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Experimental studies of stress-strain state of metal, energy and power parameters and main quality indicators during strip sections rolling

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Nadiya Vlasova
Senior lecturer, separate structural unit ‘’Technological Specialized College of the State University of Economics and Technology", Kryvyi Rih, Ukraine
e-mail: vlasova@kmt.in.ua
ORCID ID: 0009-0007-9762-6323

Maryna Korenko
Senior lecturer, State University of Economics and Technology, Kryvyi Rih, Ukraine
e-mail: marinak20162010@gmail.com
ORCID ID: 0000-0002-4582-1756

Daria Kassim
Prof. DSc, State University of Economics and Technology, Kryvyi Rih, Ukraine
e-mail: kassim@duet.edu.ua
ORCID ID: 0000-0002-1750-1237

Volodimer Kryvenko
Senior lecturer, State University of Economics and Technology, Kryvyi Rih, Ukraine
e-mail: marinak20162010@gmail.com
ORCID ID: 0000-0001-7822-6358

Viktoriya Hrihorieva
Assoc. Prof. PhD, State University of Economics and Technology, Kryvyi Rih, Ukraine
e-mail: kr_filial@ukr.net
ORCID ID: 0000-0002-1397-0546

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Nadiya Vlasova
Senior lecturer, separate structural unit «Technological Specialized College of the State University of Economics and Technologiy», Kryvyi Rih, Ukraine
e-mail: vlasova@kmt.in.ua
ORCID ID: 0009-0007-9762-6323

Maryna Korenko
Senior lecturer, State University of Economics and Technology, Kryvyi Rih, Ukraine
e-mail: marinak20162010@gmail.com
ORCID ID: 0000-0002-4582-1756

Daria Kassim
Prof. DSc, State University of Economics and Technology, Kryvyi Rih, Ukraine
e-mail: kassim@duet.edu.ua
ORCID ID: 0000-0002-1750-1237

Volodimer Kryvenko
Senior lecturer, State University of Economics and Technology, Kryvyi Rih, Ukraine
e-mail: marinak20162010@gmail.com
ORCID ID: 0000-0001-7822-6358

Viktoriya Hrihorieva
Assoc. Prof. PhD, State University of Economics and Technology, Ukraine, Kryvyi Rih,
e-mail: kr_filial@ukr.net
ORCID ID: 0000-0002-1397-0546

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Keywords: rolled metal products, rolling mill, hot rolled strip, rolling rolls, local characteristics of the stress state of metal, installation for plastic deformation of metal, roll calibration schemes for strip rolling.

Introduction

In Ukraine, the production of rolled metal is mostly concentrated at specialized integrated metallurgical plants and factories. They are located in the large industrialized regions of the country like Donetsk, Dnipropetrovsk, Zaporizhzhia, and Luhansk regions (*Stasovskiy, 2015*)

Graded rolling mills in Ukraine were mainly put into operation in the 60-70s of the 20th century, and their physical wear level is ranging from 29 to 90%. Taking into account the reconstruction of existing facilities and the commissioning of new ones, as well as their maintenance in good physical condition due to capital repairs with modernization elements, today grade rolling mills are still capable of producing rolled steel of the required quality (*Stasovskiy, 2015*)

Before Moscow invaded Ukraine, the utilization of rolling stock capacity had been on average 77,8%, though some enterprises had not exceeded 20%.

Industrial production of hot-rolled flat rolled metal was one of the most dynamically developing areas in ferrous and non-ferrous metallurgy. The range, quality indicators, and production volumes of flat rolled metal can be considered as a marker of the degree of industrialization and development of scientific and technical progress at the state level (*Konovalov, 2008*; *World Steel in Figures. Review, 2006*; *Zaykov, Polukhin, Zaykov, Smirnov, 2004*; *Mazur, 2010*); *Frantsenyuk, 1995*).

The post-war recovery will most likely create a significant demand for long-rolled products. Also, it will require the deployment of additional capacities for the manufacturing of flat-rolled products. Therefore, it is extremely important to pay special attention to the technical rearmament of metallurgical enterprises of Ukraine due to the installation of modern equipment and the use of new technologies

The metallurgical industry has been particularly badly affected by the war, as Ukraine has temporarily lost control over several metallurgical plants and about 50% of iron ore deposits located in territories not controlled by Ukraine or in areas significantly affected by prolonged hostilities (*Horodnichenko, Solohub, Beatrice, 2022*).

Currently, the main producers of hot-rolled strip profiles in Ukraine are continuous small-grade rolling mills 250 of three generations.

The rolling process with the use of accelerating gauges, i.e. with the use of working rolls with convex shaped forming surfaces, intensifying the transverse plastic flow of metal, can be of interest from the point of view of expanding the degrees of free choice for the purposeful regulation of the final thickness and width of hot-rolled strips obtained from the same billet (Fig. 1) (*Ilyukovych, 2002*)

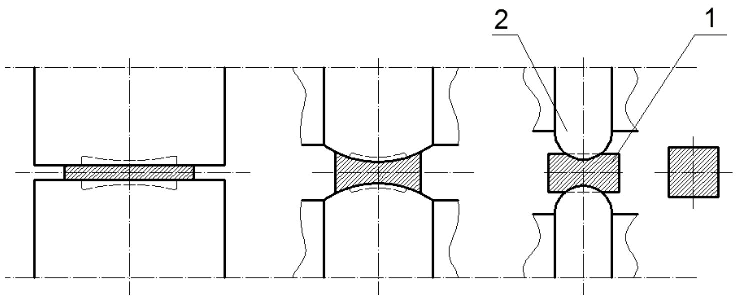


Figure 1. The principle technological diagram of the hot-rolled strip production process based on the process of hot rolling of blanks using acceleration gauges (*Ilyukovych, 2002)*

In general, the variety of possible technical solutions indicates the presence of sufficiently wide prospects for further improvement of technologies and equipment for the processes of hot rolling of high-quality strip profiles.

