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RESEARCH ON COLD ROLLING OF TRB TYPE STRIPS USING A GROOVED ROLL

This article presents the results of an experimental study of cold rolling TRB strips of S235JR steel applying one grooved roll and another plain roll. The purpose of the study was to determine the possibility of rolling TRB strips with the technology studied, depending on the dimensions of the charge and the number of rolling passes. In addition, the possibility of reducing the magnitude of TRB strip curvature due to the introduction of asymmetry into the process was investigated. The effect of the rolling process and shape variation on the material's hardening was evaluated by measuring hardness. Based on the results, it was determined that the greater the initial thickness of the charge, the higher the shape tolerances can be obtained. In addition, hardness variation was observed on the cross-section of TRB strips, which decreased with increasing values of plastic deformation. It has also been shown that it is possible to reduce the curvature of the TRB strip due to the use of double asymmetry.

Keywords: Asymmetric rolling; strip curvature; roll force; steel S235; hardness

1. Introduction

A noticeable trend since the beginning of the 21st century in many industries is the effort to reduce material and energy consumption during the production of metal products. This can be achieved, among other things, by obtaining the desired microstructure and material properties, and as a result of optimizing the shape and dimensions of products for working conditions [1]. One group of products meeting these objectives is called Tailored Blanks (abbreviated TB). Products belonging to this group are characterized by at least one variable, for example: variable thickness, variable material or variable material properties on the cross-section of the sheet. TB blanks are widely used in the automotive industry due to their lower weight, among other reasons. The most common examples of TB blanks in the industry, are tailor welded blanks (TWB) and tailor rolled blanks (TRB). The first case refers to semi-finished products in which varying thicknesses, or varying material properties, are achieved by joining different metal sheets together by welding [2]. TWB is used, among others, for the production of stamped parts of vehicles i.e.: roof rails, center pillar, or inner door panel. The problem of TWB is the occurrence of stress concentrations at sheet joints resulting from the rapid change in thickness. This results in a reduction in the deformability of such products compared to those with uniform thickness [3]. In order to overcome this problem, TB blanks produced by rolling technology with a variable and controlled rolling gap (so-called flexible rolling) were developed [4]. This made it possible to obtain semi-finished products of variable cross-section with linear transitions between the different thicknesses. This eliminated areas of stress concentration, which made it possible, among other things, to increase the deformability of TRB blanks [5]. The problem of TRB blanks produced by flexible rolling was that they could be given a variable shape only in the direction longitudinal to the rolling direction. Consequently, research began to be conducted into a new rolling process that would allow a variable cross-section in the transverse direction. In this case, when using conventional sheet rolling, it is very difficult to obtain different thickness distributions across the width of the strip. This is due to the variation in material elongation caused by different values of deformation in the material, which in turn contributes to the formation of shape defects in the form of waviness. Accordingly, ongoing research has focused on making the material flow transverse to the rolling direction during the rolling process. To this end, during the work described in [6], a special system of rolls was used, arranged side by side, which, by gradually shaping the material, allowed the final shape to be obtained in 30 to 40 rolling passes. In contrast, during the work

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described in the article [1], specimens of variable cross-section with a thickness ratio of 1:1.8 were obtained through the use of special shaping rolls. The process involved obtaining the final shape of the strip in four to six rolling passes and involved preliminary flattening and bending of the material at the edges of the shaped blank. The present article presents the results of a study on rolling TRB strips with variable cross-section in the transverse direction using a groove roll.

During the research, the possibility of forming strips with only one variable surface was tested. Accordingly, a set of rolls consisting of one grooved roll and a second plain roll was used. The investigated technology has advantages over the other methods, which include: the possibility of obtaining the final shape of the strip even in a single pass, the relatively simple conduct of the process, and the lack of limitation of the length of the products by the magnitude of the tools (in the case of forming products with a variable cross-section in the transverse direction). Due to these advantages, this technology can be used for forming TRB strips, which are semi-finished products for various types of sections. On the other hand, the disadvantages of this technology are the curvature of the strip after leaving the rolling gap (it occurs only in the case of a strip with a one-sided variable surface), as well as aforementioned the uneven elongation of the material during rolling, contributing to the formation of so-called shape defects (Fig. 1).

As part of the work carried out, the impact of the investigated technology was examined in terms of material changes and the possibility of reducing strip curvature, as a result of introducing intentional and controlled asymmetry into the rolling process. During the study, asymmetry was introduced into the process as a result of varying the linear speed of the rolls and as a result of varying the friction conditions between the rolls. The material tested was S235JR steel.

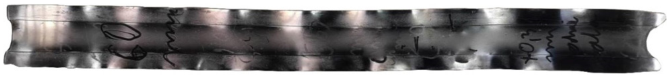

Fig. 1. Example of a shape defect caused by rolling TRB strips (wavy forms)

2. Methodology

The cross-section of the TRB strip was developed on the basis of numerical tests performed in the Simufact Forming program (Fig. 2). During these tests, a shape of the strip cross-section was developed for which the difference in material elongation after rolling was as small as possible. As a result of these tests, a strip of thickness ratio 1:1.4 was developed, the diagram of which is shown in Fig. 3. The developed shape of the strip cross-section made it possible to produce various strips in the width range from 50 to 105 mm.

