ANALYSIS OF THE PROCESS OF PLATE ROLLING ON THE REVERSING MILL

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Received 31 October 2019
Accepted 16 December 2019

ABSTRACT

The paper presents and describes the results of testing the asymmetric rolling process of S355J2 + N steel plates, fed at an angle to the roll gap. The asymmetrical rolling process was used to counteract the uncontrolled bending of the angled band in order to eliminate the unfavorable bending of the band downwards. The range of acceptable values of velocity asymmetry coefficients of peripheral working rolls in a preliminary rolling mill and other parameters of the rolling process at which it is possible to obtain a straight band or change the direction of its bending was determined. Theoretical research was carried out using the Forge computer program based on the finite element method.

Keywords: asymmetric rolling process, steel S355J2+N, asymmetry coefficient, band bending.

INTRODUCTION

Rolling flat products is among the most common and most frequently applied plastic working processes used to form metals. The manufacture of flat products and implementing them in various fields of industry, such as the defence, automotive, household articles, conventional, wind and nuclear energy industries is the hallmark of the scale of modernity and development of a given country's metallurgical industry.

Flat products must meet the requirements of demanding purchasers in terms of their plastic properties, shape and allowable thickness deviations, or chemical compositions. Among flat products, plates and slabs make up an important group. They are most commonly manufactured in tandem plate rolling mills equipped with a vertical roll stand and two horizontal four-high stands, on which rolling is done by the reversing method.

When the stock is fed to the roughing stand, and the band is fed to the finishing stand of the Plate Rolling Mill, the neutral axis of the stock or band is, in the majority of cases, does not coincide with the neutral axis of the roll gap; whereas, the shorter the band, the larger the angle at which it is introduced to the deformation zone. As a consequence, the geometrical conditions of band deformation on the upper and lower working roll sides are disturbed, and the rolling process itself becomes an asymmetric process, which will vary in each subsequent pass [1, 2]. This phenomenon causes an adverse bending of the band towards either lower or upper roll. The bent band is then straightened by roller table rollers; yet, its beginning has a permanently distorted (wavy) shape. So, distorted product is difficult to "repair", or straighten, either in a further rolling process, or on separate straightening machines, due to the high rigidity of the band.

Based on many years study and analysis of the quality of products manufactured in the Plate Rolling Mill, we can state that a large technological waste occurs during this production, which is due to the waviness of the rolled bad front end. Moreover, the rolling mill equipment and roller table rollers undergo rapid wear.

In order to prevent the phenomenon of band front end bending after band exit from the roll gap, a modern work table level setting system should be implemented, which would enable the so-called neutral line of the rolled feedstock to coincide with the neutral line of the roll gap in each successive rolling pass. Another alternative method of improving the band shape is to introduce a controlled asymmetric rolling process, which will rely on the use of differentiated rotational speeds of individual working rolls [3 - 7]. By introducing such an asymmetry (i.e. kinetic asymmetry), the state of stress and strain in metal in the roll gap could be changed, thus eliminating the adverse bending of the front end of band exiting the deformation zone [8].

EXPERIMENTAL

The analysis of the steel plate rolling process was made for the roughing stand of a sample 3600 Plate Rolling Mill furnished with two horizontal four-high mills. For this roughing stand, the roller tables before and after the stand are positioned in such a manner that the distance between the upper roller table surface and the tangent to the surface of the lower roll at its upper surface is 25 mm. In the Rolling Mill under consideration, 50 - 120 mm thick plates are produced from 225 mm thick continuous castings. Rolling reductions, $\varepsilon = \Delta h/h_0$ (where: $\Delta h = h_0 - h_1$, h_0 - band height prior to the pass, mm, h_1 - band height after the pass), used in this stand, range from several percent to 20 %. The difference between the neutral axis of the feedstock and the neutral axis of the roll gap changes in subsequent passes from approx. 9 mm to approx. 25 mm. This location of the roller tables and the change in the magnitudes of the relative reduction and the roll shape factor h_0/D (where: h_0 - band height before the pass, D - working roll diameter) in the subsequent passes causes the feedstock to be introduced into the roll gap at a certain angle, which creates a non-uniform strain and stress field in the metal in the roll gap and causes the band to bend upon leaving the roll gap (past the stand).

