Metallurgical technologies / Металлургические технологии

UDC 621.771.06
DOI 10.17073/0368-0797-2025-1-14-20

Original article
Оригинальная статья

Stiffness modulus of stands in finishing group of continuous wide-strip hot rolling mill

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Abstract. Stiffness modulus is an important technical parameter of each four-high stand of continuous wide-strip hot rolling mill and characterizes the roll force that causes elastic deformation of all structural elements of the working stand in the assembly. Accuracy of deviations of longitudinal and widthwise profile of hot-rolled strips and quality of sheet products directly depends on reliability of determination of such parameter at the design stage of efficient technological rolling schedule. After review of classical methods for calculating elastic deformations of four-high stands based on the laws of the elasticity theory and modern publications, it was concluded that it is necessary to take into account the dynamic component when determining the stiffness modulus of the working stands of hot and cold rolling mills. Lack of record-keeping above the specified component entails significant errors in the alignment of the roll gaps at the stage of mill setting for rolling the strips of the required final thickness. In this work, we studied the stiffness modulus of the finishing stands of the operating continuous wide-strip mill, taking into account their constructional features in the production of hot-rolled strips of various sheet gauge of low-carbon steels, mainly intended for further cold rolling. When analyzing experimental data, reliable regression equations were obtained that allow taking into account the effect of the rolled strip width on the stiffness modulus of stands. The results of investigations are presented in graphical and tabular form, demonstrating the change in the stiffness modulus for different mill stands. The results allow us to design and make changes to the existing hot rolling modes in order to ensure the required accuracy of the longitudinal and widthwise profile of hot-rolled strips.

Keywords: stiffness modulus of four-high stand, continuous wide-strip hot rolling mill, rolling force, rolling gap, strip width, regression equations, rolling schedule

For citation: Pospelov I.D. Stiffness modulus of stands in finishing group of continuous wide-strip hot rolling mill. *Izvestiya. Ferrous Metallurgy*. 2025;68(1):14–20. https://doi.org/10.17073/0368-0797-2025-1-14-20

Исследование модуля жесткости клетей чистовой группы непрерывного широкополосного стана горячей прокатки

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Аннотация. Модуль жесткости является важным техническим параметром каждой клети «кварто» непрерывного широкополосного стана горячей прокатки и характеризует величину усилия прокатки, вызывающую упругую деформацию всех конструктивных элементов рабочей клети в сборе. От достоверности определения такого параметра на этапе проектирования эффективных технологических режимов прокатки напрямую зависит точность отклонений продольного и поперечного профиля горячекатаных полос и качество листового проката. При обзоре классических методов расчета упругих деформаций рабочих четырехвалковых клетей, основанных на законах теории упругости, и современных публикаций сделан вывод, что необходимо учитывать динамическую составляющую при определении модуля жесткости рабочих клетей станов горячей и холодной прокатки. Отсутствие учета вышеуказанной составляющей влечет за собой существенные ошибки в выставлении межвалковых зазоров на этапе настройки стана под прокатку полос требуемой конечной толщины. В данной работе выполнено исследование модуля жесткости клетей чистовой группы действующего непрерывного широкополосного стана с учетом их конструктивных особенностей при производстве горячекатаных полос различного листового сортамента низкоуглеродистых сталей, преимущественно предназначенных для дальнейшей холодной прокатки. При анализе экспериментальных данных получены достоверные уравнения регрессии, позволяющие учитывать влияние ширины прокатываемой полосы на модуль жесткости клетей. Исследование представлено в графической и табличной форме, демонстрирующей изменение значений модуля жесткости для различных клетей стана. Результаты исследования позволяют проектировать и вносить изменения в существующие технологические режимы горячей прокатки с целью обеспечения требуемой точности продольного и поперечного профиля горячекатаных полос.

Ключевые слова: модуль жесткости четырехвалковой клети, непрерывный широкополосный стан горячей прокатки, усилие прокатки, межвалковый зазор, ширина полосы, уравнения регрессии, режимы прокатки

Для цитирования: Поспелов И.Д. Исследование модуля жесткости клетей чистовой группы непрерывного широкополосного стана горячей прокатки. *Известия вузов. Черная металлургия*. 2025;68(1):14–20. https://doi.org/10.17073/0368-0797-2025-1-14-20

Introduction

In recent decades, global production standards have tightened tolerances for deviations in the longitudinal and widthwise profile of hot-rolled strips made of low-carbon steels. This trend is driven by the increasing requirements for the quality of sheet products. These requirements apply both to the thinnest hot-rolled strips (0.8 – 1.5 mm thick), which are directly used in mechanical engineering and construction, and to strips with a thickness of 1.8 – 5.5 mm, which serve as semifinished rolled stock for cold rolling mills, where they undergo further processing to meet strict geometric tolerances for longitudinal and widthwise profiles.

