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SYSTEM FOR AUTOMATIC FRONT ENDS CONTROL OF THICK PLATES BY ASYMMETRIC HOT ROLLING

Abstract. Research has been carried out and the problem of uncontrolled front ends bending of thick sheets in a hot rolling mill has been solved. A set of main factors has been determined that explain the reasons for the formation of the front end bending of the sheets during normal rolling. With the use of finite element modeling, a method of adequate influence on the front end plate curvature by the mismatch of the drives speed during the capture period is developed, depending on the entry plate thickness and the form factor of the deformation zone. The following influencing factors are considered: the "run length" of the faster roll over the sheet surface in the neutral section; the difference of contact stresses on the rolls; the neutral angles displacement and metal forward slip in the contacts with both rolls. Based on the established regularities, a control model was built. The model is implemented in the automatic control system of the industrial plate hot rolling mill 3600 of Huta Częstochowa (Poland). Leveling of the front ends of thick plates is realized by a controlled high-speed asymmetry of the rolling process during the sheets biting by the rolls, which made it possible to eliminate of the front end curvature of the sheets and increase the output product quality. The number of sheets with curvature, which requires re-hot straightening, has been reduced by 25%.

Key words: steel sheet, hot rolling mill, drive speed control, high-speed asymmetry, front end bending.

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1. Introduction

Almost in every of thick plates hot rolling mills, as well as in the roughing stands of thin plates rolling mills, the problem exists of the front end bending up or down in the vertical plane, the so-called "ski" or “snake” effect. When the front end is bent upwards, especially when the work roll diameter is small, steel plate entering in the stand or the subsequent technological unit is difficult. When the front end is bent down, the guiding rollers and the transportation table rollers experience shock impacts during the rolled metal motion, thin sheets gets stuck in the roller table, and it is impossible to grip the plate in the following stands or passes. The direction and magnitude of the front end bending of the plate is determined by a significant number of factors, which cause asymmetric conditions for rolled metal in the deformation zone.

If there is an individual drive of every roll in the stand, it is possible to influence the curvature of the front end in order to reduce it or eliminate at all. To do this, it is necessary to automatically set the calculated difference between the rotation speeds of the upper and lower rolls until the metal is gripped and then smoothly reduce this speed difference after the rolling of the front end of the sheet, so as not to overload one of the drives during rolling and to equalize the loads. Such an algorithm for controlling the main drives requires the use of modern automation and digital signal processing tools.

A large number of research works [1-7], [12-71] have been devoted to the study of the effect of bending of the front ends of sheets during hot rolling, and many approaches to solve this problem have been proposed and patented, in particular, see [8-11].

Some leading manufacturers of plate mills offer in the package of options for upgrading or supplying with new mills the systems for front ends bending control of the plates [2, 32]. However, scientists are constantly trying to improve these systems in order to solve the problem of unpredictable bending of the front end of the sheets that follows from many relevant publications on this topic.

2. Factors and patterns of the front end bending of the sheet

Formation of the front end bending patterns (fig. 1) depends on several factors:

- the difference in the diameters and initial linear speeds of the rolls immediately before rolling;
- the difference in temperature, hence, the yield stress of the lower and upper surfaces of the sheet;
- the difference in the friction conditions in the contacts with the upper

and lower rolls associated with the amount and properties of the oxidation scale on the metal surfaces;

- the difference in torsional stiffness of the upper and lower rolls drivelines due to additional long intermediate shaft in one of the drivelines (upper roll in the investigated mill);
- the difference of angle of the metal entering into the roll gap, which depends, among other things, on the work rolls displacement for their better stability in the stand;
- the difference in the levels of the lower work roll surfaces and roller table rollers from the inlet and outlet sides of the stand;
- the initial bending, including periodic pattern, formed in the previous roughing stand or passes.

Figure 1 – Typical front end bending of the sheet

Observations in the mill 3600 have shown that even when the rolls have the same linear speed before loading (with taking into account the actual rolls diameters) the front end bending of the sheet occurs systematically upward. It is also noticed that the greater the front end bending of the sheet after rolling in the roughing stand, the greater the bending in the same direction in the first pass of finishing stand. Also, the longer the pause before rolling into the finishing stand, the greater the upward bending. With an increase in the pause time, the temperature difference on the upper and lower surfaces increases, since there is an air gap and re-radiation between the lower surface of the sheet and the transportation rollers, despite they are water-cooled. However, some researchers at other mills performed simultaneous measurements of the upper and lower surfaces temperature and determined that with water-cooled rollers the temperature of the lower surface is usually lower than the top by about 10-20°C.

Various patterns of the front ends bending are observed depending on the rolling level, i.e. the difference in height between the surface of the lower work roll and the transportation rollers (usually +10 mm, that is, the rolls are located above the rollers).

When considering methods to adequately influence the front end curvature of the sheet during rolling in rolls of the same diameter, it is important to understand what causes the front end of the sheet to bend towards the roll with the higher or lower speed.

Analysis of the process patterns shows that the following main reasons play a role [71]:

1. The "run length" of the faster roll over the sheet surface is greater than that of the slower roll. In the general case, under conditions of low reduction and forward slip during rolling, this factor causes bending of the sheet towards the surface of a shorter length, i.e. towards the slower roll.
2. When the end of the sheet is bent, the length of the deformation zone from the side where the sheet is bent increases, and from the opposite side it decreases. On the side from which the end bends, the average contact stresses increase and the deformation increases. On the side to which the end is bent, the average contact stresses are reduced and the deformation is reduced. This factor contributes to the bending of the sheet towards the slower roll.
3. Difference in linear speeds of rolls causes mismatch of neutral angles in the deformation zones. The limit value of the neutral angle on the leading in speed (driving) roll tends to zero. The forward slip also disappear (there is a continuous metal lagging zone on the roll). At the same time, the neutral section on the slower roll is shifted towards the entry, and the forward slip of the sheet increases together with a decrease in the "run length". Neutral sections positions change symmetrically – one to the input, the second to the output. However, displacement towards the exit gives a smaller thickness change than displacement to the entrance of the deformation zone. This is because the specific thickness change per contact angle unit is greater from the entrance to the deformation zone. Therefore, a decrease in the neutral angle on the faster roll reduces the forward slip and the sheet exit speed, and the same increase in the neutral angle on the slower roll increases these parameters (see fig. 2). Moreover, the influence of a forward slip change on the slower roll is much higher, since the change in the sheet thickness for larger enter angles is greater per angle unit. This factor prevents the sheet from bending towards the slower roll.
4. With an increase of sheet relative deformation above the so-called critical degree, all other things being equal, the speed asymmetry (which value is comparable with the relative sliding speed of the metal in the forward slip zone) begins to compensate for the influence of unequal rolls “run length” on the sheet curvature due to the unequal changes of forward slip. In the region of the supercritical degree of deformation, the front end bending occurs towards the faster roll. With an increase of asymmetry, the forward slip on the faster roll decreases, tends to zero, and on the slower roll it continues to increase until the full slip of faster roll. The influence of forward slip increase on the slower roll with an increase in the degree of deformation

(with a constant speed asymmetry) is the reason for the dominance of this factor, leading to the front end bending towards the faster roll.