Laboratory tests were conducted on a WD-2 rolling mill of the DUO type, which is on the equipment of the Lukasiewicz Research Network – Poznan Institute of Technology (Fig. 4). It allows the measurement of forces during rolling, as well as to vary the speed of the rolls. The diameter of both rolls was the same and was 187 mm. The initial thickness of the material was 2 mm. The tests were conducted for 3 different strip widths: 56, 80 and 92 mm. Due to the values of forces during rolling (485 kN for 56 mm width strips), only 56 mm wide strips were rolled in one rolling pass. The 80 mm wide strips were rolled

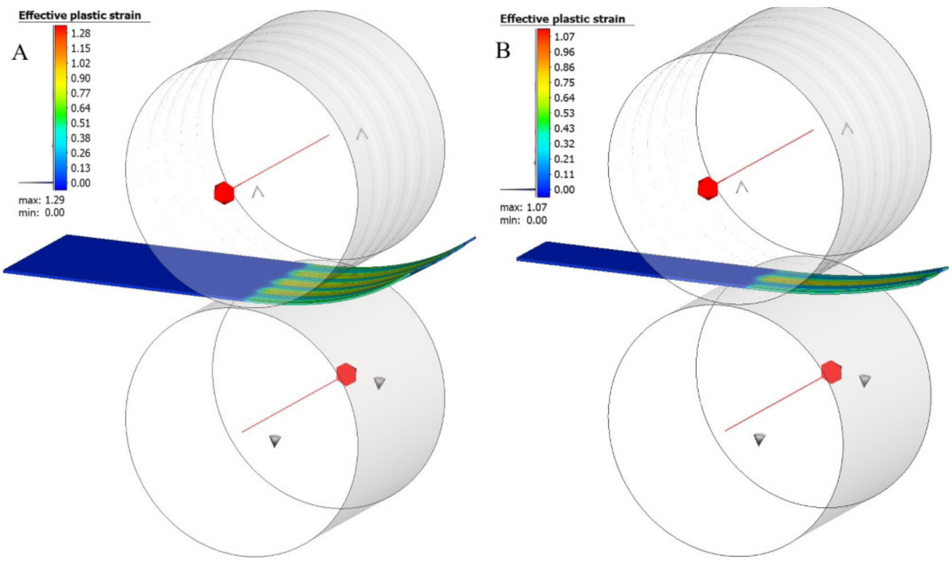

Fig. 2. Numerical study of the TRB strip rolling process in the Simufact Forming program. A – 105 mm charge width. Linear speed of both rolls of 50 mm/s

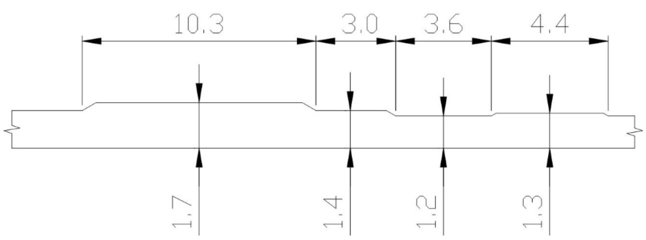

Fig. 3. Scheme of the cross-section of the designed strip

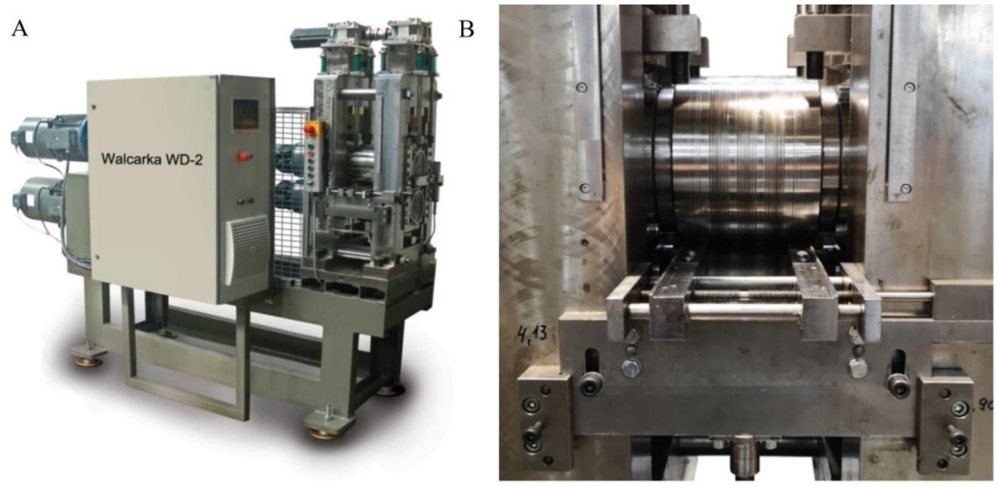

Fig. 4. Laboratory equipment: A – WD-2 laboratory rolling mill, B – rolling mill with grooved roll

in two passes, of which the first pass was carried out on plain rolls, with a rolling reduction value of ε = 12.5%. In the case of 92 mm wide strips, on the other hand, it was necessary to apply an intermediate heat treatment after the first rolling pass. Heat treatment was carried out for 2 hours at 700° and in an argon atmosphere. The thickness and hardness of the material in different areas of the strips were measured. The effect of speed asymmetry and friction coefficient asymmetry on strip curvature, rolling forces and the shape of the strips was then studied. Velocity asymmetry was introduced by decreasing the speed of the upper roll, while keeping the linear speed of the lower roll constant at 50 mm/s.

Friction coefficient asymmetry was introduced by lubricating only one of the rolls (lower or upper), while keeping the other without lubrication rolling oil Somentor EH 45 was adopted for the study. The value of friction asymmetry coefficient $a_\mu = \dfrac{\mu_g}{\mu_d}$ (μ_g – the value of the coefficient of friction for a lubricant applied to the upper roll, μ_d – the value of the coefficient of friction for a lubricant applied to the lower roll) was 0.2 when only the upper roll was lubricated, while it was 5.4 when only the lower roll was lubricated. Specimens of 2 × 50 × 100 mm (thickness, width, length) of S235JR steel were prepared for testing.

3. Results and discussion

The work began by measuring the hardness of S235JR steel in the delivery condition with the following chemical composition: 0.13% C, 0.02% Si, 0.037% Al, 0.005% S, 0.02% Cu, 0.52% Mn, 0.008% P, 0.006% N, 0.01% Cr, 0.01% Ni. Hardness measurements were made using the Vickers method, with a load equal to 4,903 N, at a temperature of 23.2°C. These tests were carried out at 0.2 mm distances, transverse to the rolling direction over the entire thickness of the sheet. The results of the hardness measurement are shown in Fig. 5, while photos of the material structure in cross-section are shown in Fig. 6.