If we review the state of affairs in the field of technologies and equipment used in the production of hot-rolled strips and determine the main prospects for their further development we can identify the following areas: improving the quality of initial billets by enhancing the technologies of their production and processing at the previous stages (*Chumakov, Korenko,2009*) ; creation of new (including combined foundry-rolling units) and reconstruction of the existing equipment of rolling mills, providing an increase in their technical and economic indexes (*Frantsenyuk , I.V. Frantsenyuk L.I, 1995*; *Minayev, 2008*; *Smirnov, 2005*); improvement of existing technologies of hot rolling process and used calibrations, including calibration-free rolling processes, conditioning processes, use of dispersed calibers and so on, providing reduction of specific operating costs while improving the quality of finished steel products (*Kandaurov, 1998*; *Tokarev, Markov, 1983*; *Vladimirov, Nyzhnyk, Purtov, 1985*; (*Kaplanov, Chumakov, Korenko, 2010*); creation of forced kinematic asymmetry in circumferential rotation speeds of working rolls, contributing (as shown by the results of theoretical and experimental studies of hot and cold rolling processes (*Fedorinov, Satonin, Gribkov, 2010*;

Konovalov, Budakva, Goncharov, Zavrazhniy , 1987; *Svichinskiy, Binkyevich, Mazur, Holubchenko, 1992*) to reducing the levels of deforming forces and improving the accuracy of the resulting geometric characteristics; improvement of the composition and design parameters of the main and auxiliary equipment of hot rolling mills of long sections, including a number of measures (*Myedvyedyev, Krukov,.Osipenko, 2004*); *Myedvyedyev, 2008; Polukhin , Khloponin, Sigitov, 1975*; *Mazur, Safiyan, Prikhodko, Yatsenko, 1997*); increasing the degree of automation of technological modes of the process of hot rolling of long sections with simultaneous tightening of control of geometric characteristics, kinematic parameters, temperature conditions, as well as the resulting physical and mechanical properties of finished metal products (*Klimenko, Kashayev, Minayev, 1983*).

The aim of this work is to expand the volume and range of hot-rolled strip profiles with a mandatory increase in their quality and cost reduction, as well as to improve existing technologies and create new efficient equipment.

Lack of finances makes it necessary for the metallurgical enterprises to ensure maximum saving of material resources on the basis of increasing the degree of scientific validity of technical decisions taken in each particular case.

The necessity of scientific validity increasing imposes additional requirements to the scope and reliability of the theoretical and experimental studies results of the hot rolling process of strip sections, as well as to the practical recommendations developed on their basis. Under these circumstances, not only local and integral characteristics of stress-strain state of metal, but also basic quality indicators and a number of other indicators determining consumer properties of finished rolled metal products should be considered as the above results (*Stasovskiy, 2015*; *Mazur, Nogovitsyn, 2010*; *Frantsenyuk I.V. Frantsenyuk, L.I.*, 1995; *Ilyukovych, Nekhayev, Merkuriyev, 2002*; *Myedvyedyev, Krukov, Osipenko, 2004*; *Myedvyedyev, 2008*; *Fedorinov, Satonin, Gribkov,2010*; *Byenyakovskiy, Bohoyavlenskiy, Vitkin, 1991*; *Nikolayev, Mazur, 2000*; *Myedvyedyev, 2009*; *Rokotyan, 1981*).

From the point of view of ensuring the economy of material resources in scientific research, the priority is the implementation of theoretical approaches. As for the results of experimental research, they should be aimed at clarifying the initial assumptions, assessing the degree of reliability of the theoretical solutions obtained and approbation of specific practical recommendations received on their basis.

Materials and Methods

Experimental estimation of the values of normal contact stresses current along the length of the deformation center occurring under different technological conditions (including asymmetric kinematic conditions of the realization of the strip sections rolling process) is carried out using a special device for plastic deformation of metal. This device has a deforming tool that simulates the working rolls of large radius mills, which allows us to increase substantially the scale of geometric properties of the deformation center and, as a result, to increase the accuracy of the results obtained (*Potapkin, Fyedorinov, Satonin, Dobronosov, 2005 ; Chyekmaryev, 1969*). Taking into account the diameter of the measuring head of the pin part of the point pressure capsule d_p = 2 mm, the ratio L/d_p corresponded to L/d_p =19÷41, which according to the scientific recommendations (*Chyekmaryev, 1969)* is quite sufficient to ensure the required degree of accuracy of the obtained experimental distributions of normal contact stresses p_x.

Results

For modeling the process of hot rolling of strip sections in the last finishing working stand a rolling mill with working rolls of radius $R_{av} \approx 150$ mm at initial h_0= 3÷6 mm and final h_1 = 2÷4 mm values of thicknesses was used. Taking into account quantitative estimates of the ratios R_{av}/h_0 = 25÷50; h_0/h_1 = 1,25÷1,5 when performing experimental studies, following the condition of geometric similarity, the billets with nominal values of initial and final thicknesses h_0 = 26 mm, h_1 = 18 mm (R/h_0 = 750/26=28,8; h_0/h_1 = 26/18=1,44), and also h_0 = 15 mm, h_1 = 10 mm (R/h_0 = 750/15=50; h_0/h_1 = 15/10=1,5) were rolled. The width of the rolled lead specimens corresponded to B = 50 mm and their length was L_0 = 100 mm. The values of kinematic asymmetry coefficients of the rolling process determined by the ratio of arms L_0 and L_1 of the slave segment rod fixation on the additional arm are taken as K_v =1,0; 1,25; 1,75.

Rolling was carried out at a speed of ~3,33 mm/s, technological lubricants were not used**,** and the contact surfaces of deformed samples and working segments were degreased with acetone before each crimping. Lead C1 was used as a material for deformable blanks. To clarify its mechanical properties, a number of preliminary experimental studies on the settlement of cylindrical samples made of lead of this grade were carried out on a specialized hydraulic press machine.

