UDC 621.73.043.62-52
DOI: 10.37128/2520-6168-2025-1-2

RESEARCH OF THE KINEMATICS OF FORMING COMPLEX-PROFILE PRODUCTS OF AGRICULTURAL MACHINERY MANUFACTURING DURING ROLLING STAMPING

Vitalii YANOVYCH, Doctor of Technical Sciences, Professor
Andrii SHTUTS, Candidate of Technical Sciences, Senior Lecturer
Iryna HUNKO, Candidate of Technical Sciences, Professor
Lyudmila SHVETS, Candidate of Technical Sciences, Associate Professor
Vinnytsia National Agrarian University

ЯНОВИЧ Віталій Петрович, д.т.н., професор
ШТУЦЬ Андрій Анатолійович, к.т.н., старший викладач
ГУНЬКО Ірина Василівна, к.т.н., професор
ШВЕЦЬ Людмила Василівна, к.т.н., доцент
Вінницький національний аграрний університет

The article investigates the kinematics of forming agricultural machinery products during rolling stamping (RS), focusing on the peculiarities of local deformation of the workpiece material and the possibilities of controlling material flow. Rolling stamping of workpieces is an important non-stationary rotational process used for metal forming under pressure, particularly in the production of complex-profile products for agricultural machinery manufacturing. This process involves rotating rollers that act on the workpiece material in an axial or inclined direction, promoting its local deformation. The localization of the plastic zone allows reducing deformation forces, thereby improving forming processes. The essence of this process lies in the fact that the workpiece material is subjected not only to compression but also to stretching, allowing for the production of high-precision and complex-shaped products.

Controlling the direction of material flow is a crucial aspect of achieving the desired geometric and mechanical properties of products, as this factor determines the accuracy and quality of the finished parts. In agricultural machinery manufacturing, such parts must not only have complex geometry but also possess high-performance characteristics, which is critically important under agricultural production conditions where parts must withstand significant mechanical loads and harsh operating environments.

Using analytical geometry and theoretical mechanics, the kinematics of the RS process with a conical roller was modeled. It was found that the radial flow of the workpiece metal is caused by the action of the radial component of the sliding friction force, which arises due to the different orientations of the velocity vectors of the workpiece and the tool in the contact area. The direction and intensity of material flow are determined by the angle between these vectors. The main parameters influencing the direction of material flow during RS are the tilt angle of the roller axis α, as well as the magnitude and direction of the roller apex displacement δ relative to the workpiece rotation axis.

For a more detailed analysis, simulation modeling of the RS processes using the finite element method (FEM) was applied. A computational model was developed, consisting of a cylindrical tube workpiece, a deforming conical roller, a die, and a mandrel. The distribution of deformation intensity in the flange at various deformation stages was obtained. The modeling results enabled the development of models describing the influence of technological parameters on shape change and the stress-strain state of the workpiece.

The research confirmed the possibility of expanding the technological capabilities of the rolling stamping process by controlling the flow of the workpiece metal. The use of simulation modeling improves the accuracy of predicting the kinematics of product formation, which is important for optimizing production processes in agricultural machinery manufacturing.

Key words: *rolling stamping, cylindrical roller, tubular products, elastic deformation, complex-profile workpieces, research, analysis, mechanics, forming, stress-strain state, forces, agricultural machinery manufacturing.*

Eq. 7. Fig. 8. Ref. 14.

1. Problem formulation

The rolling stamping (RS) process provides advantages such as high dimensional accuracy, minimized material waste, and reduced energy consumption. However, due to the complexity and multifactorial influence of various parameters, such as the roller tilt angle, roller apex displacement, and others, this process remains insufficiently studied. The uncertainty regarding the impact of these parameters on forming results limits opportunities for optimizing the technology.

Research in this area is of great importance since the effectiveness of the process depends on the accuracy of predicting kinematic characteristics. Modern modeling and simulation methods, particularly the use of the finite element method (FEM), allow for a more precise study of the influence of various technological parameters on the rolling stamping process. However, the lack of sufficient research on material flow control and forming in such processes necessitates further in-depth studies to expand the capabilities of rolling stamping, improve its accuracy, and enhance its economic efficiency.In particular, the development of models that enable the prediction and precise control of material flow direction is crucial to ensuring the reliability and durability of agricultural machinery and its components.

2. Analysis of recent research and publications

The study investigates the properties and stress-strain state of the surface layer of workpieces during the modeling of plastic deformation processes. Special attention is given to examining the impact of key technological parameters, such as the tilt angle of the roller axis and the displacement of the roller apex relative to the workpiece rotation axis, on the direction and intensity of material flow during the rolling stamping (RS) process. This enables precise process adjustment to obtain complex-profile products with specified characteristics.

Plastic deformation (PD) is used to shape the required operational properties of the surface layer and finished products as a whole. PD methods are classified into static and impact methods. In static methods, the working tool acts on the surface with a constant force, including various types of smoothing, rolling, burnishing, swaging, and mandrel processing. In impact methods, the tool acts on the part with a variable force. Impact methods include shot blasting, ultrasonic, centrifugal, vibrational processing, impact rolling, strengthening, peening, and more. Forming tools and working bodies such as rollers, balls, smoothers, mandrels, and shot are used.

