# KINEMATICS OF METAL FLOW DURING ROLLING OF ASYMMETRIC THIN-WALLED SECTIONS UNDER NON-UNIFORM PLASTIC STRAIN CONDITIONS

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## ABSTRACT

*To assess the effectiveness of the use of special rolled products, development and improvement of technology, it is necessary to know the patterns of changes in the process parameters depending on production conditions. It is of interest to study the kinematics of metal flow, velocity, force parameters of the process of producing special sections which have shown effectiveness in the automotive and aviation industries.*

*Keywords: rolled, metal, profile, stress state, metal saving.*

## INTRODUCTION

Under current economic conditions, metallurgical enterprises are faced with the problem of increasing the competitiveness of rolled products in the domestic and foreign markets by reducing energy and material costs.

One of the main directions of development of metallurgical complex of the country is the reduction of metal consumption, material and energy costs in production field. The solution of these problems in the production of transport metal requires the search for new scientific and technological solutions along the entire chain of metallurgical production: improving the quality of raw materials, development of production of low-impurity pig iron, further improvement of converter operations with steel processing in the ladle-furnace, vacuum degasser and casting at CCM, application of new schemes of billet reduction to ensure effective control of macrostructure and, later, during subsequent heat treatment, micro-structure, phase composition of the metal, its composition and chemical composition [1 - 5].

An urgent problem of domestic production is to improve the accuracy of roughing wheels in order to reduce the allowance for machining. The solution to this problem is associated with the development of known technological scheme, development of new methods of processing continuously cast billets by pressure, adjustment of modes of preliminary and final forging based on new technical solutions to ensure uniform radial flow of metal along the perimeter of the forging and high size accuracy of the rim, disk and hub of the forging [6 - 8]. In this case it is possible to minimize the eccentricity value of the hub and rim during rolling, increase the accuracy of dimensions of the roughing wheel after the press bending, straightening and calibration. Analysis of the influence of technological parameters on the accuracy of wheels and selection of a rational technological scheme of stamping and rolling to reduce the allowance for turning can be accelerated if we apply mathematical modeling of processes for the study of metal forming changes [9 - 14]. An important step in improving the methodology of solving boundary problems of metal forming is the development of finite element modeling of processes based on the application of variational principles of mechanics, deformed media models, taking into account the evolution of grain structure of steel, the development of asymmetry index of forged forgings and roughing wheels, theoretical analysis of the effect of technological factors on the accuracy of roughing wheels [15 - 19].

In the automotive industry, there is a clear trend in the production of truck and bus wheels to improve designs by reducing the rim component. This makes it possible to reduce the metal consumption of the rim by reducing the overlap between rim parts. There is a need for a single-piece rim. In addition, the profile itself undergoes changes towards a more rational distribution of metal over the cross-section, ensuring in a certain way its even-strength: the more loaded areas are reinforced and the less loaded elements are thinned. The upper profile of the rim has an equal thickness cross-section, although the loading across the width is different. The lower profile is designed to vary the cross-section width, with a 5° seating flange, to which the tyre bead sits snugly. In the first design, the bead ring is machined into the center section.

The study of metal forming during rolling of complex sections allows to obtain a qualitative and quantitative model of the formation of rolled products during plastic strain, to reveal general patterns of metal flow under non-uniform reduction and to assess the influence of gauge geometry on the lateral movement of metal, shear deformation, general laws of forming by body volume.

## EXPERIMENTAL

To study the strain at obtaining the section used steel billets A621 (0.15 - C; 0.2 - Cr; 0.06 - Si; 0.35 - Mn; rest Fe, weight %) with cross-sectional dimensions H x B = 90 x 270 mm and a length of 1000 - 1700 mm (Fig. 1). Holes were drilled on the horizontal faces of workpiece at 50 mm intervals, and screws with M16 thread were screwed into them, every 10 mm of which were punched to make it easier to measure the strained "witness". Unfinished sections were selected after heating and rolling, and templates were cut and shaved from them. Rolling was carried out on mill 550 of Dniepropetrovsk Iron & Steel Works, which rolls channels No. 12, 16, 18, angle steel No. 8, 9, rebar sections No. 14, 16, autobody of different structures and sizes, axles, plowshares, etc. The mill has volumetrically strained stands, a sufficiently high rolling speed of 7 m/s and favourable arrangement of the stands, which makes it possible to roll thin-walled sections of medium and large widths with narrow tolerance range. Rolling is carried out in eight stands, arranged in two rows.

## RESULTS AND DISCUSSION

Figs. 2, 4, 6, 8, 10, 12, 14 show cross sections of workpieces for all passes with "witnesses", on which the displacements of screw centers from pass to pass depending on the mode of reduction were determined to analyze the longitudinal and transverse metal flow (Figs. 3, 5, 7, 9, 11, 13, 15). Figures show qualitative curves of relative width compression calculated using standard formulas. All data was obtained experimentally by crosscutting the rolled billet and measuring the "witness" reference points after each pass.

