



UDC 621.771

DOI 10.17073/0368-0797-2025-4-417-423



Original article
Оригинальная статья

METHODOLOGY FOR CALCULATING THE FLATNESS OF COLD-ROLLED STEEL STRIPS

D. L. Shalaevskii

Cherepovets State University (5 Lunacharskogo Ave., Cherepovets, Vologda Region 162600, Russian Federation)

shal-dmitrij@yandex.ru

Abstract. A known cause of flat shape defects in finished cold-rolled steel strips is the inequality of the drawing ratios across the strip width. Difference in the values of these ratios is affected by the roll barrel profiling parameters, energy-power parameters of rolling, operating parameters of the automatic profile and strip shape control system. The impact of all technological factors on the strip shape is complex. The paper considers an approach that takes into account the main operating parameters of rolling equipment allowing to estimate the type and amplitude of flatness defects in finished steel strips. When implementing this approach, 6 calculation stages were performed: energy-power calculation of the cold rolling process; calculation of elastic deformations of the working roll barrel surface; assessment of wear of the working roll barrel surface; calculation of the roll thermal profile; assessment of convexity of the steel strip transverse profile; assessment of flatness indicators of the finished strip. To calculate the parameters affecting the flatness of the rolled product, known calculation methods adapted to specific process conditions were used. The results of assessing the shape indicators of the rolled strip obtained using the model were compared with the results of modeling in the Deform 3D program. The modeling results demonstrated reliability of the proposed approach to assessing the rolled product quality.

Keywords: flatness of cold-rolled steel strips, continuous rolling, rolling mode, shape defects, roll barrel profiling, elastic deformation of roll barrel, thermal profile of roll barrel, defect amplitude

For citation: Shalaevskii D.L. Methodology for calculating the flatness of cold-rolled steel strips. *Izvestiya. Ferrous Metallurgy*. 2025;68(4):417–423. <https://doi.org/10.17073/0368-0797-2025-4-417-423>

МЕТОДИКА РАСЧЕТА ПЛОСКОСТНОСТИ СТАЛЬНЫХ ХОЛОДНОКАТАНЫХ ПОЛОС

Д. Л. Шалаевский

Череповецкий государственный университет (Россия, 162600, Вологодская обл., Череповец, пр. Луначарского, 5)

shal-dmitrij@yandex.ru

Аннотация. Известной причиной возникновения дефектов плоской формы на готовых стальных холоднокатаных полосах является неравенство коэффициентов вытяжки по ширине полосы. На разницу значений этих коэффициентов оказывают влияние параметры профилировок бочек валков, энергосиловые параметры прокатки, параметры работы системы автоматического регулирования профиля и формы полосы. Воздействие всех технологических факторов на форму полосы будет иметь сложный характер. В работе рассмотрен подход, учитывающий основные параметры работы прокатного оборудования и позволяющий оценить вид и амплитуду дефектов плоскостности готовых стальных полос. При реализации такого подхода выполнены шесть этапов расчета: энергосиловой расчет процесса холодной прокатки; расчет упругих деформаций поверхности бочки рабочего валка; оценка износа поверхности бочки рабочего валка; расчет теплового профиля валка; оценка выпуклости поперечного профиля стальной полосы; оценка показателей планшетности готовой полосы. Для вычисления параметров, влияющих на планшетность проката, использованы известные методики расчета, адаптированные под конкретные технологические условия. Результаты оценки показателей формы катаной полосы, полученные с помощью модели, сопоставлены с результатами моделирования в программе Deform 3D. Результаты моделирования продемонстрировали достоверность предложенного подхода оценки качества проката.

Ключевые слова: плоскостность холоднокатаных стальных полос, непрерывная прокатка, режим прокатки, дефекты формы, профилировка бочки валка, упругая деформация бочки валка, тепловой профиль бочки валка, амплитуда дефекта

Для цитирования: Шалаевский Д.Л. Методика расчета плоскостности стальных холоднокатаных полос. *Известия вузов. Черная металлургия*. 2025;68(4):417–423. <https://doi.org/10.17073/0368-0797-2025-4-417-423>

INTRODUCTION

The primary causes of flatness defects in cold-rolled steel strips are non-uniform deformation across the strip width and low sectional stiffness. The latter is a characteristic feature of flat-rolled products.