The development of PD processes is driven by their ability to alter surface roughness and relief, as well as the strength and plasticity characteristics of the material in the surface layer. These processes increase hardness and residual stresses and change the material's structure and texture. Research shows that using static and impact methods with similar impact loads and application frequency can yield different results. Static PD methods typically provide lower surface roughness with a favorable micro-roughness profile, while impact methods can achieve a higher degree of strengthening. However, due to the complexity and instability of PD processes, predicting surface layer characteristics and product quality solely based on previous studies and their analytical generalizations is not feasible.

The most general characteristics for shaping operational properties are the strength and plasticity of the material, as well as the level of residual compressive stresses in the surface layer of the product treated with PD. Information about the magnitude and distribution pattern of accumulated deformation and the residual plasticity resource in the surface layer is particularly important. These characteristics determine the material's ability for further plastic processing and, combined with the acquired residual stress, are critical for enhancing the durability of products.

Recently conducted studies of the effect of PD on the final plasticity of the material [1,2,3] are mainly theoretical in nature, which does not allow taking into account the influence of all the main features of deformation on the depletion of the plasticity resource by the material and on the quality of the manufactured products. Experimental and computational methods [4] are recognized as more effective when analyzing the deformability of metals in the case of surface hardening of parts. Using these methods, we conducted studies aimed at evaluating the influence of PD parameters on the service characteristics of products [5].

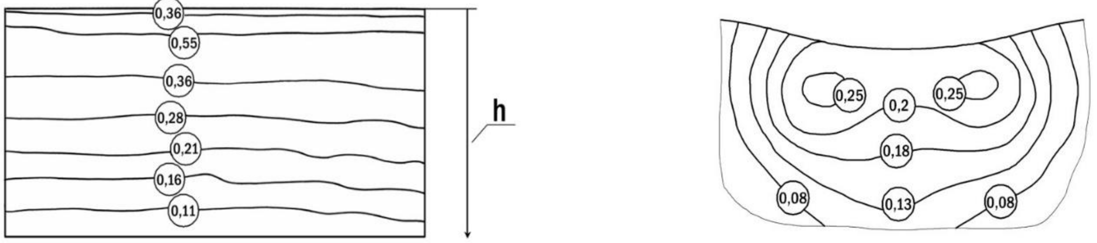
The main parameters of PD, which form the service characteristics of the surface layer and the product as a whole, include: area and form of contact of the tool with the workpiece; the amount of elastic and plastic deformation in the area of deformation, incl. the dimensions of the plastic area and the nature of VAT changes; force or energy of impact of the tool on the workpiece; multiplicity of impact of the tool; the magnitude of friction forces, characteristics of thermal processes, etc.

To study the processes of plastic hardening and the degree of influence of various factors on the surface layer, we implemented modeling of PD by single and multiple pressing of balls into a plane, as well as multiple pressing of a roller with displacement along the hardened surface. The tests were carried out on the EP718 alloy, which is high-tensile, with a strong dependence of the hardness HV on the intensity of deformations ε_i. This makes it possible to determine both the intensity of stress σ_i and the intensity of deformations ε_i with a high degree of accuracy by measuring the hardness at relatively high degrees of deformation. The deformed state of other steels and alloys with the same dimensions of the center of tool penetration and contact conditions of friction will be similar.

Research was carried out by pressing balls to different depths with different boundary conditions: dry, and also using colloidal graphite, polyethylene, lead and copper foil as lubricants.

Then the samples were cut by the electrospark method along the diametrical plane of the print, filled with epoxy resin in the holders, ground and carefully polished in conditions that excluded slander from processing. Vickers hardness (HV) was measured on the prepared sections in the impression zone with a load of 50 N on the indenter. In addition, the microhardness (μHV) was additionally measured in the narrow near-contact area under a load of 1N and a stable hold of 15 seconds. Thus, more than 20 impressions obtained under various pressing conditions were processed.

In fig. 1, and the typical nature of the distribution of the degree of deformation in the impression zone, obtained by the hardness change method, is given.



a) ***b)***

Fig. 1. The nature of the distribution in the plastic region of the imprint is isoline $\varepsilon_i = const$ ***obtained from the results of hardness measurement during single (a) and repeated (b) indentation of the ball with displacement along the surface.***

As follows from fig. 1, a, the character of the deformed state in the imprint zone is very uneven. The degree of deformation at the surface of the hole is only 50–80% of the maximum. The greatest degree of deformation occurs near the center of the print and is further away from the contact surface ≈0,1 d, where d is the diameter of the imprint or its width. The maximum degree of deformation in the impression zone can be approximately determined by the ratio ε_i^{max}≈(0,4. 0,5) d/D, and the depth of the plastic zone h_{pl}= (1,4...1,6) d, where d and D – diameter of the imprint and the ball respectively.

Thus, if it is necessary to provide a thin, strongly reinforced layer, then it is necessary to use deforming bodies with a small diameter, appointing a multi-pass process, with the greatest possible relative depth of penetration. In the case of a need for a deep, moderately hardened surface layer, it is necessary to appoint a low-transition process of surface deformation with bodies of relatively large sizes.

The non-uniform nature of the deformation distribution is mainly caused by contact friction. A similar picture is observed during the sedimentation of cylindrical samples, when stagnant zones with a reduced level of deformation are formed due to friction on the contact of the sample with the tool. In the presence of lubricant and intermittent load application, the unevenness of the deformed state is reduced.

Detailed studies of the zone of plastic deformation during shot peening (dry friction) and hydroshot peening (liquid friction) are given in [7, 10]. A comparison of the impression zones on D16T and VT8 alloys showed that the following characteristics increase with hydroblasting compared to shot blasting: the depth of the hole up to 20%, the relative location in the radial direction of the top of the plastic roller around the impression - up to 34%, and the radius of the roller - 2.6 times when the relative height of the roller is reduced to 40%.

