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ANALYSIS OF THE INFLUENCE OF KINEMATIC AND FRICTION ASYMMETRY ON THE CURVATURE OF THE STRIP AND FORCE PARAMETERS OF THE ROLLING PROCESS

ANALIZA WPŁYWU ASYMETRII KINEMATYCZNEJ ORAZ ASYMETRII TARCIA NA KRZYWIZNĘ PASMA I PARAMETRY SIŁOWE PROCESU WALCOWANIA

Key words: asymmetric rolling, frictional asymmetry, kinematic asymmetry, strip curvature, roll force, FEM studies.

Abstract: This paper presents the numerical analysis results in Simufact Forming 2016 of the asymmetric cold rolling process of S235JR steel. The research determined the effect of kinematic asymmetry, frictional asymmetry and their combination on the strip curvature, as well as the force parameters of the rolling process. During the conducted research, the aim was to determine the parameters of the asymmetric rolling process, allowing the highest possible reduction of forces (in relation to symmetric rolling) while maintaining the curvature of the strip with an acceptable value $|\delta|\leq1.5$. For this purpose, "process maps" were developed based on the obtained results, allowing for selecting the most favourable process parameters for the different rolling reductions. In addition, the results made it possible to determine the effect of the various asymmetries obtained on the process forces and strip curvature depending on the size of the rolling reduction.

Słowa kluczowe: walcowanie asymetryczne, asymetria tarcia, asymetria kinematyczna, krzywizna pasma, siła nacisku walców, badania MES.

Streszczenie: W artykule przedstawiono wyniki analizy numerycznej w programie Simufact Forming 2016 procesu walcowania asymetrycznego na zimno stali S235JR. W ramach prac określono wpływ asymetrii kinematycznej, asymetrii tarcia oraz ich połączenia na krzywiznę pasma, a także parametry siłowe procesu walcowania. Podczas przeprowadzonych badań dążono do określenia parametrów procesu walcowania asymetrycznego, pozwalających na możliwie wysoką redukcję sił (w odniesieniu do walcowania symetrycznego) przy jednoczesnym zachowaniu krzywizny pasma na dopuszczalnym poziomie W tym celu opracowano na podstawie analizy uzyskanych wyników „mapy procesowe", umożliwiające dla różnych gniotów dobór najkorzystniejszych parametrów procesu. Dodatkowo uzyskane wyniki badań pozwoliły na określenie wpływu poszczególnych asymetrii na siły procesu oraz krzywizny pasma w zależności od wielkości wprowadzonych odkształceń.

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INTRODUCTION

In the classical rolling process, despite the theoretical assumptions about its symmetry, uncontrolled and difficult-to-determine asymmetries occur, affecting the process itself and the final product to a greater or lesser extent. In some cases, they can contribute to defects in the geometry of manufactured products occurring, for example, in falciform or wavy forms **[L. 1–4]**. One method of levelling these unfavourable phenomena is to introduce intentional and controlled asymmetry into the rolling process. This technology is called asymmetric rolling and is achieved by, among other things: variation in roll speeds (kinematic asymmetry), different diameters of working rolls (geometric asymmetry), variation in friction conditions between rolls and the material (friction coefficient asymmetry), changing the feed angle of the feedstock, and by uneven heating of the feedstock **[L. 1, 5–11]**. Introducing the asymmetries mentioned above into the rolling process causes the neutral points. These are theoretical points at which the speed of the shaped material on both sides of it takes on the speed of the working rolls to shift relative to each other (**Fig. 1**). As a result of this displacement, additional shear stresses are created. This results in a complex deformation state in the shaped material, consisting of a state of the plane strain and simple shear in the rolling direction **[L. 5, 6, 10–13]**.

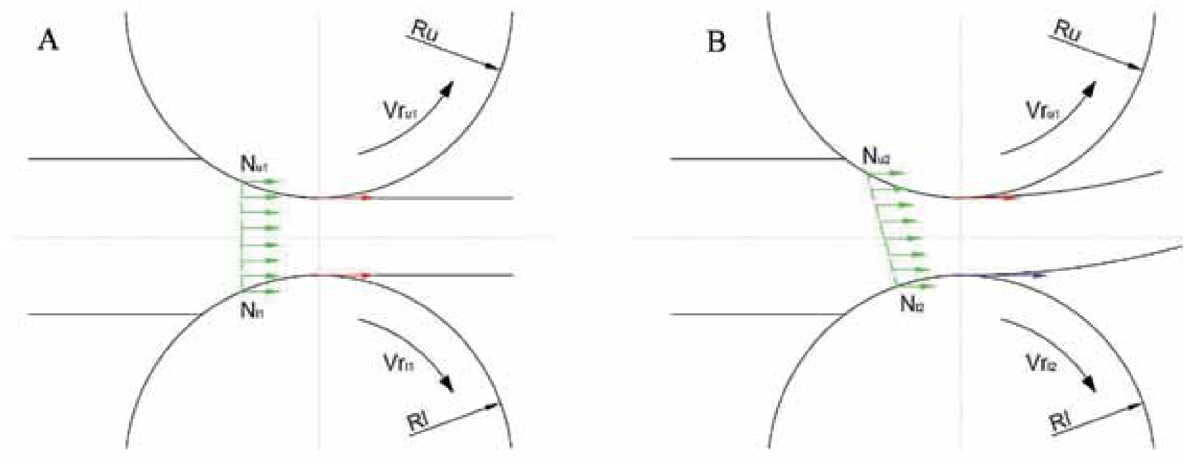

Fig. 1. Change in the position of neutral points in the asymmetric rolling process. A – symmetric rolling process $Vr_{u1} = Vr_{l1}$, B – rolling process with kinematic asymmetry $Vr_{u2}<Vr_{l2}$. Vr_u – rotational speed of the upper roll, Vrl – rotational speed of the lower roll

Rys. 1. Zmiana w położeniu punktów neutralnych w procesie walcowania asymetrycznego. A – symetryczny proces walcowania $Vr_{u1} = Vr_{l1}$, B – proces walcowania z asymetrią kinematyczną $Vr_{u2}<Vr_{l2}$. Vr_u – prędkość obrotowa walca górnego, Vr_l – prędkość obrotowa walca dolnego

This phenomenon is considered a great advantage of the process and contributes, among other things, to lowering the force-energy parameters (forces and moments) of the rolling process, which in turn results in:

- reducing the elastic deflection of the rolling stand,
- increasing the durability of the rolling mill components,
- increasing the rolling reduction in a single rolling pass **[L. 1, 5, 8, 14, 15]**.

In addition, this technology contributes to favourable changes in the material's microstructure. When higher asymmetry values are used, greater grain fineness occurs, contributing to higher tensile strength, yield strength, and hardness **[L. 5, 11, 13, 16, 17]**. However, this technology has the disadvantage of strip bending **[L. 1, 7, 18]**. Excessive curvature of the strip can significantly hinder or even make it impossible to continue the rolling process **[L. 1]**. Therefore, it is extremely important to keep the magnitude of this parameter at an acceptable level. The curvature of the strip is expressed as the reciprocal of the radius of the strip after exiting the deformation gap $\delta = 1/R$ [1/m] **[L. 2, 3]**, and its acceptable value takes $|\delta| \leq 1.5$ **[L. 19]**.