Deformed samples from lead C1 had diameter D_s =30 mm and height H_s =30 mm, which corresponded to the ratio $D_s/H_s \approx 1$, at which, from the point of view of the stress-strain state, following the results of a number of studies [32, 33], the influence of external zones and contact friction forces is minimal and, as a consequence, the value of yield stresses can be determined on the basis of the dependency

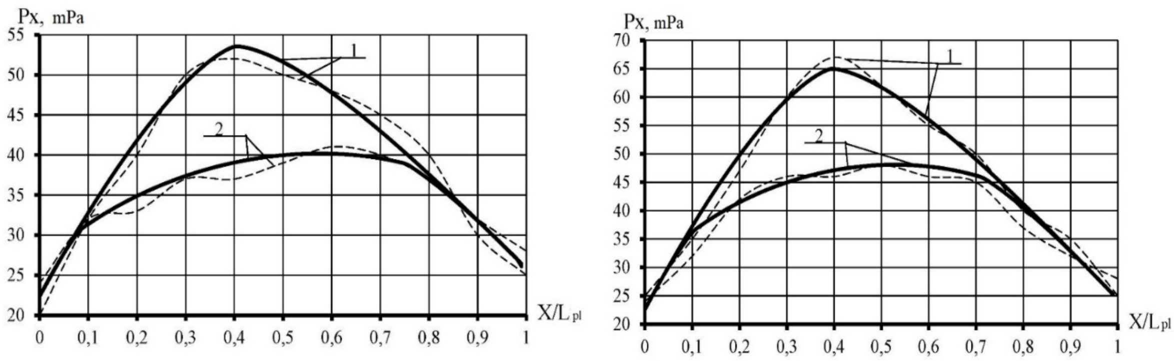
$$\sigma_т = 4P_{sl} / (\pi D_{sl}^2) = \rho D_p^2 / D_{sl}^2, \quad (1)$$

where P_{sl} is the force value of the precipitation process, measured by the readings of the manometer MP4-U, fixing the pressure of the working fluid ρ in the hydraulic system; D_p is the piston diameter of the power hydraulic cylinder.

Besides, the value of force P_{sl} was controlled by pressing capsules, and its quantitative estimation was in the range P_{sl} = 13÷15 кН, which according to expression (1) corresponds to yield stresses $\sigma_т$ = 18,4÷21,2 MPa. The average value of this range $\sigma_т$ = 19,8 MPa was accepted as initial data for numerical realization of the previously developed one-dimensional mathematical models, the results of which p_{xc} were compared with the corresponding empirical distributions p_{xe} of normal contact stresses along the length of the deformation center.

Summarizing the results of the performed experimental studies, which are presented in Fig. 2 in the form of calculated p_{xc} and empirical p_{xe} distributions of normal contact stresses along the length of the deformation zone, characterized by the relative value X/L, it is necessary to note the following:

- with the increase of the ratio L/h_{av}, which is a geometric indicator of the shape of the deformation center, the levels of current values of normal contact stresses p_x increase quite significantly;
- creation and increase in the degree of kinematic asymmetry of the rolling process causes a decrease in the values of normal contact stresses p_x along the length of the deformation center, while the intensity of this decrease with increasing geometric index L/h_{av} increases.



a – $h_0 = 27$ mm, $h_1 = 18$ mm, $L / h_{av} = 3,65$ b – h_0=15 mm, h_1=10 mm, L/h_{av}=4,9,

1 – $K_v = 1,0$; 2 – $K_v = 1,25$.

Figure 2. Empirical (— —) and calculated (———) distributions of normal contact stresses p_x along the length of the deformation center of the rolling process of lead billets with different values of the kinematic asymmetry coefficient K_v

The comparative analysis of empirical p_{xe} and calculated p_{xc} distributions of normal contact stresses has shown that the relative error in this case is in the range δp_x = -5,3...8,1 %, the average sample value of the ratio is equal to $\overline{p_{xe} / p_{xc}} = 1,038$, thus the lower and upper limits of the confidence interval at confidence probability 0,95 corresponded $1,014 < \left(p_{xei} / p_{xci}\right) < 1,061$, that testifies to a sufficient degree of reliability of the received earlier numerical mathematical models of the stressed deformed state of metal at hot rolling of strip sections in the numerical model of stressed deformed state of metal at hot rolling.

Experimental studies of energy-force parameters during hot rolling of strip sections in laboratory conditions were carried out on the basis of a laboratory mill.

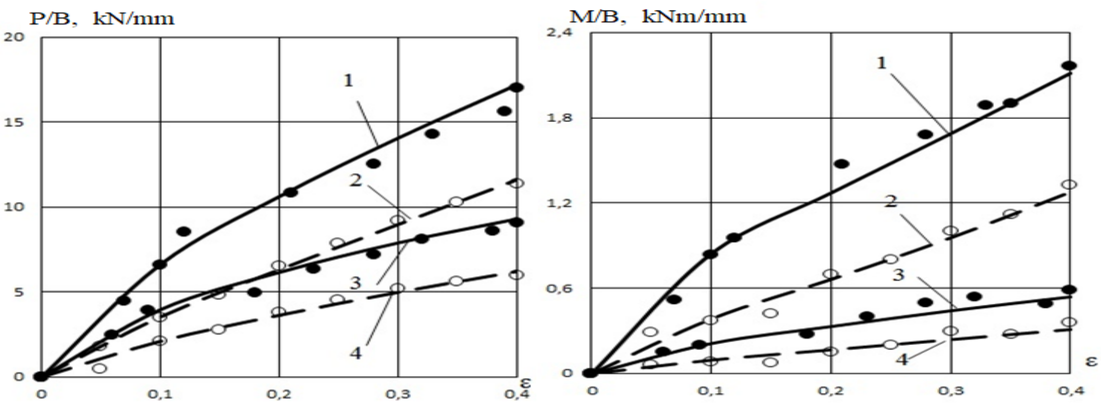
When performing these experimental studies, hot rolling was subjected to billets of steel 10 with an initial thickness of 3 mm and of steel 30ХГСА with an initial thickness of 6 mm in working rolls with radius R = 130 mm**.** The width of the billets in all cases corresponded to 50 mm, and their heating to temperatures of 700, 800 and 900ºC was carried out in an electric resistance furnace OKB 333C.

The rolling process was carried out with different relative compression in the range $\varepsilon = 0,05 \div 0,4$ at speed $V_1 \approx 0,3$ m/s. The integral characteristics of the stress state of the rolled metal were also calculated with respect to the corresponding technological modes of crimping in order to further compare and assess the degree of reliability of the numerical mathematical model.