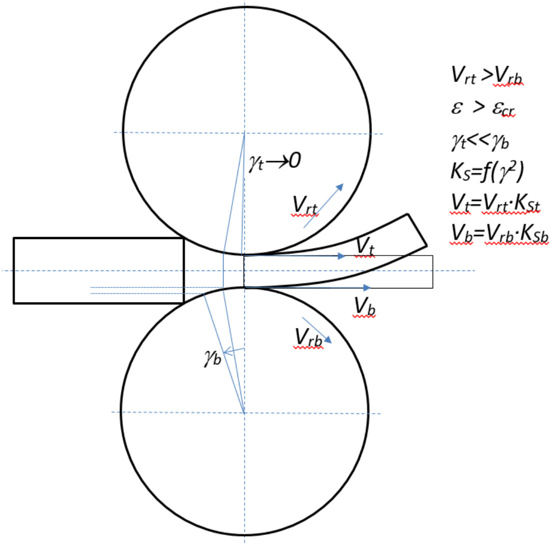


Figure 2 – Diagram explaining the formation of bending towards the drive roll when the degree of deformation is higher than the critical value

The case is shown in fig. 2 where the degree of deformation exceeds the critical value ε_{cr}, when the neutral angle γ on the slower roll has a greater effect on the metal exit speed than the restraining effect of the linear speeds difference of the rolls. Designations in the figure: V_r - linear rotation speed of the rolls; γ - neutral angle; K_s - metal forward slip coefficient. Additional subscripts *t* and *b* refer to the upper and lower rolls, respectively.

For the case of asymmetric rolling, the forward slip of the sheet can be estimated by the dependencies [67] using the Golovin-Dresden formula, respectively, from the top work roll:

$$S_t = S_t' + 0{,}5\left(\frac{V_b}{V_t} + 1\right); \qquad (1)$$

and the lower work roll:

$$S_b = S_b' + 0{,}5\left(\frac{V_t}{V_b} + 1\right) \qquad (2)$$

where $S_t' = R_t\gamma_t^2/h$; $S_b' = R_b\gamma_b^2/h$; R – roll radius, γ - neutral angle; h – exit strip thickness.

In this case, the corresponding forward slip coefficients K_S are equal to:

$$K_{St} = 1 + S_t;\ K_{Sb} = 1 + S_b. \tag{3}$$

From these dependences it follows that the forward slip during rolling from the side of the slow roll, where the neutral angle significantly exceeds the neutral angle from the side of the faster roll, due to the proportionality to the neutral angle square of the metal flow rate under conditions when the degree of deformation is higher than the critical value, causes the sheet to bend towards the faster roll.

The critical value of the form factor $l_d/h_m \approx 2$, where l_d – is the length of the deformation zone; h_m is the average sheet thickness in the deformation zone. In this case, in the range of $H/R < 0,14$, the front end bending occurs towards the faster roll, while in the range of $H/R > 0,14$ – towards the slower roll [67], where H is the initial sheet thickness, R is the radius of the work rolls.

The expression corresponding to the critical conditions of deformation, in general form:

$$\frac{V_b}{V_t} = \frac{1+S_t}{1+S_b}. \tag{4}$$

These conditions should be interpreted as the conditions for the insensitivity of the kinematic asymmetry of the rolling process to the front end bending of the sheet.

Analytical expressions for the critical conditions of deformation during rolling have been obtained by various authors. More often, regression expressions are used, built based on processing calculated data obtained by finite element modelling of the asymmetric rolling process.

At the same time, an analytical approach can be used to solving this problem. One of such solutions is the expression of the critical value of the form factor of deformation zone [68]:

$$\log(\delta) = \sqrt{\frac{17{,}4+2{,}3\log(U_t/U_b)}{460{,}9+62{,}3\log(\sigma_Y/E)}}, \tag{5}$$

where, in the notations of the original source, $\log(\delta)$ is the decimal logarithm of the roll gap aspect ratio; U_t/U_b is the ratio of the linear speed of the upper and lower rolls; σ_Y/E is the ratio of the yield stress of the metal (resistance to plastic shear) to the elastic modulus in the deformation zone (Young's modulus). Hence, it follows that the critical values of the form factor of deformation zone are in the range of 1,7-2,3 under various actual conditions of asymmetric rolling. If to relate two expressions $l_d/h_m = 2$ and $H/R = 0,14$, then for such conditions we get a quadratic equation:

$$0{,}56\varepsilon^2 - 6{,}24\varepsilon + 2{,}24 = 0 \tag{6}$$

The first root of this equation is equal to the critical degree of deformation $\varepsilon_{cr} \approx 0{,}371$, at which, regardless of the mismatch of the rolls rotation speeds, the curvature of the front end is absent. This conclusion coincides very closely with the estimates given in [68].

If we express the average thickness at the deformation zone as the geometric mean of the entry and exit thicknesses, the relationship between ε and l_d/h_m is as follows:

$$\varepsilon = \frac{\frac{H}{R}\left(\frac{l_d}{h_m}\right)^2}{1+\frac{H}{R}\left(\frac{l_d}{h_m}\right)^2}. \tag{7}$$

The amount of forward slip during rolling cannot exceed under any circumstances the relative degree of deformation of the sheet. The degree of mismatch of the rolls rotation speeds higher than the forward slip value in a symmetric process should lead to sliding of the faster roll and instability of the rolling process. Therefore, for various rolling conditions, with a different coefficient of friction, such a critical degree of asymmetry, at which the forward slip on the faster roll is zero, is the one at which the degree of asymmetry is equal to the amount of the forward slip during rolling. The greater the metal reduction, the greater the forward slip of the sheet. If the value of the asymmetry index of the rolling process [%] is equal to or exceeds the value of the forward slip during rolling [%], then an unstable state of the rolling process occurs. These circumstances should be taken into account when imposing restrictions on the speed asymmetry of the process in order to control the front end bending of the sheet under various rolling conditions.

3. FEM asymmetric rolling modelling and control model development

In order to develop a control model for individual drives of the finishing rolling stand by creating a controlled asymmetry of the rolling process, a FEM simulation of the process is performed in a specialized software package QForm [64].

The following options are calculated: initial sheet thickness 7; 10; 20; 30; 40; 60; 80 and 100 mm, degree of deformation 5; 10; 15; 20; 25; 30 and 35%. The diameter of the work rolls is 965 mm, the peripheral speed of the bottom roll is 50 rpm, top – 47,5 rpm (5% degree of mismatch). The temperature of the metal is assumed +800°C.