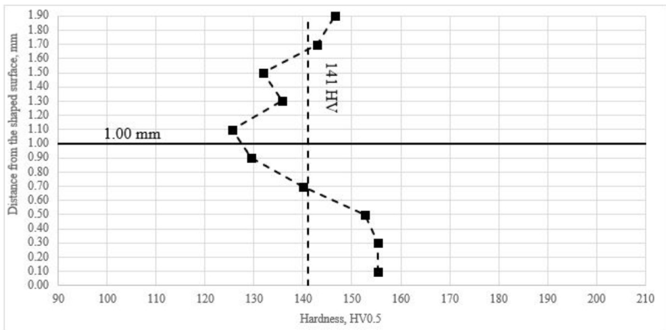

Fig. 5. HV0.5 hardness results for S235JR steel in delivery condition

Fig. 6. Images of material microstructure under delivery conditions for transverse surfaces: A – microstructure at the top surface, B – microstructure inside the material, C – microstructure at the bottom surface

In Fig. 5, a continuous horizontal line marks the center of the thickness of the test specimen, while a dashed vertical line marks the average hardness value. The results of the measurements showed higher hardnesses in the near-surface areas compared to the areas inside the material. This is due to the hardening state of the material as a result of rolling where plastic deformation is mainly concentrated in the surface layer. This can be confirmed by qualitative analysis of the microstructure, from which no other reasons for the variation in the hardness of the initial material were found, i.e. significant differences in size of the grain, or macrosegregation. The variation of hardness in the starting material, caused by the difference in the state of hardening, can affect the formation of mechanisms of material hardening during subsequent rolling. For this reason, measuring hardness across the thickness of the material in the delivery state was important for analyzing the hardening state in the resulting TRB strips after rolling. After examining the material in the delivery state, laboratory tests of rolling strips with variable cross-section were proceeded. The resulting strips are shown in Fig. 7.

Fig. 7. Strips obtained after rolling. From left: 56, 80 and 92 mm strips

All strips were rolled with an equal rolling gap of $g_1 = 0.5$ mm and a linear speed of both rolls of 50 mm/s. No visible shape defects were observed in the received strips, which are classified in the rolling industry as “abnormal sheet shape” and occur in in falciform and wavy forms (Fig. 1). Since the rolling process of each strip differed, their thicknesses were measured in different areas according to the designations in Fig. 8. The results of these measurements with respect to the assumed values are shown in Fig. 9.

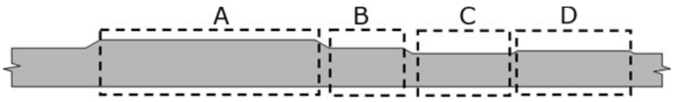

Fig. 8. Markings of measurement areas in TRB strips

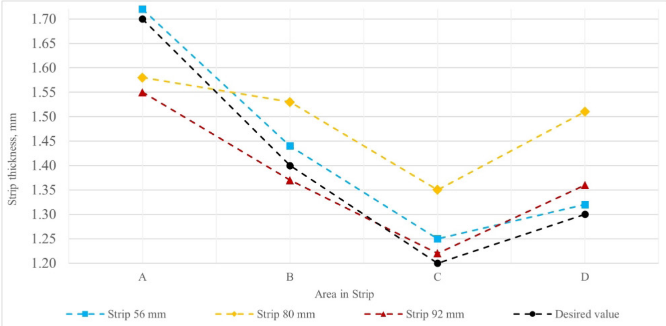

Fig. 9. Results of thickness measurements for the obtained strips

Analysis of the results showed that the greatest accuracy with the desired values was obtained for 56 mm wide strips formed in a single rolling pass. Depending on the tested area, the dimensional variance was different and ranged from +0.02 to +0.05. However, the biggest difference occurred when rolling 80 mm wide strips in two rolling passes. In this case, greater thicknesses were obtained in areas B, C and D, by up to 0.21 mm. This was due to the hardening of the material after the first rolling pass, which in turn caused greater deflection of the rolling mill and reduced the plastic flow of the material.

In the “A” area, however, there was a rubbing of the material by about 0.12 mm. The improvement in the results was obtained after the introduction of an intermediate heat treatment applied during the rolling of 92 mm wide strips. Measurements showed improved dimensional conformance in areas B, C and D, at the expense of greater thinning in area “A.” The probable reason for the excessive thinning of area “A” in the second rolling pass (on grooved rolls), regardless of the case, was that the material thickness was too thin before this operation. In the case of rolling applying at least one grooved roll, there is variation in the melt velocity and elongation of the material (Fig. 10). Material in areas with higher rolling reduction (C and D) moves at a higher speed

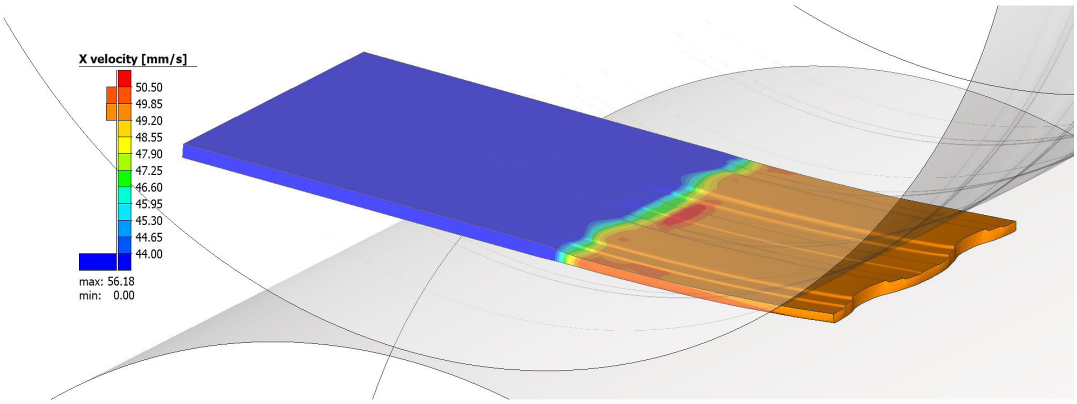

Fig. 10. Velocities of different areas of the strip in the deformation gap. Simulation of rolling a 50 mm wide strip with a linear speed of both rolls of 50 mm/s