Most established studies consider the variation in drawing ratios across the strip width as the main criterion for flatness loss. Among the influencing factors, some are viewed as more critical than others [1 – 18].

Studies [2 – 4] propose flatness criteria based solely on drawing ratio values across the strip width. The research findings reported in [5 – 8] highlight the potential to assess flatness defects through cross-sectional characteristics of the strip.

Models that incorporate multiple technological parameters for evaluating strip flatness are presented in [9 – 11].

Approaches focusing on transverse profile characteristics for identifying flat shape defects are described in [12 – 14].

Further models, found in [15 – 18], attribute flatness loss to post-rolling strip cooling processes.

The flatness evaluation method outlined in [9] enables the calculation of defect amplitudes based on rolling process parameters. This method accounts for nearly all relevant factors, including roll barrel profiling, potential work roll wear, roll axis misalignment, and several other significant influences.

The aim of this study was to develop a method for evaluating the amplitude of waviness and buckling in cold-rolled strips based on the variation in drawing ratios across the width, and to validate it by comparing calculated results with those generated using the DEFORM-3D simulation software.

PROBLEM STATEMENT AND RESEARCH METHODS

Calculating the amplitude of *waviness* or *buckling* in cold-rolled steel strips, based on the variation in drawing ratios across the strip width, requires comprehensive input data. This includes the elastic deformations of the work and backup rolls, the wear of their barrel surfaces, and the non-uniform thermal expansion across the width of the rolled strip.

Study [19] presents a regression-based model describing the elastic deformation of a four-high (“quarto”) mill stand along the work roll barrel. This relationship was derived through numerical simulation of elastic deformations in the roll system and was previously applied to model flatness formation in hot-rolled strips produced on a continuous wide-strip mill. It is also applicable to the integrated method proposed in the present study.

Additional research [20 – 22] offers methods for evaluating barrel surface wear and non-uniform thermal expansion along the roll barrel.

The type and amplitude of flatness defects in cold-rolled strips can be assessed using the methodology described in [23].

The reliability of the calculated results can be verified by evaluating strip shape quality indicators using the DEFORM-3D simulation software.

RESULTS AND DISCUSSION

The procedure for calculating the type and amplitude of flatness defects in cold-rolled steel strips included the following stages:

- Stage 1: calculation of the energy–power parameters of the cold rolling process;
- Stage 2: analysis of elastic deformation of the work roll barrel surface;
- Stage 3: assessment of wear on the work roll barrel surface;
- Stage 4: calculation of the roll thermal profile;
- Stage 5: evaluation of the convexity of the strip’s transverse profile;
- Stage 6: assessment of flatness parameters of the finished strip.

The first stage was implemented using a model of energy–power parameters that takes into account elastic deformation zones along the deformation zone length [24 – 25].

The second stage involved modeling elastic deformations of the four-high (quarto) mill roll system using a numerical simulation tool for analyzing process mechanics.

To determine the deformation of the work roll barrel surface, taking into account elastic flattening in the contact zones with the backup roll barrel and the strip during rolling, three-dimensional computational models were developed for the work and backup roll sets of a five-stand 1700 mm continuous cold rolling mill.

The roll set was imported into the MechanicalStructure module of ANSYS R1 (Fig. 1).

In the module’s pre-processor, a mesh was generated (Fig. 1). In ANSYS Workbench, high-carbon steel with a yield strength of 900 MPa was assigned as the roll material. To simulate support conditions, boundary constraints were applied to the backup roll necks along the X , Y , and Z axes (vertical direction), and to the work roll necks along the X and Y axes. In the vertical direction, the work roll rested on the backup roll barrel.

During the creation of the solid model, a specific region was defined on the surface of the work roll barrel