Depending on the manner and magnitude of the asymmetry introduced, the strip curves in a certain direction after exiting the deformation

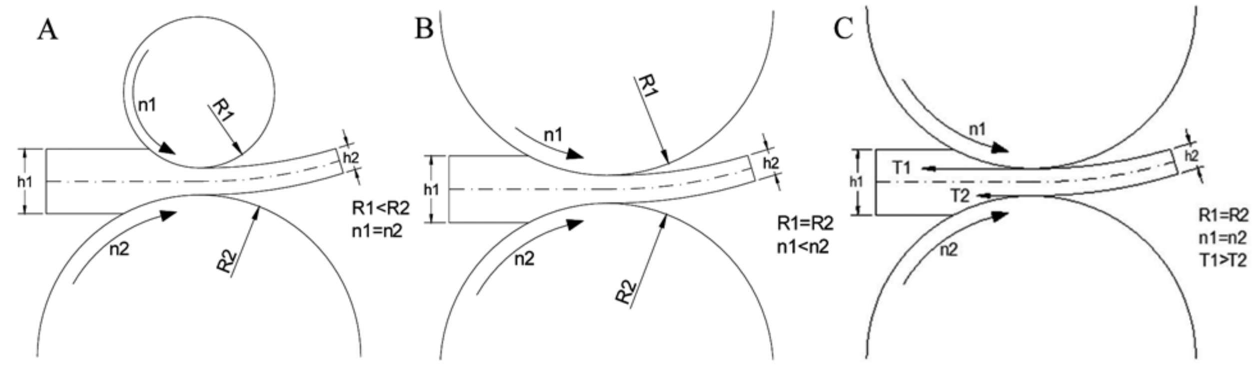

Fig. 2. Example of the theoretical direction of stirp curvature depending on the type of asymmetry. A – geometric asymmetry, B – kinematic asymmetry, C – frictional asymmetry

Rys. 2. Przykład teoretycznego kierunku krzywienia się pasma w zależności o typu asymetrii. A – asymetria geometryczna, B – asymetria kinematyczna, C – asymetria tarcia

gap. In theory, in the case of geometric asymmetry, the strip bends toward the smaller-diameter roll; for kinematic asymmetry, the strip bends toward the slower roll, while in the case of frictional asymmetry, the strip bends toward the roll with a higher coefficient of friction **[L. 5, 20, 21]**. In fact, the issue is much more complex and, depending on the magnitude and type of asymmetry, the material grade, the initial thickness of the charge, and the value of rolling reduction, can result in different results **[L. 7, 12, 14, 18, 22]**.

The article **[L. 18]** presents the case of rolling low-carbon steel with geometric asymmetry $a_V = \frac{R_u}{R_l}$ (R_u – radius of the upper roll, R_l – radius of the lower roll) for a relative rolling reduction of ε = 0.07. By analysing the results presented in the article, it can be seen that for strips of smaller thickness. ($1.94 \leq H_1 \leq 3.13$), the strip curves towards the smaller diameter roll. However, the magnitude of the strip curvature decreases as the thickness of the charge increases, and for values of $H_1 = 3.22$ and $H_1 = 3.33$, it is close to zero. Above these values ($3.53 \leq H_1 \leq 7.5$) the strip curved toward the larger diameter roll. When the relative rolling reduction was increased from ε = 0.07 to ε = 0.10, the strip, regardless of the input thickness of the material, always bent toward the roll of larger diameter. A similar trend was also observed in the article **[L. 12]**. In this case, the effect of strain magnitude and velocity asymmetry on the curvature of a strip made of AA7050 aluminium alloy with an initial thickness of 20 mm was studied. The study was conducted for values of relative rolling deformation in the range of ε = 0.10–0.50, a constant speed of the upper roll of $3\frac{m}{min}$ and a variable speed of the lower roll in the range of $3-4.8\frac{m}{min}$. Analysis of the results showed that at a low value of rolling reduction, the strip curves toward the slower roll, while a higher value of rolling reduction results in the opposite phenomenon. In addition, it was observed that the amount of strain needed to change the direction of the strip curvature increases as the difference in roll speeds increases. Based on this, it can be seen that the magnitude and direction of the curvature of the strip depend on many factors simultaneously. For this reason, it is extremely difficult to accurately estimate the behaviour of the strip for any rolling case. For this purpose, it is necessary to carry out a series of theoretical studies to determine for a given case such values of asymmetry coefficients, at which it will be possible to obtain a straight strip or a strip with acceptable curvature. In addition to the use of a single asymmetry, cases of applying two types of asymmetry simultaneously into the rolling process are also studied. Such a practice allows for better control over the process and obtaining a straight strip while decreasing forces, which is sometimes problematic when using only one asymmetry. The results presented in the article **[L. 1]** show the effect of kinematic and geometric asymmetry applied together and separately. Kinematic asymmetry ($a_V = V_l/V_u$, V_l – speed of the lower roll, V_u – speed of the upper roll) was introduced in the range of 1.05÷1.20 by decreasing the speed of the upper roller while keeping the speed of the lower roll constant at V_l = 80 rpm. In the case of geometric asymmetry ($a_D = D_l/D_u$, D_l – diameter of the lower roll, D_u – diameter of the upper roll), the diameter of the lower roll was reduced in the range of 1.05÷1.20 while keeping the diameter of the upper roll constant at ∅ 970 mm. The study showed that when only one type of asymmetry was used, a decrease in forces was obtained, but at the expense of bending the strip's start. On the other hand, introducing a second asymmetry into the process decreased the forces (up to 30%) while maintaining the acceptable curvature of the strip. The present study analysed the effects of two asymmetries (kinematic and friction coefficient) used together and separately on the strip curvature and the values of the forces on the rolls. The study aimed to determine the parameters of asymmetric rolling, allowing to obtain of a straight strip with the highest possible decrease in the force of the rollers on the material.

RESEARCH METHOD

The research was conducted using numerical analysis in the Simufact Forming 2016 program. The simulation model was created based on the WD-2 laboratory rolling mill on the Łukasiewicz Research Network – Poznan Institute of Technology equipment. The input material was S235 steel strips with 2 x 50 x 100 mm dimensions. The model consisted of two rolls with a diameter of ∅ = 187 mm and a guide 40 mm away from the centre of the rolls and positioned in such a way that the centre of the charge coincided with the neutral axis of the rolling gap. In addition, a pusher was introduced into the model to insert the strip between the rolls.