The deformed state diagram is adopted in three dimensions. The process is non-isothermal, thermal processes and contact heat exchange with work rolls (heat transfer coefficient 50 kW/(m^2K), having an initial mass average temperature of 38°C) are taken into account. The work rolls are taken in the calculations to be incompressible, absolutely rigid, moving in the vertical plane of the stand with a stiffness modulus of 6,5 MN/mm, which is close to the actual value at the edges of the barrel without taking into account the elastic deflections of the roll. The deformable medium of the sheet is elastic-plastic. The deformable material is homogeneous isotropic, steel grade S355J2G3. The law of friction - Coulomb, the coefficient of friction is assumed constant and equal to $f = 0,3$. As a result of the numerical solution of the problem, the characteristics of the stress-strain state of the metal, the temperature field and the metal flow rate in the direction of rolling were determined (fig. 3).

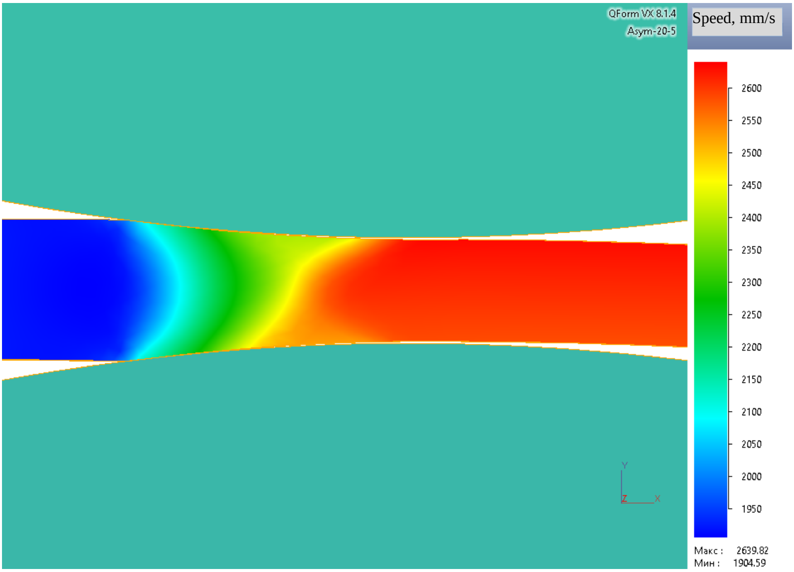


Figure 3 – The distribution of the metal flow rate along the X axis when rolling a sheet with an initial thickness of 30 mm; the mismatch of the rolls rotation speed -5%; the degree of deformation 25%; bending of the sheet towards the faster lower roll

The simulation results are summarized in the graphs in fig. 4, which shows the direction and magnitude of the curvature of the front end of the sheet depending on the initial thickness and form factor of the deformation zone (DZ) at known values of the degree of deformation. It follows from the figure that with an increase in the degree of deformation, the front end first bends towards the slower roll that corresponds to the dominance of the above mentioned factors 1 and 2. Upon reaching the critical value of the form factor of DZ (1,7-2,4) and corresponding to the rolling conditions of various thickness values of the degree of deformation (7,5-37,5%), the curvature changes sign to the opposite that corresponds to the dominance of the factors

3 and 4. This qualitative regularity was established by many authors who performed similar calculations and analysis (see, for example, [5]).

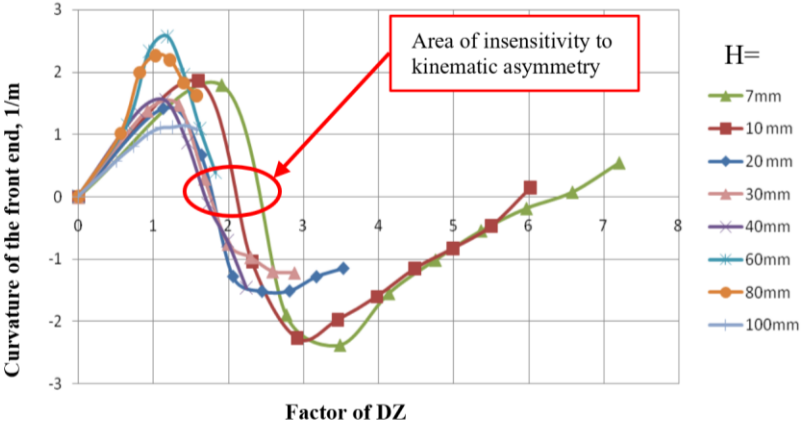


Figure 4 – Change in the curvature of the front end of the sheet depending on the initial thickness and shape factor of the deformation zone when the degree of deformation changes. Unbalance coefficient $k_{sym} = V_{up} / V_{dn}$ = 0,95. Markers indicate the values of curvature at the degree of deformation sequentially 0; 5; 10; 15; 20; 25; 30; 35%, etc.

The critical values of the degree of deformation and the values of the form factor of the DZ corresponding to the rolling conditions are located at the points of intersection of the curves with the abscissa axis. In such conditions, on the one hand, the rolling process from the view point of the front end curvature becomes insensitive to disturbances of kinematic asymmetry, that is good. However, on the other hand, in these cases, theoretically, there is no possibility of the front end correction by purposefully influencing the mismatch of the rolls speed.

In addition, the cases of the action of various disturbing factors were simulated, such as the difference of the temperature between the lower and upper surfaces in the range from 25 to 50 °C, the difference in friction conditions in contact with the upper and lower rolls (the coefficient of friction f was changed in the range of 0,25-0,35 with the setting of a larger edge value of the range from the side of the upper work roll and a smaller one from the side of the lower).

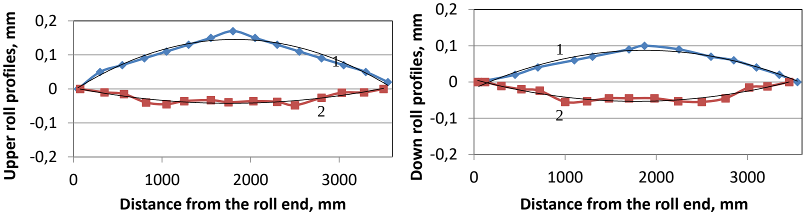
The calculation results are shown in Table 1, which shows the values of the curvature of the front end of the sheet H_0 at the same linear speed of the rolls and the degree of deformation ε = 20%, depending on the initial thickness of the sheet H_0, the difference between the surface temperature of the sheet from bottom and from top $\Delta T = T_b - T_t$, as well as the values of the coefficient of friction above f_t and below f_b. From the side of the metal entrance into the rolls, the influence of the roller table and the guiding rolls with which the sheet contacts at the moment of gripping and in the process of rolling in the form of limiters for the movement of rolled products from the bottom was taken into account.

Table 1 – Results of calculations

Variants	Variable parameters of the rolling process				Curvature *
	H_0, mm	ΔT, °C	f_t	f_b	ρ, 1/m
1	30	25	0,3	0,3	0,028
2	30	50	0,3	0,3	0,117
3	60	25	0,3	0,3	0,073
4	60	50	0,3	0,3	0,081
5	30	0	0,35	0,25	0,577
6	60	0	0,35	0,25	0,149
7	30	0	0,332	0,3	0,204
8	60	0	0,332	0,3	0

* - positive curvature values correspond to the upward front end bending of the sheet and vice versa.