A sample scheme of rolling 81.0x2130x6700 mm plate of steel S355J2+N in two four-high stands is shown in Table 1. The rolling feedstock was a 225x1800x2830 mm continuous casting. The dimensions of the rolls were as follows: the roughing stand D_{opd} = 1761, mm; D_{opg} = 1762.0 mm; D_{rd} = 1102.1 mm; D_{rg} = 1101.1 mm; the finishing stand: D_{opd} = 1767.0 mm; D_{opg} = 1744.0 mm; D_{rd} = 996.6 mm; D_{rg} = 999.7 mm. Chemical composition of the steel: C 0.20 %; Mn 1.6 %; Si 0.55 %; P 0.025 %; S 0.025 %, Cr 0.030 %; Ni 0.80 %; Cu 0.55 %, Mo 0.080 %; V 0.100 %; Nb 0.060 %; Ti 0.050 %.

Table 1. A sample scheme of the process of rolling S355J2+N steel plate.

Pass No	h_n mm	h/D	Δh mm	ε	Bandwidth, mm	Neutralaxesdistance, mm	P kN	T_{entry} °C
Roughing stand								
0	228.37	0.2074	-	-		-	-	1147
1	198.42	0.1802	29.95	0.131		-9.53	32690	951
2	192.66	0.1750	5.76	0.029	2121	-22.12	13250	964
3	166.78	0.1515	25.88	0.134		-12.06	27110	934
4	141.14	0.1282	25.64	0.154	2131	-12.18	27640	957
5	141.01	0.1281	0.13	0.001		-24.93	3220	930
6	140.40	0.1275	0.61	0.004		-24.70	1440	952
7	131.85	0.1198	8.55	0.061		-20.72	16240	909
8	119.93	0.1089	11.92	0.090	2131	-19.04	22120	931
9	112.29	0.1020	7.64	0.064		-21.19	15950	891
10	110.71	0.1006	1.58	0.014		-24.16	9640	932
Finishing stand								
0	110.71	0.1112	-	-		-	-	855
1	99.68	0.1000	11.03	0.010	2131	-4.54	25650	832
2	88.61	0.0890	11.07	0.111	2131	-4.46	30270	832
3	82.58	0.0829	6.03	0.068	2131	-1.99	23870	823
4	81.05	0.0814	1.53	0.019	2131	-4.23	14890	823

h_n – band height after the pass, P – measured total pressure, T_{entry} – measured band temperature before the pass.

To prevent the process of band bending beyond the roll gap, the authors of this article propose to introduce an asymmetric rolling process, i.e. a kinetic asymmetry that consists in a differentiation of the circumferential speeds of the working rolls. Thereby, the rolling process would take place with two asymmetries: the geometric asymmetry (resulting from the feedstock being fed at an angle) and the kinetic asymmetry (obtained by varying the rotational speeds of individual rolls).

To determine the effect of the value of the angle, at which the band is introduced to the roll gap, relative reductions, ε, and the applied type of asymmetry of working roll circumferential speeds on the front-end band bending for different values of the roll shape factor, h_0/D, numerical modelling of the process of plate rolling on the roughing mill was performed using the FORGE software program.

The correct determination of the properties of steel in the form of stress–strain diagrams, allowing for the effect of band temperature and strain rate, enhances the accuracy of numerical computations, in which the finite element method is utilized. To this end, plastometric tests of steel S355J2+N (Table 2) were carried out, based on which steel property diagrams were determined, the coefficients of yield stress function were selected, and tables with actual plastometric test data were created, which were then used in carrying out computer simulations of the rolling process.

Working rolls, each of a diameter of 1103 mm, and a constant lower working roll rotational speed of n = 55 rpm were assumed for the numerical studies of the rolling process. The range of applied relative reductions was ε = 0.05 - 0.30. The asymmetric rolling process was conducted by:

- changing the rotational speed of the upper roll to be lower than that of the lower roll (kinetic asymmetry). The range of variation of the roll rotational speed asymmetry factor, $a_v = v_d/v_g$, was 1.01 - 1.10;
- changing the angle of band feeding to the roll gap (geometric asymmetry). The range of variation of the feedstock feed angle was θ = 0 - 3º.

A band shape factor of h_0/D = 0.1887 and 0.0660, respectively, was assumed. The rolled feedstock temperature for the steel under investigation was changed, depending on the initial height, h_0:

h_0 = 200 mm, the rolling temperature T = 950°C,

h_0 = 70 mm, the rolling temperature T = 850°C.

