Comparative evaluation of the kinematic parameters at symmetric and asymmetric cold rolling of strip using computer simulation

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Computer simulation of symmetric and asymmetric cold rolling of AISI-1008 steel strip in three passes was carried out. DEFORM finite element method (FEM) software was used for computer simulation. Technique allowing neutral line location determination was designed and this technique is based on the processing of FEM computer simulation results. Neutral line location during each of three passes at different working roll diameters combinations (symmetric rolling, rolling with 0.83 %, 1.67 % and 5 % working rolls diameters asymmetry) was detected using designed technique. It was established that working rolls diameters asymmetry increase till 5 % moves the middle of the neutral line towards rolling direction in 0.250 mm for the first pass, 0.199 mm – for the second pass, 0.133 mm - for the third pass. That is, influence of working rolls diameters asymmetry increase becomes weaker with the decrease of absolute value of height reduction. Three-dimensional graphs were made: one is illustrating dependence of position of the neutral line's midpoint from rolling speed and working rolls diameters asymmetry and the other one is illustrating dependence of the neutral line inclination angle from rolling speed and working rolls diameters asymmetry. Weak direct correlation between working rolls diameters asymmetry and position of neutral line's middle point and strong direct correlation between rolling speed and position of neutral line's middle point were detected. Velocity diagrams along vertical lines in lag zone and lead zone of the deformation zone at asymmetric rolling show that velocity at point of contact of upper roll and strip is less than velocity at point of contact of lower roll and strip.
Key words: cold rolling, asymmetric rolling, symmetric rolling, computer simulation, neutral line, velocity diagram, rolling speed, working rolls diameters asymmetry.
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Introduction

Asymmetric rolling processes are the rolling processes when there is a difference, with respect to each of the rolls, in: the way forces act on the rolled strip or plate, conditions on the contact area, stress-strain state and kinematic parameters in deformation zone [1, 2]. Asymmetric rolling of metallic powder with different geometric, kinematic and boundary conditions for each of the rolls is investigated in [3]; flexible asymmetric rolling with three rolls (two working and one auxiliary roll) was studied in [4]; authors of [5] realized two-high asymmetric rolling with one roll driven and one idle. Asymmetric rolling for manufacturing of foils and ultrathin strips was examined in [6]. Vertical asymmetry at rolling as a result of temperature gradient through strip's thickness was analyzed in [7, 8].

Computer simulation is often used for investigation of asymmetric rolling, for example in [9-13]. Article [14] is dedicated to detailed review of different asymmetric rolling processes and this paper clearly demonstrates the effectiveness of computer simulation using DEFORM FEM software for comparison of strip's stress-strain state while symmetric and asymmetric rolling. The effectiveness of using DEFORM FEM software while research of rolling processes is shown by different authors [15-22].

A number of articles connected with identification of neutral section dimensions and position can be distinguished [23-28] among studies dedicated to strip rolling processes,. Neutral line dimensions and position detection is, definitely, important objective because neutral angle is one of the key parameters while estimation of deformation zone parameters at rolling [29].

According to the results of the review, it was found out that asymmetric rolling process of strip at the condition of equal circumferential speed of upper and lower rolls but with different diameters has not been practically studied. Taking this into account, it seems actual to estimate the kinematic parameters of the deformation zone while asymmetric rolling with different diameters of working rolls and equal circumferential speed of the rolls.