The regularities of the upper and lower work rolls profile wear are such that increased wear takes place on the upper work rolls, and their wear is approximately 1,5 times greater in comparison with the lower rolls (fig. 5).



(a) (b)

Figure 5 – Initial profile (1) and wear (2) of the upper (a) and lower (b) work rolls

Since the wear rate is directly proportional to the sliding friction coefficient approximately to the 4th power [66], then with the ratio of the wear rate of the upper rolls to the lower ones equal to 1,5, and all other things being equal, the ratio of the friction coefficients in the deformation zone from above to below should be approximately $1{,}5^{0.25}$ (see table 1 options 7 and 8).

Calculated estimates showed, on the whole, an insignificant effect of the temperature difference on the upper and lower surfaces of the sheet in real ranges of temperature variation, while the influence of the frictional interaction of the rolls and the sheet (coefficient of friction) plays a significant role in the systematic upward bending of the sheets without compensating for this effect through mismatch roll speed.

So, for example, the curvature of the front end of the sheet (see the conditions in the caption to fig. 3 and in table 1) towards the colder upper surface, caused by the difference in temperature and, accordingly, the yield stress, is approximately (0,001...0,003) ΔT (m °C)$^{-1}$. The influence of the difference in the coefficient of friction (Δf) on the upper and lower rolls on the curvature of the sheet is estimated approximately (1,5...6) Δf (m^{-1}).

Note that the difference in temperature along the height of the rolled sheet affects its curvature after cooling and temperature averaging. For example, the difference in temperature between the lower and upper surfaces of a rolled sheet is its latent longitudinal curvature, which appears after cooling. For example, the difference 1 °C of the surface temperature of the sheet from the average value over the height corresponds to the latent longitudinal curvature of the steel sheet 1,2 IU, or about 0,5 mm over a length of 1 m, depending on the thickness of the sheet.

The cumulative effect of differences in temperature and friction conditions is most obvious for explaining the reasons for the systematic upward bending of the front end of the sheets in the finishing stand during symmetric rolling. Asymmetry factors such as the unequal diameter of the work rolls and the displacement of one of the rolls in the direction of rolling have a lesser effect in view of the small practical values of these parameters.

If to proceed from the fact that as a result of the action of the complex of factors considered, including systematic temperature gradients between the lower hotter surface of the sheets and the colder upper one, the difference in the torsional rigidity of the drivelines of the upper (with an additional intermediate shaft) and lower rolls, as a result of an increased coefficient of friction in contact with the upper roll, a systematic upward bending of the front end of the sheet occurs, then given a certain amount of curvature, which should be eliminated by creating a high-speed asymmetry of the rolling process, it is possible to obtain a model of control actions depending on the rolling conditions (fig. 6).

A discrete model has been implemented and the control algorithm provides for two steps.

1) The values of the actions between the curves for adjacent values of the initial thickness are calculated. In this case, the weighting factors take into account the degree of closeness of a particular input thickness to its fixed values, for which the nodal points are calculated and curves are plotted.

2) The required intermediate values between the obtained nodal points are calculated depending on the degree of deformation by the interpolation method.

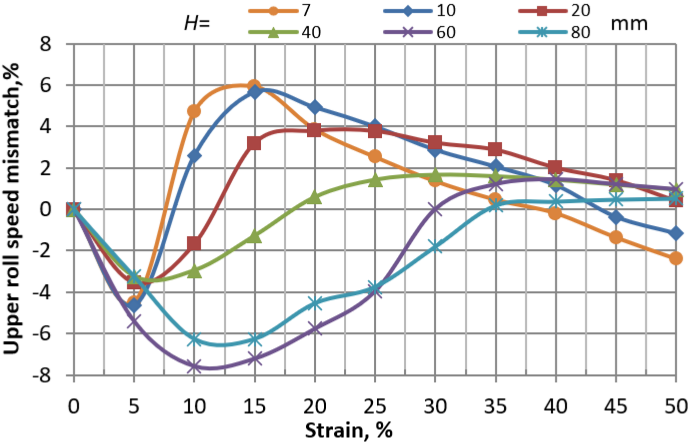


Figure 6 – Basic model of control actions required to compensate for systematic upward curvature of the front end of the sheet

4. Development and implementation of a control system

The development of the system was carried out in two stages. At the first stage, a simplified model of a digital controller was created and tested using the ADC/DAC USB-4704-AE ADVANTECH module for interaction with the existing analogue system for automatic control of electric drives of the stand and a local computer, where the controller itself was implemented in the software environment. At the second stage, an industrial fully functional prototype of a digital controller was implemented, in which the initial mismatch of the rolls rotation speed immediately before the sheet rolling automatically generated and the drives speed is controlled along the several passes depending on the assortment. Besides, visualization of the signals of the finishing mill stand and network communication with the server of the second level is provided. The scheme of data exchange and interaction with the existing rolling mill control subsystems is shown in fig. 7.

Taking into account the frequent cases of operation of the drives of one of the rolls in the generator mode with significant rolling asymmetry and the transition of the load torque through zero, the control algorithm in the digital controller provides only positive additions to the speed setting of one of the drives. This eliminates the opening of gaps in the drivelines when braking motors and the occurrence of dynamic processes in the drivelines.

At the first level, analogue-to-digital and digital-to-analogue conversion of signals is carried out using ibaNet750 components for interaction with the main control loops of the drives, and the digital controller itself is implemented in the ibaLogic software environment.

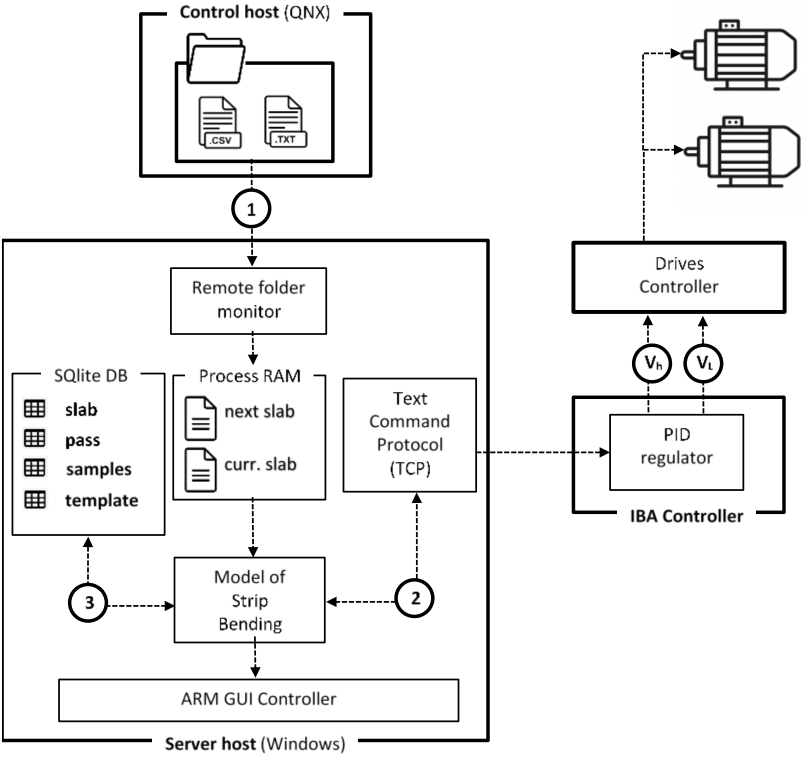


Figure 7 – Scheme of data exchange between the new system and mill control subsystems