The tests were carried out for three sizes of relative rolling reductions: ε_1 = 0.15, ε_2 = 0.25, ε_3 = 0.40. Kinematic asymmetry was applied by changing the linear velocity of the upper roll relative

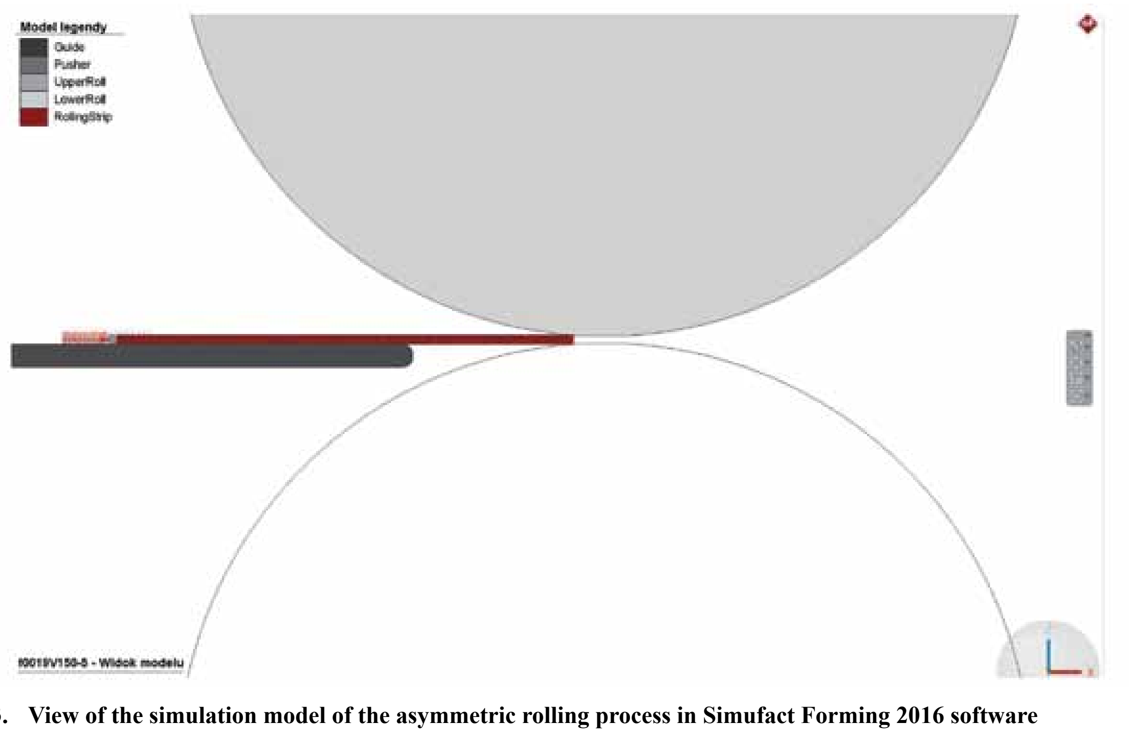

Fig. 3. View of the simulation model of the asymmetric rolling process in Simufact Forming 2016 software
Rys. 3. Widok modelu symulacyjnego procesu walcowania asymetrycznego w programie Simufact Forming 2016

to the lower roll. The value of the asymmetry coefficient was expressed as the quotient of the linear velocity of the upper roll to the linear velocity of the lower roll ($a_V = V_u/V_l$, V_u – the velocity of the upper roll, V_l – the velocity of the lower roll) and took the range from a_V = 0.67 ÷ 1.50. That is, for the asymmetry range of $0.67 \leq a_v < 1.00$ the velocity of the upper roll was decreased, while in the range of $1.00 > a_v \geq 1.50$ it was increased. On the other hand, the lower roll's linear velocity was constant at 100 mm/s. In the case of asymmetry of the coefficient of friction, the coefficient of friction of the lower roll was changed while keeping the value for the upper roll constant at μ_u = 0.113. The magnitude of the coefficient of friction on the lower roll corresponded to the values that this parameter takes for different lubricants used in the cold rolling process:

- 0.019 – palm oil,
- 0.045 – spindle oil,
- 0.052 – petroleum oil-based emulsifying oil,
- 0.113 – dry rolling **[L. 23]**.

The value of the coefficient of friction asymmetry was expressed as the ratio of the coefficient of friction of the upper roll to that on the lower roll and was in the range a_μ = 1.0÷7.5. This meant that as the value of asymmetry increased, the value of the coefficient of friction of the lower roll decreased. The exact values of the process parameters are shown in **Table 1**.

The study was conducted over a wide range of asymmetries to determine the areas with the most favourable parameters of the rolling process based on the results obtained.

Table 1. Process table. V_u – speed of the upper roll, μ_l – value of the friction coefficient on the lower roll
Tabela 1. Tabela procesowa. V_u – prędkość walca górnego, μ_l – wartość współczynnika tarcia na walcu dolnym

Process table			**Velocity asymmetry V_l = const.**				
		V_u [mm/s]	67	80	100	125	150
Friction coefficient asymmetry μ_u = const.	μ_l	**Asymmetry ratio**	**0.67**	**0.80**	**1.00**	**1.25**	**1.50**
	0.113	**1.0**					
	0.052	**2.2**					
	0.045	**2.5**					
	0.019	**5.9**					
	0.015	**7.5**					

– Symmetric process
– Friction coefficient asymmetry
– Velocity asymmetry
– Mixed asymmetry

RESULTS

The analysis of the obtained results focused on measuring the curvature of the strips and the forces of the rolls on the material. For this purpose, the tools available in Simufact Forming 2016 were used. The curvature value was calculated from the measured radii of the strips after rolling (**Fig. 4**). The load acting on the material, on the other hand, was determined from the average value of the force acting on the rolls. It was measured during the actual rolling process (the values of forces during their rise and fall were omitted, **Fig. 5**).

Based on the obtained curvatures and forces, “process maps” were created for each value of