and elongates more after exiting the rolling gap than material in an area where rolling reduction is lower (A). As a result, the faster elongating areas pull material from the slower flowing areas, causing it to thin. In the case of single pass rolling, during which the initial thickness of the material was 2 mm, this thinning may not have occurred or may have been significantly less, due to the larger difference in material thickness, which was Δh = 0.3 mm in area "A".

When rolled in two passes, the thickness of the material before the second grooved pass was 1.75 mm, making the difference in thickness only 0.05 mm. Due to such a small difference in material thickness, its desired value in area "A" is much more likely to be affected by rubbing caused by differences in melt speed and material elongation. Next, hardness tests were carried out for each type of strip in different areas throughout its thickness. For each area, hardness was measured every 0.15 mm counting from the shaped surface. The results obtained are shown below.

Analysis of the results obtained for the 56 mm wide strip showed an apparent increase in hardness in each of the areas tested. As expected, as a result of the hardening of the material, the largest increase occurred in the most deformed area (area C), while the smallest increase occurred in the least deformed area (area A). The occurrence of variation in the hardness of the material is an advantageous situation, because it makes it possible to obtain areas of different purpose in the developed TRB strips (for example, the load-bearing area and the area intended for further forming). This will make it possible to form the obtained strips, without the need to introduce an additional process in the form of annealing. In addition, an increase in the uniformity of hardness in relation to the starting material was observed for each of the tested areas. Analyzing the diagrams in Figs. 11 and 12, it can be seen that as the hardness increases, its distribution decreases in the range of rolling reductions from 14 to 28% (areas A and B). This is related to the hardening uniformity in the material due to the introduction of plastic deformation. Initially, during rolling, the material hardens in the areas in contact with the tools, i.e. in the surface layers. This is caused by the movement of dislocations in the slip bands. When these dislocations are blocked, hardening of the surface layer occurs, causing further hardening to be realized in areas where

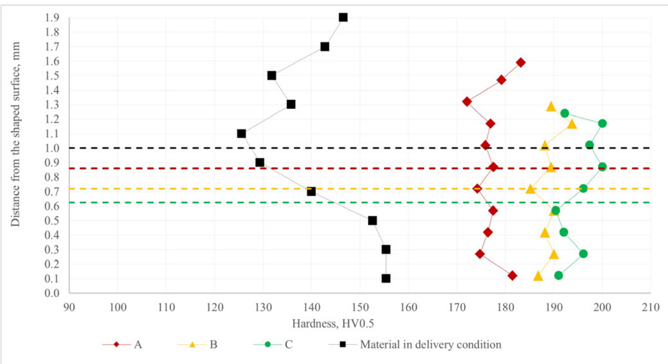

Fig. 11. The result of hardness measurements on the cross-section of different areas in a 56-mm-wide strip. The horizontal dotted lines indicate the centers of thickness for each area

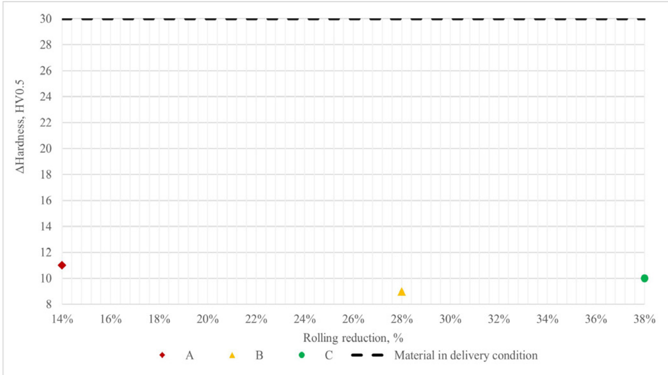

Fig. 12. Distribution of hardness for each areas in a 56 mm wide strip

it has not yet occurred, i.e. in the deeper layers of the material. This results in a reduction in the distribution of hardness over the cross-section of the material, which is evident in area "A", where the value of the rolling reduction was 14%. In this area, however, there are still differences in hardness between the top layer of the material and its deeper layers. This indicates that with these deformations, hardening has not yet occurred in the depth of the material, and there are still areas in the deeper layers where crystallographic deformation of grains can occur. Further movement of dislocations in the deeper layers of the material will only occur as plastic deformation increases, until dislocations are blocked throughout the thickness of the material. At this point, the material becomes as homogeneously hardened as possible, so that the distribution of hardness throughout its thickness is the lowest. In the considered case of rolling TRB strips, this effect can be seen in area "B", where the value of the rolling reduction was 28%, and the difference in hardness was equal to 9 HV0.5. Larger deformations in the material that occurred in area "C" at the value of the rolling reduction of 38% caused an increase in the variation in hardness. This was caused, by exceeding a certain value of deformation, at which further movement in the range of slip bands was no longer possible. This in turn led to the activation of other deformation mechanisms. In this case, non-crystallographic shear bands were formed, whose angle of alignment depended on the direction of macroscopic shear stresses occurring during the process. In the case of rolling, this angle is about 35° relative to the rolling plane [7]. This phenomenon results in the formation of so-called lenticular structures, i.e. areas that are much less hardened and located in the areas between shear bands. Areas of this type generally form inside the material and cause local decreases in hardness, as can be seen in the case of area "C" in Figs. 11 and 12. The distribution of hardness in this area, however, is not high, which may indicate the small contribution of lenticular structures, for these values of plastic deformation. In order to determine the presence of shear bands in the "C" area, the microstructure of this area was observed in a plane transverse to the rolling direction (Fig. 13).

