Research And Simulation of The Sheet Leveling Machine Manufacturing Capabilities

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RESEARCH AND SIMULATION OF THE SHEET LEVELING MACHINE MANUFACTURING CAPABILITIES

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Abstract: *One of the main tasks to determine the technological settings of the sheet leveling machine (leveler) is to identify the maximum roll overlap. In the well-known works on the study of sheet metal-roll leveling, the overlaps are set on the basis of experimental data, that is applicable for the leveling sheets from material with the 800 MPa yield strength. But for materials with a higher yield strength additional research is required. The purpose of this work is to establish criteria affecting the maximum allowable overlap for the working rolls by the leveler and to determine the dependencies for the most rational working rolls adjustment. When solving the set tasks, developed by the authors, a numerical analytical mathematical model of the leveling process was used as an objective function, that allows to determine the energy-power characteristics and the sheet curvature after leveling, depending on the individual settings of the leveler rolls. Within the framework of studies, an algorithm of a mathematical model was developed that allows to determine the leveler technological settings necessary for correcting the longitudinal curvature and comes down to determining the aligning coordinates for each of the movable rolls depending on the known characteristics of the metal being processed, the leveler geometric parameters, and the permissible value of the sheet residual curvature after leveling. In consequence of studying the influence of the working rolls setup on the sheet metal-roll quality during leveling on a multi-roll leveling machine, the laws for the rational rolls positioning were established. The linear and sinusoidal laws were identified as optimal ones. Boundary factors were also established as affecting the maximum overlap of the rolls. These factors included the condition of the pickup and the condition of the rolls strength. Using the example of implementing the developed finite element model of the sheet leveling process at the leveler of NKMZ (Ukraine), it was found that the pickup condition has a dominant influence when leveling sheets with a thickness of less than 6 mm, and with larger thicknesses the condition of the rolls strength is prevailing. With a decrease in the yield strength of the material or the width of the sheets, this ratio will be redistributed towards the pickup condition.*

Keywords: *Leveler, Sheet Straightening, Finite Element Model, Working Rolls, Technological Settings, Gripping Condition, Strength Condition, Straightening Quality*

1 State of the art and literature review

The sheet leveling is one of the important stages in obtaining high-quality metal products. The increasing requirements for the geometric characteristics of flat-rolled products determine the development of sheet leveling machines in terms of increasing the efficiency of the process and expanding their capabilities for the implementation of leveling sheets from high-strength steel grades.

The main task of the sheet metal-roll leveling mathematical description is to determine the energy-power characteristics required for the equipment design and to identify the residual sheet curvature required to determine the technological settings of the machine.

When leveling simulation, the accepted boundary conditions are of great importance. They include friction conditions, features of alternating elasto-plastic strain, and limiting values of reducing.

To take into account the alternating deformation in the model, as a rule, the description of the Bauschinger effect is included, namely, attention is paid to testing for cyclic loads and their adaptation to design calculations of the sheet leveling technology [1, 2].

The description of contact interactions is also important. So, in the work [3], experimental studies of friction between the sheet and the rolls during leveling were carried out. The data obtained were adapted to finite element modeling, recommendations were given on the friction coefficients for various materials.

Strength test results are used to estimate the maximum allowable deformation. But through the experience it has been found that this is not enough and more research is needed. For this purpose, in the paper [4], a technique was developed and recommendations were given for assessing the elasticity of various steel grades edges, including high-strength ones.

To assess the inhomogeneity of deformation along the thickness of sheet in the paper [5], a model of layer displacement with neutral stress was created based on the theory of three-point bending, the characteristics of the steel sheet bending and the theory of layers in the course of leveling. The phenomenon of layer displacement with neutral stress and the relationship between the contraflexure radius, plate thickness and deformation capacity of the metal have been proven theoretically and by the leveling experiment.

Numerical [6, 7] and finite element models [8, 9] or their combinations [10, 11] are used as methods for leveling simulation. Numerical models have fast response, which allows them to be used in the automatic control system. Finite element models require a large amount of computer time for calculation, but they let obtaining more accurate results, taking into account the influence of factors on the process.

Another approach to solving leveling problems is usage of the accumulated industrial data obtained on the operating equipment. The deep learning method was proposed to be used to improve the leveling technology in the paper [12]. This approach is based on the use of leveling experience with the most successful sheet leveling machine settings.