### First pass

When forming the wheel rim in the first pass (Fig. 2), a cut gauge is used, that splits the strip into separate sections where the onboard, locking and central parts of the section are formed. In this gauge, there is a significant unevenness of reduction across the width and height, where at the initial moment from the side of the upper roll the metal is in contact with the tool in the places of the largest protrusions (Fig. 2). This results in longitudinal and transverse bending of the rods. For the rod 5 in the area of the future lock part, located in the zone of maximum reduction, it is seen that in addition to the bend, it has a thickening of the diameter on the side of the upper roll. The metal moves freely in a transverse direction towards the upper connector of the gauge. This contributes to the development of vertical

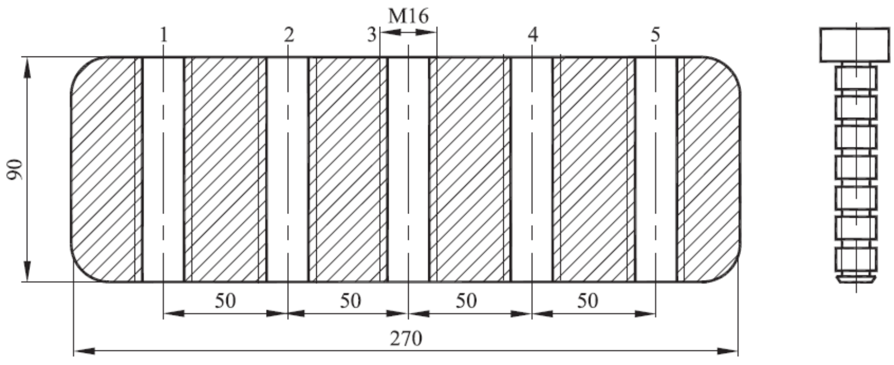


Fig. 1. Location of "witnesses" in the workpiece, 1...5 - order of screws.

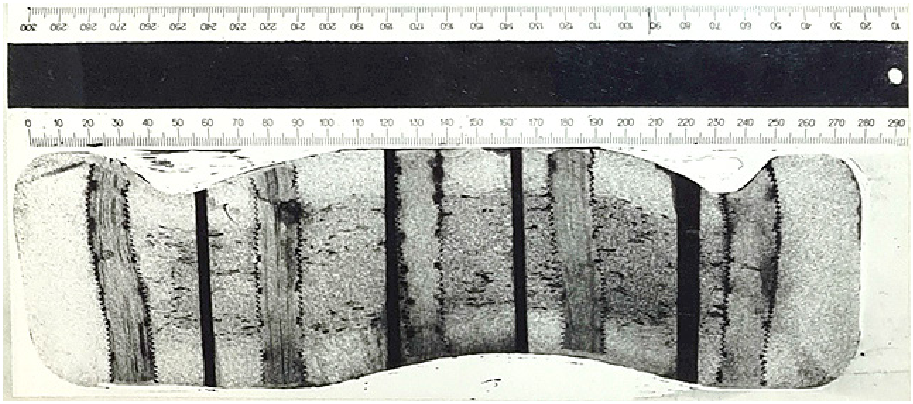

Fig. 2. Location of "witnesses" after the 1st pass, 1...5 - location of screws.

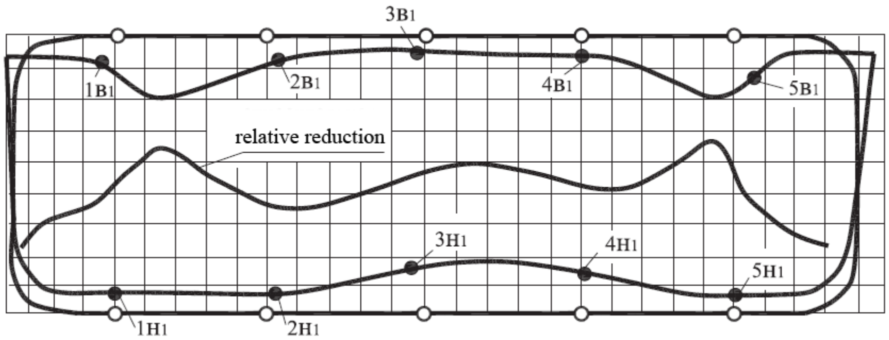


Fig. 3. Scheme of transverse movement of screws after the 1st pass. The white dots (o) show the witness reference points on the workpiece before deformation. The dark dots (•) are the witness control points on the workpiece after deformation. Relative width compression curves, calculated using standard formulas.

strain in this element of the strain zone. At the opposite end of the screw 5 there is no such movement due to the limitation of the extension and there is no such impact from the roll. Vertical strain in this zone is lower, and that is determined by the diameter of the "witness" in its lower part.