In Fig. 13, one can see the shear bands that initially appear in some particularly oriented grains. Only an increase in strain could make these bands move to the other grains [8,9]. Next, hardness were measured in the strips obtained in two rolling

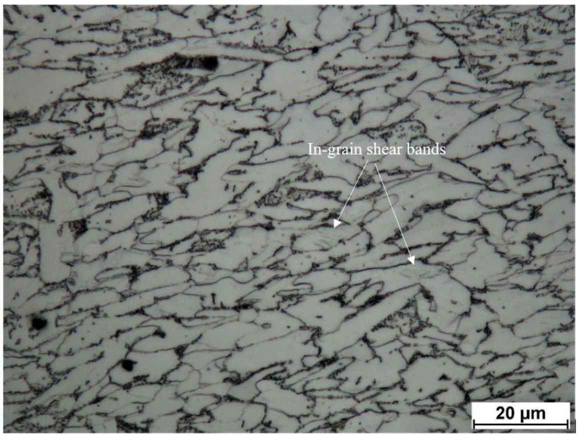

Fig. 13. Microstructure of a 56 mm wide strip in the "C" area in the longitudinal plane

passes, the first of which was carried out on plain rolls at a crease value of 12.5%, while the second was carried out on grooved rolls. The results obtained from the hardness measurement, along with the distribution depending on the area tested, are shown in Figs. 14 and 15. For the strips obtained in the two passes, the greatest increase in hardness occurred after the first rolling pass, conducted on plain rolls. The increase obtained in the second pass (on grooved rolls) compared to the first regardless of the area tested was small, and the values obtained in different areas of the strip were similar to each other. This was due to the small differences in strip thicknesses and the associated magnitudes of plastic deformation. Analyzing the results of hardness measurements on the cross-section of the strips (Fig. 14), it can be seen that after the first pass, i.e. at a relative rot value of 12.5%, there is still a noticeable difference in hardening between the surface layers and the layers inside the material. Despite this, however, the highest homogeneity of hardness was obtained, with a distribution of 8 HV0.5. This may indicate that for the S235JR steel under study, such a value of plastic strain does not cause movement and locking of dislocations across the material, but it is close to such a value. Comparing these results to those obtained for the TRB strip obtained in one pass (Figs. 12 and 13), it can be seen that there are differences in the hardening of the material. In the "A" area of TRB strip with a width of 56 mm, where the rolling reduction was 14%, lower hardness and a greater distribution of hardness were obtained than in the case of plain-rolled strip at a rolling reduction value of 12.5%. Similar hardness values and their distribution in TRB strip occurred only in the "B" area, with a rolling reduction of 28%. Based on these results, it can be concluded that in the case of rolling strips with variable cross-section, the way of material hardening proceeds differently than for flat bars. This is probably due to the occurrence of variation in material elongation when rolling TRB strips. Therefore, in addition to the deformation of grains due to the pressure of the rolls, there may be additional deformation due to the pulling of material from less deformed areas through more deformed areas.

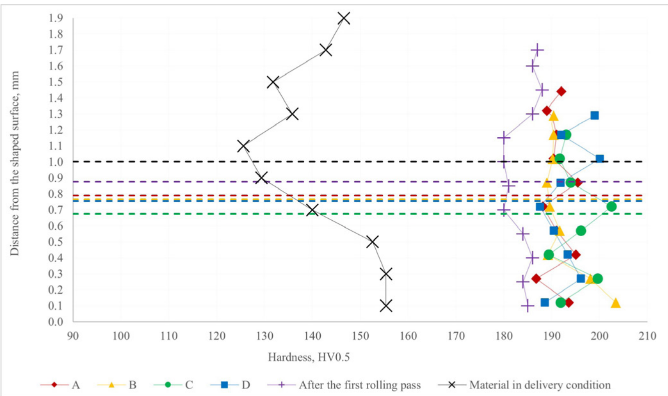

Fig. 14. The result of the hardness measurement on the cross-section of different areas in the 80 mm wide strip. The horizontal dotted lines indicate the centers of thickness for each area

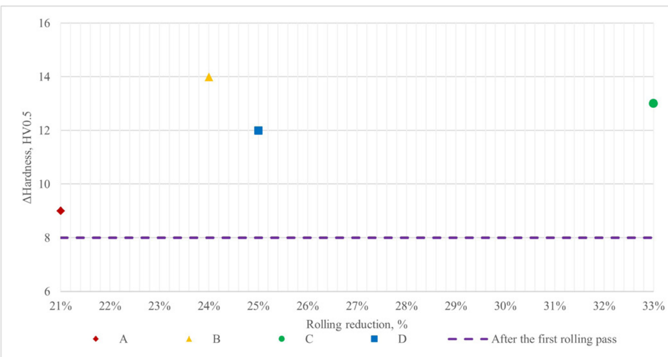

Fig. 15. Distribution of hardness for each areas in a 80 mm wide strip

The 92 mm wide strips were pre-rolled on groove rolls (the rolling reduction value was ε = 12.5%), then annealed at 700°C in argon atmosphere for 2 hours and then rolled on groove rolls. The results of measuring these strips showed that the lowest hardness were obtained in the near-surface areas (Fig. 16). The reason for the drop in hardness near the surface of the material, may have been decarburization that occurred during the annealing process. Due to the lower carbon amount near the surface of the material, there was less strain hardening compared to areas inside the material where the carbon amount was higher. However, during the annealing process of the material, a protective atmosphere was used, which should prevent decarburization. Therefore, the decrease in hardness in the material, could be