When using any approach, the main parameter in the leveling technology design is the plastic deformation coefficient, which shows the efficiency of the process. In the paper [13], it was proposed to evaluate the quality of sheet leveling not only with the help of this coefficient, but also to take into account the pickup ability of the rolls. In particular, the authors propose to use a skewing leveling strategy for static pressure leveling with the time delay.

When solving tasks in CAE systems, the main criterion is the response function. The authors of the paper [14] performed optimization of steel cord leveling using the finite element method. The numerical values of the nodal points on the billet surface after leveling were used as an optimization parameter. On the basis of this criterion, a rational drafting schedule was obtained. But in spite of the result obtained, this approach can be used only for a narrow range of products because of the large amount of time spent on one calculation.

Among the numerical models, the most widespread are various kinds of solutions to the beam deflection equation when the metal being straightened is represented as a statically undeterminable multi-support beam. In the paper [15], in order to determine the distribution of residual stresses in the sheet after leveling, a numerical model of a leveling machine with seven rolls was used. To achieve this goal, a strategy was introduced based on the use of three independent load triangles. The first load triangle on the second roll was used to determine plastic deformation, the triangle in the middle of the fourth roll was used to determine the effect on the residual stresses distribution, and the last one on the sixth roll predicted the sheet flatness. It was proposed to determine the characteristics of the strip by measuring the force in the first load triangle. The work proposes to use the results obtained to adjust the leveling process control setting, which can provide both a flat sheet and a certain distribution of residual stresses, depending on the characteristics of the sheet.

When designing sheet leveling machines, the most urgent task is to determine the technological capabilities of a machine with different design requirements, that is, whether a particular sheet leveling machine is able to process the required products. There are several approaches to solving this problem.

In the paper [16], an optimization model was proposed to determine the leveling capacity of a sheet leveling machine. The strategy is based on determining the maximum yield strength of sheets that can be leveled. These boundary curves are related to sheet thicknesses, maximum roll movement and drive power.

Besides the penetration of sheet plastic deformation during leveling, it is important to take into account the pickup conditions. The authors of the paper [17] presented an analytical model of sheet pickup by rolls of a leveling machine, which takes into account the relationship between roll pickups and the curvature of sheet bending during the process. Based on the implementation of the model, a four-dimensional database of the optimal settings for the sheet leveling machine was built taking into account the limiting elastic curvature of the sheet material, and the expected coefficient of plastic deformation. In the paper [18], a mathematical model was developed for a sheet pickup by rolls, which was tested using a finite element model of sheet leveling.

The tasks of determining the sheet leveling machine technological capabilities have an optimization nature, and the computer time plays an essential role in this matter. For this purpose, the authors of the work [19] described the results of the analytical model using regression dependences, which can dramatically reduce the calculation time.

When calculating leveling schedule, taking into account as many factors as possible is very important. In the paper [20], the influence of the leveling speed, hardening coefficient, elastic coefficient, and sheet width on the technological capabilities of leveling was studied. The authors obtained graphic charts that show the boundary conditions for leveling depending on the yield strength, sheet thickness, including the plasticity coefficient, leveling force and drive power.

In the design of leveler equipment, the task of determining the strength characteristics of leveling is highlighted. In the paper [21], a mathematical method is proposed for determining the forces and moments during cold bending of a thick sheet on three-roll sheet bending systems. Calculations allow to determine the reaction of the roll supporting arms, the residual stress, the proportion of plastic deformation across the sheet thickness and the relative deformation of the sheet longitudinal surface fibers during bending as a function of the roll radius, distance between the rolls, sheet drafting by the upper roll, sheet thickness, Young's modulus, yield strength, and hardening coefficient of steel sheet.

The relationship between the results of the analytical and finite element models is presented in the work [22]. Based on this relationship, a semi-analytical model of the sheet leveling process has been developed. It allows us to calculate the critical leveling requirements, that is, the deformation force and rate in real time.

The authors of the paper [23], using associative models of the "roll-strip" system, calculated rational technological requirements of sheet leveling on a 23-roll leveling machine. At the same time, the operating characteristics of all leveling mechanisms were taken into account, including bridles and bobbin machines.

Analysis of literary sources shows that it is efficient to use analytical models in the development of sheet leveling technology. But the influence of numerous factors, including ones from auxiliary equipment, requires the use of finite

element models. In this case, it makes sense to represent the results of finite element modeling in the form of regression descriptions or alternative type of boundary conditions.