The nature of transverse bending of edge rods 1.5 in the area of side and lock parts shows that on the side of the upper roll the metal spreads out in opposite directions from under the gauge swells, that is determined by the nature of the bending of the upper parts of the "witnesses". The bend of lower parts of the screws is fixed in transverse direction and on the side of the central swell of the lower roll. The screws on the opposite side are not warped. In lateral areas on the bottom surface there is practically no transverse displacement of screws. This indicates a different effect on the metal of the tool at different points of strain zone. Different zones of plastic flow appear in terms of intensity. Obtained data and those of the authors show that the plastic strain in certain parts of the gauge is determined by the shape of the tool [20]. This is due to the possibility of transverse metal flow in this area. If this flow is limited or there is a counter displacement of surfaces from the side of the pressing tool, the vertical plastic strain is minimal or missing at all, that is clearly illustrated by the example of forming a rhombic profile in a rhombic gauge that has closed roll channels [21].

Fig. 3 shows that the centers of "witnesses" in the first pass from the zones of higher reduction move to the areas of lower reduction or pressure, i.e. the reduction from the upper and lower rolls determines the movement of witnesses on the upper and lower surfaces of the section.

Comparing the displacements, it should be noted that they are limited to the sections of maximum and minimum strains. There are transverse shear strains. They can change their sign along the width of the gauge

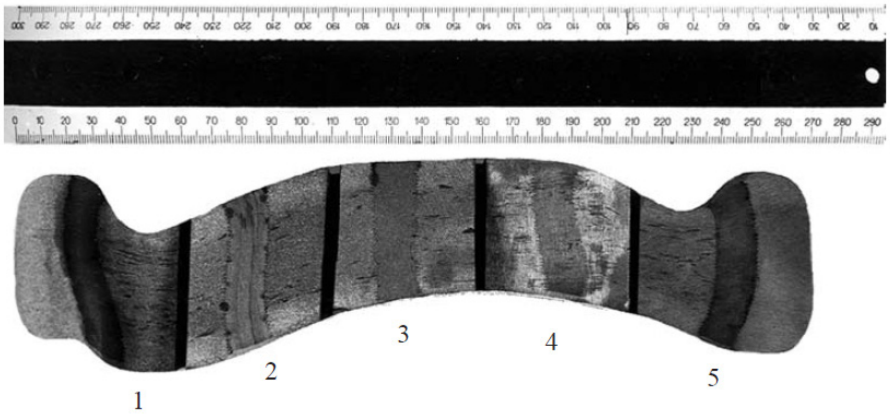


Fig. 4. Location of “witnesses” after the 2nd pass, 1...5 - location of screws.

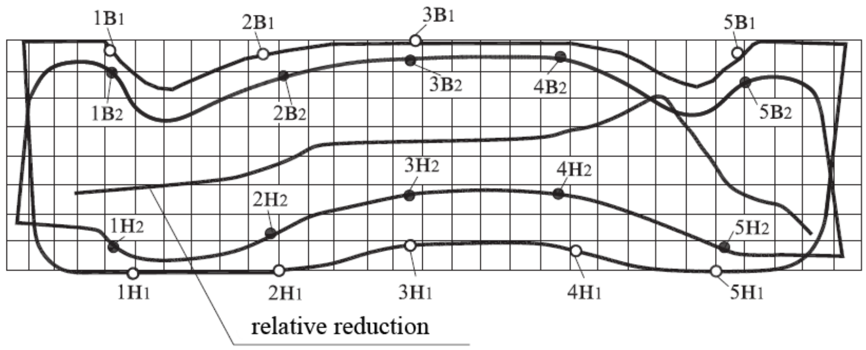


Fig. 5. Scheme of transverse movement of screws after the 2nd pass. Screw centers “witnesses” of the 1st pass (o) and after strain in the second gauge (•).

due to the action of the tool.

Zones of transverse strain tension in the volume alternate with zones of plastic reduction, increasing in the latter case the drawing capacity of the strip in some areas. The position of experimental points of the reduction curve, where there is a change in the sign of transverse strain, determines the metal flow interface affecting the filling of the gauge in the lateral zones.

**Second pass**

The shape of the section and the strain mode determine the nature of metal flow in a given pass (see Fig. 4).

In the second rolling pass it is possible to set the reduction coefficients so as to reduce the influence of non-uniformity of plastic strain on the transverse flow of metal. The graph of relative reductions (Fig. 5) shows that the reductions across the width of the strip are asymmetrical and there is a peak in the right part of the gauge, in the area of the groove for the hook.