As an example of the results of the performed experimental studies, Figs. 3-5 presents the calculated and empirical distributions of the reduced to unit width values of the force P/B and total moment M/B of rolling obtained for different materials at varying values of the radii of the working rolls R and heating temperatures of the initial billets t, as well as the value of the relative compression ε.

The results of the analysis of the presented calculated and experimental distributions (see Fig. 3-5) indicate that with increasing radii R, relative compression value ε, with increasing level of physical and mechanical properties and initial thickness h_0, as well as with decreasing temperatures t, the energy-force parameters of the hot rolling process of strip sections increase quite significantly.

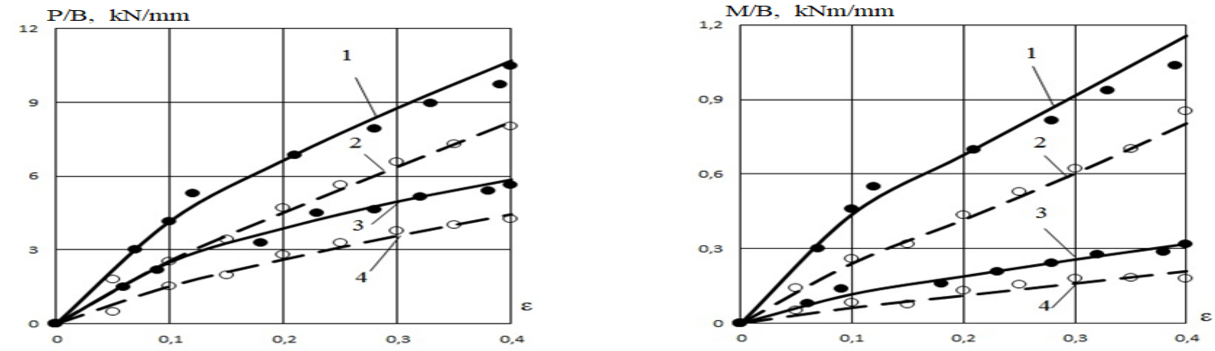
Concerning the comparison of calculated and empirical distributions of the values of force P_c/B, P_e/B and total moment M_c/B, M_e/B of rolling reduced to unit width it is necessary to note that the average sample values of their ratios P_c/P_e, M_c/M_e were in the range 0,97÷1,04, and the minimum and maximum values of confidence intervals obtained taking into account the confidence probability 0,95 corresponded to 0,966; 1,038 for the force and 0,958; 1,041 for the total rolling moment.



a b

1 – h_0 = 6,0 mm, steel 30 HGSA; 2 – h_0 = 3,0 mm, steel 10; 3 – h_0 = 6,0 mm, steel 30HGSA; 4 – h_0 = 3,0 mm, steel 10

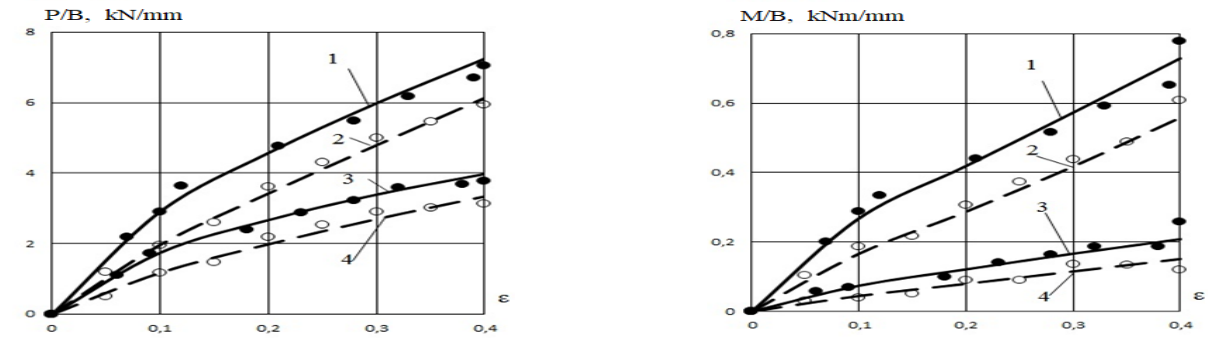
Figure 3.Calculated (——— , — —) and experimental (●, ○) distributions of force P/B (a) and total moment M/B (b) values reduced to unit width, obtained for hot rolling t = 700ºC of strip billets of working rolls R = 130 mm (1, 2) and R = 52,5 mm (3, 4) at different values of relative compression



a b

1 – h_0 = 6,0 mm, steel 30HGSA; 2 – h_0 = 3,0 mm, steel 10; 3 – h_0 = 6,0 mm, steel 30HGSA; 4 – h_0 = 3,0 mm, steel 10

Figure 4. Calculated (——— , — —) and experimental (●, ○) distributions of force P/B (a) and total moment M/B (b) values reduced to unit width obtained for hot rolling t = 800ºC of strip billets in working rolls R = 130 mm (1, 2) and R = 52,5 mm (3, 4) at different values of relative compression ε



a b

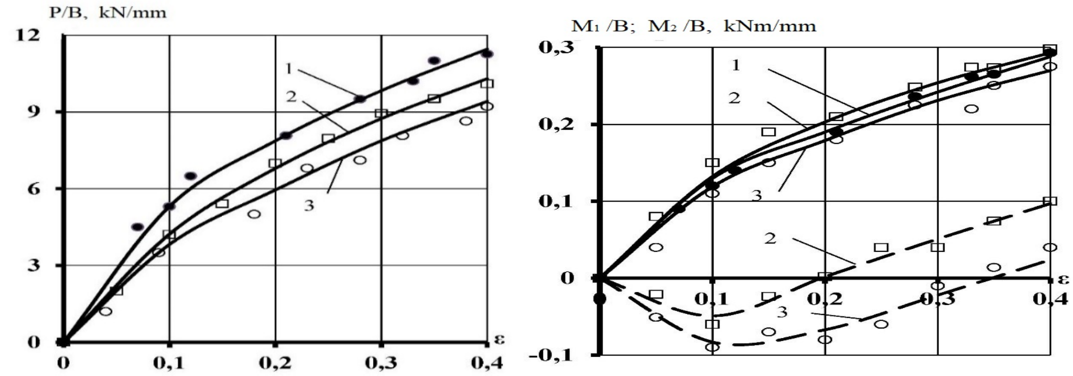
1 – h_0 = 6,0 mm, steel 30HGSA; 2 – h_0 = 3,0 mm, steel 10; 3 – h_0 = 6,0 mm, steel 30HGSA; 4 – h_0 = 3,0 mm, steel 10.