2 Introduction

2.1 Actuality of research

One of the main tasks of determining the technological settings of a flattening machine is to determine the overlap of the rollers to ensure maximum flatness of the sheet after straightening. There are known solutions to this problem based on experimental data. Numerical solution requires the formulation of an optimization plan tasks. However, it takes a lot of machine time. This is especially true for materials with a yield strength of more than 800 MPa, since for them the range of successful implementation is very narrow. This makes it relevant to determine the boundary conditions for the technological settings of the leveler in order to reduce the search range for optimal technological modes.

2.2 Aims and scopes

The purpose of this work is to establish criteria affecting the maximum allowable overlap for the working rolls by the leveler and to determine the dependencies for the most rational working rolls adjustment. To achieve this goal, the following tasks were set and solved: an algorithm of a mathematical model was developed that allows to determine the leveler technological settings necessary for correcting the longitudinal curvature and comes down to determining the aligning coordinates for each of the movable rolls depending on the known characteristics of the metal being processed, the leveler geometric parameters, affecting the maximum overlap of the rolls, and the permissible value of the sheet residual curvature after leveling.

2.3 Prime novelty statement

The main contribution to the design of technology and equipment for sheet straightening is taking into account the influence of technological and design factors on the maximum settings of the levelers, which allows narrowing the range of searching for the rollers optimal settings, as well as determining the technological capabilities of the leveler. The proposed model expands the understanding of the process and assesses the impact of baseline characteristics on the finished product.

Theoretically, for the first time, a mathematical model was developed for designing the leveler technological settings, which takes into account the influence of such factors as pickup condition, conditions for the rollers strength, a sufficient level of plastic deformation penetration through the thickness of the sheet and a rational law of work rollers positioning.

In the field of experimental research, a model was implemented when designing a sheet straightening machine 2850 designed by Novokramatorsk Machine-Building Plant (Ukraine), which was put into operation in 2020. Determination of the technological capabilities of the machine made it possible to reduce its metal consumption and distribute the assortment of products between 5, 9 and 11-roller schemes.

In industrial applications, the results are of interest to developers of equipment for the levelers production. The developed model makes it possible to determine the boundary conditions for the leveling realization and, on their use, to determine the rational parameters of the equipment, which makes it possible to reduce its metal consumption.

3. Theoretical research

3.1 Mathematical model

Finite element modeling was performed in the Abaqus CAE. The numerical model of sheet straightening was based on flow theory. The workpiece material is considered as an incompressible elastic-plastic body. Considered in relation to the analysis of the sheet straightening, a computational scheme for 11 rollers (Fig. 1) and a similar scheme for 9 and 5 rollers, respectively, were used. The scheme consisted of a deformable workpiece 1 and working rollers 2 (Fig. 1).

1 – workpiece; 2 – working rollers

Figure 1: Finite element model of sheet straightening in the global coordinate system

According to the design scheme (see Fig. 1), the machine step t was taken as 275 mm, the diameter of the working rollers was equal to 260 mm. The direct simulation of the straightening process was carried out for a sheet with a thickness of 10 mm. In order calculations and input of initial data, the material was considered non-strengthened with elastic properties for steel $E=2,1 \cdot 10^5$ MPa, $\mu=0,3$, $\sigma_s=400$ MPa. The finite element model has the following boundary conditions: rollers have one rotational degree of freedom. The calculation used the model of classical plasticity of the metal.

The contact between the sheet and the rollers was set using the surface-to-surface contact model by setting the friction coefficient $\mu = 0,2$.

The working rollers were driven into rotation with an angular speed of 0.95 rad / sec. The sheet travel speed is taken equal to 1000 mm / sec. The step time was taken as 2.5 sec.

To evaluate the results obtained, the output parameters in this case were the projections of the reactions at the control points of the rollers in the global coordinate system RF2, RM3, as well as displacements, deformations and stresses in the nodes of the sheet finite elements.

In view of the above, the volume (construction of a finite element mesh) occupied by the model was discretized into elementary areas (finite elements). Three-dimensional non-deformable elements were used to model the calibers. To simulate the workpiece, eight-node linear, solid reduced elements with fracture control were used.

3.2 Calculation results

The calculation process in the CAE environment takes considerable time, which largely depends on the number of finite elements. In order to determine the optimal number of them, studies were carried out on the influence of the metal volume partition discreteness on the accuracy of calculating the straightening forces, their spread, as well as on the calculation time.