Significant asymmetric unevenness of reduction is acceptable in roughing gauges where the metal temperature is high enough, and a large strip thickness reduces the influence of underlying friction forces. Reduction on the lower roll side is greater than on the upper roll side, as evidenced by the profile geometry after the second pass. Measurements of “witnesses” center positions along the length of the temple show that orientations of the upper and lower centers are different in the rolling direction. The upper layers of metal are ahead of the lower layers. In places with high reduction, the screws have moved further back in longitudinal direction than in places with lower reduction. This is due to the drafting ability of the rolls in longitudinal direction that is determined by the “sloping” movement of the metal.

The more reduction on the lower roll side, the more the lower layers lag behind the upper layers. Unevenness of reduction also shows itself through the stress state. On the upper surface of the strip, metal has marked a withdrawal from the screws under the tensile stresses. On the opposite surface, where the reduction is greater and the underlying effect of reduction stresses is more significant, the opposite phenomenon occurs; the empty spaces in the metal are welded.

In the central part there are transverse bends of the screws in opposite directions on the side of the contact surfaces. The central “witness” 3 has no such bend. There is a shear effect of the inclined roll surfaces to the left of the central screw in one direction and to the right - in the opposite direction. Predominant metal flow is along the surfaces in opposite directions in height. Linear and shear flows are determined by contact stresses. Normal contact stresses and specific frictional forces can be directed in opposite directions, and this increases transverse shear. The third screw, located at the top of the central section of the profile, has no bends in transverse direction due to the absence of transverse shear components of normal pressures. The complex nature of flow in local volumes does not affect the overall pattern of metal movement. It can be seen (Fig. 5) that the centers of “witnesses” on both sides of the upper and lower rolls in the cross direction shift according to the mode of reduction and the metal tends to flow from zones of greater reduction to zones of less reduction. Analysis of the shape and position of the fifth screw, located in the area of the locking section, shows that in the section of maximum reduction there is the interface line of metal flow. Particles move in opposite directions. Since the thickness of the strip is large, the metal, despite the complex geometry of the profile, can move in a transverse direction along the lines without a sharp change in direction. The nature of contact stresses can have a mutually opposite direction, and this reduces the effect of contact friction and creates favorable conditions for the transverse flow of metal.

The first screw, having the same shape as the fourth, indicates that the shear of the metal in the transverse direction in the area of the side part is similar to the shear in the right part of the central element. And these shears have the opposite sign compared to the profile element located in the area of the second screw. Metal in the local volume moves in opposite directions: toward the swell area on the upper roll and toward the base of the sidewall stand on the lower roll.

Analysis of the second pass strain suggests that in the areas of inclined sections, the profile is formed not only due to different in magnitude vertical strain, but also due to alternating transverse shifts.

**Third pass**

The cross section of the strip with “witnesses” after the third pass is shown in Fig. 6. In relation to the second pass, the orientation of the first “witness” and the location of the screws on both surfaces of the gauge have changed. The first, second, and third “witnesses” are positioned on the top surface about the same line (from the side to the locking part). The fourth and fifth are somewhat backward. This longitudinal positioning of the screws also takes place on the underside. An interesting fact is the appearance of internal layers of metal on the surface of the strip.

The side surfaces of the “witnesses” (from the first to the fourth screw on the upper surface) are renewed during reduction. In the third pass, the strip width strain is very uneven. Superimposed contours of the gauge templates after the second and third passes with marked centers and a graph of the relative reductions

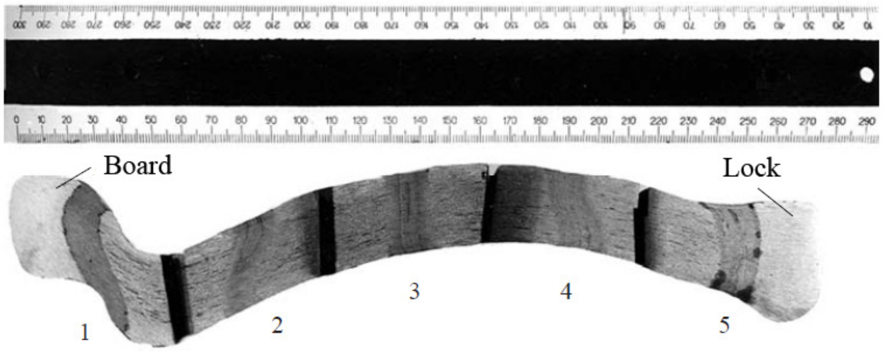


Fig. 6. Location of “witnesses” after the 3rd pass, 1...5 - location of screws.

