UDC 621.771 DOI: 10.17580/cisisr.2018.02.04

FURTHER DEVELOPMENTS IN SIMULATION OF METAL FORMING PROCESSES

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Key words:

mathematical model, relevance, effectiveness, large plates, plate mill, height of the deformation zone, stress state index, yield stress, rolling force.

ABSTRACT

The authors of this paper propose to use such additional characteristics as 'Relevance' and 'Effectiveness' when analysing a simulation model. These indicators provide a model characterization within the entire range of variations of the output parameters of the object. Relevance is defined as a degree to which the ideal trend matches the real one on the relevance chart showing the predicted and actual values of a simulated parameter. Effectiveness is defined as a proportion of observations of the predicted values of a parameter deviating from the actual values with a relative error not exceeding the specified level to the total number of observations.

The paper describes an example of a model for predicting the rolling force required to produce large plates in plate mills and of how to build and analyse such model. The first feature that differentiates this model from the existing ones is that a more detailed differentiation of rolling instances in terms of height of the deformation zone is taken into account when calculating the stress state index in the deformation zone. The second distinctive feature is that L. V. Andreyuk's modified formula was used for yield stress calculations. Data from two-stand plate mill 2800 and single-stand plate mill 5000 were used to analyse the quality of the model. The rolling force calculations performed with the developed model had a relative error within −15.1 to +20.8%. The model showed an 11% increase in relevance and a 48% increase in effectiveness.

Introduction

Considering the general definition of mathematical model [1–3 et al.] and how it is defined in the field of metal forming [e.g. 4–6], we shall regard a mathematical model as a combination of mathematical objects and relations between them which follow a certain algorithm. In terms of building a mathematical model, we shall consider to be acceptable the sufficiency principle, which says that the variety of types and the quantity of mathematical objects constituting a model shall be considered sufficient if the model can simulate the phenomenon of investigation with required accuracy. L. A. Kuznetsov arrived at a similar conclusion, which he worded differently. He says in his paper [7]: The content of a model should be adequate to the problems it is designed to help solve (the model should reflect such relationships between the inputs and the outputs with such accuracy as necessary for the problem in view).

A conventional practice is to use absolute and relative errors [e.g. 8–13] to analyse the modelling accuracy. However, the above are point estimates which fail to cover all the variations of the output parameters of the object when characterizing the quality of the model. Therefore, we believe it would be reasonable to apply additional estimates which we refer to as 'relevance' and 'effectiveness'.

Estimating the relevance and effectiveness of the model

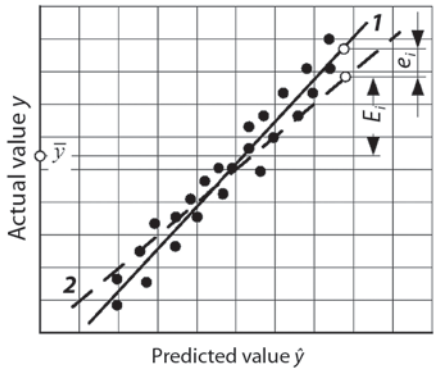

Fig. 1. Relevance Chart

Relevance is the ability of the model to adequately represent the phenomenon under investigation both in terms of quantity and quality. A chart showing a comparison of the simulation results with experimental data [14], referred to as 'Relevance Chart' (Fig. 1), provides a good illustration of the above ability. The dots in the chart represent estimated values $\hat{y}$ of a Y property obtained using the developed model in the same conditions in which the actual values y were documented. A least square line $y = k\hat{y} + c$ was built over the dots that represent an actual relevance trend (line 1 in Fig. 1). The chart also shows an ideal relevance trend built over the dots arranged to the statement $\hat{y}_i = y_i$ (line 2 in Fig. 1). If both are rising trends, it means that the model is in qualitative relevance to the phenomenon of interest. A coefficient of determination, which is calculated using the following formula: $C^2 = 1 - \sum e_i^2 / \sum E_i^2$, can serve as the measure of quantitative relevance (capability, quality of conformance). In the context of this paper, $\sum e_i^2 = \sum (y_i - \hat{y}_i)^2$ is a sum of squared deviations of the actual trend from the ideal one, whereas $\sum E_i^2 = \sum (y_i - \bar{y})^2$ is a sum of squared de-

Table 1. **Model Effectiveness Estimation Scale**

Effectiveness, %	Estimate
95 to 100	Excellent
81 to 94	Good
71 to 80	Satisfactory
50 to 70	Unsatisfactory
Less than 50	Poor

viations of *n* dots of the actual relevancetrend from the sample mean of the actual values ($\overline{y} = 1/n \sum y_i$).