The accuracy requirements for hot-rolled steel sheets supplied in stacks and coils are regulated by GOST 19903–74, which classifies sheets into two accuracy groups: high accuracy (Group A) and normal accuracy (Group B). Depending on their thickness and width, these sheets are subject to different thickness tolerances. For example, sheets with a thickness of 1.8 – 2.0 mm and a width of 1500 – 1820 mm have a thickness tolerance of ±0.17 mm for high accuracy and ±0.20 mm for normal accuracy. However, even stricter requirements apply to hot-rolled strips intended for cold rolling mills for the production of autobody sheet. In such cases, thickness deviations across the entire surface must not exceed ±(2 – 5) % of the nominal thickness of the semifinished rolled stock [1].

Reducing deviations in the standardized characteristics of the longitudinal profile of hot-rolled strips within the specified tolerances has driven the development of thin-strip hot rolling theory [2 – 4]. Based on this theory, models have been developed to control longitudinal and widthwise thickness deviation, considering all significant technological parameters of the rolling schedule [5 – 7].

A review of international publications reveals a direct correlation between the accuracy parameters of the longitudinal and widthwise profile of hot-rolled [8 – 10] and cold-rolled strips [11; 12] and the stiffness parameters of both individual structural elements and the assembled four-high stands. Similar studies are widely represented in classical domestic textbooks [13 – 15]. Of particular interest is the stiffness modulus of each stand in the continuous rolling mill, as the accuracy of determining this characteristic directly affects the proper setting of the rolling gap [16; 17]. This, in turn, influences the precision of the initial mill setup and the effectiveness of control actions for adjusting strip thickness accuracy during rolling [18 – 20].

The objective of this study is to investigate changes in the stiffness modulus of finishing stands in continuous hot rolling mills for various strip gauges by analyzing experimental data obtained from an operating wide-strip rolling mill.

Materials and methods

The equation describing the direct linear relationship between the elastic deformation of the four-high stand and the rolling force P_i acting on the rolls can be expressed as follows:

$$P_i = M_{st}(h_i - S_i), \tag{1}$$

where M_{st} is the stiffness modulus of the four-high stand, MN/mm; h_i is the strip thickness after rolling in the i-th stand, mm; S_i is the initially set roll gap in the i-th working stand, mm.

As previously noted, the accuracy of determining M_{st} in equation (1), given a specified strip thickness h_i, directly affects the correct initial setting of the roll gap S_i and, consequently, the overall rolling precision.

During metal reduction to the required thickness h_i, the working rolls experience a rolling force P_i, which can be assumed to act vertically. This force is transmitted through all structural elements of the assembled stand, including the four-high roll system, thrust bearings with pressure capsules, back-up chocks, thrust bearings of mill screws, mill screws, packing nuts of mill screws, and close-top roll housings (Fig. 1). Classical methods for calculating elastic deformations in four-high working stands [13 – 15] are based on the assumption that all structural components deform according to the laws of elasticity. Using this assumption, the stiffness modulus of each four-high working stand in a continuous mill is determined through well-established theoretical formulas for the elastic deformation of all the aforementioned components that bear the vertical rolling force during operation. However, as noted in [13 – 15], these formulas apply only to the static stiffness modulus and do not account for key dynamic factors, such as the influence of back-up roll rotational speed on deformation within hydrodynamic bearings, the horizontal displacement of vertical axial planes of back-up and working rolls relative to each other [21], and other rolling dynamics [10 – 12] affecting all assembled stand components.