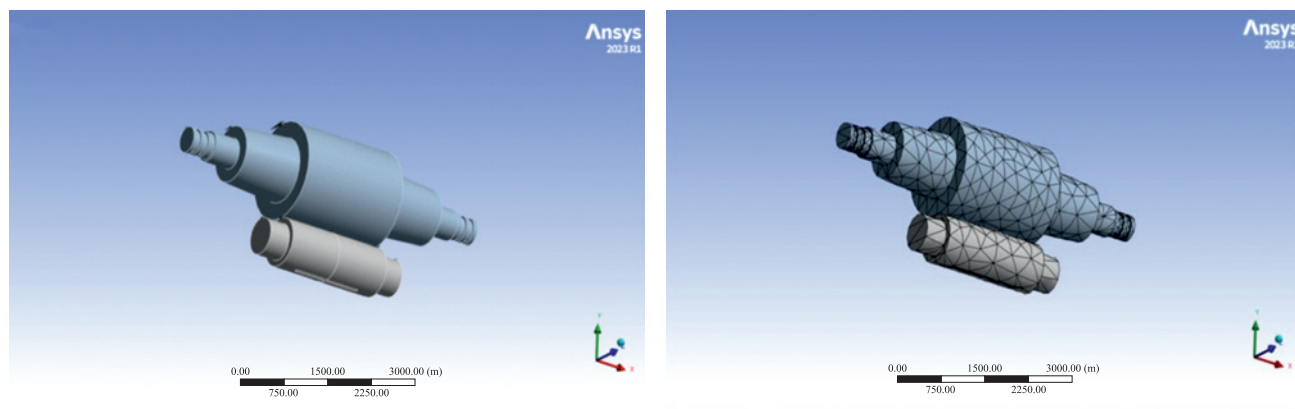


Fig. 1. Model of the roll system of “quarto” stand

Рис. 1. Модель валковой системы клети «кварто»

to represent the deformation zone, where contact pressure would be applied. In this region, a pressure load equivalent to the normal stress in the deformation zone was assigned. To enable this setup, the Static Structure solver was launched in advance.

To simulate anti-bending force, concentrated vertical loads were applied to the ends of the work roll necks along the Y -axis.

During the simulation, the following parameters were varied within defined ranges: the contouring of the work and backup roll barrels, contact pressure in the deformation zone, strip width, and the anti-bending force applied to the work rolls.

A contour plot illustrating the results of elastic deformation calculations is presented in Fig. 2.

The difference in elastic deformation of the work roll barrel surface between the strip edge and center (elastic deflection across the strip width) was generalized into the following regression equation

$$\Delta_{dc} - \Delta_{dedg} = 0.00001632 \cdot 10^{-5} b + 0.007703 P - 0.00000305 P_{bend} - 0.0200 \Delta D_{g.c.} - 0.0169 \Delta D_{g.c.b}, \quad (1)$$

where P is the rolling force in the i -th stand, MN; P_{bend} is the anti-bending force applied to the work rolls, kN; b is the strip width, mm; $\Delta D_{g.c.}$ is the ground crown of the work

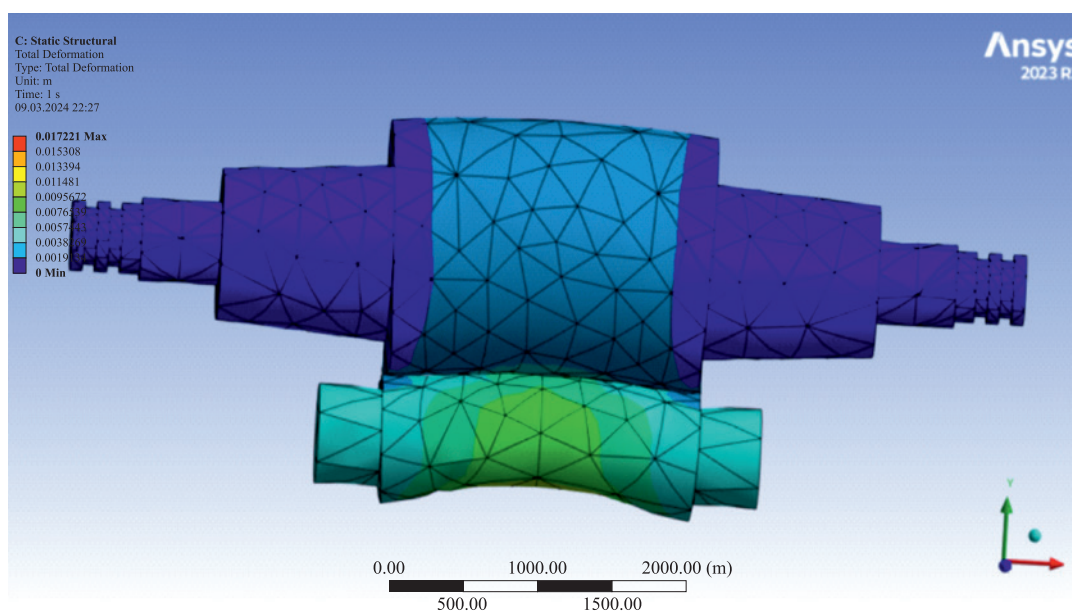


Fig. 2. Example of the result of calculating elastic deformations in vertical axial plane of the rolls of “quarto” stand in the MechanicalStructure module of the Ansys R1 program