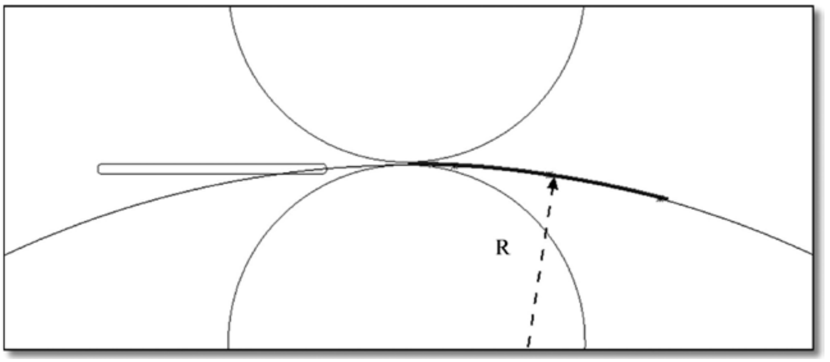

Fig. 4. Measurement of strip radius
Rys. 4. Pomiar promienia pasma

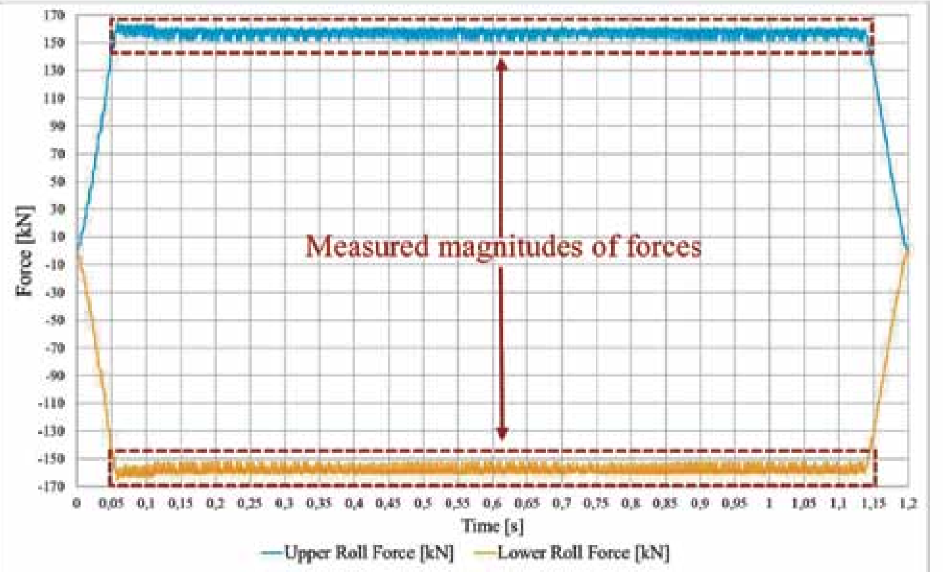

Fig. 5. Plot of forces on rollers during the rolling process without asymmetry for rolling reduction ε_1 = 0.15
Rys. 5. Wykres sił na walcach w trakcie procesu walcowania bez asymetrii dla gniotu ε_1 = 0,15

the rolling reductions (**Figures 6–8**). These charts show the relationship between the magnitudes of the applied asymmetry coefficients, the obtained strips curvatures, and the forces on rolls.

The process maps were developed to estimate the values of asymmetry coefficients for which it will be possible to obtain the largest force reduction while maintaining a straight strip. On the charts on the “x” axis are placed the values of the kinematic asymmetry coefficient ($a_V = V_u/V_l$) in the range of $a_V = 0.67 \div 1.50$. The frictional asymmetry ($a_\mu = \mu_l/\mu_u$) is marked on the charts with different colours in the range of values of the asymmetry coefficient a_μ = 1.0÷7.5. The values of the obtained forces are placed on the left side on the “y” axis, which is referred to by points marked with “dots” and connected by continuous lines. On the right side, however, on the „y” axis are placed the values of the obtained curvatures, to which the points marked with „squares” refer and connected by dashed lines. The grey area indicates the range in which the values of the strip curvature take acceptable values of $-1.5 \leq \delta \leq 1.5$. The dashed grey line, on the other hand, indicates the value of the force during rolling without any asymmetry. The areas marked in yellow are called „process windows” and represent ranges of values of asymmetry coefficients for which the relationships between force gradients and curvature magnitudes are most favourable. Based on the analysis of process maps, decreases in forces were observed for asymmetric processes (with single asymmetry and mixed asymmetry) relative

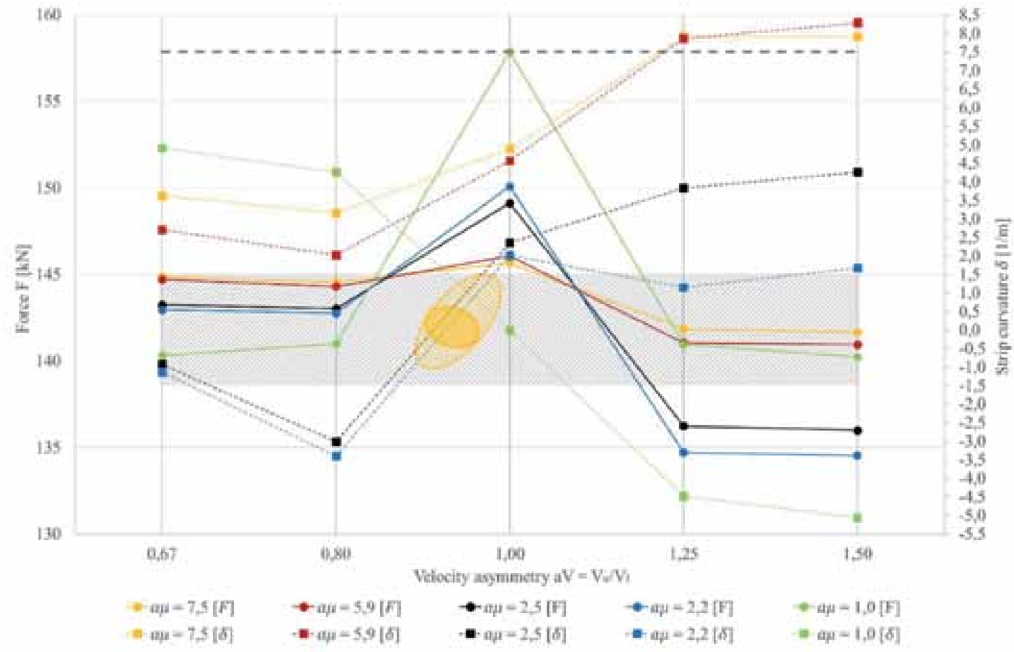

Fig. 6. Process map for rolling reduction ε_1 = 0.15. Points marked with dots refer to force values. Points marked with squares refer to curvature values. The gray dashed line indicates the force value obtained for the process without asymmetry. The gray hatched box marks the area where the strip curvature takes acceptable values of -1.5≤δ≤1.5

Rys. 6. Mapa procesowa dla gniotu ε_1 = 0,15. Punkty zaznaczone kropkami odnoszą się do wartości sił. Punkty zaznaczone kwadratami odnoszą się do wartości krzywizn. Szarą przerywaną linią zaznaczono wartość siły uzyskaną dla procesu bez asymetrii. Szarym zakreskowanym polem zaznaczono obszar, w którym krzywizna pasma przyjmuje dopuszczalne wartości -1,5≤δ≤1,5