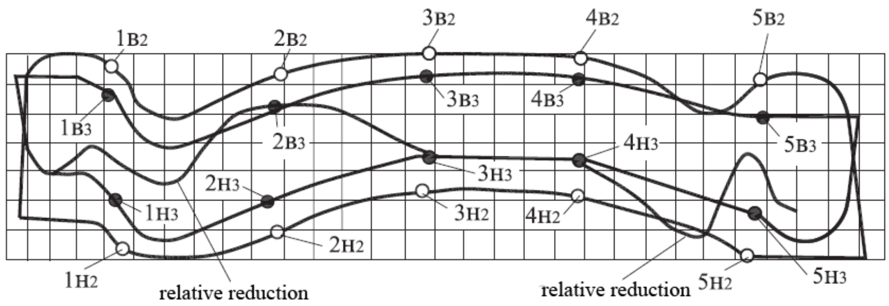


Fig. 7. Scheme of transverse movement of screws after the 3rd pass. Screw centers "witnesses" of the 2nd pass (o) and after strain in the three gauge (•).

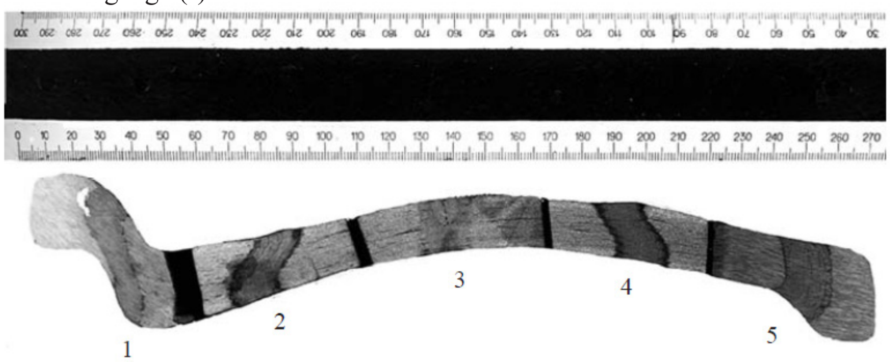


Fig. 8. Location of "witnesses" after the 4th pass, 1...5 - location of screws.

in width are shown in Fig. 7. In this case, the maximum reduction is located on the left side of the profile, in the area of the upcoming tapered section and the adjoining bed. The screws are tilted uniformly in relation to the rolling direction.

The analysis of "witnesses" movements shows that the metal "spreads" in opposite directions relative to the zone of maximum reduction. The metal flow interface is on the left side of the profile. Metal flow in the right side occurs in most of the strip in the same direction. Minor variations in the vertical strain in the area of the lock part do not change the general trend in the movement of metal to the right. In the shank area, there is also a tendency for the metal to flow into the lower reduction area, but shear strains prevent such movement.

Metal flowing from element to element can be interpreted as lateral reduction, increasing its draw. Thus, it is possible to link the data on the transverse flow of metal with the calculation of kinematic parameters of rolling complex sections.

Double bending of screws with numbers one, two and four is explained by shear strains and inclination of pressure surfaces. The transverse components of normal roll pressures form pairs of forces that contribute to these strains. The third screw has no bends, with direct reduction on the roll side at the bend in the bed.

**Fourth pass**

The shape of "witnesses" after the fourth pass repeats the shape after the third pass, which is determined by the geometry of the rolls and profile (Fig. 8). Inclined areas contribute to metal shear in the transverse direction, and a change in the sign of these shifts is determined by a change in the slope of the pressure surfaces. It should be assumed that on the inclined sections the reduction is formed due to shear strains. This contributes to the intensification of the process, reducing contact pressures and the possibility of stable filling of necessary sections of the profile.

The fourth pass is characterized by a high degree of strain on the bed in comparison with other elements of the profile. In the area of the shank stand, the relative reduction is small due to the possibility of large axial forces. Quite large reductions are also in the right part of the profile.

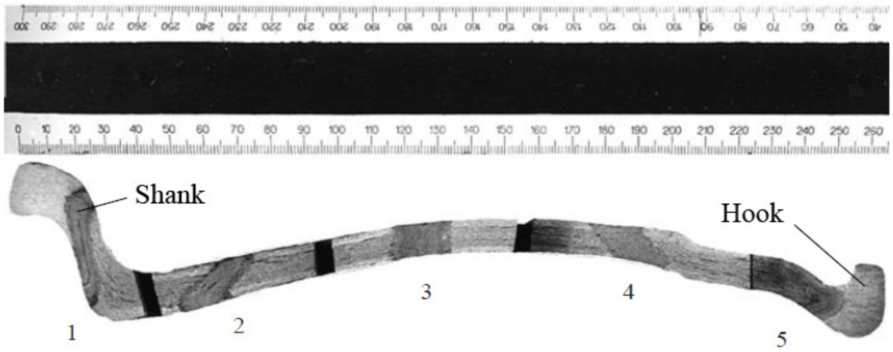

Fig. 9. Scheme of transverse movement of the screws after the 4th pass.