The aim of the work was evaluation of kinematic parameters at symmetric and asymmetric cold rolling of strip,

Table 1. **Parameters of the investigated rolling process**

	Rolling speed, m/s	Entry strip thickness, mm/exit strip thickness, mm
First pass	4.2	2/1.4
Second pass	6.25	1.4/0.98
Third pass	10	0.98/0.66

Table 2. **Variants of combinations of working rolls diameters**

	Upper roll diameter, mm	Lower roll diameter, mm
Variant 1 (Symmetric rolling, 0 % asymmetry)	600	600
Variant 2 (0.83 % asymmetry)	595	600
Variant 3 (1.67 % asymmetry)	590	600
Variant 4 (5 % asymmetry)	570	600

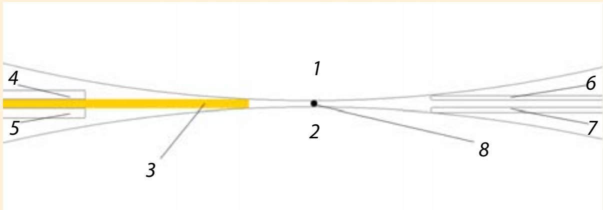


Fig. 1. View of the deformation zone in DEFORM pre-processor prior to simulation:
1 – upper working roll, *2* – lower working roll, *3* – strip, *4,5* – entry side guides, *6,7* – exit side guides, *8* – origin

namely: assessment of the position and inclination of the neutral line, assessment of velocity diagram for the lag zone and lead zone of the deformation zone. Estimation of these parameters was done using computer simulation of symmetric and asymmetric cold rolling of strip with the help of DEFORM FEM software.

Research method

Computer simulation of symmetric and asymmetric cold rolling of AISI-1008 steel strip was carried out using DEFORM FEM software in relation to first three stands of the 1700 continuous mill of PAO Severstal [30].

The rolling process was investigated with the parameters presented in **Table 1.** Four combinations of working rolls diameters were used for simulation of each of three passes (**Table 2**). At that, asymmetry index was calculated in percent as ratio of working rolls diameters difference to greater diameter of working roll.

Previously, flat sketches, containing rolls, a strip, a pusher and guides were created using SolidWorks software. Sketches were saved in .dxf format and loaded into DEFORM pre-processor. DEFORM pre-processor model for the simulation of cold rolling of strip from 2 mm to 1.4 mm thickness with 590 mm upper working roll diameter and 600 mm lower roll diameter is presented on **Fig. 1**. Simulation parameters were set after file was loaded form SolidWorks to DEFORM pre-processor. Strip material was set AISI-1008.

The "Shear" law of friction was used. Friction factor, according to DEOFRM user manual, is calculated according to the formula:

$$m = \frac{f_s}{k}, \tag{1}$$

where m – friction factor, k – shear yield stress, Pa, f_s – friction stress, Pa.

According to DEFORM user manual, friction factor should lie within 0.08-0.1 for "roll-strip" interaction when "Shear" friction law is used for cold forming processes. Friction factor for "roll-strip" couple was set 0.1 while simulation, and friction factor for "pusher-strip" couple and "guide-strip" couple was set 0.01. Rolls, guides and pusher were considered as rigid objects, i.e. they did not undergo neither elastic nor plastic deformation. A coordinate system was introduced for the convenience of processing the simulation results. Origin was on the vertical line passing through working rolls' centers and on the equal distance from the surfaces of each of the working rolls (Fig. 1). At that, specified vertical line was y-axis with positive direction upward. Horizontal line which is perpendicular to specified vertical line and passing through origin was x-axis with positive direction to the right.

Technique for neutral line position detection was designed. The techniques idea is the following. When the simulation was over, DEFORM post-processor menu tools were used to show the contact of the upper roll and the strip. This contact is represented by some arc. X-coordinate, roll's x-axis velocity and strip's x-axis velocity were calculated used DEFORM post-processor tools for each point of the contact arc. X-axis velocity of the upper roll was calculated for each of the contact arc point using formula:

$$V_{\text{rxu}} = \omega_{\text{u}} \cdot R_t \cdot \cos\left(\arcsin\left(\frac{x_{\text{pu}}}{R_t}\right)\right), \tag{2}$$

where V_{rxu} – x-axis velocity of the upper roll at the point of the contact arc, mm/s, ω_{u} – angular velocity of the upper working roll, rad/s, R_t – radius of the upper working roll, mm, x_{pu} – x-coordinate of the contact arc point.