Рис. 2. Пример результата расчета упругих деформаций в вертикальной осевой плоскости валков клети «кварто» в модуле MechanicalStructure программы Ansys R1

Table 1. Results of checking the significance of coefficients of the equation for calculating elastic deformations

Таблица 1. Результаты проверки значимости коэффициентов уравнения для расчета упругих деформаций

Parameter	Statistical significance level (<i>p</i> -value)
Strip width, mm	0.01
Rolling force in the <i>i</i> -th stand, MN	$2.07 \cdot 10^{-30}$
Anti-bending force applied to work rolls, kN	$4.31 \cdot 10^{-9}$
Ground crown of the work roll barrel at its center, mm	0.02
Ground crown of the backup roll barrel at its center, mm	$4.36 \cdot 10^{-8}$
Note. A parameter is considered statistically significant if the <i>p</i> -value is less than 0.05.	

roll barrel at its center, mm; $\Delta D_{g.c.b}$ is the ground crown of the backup roll barrel at its center, mm.

The coefficient of multiple determination R^2 was 0.86, indicating a high degree of reliability for the derived equation.

The statistical significance of the coefficients in Equation (1) was assessed using *p*-values, based on a dataset of forty simulation variants previously reported in [19]. The results of this evaluation are presented in Table 1.

The third stage – evaluation of wear on the work roll barrel surface – was based on experimental data that included roll operating parameters, surface hardness, and barrel contour geometry [20].

As shown in Table 2, roll wear is influenced by the rolling force, surface hardness of the roll barrel, barrel diameter, and the total length of strip rolled. Initial concavity was found to have a negligible effect.

A relationship was established to estimate roll barrel wear at both the center and strip edges, depending on the influencing parameters:

$$\Delta_c = k_w P + k_L L_m, \quad (2)$$

where P is the average rolling force in the working stand since the installation of the work roll, MN; L_m is the total length of strip rolled on the work rolls in stand, m; k_w is the coefficient representing the influence of rolling force on the wear of the work roll barrel surface; k_L is the coef-

ficient representing the influence of the strip length rolled on the work rolls in the stand on roll barrel wear.

The values of these coefficients, for example at the center of the roll barrel (i.e., along the strip centerline), were determined using the following regression equations

$$k_w = -0.00025HSD + 0.0000285D, \quad (3)$$

where HSD is the Shore hardness of the roll barrel surface, D is the diameter of the work roll barrel, mm. The coefficient of determination for this equation is $R^2 = 0.89$, indicating a high degree of reliability;

$$k_L = -0.0000011HSD + 0.00000011D. \quad (4)$$

The forth stage was the calculation of the roll thermal profile.

The thermal behavior of the continuous cold rolling mill was analyzed by formulating and solving a system of heat balance equations for the work rolls, backup rolls, and strip. The application of this model for both cold and hot continuous strip rolling has been discussed in prior studies [21; 22].

The thermal crown of the roll barrel across the strip width was calculated using the temperature distribution determined from the system of equations, with particular focus on the roll barrel center.

Table 2. Results of assessing the Pearson correlation coefficients of the rolls parameters and technology with amount of the barrel surface wear

Таблица 2. Результаты оценки коэффициентов корреляции Пирсона параметров валков и технологии с величиной износа поверхности бочки

Parameter	Rolling force, MN	Roll barrel hardness, <i>HSD</i>	Roll barrel diameter, mm	Length of strip rolled, m	Initial concavity of the roll barrel surface at its center, mm
Correlation coefficient	−0.4755	0.4277	−0.4055	0.4839	0.012

The fifth stage involved assessing the strip's profile using the components obtained in previous stages, which define the cross-sectional shape of the flat-rolled product at the roll gap exit:

- initial ground crown, adjusted for current wear, Δ_{gy} ;
- elastic deformation of the work roll barrel surface, Δ_{dy} ;
- thermal profile (thermal crown) of the roll barrel surface, Δ_{ty} ;
- nominal strip thickness, h_i .