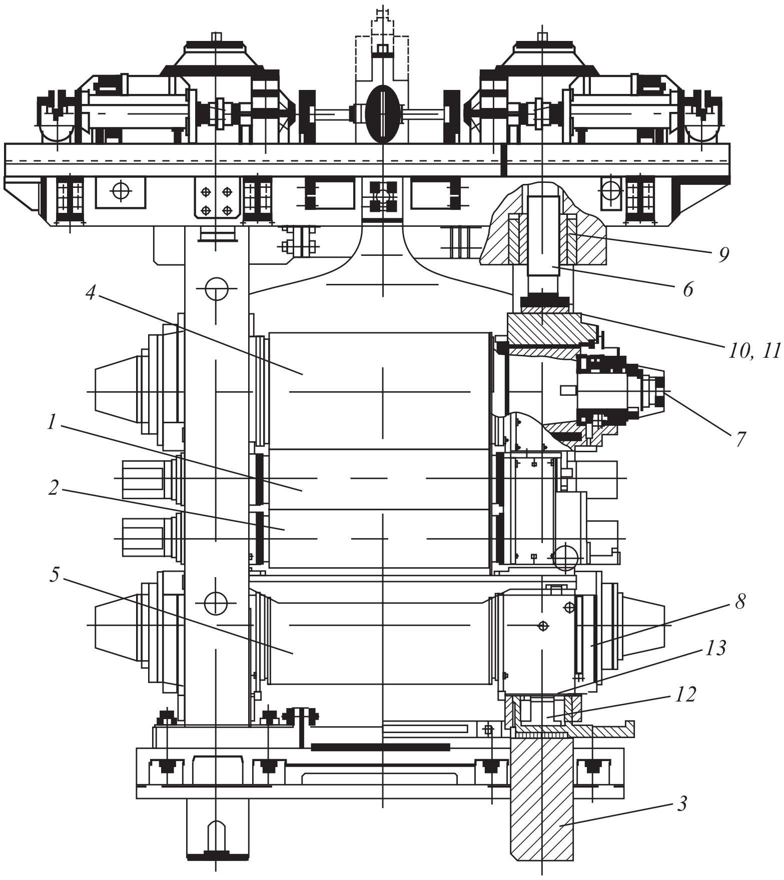

Fig. 1. Construction of four-high stand of hot rolling mill:
1, *2* – working rolls; *3* – close-top roll housing; *4*, *5* – back-up rolls; *6* – mill screw; *7*, *8* – back-up chocks; *9* – packing nut; *10* – thrust bearing of mill screw; *11* – pressure capsule of mill screw; *12* – bearing part of lower back-up chocks; *13* – pressure capsule of lower back-up chocks

Рис. 1. Конструкция четырехвалковой клети стана горячей прокатки:
1, *2* – рабочие валки; *3* – станина закрытого типа; *4*, *5* – опорные валки; *6* – нажимной винт; *7*, *8* – подушки опорных валков; *9* – гайка нажимная; *10* – подпятник нажимного винта; *11* – месдоза нажимного винта; *12* – опора подушки нижнего опорного валка; *13* – месдоза нижней подушки

Under modern operating conditions, assessing the stiffness modulus of mill stands is most efficiently conducted using loading curves obtained by pre-stressing the rotating working rolls into the pre-stressed stand position. This method was applied to evaluate the stiffness modulus of the four-high stands in the finishing group of hot rolling mill 2000 at PAO Severstal. The loading force during the assessment was varied within the actual operating rolling force range: from 0 to 30 MN for stands *6 – 9* and from 0 to 20 MN for stands *10 – 12*, while maintaining a constant working roll rotation speed equal to the average strip rolling speed in the *i*-th stand. To minimize the additional measurement errors, a coolant was applied to the rolls during loading before the start of measurements.

The experimental data on loading force $P_{\text{ld}.i}$ and total elastic deformations in the *i*-th finishing stand $S_{\text{st}.i}$ were recorded by the automated process control system (APCS) of the finishing group of hot rolling mill 2000. The processed data were then presented graphically in Fig. 2, showing the relationship between the total loading force $P_{\text{ld}.i}$ of each stand and the elastic deformation of all structural elements of the stand $S_{\text{st}.i}$. The material properties and nominal diameters of the working and back-up rolls are listed in Table 1.

The stiffness modulus of the pre-stressed stand in the *i*-th stand $M^0_{\text{st}.i}$ was determined based on the linear portion of the curves in Fig. 2, using the ratio of the loading force $P_{\text{ld}.i}$ to the elastic deformation of the stand $S_{\text{st}.i}$:

$$M^0_{\text{st}.i} = \frac{P_{\text{ld}.i}}{S_{\text{st}.i}}. \qquad (2)$$

Analysis of the curves in Fig. 2 showed that for all mill stands, the onset of the linear deformation region occurs at a loading force of 6.484 – 3.041 MN, with higher values corresponding to the first stands. As the loading force increases further, the stand deformation follows a strictly linear trend, remaining fully compliant with elasticity laws across the entire operating force range.