Difference between x-axis velocity of the roll and x-axis velocity of the strip was calculated for every point of the contact arc. Two neighboring points are chosen among all the points of contact arc. At that, difference between the x-axis velocity of roll and x-axis velocity of strip for the point which is further from the origin is positive; difference between the x-axis velocity of roll and the x-axis velocity of strip for the point which is closer to the origin is negative. X-coordinate of the point in which difference between the x-axis velocity of roll and the x-axis velocity of strip equals zero is calculated using formula:

$$x_u = \frac{x_{ul}\,|\Delta V_{ur}| + x_{ur}\,|\Delta V_{ul}|}{|\Delta V_{ul}| + |\Delta V_{ur}|}, \quad , \tag{3}$$

where x_u — x-coordinate of the point for which difference between the x-axis velocity of roll and x-axis velocity of strip equals zero, x_{ul} — x-coordinate of the point for which difference between the x-axis velocity of roll and the x-axis velocity of strip is positive, ΔV_{ul} - difference between the x-axis velocity of roll and the x-axis velocity of strip for this point, mm/s, x_{ur} — x-coordinate of the point for which difference between the x-axis velocity of roll and the x-axis velocity of strip is negative, ΔV_{ur} - difference between the x-axis velocity of roll and the x-axis velocity of strip for this point, mm/s.

Y-coordinate of the point for which difference between the x-axis velocity of roll and the x-axis velocity of strip equals zero is calculated using formula:

$$y_u = y_{rt} - \sqrt{R_t^2 - (x_{rt} - x_u)^2}, \tag{4}$$

где y_u - y-coordinate of the point for which difference between the x-axis velocity of roll and the x-axis velocity of strip equals zero, y_{rt} — y-coordinate of the upper roll's center, x_{rt} — x-coordinate of the upper roll's center, x_u — x-coordinate of the point for which difference between the x-axis velocity of roll and x-axis velocity of strip equals zero, R_t — upper roll's radius, mm.

The contact area of the strip and the lower roll, which is an arc, is then displayed using DEFORM post-processor tool. X-coordinate, roll's x-axis velocity and strip's x-axis velocity for each point of the contact arc were calculated used DEFORM post-processor tools. X-axis velocity of the lower roll was calculated for each of the contact arc point using formula:

$$V_{rxl} = \omega_l \cdot R_b \cdot \cos\left(\arcsin\left(\frac{x_{pl}}{R_b}\right)\right), \tag{5}$$

где V_{rxl} — x-axis velocity of the lower roll at the point of the contact arc, mm/s, ω_l — angular velocity of the lower working roll, rad/s, R_b — radius of the lower working roll, mm, x_{pl} — x-coordinate of the contact arc point.

Difference between the x-axis velocity of roll and the x-axis velocity of strip was calculated for every point of the contact arc. Two neighboring points are chosen among all the points of contact arc. At that, difference between the x-axis velocity of roll and x-axis velocity of strip for the point which is further from the origin is positive; difference between the x-axis velocity of roll and x-axis velocity of strip for the point which is closer to the origin is negative. X-coordinate of the point in which difference between the x-axis velocity of roll and the x-axis velocity of strip equals zero is calculated using formula:

$$x_l = \frac{x_{ll}\,|\Delta V_{lr}| + x_{lr}\,|\Delta V_{ll}|}{|\Delta V_{ll}| + |\Delta V_{lr}|}, \tag{6}$$

where x_l — x-coordinate of the point for which difference between the x-axis velocity of roll and the x-axis velocity of strip equals zero, x_{ll} — x-coordinate of the point for which difference between the x-axis velocity of roll and the x-axis velocity of strip is positive, ΔV_{ll} - difference between the x-axis velocity of roll and x-axis velocity of strip for this point, mm/s, x_{lr} — x-coordinate of the point for which difference between the x-axis velocity of roll and x-axis velocity of strip is negative, ΔV_{lr} - difference between the x-axis velocity of roll and x-axis velocity of strip for this point, mm/s.