The strip thickness at any point along the width (coordinate y) was calculated as:

$$\Delta_{ty} = h_i - \Delta_{gy} + \Delta_{dy} - \Delta_{ty}.$$

The six stage – evaluation of flatness parameters of the finished strip – was performed using the relationships described in [23].

By knowing the initial slab and final strip thickness profiles across the width – and thus the drawing ratios at the edges and center of the strip – it is possible to estimate the most important flatness defect parameter defined in GOST 19903–2015 – the defect amplitude:

- for “waviness” formed in the i -th stand of a continuous group of stands:

$$a_{wi} = \frac{hE \left[1 - \cos \left(\frac{2\sigma_k (\lambda_{cr} - \lambda_c)}{hE} \right) \right]}{\sigma_k}, \quad (5)$$

where h is the strip thickness, E is the strip's Young's modulus, σ_k is the critical buckling stress, λ_{cr} , λ_c are

the drawing ratios at the strip edge and center, respectively, based on the entry and exit cross-sections;

- “buckling” formed in the i -th stand of the continuous rolling mill:

$$a_{bi} = \frac{hE \left[1 - \cos \left(\frac{2\sigma_k (\lambda_c - \lambda_{cr})}{hE} \right) \right]}{\sigma_k}. \quad (6)$$

It has been confirmed [23] that flatness defects accumulate as the strip passes from stand to stand. Therefore, if the same type of defect occurs in subsequent stands, its amplitude increases additively.

The accuracy of the calculated amplitude and type of waviness using Equations (5) and (6) was validated by simulating the rolling process in DEFORM-3D. For this purpose, roll barrel models were created with longitudinal profiles incorporating both elastic deformation and thermal crown across the strip width. Non-uniform roll barrel wear could also be taken into account. An entry slab was modeled with a specified cross-sectional profile, and the rolling process was simulated. In the post-processor, vertical displacement differences between the strip center and edges were tracked across the width.

In Fig. 3, Line 3 represents the vertical displacement at the strip edge, while Line 1 represents displacement at the center. The difference between them was taken as the defect amplitude.

An example of amplitude evaluation using DEFORM-3D is shown in Fig. 4.

The validation results obtained from DEFORM-3D simulations confirm the sufficient accuracy of the analytical model for predicting the flatness of cold-rolled steel.

CONCLUSIONS

A well-known cause of flatness defects in finished cold-rolled steel strips is the variation in drawing ratios

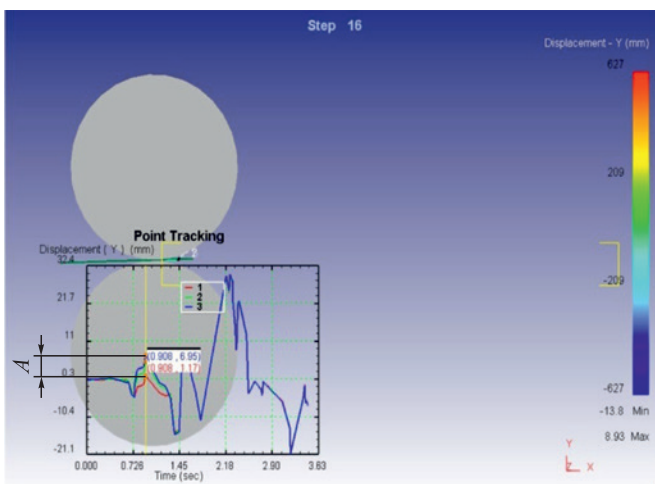


Fig. 3. Example of assessing flatness defect of the “wave” strip (A – amplitude of “wave” on the strip)

Рис. 3. Пример оценки дефекта плоскостности полосы «волна» (A – амплитуда «волны» на полосе)