As for the physical side of the process, overcoming dry friction, which takes about 30% of the impact energy during shot peening, leads to the following consequences [9, 10]:

- firstly, to the unevenness of the deformation under the strengthening layer, characterized by the presence of barrel-likeness (the coefficient of barrel-likeness for the central "column" in the area of the hole reaches 14 with the expansion coefficient of up to 36%). This, mainly, predetermines the reduction of final stresses on the surface of the hole;

- secondly, in the process of shot peening, ≈30% of the energy of the pellets is spent on overcoming contact friction, which leads to instantaneous additional heating of the surface layer of the part to significant temperatures (Al 2024-T4≈390 °C, Ti-5Al-2.5Mo≈790 °C) and, as a result, to thermoplastic deformations, leading to a decrease in the level of compressive ultimate stress in the surface layer. During hydroblasting, the energy of the impact is mainly used to increase the volume of the plastic zone and the degree of deformation with the corresponding heating of the entire deformable metal by 2–7 °C, which practically does not affect the change in final stresses.

The noted nature of the distribution of the deformed state in the depth of the surface layer is also observed during multi-transition deformation (with displacement of the deforming body along the surface) (Fig. 1, b). In this case, the pre-extruded rollers are alternately transformed into wells. An intensive increase in hardness is observed only at the first stages of deformation, then the intensity decreases. Taking into account the fact that the accumulation of deformation occurs throughout the PD process, this fact can be explained by the decrease in the intensity of metal hardening as the deformation increases. In other words, the metal goes into a state corresponding to the saturation section of the hardening curve σ_i (ε_i), and its hardness and strength do not increase with subsequent deformation.

At the same time, along with hardening, a softening of the metal occurs in the surface layer, caused by the Bauschinger effect due to a change in the sign of deformation. Particularly intensive softening is observed in the case of over-lapping and excessive accumulation of plastic damage, which leads to a subsequent decrease in the hardness and strength of the processed metal. Thus, the main factors of hardness reduction are:

a) the manifestation of the Bauschinger effect, which consists in alternating sign deformations– increases with the growth of the plastic wave;

b) the presence of contact friction and an increase in temperature in the contact zone;

c) metal deformation and exhaustion of the plasticity resource.

As a result, during long-term plastic hardening, the measurement of hardness does not give an idea of the degree of deformation of the hardened layer. In this case, the hardness characterizes the strength properties of the metal and is indirectly related to the final stresses. If it is necessary to determine the degree of deformation accumulated for a certain number of passes or deformation time, then with the help of hardness measurement it should be determined with a limited number of passes or processing time (the smaller the metal hardening coefficient). The degree of deformation accumulated over the entire processing process can be defined as the total of the passes or processing time (taking into account the step-by-step reduction due to the hardening of the metal, if the deformation is carried out under constant load or impact energy).

Intensive plastic loosening of the material, which is observed at a certain stage of PD and is accompanied by a drop in hardness (microhardness), indicates the further negative influence of the PD process on the service characteristics of the surface layer (Fig. 2, curve 2).

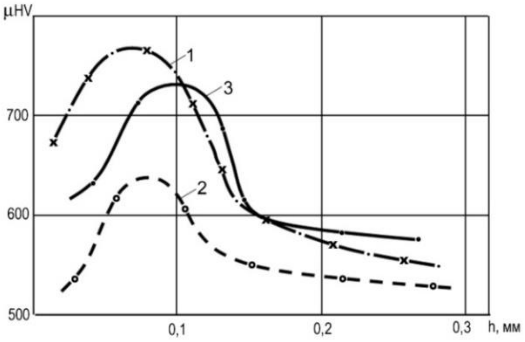


Fig. 2. Characterization of the distribution of microhardness along the depth of the surface layer of the rolling rod with EP718 balls, with different number of passes and amount of crimping: 1 – 2 passes with crimping; 2 – 15 passes, $\Delta h = 0,04\ mm$***; 3 – 1 pass,*** $\Delta h = 0,07\ mm$***.***

According to the data of fig. 2), the maximum value of the intensity of deformations, for curves 1 and 3, was observed at a depth of 0.1 mm and was $\varepsilon_i \approx 0,2$, which was in accordance with the regularities determined by the depth of the ball's insertion and the number of overlaps by the ball's track of the width of the hole of the rolling track. It is no longer possible to determine the accumulated deformation from the results of curve 2.

Thus, hardness measurement can be used to determine the VAT of the material of the surface layer of the workpiece at the initial stages of the PD process and to determine the factors that shift the region of maximum deformations to the surface of the workpiece, as well as criterion limiting the processing process at the moment of the hardness drop of the hardened layer.

For a more complete study of the VAT of the material in PD processes, we used the method of coordinate dividing grids, based on the use of the technique based on the theory of R-functions [1,9]. At the same time, step-by-step pressing of the ball into the workpiece (axisymmetric problem) and multiple (with displacement along the surface) step-by-step pressing of the roller (flat problem) were carried out. Pressing was carried out in a workpiece made of Inconel 718 alloy, having the shape of a parallelepiped with dimensions of 50x30x20 mm and consisting of two identical halves of 50x15x20 mm, connected by pins. A rectangular grid was applied to the plane of the connector of one of the halves with the help of a needle on an instrument microscope. The pitch of the grid along the X and Y axes, due to the different dimensions of the deformation center, was taken to be approximately 0.5x0.25 mm for a flat task and 0.15x0.15 mm for an axisymmetric task. The coordinates of the nodes of the initial mesh were measured on an instrument microscope, then the halves were clamped in a special device and the ball (roller) was pressed in N stages (the undeformed workpiece was considered the zero stage). After each stage, the process was interrupted, the sample was removed from the fixture, and the coordinates of the lth node (l=1,..., L, where L is the number of nodes) of the distorted grid at the nth stage (n=0,..., N): X̃,l (t,n), Ỹ,l (t,n) were measured on an instrument microscope.