Based on the previous study [15], effectiveness shall be defined as the ability of the model to produce simulation results that would be similar to the actual performance of the object of simulation. For a certain *Y* property after *n* tests, the effectiveness of the model is $E_\delta = 100 \cdot m_\delta / n\,(\%)$, where m_δ is the number of predicted values of the object's property that deviate from the actual values with the relative error not exceeding $|\delta|$. The authors propose [15] to use a Model Effectiveness Estimation Scale (**Table 1**). If the effectiveness was estimated to be 'excellent' or 'good', the obtained models can be recognized as capable of adequately representing the objects or processes under investigation.

Table 2. **Mill 2800 and mill 5000 stands and drives**

Characteristic	Plate Mill 2800		Plate Mill 5000
	Stand		
	Duo	Quarto	Quarto
Work Roll Diameter, mm	1200–1300	1050–1150	1110–1210
Back-Up Roll Diameter, mm	–	1620–1680	2100–2300
Main Drive Motor			
Power, kW	3350	2×5000	2×12000
Speed, RPM	0–30–60	0–60–120	0–60–115
Max. Mill Speed, m/sec.	2.7	5.4	7.3
Max. Rolling Force, MN	32.5	60	120
Max. Torque, MN·m	2.12	0.596	7.64

Table 3. **Ratios for calculating the stress state index in the deformation zones of various height**s

n_σ formula	Formula no.	*m* range	Authors	Source
$m^{-0.42}$	(1)	0.3–0.7	V. F. Pushkarev	[18]
$m^{-0.2}$	(2)	0.7–1.0	V. F. Pushkarev	[18]
$m^{-0.4}$	(3)	< 1.0	V. S. Smirnov	[19]
$1.25\ln\left(\frac{1}{m}\right)+1.25m-0.25$	(4)	0.12–1.0	V. M. Lugovskoy	[20]
$0.5m+0.6\frac{1}{m}+0.04\left(\frac{1}{m}\right)^2$	(5)	0.28–1.0	A. D. Tomlenov	[21]
$0{,}5\left(m+\frac{1}{m}\right)$	(6)	1.0–2.0	M. Ya. Brovman	[22]
$0.75 + 0.25m$	(7)	> 2.0	M. Ya. Brovman	[21]
$\frac{2h_\gamma}{\Delta h(\delta-1)}\left[\left(\frac{h_\gamma}{h_1}\right)^\delta-1\right]$	(4.1.68) (8)	2.0–4.0	A. I. Tselikov	[22]
$h_\gamma = h_1\left\{\frac{1+\sqrt{1+(\delta^2-1)(h_0/h_1)^\delta}}{\delta+1}\right\}^{1/\delta}$	(9)			
$\delta = 2\mu_y\frac{l_x}{\Delta h}$	(10)			
$0.72 + 0.28m$	(11)	1.0–3.7	V. M. Lugovskoy	[20]

Developing and analyzing a mathematical model to predict the rolling force for rolling large plates

Large plates are produced in special plate mills. At the same time the production of new products of this type may be hampered due to power limitations of rolling stands and drives used [16]. Because of this the problem of improving the prediction accuracy of the rolling force as a variable which can significantly influence the other power characteristics of the process is given an ever rising attention.

Plate mill 2800 and plate mill 5000 were considered for the purpose of improving the accuracy of the model predicting the rolling force required to produce large plates. Plate mill 2800 consists of a vertical stand and two horizontal roll stands — a duo roughing mill and a quarto finishing mill with conventional rolls. Plate mill 5000 is only comprised of a quarto universal mill with CVC$^{\text{PLUS}}$ horizontal rolls. **Table 2** below shows the main characteristics of the stands and drives of the above mills.

Irrespective of the number of stands in a mill, the process of rolling large plates includes a roughing stage and a finishing stage. 170 roughing stage observations and 128 finishing stage observations were considered. During the roughing stage, the height of the deformation zone, which is defined as a ratio of the length of the deformation zone to the average plate thickness: $l_x/\overline{h} = 2\sqrt{R(h_0-h_1)}/(h_0+h_1)$, stays mainly within the range of 0.4–0.6 to 1.0–1.2 (**Fig. 2, *a***), while the line rolling force (i.e. a force related to the plate width *b*) $P_1 = P/b$ varies predominantly from 4 to 12 kN/mm (**Fig. 2, *c***). In the case of finishing rolling (**Fig. 2, *b*** and **Fig. 2, *d***), the following parameters can be observed: $l_x/\underline{h}$ = 0.6–3.0 (predominantly, 1.0–2.6) and P_1 = 6–24 kN/mm (predominantly, 8–20 kN/mm).