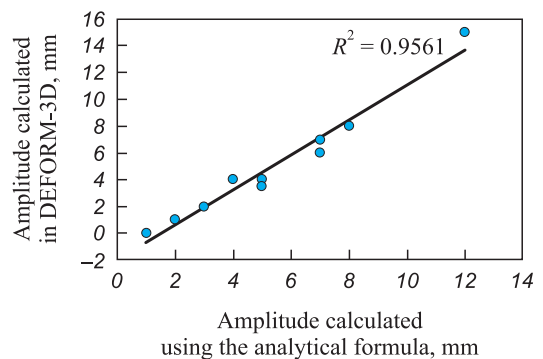


Fig. 4. Comparison of the results of calculating the non-flatness amplitude

Рис. 4. Сравнение результатов расчета амплитуды неплоскостности

across the strip width. This variation is influenced by the roll barrel contouring parameters, the energy–power parameters of the rolling process, and the operating parameters of the automatic profile and flatness control system. The combined effect of these technological factors on strip shape is complex. This paper presents an approach that incorporates the key operational parameters of rolling equipment and enables the evaluation of the type and amplitude of flatness defects in finished steel strips.

REFERENCES / СПИСОК ЛИТЕРАТУРЫ

1. Shalaevskii D.L. Models for the formation of flatness defects of steel strip during its rolling and heat treatment. *Russian Metallurgy (Metally)*. 2024;2024(7):1760–1764. <https://doi.org/10.1134/S0036029524703063>
2. Budakva A.A., Kononov Yu.V., Tkach K.N. Roll Profiling for Sheet Metal Mills. Kiev: Tekhnika; 1986:190. (In Russ.).
Будаква А.А., Коновалов Ю.В., Ткалич К.Н. Профилирование валков листовых станов. Киев: Техника; 1986:190.
3. Maksimov E.A., Shatalov R.L., Boskhamdzhev N.Sh. Production of Flat Strips by Rolling. Moscow: Teplotekhnika; 2008:355. (In Russ.).
Максимов Е.А., Шаталов Р.Л., Босхамджиев Н.Ш. Производство планшетных полос при прокатке. Москва: Теплотехник; 2008:355.
4. Shatalov R.L., Maksimov E.A., Verkhov E.Yu. Rational modes of control of strip flatness in thin-sheet reversible rolling. In: *Scientific and Technical Progress in Ferrous Metallurgy: Proceedings of the II Int. Sci. and Tech. Conf. (October 7–9, 2015)*. Cherepovets: Cherepovetskii gos. un-t; 2015:148–151. (In Russ.).
Шаталов Р.Л., Максимов Е.А., Верхов Е.Ю. Рациональные режимы управления плоскостностью полос при тонколистовой реверсивной прокатке / *Научно-технический прогресс в черной металлургии: Материалы II Международной научно-технической конференции (7–9 октября 2015 г.)*. Череповец: Череповецкий государственный университет; 2015:148–151.
5. Shatalov R.L., Maksimov E.A. Clarification of the method for calculating critical stresses and flatness indices of strip during thin-sheet rolling. *Stal'*. 2016;(4):26–30. (In Russ.).
Шаталов Р.Л., Максимов Е.А. Уточнение метода расчета критических напряжений и показателей плоскостности полосы при тонколистовой прокатке. *Сталь*. 2016;(4):26–30.
6. Ievlev N.G. Mathematical models of flatness of thick sheet metal applied to automated process control systems. *Matematichni mashini i sistemi*. 2018;(1):67–77. (In Russ.).
Иевлев Н.Г. Математические модели плоскостности толстолистного проката применительно к АСУ ТП. *Математичні машини і системи*. 2018;(1):67–77.
7. Shatalov R.L., Maksimov E.A. Analysis of asymmetric rolling efficiency for increasing accuracy of rolled strips. *Metalurg*. 2016;(7):80–84. (In Russ.).
Шаталов Р.Л., Максимов Е.А. Анализ эффективности технологии асимметричной прокатки для повышения точности прокатываемых полос. *Металлург*. 2016;(7):80–84.