At the second level of control, a server operates, which interacts with the sheet tracking system at the workshop level. The server has the functions of monitoring the parameters of the technological process and the actions of the operators to change the settings of the stand (the number of passes, reduction and sheet thickness, the end of rolling), synthesis of the developed model of control actions for the first-level controller in each pass, saving the calculated and actual parameters in the database, displaying system status and recommendations for mill operators.

At idle running without load, the PI-controller coefficients were adjusted and the stability of the entire control system was checked when the digital subsystem was connected in parallel with the main control loops of the electric drives of the finishing mill stand.

Communication between the mill control computer (QNX Neitrino OS) and the motor speed control server (Windows OS) is performed using file transfer using a Windows network folder. This method of exchange was chosen to simplify the data transfer process with minimal changes to the existing software of the mill control system and monitoring the rolling process. The control program has been modified accordingly in order to generate files of a predetermined format in a given directory:

- csv-files contain information about the rolled sheet;
- txt files contain an additional set of flags about the roll processing mode.

On the server side, a module is implemented to track events for the appearance of new files in a specified network folder. When a new file appears, data from it is read, recognized and placed into the server's RAM (fig. 7, link 1). For the same roll, these mill settings for passes can be changed several times. In this case, the server recognizes this situation and, instead of creating a new record about the rolled sheet, updates the information in the previously created record. At the same time, two records are stored in the server's memory: for the current sheet and the next sheet that will be rolled after it.

The model of targeted front end bending of the sheet is implemented as a separate module. As the initial data for the calculation, the values from the record about the current rolled sheet are read. Part of the sheet information is transferred to the IBA controller. For this, a set of text commands is used, implemented over the TCP data transfer protocol (fig.7, link 2). Next, the setpoints are calculated and transferred to the IBA controller. The final setpoints are calculated using a PID controller and transferred as additional analog signals to the execution of the existing system, which directly controls the drives.

After the rolling stock has been rolled (in each pass), the controller transmits to the server the actual parameters of the rolling process in the form of individual values or arrays of numbers. After receiving data on the completion of the pass, the information is updated on the graphical user interface in the mill operator pulpit.

All information about rolled sheets is stored in the SQlite database (fig. 7, link 3). In addition to the sheet parameters, the parameters of all passes are saved. For each pass, various signals actually measured are stored, for example deviation of the sheet thickness from the target value. For each signal, its statistical characteristics are calculated and saved.

In addition to storing information in the database, the server carries out full logging of all important events in the form of text log files on the hard disk.

The mill operators have the opportunity at any time to turn off the automatic mode of setting the speed mismatch and switch to the manual control mode.

5. Adaptation of the control model

In order to clarify the critical values of the deformation zone form factor (abscissas of the intersection of the curves with the X-axis for different values of the sheet thickness, see fig. 3), a passive experiment[1]. was performed. On a sufficient number of rolled sheets, there have been cases of rolling without the front end bending of the sheets. It was expected that statistically stable cases of flat front ends would indicate critical values of the degree of deformation for various groups of initial sheet thicknesses.

The data were processed (fig. 8) and found out the "successful" rolling conditions (initial thickness, degree of deformation, as well as the degree of mismatch of the rolls speed). These cases are shown in fig. 8, from which it follows that "successful" cases (without the front ends bending of the sheets) in the passes when rolling sheets with an initial thickness of 50 mm and above correspond to the conditions when the degree of their deformation in absolute value is close to the degree of mismatch of the rotation speed of the upper work roll relative to bottom. In the area of real values of the degree of deformation (up to 15%) when rolling plates with a thickness of 50 mm or more, this regularity was taken into account by correcting the control model (fig. 6).

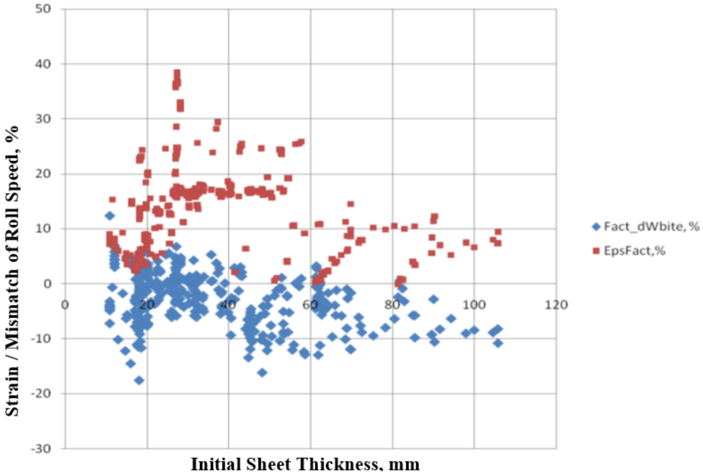


Figure 8 – Relationship between the degree of deformation (EpsFact, %) and the degree of asymmetry of the linear speed of the rolls (Fact_dWbite, %) in the absence of the front ends bends of the sheets

The values of the control actions obtained using the FEM model were also corrected based on the processing of statistical data when debugging the

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[1] With the participation of Krystian Pakuła

system using correction factors and additives separately for positive and negative values. In the subsequent system operation, the staff of the mill did not make any changes in these control settings.

Empirically, the maximum allowable speed difference (10%) from the current average speed of the drives was determined, at which the slower roll drive approaches complete unloading before switching to the generator mode. This limitation is implemented on the interface of the 2nd level server.

Nevertheless, operators can adjust some settings of the regulator, which include: the initial mismatch in the speed of the rolls before rolling, the duration of the stage of smooth reduction of this misalignment to its second level (normal rolling) and the mismatch in the speed of the second level when rolling the main part of the sheet length. Usually, the speed mismatch of the second level was set equal to zero (symmetric rolling process), however, the possibility of setting some asymmetry in the rolling process of the main part of the sheet length is also possible in the system.