RESULTS AND DISCUSSION

The effect of the relative reduction ε and the value of the roll gap band feed angle θ on the magnitude of band curvature ρ

Sample results of the investigation into the effect of the feedstock roll gap feed angle θ (geometric asymmetry) resulting from the non-coincidence of the feedstock neutral axis with the deformation zone neutral axis and the relative reduction ε on the band curvature magnitude, in symmetric and asymmetric rolling S355J2+N steel grade feedstock are illustrated in Figs. 1, 2.

The relationships illustrated in Fig. 1 show that in symmetric rolling, introducing the feedstock to the deformation zone at an angle of θ causes the front end of the exiting band to bend towards the lower roll. The band curvature grows with increasing the feed angle. The application of the second type of asymmetry results in a change in band front-end bending direction. The data in this figure show that for each analyzed feedstock feed angle there is a kinetic asymmetry factor value, for which a straight band is obtained.

Similar results were also obtained for feedstock of an initial height of h_0 = 70 mm. The data in Fig. 2 show that when introducing feedstock to the symmetric roll gap at an angle of θ, the band bends towards the lower roll upon exit from the deformation zone. Whereas, the greater the feed angle magnitude, the larger the band curvature is obtained after band exit from the deformation zone. By applying the asymmetric process through

Table 2. The values of the parameters A and m_1 - m_9 used for determining the values of σ_p for steel S355J2+N.

Steel	The values of the parameters A and m_1 - m_9 used for determining the values of σ_p								
	A	m_1	m_2	m_3	m_4	m_5	m_7	m_8	m_9
S355J2+N	0.000155	-0.005730	0.389854	-0.084144	-0.000175	-0.001172	-0.229122	0.000221	2.950474

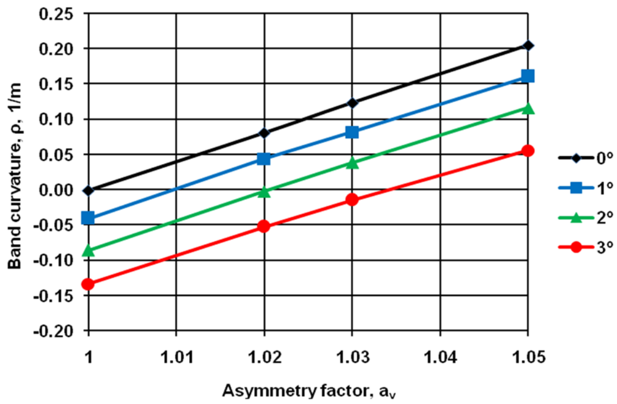

Fig. 1. The effect of the asymmetry factor a_v and the value of the deformation zone feedstock feed angle θ on the magnitude of band curvature after symmetric and asymmetric rolling 200 mm high feedstock with a relative reduction of ε = 0.10.

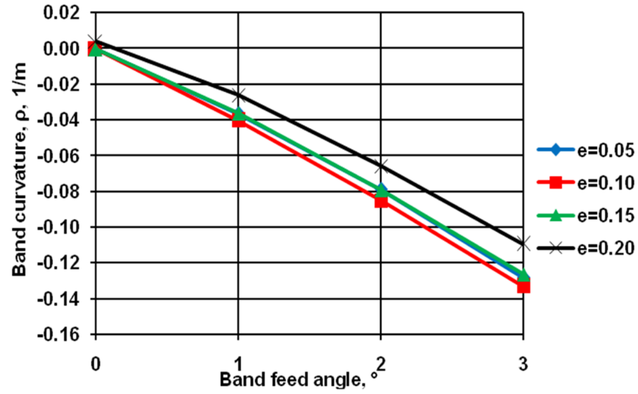

Fig. 3. The effect of the deformation zone feedstock feed angle θ and the relative reduction ε on the variations in the magnitude of band curvature after symmetric band rolling (a_v = 1.00) from 200 mm high feedstock.

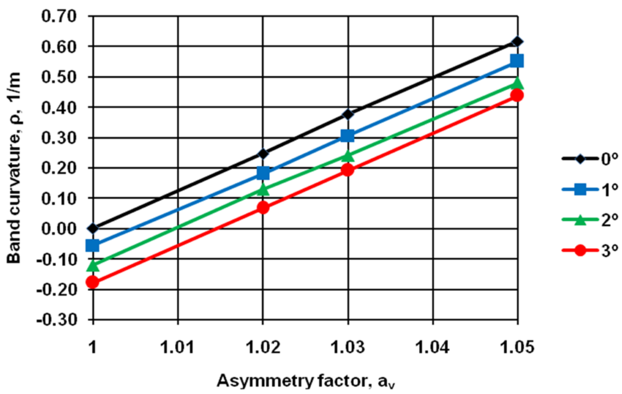

Fig. 2. The effect of the asymmetry factor a_v and the value of the deformation zone feedstock feed angle θ on the magnitude of band curvature after symmetric and asymmetric rolling 70 mm high feedstock with a relative reduction of ε = 0.10.