Figure 5. Calculated (——— , — —) and experimental (●, ○) distributions of force P/B (a) and total moment M/B (b) values reduced to unit width obtained for hot rolling t = 900°C of strip billets in working rolls R = 130 mm (1, 2) and R = 52,5 mm (3, 4) at different values of relative compression ε

All of the above indicates a sufficient degree of reliability of the developed numerical and regression mathematical models, and this, in turn, indicates the possibility of their further use to solve a wide range of problems associated with the analysis, computer-aided design and improvement of the investigated technologies and equipment.

Experimental studies of the conditions of realization of the process of asymmetric kinematic rolling of strip sections were carried out on a laboratory mill, while rolling samples of different thicknesses made of lead. The yield stress of this material, determined experimentally, corresponded to the $\sigma_т \approx 40$ МПa. The degree of kinematic asymmetry provided by replacing the driven gear wheel of the gear reducer stand corresponded $\omega_{d1} / \omega_{d2} = 1,0; 1,08; 1,16$, and the direct processing of the obtained empirical distributions was carried out using a computer.

The distributions of calculated Pc/B, M1c/B, M2c/B, and empirical Pe/B, M1e/B, M2e/B values of force P and rolling moments on the lower driving M1 and upper driven M2 working rolls were presented as examples of the performed theoretical and experimental studies results in Figs. 6 and 7. The results of the analysis of the presented distributions show that an increase in the degree of kinematic asymmetry Kv of the rolling process of strip billets leads to a decrease in the force P, as well as to a very significant redistribution of moments between the leading M1 and driven M2 working rolls. In this case, the intensity of force reduction with decreasing thickness, that is, with increasing geometric ratio L/h_{av} increases significantly, which, in turn, can be used as an additional control factor of the considered technological scheme of the hot rolling process.



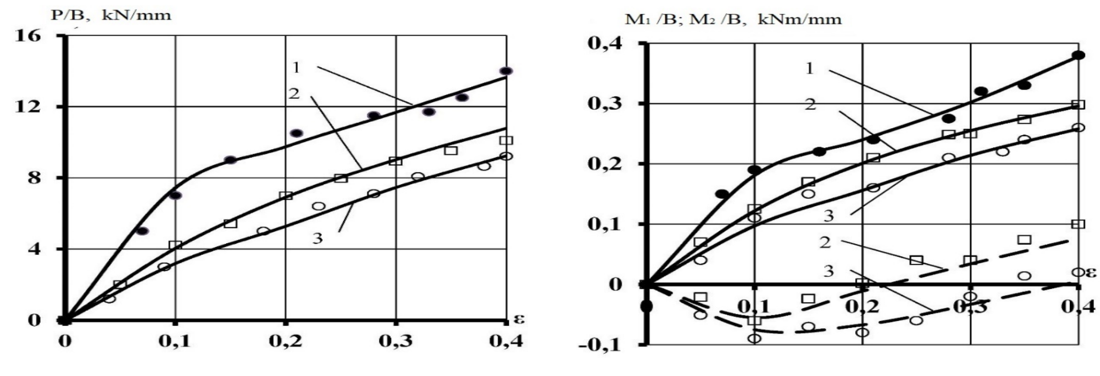
a b

1 – K_v = 1; 2 – K_v = 1,08; 3 – K_v = 1,16.

Figure 6. Calculated (——— , — —) and experimental (●, ○, □) distributions of values of force P/B (a) and moments M_1/B, M_2/B, (b) reduced to unit width for rolling of strip billets h_0 = 1 mm in working rolls R = 50 mm depending on the value of relative compression **ε** and the index of the degree of kinematic asymmetry

Comparison of calculated and empirical distributions of the values of force P_c, P_e and rolling moments M_{1c}, M_{1e}, M_{2c}, M_{2e}, M_c, M_e (see Fig. 6, 7) showed that the average sample values of their ratios P_c/P_e, M_{1c}/M_{1e}, M_{2c}/M_{2e} M_c/M_e were in the range of 0,95÷1,05, and the minimum and maximum values of confidence intervals obtained taking into account the confidence probability of 0,95 corresponded to 0,958; 1,041 for force and 0,951; 1,053 for rolling moments.

Using the equipment of the laboratory mill with the diameter of working rolls 260 mm and the laboratory mill with the diameter of working rolls 100 mm, experimental studies of the process of flattening of initial round billets were also carried out. Aluminum (A1) wire with initial values of diameters d_0 = 2,25 mm and d_0 =3,05 mm was subjected directly to conditioning with different values of compression characterized by the ratio h_1/d_0.

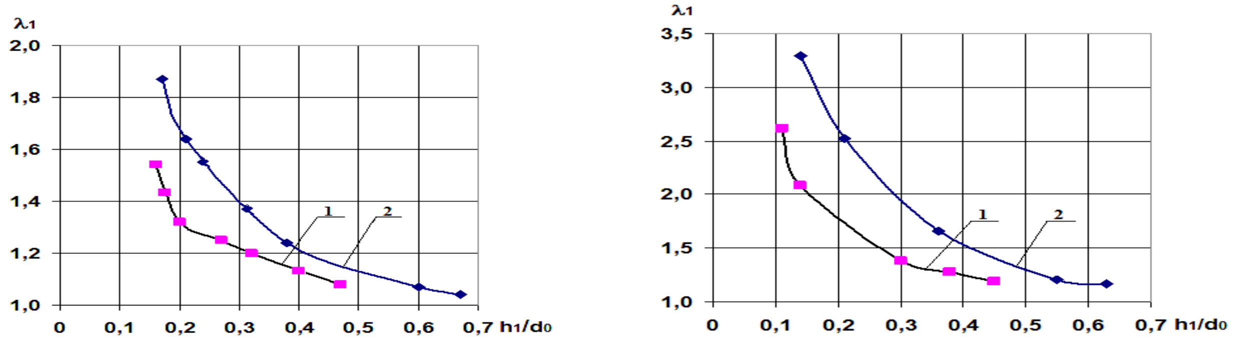


a b

1 – K_v = 1; 2 – K_v = 1,08; 3 – K_v = 1,16.