Y-coordinate of the point for which difference between the x-axis velocity of roll and x-axis velocity of strip equals zero is calculated using formula:

$$y_l = y_{rb} - \sqrt{R_b^2 - (x_{rb} - x_l)^2}, \tag{7}$$

where y_l - y-coordinate of the point for which difference between the x-axis velocity of roll and x-axis velocity of strip equals zero, y_{rb} — y-coordinate of the lower roll's center, x_{rb} — x-coordinate of the lower roll's center, x_l — x-coordinate of the point for which difference between the x-axis velocity of roll and the x-axis velocity of strip equals zero, R_b — lower roll's radius, mm.

It is accepted that the neutral section (and therefore the neutral line) passes through points with coordinates (x_u, y_u), (x_l, y_l) and is perpendicular to the side faces of the strip.

Results and discussion

Visual estimation of the x-axis velocity field of the strip while symmetric rolling allowed revealing the tendency. This tendency is that edges of the color layers, displaying the corresponding intervals of the velocity values, are located on vertical lines on the contact arc (**Fig. 2***a*). While in the case of asymmetric rolling the inclination of the layers at some angle was observed (Fig. 2), which leads to a shift from the vertical.

It can be assumed that neutral line at asymmetry rolling will not be perpendicular to rolling direction considering the inclination of color layers of Fig. 2*b*. Similar trend was revealed in [31], but it was for the asymmetric rolling with different circumferential speed of working rolls.

Neutral lines (**Fig. 3**) were constructed for each of the passes (table 1) and rolls' diameters combinations (Table 2) using the technique described in the previous section of the paper.

According to Fig. 3, increasing of asymmetry of working rolls diameters and rolling speed moves neutral line towards rolling direction. The increase of asymmetry of working rolls diameters to 5 % moves neutral line's middle point towards

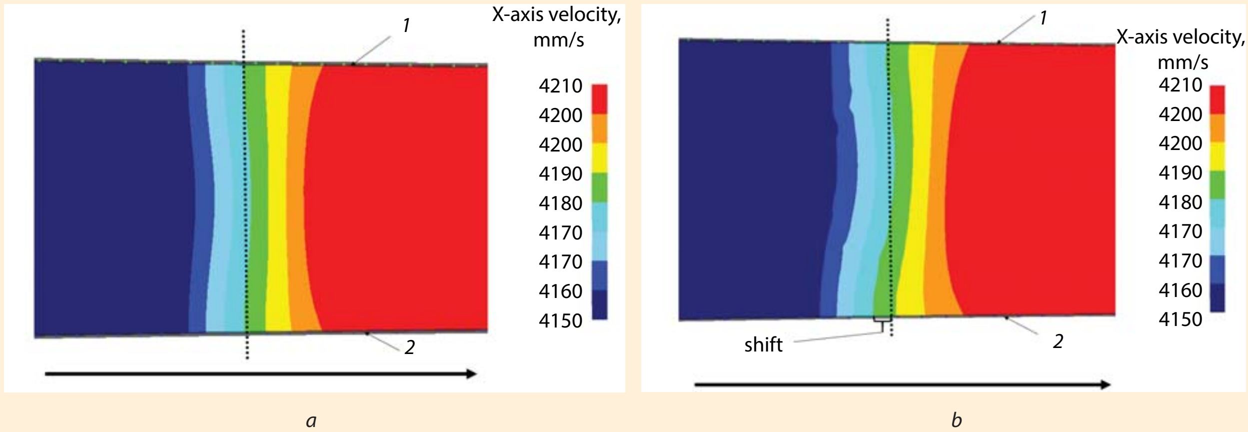
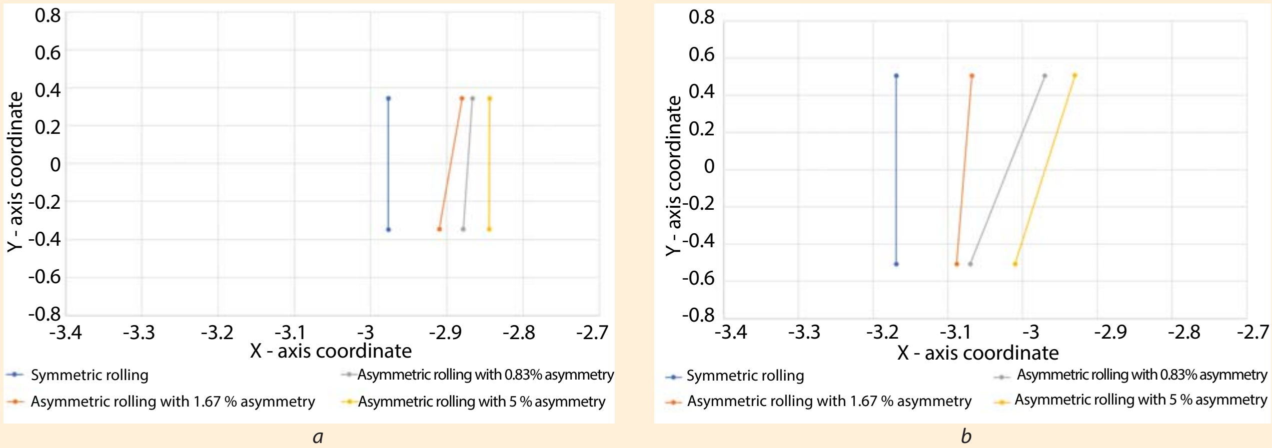