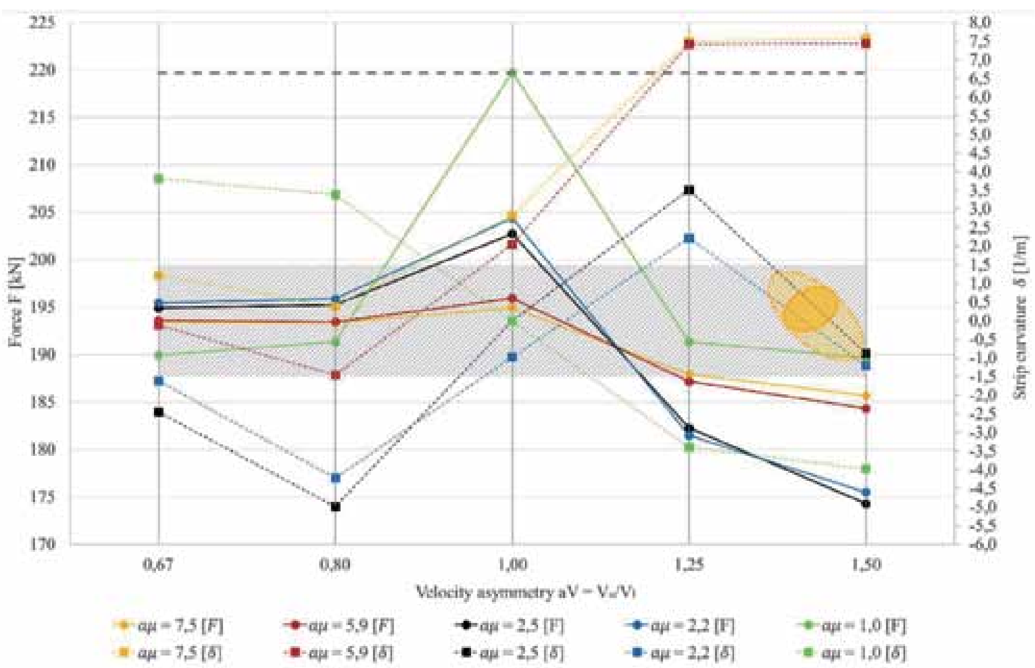

Fig. 7. Process map for rolling reduction ε_2 = 0.25. Points marked with dots refer to force values. Points marked with squares refer to curvature values. The gray dashed line indicates the force value obtained for the process without asymmetry. The gray hatched box marks the area where the strip curvature takes acceptable values of -1.5≤δ≤1.5

Rys. 7. Mapa procesowa dla gniotu ε_2 = 0,25. Punkty zaznaczone kropkami odnoszą się do wartości sił. Punkty zaznaczone kwadratami odnoszą się do wartości krzywizn. Szarą przerywaną linią zaznaczono wartość siły uzyskaną dla procesu bez asymetrii. Szarym zakreskowanym polem zaznaczono obszar, w którym krzywizna pasma przyjmuje dopuszczalne wartości -1,5≤δ≤1,5

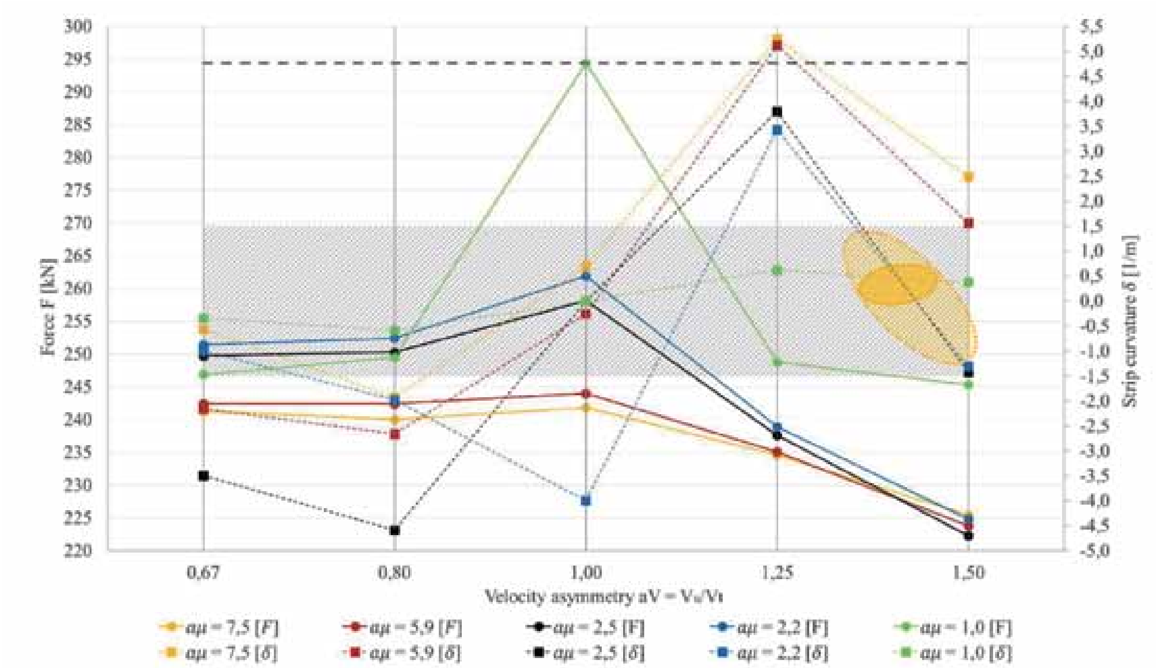

Fig. 8. Process map for rolling reduction ε_3 = 0.40. Points marked with dots refer to force values. Points marked with squares refer to curvature values. The gray dashed line indicates the force value obtained for the process without asymmetry. The gray hatched box marks the area where the strip curvature takes acceptable values of $-1.5 \leq \delta \leq 1.5$

Rys. 8. Mapa procesowa dla gniotu ε_3 = 0,40. Punkty zaznaczone kropkami odnoszą się do wartości sił. Punkty zaznaczone kwadratami odnoszą się do wartości krzywizn. Szarą przerywaną linią zaznaczono wartość siły uzyskaną dla procesu bez asymetrii. Szarym zakreskowanym polem zaznaczono obszar, w którym krzywizna pasma przyjmuje dopuszczalne wartości $-1,5 \leq \delta \leq 1,5$

to symmetric rolling for all tested values of rolling reductions. In each case, the decreases in force values due to single asymmetry (either kinematic asymmetry or frictional asymmetry) were greater the higher the values of the asymmetry coefficients. For the rolling reductions ε_1 = 0.15 and ε_2 = 0.25, using only a single process asymmetry, the force reductions were always greater for kinematic asymmetry. Only for the largest rolling reduction, ε_3 = 0.40, greater force drops, relative to all kinematic asymmetries tested, were obtained for frictional asymmetries of a_μ = 5.9 and 7.5.

For the rolling process with mixed asymmetries, the values of the drops in these forces were more complex and depended on the amount of deformation applied. In the case of the smallest rolling reduction ε_1 = 0.15 for the kinematic asymmetry obtained by slowing down the upper roll (a_V = 0.67 and 0.80), the largest force reductions were obtained for a single kinematic asymmetry. When mixed asymmetry was applied regardless of the magnitude of the friction asymmetry factor, the reductions in these forces were smaller. However, as can be observed in **Figure 6**, in the case of mixed asymmetry, the values of curvatures are closer to the acceptable range, and for the values of frictional asymmetry coefficients a_μ = 2.2 and 2.5 take acceptable values. Using higher frictional asymmetry coefficients of a_μ = 5.9 and 7.5, with kinematic asymmetry a_V = 0.67 and 0.80, results in curvature of the strip in the direction of the upper roll. Lower values of frictional asymmetry a_μ = 2.2 and 2.5 cause the strip to curve toward the lower roll. In the case of mixed asymmetry, in the range of higher upper roll velocities (a_V = 1.25 and 1.50), the highest force drops were obtained for values of frictional asymmetry a_μ = 2.2 and a_μ = 2.5. The use of mixed asymmetry (in the range of a_V = 1.25 and 1.50) at higher values of frictional asymmetry (a_μ = 5.9 and a_μ = 7.5) resulted in smaller force drops compared to single, kinematic asymmetry and at the same time, larger values of strip curvature. On the other hand, at values of frictional asymmetry a_μ = 2.2 and 2.5 (in the range of a_V = 1.25 and 1.50), smaller curvatures were obtained than those obtained with single kinematic asymmetry. In the case of mixed asymmetry for all values of frictional asymmetry (with a_V = 1.25 and 1.50), the strip curved toward the upper roll, while in the case of single kinematic asymmetry, the strip curved toward the lower roll. In the mixed asymmetry range, where the upper roll was accelerated (a_V = 1.25 and 1.50), a straight strip was obtained for a_V = 1.25 and a_μ = 2.2.