To reduce the calculation time and based on the principles of the straightening process, the number of elements along the sheet height was taken equal to five. The sheet was divided into a different number of cells, as follows: 300 (Fig. 2, a); 1224 (Fig. 2, b); 4545 (Fig. 2, c); 7191 (Fig. 2, d); 15014 (Fig. 2, e).

Figure 2: Models of sheets with different discretization of volume

During the calculation, the calculation time (Fig. 3) and the straightening force on the third roll (Fig. 4) were recorded. It was found that with an increase in the discretization of the deformed material volume, the calculation time increases almost linearly and with the number of cells 15120 is 4.2 hours (see Fig. 3). The obtained values of the straightening force have a significant scatter, which decreases with an increase in the number of elements (Fig. 4).

Figure 3: Dependence of the calculation time on the number of cells

Figure 4: Values of straightening forces during the deformation process depending on the number of cells

Using the series of straightening forces obtained during the calculation, the coefficient of variation of their scatter was determined for each case of volume discretization, which amounted to more than 65% in the case of using a grid of 300 elements and about 20 ... 25% with an increase in sampling of more than 4000 sampling elements (Fig. 5). It was found that in the simulation, the rational amount is 6000 finite elements per 1 meter of sheet when calculating the value of the straightening force on the third roller. The model implementation time is approximately 1.17 hours with the value of the straightening force variation coefficient 1% higher than a relatively more accurate value.)

Figure 5: Values of the straightening force on the third roller and its coefficient of variation depending on the number of cells

4 Methodology to determine the factors affecting the limiting settings of the sheet leveling machine

The purpose of this work is to determine the technological capabilities of the sheet leveling machine (leveler) by finding the maximum possible overlap of the working rolls, depending on the processed products.

When solving the set tasks, a numerical mathematical model of the leveling process [10] was used as an objective function, including its software implementation, which allows to determine the energy-power characteristics and curvature of the sheet after leveling, depending on the individual settings of the leveler rolls. Also, a finite element model of sheet leveling was used in the work to determine the power characteristics of the process and fulfill the pickup conditions.

In the scope of this paper, a mathematical model algorithm was developed allowing to determine the technological settings of the leveler that are necessary to correct the lengthwise curvature. This algorithm comes down to determination of setup coordinates for each movable roll, depending on the known characteristics of the metal being processed, the geometric parameters of the leveler, including the permissible value of the residual curvature of the sheet after leveling.

The main factors affecting maximum roll overlap are:

- determination of the most rational law for the individual setup of the rolls according to the condition of ensuring the minimum resulting curvature of the sheets to be not higher than one required by the standards for sheet quality;
- determination of the minimum rolls overlap to ensure the required penetration of plastic deformation through the sheet thickness;
- provision of conditions for sheet pickup by the working rolls of the leveler;

- ensuring the power characteristics of the process below the permissible ones according to the technical characteristics of the leveler.

The algorithm for determining the boundary settings of the leveler, which describes its technological capabilities, is shown in Fig. 6. This technique assumes successful leveling of a given standard size sheet if the condition for ensuring the required quality is satisfied, subject to the pickup conditions, the conditions for the rolls strength and the required level of plastic deformation penetration through the thickness of the sheet.

Figure 6: Algorithm for determining the technological capabilities of the leveler

5 Simulation of the influence of factors affecting the limiting settings of the sheet leveling machine

The traditional law for setting the working rolls by a sheet leveling machine is a linear law. In connection with the use of individual setup of working rolls, it is reasonable to study other laws.

In this paper, the following laws were investigated:

- linear;
- parabolic;
- exponential;
- sinusoidal.

The positioning of the rolls in accordance with the adopted laws is graphically shown in Fig. 7.

At the same time, the laws for setting up rolls №№ 5 7; 9 in relation to the 11-roll leveler ($n = 11$; $d = 260$ mm; $t = 275$ mm) can be represented by the following formulas:

linear law

$$W(i)|_{i=5;7;9} = W(3)(2 - i); \quad (1)$$

parabolic law

$$W(i)|_{i=5;7;9} = W(3) - a\left(\frac{i-1}{2}\right)^2; \quad a=0.1 \dots 0.5; \quad (2)$$

a

b

Figure 7: Graphic presentation of the rolls positioning in accordance with the adopted laws: a - mutual bracing of rolls; b - deformation of the strip

exponential law

$$W(i)|_{i=5;7;9} = W(3) - \exp\left(a \frac{i-3}{2}\right); \quad a = \frac{\ln(W(3))}{n-7}; \quad (3)$$

sinusoidal law

$$W(i)|_{i=5;7;9} = W(3) - a \cdot \sin\left(b \frac{i-1}{2}\right); \quad b = \frac{\arcsin(W(3)/a)}{n-7}; \quad a=10 \dots 20. \quad (4)$$