Fig. 2. X-axis velocity field for the strip in the deformation zone at symmetric rolling (*a*) and asymmetric (5 % asymmetry) rolling (*b*): *1* – the contact arc between the strip and the upper roll, *2* – the contact arc between the strip and the lower roll



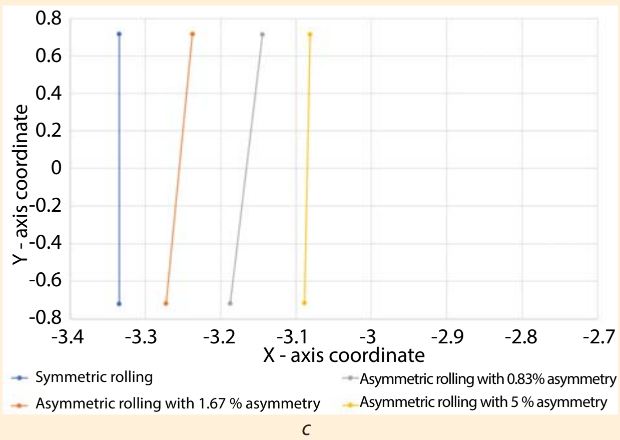
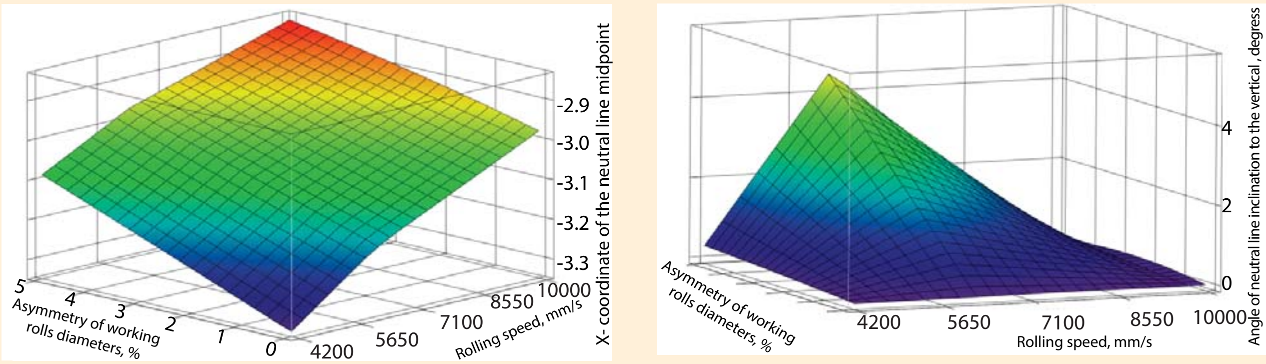