In the case of the ε_2 = 0.25 rolling reduction (**Fig. 7**) for mixed asymmetry, with kinematic asymmetry a_V = 0.67 and 0.80, just as in the case of the ε_1 = 0.15 rolling reduction, larger force drops occurred for single kinematic asymmetry. However, strip curvature with acceptable values was obtained when mixed asymmetry was used for aμ = 5.9 and 7.5. For mixed asymmetry, greater force reductions occurred for values of kinematic asymmetry a_V = 1.25 and 1.50 compared to single asymmetry. The largest reduction occurred for values of a_μ = 2.2 and 2.5. Acceptable curvature values, however, were obtained for mixed asymmetry with values of a_V = 1.50 and a_μ = 2.2 and 2.5.

In the case of rolling reduction ε_3 = 0.40 (**Fig. 8**), with mixed asymmetry in terms of slowing down the upper roll (a_V = 0.67 and 0.80), the largest decreases in forces occurred for a_μ = 5.9 and 7.5. In contrast, the curvature values were larger in relation to single kinematic asymmetry. Acceptable values of strip curvature were obtained for mixed asymmetry with a_V = 0.67 and a_μ = 2.2 and 7.5. In the case of mixed asymmetry in terms of increasing the speed of the upper roll (a_V = 1.25 and 1.50), larger force drops were obtained compared to the case with single asymmetries. In contrast, curvature values were higher with mixed asymmetry than single kinematic asymmetry and friction asymmetry of a_μ = 5.9 and 7.5. In the case of mixed asymmetry, acceptable curvature values were obtained for asymmetry values of a_V = 1.50 and aμ = 2.2 and 2.5. Based on the „process windows" for each value of rolling reduction, such parameters were selected at which the value of strip curvature would be most close to $\delta \approx 0$, with the greatest possible decrease in the forces on the rollers and high process speeds. The tests were conducted in such a way that only the values of kinematic asymmetry were modified, while the values of frictional asymmetry were not changed. Tests were conducted for all three rolling reductions for values of a_μ = 2.2 and a_μ = 2.5. In the case of ε_1 = 0.15, the range of values of asymmetry a_V = 0.80 ÷ 1.00 was studied, while for ε_2 = 0.25 and ε_3 = 0.40 the range of values of asymmetry a_V = 1.25÷1.50. The results of the tests for which the most favourable results were obtained are shown in **Table 2** and **Figures 9–11**.

Table 2. Results obtained by selecting the most favorable values of asymmetry coefficients
Tabela 2. Wyniki uzyskane wskutek doboru najkorzystniejszych wartości współczynników asymetrii

ε	a_V	$a\mu$	δ [1/m]	F [kN]	Force reduction [%]	Strip velocity without rolling asymmetry	Strip velocity with rolling asymmetry	Velocity different [%]
0.15	0.99	2.5	-0.10	148.4	6	102.99	101.91	-1
0.25	1.31		-0.11	175.8	20	103.28	130.58	26
0.40	1.35		-0.03	227.1	23	105.35	136.22	29

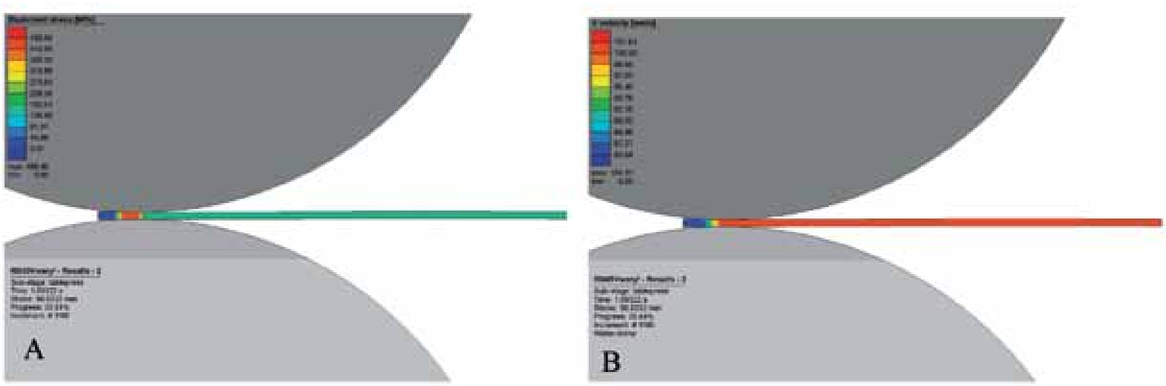

Fig. 9. Simulation results for ε_1 = 0.15, aV = 0.99, α_μ = 2.5. A – stress results, B – strip velocity results
Rys. 9. Wyniki symulacji dla ε_1 = 0,15, a_V = 0,99, α_μ = 2,5. A – wyniki naprężeń, B – wyniki prędkości pasma

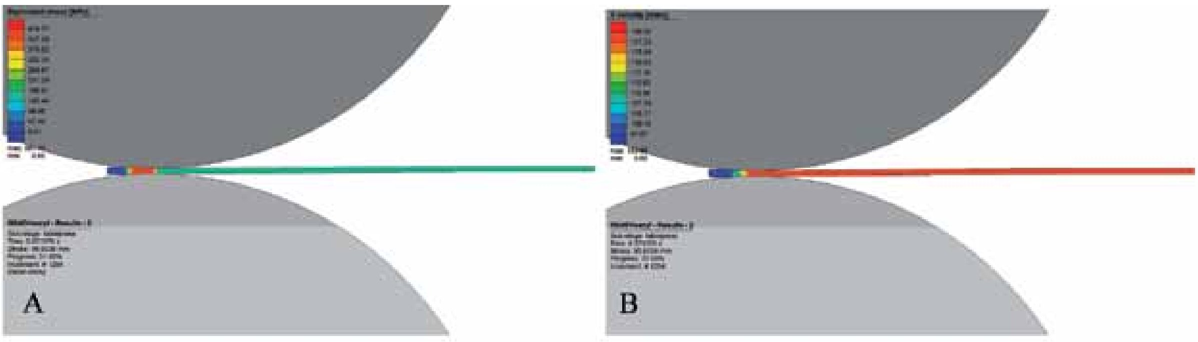

Fig. 10. Simulation results for ε_2 = 0.25, aV = 1.31, α_μ = 2.5. A – stress results, B – strip velocity results
Rys. 10. Wyniki symulacji dla ε_2 = 0,25, a_V = 1,31, α_μ = 2,5. A – wyniki naprężeń, B – wyniki prędkości pasma