Then the sample was collected again, placed in the device and continued the process of de-forming at the next stage. It should be noted that the process may consist of several transitions, at each of which the law of motion of the tool differs. So, in the case under consideration, the ball pressing process consists of one transition, and the roller pressing process consists of three, i.e. to the roller is successively pressed with an offset into different parts of the workpiece.

Coordinate arrays of grid nodes X̃l (t, n), Y, l (t, n) at all stages of deformation are the initial data for determining the kinematics of deformation.

By processing the results of ball and roller indentation experiments, with the use of a computer-developed technique, the accumulated deformation isolines were constructed in the plastic zone of the impression (Fig. 3). The nature of the isoline distribution ε_i=const in the imprint zone (Fig. 3), obtained from the results of the coordinate dividing grid measurement, coincided with that obtained from the hardness measurement results (Fig. 3).

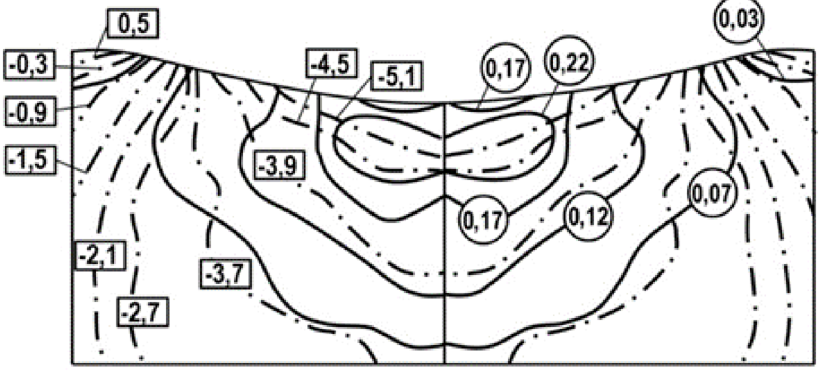


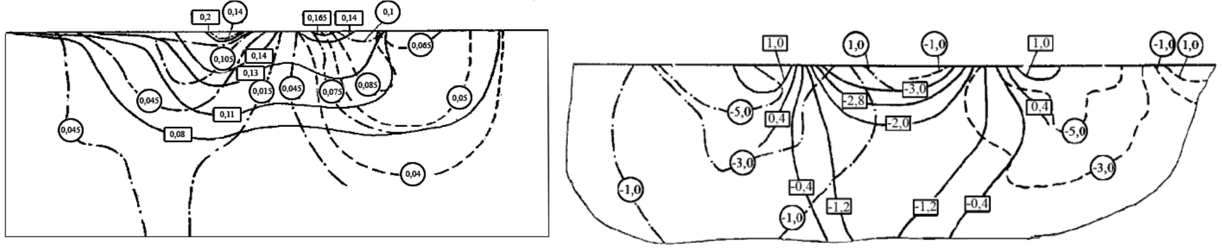
Fig. 3. The character of the distribution in the plastic region of the impression of the ball isolines of the studied characteristics: ☐ – $\eta = const$; ○ – $\varepsilon_i = const$.

In fig. 4 shows the process of formation of a deformed state during step-by-step pressing into the roller workpiece with displacement (three steps).

It has been established that the degree of deformation accumulates during the hardening of the surface layer in the area of overlap of plastic zones of individual prints. And since the indentation is discrete, the value ε_i is unevenly distributed along the surface layer. With insignificant accumulated deformation, when intensive hardening of the metal is still taking place, the hardness values along the hardened surface will also have a scatter.

As a result of alternating indentation, the displacement of a metal particle in different directions is observed, which leads to a change in the sign of the deformation components and the manifestation of the Bauschinger effect. Apparently, the Bauschinger effect and the accumulation of microdamages are the main factors in the reduction of hardness with excessive hardening of the surface layer, as was already noted above.

The indicator η when pressing the ball changes from the values corresponding to all-round compression (η=-5...-3) on the axis of symmetry of the print, to shear-tension (η≥0) at the edge of the hole, in the area of the plastic roller (Fig. 3). In a similar way, the indicator η is distributed in the plastic region at a single indentation of the roller.



a) ***b)***

Fig. 4. The nature of the distribution of the strain intensity $\varepsilon_i = const$ (a) and the stress state indicator $\eta = const$ (b) in the plastic area with three times indentation of a roller with a diameter of 12 mm (print width 2.5 mm, distance between the first and second prints 2 mm) after indentation: _- first; _._._- the second; ______ - the third.

When alternately introducing a deforming body, in particular, when introducing a roller in the area between the formed holes (Fig. 3.4), the indicator η changes slightly. In the center of the newly formed hole, it is equal to η=-2...-4, and at the edge of the hole η=0...1. The increase in the indicator η and, consequently, the tightening of the stress state scheme is explained by the decrease in hydrostatic support on the part of the sample material, caused by the surrounding of the indentation zone with depressions from the previous indentation.