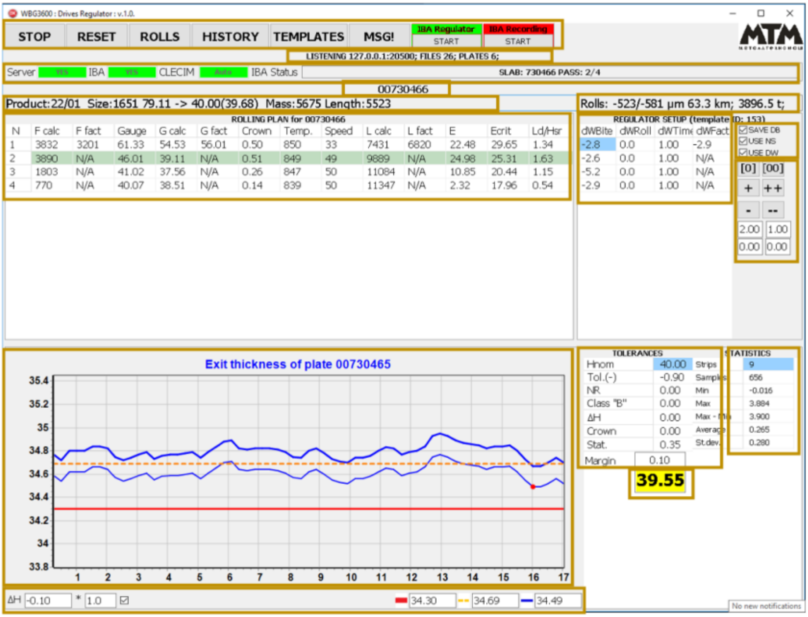
To improve the accuracy of working out the set values of the mismatch, the range of the controller dead zone was set to ± 6 rpm in order to exclude the system's response to fluctuations in the idle speed due to the imbalance of the spindles.

The averaging time of the speed signal of the drives is set at 200 ms, which is fed to the input of the regulator. The optimal time for working out a given mismatch is determined to 2 s with its smooth decrease from the initial value, acting before rolling, to the second set level, acting when rolling the main part of the sheet. Since the roll way is continuously monitored during rolling of each sheet, it is possible to set a predetermined length of the front end of the sheet being rolled with a decreasing roll speed mismatch and determine the corresponding time of action to smoothly reduce the speed mismatch to a second value.

There are a number of restrictions on the operation of the regulator implemented in the program, in particular, checking the presence of an inter-roll gap before the rolls pick up the sheet, so as not to try to create asymmetry in the linear speed of rotation of the work rolls pressed against each other before picking up in cases of rolling the thinnest sheets in the last passes.

6. System interface and performance

The interface of the system is shown in fig. 9, where in the upper part there is a plan of passes with the calculated parameters and settings for the mismatch of the rotation speed of the rolls, as well as the measured length of the sheet along the passes Lfact, taking into account the forward slip. The calculated degrees of reduction E and their critical values Ecrit are as well visible. Also, it is shown the current operating time of rolls from their last replacement (in “km” and “tonnes” of rolled products), as well as the current calculated roll wear, expressed in a decrease in the initially machined convexity of the work rolls (in microns).



LISTENING 127.0.0.1:20500; FILES 26; PLATES 6;

Server YES IBA YES CLECIM Auto IBA Status SLAB: 730466 PASS: 2/4

00730466

Product:22/01 Size:1651 79.11 -> 40.00(39.68) Mass:5675 Length:5523

Rolls: -523/-581 µm 63.3 km; 3896.5 t;

ROLLING PLAN for 00730466

N	F calc	F fact	Gauge	G calc	G fact	Crown	Temp.	Speed	L calc	L fact	E	Ecrit	Ld/Hsr
1	3832	3201	61.33	54.53	56.01	0.50	850	33	7431	6820	22.48	29.65	1.34
2	3890	N/A	46.01	39.11	N/A	0.51	849	49	9889	N/A	24.98	25.31	1.63
3	1803	N/A	41.02	37.56	N/A	0.26	847	50	11084	N/A	10.85	20.44	1.15
4	770	N/A	40.07	38.51	N/A	0.14	839	50	11347	N/A	2.32	17.96	0.54

REGULATOR SETUP (template ID: 153)

dWBite	dWRoll	dWTime	dWFact
-2.8	0.0	1.00	-2.9
-2.6	0.0	1.00	N/A
-5.2	0.0	1.00	N/A
-2.9	0.0	1.00	N/A

☑ SAVE DB
☑ USE NS
☑ USE DW

2.00 1.00
0.00 0.00

TOLERANCES

Hnom	40.00
Tol.(-)	-0.90
NR	0.00
Class "B"	0.00
ΔH	0.00
Crown	0.00
Stat.	0.35
Margin	0.10

39.55

STATISTICS

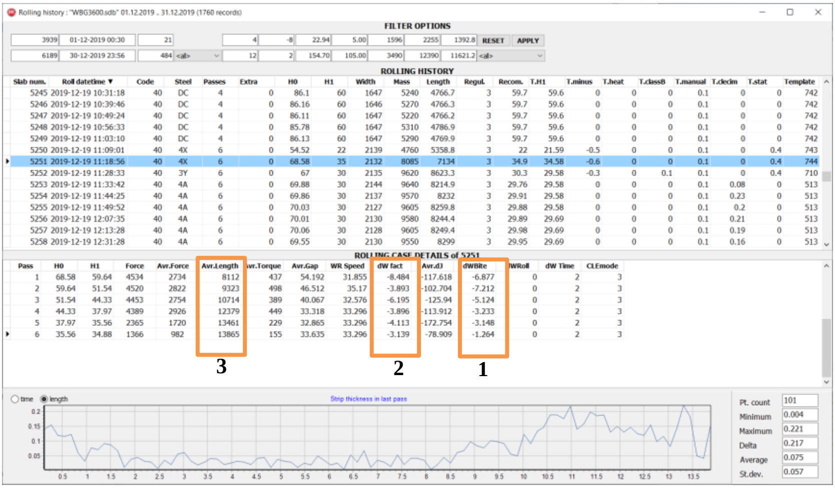
Strips	9
Samples	656
Min	-0.016
Max	3.884
Max - Min	3.900
Average	0.265
St.dev.	0.280

ΔH -0.10 * 1.0 ☑ 🟥 34.30 ‒ ‒ 34.69 ‒ 34.49

Figure 9 – System interface with areas of visualization of rolling modes and setting the parameters of the digital controller of the 1st level

The lower part shows a graph of the distribution of the actual thickness of the previous rolled sheet with the corresponding statistical estimates and a reference value of the thickness for the current sheet (another function of the system, not considered in this article, which provides a decrease in metal losses in the form of the difference between the actual and theoretical weight of the sheets by issuing recommendations to the operator to set the final sheet thickness, taking into account the actual rolling accuracy, the rules for thickness allowances, according to the order, and control of the length).