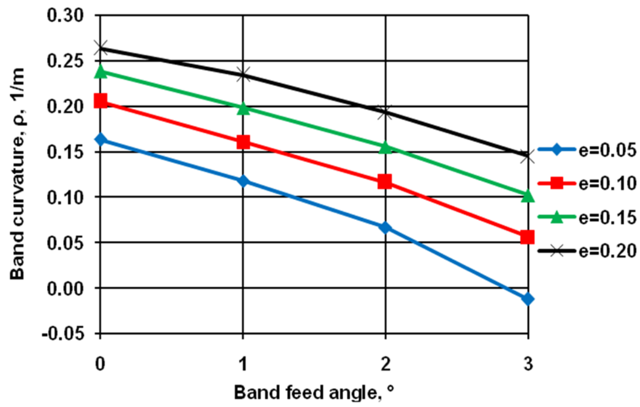

Fig. 4. The effect of the deformation zone feedstock feed angle θ and the relative reduction ε on the variations in the magnitude of band curvature after symmetric band rolling (a_v = 1.05) from 200 mm high feedstock.

differentiating the working roll rotational speeds, a change in the direction of band bending can be obtained.

The greatest band bending towards the lower roll (ρ = 0.1786 m^{-1}) occurred when rolling the feedstock with a relative reduction of ε = 0.10, with setting no roll rotation speed asymmetry and with a deformation zone band feed angle of θ = 3°. The greatest band bending towards the upper roll (ρ = 0.6167 m^{-1}) occurred for ε = 0.10; an asymmetry factor of a_v = 1.05; and with horizontal band feed to the deformation zone. For all analyzed feed angles and specified kinetic asymmetry factor values, a straight band front end can be obtained.

Figs. 3 and 4 show sample results of testing for the effect of the relative reduction ε and the deformation zone band feed angle θ on the magnitude of the curvature of band rolled asymmetrically (a_v = 1.00) and asymmetrically (a_v = 1.05) from feedstock of an initial height of h_0 = 200 mm.

The data in Fig. 3 show that feedstock of an initial height of h_0 = 200 mm when rolled symmetrically (rotational speed asymmetry factor, a_v = 1.00) with a reduction in the range of ε = 0.05 - 0.20, while being fed to the deformation zone at an angle, bends downward. The band curvature grows with increasing band feed angle θ for all the examined values of the relative reduction ε. For this case, straight bands on exist from the roll gap can be only obtained when the feedstock is fed horizontally. However, due to the fixed positioning

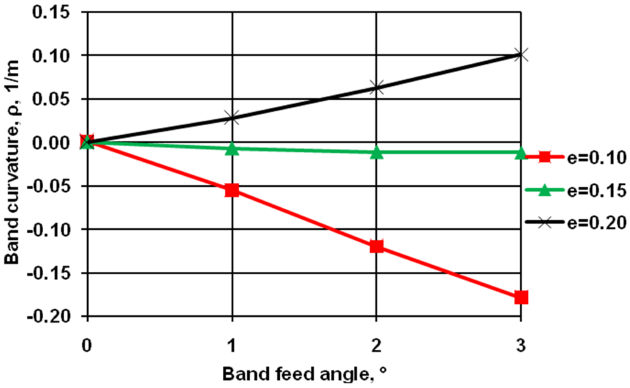

Fig. 5. The effect of the deformation zone feedstock feed angle θ and the relative reduction ε on the variations in the magnitude of band curvature after symmetric band rolling (a_v = 1.00) from 70 mm high feedstock.