Thus, complex multistage deformation occurs during PD. Its essence consists in the formation of deposits near the extruded holes and grooves with their subsequent pressing. At the same time, there is an alternating transformation of inflows into holes, a change in the sign of the deformation components and the indicator η from η =-2...-4 to η =0...1 for each material point near the surface of the workpiece.

3. The purpose of the article

The purpose of this study is to expand the technological capabilities of the rolling stamping (RS) process by developing methods for controlling the flow of the workpiece material. This will optimize the kinematics of product forming, improve the accuracy of geometric parameters, and enhance the mechanical properties of finished parts.

An important component of this goal is to study the localization of the plastic deformation zone, which reduces deformation forces, minimizes energy consumption, and increases the efficiency of material processing using RS. This is particularly relevant to manufacturing components for agricultural machinery, which require high mechanical properties, wear resistance, and the ability to withstand aggressive operating conditions.

Achieving this goal involves not only analytical modeling of the RS process kinematics but also the application of modern methods. This will allow a more detailed study of the stress-strain state of the workpiece material at different stages of the process and predict the nature of workpiece shape changes.

Thus, the objective of this study is to develop scientifically grounded approaches to controlling material flow during rolling stamping, contributing to improved product quality, reduced production costs, and ensuring the reliability and durability of agricultural machinery.

4. Results and discussion

To model the kinematics of the SH process using a conical roll, the analytical geometry apparatus and theoretical mechanics were used, which concerns the rotational motion of a solid body around a fixed axis. The flow of the workpiece metal in the radial direction is due to the action of the radial component of the sliding friction force. This force arises due to the difference in the directions of the velocity vectors of the workpiece and the tool in the contact zone. Therefore, the direction and intensity of the material flow are determined by the angle between the velocity vectors of the workpiece and the tool.

For a more detailed analysis, a simulation modeling of the SH process was carried out using the finite element method. A tubular cylindrical workpiece and a deforming conical roll were chosen as the calculation model. The modeling showed the nature of the workpiece shaping and the distribution of the intensity of deformations in the collar at different stages of the SH process. Boundary conditions were imposed on the roll for movement along the workpiece axis and rotation around this axis, and the contact between the roll and the workpiece was determined by an automatic surface-to-surface contact algorithm.

One of the main factors limiting the technological application of cold forging processes is metal fracture during plastic deformation. The DEFORM-3D software package has built-in tools for predicting fracture during cold forging. The "default" criterion is the Cockroft-Latham criterion.

$$\int_0^{\bar{e}_i} \frac{\langle \sigma_1 \rangle}{\sigma_i} \cdot d\bar{e}_i = C \tag{1}$$

where $\langle \sigma_1 \rangle = \begin{cases} \sigma_1, \sigma_1 \geq 0 \\ 0, \sigma_1 < 0 \end{cases}$ – maximum principal tensile stress; σ – material constant.

In [13, 14] it is shown that for steady cold deformation ($\eta = const$) model becomes identical to relation.

From this relation it follows that:

$$\lim_{\eta \to -1+0} \bar{e}_{fs}(\eta) = \infty \tag{2}$$

To model the deformation paths depicted by trajectories 1, 2, we constructed a parametrically defined function:

$$\begin{cases} \eta(t) = \dfrac{b \cdot \left(tg(t) - t\right) + a \cdot \sqrt{1+c} \cdot t}{\sqrt{tg^2(t) + c \cdot t^2}} \\ \bar{e}_{eq}(t) = m \cdot \displaystyle\int_0^t \sqrt{\frac{1}{\cos^4 x} + 3} \cdot dx \end{cases}, \qquad t \in \left(0, \frac{\pi}{2}\right) \tag{3}$$

where a, b, c – approximation parameters.

Let's check whether the proposed model of deformation paths satisfies some boundary conditions:

$$\lim_{t \to 0+} \eta(t) = 1{,}7\,, \tag{4}$$

$$\lim_{t \to \frac{\pi}{2} - 0} \eta(t) = -1.5 \div -1. \tag{5}$$

Indeed, for the first condition we have:

$$\begin{gathered} \lim_{t \to 0+} \eta(t) = \lim_{t \to 0+} \frac{b \cdot \left(tg(t) - t\right) + a \cdot \sqrt{1+c} \cdot t}{\sqrt{tg^2(t) + c \cdot t^2}} = \\ = \lim_{t \to 0+} \frac{b \cdot \dfrac{tg(t)}{tg(t)} + \left(a \cdot \sqrt{1+c} - b\right) \cdot \dfrac{t}{tg(t)}}{\sqrt{\dfrac{tg^2(t)}{tg^2(t)} + c \cdot \dfrac{t^2}{tg^2(t)}}} \end{gathered}. \tag{6}$$

Taking into account the first defined boundary:

$$\lim_{t \to 0} \frac{\sin(t)}{t} = 1 \cdot$$

and conditions:

$$\lim_{t \to 0} \cos(t) = 1 \cdot$$

we will have:

$$\lim_{t \to 0+} \eta(t) = a \cdot \tag{7}$$

It follows that the parameter a is equal t $a = 1.7$.

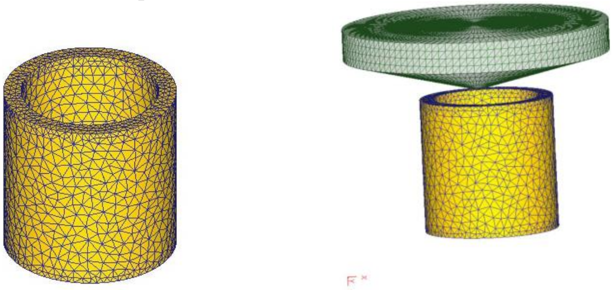


Fig. 5. Modeling the intensity of deformations in the rolling stamping process.