The screen form in fig. 10 shows the analytics resulted from the interaction with the database of rolling parameters both calculated values and their actual execution before rolling and during each pass. The example is indicated by the cursor and frames of the sheet rolled with an initial thickness of 68,58 mm to a final size of 35×2132 mm from steel 4X in 6 passes. The set values of the rolls rotation speed mismatch along the passes (dWbite, rpm) and actually executed (dWfact) at the moment of sheet capture. The technological parameters of the process, the calculated length of the sheet by passes, as well as the graph of the deviation of the thickness of the finished sheet are also given. The length of the sheet along the passes is calculated on the basis of the integral of the linear speed of the work rolls, taking into account the change in the calculated value of the forward slip during rolling. This allows operators to accurately control the execution of rolling plan not only in terms of sheet thickness, but also along its length.



Rolling history : "WBG3600.sdb" 01.12.2019 .. 31.12.2019 (1760 records)

FILTER OPTIONS

3939 | 01-12-2019 00:30 | 21 | 4 | -8 | 22.94 | 5.00 | 1596 | 2255 | 1392.8
6189 | 30-12-2019 23:56 | 484 | <all> | 12 | 2 | 154.70 | 105.00 | 3490 | 12390 | 11621.2 | <all>

ROLLING HISTORY

Slab num.	Roll datetime ▼	Code	Steel	Passes	Extra	H0	H1	Width	Mass	Length	Regul.	Recom.	T.H1	T.minus	T.heat	T.classB	T.manual	T.decim	T.stat	Template
5245	2019-12-19 10:31:18	40	DC	4	0	86.1	60	1647	5240	4766.7	3	59.7	59.6	0	0	0	0.1	0	0	742
5246	2019-12-19 10:39:46	40	DC	4	0	86.16	60	1646	5270	4766.3	3	59.7	59.6	0	0	0	0.1	0	0	742
5247	2019-12-19 10:49:24	40	DC	4	0	86.11	60	1647	5220	4766.2	3	59.7	59.6	0	0	0	0.1	0	0	742
5248	2019-12-19 10:56:33	40	DC	4	0	85.78	60	1647	5310	4786.9	3	59.7	59.6	0	0	0	0.1	0	0	742
5249	2019-12-19 11:03:10	40	DC	4	0	86.13	60	1647	5290	4769.9	3	59.7	59.6	0	0	0	0.1	0	0	742
5250	2019-12-19 11:09:01	40	4X	6	0	54.52	22	2139	4760	5358.8	3	22	21.59	-0.5	0	0	0.1	0	0.4	743
5251	2019-12-19 11:18:56	40	4X	6	0	68.58	35	2132	8085	7134	3	34.9	34.58	-0.6	0	0	0.1	0	0.4	744
5252	2019-12-19 11:28:33	40	3Y	6	0	67	30	2135	9620	8623.3	3	30.3	29.58	-0.3	0	0.1	0.1	0	0.4	710
5253	2019-12-19 11:33:42	40	4A	6	0	69.88	30	2144	9640	8214.9	3	29.76	29.58	0	0	0	0.1	0.08	0	513
5254	2019-12-19 11:44:25	40	4A	6	0	69.86	30	2137	9570	8232	3	29.91	29.58	0	0	0	0.1	0.23	0	513
5255	2019-12-19 11:49:52	40	4A	6	0	70.03	30	2127	9605	8259.8	3	29.88	29.58	0	0	0	0.1	0.2	0	513
5256	2019-12-19 12:07:35	40	4A	6	0	70.01	30	2130	9580	8244.4	3	29.89	29.69	0	0	0	0.1	0.21	0	513
5257	2019-12-19 12:13:28	40	4A	6	0	70.06	30	2128	9605	8249.4	3	29.98	29.69	0	0	0	0.1	0.19	0	513
5258	2019-12-19 12:31:28	40	4A	6	0	69.55	30	2130	9550	8299	3	29.95	29.69	0	0	0	0.1	0.16	0	513

ROLLING CASE DETAILS of 5251

Pass	H0	H1	Force	Avr.Force	Avr.Length	vr.Torque	Avr.Gap	WR Speed	dW fact	Avr.dJ	dWBite	IWRoll	dW Time	CLEmode
1	68.58	59.64	4534	2734	8112	437	54.192	31.855	-8.484	-117.618	-6.877	0	2	3
2	59.64	51.54	4520	2822	9323	498	46.512	35.17	-3.893	-102.704	-7.212	0	2	3
3	51.54	44.33	4453	2754	10714	389	40.067	32.576	-6.195	-125.94	-5.124	0	2	3
4	44.33	37.97	4389	2926	12379	449	33.318	33.296	-3.896	-113.912	-3.233	0	2	3
5	37.97	35.56	2365	1720	13461	229	32.865	33.296	-4.113	-172.754	-3.148	0	2	3
6	35.56	34.88	1366	982	13865	155	33.635	33.296	-3.139	-78.909	-1.264	0	2	3

○ time ● length

Pt. count: 101
Minimum: 0.004
Maximum: 0.221
Delta: 0.217
Average: 0.075
St.dev.: 0.057

Figure 10 – Interface of the system for viewing historical data on the parameters of sheet rolling, indicating the reference value for the misalignment of the rolls speed (1) and their actual performance (2) by passes, including the length of the sheets (3)

The example of system operation with the corresponding graphs of the signals for controlling the rotation speed of the upper and lower drives are shown in fig. 11. The upper graph (a) shows the rotation speeds of the upper and lower rolls (rpm), their difference and the rolling force (kN 10^{-1}).

The sections on the time lines (a) correspond to each reversal pass. The middle graph (b) shows the changes in the torques of the upper and lower drives (kN m), as well as their differences. It is noticeable that in passages 5 and 6 the moment of the top drive changes its sign, that is, it can operate for a short time in the generator mode. That is why the regulator works in such a way that it creates a given speed mismatch only by positive additions to the speed of one of the rolls (lower graph) in order to prevent the gaps in the drivelines from opening and not to cause shock loads in them. From the graphs for the example of the 1st pass, it is clearly noticeable that after the start of the acceleration of the mill pass, the system creates a pre-calculated mismatch in the rolls rotation speed. And it smoothly decreases it in after the stage of the front end rolling to the second set value (usually 0). Graph (c) shows the system output signals to correct the rotation speed of the upper and lower drives (rpm).

Figure 11 – An example of the operation of the automatic control system for the mismatch of the rotation speed of the upper and lower rolls, see explanations in the text

7. Conclusions

The following new scientific results were obtained:

1. Using finite-element modeling, the regularities and numerical values of changes in the curvature of the front end of the sheets depending on their thickness, the shape factor of the deformation zone, and the value of the inconsistency of the rolls' rotation speed were determined. It is shown that when the ratio of the sheet thickness to the roll radius is 0,014-0,2, the range of values of the deformation zone shape factor is 1,7-2,4, at which the front end bending is insensitive to the speed asymmetry of the rolling process, if other parameters of the rolling process are symmetrical, and under such conditions it is impossible to control the bending of the front end of the sheet. These numerical dependencies indicate the deformation conditions of rolling under which the change in the curvature of the front end of the sheets as a result of the kinematic asymmetry of the rolling process is minimal. This makes it possible to run the rolling process with optimal deformation levels outside the insensitivity zone.