Besides the determining a rational law for the working rolls position, it is also necessary to take into account the condition of the metal pickup by the roll and the conditions of the working and support rolls strength. The pickup process was analyzed by the leveling model technique for a 5-roll leveler in the Abaqus CAE environment. The position of the 3rd roll was a varied characteristic in the simulation. The 3rd roll at the beginning of the calculation was set to the lowest position, which is determined by the distance between the 2nd and 3rd (3rd and 4th) ones, sufficient for the sheet to pass between them. In this case, as a rule, the sheet was bent into the space between the 2nd and 4th rolls. Then the 3-rd roll was lifted until the sheet was picked up and passed along the leveling line (Fig. 8).

Simulation in the Abaqus CAE environment was also performed to analyze the strength conditions of the working and support rolls. For this case, a 5-roller model was also used. At the same time, for a sheet of a certain thickness, the maximum width and maximum yield strength were set according to the product variety. To determine the leveling force $P()$, the reactions in the vertical plane were used according to the reference point in the center of the 3rd, 5th and 7th rolls circle (Fig. 9).

For the leveling process efficiency, the penetration of plastic deformation through the sheet thickness must be at least 60%. This criterion should also be checked when determining the technological settings of the leveler.

The overlap on the 3rd roller is determined by the specified plastic deformation penetration coefficient K :

$$f_{\max} = \frac{\sigma_s \cdot t^2}{K \cdot E \cdot h}, \quad (5)$$

where σ_s – yield strength of the processed material; t – roll pitch; E – elastic modulus of the processed material; h – sheet thickness.

Graphically, the influence of the working roll positioning on the distribution of deformations through sheet thickness is shown in the Fig 10.

Figure 8: Step-by-step deformation of the sheet when picking up by rolls

Figure 9: Leveling forces change on the 3rd, 5th and 7th rolls of the leveler during leveling

Figure 10: Graphical presentation of the working roll positioning influence on the penetration of plastic deformation through the sheet thickness (PEEQ - equivalent plastic deformation): a - 40%; b - 80%

Rational values of this coefficient were determined from the experience of cold leveling of sheets at the leveler of the Asha metallurgical plant

$K = 2.5...3.6$ with $h < 20$ mm;

$K = 3.0...4.0$ with $h \geq 20$ mm.

One of the main conditions for a leveling machine is to provide the required sheet waviness. Waviness is determined by measuring the wave height at a certain length, for example, it should be not more than 2 mm/m. To determine this characteristic of the sheet leveling quality in the developed mathematical model, the parameter of the residual relative curvature is used:

$$\chi_{res} = \frac{1}{R_{res}}. \quad (6)$$

According to the standards, the leveling quality index (flatness) of the sheets is determined by the wave amplitude (1 meter according to GOST). You can change one index into another according to the following dependance

$$A_{res} = \frac{1}{\chi_{res}} - \sqrt{\left(\frac{1}{\chi_{res}}\right)^2 - \frac{L_{base}^2}{4}}, \quad (7)$$

where L_{base} – base on which waviness is determined.

6 Results and Discussion

As an example, Fig. 11 shows the distribution of the final sheet waviness (mm/m) when implementing various laws for setting the rolls. In the figure, under the position of the 9th roll, all the rolls of the upper cassette were taken from the 5th to (n-2)-th according to the investigated law of setup (1) ... (4). Explanations are presented in the Fig. 12.

As can be seen from the analysis of the obtained dependencies, the greatest flatness of rolled products is obtained under linear and sinusoidal setup.

Figure 11: Distribution of the final sheet waviness (mm/m) when implementing various leveler settings according to the laws (1)...(4) ($h=2$ mm; $\sigma_s=760$ MPa; $n=11$; $d=260$ mm; $t=275$ mm)

Figure 12: Explanations for the calculation of sheet waviness for various setup laws

As a rule, the initial sheets have different waviness and for effective leveling it is necessary to achieve certain values of the plastic deformation penetration level, which is mainly determined by the deformation of the 3rd roller. As an example of such a study, the Fig. 13 shows the case of leveling a sheet with a 6 mm thickness. Its analysis shows that the level of the necessary penetration of plastic deformation (more than 60%) is achieved when the 3rd roll is overlapped by more than 10 mm.

