 Control of strip quality and deformability in rolling Steel in Translation 34(9) 43–47
[2] Shatalov R L, Maksimov E A and Babkin A G 2011 Adjustment of rolling mills to produce flatter steel strip Steel in Translation 41(10) 845–848
[3] Shatalov R and Genkin A 2015 Sheet mill control in steel strip hot rolling Journal of Chemical Technology and Metallurgy 50(6) 624–628
[4] Belsky S M, Mazur I P, Lezhnev S N and Panin E A 2016 Shaping strip for sheet rolling (Temirtau) p 161
[5] Tretyakov A, Garber E and Davletbaev G 1976 Calculation and study of rolling rolls (Moscow: Metallurgy) p 256
[6] Grigoryan G G, Zheleznov Yu D, Cherny V A, Kuznetsov L A and Zhuravsky A G 1975 Setting, stabilization and control of the sheet rolling process (Moscow: Metallurgy) p 368
[7] Polukhin V P 1972 Mathematical modeling and computer calculation of sheet rolling mills (Moscow: Metallurgy) p 512
[8] Budakva A A, Konovalov Yu V and Tkalich K N 1986 Profiling rolls sheet mills (Moscow: Technique) p 190
[9] Bolobanova N L 2015 Development of methods for modeling profiling and elastic deformations of rolls of sheet mills with the aim of improving the technology of rolling wide lanes (Cherepovets) p 123
[10] Zhengwen Yuan, Hong Xiao, Hongbiao Xie 2014 Practice of Improving Roll Deformation Theory in Strip Rolling Process Based on Boundary Integral Equation Method Metallurgical and Materials Transactions \textbf{45(2)} 1019–1026

[11] Shao Jian, Li Bo, He Anrui, Sun Wenquan, Liu Zhubin and Zhou Jie 2015 Roll Deformation Model of Four High Hot Rolling Mills Based on Improved Influence Function Method The Open Automation and Control Systems Journal \textbf{7} 93–99

[12] Salganik V M, Melzer V V and Omelchenko B Ya 1977 Calculation of profiling rolls of sheet rolling mills (Sverdlovsk) p 57

[13] Salganik V M 2002 Mathematical modeling of roll load and deformation in a four-high strip mill. Metal Forming The University of Birmingham

[14] Salganik V M 2009 \textit{Modeling deformations and loads of the quarto roll system and improving the quality of sheet products along the profile} (Magnitogorsk) p 133

[15] Salganik V M, Poletskov P P, Sinitsky O V, Soloviev A G and Lytyaykina Yu B 2003 \textit{Increasing the flatness of wide bands on the hot rolling mill 2500 of MMK in the conditions of preferential production of narrow bands} (Cherepovets)

[16] Omelchenko B Ya 2006 \textit{Model of the formation of the strip profile in the finishing group of the wide-strip hot rolling mill. Materials of the 64th scientific and technical conference on the results of scientific research for 2004–2005} (Magnitogorsk)

[17] Novik F S and Arsov Ya B 1980 \textit{Optimization of metal technology processes by experiment planning methods} (Moscow: Mechanical Engineering) p 304

[18] Barkaya V F, Rokotyan S E and Ruzanov F I 1976 Sheet metal change (Moscow: Metallurgy) p 264

[19] Rokotyan S 1991 Theory of rolling and the quality of the metal (Moscow: Metallurgy) p 223

[20] Rumyantsev M I and Tulupov O N 2018 Further developments in simulation of metal forming processes \textit{CIS Iron and Steel Review} \textbf{16} 21–24.