8. Bartkhol'dt Kh., Kopin F., Dzhelali M. Universal flatness model for process optimization in cold rolling mills. *Chernye metally*. 2015;(3):53–58. (In Russ.).
Бартхольдт Х., Копин Ф., Джелали М. Универсальная модель плоскостности для оптимизации процесса холодной прокатки. *Черные металлы*. 2015;(3):53–58.
9. Shalaevskii D.L., Mitrofanov A.V., Korepina K.P. Improvement in the flatness of finished steel strips under energy saving regimes of continuous hot rolling. *Stal'*. 2022;(2):15–17. (In Russ.).
Шалаевский Д.Л., Митрофанов А.В., Корепина К.П. Повышение плоскостности готовых стальных полос на энергосберегающих режимах непрерывной горячей прокатки. *Сталь*. 2022;(2):15–17.
10. Garber E.A., Shalaevskii D.L., Mishnev P.A., Mikheeva I.A., Paligin R.B. Improving the flatness of high-rolled steel strips by optimizing the settings of process mode parameters. In: *Int. Sci. and Pract. Conf. "Problems of Ferrous Metallurgy – 2015. Int. Sci. Seminar"*. 2016:76–82. (In Russ.).
Гарбер Э.А., Шалаевский Д.Л., Мишнев П.А., Михеева И.А., Палигин Р.Б. Улучшение плоскостности горячекатаных стальных широких полос путем оптимизации настройки параметров технологического режима / *Всероссийская научно-практическая конференции «Проблемы черной металлургии – 2015. Международный научный семинар»*. 2016:76–82.
11. Grigoryan G.G., Zhelezov Yu.D., Chernyi V.A., etc. Adjustment, Stabilization and Control of Thin Sheet Rolling Process. Moscow: Metallurgiya; 1983:120. (In Russ.).
Григорян Г.Г., Железов Ю.Д., Черный В.А. и др. Настройка, стабилизация и контроль процесса тонколистовой прокатки. Москва: Металлургия; 1983:120.
12. Pimenov V.A., Bel'skii S.M., Kuznetsova E.V., Shkarin A.N. Mathematical model for identifying the shape of profile with primary cross-section of hot-rolled strips and distribution of extensions across the width of cold-rolled strips. Report 1. *Proizvodstvo prokata*. 2018;(1):11–15. (In Russ.).
Пименов В.А., Бельский С.М., Кузнецова Е.В., Шкарин А.Н. Математическая модель идентификации формы профиля поперечного сечения горячекатаных полос и распределения вытяжек по ширине холоднокатаных полос. Сообщение 1. *Производство проката*. 2018;(1):11–15.
13. Pimenov V.A., Bel'skii S.M., Kuznetsova E.V., Shkarin A.N. Mathematical model for identifying the shape of profile with primary cross-section of hot-rolled strips and distribution of extensions across the width of cold-rolled strips. Report 2. *Proizvodstvo prokata*. 2018;(6):9–14. (In Russ.).
Пименов В.А., Бельский С.М., Кузнецова Е.В., Шкарин А.Н. Математическая модель идентификации формы профиля поперечного сечения горячекатаных полос и распределения вытяжек по ширине холоднокатаных полос. Сообщение 2. *Производство проката*. 2018;(6):9–14.
14. Shkarin A.N. Formation of flatness of cold-rolled strips taking into account the features of cross-section profile of hot-rolled rolled products: Extended Abstract of Cand. Sci. Diss. 2021. (In Russ.).
Шкарин А.Н. Формирование плоскостности холоднокатаных полос с учетом особенностей профиля поперечного сечения горячекатаного подката: Автореферат диссертации ... кандидата технических наук. 2021.