The upper screws are slightly farther away from the lower screws, because their displacement along the length of the strip gradually begins to increase due to the geometric factor. Free space formed in previous passes is welded. Internal metal layers continue to surface in the longitudinal direction.

The nature of metal transverse flow in the fourth pass is somewhat different from the previous ones. The high degree of strain across the bed and, roughly, its uniform distribution in this zone gives no advantage in the character of transverse flow. Here, shifts play a decisive role due to the action of inclined roll surfaces (Fig. 9). Fig. 9 shows that the "witnesses" moved to the right compared to the previous pass in the right part and to the left in the left part of the profile.

The bed is rolled with backing and gives away excess metal to the left and right of the profile inflection line or the metal flow interface line. It should be emphasized that the metal moves in the area with less reduction, but this movement can be of a different nature.

**Fifth pass**

The fifth pass refers to the finishing passes, where the filling of end elements of the profile determines the quality of the finished product. The peculiarity of this pass is the formation of a hook groove, which causes intensive reduction of the formed area. The roll's shoulder is introduced into the prepared part of the profile, where a local "cut" of the strip is made. As a result, the metal spreads out on both sides of the shoulder increasing the height of the "jaw" at the same time. This often leads to overfilling of the gauge and the formation of a "sunset" in the subsequent pass. On "witnesses" after the fifth pass (see Fig. 10) it is visible that metal at the opposite end of the profile moves from the tail part of the profile to the rack, i.e. in the inner sections of the profile flows from the area of greater reduction to the area of lesser reduction (to the rack of the shank). The end element, the shank, has no extension and is retracted by moving the particles towards the less crimped area - the rack. This is an interesting fact, because the strip widening appears as an increase in its width, while at the same time, having the overflow into the neighboring less reduced element; there is a decrease in the overall width of the profile, i.e. tightening.

In the area of maximum reduction the transverse size of the second "witness" from the side of the upper roll decreased significantly (Fig. 10).

The relative strain across the bed is unevenly distributed (Fig. 11).

The second peak of reduction is marked in the left part of the profile, in the area of tapered section that is associated with compensation for possible curvature of the strip in the process of leaving the rolls. Strain along the shank is quite large. Its magnitude and relation to the strain along the shank stand determines the widening or tightening of the shank in the transverse direction.

Significant "witnesses" distortion along the length of the strip is noted, where the upper parts of screws are farther away than the lower parts. However, the reduction on the side of the upper roll is much higher than on the side of the lower roll (Fig. 11). Free space formed in previous passes was welded, which is explained by significant reduction stresses. To a greater extent than in the fourth pass, there is an output on the surface of the inner layers of the metal.

In the fifth pass, as in the previous one, there is a transverse flow of metal (Fig. 11). At a uniform strain

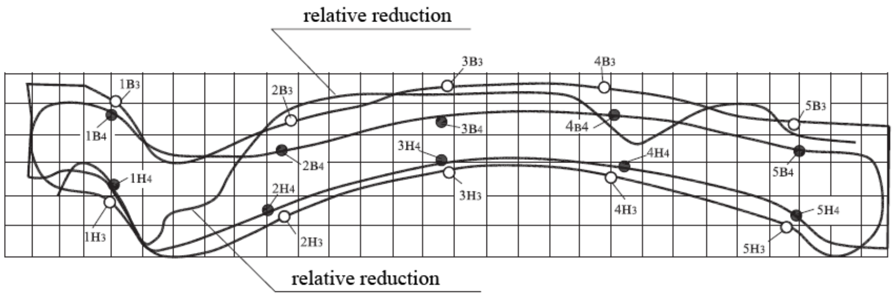


Fig. 10. Location of "witnesses" after the 5th pass, 1...5 - location of screws.

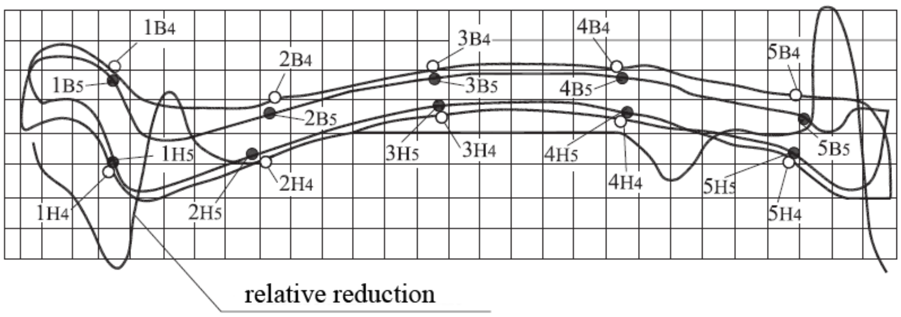


Fig. 11. Scheme of transverse movement of the screws after the 5th pass.

along the bed of the thin-walled part of the section, a metal flow interface line is outlined in the bend zone of the bed. The artificial symmetry line is defined as the line of flow interface. In this part there is a displacement of metal to the right relative to the line of maximum strain and to the left, from the left side of the bed. There is a transverse reduction of the plastic medium that leads to a decrease in the diameter of the screw.