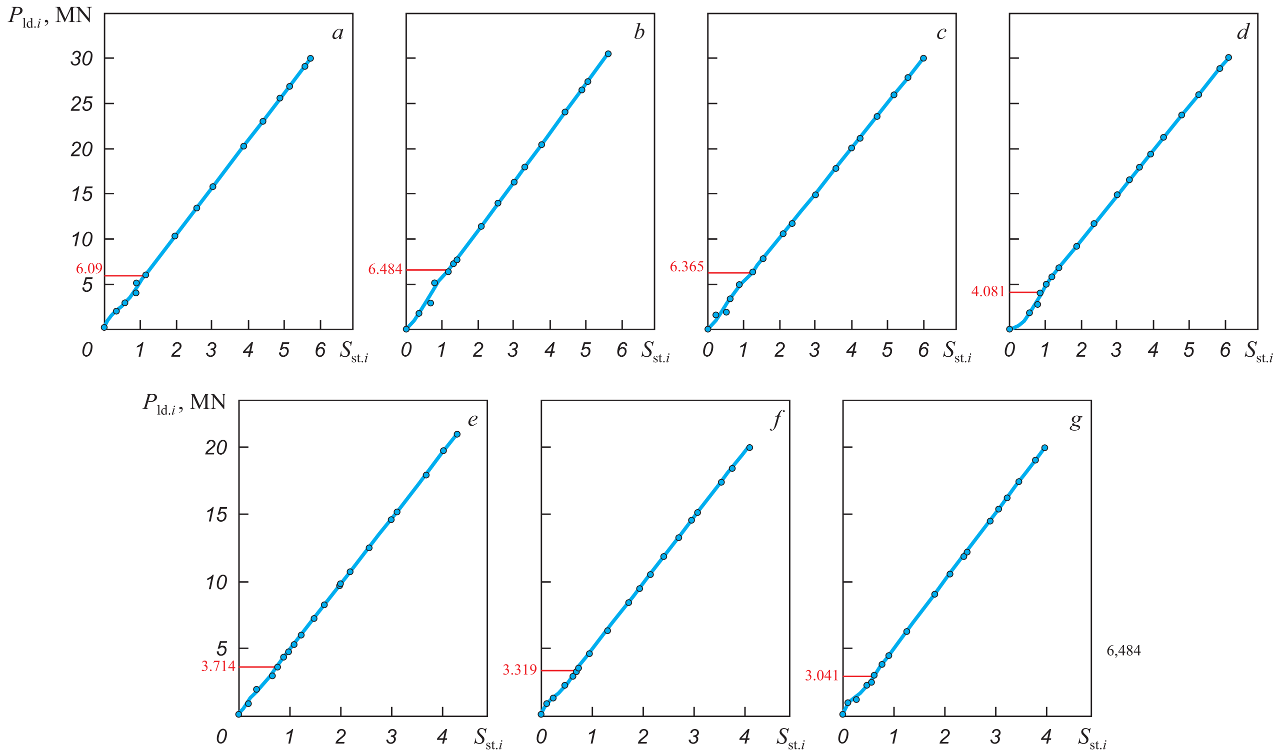

Fig. 2. Graphics of loading pre-stressed stands of rotating work rolls:
a – stand *6*; *b* – stand *7*; *c* – stand *8*; *d* – stand *9*; *e* – stand *10*; *f* – stand *11*; *g* – stand *12*

Рис. 2. Графические схемы нагружения клетей стана методом предварительного сжатия вращающихся рабочих валков:
a – клеть *6*; *b* – клеть *7*; *c* – клеть *8*; *d* – клеть *9*; *e* – клеть *10*; *f* – клеть *11*; *g* – клеть *12*

Determining the stiffness modulus of the pre-stressed stand $M^0_{st.i}$ using equation (2), based on the data from Fig. 2, and its subsequent application without significant error is valid for rolling strips in the finishing group of hot rolling mill 2000 at a maximum width of b_i = 1820 mm.