Using the analytical geometry apparatus and the section of theoretical mechanics, which concerns the rotational motion of a solid body around a fixed axis, the kinematics of the process of rolling of workpieces with a conical roll were modeled. The flow of workpiece metal in the radial direction is due to the action of the radial component of the sliding friction force, which in turn is caused by the different directions of the velocity vectors of the workpiece and the tool in the contact spot. Therefore, the direction and intensity of the flow of workpiece material in the radial direction is determined precisely by the angle between the velocity vectors of the workpiece and the tool.

The main parameters that affect the direction of the flow of workpiece material during rolling of workpieces with a conical roll were the angle of inclination α of the roll axis, as well as the magnitude and direction of the displacement of the top of the roll δ relative to the axis of rotation of the workpiece [1]. Analysis of the obtained research results showed that with a positive displacement of the top of the roll (from the axis of rotation of the workpiece in the direction of the contact spot), the material flows from the center of the workpiece $(\varphi < 0)$, and with a negative value – to the center $(\varphi > 0)$. The flow intensity is not symmetrical with respect to zero displacement, i.e. the material flows more intensively in the direction from the center. With increasing angle α, the centrifugal flow intensity increases. The maximum flow intensity is observed at a distance r<0.2 R from the center of the workpiece.

An alternative to experimental research and theoretical analysis is the use of simulation modeling of SH processes using the finite element method. A model consisting of a tubular cylindrical workpiece and a deforming conical roll was adopted as the calculation model (Fig. 6).

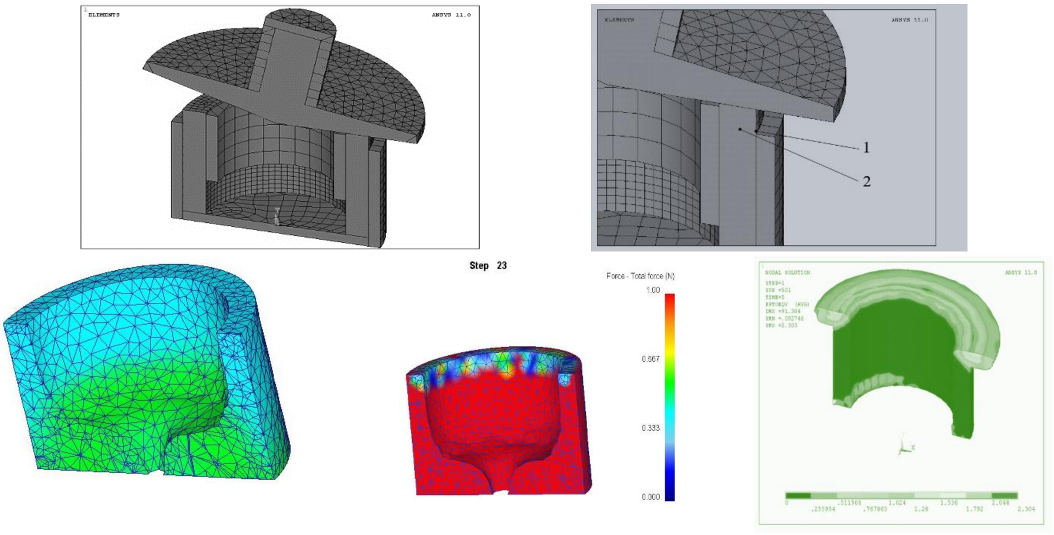


Fig. 6. The nature of the shape changes of the distribution of deformation intensity in the cross section of the collar at different stages of the landing of the SH.

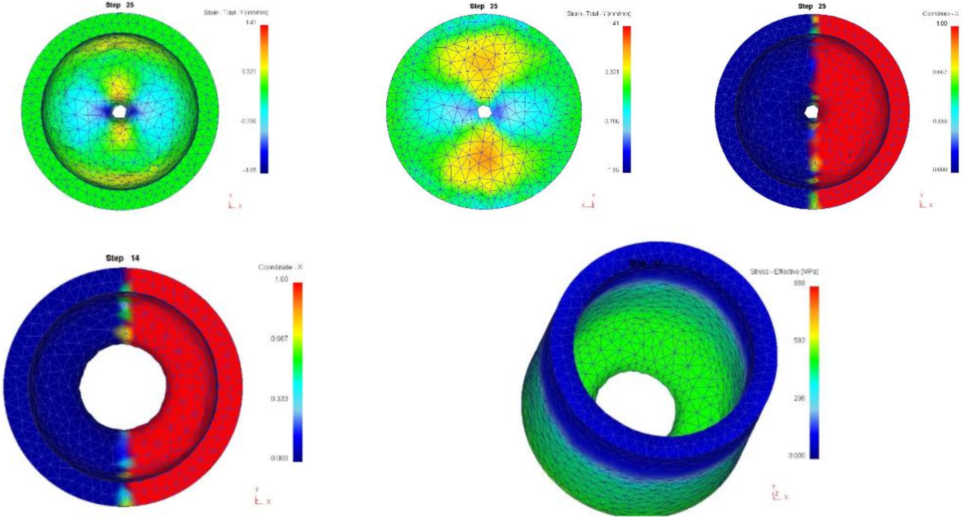


Fig. 7. Distribution of stress intensity in the workpiece material at different stages of the process of forming its inner collar.