Figure 7. Calculated (——— , — —) and experimental (●, ○, □) distributions of values of force P/B (a) and moments M_1/B, M_2/B, (b) reduced to unit width for rolling of strip billets h_0 = 3 mm in working rolls R = 50 mm depending on the value of relative compression **ε** and the index of the degree of kinematic asymmetry

Analyzing the empirical distributions of longitudinal elongation of the billets λ_1 (Fig. 8), defined as the ratio of the resulting and initial values of their length, it should be noted that in the implementation of the process of flattening there is not only transverse, but also longitudinal plastic flow of metal. With increasing compression, characterized by decreasing h_1/d_0, the resulting value of drawing increases, in addition, some increase in the index λ_1, all other conditions being equal, also occurs in the case of reducing the diameter of the working rolls, that is, when the total extent of the deformation zone decreases. The above mentioned confirms the expediency of using numerical, including finite element approaches (*Kaplanov, Chumakov, Korenko, 2010*), rather than engineering (*Gmurman, 2002*) approaches to analyze the stress-strain state of the metal of flattened strip blanks.



$a - d_0 = 2,25$ mm $\qquad$ $b - d_0 = 3,05$ mm

Figure 8. Experimental distributions of the draw ratio as λ_1 a function of the relative strain index h_1/d_0 during the flattening of aluminum wire with diameters of $d_0 = 2,25$ mm and of $d_0 = 3,05$ mm in working rolls with radii $R = 50$ mm (1) and $R = 130$ mm (2).

Similar results in terms of the feasibility of predicting the intensity ratio of longitudinal and transverse plastic flows of metal on the basis of the finite element method were obtained on the basis of the experimental studies results of the rolling process of strip sections in the run-up gauges (see Fig. 1.), performed with using a two-roll working stand of the laboratory mill 130.

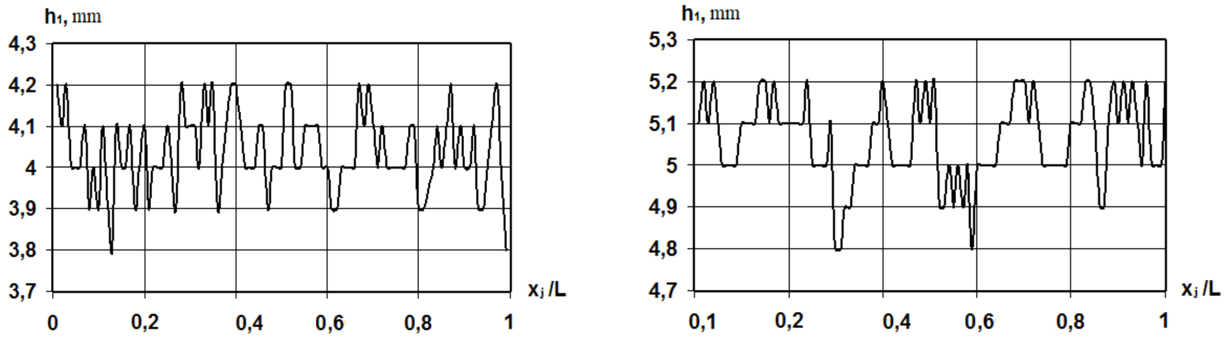
Experimental studies of the accuracy of the resulting geometric characteristics have been carried out on a first-generation 250 small section mill as applied to the industrial production of hot-rolled steel strip billets of 10 steel sizes $h \times B = 4 \times 40$ mm and $h \times B = 5 \times 80$ mm. The volume of experimental samples corresponded to 30 strips of each size.

Due to the limited possibilities of measuring the whole complex of technological parameters, only the distributions of initial and final thickness of the roll before and after the last horizontal finishing working stand were subjected to experimental studies of the process of hot rolling of strip sections on the small section mill 250 of the first generation. These measurements were made on a rack cooler using an MK-25 micrometer. In order to investigate the initial geometric characteristics used as input data for the numerical realization of the corresponding mathematical model, rolling in the last working stand was not performed. In addition, with the use of pyrometer "Promin" were measured temperatures of the beginning and end of rolling, knowledge of which is also necessary in relation to the numerical realization of the mathematical model of the accuracy of the resulting geometric characteristics during hot rolling of strip sections.

As an example of the results of the performed experimental studies, Fig. 9 presents empirical distributions of the final thickness h_1 as a function of the relative length index of hot-rolled strips X_j/L. In addition, Figs. 10 and 11 show empirical and calculated histograms, as well as distribution functions of the final thickness h_1, and their comparative analysis was performed on the basis of the Smirnov's criterion, the analytical form of which has the form:

$$\Delta \le [\Delta_\alpha] = \sqrt{0,5(1/n_{se} + 1/n_{sc})\ln(1/\alpha)} = 0,1024, \quad (2)$$

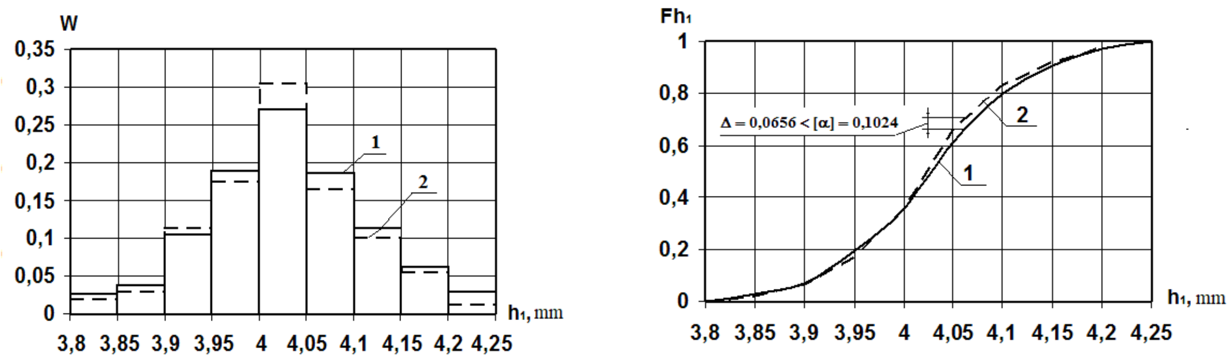
where Δ is the maximum difference between the empirical and calculated distribution functions of the final thickness of hot-rolled strip billets (see Fig. 10, b, 11, b); $[\Delta_\alpha] = 0,0389$ is the maximum permissible difference $\alpha = 0,05$ between the compared distribution functions at the accepted significance level; $n_{se} = 2970$, $n_{sc} = 150$ are the volumes of the compared experimental and calculated samples.