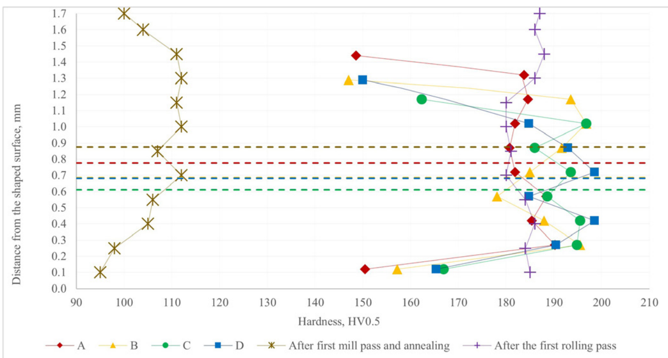

Fig. 16. The result of the hardness measurement on the cross-section of different areas in a 92 mm wide strip. The horizontal dotted lines indicate the centers of thickness for each area

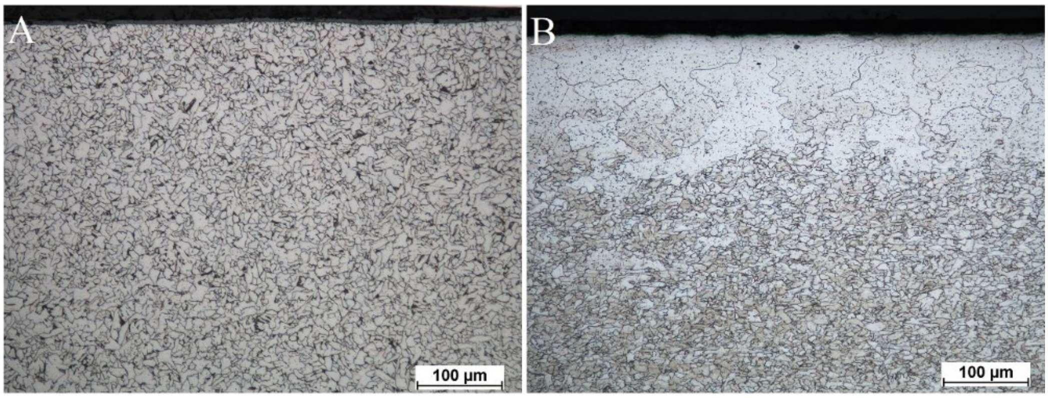

Fig. 17. Microstructure images for transverse surfaces in near-surface areas: A – material in the delivery state, B – material in the "B" area in the 92 mm wide TRB strip

related to the so-called critical deformation. After the first rolling pass, the deformation of the material may have been below the critical level, by which grain growth occurred during recrystallization caused by annealing. To investigate the cause of the decrease in hardness, microstructure observation was carried out in 92 mm wide strips after the second rolling pass (Fig. 17B).

The observation of the microstructure in TRB strips after pre-rolling and annealing, may suggest that decarburization has occurred in the surface layers of the material. Therefore, it was decided to measure the thickness of this layer, in different areas of the TRB strip. The results obtained were approximate values, estimated from images of the microstructure. The results obtained are shown in TABLE 1.

TABLE 1

Approximate thicknesses of decarburized layer in different areas of the strip

Side of the strip	Approximate thickness of decarburized layer in each area, μm			
	A	B	C	D
Shaped	197	154	119	150
Plain	209	160	132	161

Measurements of the thickness of the near-surface layer show that it varies depending on the observed area. Therefore, it can be concluded that the thickness of this layer is dependent on the amount of deformation and decreases as the deformation increases. In the case of decarburization, the thickness of this layer should be relatively uniform, suggesting that in this case there was grain growth caused by critical deformation. In order to clearly determine which case is true, it would be necessary to measure the chemical composition on a cross-section of the material. Despite the decrease in hardness in the surface layers, a significant increase in hardness was obtained inside the strip, for all areas tested. The hardnesses obtained were not significantly different from those obtained for other 56- and 80-mm-wide strips. The measured values show variation in hardness between areas, but not as pronounced as in the case of strips rolled in a single pass.

In the case of the hardness scatter analysis (Fig. 17), due to the presence of decarburization/grain growth, only areas where they were not present were accepted for analysis. In addition, due to grain recrystallization after annealing, the initial thickness of the material before the second pass was assumed to be 1.75 mm. Therefore, the values of the rolling reductions were relatively low, and the increase of the scatter with the magnitude of the strain indicates hardening due to movement and locking of dislocations mainly in the surface layers of the material. This can be observed by analyzing the diagram in Fig. 18, which shows visible decreases in hardness within the material.

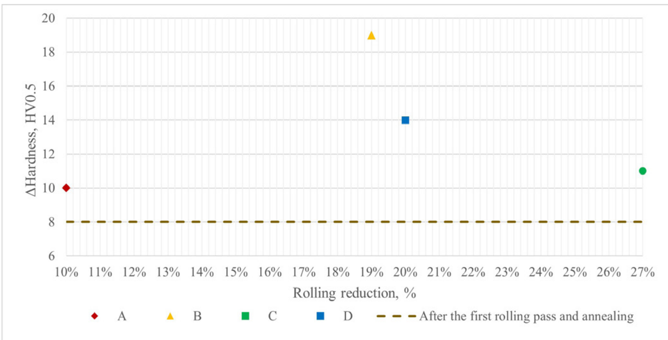

Fig. 18. Distribution of hardness for each areas in a 92 mm wide strip

The study showed that the most favorable case of cold rolling of TRB-type strip is the one in which the final shape was obtained in a single rolling pass. This made it possible to obtain the smallest dimensional variation and visible variation in material hardness between strip areas, which will be advantageous when these strips are used as semi-finished products for various types of sections. Since the values of forces during rolling did not allow wider strips to be obtained in a single pass, further research was conducted for strips with widths of less than 56 mm. These studies focused on determining the effect of the asymmetry of the rolling process on the curvature of the strip and the force parameters of the rolling process. The phenomenon of strip curvature during asymmetric rolling is a complex issue even in the case of flat bar rolling, due to the multitude of parameters affecting the magnitude and direction of strip curvature [10-12]. The current state of knowledge indicates that on the magnitude and direction of the strip curvature, in addition to the type and value of asymmetry, the value of the rolling reduction in a given pass also has a crucial influence. For example, during asymmetric rolling of flat bars, a change in the value of plastic deformation (with constant values of asymmetry) can not only reduce the value of curvature, but can also change its direction [13,14]. In the case of rolling strips with variable cross-section, the issue is even more complex, due to the variable value of plastic deformation on the strip cross-section. Therefore, the experiment conducted was aimed at determining the factors affecting the curvature of a strip with a variable cross-section. The tests were conducted according to the table shown below (TABLE 2) and with a rolling gap of $g_2 = 0.65$.