15. Wang X., Yang Q., He A. Calculation of thermal stress affecting strip flatness change during run-out table cooling in hot steel strip rolling. *Journal of Materials Processing Technology*. 2008;207(1-3):130–146.
<https://doi.org/10.1016/j.jmatprotec.2007.12.076>
16. Hrabovsky J., Pohanka M., Lee P.J., Kang J.H. Experimental and numerical study of hot-steel-plate flatness. *Materials and Technology*. 2016;50(1):17–21.
<https://doi.org/10.17222/mit.2014.153>
17. Wu H., Sun J., Lu X., Peng W. Predicting stress and flatness in hot-rolled strips during run-out table cooling. *Journal of Manufacturing Processes*. 2022;84:815–831.
<https://doi.org/10.1016/j.jmapro.2022.10.053>
18. Bozhkov A.I., Kovalev D.A., Chernikov O.V., Yusupov V.S., Ivliev S.N., Degtev S.S. Influence of heat treatment on the planarity of isotropic electrical steel strip. Part 2. *Steel in Translation*. 2019;49(2):131–133.
<https://doi.org/10.3103/S0967091219020049>
Божков А.И., Ковалев Д.А., Черников О.В., Юсупов В.С., Ивлиев С.Н., Дегтев С.С. Влияние режимов термообработки на плоскостность полос электротехнических изотропных сталей. Сообщение 2. *Сталь*. 2019;(2):26–28.
19. Shalaevskii D.L. Prediction of steel strip flatness based on the difference in drawing coefficients along its width during steel strip rolling. *Ferrous Metallurgy. Bulletin of Scientific, Technical and Economic Information*. 2024;80(10): 20–27. (In Russ.).
Шалаевский Д.Л. Прогнозирование плоскостности стальной полосы на основе разности коэффициентов вытяжек по ее ширине при прокатке. *Черная металлургия. Бюллетень научно-технической и экономической информации*. 2024;80(10):20–27.
20. Shalaevskii D.L., Sidorov A.V. Study of wear on surface of work rolls barrels of continuous stands of a wide strip hot rolling mill. *Zagotovitel'nyye proizvodstva v mashinostroyeni*. 2024;22(7):315–318. (In Russ.).
<https://doi.org/10.36652/1684-1107-2024-22-7-315-318>
Шалаевский Д.Л., Сидоров А.В. Исследование износа поверхности бочек рабочих валков непрерывной группы клетей широкополосного стана горячей прокатки. *Заготовительные производства в машиностроении*. 2024;22(7):315–318.
<https://doi.org/10.36652/1684-1107-2024-22-7-315-318>
21. Garber E.A. Cold Rolling Mills: (Theory, Equipment, Technology). Moscow: Chermetinformatiya; 2004:412. (In Russ.).
Гарбер Э.А. Станы холодной прокатки: (теория, оборудование, технология). Москва: ОАО “Черметинформация”; 2004:412.
22. Shalaevskii D.L. Investigation of thermal mode of hot-rolling mill working rolls in order to improve the accuracy of calculating the thermal profile of their barrels' surface. *Izvestiya. Ferrous Metallurgy*. 2023;66(3):283–289.
<https://doi.org/10.17073/0368-0797-2023-3-283-289>
Шалаевский Д.Л. Исследование теплового режима рабочих валков стана горячей прокатки с целью повышения точности расчета температур поверхностей их бочек. *Известия вузов. Черная металлургия*. 2023; 66(3):283–289.
<https://doi.org/10.17073/0368-0797-2023-3-283-289>
23. Shalaevskii D.L. Investigation of the influence of technological factors on continuous high-speed rolling on flatness of thin steel sheets with the aim of increasing their quality. *Metally*. 2024;(5):62–68. (In Russ.).
<https://doi.org/10.31857/S0869573324056268>
Шалаевский Д.Л. Исследование влияния технологических факторов при непрерывной горячей прокатке на плоскостность тонких стальных листов с целью повышения их качества. *Металлы*. 2024;(5):62–68.
<https://doi.org/10.31857/S0869573324056268>
24. Shalaevskiy D.L., Kozhevnikov A.V. Algorithm and design methodology for energy-efficient sheet products production technology. *IOP Conference Series: Materials Science and Engineering*. 2020;718:012015.
<https://doi.org/10.1088/1757-899X/718/1/012015>
25. Garber E.A., Shalaevskii D.L., Kozhevnikova I.A., Traino A.I. Procedure and algorithms for the energy-force calculation of cold rolling allowing for the number of neutral sections in the deformation zone. *Russian Metallurgy (Metally)*. 2008;2008(4):315–325.
<https://doi.org/10.1134/S0036029508040083>

Information about the Author

Dmitrii L. Shalaevskii, Cand. Sci. (Eng.), Assist. Prof. of the Chair “Metallurgy, Mechanical Engineering and Technological Equipment”, Cherepovets State University
ORCID: 0000-0002-0443-4135
E-mail: shal-dmitrij@yandex.ru

Сведения об авторе

Дмитрий Леонидович Шалаевский, к.т.н., доцент кафедры металлургии, машиностроения и технологического оборудования, Череповецкий государственный университет
ORCID: 0000-0002-0443-4135
E-mail: shal-dmitrij@yandex.ru

Received 25.04.2025
Revised 19.06.2025
Accepted 20.06.2025

Поступила в редакцию 25.04.2025
После доработки 19.06.2025
Принята к публикации 20.06.2025