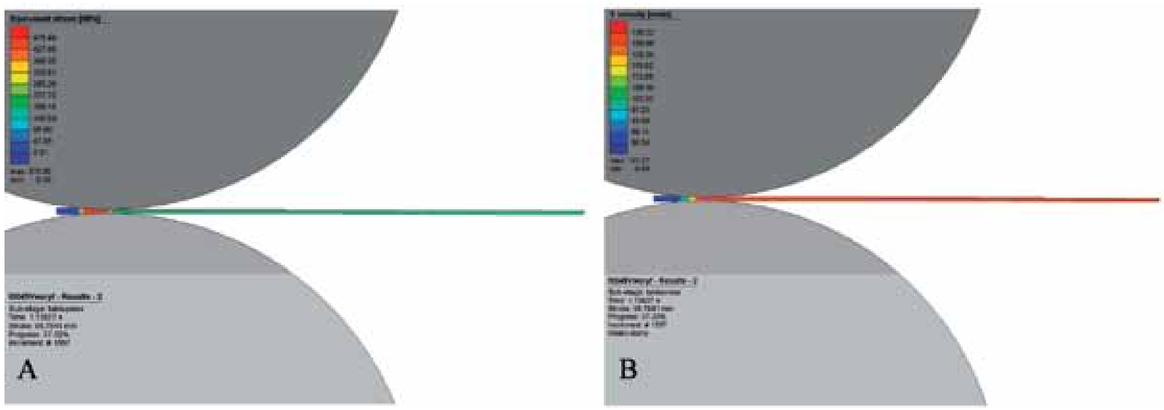

Fig. 11. Simulation results for ε_3 = 0.40, aV = 1.35, α_μ = 2.5. A – stress results, B – strip velocity results
Rys. 11. Wyniki symulacji dla ε_3 = 0.40, a_V = 1,35, α_μ = 2,5. A – wyniki naprężeń, B – wyniki prędkości pasma

By analysing the results in **Table 2**, it can be seen that due to the selection of parameters based on the previously developed process maps, it was possible to achieve a very low level of strip curvatures. The largest value was obtained for ε_2 = 0.25 and was δ = -0.11. In addition, a reduction in the forces was obtained, with the largest rolling reductions occurring for ε_2 = 0.25 and ε_3 = 0.40 and amounting to 20 and 23%, respectively, with additional increases in the rolled strip speed of 26 and 29%. In the case of ε_1 = 0.15, the force reduction value was 6%, with a decrease in speed of 1%. This was due to the fact that the straight strip in this case occurred in the range of lower velocities and reductions in roll forces (**Fig. 6**, a_V range from 1.25 to 1.50). An analysis of the effect of the size of the rolling reduction, on the values and directions of the curvature of the strips, depending on the type and size of the single asymmetry introduced, was carried out. The results of these tests are shown in **Figure 12** for kinematic asymmetry and **Figure 13** for frictional asymmetry.

Based on an analysis of the results for kinematic asymmetry (**Fig. 12**), it was observed that for relatively low relative rolling reductions (ε_1 i ε_2), the strip always curves toward the roll with the lower velocity. The magnitude of this curvature increases with increasing velocity difference between the rolls, while it decreases with increasing rolling reduction. For a larger rolling reduction ε_3 = 0.40, the relationship is reversed and the strip curves in the direction of the roll with the higher velocity. The magnitude of this curvature is greatest at a_V = 0.80 and 1.25 and decreases as the difference between the velocities of the rolls increases, i.e. for a_V = 0.67 and 1.50.

In the case of frictional asymmetry (**Fig. 13**) for the smallest rolling reduction (ε_1), the strip always curved toward the roll with a higher coefficient of friction. The magnitude of this curvature increased as the friction coefficient on the lower roll decreased. For the rolling reduction (ε_2), at the smallest value of friction asymmetry (a_μ = 2.2), the strip curved toward the lower roll, while as this asymmetry increased, the strip curved more and more toward the upper roll. For the highest rolling reduction (ε_3 = 0.40), for smaller values of frictional asymmetry a_μ = 2.2 and 2.5,

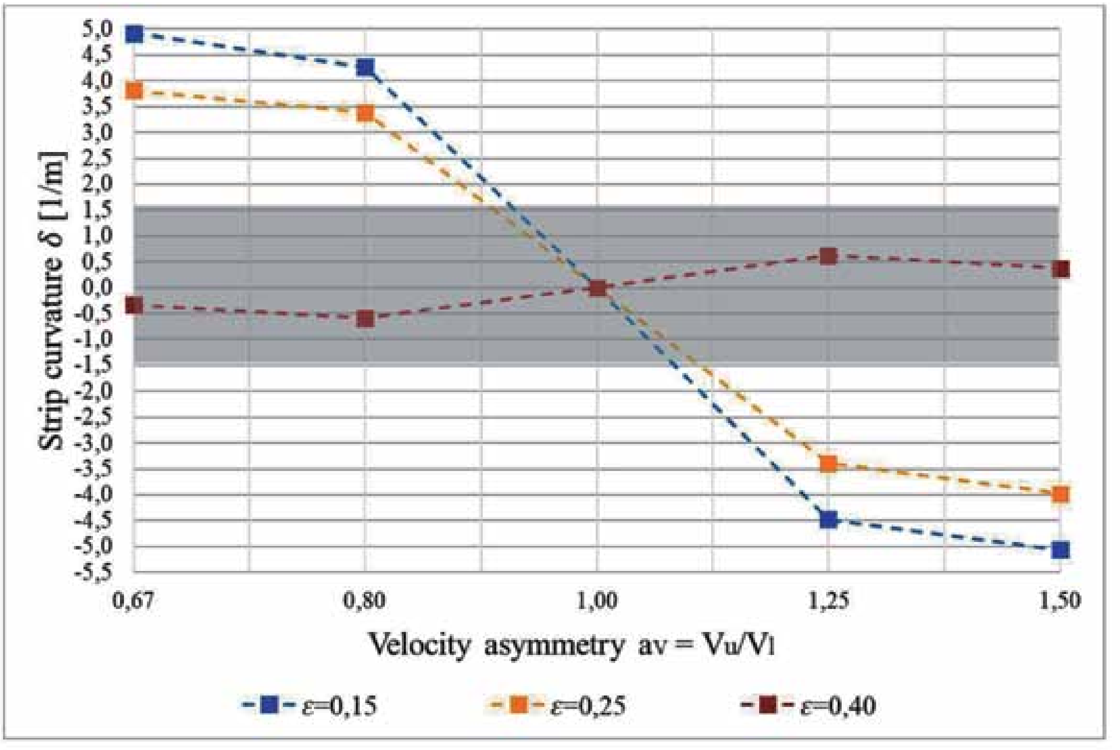

Fig. 12. Effect of kinematic asymmetry as a function of rolling reduction size on strip curvature. The area in grey indicates the range in which the strip assumes acceptable values of -1.5≤δ≤1.5

Rys. 12. Wpływ asymetrii kinematycznej w zależności od wielkości gniotu na krzywiznę pasma. Obszarem na szaro zaznaczono zakres, w którym pasmo przyjmuje dopuszczalne wartości -1,5≤δ≤1,5