Metal displacement in the transverse direction of the right part of the profile is realized at a sufficiently large distance, the hook area is intensively reduced. Deformation analysis of the fifth screw shows that on the upper roll side it is reduced more intensively than on the lower roll side: the left upper half of the notch shifted to the left, the right lower half of the base shifted to the right. Maximum reduction zone is in the notch, where there is a movement of particles in opposite directions. In this part of the profile metal counter flow is possible, which contributes to transverse reduction and an increase in longitudinal drawing. At such kinematics of flow, the center of the screw is displaced to the right, it was fixed during processing of experimental data (Fig. 10).

The distortion of the second and fourth "witnesses" in the transverse direction increased, indicating an increase in the influence of the geometric factor and shear strains.

In transverse directions there are local strains of reduction and extension associated with the places of maximum and minimum reductions. It is of interest to shape the profile by shear strains which can be obtained not only by tilting the pressure surfaces, but also with a certain kinematics of the metal flow.

**Sixth pass**

Fig. 12 shows the "witnesses" after the sixth pass. In the area of the shank stand, transverse strain is difficult, although there is metal movement from the shank to the area of minimal reductions (stand). In addition, the first screw in the area of the lateral surface of the side part (turning the top of the screw) has some local thickening which is typical for intense flow of metal under pressure surface. On the side of the lower roll there is a decrease in the thickness of the "witness", this determines the reduction of the rack in the transverse plane. The second "witness", as in the previous pass, has a smaller width at the contact with the top roll.

Reduction mode in the sixth pass, with some exceptions, is similar to the fifth pass: uniform distribution of reduction along the width of the bed, minimum reduction along the stand with subsequent increase towards the shank. There is a local peak of reduction in the area of the groove. It is caused by

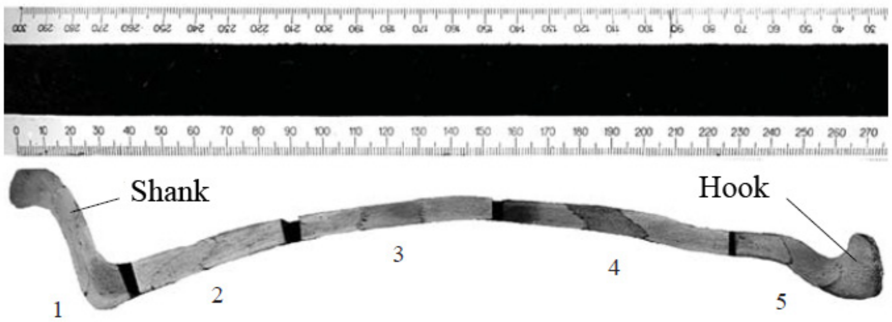


Fig. 12. Location of “witnesses” after the 6th pass, 1...5 - location of screws.

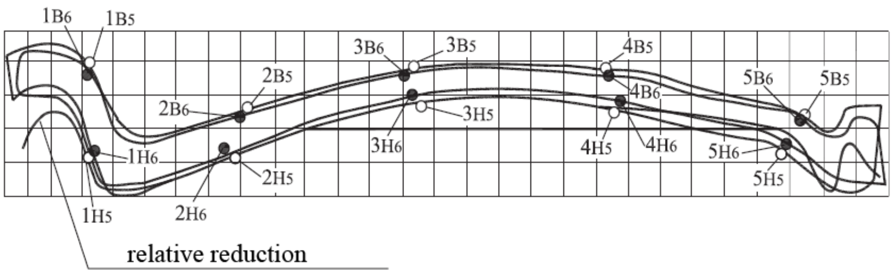


Fig. 13. Scheme of transverse movement of the screws after the 6th pass.