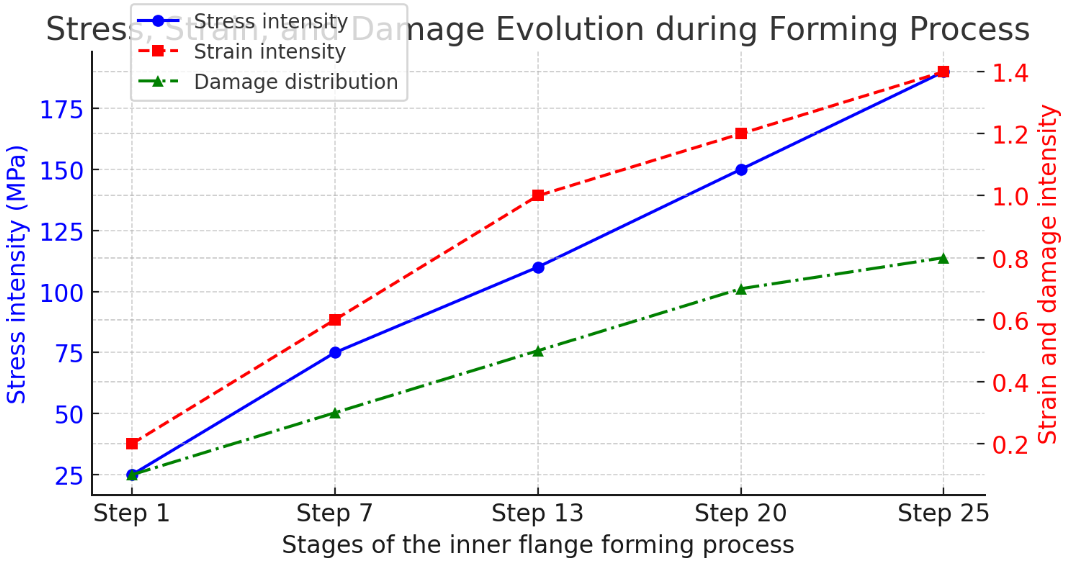


Fig. 8. The graph shows the distribution of stress, strain and damage intensity at different stages of the inner collar formation process. The graph contains three curves: 1. Stress intensity (blue color) on the left y-axis, 2. Strain intensity (red color) and damage distribution (green color) on the right y-axis.

5. Conclusion

The article provides a detailed study of the kinematics of the roll-forming process (RF) for forming complex-profile products of agricultural engineering. It was found that this process has significant advantages, in particular in reducing deformation efforts and increasing the accuracy of manufactured parts due to effective material flow control.

Key results of the study:

1. Roll-forming is an important rotational process that allows achieving high accuracy of geometric parameters of products due to the localization of the plastic deformation zone and reducing efforts at the processing stage.
2. Controlling the direction of material flow is critical for ensuring the desired geometric and mechanical characteristics of finished products, which is especially important for agricultural engineering.
3. Modeling the kinematics of the roll-forming process using analytical methods and the finite element method allows for accurate prediction of the intensity and direction of material flow. This is important for optimizing the technological process and achieving the specified product characteristics.
4. It was determined that the angle of inclination of the roll and the displacement of its top relative to the axis of rotation of the workpiece significantly affect the intensity and direction of the material flow, which allows you to adjust the process to achieve the desired results.
5. The use of simulation modeling has revealed the potential to improve the accuracy of predicting the kinematics of the process, which provides greater economic efficiency and improved product quality.

The study confirmed that methods for controlling the flow of material during rolling stamping can significantly expand the technological capabilities of this process, increasing the efficiency of the production of complex-profile products for agricultural engineering. The results also open up new prospects for further research aimed at optimizing process parameters and improving the mechanical properties of finished products.

References

1. Matviychuk, V., Shtuts, A. (2022). Construction of curve boundary deformations of metals. In: *Traditional and innovative approaches to scientific research: theory, methodology, practice: Scientific monograph.* Riga, Latvia: Baltija Publishing. [in English].
2. Matvijchuk, V., Shtuts, A., Kolisnyk, M., Kupchuk, I., Derevenko, I. (2022). Investigation of the Tubular and Cylindrical Billets Stamping by Rolling Process with the Use of Computer Simulation. *Periodica Polytechnica Mechanical Engineering*, 66 (1), 51–58. [in English].