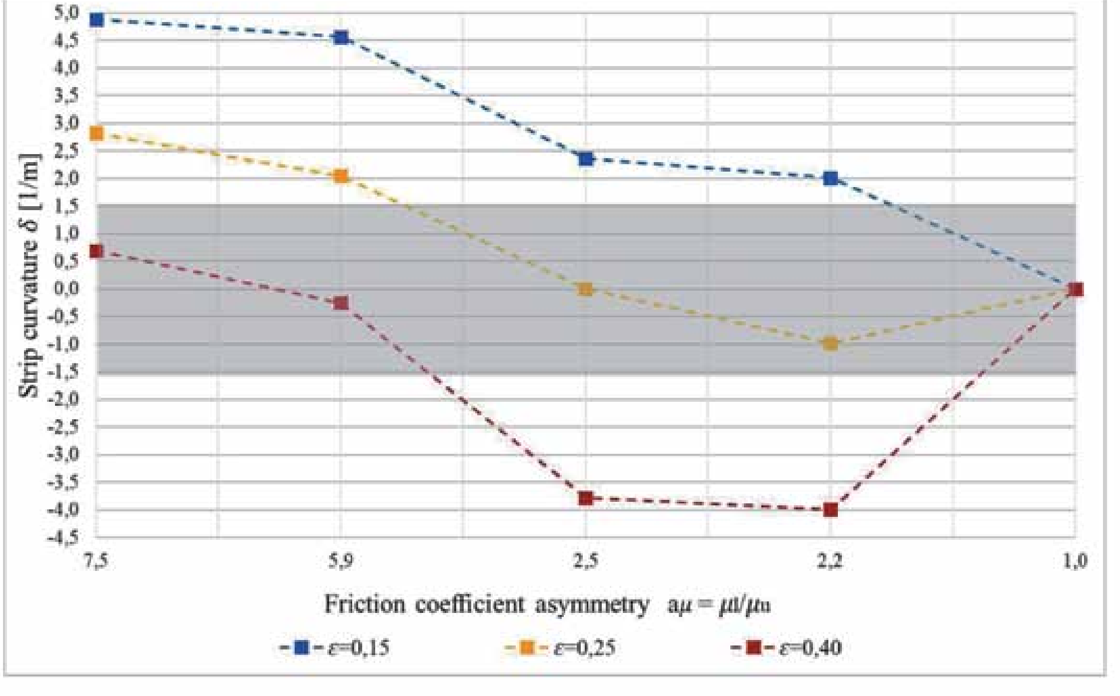

Fig. 13. Effect of frictional asymmetry as a function of rolling reduction size on strip curvature. The area in grey indicates the range in which the strip assumes acceptable values of -1.5≤δ≤1.5

Rys. 13. Wpływ asymetrii tarcia w zależności od wielkości gniotu na krzywiznę pasma. Obszarem na szaro zaznaczono zakres, w którym pasmo przyjmuje dopuszczalne wartości -1,5≤δ≤1,5 the strip curved toward the roll with the smaller frictional coefficient value (the lower roll), while at values of frictional asymmetry a_μ = 5.9 and 7.5, the strip curved toward the upper roll.

The values of curvature obtained during the simulation tests were related to the preliminary laboratory results carried out on the WD-2 rolling mill. These tests were carried out for specimens with initial dimensions the same as those of the FEM tests but for DC04 steel, relative rolling reductions in the range ε = 0.05–0.25 and kinematic asymmetry in the range a_V = 1.00–1.50. The results obtained are shown in **Figure 14**.

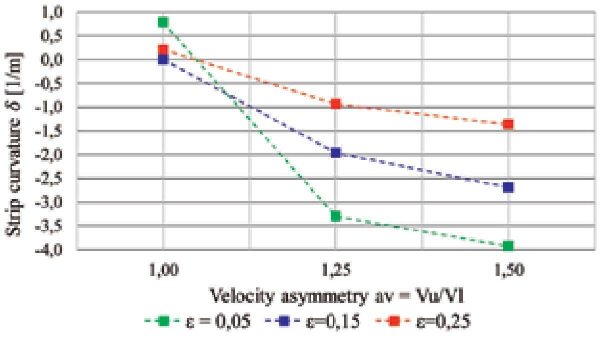

Fig. 14. Results of laboratory tests on the WD-2 rolling mill for DC04 steel

Rys. 14. Wyniki badań laboratoryjnych na walcarce WD-2 dla stali DC04

Due to the different grades of materials and other ranges of deformation and asymmetry, these tests were carried out qualitatively, while quantitative tests to thoroughly verify the simulation results will be carried out in further work. Despite the differences in the boundary conditions compared to the FEM studies, the laboratory tests conducted confirmed the relationship between the magnitude of the rolling reduction and the difference in roll velocities and the curvature of the strip.

CONCLUSIONS

Based on the analysis of the results obtained, it was concluded that:

- The introduction of kinematic asymmetry into the rolling process, regardless of the size of the rolling reduction, always results in a decrease in the forces regardless of whether the asymmetry is introduced by accelerating or decelerating a roll.
- The decrease in forces during rolling with velocity asymmetry is greater the greater the difference between the velocities of the rolls.
- The magnitude and direction of the strip curvature in the case of kinematic asymmetry depend simultaneously on the asymmetry's magnitude and the strain's magnitude. For small rolling reductions ε_1 = 0.15 and ε_2 = 0.25, the strip curves in the direction of the roll with the lower speed, and the magnitude of this curvature decreases as the crumple increases. For larger rolling reductions ε_3 = 0.40, the direction of strip curvature is the opposite, that is, in the direction of the faster roll.
- For all the rolling reductions studied, the introduction of frictional asymmetry into the rolling process results in a decrease in forces. The value of this decrease is greater the greater the value of the introduced asymmetry.
- Due to the introduction of frictional asymmetry, the magnitude and direction of the curvature of the strip depend on the magnitude of this asymmetry and the size of the rolling reduction. For each rolling reduction tested, as the frictional asymmetry increased, the strip curved more and more toward the roll with a higher coefficient of friction. However, for rolling reductions ε_2 = 0.25 and ε_3 = 0.40 for lower values of friction asymmetry, the initial direction was the opposite. The larger the rolling reduction was introduced, the higher the coefficient of frictional asymmetry value had to be introduced to change the direction of curvature of the stion, from the direction of curvature toward the lower roll to the direction toward the upper roll.
- The results of the mixed asymmetry tests allowed the creation of process maps that enabled the determination of the most favourable parameters for the process based on them.
- By using the process maps, the values of the double asymmetry coefficients were selected at which it was possible to obtain a straight strip, obtaining at the same time the highest possible reduction in forces and an increase in strip velocity for the rolling reduction. ε_2 = 0.25 and ε_3 = 0.40. The highest reduction in forces and increase in the strip's speed while keeping the strip straight were obtained for the rolling reduction ε_3 = 0.40, velocity asymmetry a_V = 1.35 and friction asymmetry a_μ = 7.5. The reduction in forces was 23%, while the increase in speed was 29% compared to rolling without asymmetry.

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