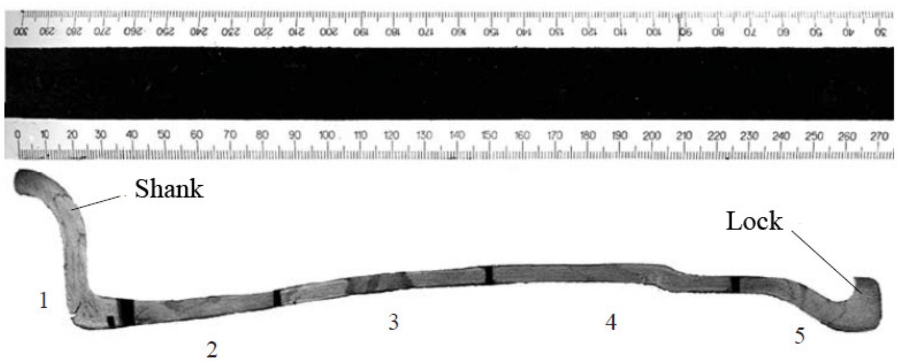


Fig. 14. Location of “witnesses” after the 7th pass, 1...5 - location of screws.

the expansion of the hook’s groove in the transverse direction.

The longitudinal distortion of the “witnesses” along the length of the strip and the offset of the “witnesses” along the width also increases. Transverse metal flow in the bed area is the same as in the fifth pass (Fig. 13).

The metal slightly spreads out relative to the flow interface (bed bend) in opposite directions.

In the right part of the profile (profile groove) metal particles move to the zone of minimum reductions, i.e. to the right (Fig. 13).

The fifth screw has a significant bend in height (Fig. 12), which is associated with the previous modes of plastic strain and shear reduction in the direction of the hook jaw.

As mentioned earlier, local strains in different areas of the strip during the formation of individual elements of the profile play a significant role.

**Seventh pass**

The seventh pass has the same pattern of width reduction and strain as the previous passes and corresponds to the whole group of finishing gauges when rolling the auto rims. The strain effect on the metal in the area of the first screw on the side of the top roll is intensified (Fig. 14).

Fig. 15 shows that the transverse flow of metal in the finishing pass corresponds to the patterns that were noted earlier in the previous finishing and roughing passes. The metal spreads in opposite directions at the

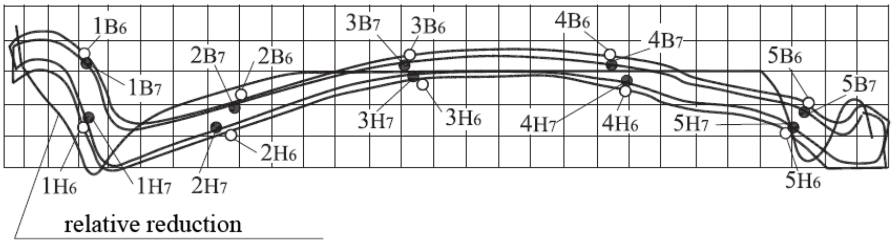


Fig. 15. Scheme of transverse movement of the screws after the 7th pass.

bend point in the central part of the bed and moves to the minimum reduction zones.

An increase in the diameter of the "witness" in the lateral part of the shank can be seen. At the same time, from the side of the lower roll a space where metal is "sucked" from the shank into the rack was determined. The rod does not come out on the surface of the strip in all finishing passes. Obviously, this circumstance explains the tightening and increment of the shank in the finishing gauge (Fig. 14).

As in the sixth pass, there is a local peak of plastic strain in the hook area in the right part of the profile, which is associated with its final formation (Fig. 15).

## CONCLUSIONS

Summarizing this study, we can note that there is a clear impact of uneven reduction across the width of the strip on the overall and local strain of the metal in the transverse and longitudinal directions. The metal moves from areas of greater reduction to areas of lesser reduction, which leads to the appearance of metal flow interface lines, areas of transverse strain reduction and stretching. Areas of interest are those where the sign of transverse plastic strain changes.

In roughing gauges, where the movement of large amounts of metal in different directions is limited to the surface of a single roll, areas of delayed strain appear. Plastic strain is limited in areas where all-round strain reduction on the tool side is realized. Metal flow section and pressure surface geometry is defined. In finishing passes, the profile bend changes the sign of shear strains, hence the change in direction of transverse flow of metal occurs. Shears contribute to the complex metal flow in the shank area and the shank stand. It was found that in the last passes the metal moves from the shank to the stand indicating that the metal flows from the areas of greater reduction to the area of lesser reduction. Moreover, the peculiarity of metal flow in the tail section of the profile in the last sections along the rolling path is the countercurrent flow of metal. The nature of "witness" strain shows that the metal moves from the rack to the shank on the upper roll, while on the side of the lower roll the metal moves in the opposite direction - from the shank to the rack. Strains are accompanied by significant shifts in the area adjacent to the shank. The complex nature of metal flow in this element leads to the need for large tolerances on the width of the shank (± 3 mm).

Thus, shears can form separate sections of the profile. Analysis of the experimental data shows that there is a significant influence of unequal width of reduction on the kinematics of metal flow in different directions.

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