a b

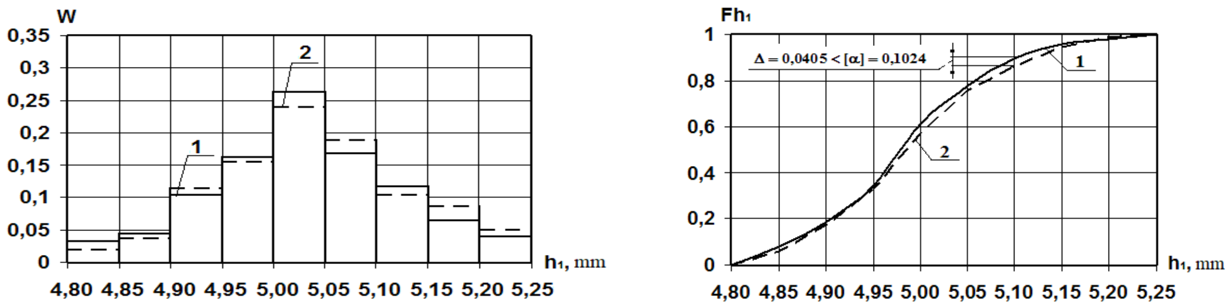
Figure 9. Empirical distributions of final thickness h₁ as a function of the relative length index X_j / L of hot-rolled strips of sizes $h \times B = 4 \times 40$ mm (a) and $h \times B = 5 \times 80$ mm (b), obtained under conditions of the first generation industrial small section mill 250.

The criterion evaluation carried out in accordance with (2) (see Fig. 10, b, 11, b), as well as the results of additional numerical analysis performed on the basis of the Wilcoxon criterion (*Gmurman, 2002*) showed that empirical and calculated samples of the final thickness h₁, obtained in industrial conditions of hot-rolled strip sections production, correspond to a general commonality. The above data confirm a sufficient degree of reliability of the previously developed mathematical model of the resulting geometric characteristics accuracy during hot rolling of strip sections, and this, in turn, indicates the possibility of its further use to solve various problems associated with the improvement of technology and equipment of the corresponding hot rolling mills.



a b

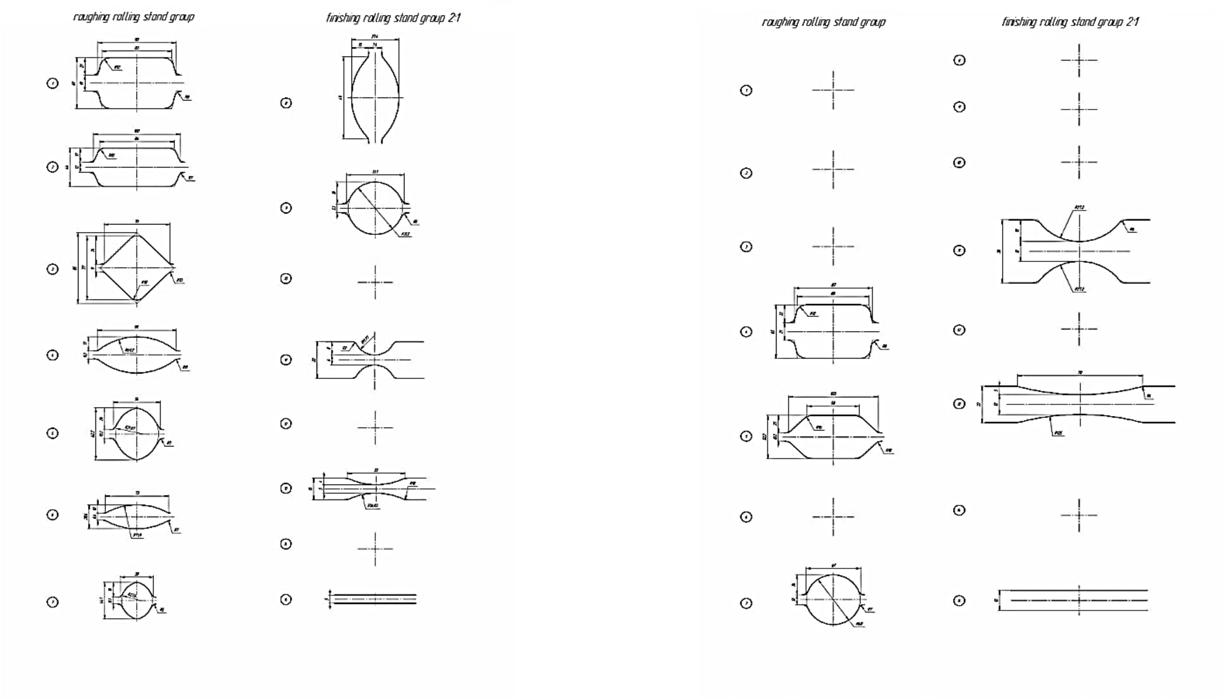
Figure 10. Empirical (1) and calculated (2) histograms (a), as well as functions (b) of the final thickness h₁ distributions obtained during hot rolling of strips (Steel 10 $h \times B = 4 \times 40$ mm)at the first generation industrial small section mill 250.