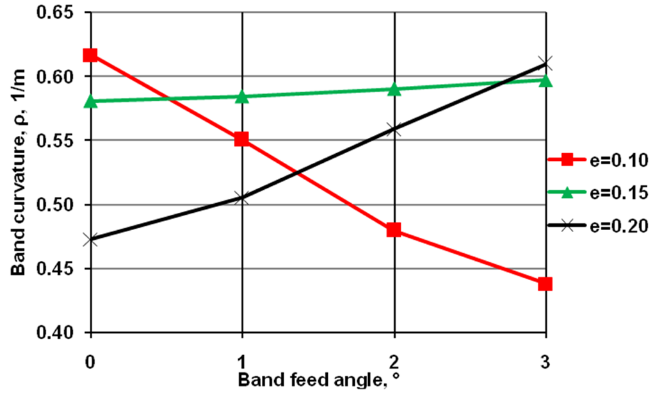

Fig. 6. The effect of the deformation zone feedstock feed angle θ and the relative reduction ε on the variations in the magnitude of band curvature after symmetric band rolling (a_v = 1.05) from 70 mm high feedstock.

of the working roller table relative to the upper surface of the lower roll in relation to the working roller table, feeding feedstock to the deformation zone horizontally is practically impossible.

Introducing a small asymmetry in working roll circumferential speeds resulted in a change in the direction of bending of the band leaving the roll gap (Fig. 4).

After asymmetric rolling of the feedstock with an asymmetry factor of a_v = 1.05 (Fig. 4), the band bent towards the upper roll only for ε = 0.05 and θ = 3°. The band curvature magnitude was small, amounting to ρ = -0.0119 m^{-1}. The remaining curvature magnitudes were positive (the band front end bent towards the upper roll) for all the variable parameters of the examined rolling process.

Figs. 6 and 7 show sample results of testing for the effect of the relative reduction ε and the deformation zone band feed angle θ on the magnitude of the band curvature ρ after the asymmetric (a_v = 1.00) and asymmetric (a_v = 1.05) process of rolling 70 mm high feedstock.

The data in Fig. 5 show that after the symmetrical rolling of feedstock of an initial height of h_0 = 70 mm with a relative reduction of ε = 0.15, being fed to the roll gap at an angle of θ, a very small band bend towards the lower roll occurs upon band exit from the deformation zone. The magnitude of the curvature is the same for all the examined feedstock feed angles. By increasing the deformation to a value of ε = 0.20, a change in the direction of band front-end bending (the band bends towards the upper roll) and an increase in its curvature can be obtained with the increase in feedstock feed angle. By contrast, reducing the deformation value to ε = 0.10 results in a change in band bending direction – the band front end bends towards the lower roll. The band curvature magnitude also increases with the increase in the angle of band feed to the deformation zone.

After applying asymmetric rolling (a_v = 1.05) by reducing the rotational speed of the upper roll, for each examined parameters, the band would towards the upper roll upon exit from the deformation zone. After applying a relative deformation of ε = 0.15, the magnitude of band curvature was similar, irrespective of the feedstock feed angle. After increasing the relative deformation value to ε = 0.20, the magnitude of band curvature increased with increasing the feed angle, while after applying a relative deformation of ε = 0.10, the band curvature magnitude would decrease (Fig. 6).

Strain rate intensity fields and stress intensity fields

Figs. 7 - 9 show sample distributions of strain rate intensities $\dot{\varepsilon}_i$; the determined neutral surfaces on the upper roll side (in white) and on the lower roll side (in black) are also shown.

Feeding feedstock of an initial height of h_0 = 200 mm to the deformation zone at an angle of θ = 3° causes a non-uniform distribution of strain rates. In metal layers in contact with the upper roll, strain rate intensity values are greater than in layers in contact with the lower roll. The upper layers of the band metal move faster than the lower layers do, which results in the band front end bending towards the lower roll. As shown by the data in Fig. 7, the surfaces unaffected by the lower and the upper rolls (neutral surfaces) coincide with one another.

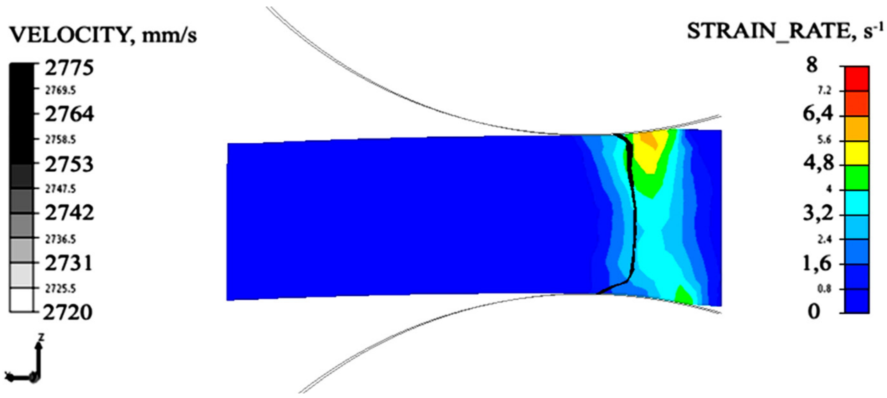

Fig. 7. Distribution of strain rate intensities $\dot{\varepsilon}_i$ for feedstock of an initial height of h_0 = 200 mm, rolled with a reduction of ε = 0.10, with an asymmetry factor of a_v = 1.00, and at a deformation zone feedstock feed angle of θ = 3˚.