TABLE 2

Diagram of the applied asymmetries when conducting the rolling process for 50 mm wide strips rolled in a single pass

Process table	Friction coefficient asymmetry			
Velocity asymmetry	Asymmetry ratio	0.2	1.0	5.4
	0.93	Combined asymmetry	Velocity asymmetry	Combined asymmetry
	1.00	Friction asymmetry	No asymmetry	Friction asymmetry

Based on the study, a diagram was developed showing the effect of the applied asymmetries (velocity, friction and their combination) on strip curvatures in the longitudinal direction and forces during the process (Fig. 19).

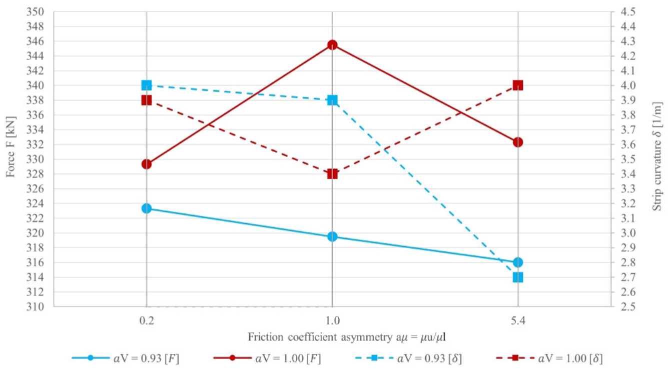

Fig. 19. Results obtained for rolling TRB strips. Points marked with circles refer to values of forces. The points marked with squares refer to the values of curvatures

In the diagram, the tested values of friction coefficient asymmetry are marked in the "x" axis, while different values of velocity asymmetry are marked with different colors in the diagram. In the "y" axis, the values of the process forces were placed on the left, to which the points marked with circles and connected by continuous lines refer. The values of measured curvature, on the other hand, are placed on the right side of the "y" axis and are referred to by points marked with squares and connected by dashed lines. Analysis of the results showed that the introduction of any asymmetry into the rolling process results in a reduction in process forces compared to the process without asymmetry. This is due to the formation of additional shear stresses, as a result of which a complex state of deformation is generated in the material being formed, the components of which are plane strain and simple shear in the rolling direction [13,15,16]. On the other hand, the reduction of curvature in relation to the value obtained for the symmetrical process was obtained only in the case in which the value of the velocity asymmetry was equal to 0.93 ($aV = 0.93$) and the asymmetry of the friction coefficient was 5.4 ($a\mu = 5.4$). This was a case in which the speed of the upper roll was reduced and the lower roll was lubricated with Somentor 45 EH oil. This means that in the case of strip rolling applying only one grooved roll, it is advantageous to simultaneously reduce its speed along with reducing the friction coefficient for the plain roll. Moreover, in such a case, the greatest decrease in forces was obtained compared to the process without asymmetry. Interestingly, when the same asymmetry parameters ($aV = 0.93$ or $a\mu = 5.4$) were applied separately, there was a greater strip curvature in the direction of the roll with lower speed or friction coefficient value (towards the grooved roll). In the case of velocity asymmetry, the increase in curvature is referenced in the literature for flat bar rolling cases, for relatively low values of rolling reductions at which the strip curves toward the slower roll [17]. However, when only friction asymmetry was introduced, regardless of which roll was lubricated, strip curvature always increased. This demonstrates the high complexity of this phenomenon in TRB strip rolling, and in order to determine more precisely the relationship between the asymmetries and the magnitude and direction of strip curvature, further laboratory studies are required. The resulting strips, were then measured to determine the differences in material elongation, between different areas. The measured areas, along with sample results, are shown in Fig. 20.

Based on the results obtained, the effect of the magnitude of the asymmetry on the formation of the difference in material elongation was studied. For this purpose, the values of decreases in forces caused by the introduction of asymmetry were compared with each other with the corresponding average differences in material elongation, for the beginning and end of the strip. The results obtained are shown in Fig. 21.

Based on the analysis of the results obtained, a near linear relationship was observed between the decrease in forces caused by the increase in asymmetry and the increase in the difference in material elongation at the end of the strip. This may be related to the appearance of additional shear stresses caused by the asymmetry of the process, which contributed to an increase in plastic flow in the most deformed areas. This may be related to the hypothesis regarding the pulling of material from less deformed areas (area "A" Fig. 9), by faster flowing material from more deformed areas (areas "C" and "D" Fig. 9). This causes the material to thins, thus losing contact with the roll surface and reducing the impact of asymmetry in those areas. A visualization of this hypothesis is shown in Fig. 22.