Fig. 3. Neutral lines for each combination of working rolls diameters at first (*a*), second (*b*), and third (*c*) passes

rolling direction by 0.250 mm in the first pass, by 0.199 mm in the second pass, and by 0.133 mm in the third. That is, as the absolute reduction of the rolling strip decreases, the effect of increasing the diameter asymmetry of the working rolls on the displacement of the neutral line along the rolling direction decreases. At the same time, the neutral line is inclined at an angle of not more than 7 degrees to the vertical in the direction of rolling for all variants of asymmetry. Three-dimensional diagrams were made in order to estimate the simulation results presented in Fig. 3. These diagrams (**Fig. 4**) show the dependence of x-coordinate of the neutral line midpoint from the asymmetry of working roll's diameters and the rolling speed (Fig. 4*a*). Diagram of Fig. 4b shows dependence of angle of the neutral line inclination to the vertical from the asymmetry of working roll diameters and the rolling speed.

According to Fig. 4*a*, the rolling speed is more important for the shift of the neutral line towards the rolling direction than the influence of the working rolls diameters asymmetry: inclination angle of the surface to the rolling speed is more



a *b*

Fig. 4. The influence of the asymmetry of working rolls diameters and rolling speed on the value of the x-coordinate of the neutral line midpoint (*a*) and the influence of the asymmetry of working rolls' diameters and rolling speed on the angle of the neutral line inclination to the vertical (*b*)

Table 3. **The correlation coefficients for the different couples of parameters**

	X-coordinate of the neutral line midpoint	Angle of inclination to the vertical (in the direction of rolling) of the neutral line
Working rolls diameters asymmetry	0.434	0.202
Rolling speed	0.854	-0.082

than the inclination angle of the surface to the asymmetry of working rolls diameters axis. According to Fig. 4*b*, maximum angle of inclination to the vertical (in the direction of rolling) of the neutral line (approximately 5-6 degrees) are at 1.67 % and 5 % asymmetry of working rolls diameters and 6250 mm/s rolling speed. Correlation coefficients were calculated using Microsoft Excel to quantify the results presented in Fig. 3-4. The coefficients were calculated for the following couples: "asymmetry of working rolls diameters - x-coordinate of the neutral lines' midpoint", "asymmetry of working rolls diameters – the angle of inclination to the vertical (in the direction of rolling) of the neutral line", "rolling speed - x-coordinate of the neutral line midpoint", "rolling speed - the angle of inclination to the vertical (in the direction of rolling) of the neutral line" (**Table 3**).

According to table 3 there is a very weak negative correlation between the rolling speed and the angle of inclination to the vertical (in the direction of rolling) of the neutral line; there is a very weak positive correlation between working roll's diameters asymmetry and angle of inclination to the vertical (in the direction of rolling) of the neutral line. A weak positive correlation was detected between working rolls diameters asymmetry and x-coordinate of the neutral line midpoint. At the same time high positive correlation links the rolling speed and the x-coordinate of the neutral line midpoint.

The neutral line inclination to the vertical at any asymmetry of working rolls diameters suggests "non-symmetric" distribution of velocities of strip's points through strip's thickness. **Fig. 5** shows velocity diagrams for the lag zone of the deformation zone (velocity of points of the strip 5 mm from the origin) the lead zone of the deformation zone (velocity of points of the strip 2 mm from the origin) at symmetric rolling and asymmetric rolling with 5 % asymmetry of working rolls diameters.