Models built through the method of averages could be particularly helpful when developing and testing design and practical solutions for predicting the rolling force requirements. In such case the line rolling force would be as follows: $P_1 = \overline{p}l_x = 1.15 n_\sigma \overline{\sigma}_s l_x$ (where $\overline{p}$ stands for the mean contact pressure calculated against the mean yield stress $\overline{\sigma}_s$

Table 4. **Stress state models considered**

Model	Formula no. at different *m* values per Table 3					
	0.12–0.3	0.31–0.70	0.71–1.00	1.01–1.50	1.51–2.00	2.01 and higher
M1	(3)			(6)		(7)
M2	(4)			(6)		(7)
M3	(4)	(1)	(2)	(6)		(7)
M4	(4)	(1)	(2)	(6)	(11)	
M5	(4)	(1)	(2)	(6)	(5)	
M6	(4)	(1)	(2)	(6)	(8)+(9)+(10)	
M7	(3)		(5)	(6)	(11)	

Table 5. **Estimated errors of the stress state model variations**

Error, %	Model						
	M1	M2	M3	M4	M5	M6	M7
δ_{min}	−12.4	−9.8	−13.6	−13.6	−13.6	−20.5	−15.1
δ_{max}	32.3	32.3	32.3	33.1	33.8	38.2	20.8
$\lvert\delta_{min}\rvert + \delta_{max}$	44.7	42.1	45.9	46.7	47.4	58.7	35.9
$\bar{\delta}$	7.7	9.4	6.9	6.5	6.2	6.3	2.5

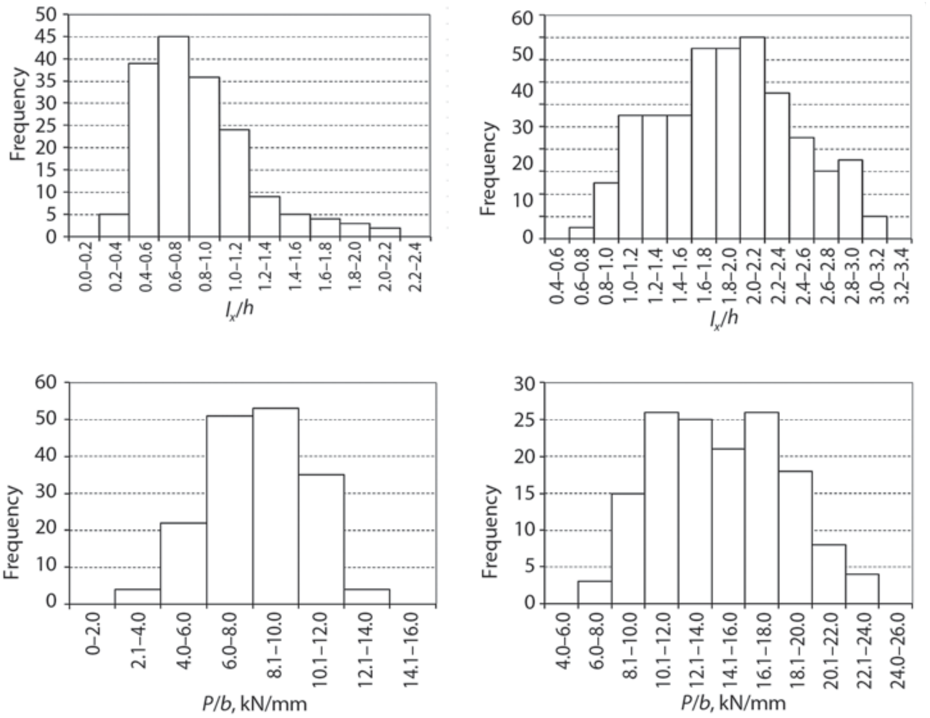

Fig. 2. Values of the height of the deformation zone and the line force observed during roughing (*a* & *c*) and finishing (*b* & *d*) passes in plate mills

in the deformation zone using the stress state index n_σ). With the purpose of improving the model accuracy, we speculated if it would be reasonable to use a more detailed differentiation of rolling instances in terms of height of the deformation zone $m = l_x/\bar{h}$ when calculating the stress state index n_σ. We also looked at the ranges of the *m* parameter and the n_σ formulae given in **Table 3**. Seven model variations (**Table 4**) were built, with estimated relevant errors given in **Table 5**. In all cases, L.V. Andreyuk's [17] modified formula was applied for yield stress calculations.