2. The proposed mechanism of sheet front end curvature and the idea of redistribution of the influence of factors that cause a change in the direction of bending of the sheet front end with increasing deformation. At a low degree of deformation, the bending occurs in the direction of the slave roll, since the “run path” of the slave roll over the sheet surface is smaller. As the degree of deformation increases, the change in the position of the neutral angles begins to play a role, as the amount of advance is proportional to the square of the neutral angle. This factor begins to restrain the curvature towards the slave roll and, at a critical degree of deformation, completely compensates for the effect of the difference in “run path”, and with a further increase in the degree of deformation, it begins to dominate.

3. The main technological factors affecting the bending of the front end of sheets when rolling in rolls of the same diameter and at the same rotational speed were investigated, and it was found that the main and systematically acting factor is the difference in frictional interaction in the contact of the upper and lower rolls with the sheet in the deformation zone. It determines the direction and magnitude of the systematic curvature of the front end of the sheet towards the working roll with more wear at the end of the campaign. The systematic effect of this factor is manifested in the form of a difference in the wear of the upper and lower rolls. In the absence of a front end bending meter, the estimated systematic value of the sheet bending towards the roll with increased wear is set, calculated from the ratio of the friction coefficients at the top and bottom, proportional to the 4th power root of the ratio of wear of the upper and lower rolls.

4. A method has been developed to prevent the curvature of the front end of sheets by influencing the speeds of the upper and lower rolls during the gripping period, depending on the thickness of the sheet and the shape factor of the deformation zone. The impacts on the speeds were proposed and implemented to be always positive for one of the rolls to avoid opening the gaps in the drive lines. That is, at each control cycle, if it is necessary to reduce the speed of one of the rolls, the acceleration of the second roll is set and vice versa. This eliminates dynamic impacts in the drive lines and reduces the risk of equipment damage.

The development of a automatic control system is carried out based on the analysis and assessment of the main operating factors leading to the front ends bending of the sheets, the revealed patterns and mechanisms of bending in various rolling conditions.

Based on the calculated numerical estimates of the effect of the difference in frictional interaction, the temperature of the upper and lower surfaces, the values of the systematic component of the curvature of the sheets upward are established. In the absence of a meter for the amount of the front end bending of the sheets and the impossibility of using even statistical data to predict it before rolling, an estimated systematic value of the bending of the sheet upward is assumed.

To eliminate (compensate) front ends bending, a control model is used that takes into account the calculated bending patterns depending on the initial sheet thickness and the degree of deformation along the passes, according to the rolling plan (reduction schedule). It is used the experimentally established regularities of obtaining flat front ends of plates with a thickness of 50 mm and more under various deformation conditions, when the speed of the lower roll is greater than the upper one in % by approximately the value of the degree of deformation during rolling in %.

The system for automatic control of the front ends of thick plates is implemented on the digital signal conversion modules ibaNet750 and the ibaLogic software control environment with minimal changes to the existing analogue control system for the individual drives of the finishing rolling stand. The problem of the front ends bending is solved by maintaining a controlled speed asymmetry of the rolls speed during the metal capture by the rolls. The system has been put into permanent commercial operation since the beginning of 2019 on the mill 3600 Huta Częstochowa in Poland. As a result of long-term operation, the system allowed a 25% reduction in the number of sheets with curvature, which requires additional heating and leveling.

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СИСТЕМА АВТОМАТИЧНОГО КОНТРОЛЮ ПЕРЕДНІХ КІНЦІВ ТОВСТИХ ЛИСТІВ НЕСИМЕТРИЧНОЮ ГАРЯЧОЮ ПРОКАТКОЮ

Анотація. Виконано дослідження та розв'язано проблему неконтрольованого вигину передніх кінців товстих листів на стані гарячої прокатки. Встановлено комплекс основних чинників, що пояснюють причини формування вигину переднього кінця листів під час симетричної прокатки. З використанням скінченно-елементного моделювання розглянуто методи адекватного впливу на кривизну переднього кінця листа неузгодженістю швидкості валків у період захоплення залежно від товщини листа і чинника форми осередку деформації. При цьому розглянуто вплив таких чинників: 1. Вплив «довжини пробігу» ведучого валка по поверхні листа в нейтральному перерізі вогнища 2. Вплив відмінності середніх контактних напружень з боку ведучого і веденого валків. 3. Вплив зміщення нейтральних кутів з боку ведучого і веденого валків на величини випередження металу з боку кожного з валків. У разі зміщення нейтрального перерізу до входу в осередок деформації з боку веденого валка це дає більшу зміну товщини в осередку деформації, ніж у разі зміщення нейтрального перерізу до виходу з боку ведучого валка. На підставі розрахункових чисельних оцінок впливу відмінності фрикційної взаємодії, температури верхньої і нижньої поверхонь встановлені значення систематичної складової кривизни листів вгору. В умовах відсутності вимірювача величини вигину переднього кінця листів і неможливості використання навіть статистичних даних для його передбачення перед прокаткою, задається оцінне систематичне значення вигину листа вгору. Для його усунення (вирівнювання) використовується побудована модель управління, що враховує встановлені розраховані закономірності вигину залежно від початкової товщини листа і ступеня деформації по проходах, згідно з планом прокатки (режимом обтисків). Використано експериментально встановлені закономірності отримання рівних передніх кінців плит завтовшки 50 мм і вище за різних деформаційних умов, коли швидкість нижнього валка більша за верхній у % приблизно на величину ступеня деформації під час прокатки у %. Систему автоматичного вирівнювання передніх кінців товстих листів реалізовано на цифрових модулях ibaNet750 перетворення сигналів і середовищі програмного регулювання ibaLogic з мінімальними змінами в існуючій аналоговій системі управління індивідуальними приводами прокатної кліті промислового товстолистового стану 3600 гарячої прокатки Huta Częstochowa. Проблему вигину передніх кінців вирішено шляхом підтримки контрольованої швидкісної несиметрії швидкості валків безпосередньо перед та у процесі захоплення металу валками, а також при прокатці головної ділянки листів, що дало змогу зменшити кривизну кінцевих ділянок листів по довжині та збільшити вихід придатної продукції. На 25% зменшилася кількість листів із кривизною, що потребує повторного гарячого виправлення.

Ключові слова: сталевий лист, гаряча прокатка, чистова кліть, швидкісна несиметрія, вигин переднього кінця листа.

Посилання для цитування: Система автоматичного контролю передніх кінців товстих листів несиметричною гарячою прокаткою / І. Ю. Приходько, П. В. Крот, В. В. Разносілін, С. О. Воробей, Є. С. Клемешов, М. С. Малигін, І. А. Семенов, K. Matyjaszczyk // *Фундаментальні та прикладні проблеми чорної металургії.* 2024. Вип. 38. С. 336-361. https://doi.org/10.52150/2522-9117-2024-38-336-361.

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