The dependence of the stiffness modulus of the four-high stands in the finishing group of hot rolling mill 2000 on the width of the rolled strip b_i was investigated using the following methodology. During steady-state rolling, all stands operate under conditions of constant positioning of the screw-down mechanisms. As the strip undergoes deformation in the *i*-th stand, the APCS of the finishing group records the average strip thickness h_i, the rolling force P_i and the average elastic deformation of the stand $S_{st.i}$. The averaged stiffness modulus of the *i*-th stand $M^b_{st.i}$, considering the variation in strip width b_i can be calculated using equation

Table 1. **Elastic material characteristics and nominal diameters of working and back-up rolls in finishing group of mill 2000**

Таблица 1. **Упругие свойства материала и номинальные диаметры рабочих и опорных валков клетей чистовой группы стана 2000**

Stand No.	D_w, mm	E_w, MPa	ν_w	Working roll material	D_b, mm	E_b, MPa	ν_b
6	930	200,000	0.29	High-chromium hardened cast iron	1600	219,000	0.35
7	890	205,000					
8	800	215,000	0.32	High-chromium heat-resistant cast iron			
9, 10	800	175,000	0.28	Indefinite chill cast iron			
11, 12	825						

N o t e: D_w – nominal diameter of working rolls; E_w – elastic modulus of working roll material; ν_w – Poisson's ratio of working roll material; D_b – nominal diameter of back-up rolls; E_b – elastic modulus of back-up roll material; ν_b – Poisson's ratio of back-up roll material.

$$M^b_{\text{st}.i} = \frac{P_i}{S_{\text{st}.i}}. \quad (3)$$

The physical meaning of this parameter $M^b_{\text{st}.i}$ reflects the change in the stand's elastic deformation due to the deflection of the roll system under the rolled strip of width b_i. The difference between the stiffness modulus of the stand without a strip $M^0_{\text{st}.i}$ and the calculated value obtained using equation (3) is denoted as $\Delta M^b_{\text{st}.i}$. Upon completion of the study, databases were compiled to record the following rolling parameters for the *i*-th stand:

– average strip width b_i and average strip thickness h_i of the rolled strip;

– value of the change in elastic deformation of the stand $S_{\text{st}.i}$;

– calculated value of the correction factor $\Delta M^b_{\text{st}.i}$.

Thus, the stiffness modulus of the stand for a strip width b_i less than 1820 mm, accounting for the correction factor $\Delta M^b_{\text{st}.i}$, can be determined using the following equation

$$M_{\text{st}.i} = M^0_{\text{st}.i} - \Delta M^b_{\text{st}.i}, \quad (4)$$

where $M^0_{\text{st}.i}$ is represents the stiffness modulus of the pre-stressed stand, MN/mm; $\Delta M^b_{\text{st}.i}$ is the correction factor for assessing the stiffness modulus of the *i*-th stand, considering the variation in rolled strip width b_i, MN/mm.

Results and discussion

The dataset prepared for regression analysis was obtained from 46 rolling schedules in the finishing group of hot rolling mill 2000, covering low-carbon steel strips with thicknesses ranging from 1.2 to 5.5 mm and widths from 1005 to 1625 mm. These strips were primarily intended for further cold rolling and were processed using different sets of working and back-up rolls. During the regression analysis, linear equations (Table 2), were derived, which accurately describe the correction factor $\Delta M^b_{\text{st}.i}$ for the stiffness modulus of the pre-stressed stand $M^0_{\text{st}.i}$ as a function of the rolled strip width b_i.

Since the actual values of Fisher's criterion F in Table 3 significantly exceed the critical value $F_{\text{cr}}(1; 44) = 4$ at degrees of freedom $k_1 = 1$ and $k_2 = 44$, the determination coefficients R^2 are statistically significant, confir-

Table 2. **Values of stiffness modulus of pre-stressed stand $M^0_{\text{st}.i}$, regression equations for $\Delta M^b_{\text{st}.i}$ calculation and their reliability**

Таблица 2. **Значения модуля жесткости клети «забоя» $M^0_{\text{st}.i}$, регрессионные уравнения расчета $\Delta M^b_{\text{st}.i}$ и их достоверность**

Stand No.	$M^0_{\text{st}.i}$, MN/mm	Regression equation for calculating $\Delta M^b_{\text{st}.i}$, MN/mm	R^2	F
6	5.25	$0.6136 - 0.000300b_i$	0.8928	183.22
7	5.45	$0.8247 - 0.000410b_i$	0.8349	111.25
8	5.00	$0.9884 - 0.000494b_i$	0.9552	469.07
9	4.95	$1.0474 - 0.000524b_i$	0.9140	233.81
10	4.89	$1.0409 - 0.000520b_i$	0.9540	456.26
11	4.93	$0.8574 - 0.000428b_i$	0.9194	205.95
12	5.055	$0.9173 - 0.000458b_i$	0.9417	355.36

Table 3. **Calculated values of rolling stands stiffness modulus and verification thereof by force calculation**

Таблица 3. **Расчетные значения модуля жесткости клети и проверка их достоверности путем расчета усилия**