The M7 model is characterized by the smallest range of error — $\lvert\delta_{min}\rvert + \delta_{max} = 35.9\%$ and the lowest mean relative error — $\bar{\delta} = 2.5\ \%$. The model has the following presentation:

$$n_\sigma = \begin{cases} m^{-0,4} & \text{при } m \le 0.7 \\ 0,5m + 0,6\dfrac{1}{m} + 0,04\left(\dfrac{1}{m}\right)^2 & \text{при } 0.7 < m \le 1.0 \\ 0,5\left(m + \dfrac{1}{m}\right) & \text{при } 1.0 < m \le 1.5 \\ 0,72 + 0,28m & \text{при } m > 1.5. \end{cases} \qquad (12)$$

The M1 model, with the following accuracy: $\lvert\delta_{min}\rvert + \delta_{max} = 44.7\ \%$ and $\bar{\delta} = 7.7\ \%$, follows M.Ya. Brovman's [22] recommendations, which are commonly applied, and has the following presentation:

$$n_\sigma = \begin{cases} m^{-0,4} & \text{при } m \le 0.5 \\ 0,5(m + 1/m) & \text{при } 0.5 < m \le 2.0 \\ 0,75 + 0,25m & \text{при } m > 2.0. \end{cases} \qquad (13)$$

The difference between models (12) and (13) is that in model (12) V. S. Smirnov's (4) and M. Ya. Brovman's (6–7) formulae are applied for different *m* ranges and A. D. Tomlenov's (5) formula was introduced for $0.7 < m \le 1.0$. The above mentioned calculations of the stress state index help improve the relevance of the line rolling force prediction model from 0.769 to 0.859 (**Fig. 3**) and enhance the effectiveness from 56.9 to 84.3% at the allowable error of $\lvert\delta\rvert \le 15\%$ (according to Table 1, from 'Unsatisfactory' to 'Good').

Concluding Remarks

The quality assessment stage of the mathematical modelling method has been complimented with such characteristics as 'Relevance' and 'Effectiveness'. In combination with the conventional error characteristics, the above estimates provide for a more sound model adequacy analysis as they characterise the quality of the model within the entire range of variations of the output parameters of the object.

A rolling force prediction model has been developed that takes into account a more detailed differentiation of rolling instances in terms of height of the deformation

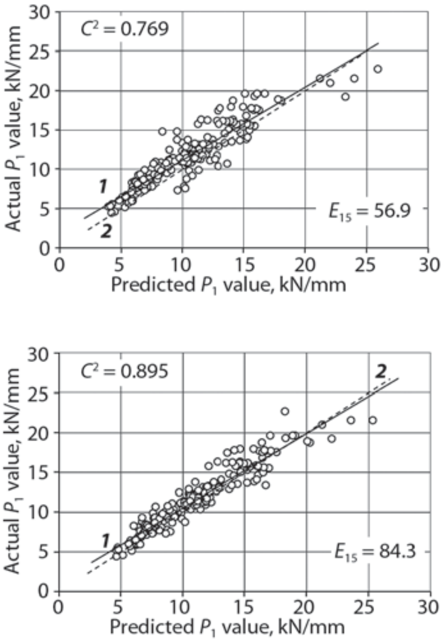

Fig. 3. Relevance charts for the rolling force prediction models with the stress state index calculated: *a* — per formula (12); *b* — per formula (13)

zone when calculating the stress state index and uses L.V. Andreyuk's modified formula to calculate the yield stress. A quality analysis of the model, which was based on the data from 298 observations made on two-stand plate mill 2800 and single-stand plate mill 5000, showed that the model can predict the rolling force with an error within −15.1 to +20.8%. The model showed a relevance of 0.859 (89.5%) and an effectiveness of 84.3% with the error not exceeding ±15%, which qualifies the model quality as good.

The authors applied the above described approach to also develop models and practical solutions applicable to the production of sheet steel for different applications [23–25].