Confirmation of this hypothesis can be seen in the marked differences in roughness in the strips occurring between the more strongly and least deformed areas (Fig. 23), the cause of

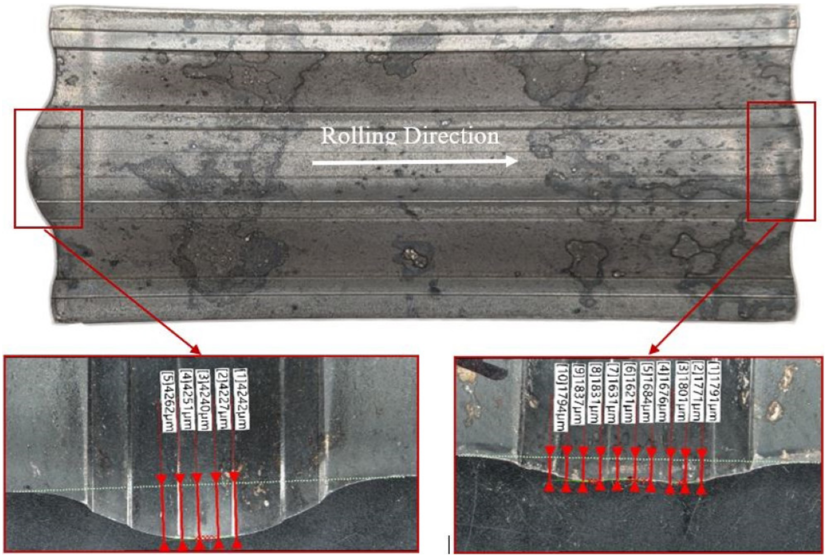

Fig. 20. The obtained strip with example measurements of the difference in elongation: A – the end of the strip, B – the beginning of the strip

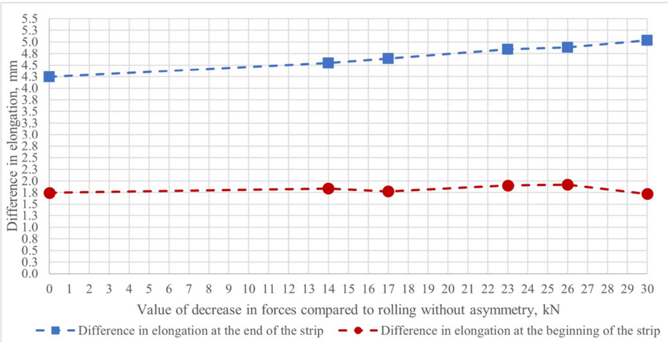

Fig. 21. Diagram of the relationship between the decrease in forces caused by the asymmetry of rolling and the elongation of the material at the beginning and end of the strip

which may be, among other things, loss of contact with the roll. The roughness measurements carried out showed that in the less deformed areas the Ra value was about 6.9 µm, while in the more hardening areas the value was about 0.62 µm.

In the case of the initial part of the strip, no obvious relationship was observed between the decrease in forces and the increase in the elongation difference in each area. This may be due to the high hardening of the edge of the strip at the time of contact with the tools and thus blocking the possibility of excessive elongation of the material in each area of the strip. This, in turn, reduces the effect of process asymmetry on the elongation of the material in the most deformed areas and does not lead to a „pull" of the material from the least deformed area.

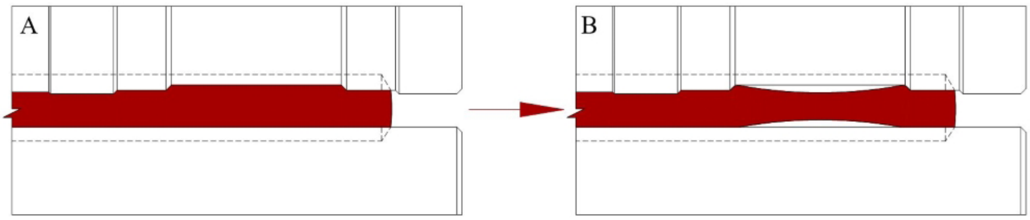

Fig. 22. Schematic of thinning of the material in the least deformed area during rolling of TRB strips. A – Theoretical, full gap filling B – Thinning in area A, due to greater material elongation in the other areas

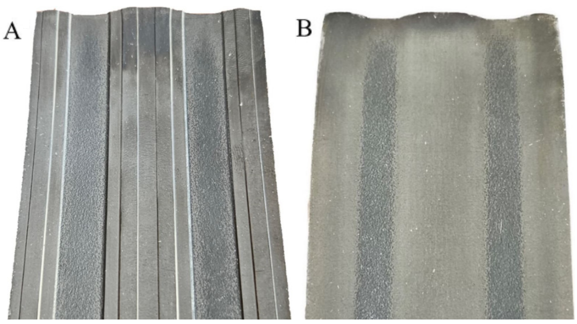

Fig. 23. Strip with visible differences in surface roughness: A – shaped surface, B – plain surface. Strip with a width of 56 mm, obtained during rolling without asymmetry

4. Conclusions

Based on the research, the following conclusions were drawn:

- The conducted research has shown the possibility of producing TRB strips with a variable cross-section in the transverse direction in a single rolling pass. Compared to current technologies, this significantly simplifies the conduct of the technological process and reduces production time.
- When rolling strips using a single groove roll, the greater initial thickness of the charge contributes to better filling of the gap between the rolls, which allows higher dimensional tolerances.

- During the tests, the occurrence of inhomogeneities in material consolidation on the cross-section of the strips was demonstrated, which are reducible due to the introduction of a suitable high state of consolidation in the material.
- In the case of symmetrical cold rolling of TRB strips applying a single grooved roll, the strip curves in the direction of the grooved roll regardless of the case. This is an important observation from the point of view of introducing asymmetry into the rolling process to reduce this curvature.
- The effect of asymmetry on the direction of curvature of a strip of variable cross-section, significantly differs from the case of rolling flat bars. On the basis of the conducted research, there was no relationship between the amount of asymmetry and the curvature of the strip. However, a synergy was observed due to the application of double asymmetry resulting from the variation of the speed of the rolls and the friction coefficients between the rolls. The simultaneous application of two asymmetries, which separately increased the strip curvature, made it possible to reduce its value. This demonstrates the complexity of the phenomenon, making it worthy of further study.
- With the increase in process asymmetry and the associated decrease in process forces, there is an increase in the elongation difference between the most and least deformed areas. Despite this increase, shape defects were not observed in any of the cases.

Acknowledgments

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