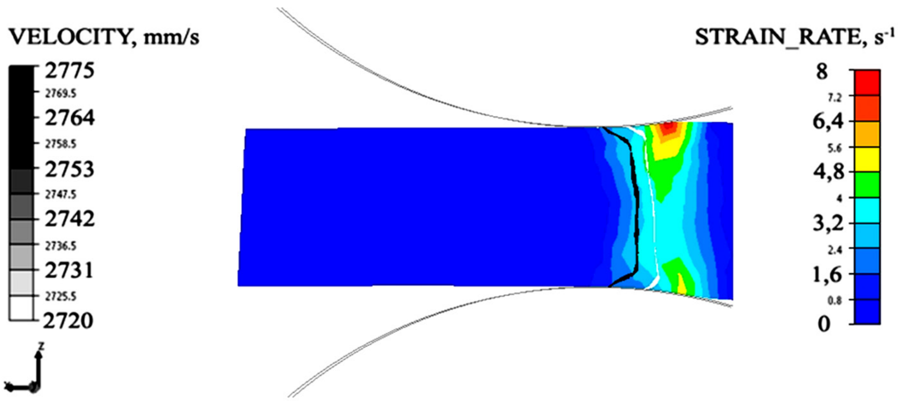

Fig. 8. Distribution of strain rate intensities $\dot{\varepsilon}_i$ for feedstock of an initial height of h_0 = 200 mm, rolled with a reduction of ε = 0.10, with an asymmetry factor of a_v = 1.02, and at a deformation zone feedstock feed angle of θ = 3˚.

Introducing a small kinetic asymmetry (a_v = 1.02) to the rolling process produces a more uniform distribution of strain rate intensities, which results in a smaller band front-end bend. For this case, a slight bend towards the lower roll was obtained. It can be seen from the position of the neutral surfaces in the deformation zone that the advance zone on the upper roll side is longer than the lower roll affected advance zone, which contributes to the band bending towards the lower roll (Fig. 8).

Increasing the asymmetry factor to a value of a_v = 1.05 resulted in an extension of the lower roll affected delay zone. In spite of this, a slight bend of the band front end towards the upper roll was obtained. This was caused by a greater lower roll rotational speed due to the applied kinetic asymmetry. Metal layers in contact with the lower roll in the delay zone flow faster, compared to metal layers contacting the upper roll in the advance zone (Fig. 9).

Figs. 10 - 12 show sample distributions of stress intensities for the examined technological cases. During symmetric rolling of feedstock of a height of h_0 = 200 mm fed horizontally to the deformation zone with a relative reduction of ε = 0.05, an uniform distribution of stress was obtained, relative to the neutral axis of the band being rolled (Fig. 10).

When feeding feedstock into the roll gap at an angle of θ, a non-uniform distribution of stress in the deformation zone was obtained, which resulted in a band front-end bend. This can be prevented by the appropriate selection of the kinematic asymmetry factor. The data in Fig. 11 show that after applying kinetic asymmetry with an asymmetry factor of a_v = 1.02 in the process of rolling feedstock of an initial height of h_0 = 200 mm introduced to the deformation zone at an angle of θ =