Diagrams of Fig. 5*a* and Fig. 5*b* are symmetric with respect to the horizontal line which passes through the middle of the strip thickness. Diagrams of Fig. 5*b* and Fig. 5*c* are non-symmetric, difference between velocities of the upper surface of the strip and lower surface of the strip is 0.7 mm/s for the lag zone and 1.7 mm/s for the lead zone. Results presented on Fig. 2, Fig. 3, and Fig. 5 allow deducing that "non-symmetric" distribution of stress-strain state parameters through strip thickness is about to take place at asymmetric rolling. Hence, such "non-symmetric" stress-strain state parameters distribution will result in "non-symmetric" distribution of properties along the thickness of the strip, for example, hardness and grain size.

Precise determination of the neutral section position regardless of the rolling scheme (symmetric or asymmetric) using designed technique will allow increasing effectiveness of rolls wear estimation, stresses in rolls, calculation of energy-power parameters of rolling. It will also allow estimation of microstructure and hardness change along the strip thickness after rolling. When asymmetry of working rolls diameters increases, neutral line moves towards rolling direction. It increases the length of the lag zone of the deformation zone, where strip x-axis velocity is less than rolls' x-axis velocity. This increases the risk of slippage. As a result, it decreases the productivity of the equipment. Also, the shift of the neutral line should be considered when developing new or adjusting the existing technology on the current rolling mills to optimize the usage of rolls on the base of combination of rolls with different diameters.