Stand No.	$\Delta M^b_{\text{st}.i}$, MN/mm	$M_{\text{st}.i}$, MN/mm	h_i, mm	S_i, mm	P_i, MN		ΔP_i, %
					calculated	measured	
6	0.386	5.0264	18.55	13.260	26.590	25.070	6.06
7	0.297	5.1583	10.02	4.510	28.422	27.588	3.02
8	0.353	4.6538	5.63	1.303	20.137	20.682	2.64
9	0.373	4.5838	3.95	0.620	15.264	15.786	3.31
10	0.372	4.5251	2.89	–0.464	15.177	15.547	2.38
11	0.306	4.6290	2.28	–0.797	14.243	14.292	0.34
12	0.328	4.7331	2.00	0.151	8.7515	8.787	0.40

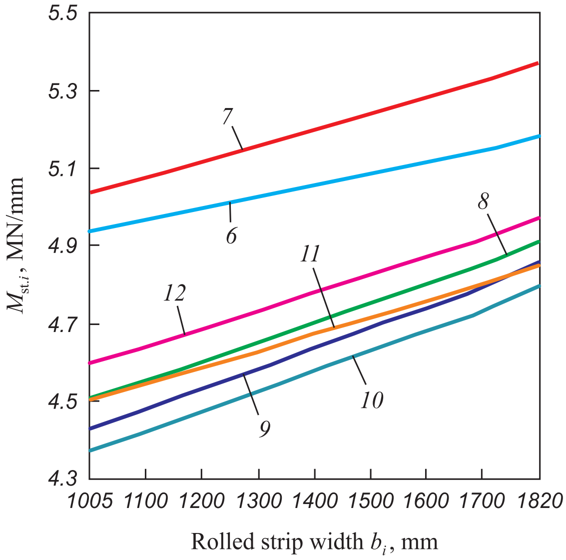

Fig. 3. Graphics of change in stiffness modulus $M_{st.i}$ depending on width of rolled strip b_i:
(numbers of curves – numbers of stands)

Рис. 3. Графики изменения модуля жесткости $M_{st.i}$ в зависимости от ширины прокатываемой полосы b_i:
(цифры кривых – номер клети)

ming the reliability of the regression equations for $\Delta M^b_{st.i}$ in Table 2. These equations are valid within the following parameter ranges:

– working roll crown profiles from –0.5 to –0.15 mm;

– working roll diameters from 930 to 800 mm;

– back-up roll diameters from 1616 to 1488 mm;

– back-up roll chamfer depth of 0.8 mm and chamfer length of 300 mm.

Based on the Table 3 data, graphs were plotted (Fig. 3) to illustrate the variation in the stiffness modulus $M_{st.i}$ for each stand in the finishing continuous group of hot rolling mill 2000, depending on the rolled strip width b_i.

The accuracy of determining the stiffness modulus $M_{st.i}$ considering the correction factor $\Delta M^b_{st.i}$ for strip width variation b_i, was verified by solving equation (1) and comparing the measured rolling force P_i in the i-th stand during the rolling of a 2.0 mm-thick, 1300 mm-wide strip of 08Yu steel. The initial roll gap S_i was recorded by the APCS of the finishing group of hot rolling mill 2000, as shown in Table 3. The calculated and measured rolling forces, along with their comparison results, are also provided in Table 3.

Since the maximum comparison error ΔP_i in Table 3 does not exceed 6.06 %, the findings of this study can be effectively applied in designing hot rolling schedules for hot rolling mill 2000. These results ensure the required longitudinal and widthwise profile accuracy of hot-rolled strips while incorporating control models for longitudinal and widthwise thickness deviations [5 – 7].

Conclusions

Based on the analysis of experimental data, reliable dependencies have been established that describe the effect of rolled strip width on the variation of the stiffness modulus of four-high stands in the finishing group of the operating hot rolling mill.

It has been determined that rolling within the finishing group, from the first to the last stand, with rolling forces below 6.484 – 3.041 MN is undesirable, as under such conditions, the stands experience nonlinear deformation, leading to additional fluctuations in the roll gap.

The research findings can be applied in the development of optimized rolling schedules for the finishing group of mill stands, ensuring the production of hot-rolled strips with minimal deviations in the longitudinal and widthwise geometric profile characteristics.

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Received 24.07.2024
Revised 18.09.2024
Accepted 29.10.2024

Поступила в редакцию 24.07.2024
После доработки 18.09.2024
Принята к публикации 29.10.2024