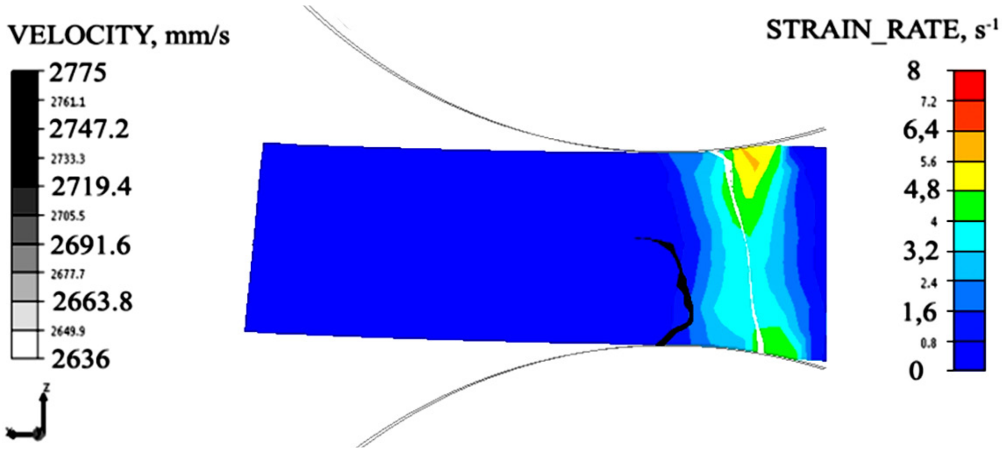

Fig. 9. Distribution of strain rate intensities $\dot{\varepsilon}_i$ for feedstock of an initial height of $h_0 = 200$ mm, rolled with a reduction of $\varepsilon = 0.10$, with an asymmetry factor of $a_v = 1.05$, and at a deformation zone feedstock feed angle of $\theta = 3^{\circ}$.

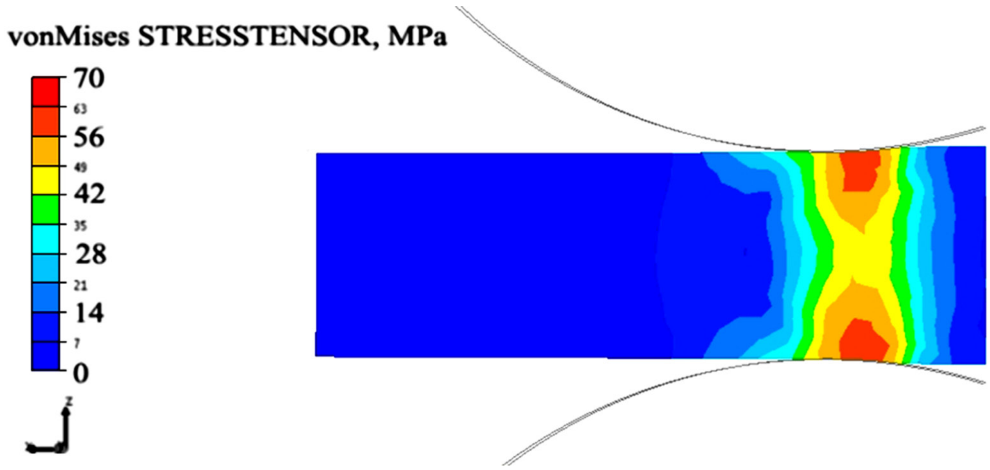

Fig. 10. Distribution of stress intensities σ_i for feedstock of an initial height of $h_0 = 200$ mm, rolled with a reduction of $\varepsilon = 0.05$ using an asymmetry factor of $a_v = 1.00$, and at a deformation zone feedstock feed angle of $\theta = 0^{\circ}$.

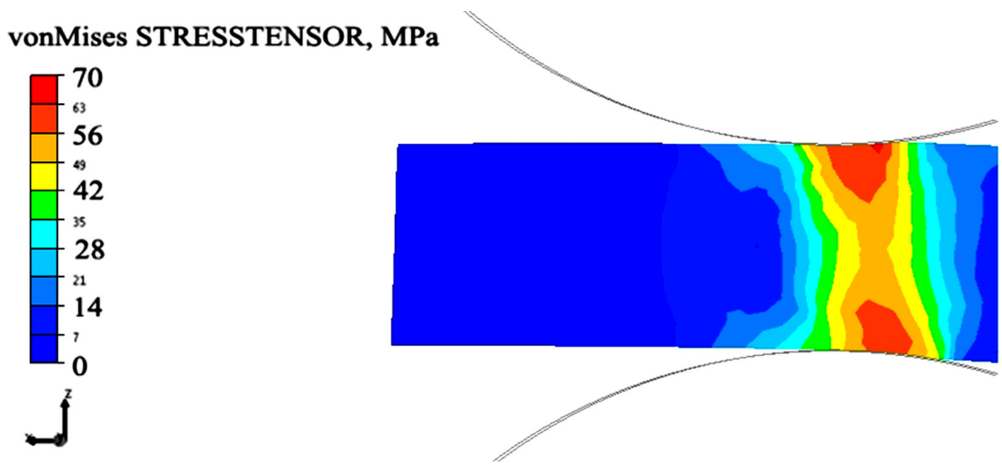

Fig. 11. Distribution of stress intensities σ_i for feedstock of an initial height of $h_0 = 200$ mm, rolled with a reduction of $\varepsilon = 0.05$ using an asymmetry factor of $a_v = 1.02$, and at a deformation zone feedstock feed angle of $\theta = 3^{\circ}$.