REFERENCES

1. Novikov A. M., Novikov D. A. Scientific research methodology. Moscow: Librokom. 2009. 280 p.
2. Larichev O. I. Objective models and subjective decisions. Moscow: Nauka. 1987. 144 p.
3. Blyumin S. L., Shuykova I. A. Models and methods of decision making under uncertainty. Lipetsk: Lipetsk Institute for Ecology and Humanities. 2001. 138 p.
4. Polukhin V. P. Mathematical modelling and computer-aided design of sheet rolling mills. Moscow: Metallurgiya. 1972. 512 p.
5. Ivanov K. M., Lyasnikov A. V., Novikov L. A., Yurgenson E. V. Mathematical modelling of forming processes. Saint Petersburg: Inventeks. 1997. 268 p.
6. Dukmasov V. G., Vydrin A. V. Mathematical models and rolling processes in high quality steel sections production. Chelyabinsk: Izdatelstvo Yuzhnouralskogo gosudarstvennogo universiteta. 2002. 215 p.
7. Kuznetsov L. A. Use of process computer for sheet rolling process optimisation. Moscow: Metallurgiya. 1988. 304 p.
8. Moller A. B., Zaitsev A. A., Tulupov O. N. Model of setting up a bar mill with a matrix description of shaping in passes of simple form. *Steel in Translation*. 1999. Vol. 29. No. 10. pp. 59–63.
9. Moller A. B., Tulupov O. N., Fedoseev S. A. Improvement of surface quality of rolled section steel for springs manufacturing. *Journal of Chemical Technology and Metallurgy*. 2017. Vol. 52. No. 4. pp. 647–654.
10. Rubin G. S., Chukin M. V., Gun G. S., Polyakova M. A. Analysis of the properties and functions of metal components. *Steel in Translation*. 2016. Vol. 46. No. 10. pp. 701–704.
11. Chukin M. V., Poletskov P. P., Nabatchikov D. G., Gushchina M. S., Alekseev D. Yu., Khakimullin K. Mechanical properties as a function of the chemical composition and heat treatment regimes in high strength sheet steel. *Vestnik Magnitogorskogo gosudarstvennogo tekhnicheskogo universiteta im. G. I. Nosova*. 2016. Vol. 14. No. 4. pp. 72–75.
12. Kern A., Walter P., Pfeiffer E., Tchersikh Kh.-Y. Complex for flat steel production in China. *Chernye metally*. 2017. No. 6. pp. 50–57.
13. Shinkin V. N. The mathematical model of the thick steel sheet flattening on the twelve-roller sheet-straightening machine. Message 2. Forces and moment. *CIS Iron and Steel Review*. 2016. Vol. 12. pp. 40–44.
14. Selivanov V. N., Kolesnikov Yu. A., Budanov B.A. et al. Use of mathematical models to study steel making processes. *Stal*. 2014. No. 5. pp. 16–20.
15. Rumyantsev M. I., Cherkasov K. E., Yakushev E.V. et al. Use of statistical prediction of properties to improve the effectiveness of pipe flat steel quality control. Magnitogorsk: Publishing House of Nosov Magnitogorsk State Technical University. 2014. 134 p.
16. Freihammer A., Krenn H., Blauensteiner P. Putting into practice the new flat rolling equipment in Austria. *Chernye metally*. 2017, No. 5. pp. 43–46.
17. Rumyantsev M., Belov V., Razgulin I. Prediction model of the flow stress for the computer-aided design hot rolling sheet and strips pattern. *METAL 2015 Conference proceedings*. pp. 395–403.
18. Kreydlin N. N. Rolling force calculations in non-ferrous rolling. Moscow: Metallurgizdat, 1963. 407 p.
19. Smirnov V. S. Theory of rolling. Moscow: Metallurgiya. 1967. 460 p.
20. Lugovskoy V. M. Sheet rolling mill control algorithms. Moscow: Metallurgiya. 1974. 320 p.
21. Tselikov A. I. Basics of the theory of rolling. Moscow: Metallurgiya. 1965. 247 p.
22. Brovman M. Ya. Power parameters and improved rolling process. Moscow: Metallurgiya. 1995. 256 p.
23. M. I. Rumyantsev. Generalized algorithm aided design modes of rolling and its application for developing technology of PLTCM 2000. *CIS Iron and Steel Review,* 2014. Vol. 9. P. 40–44.
24. Rumyantsev M. I. The methods of engineering and improving technology for the purpose of upgrade the flat-rolled steel manufacture systems. *Teoriya i tekhnologiya metallurgicheskogo proizvodstva*. 2017. No. 4 (23). pp. 26–36.
25. Rumyantsev M. I. Some results of the development and application of the metodology for enhancing steel sheet production systems. *Vestnik Magnitogorskogo gosudarstvennogo tekhnicheskogo universiteta im. G. I. Nosova*, 2017, Vol. 15. No. 1. pp. 45–55.