Therefore, a more rational strategy for determining the position of the working rolls, is the one, based on linear and sinusoidal laws.

Figure 13: Dependence of the residual waviness on the 3rd roll overlap for different laws for leveler rolls setup ($h = 6$ mm; $\sigma_s = 760$ MPa; $n = 11$; $d = 260$ mm; $t = 275$ mm)

As an example of the developed algorithm implementation Fig. 14 shows the distributions of the residual relative curvature and waviness amplitude for different setup $W(3)$ of the 3rd roll and the rolls angle of the upper magazine. The results are shown for the 11-roll version of the leveler for material with the 760 MPa yield strength.

Figure 14: Dependence of the residual curvature (a) and waviness (b) on the 3rd roll overlap for a different angle of the upper magazine for the sheet with 2 mm thickness ($h = 2$ mm; $\sigma_s = 760$ MPa; $n = 11$; $d = 260$ mm; $t = 275$ mm)

From the analysis of the results obtained, it can be concluded that there is an effect of the 3rd roll overlap (the level of plastic deformation penetration) on the quality of leveling, which indicates the need to determine its optimal value. Analytically, this dependence can be described using the following power function:

$$W_{\max} = 43.898 h^{-0.2177} . \quad (8)$$

To solve this problem, the finite element method was used in the Abaqus CAE environment. The results were obtained for a multi-roll sheet leveling machine designed by Novokramatorsk Machine-Building Plant (NKMZ, Ukraine), which has three hardware versions: 11-, 9- and 5-roll ones with limited range of products according to thickness and yield strength for each of the versions. For calculation, the maximum values of the yield strength were selected for each thickness. The calculation results are presented in Fig. 15.

Figure 15: Distribution of logarithmic strain fields at the maximum possible sheets pickup

Fig. 16 presents the calculated dependences showing the limiting capabilities of the leveler at the maximum possible yield strength and width for a given thickness. From the analysis of the obtained dependences, it can be concluded that the pickup conditions at the thicknesses less than 6 mm and the strength conditions at large rolled thicknesses affect the ultimate overlap of the rolls. If the yield strength is less than the maximum permissible or the sheet width is less than the maximum one (in this case - 2600 mm), the dependence on the strength condition will have a different form and, under certain conditions, the pickup condition may be the limitation factor. These dependencies can be used as boundary conditions in determining the technological settings of levelers, and in the design of innovative levelers.

Figure 16: The results of calculating the maximum possible overlap of the working rolls from the sheet thickness at the maximum possible value of the yield strength for the leveler of the NKMZ design: a – 11-roll scheme; b – 9-roll scheme; c – 5-roll scheme

Conclusions

The study of the working rolls setup effect on the sheet metal quality during leveling on a multi-roll leveling machine, resulted in the laws to have been established for the rational positioning of the rolls. The linear and sinusoidal laws of the working rolls arrangement were identified as optimal for their individual setup. Boundary factors affecting the maximum overlap of the rolls were also established. These factors included the pickup condition and the rollers strength condition. The pickup conditions were analyzed on the basis of a known analytical relationship based on the geometric solution of the problem and on the basis of the finite element modeling results. Based on the results of the latter, a dependence was proposed for the formulation of this condition in relation to the analyzed structure of the sheet-leveling machine. On the example of the developed finite element model implementation for the sheet leveling machine designed by the Novokramtorsk Machine-Building Plant (Ukraine), it was found that when leveling sheets with a thickness of less than 6 mm, the condition for metal pickup by rolls has a dominant impact, and for larger thicknesses the condition of the working rolls strength has the most effect ... With a decrease in the yield strength of the material or the width of the sheets, this ratio will be redistributed towards the pickup condition. The obtained dependencies can be used as boundary conditions in determining the technological settings of both multi-roll sheet leveling machines (leveler) and innovative levelers

Disclosure

The submission of the authors' paper implies that it has not been previously published, that it is not under consideration for publication elsewhere, and that it will not be published elsewhere in the same form without the written permission of the editors.

Conflict of Interests

The authors Eduard P. Gribkov, Andrii K. Kovalenko and Svetlana S. Hurkovskaya declare that there is no conflict of interests regarding the publication of this paper.

Authors' contributions

All authors participated in the design of this work and performed equally. All authors read and approved the final manuscript.

Compliance with ethical guidelines

Competing interests. The authors declare that they have no competing interests.

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