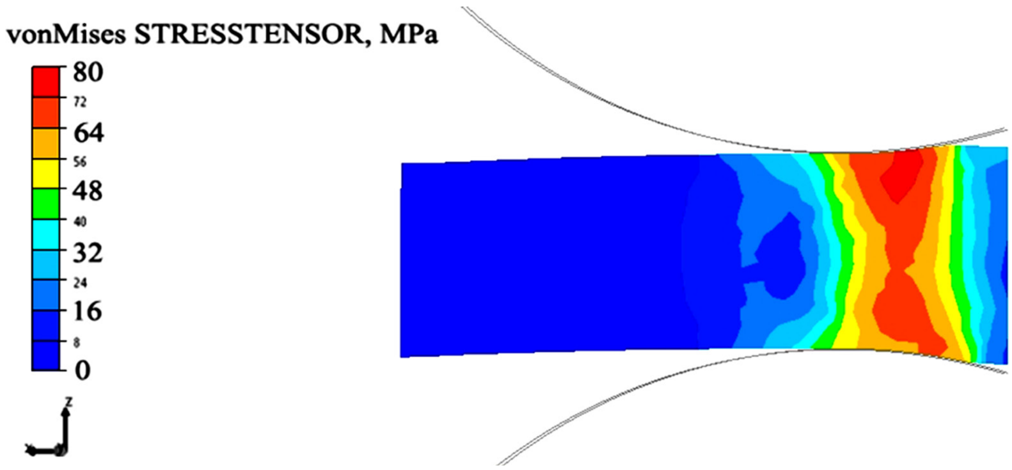

Fig. 12. Distribution of stress intensities σ_i for feedstock of an initial height of h_0 = 200 mm, rolled with a reduction of ε = 0.10 using an asymmetry factor of a_v = 1.00, and at a deformation zone feedstock feed angle of θ = 3˚.

3˚, an uniform distribution of stress σ_i occurred. Thanks to this, a straight band front end was obtained.

Introducing feedstock to the deformation zone at an angle due to the non-coincidence of the neutral axes of the feedstock and the deformation zone produces a non-uniform stress distribution in the deformation zone, relative to the neutral axis of the band being rolled. Larger stress magnitudes exist in metal layers contacting the upper roll, which causes the band front end to bend towards the lower roll (Fig. 12).

CONCLUSIONS

Based on the theoretical study of the asymmetric process of rolling S355J2+N steel plates (with a band shape factor of h_0/D = 0.1887 and 0.0660), the following can be stated:

● when rolling plates under industrial conditions in the rouging and finishing stands of the Plate Rolling Mill, in the majority of cases, the neutral axis of the feedstock or band does not coincide with the neutral axis of the roll gap, and the shorter the band, the larger the angle at which the band is fed to the deformation zone, as a consequence of which the front end of the band bends towards the lower roll;

● in the symmetric process (for a constant bad shape factor, h_0/D), increasing the roll band feed angle in the range of 0^0 - 3^0 increases the curvature of bending of the band on exit from the deformation zone towards the lower roll; therefore, in order to obtain a straight band or a band with only a slight curvature oriented to the upper roll, an asymmetric process should be employed by differentiating the rotational speed of the working rolls;

● for S355J2+N steel feedstock with a band shape factor of h_0/D = 0.1887, being fed to the deformation zone at an angle of θ = 1 - 3º, rolled with a relative reduction in the range of ε = 0.05 - 0.20, in order to eliminate the band front-end bending toward the lower roll, a roll rotational speed asymmetry factor of a_v = 1.01 - 1.05 should be used; whereas, the magnitude of the applied asymmetry factor a_v increases with increasing roll gap feedstock feed angle, while decreases with the increase in the applied relative reduction;

● for S355J2+N steel feedstock with a band shape factor of h_0/D = 0.0660, in order to obtain a straight band, a slight asymmetry of working roll rotational speeds, a_v = 1.01 and a_v = 1.02, should be employed, with a relative deformation of ε = 0,10, and a_v = 1.01 with a relative deformation of ε = 0.15. For greater relative deformation values, ε > 0.15, the band should be rolled symmetrically.

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