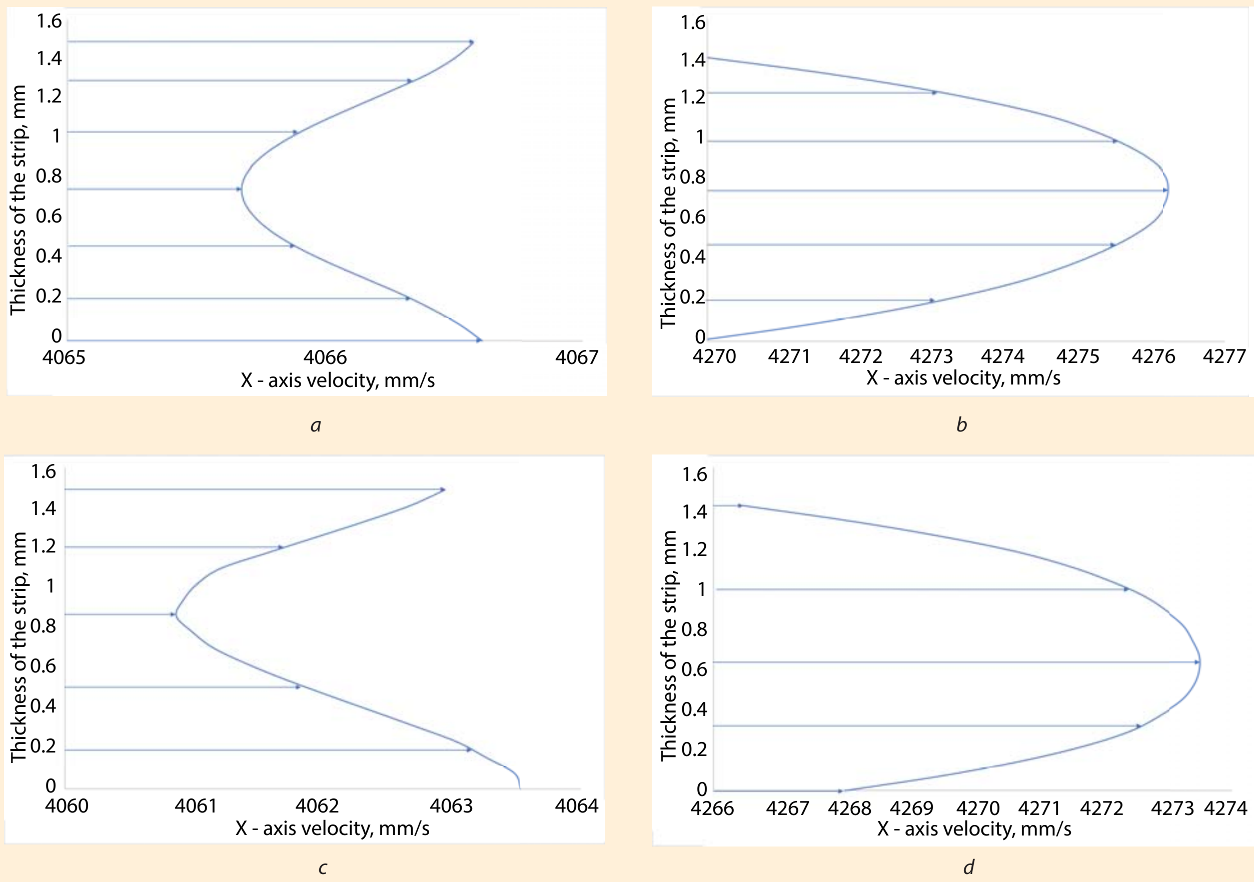


Fig. 5. Velocity diagrams for the lag zone of the deformation zone (velocity of points of the strip 5 mm from the origin) and for the lead zone of the deformation zone (velocity of points of the strip 2 mm from the origin) at symmetric rolling (*a* and *b*, correspondingly), velocity diagrams for the lag zone of the deformation zone (velocity of points of the strip 5 mm from the origin) and for the lead zone of the deformation zone (velocity of points of the strip 2 mm from the origin) at asymmetric rolling with 5 % asymmetry of working rolls diameters (*c* and *d*, correspondingly)

Conclusions

Computer simulation of symmetric and asymmetric (0.83 %, 1.67 %, and 5 % asymmetry of working rolls diameters) cold rolling of strip in the first three stand stands of the 1700 continuous mill of PAO Severstal was carried out. Computer simulation was done for the following route: 2 mm (initial strip thickness) – 1.4 mm – 0.98 mm – 0.66 mm. DEFORM FEM software was used for computer simulation. As a result of the research, technique for the detection of neutral line location was designed. The technique can be applied for both symmetric and asymmetric rolling. As a result of the research, it was established that:

1. Increase of the asymmetry of working rolls diameters moves neutral line towards rolling direction and this is true for all three passes. Neutral line shift after each next pass (with decreasing of absolute height reduction) is decreasing: 0.250 mm in the first pass, 0.199 mm in the second pass, 0.133 mm in the third pass.

2. As opposed to symmetric rolling (when neutral line is strictly vertical and perpendicular to the rolling direction), any asymmetry of working rolls diameters, in terms of investigated asymmetry values, leads to inclination of neutral line to the vertical with the angle less than 7 degrees.

3. High positive correlation between the rolling speed and the neutral line location (value of the correlation coefficient equaled 0.854) and weak positive correlation between the asymmetry of working rolls diameters and the neutral line location (value of the correlation coefficient equaled 0.434) were detected as a result of simulation data processing for all three passes.

4. X-axis velocity diagrams analysis showed that diagrams at the asymmetry rolling have non-symmetric view both for lag and lead zones of the deformation zone: x-axis velocity of the strip is less in the point of contact with the roll of smaller diameter than in the point of contact with the roll of larger diameter. X-axis velocity diagrams at equal diameters of upper and lower roll have symmetric view for both lag and lead zones of the deformation zone. View of x-velocity diagrams at asymmetric rolling suggests the difference in strip's material properties. The properties of the strip's material on the surface deformed by roll of larger diameter will differ from the properties of the strip's material on the surface deformed by the roll of smaller diameter.

5. Shift of neutral section location at sheet rolling influences the specific energy consumption of the rolling process and tendency to sliding of rolls relative to strip. Designed computer simulation scheme and analysis of asymmetric rolling process improves the provisions of the theory of rolling. It also allows the development of algorithms for the design of effective technologies for cold rolled sheet and strip manufacturing from the point of view of energy consumption, process stability and formation of required microstructure and mechanical properties of the final product.

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