a b

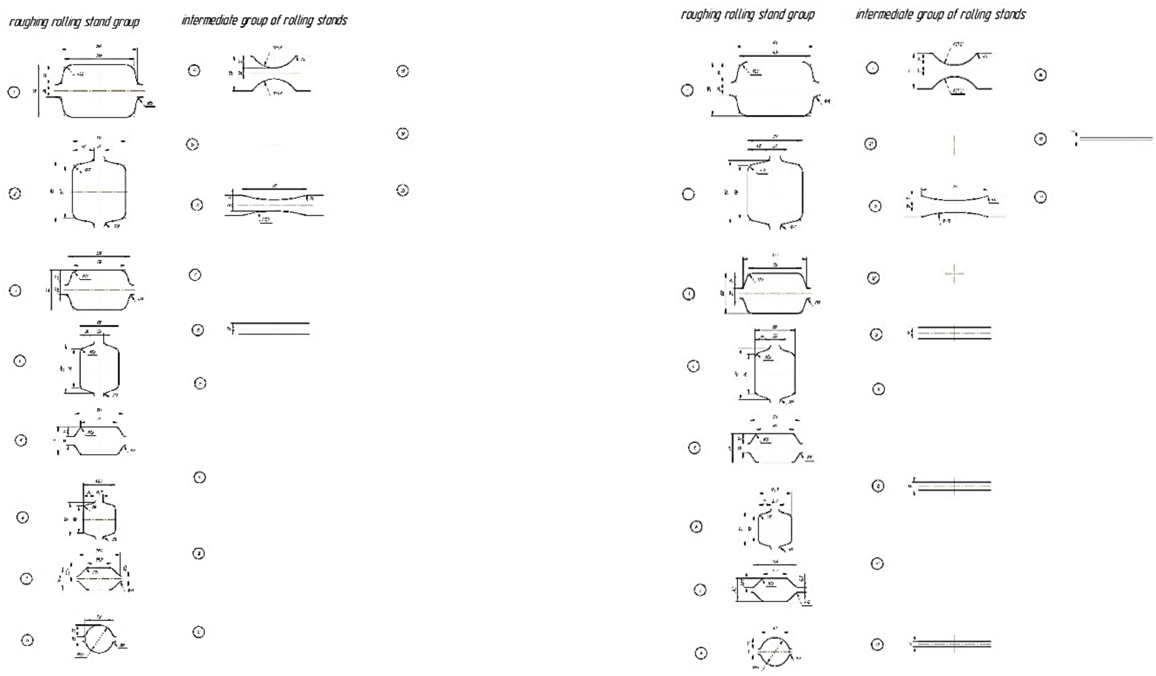
Figure 11. Empirical (1) and calculated (2) histograms (a), as well as functions (b) of final thickness h₁ distributions obtained during hot rolling of strips (Steel 10 $h \times B = 5 \times 80$ mm)on the first generation industrial small section mill 250.

On the basis of the results of theoretical and experimental studies of hot conditioning and rolling in run-up calibers, new schemes of roll calibration for strip rolling were developed. Both for rolling on small-section mills 250 (Fig. 12) and for rolling on small-section-wire mills 250/150 (Fig. 13), such schemes will allow to expand the assortment, improve the quality of strips and reduce energy consumption.



a - strip 60×5 mm   b - strip 120×12 mm

Figure 12. Calibration scheme for strip rolls for the first generation of small section mills



a - strip 120×12 mm   b - strip 124×3 mm

Figure 13. Calibration scheme for rolls for strip fine rolling on small-section-wire mills strip sections hot rolling.

Conclusions

The results of experimental studies of local characteristics of the stressed state of metal, conducted on a special facility for plastic deformation of metal, confirmed the significant influence of the degree of kinematic asymmetry K_v of the rolling process on the character of the distribution of normal contact stresses P_x along the length of the deformation center. During the process the intensity of this influence with enlarging relative extent of the deformation center increases and, in particular, the degree of reduction of current values of normal contact stresses P_x can reach 20÷40%, which can be used as an additional parameter of regulation of the investigated process of.

On the basis of the experimental studies results of the hot rolling process at the laboratory mill of different sizes strips it has been established that from the point of view of comparison of calculated and empirical distributions of the values of force P_c/B, P_e/B and total rolling moment M_c/B, M_e/B which were reduced to unit width, the average sample values of their ratios P_c/P_e, M_c/M_e were in the range of 0,97... 1,04, and the minimum and maximum values of confidence intervals obtained taking into account the confidence probability of 0,95 corresponded to 0,966; 1,038 for the force and 0,958; 1,041 for the force and 0,958; 1,041 for the total rolling moment. Comparison of calculated and empirical distributions of force values P_c, P_e and moments M_{1c}, M_{1e}, M_{2c}, M_{2e}, M_c, M_e, at asymmetric rolling on the laboratory mill 100x100 has shown that average sample values of their ratios P_c/P_e, M_{1c}/M_{1e}, M_{2c}/M_{2e} M_c/M_e were in the range of 0,95 ... 1,05. 1,05, and the minimum and maximum values of the confidence intervals obtained taking into account the confidence probability of 0,95 corresponded to 0,958; 1,041 for strength and 0,951; 1,053 for rolling moments on each of the working rolls. The above mentioned confirms a sufficient degree of reliability of the obtained numerical mathematical models of the process of hot rolling of strip sections and indicates the possibility of their further use in relation to solving problems to improve the technological modes of operation, composition and design parameters of the equipment of section rolling mills.

On the basis of the results of experimental studies of the processes of hot conditioning and rolling in accelerated calibers, the three-dimensional character of plastic flow of metal is confirmed, which, in turn, indicates the feasibility of using finite-element approaches.

The results of experimental studies of the degree of stability of the final thickness of hot-rolled strips, conducted in industrial conditions at the first-generation small-section mill 250, as well as their comparison with the corresponding calculated distributions, performed using the Smirnov's and Wilcoxon's criteria confirmed a sufficient degree of reliability of the numerical mathematical models of the resulting quality indicators during hot rolling of strip sections.

Conflicts of interest

The authors declare no conflict of interest.

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Authors contribution

Conceptualization, V.N. and K.M.; formal analysis, K.D.; Methodology, K.V, and.G.V; visualization, K.V. and K.M.; original draft, V.N. and K.M; revision and editing, K.D and G.V. All authors have read and agreed with the published version of the manuscript.

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