3. Mykhalevych, V.M., Kolisnyk, M.A., Shtuts, A.A. (2025). Study of the Stress–Strain State of the Material of the Blanks during Plastic Stamping by Rolling. *Metallophysics and Advanced Technologies, 47 (1),* 57–81. [in Ukrainian].
4. Matviychuk, V.A., Kolisnyk, M.A., Shtuts, A.A. (2022). Construction of curve boundary deformations of materials. *Vibrations in Engineering and Technology, 2 (105),* 84–90. [in Ukrainian].
5. Matviychuk, V.A., Mykhalevych, V.M., Shtuts, A.A. (2023). Analysis of stress-strain state of material of blanks during extrusion by resource-saving stamping method. *Engineering, energy, transport AIC, 1 (120),* 76–85. [in Ukrainian].
6. Mikhalevich, V.M., Lebedev, A.A., Dobranyuk, Yu.V. (2011). Scientific and technical section modeling of plastic deformation in a cylindrical specimen under edge compression. *Strength of Materials, 43 (6),* 591–603. [in English].
7. Mikhalevich, V.M., Dobranuk, Y.V., Kraevsky, V.A., Mikhalevich, O.V. (2008). Dependence of plastic ultimate strain from a friction at end faces at axisymmetric compression. *Bulet. Inst. Politehnic Din Iasi, Tomul LIV (LVIII), Fasc. 3-4,* 49–53. [in English].
8. Mykhalevych, V., Dobraniuk, Y., Matviichuk, V., Kraievskyi, V., Tiutiunnyk, O., Smailova, S., Kozbakova, A. (2023). A comparative study of various models of equivalent plastic strain to fracture. *Informatyka, Automatyka, Pomiary W Gospodarce I Ochronie Środowiska, 13,* 64–70. [in English].
9. Matviychuk, V., Mikhalevich, V., Shtuts, A. (2023). Analysis of stress-strain state (SSS) of billet material in the course of setting by resource-saving method of roll stamping. *Vibrations in Engineering and Technology, 1 (108),* 63–72. [in Ukrainian].
10. Ogorodnikov, V.A., Zyska, T., Sundetov, S. (2018). The physical model of motor vehicle destruction under shock loading for analysis of road traffic accident. *Proceedings of SPIE - The International Society for Optical Engineering,* 10808. [in Ukrainian].
11. Gozhii, S., Kryvda, L. (2006). Stamping by rolling as a means of resource conservation. *Naukovi Visti NTUU KPI, 46 (2),* 55–60. [in Ukrainian].
12. Matviychuk, V.A., Mykhalevych, V.M., Dobraniuk, Yu.V., Bubnovska, I.A. (2016). Method for determining the plasticity of metals by rolling cylindrical samples on a wedge. *MPC G01N 3/08 (2006/01), 109984,* 26.09.2016. [in Ukrainian].
13. Shtuts, A.A. (2020). Computer modeling of the rolling stamping process of cylindrical and tubular blanks using the Deform-3D software package. *Vibrations in Engineering and Technology, 4 (99),* 101–113. [in Ukrainian].
14. Shtuts, A.A., Matviychuk, V.A. (2016). Computer modeling of the rolling stamping process of tubular blanks. *Tekhnichni Nauky: Zbirnyk Naukovykh Prats VNAU, 1 (95),* 178–184. [in Ukrainian].

ДОСЛІДЖЕННЯ КІНЕМАТИКИ ФОРМУВАННЯ СКЛАДНОПРОФІЛЬНИХ ВИРОБІВ СІЛЬСЬКОГОСПОДАРСЬКОГО МАШИНОБУДУВАННЯ ПРИ ШТАМПУВАННІ ОБКОЧУВАННЯМ

У статті проведено дослідження кінематики формування виробів сільськогосподарського машинобудування при штампуванні обкочуванням (ШО), зосереджуючи увагу на особливостях локального деформування матеріалу заготовок та можливостях управління течією матеріалу. Штампування заготовок обкочуванням є важливим нестаціонарним ротаційним процесом, який використовується для обробки металів тиском, зокрема при виробництві складнопрофільних виробів для сільськогосподарського машинобудування. Цей процес включає обертальні валки, що впливають на матеріал заготовки в осьовому або похилому напрямку, сприяючи його локальному деформуванню. Локалізація пластичної зони дозволяє зменшити зусилля деформування і таким чином покращити процеси формоутворення. Суть цього процесу полягає в тому, що матеріал заготовки піддається не тільки стисненню, але й розтягуванню, що дозволяє отримати високоточні і складні форми виробів.

Управління напрямом течії матеріалу є важливим аспектом для досягнення бажаних геометричних та механічних характеристик виробів, оскільки саме цей фактор визначає точність і якість отриманих деталей. Для сільськогосподарського машинобудування такі деталі повинні володіти не лише складною геометрією, а й високими експлуатаційними властивостями, що критично важливо в умовах аграрного виробництва, де деталі повинні витримувати значні механічні навантаження та агресивні умови експлуатації.

За допомогою аналітичної геометрії та теоретичної механіки було змодельовано кінематику процесу ШО заготовок конічним валком. Виявлено, що течія металу заготовки у радіальному напрямку зумовлена дією радіальної складової сили тертя ковзання, яка виникає через різну направленість векторів швидкості заготовки та інструменту у плямі контакту. Напрямок та *інтенсивність течії матеріалу визначаються кутом між цими векторами. Основними параметрами, які впливають на напрям плину матеріалу при ШО, є кут нахилу осі валка α, а також величина і напрям зміщення вершини валка δ по відношенню до осі обертання заготовки. Для більш детального аналізу застосовано імітаційне моделювання процесів ШО методом скінчених елементів (МСЕ). Побудовано розрахункову модель, що складається з трубної циліндричної заготовки, деформуючого конічного валка, матриці та оправки. Отримано розподіл інтенсивності деформацій у бурті при різних стадіях деформування. Результати моделювання дозволили розробити моделі впливу технологічних параметрів на формозміну та напружено-деформований стан заготовки.*

Проведені дослідження підтвердили можливість розширення технологічних можливостей процесу штампування обкочуванням за рахунок управління течією металу заготовки. Застосування імітаційного моделювання сприяє підвищенню точності прогнозування кінематики формування виробів, що має важливе значення для оптимізації виробничих процесів у сільськогосподарському машинобудуванні.

Ключові слова: *штампування обкочуванням, циліндричний ролик, трубчасті вироби, пружна деформація, складнопрофільні заготовки, дослідження, аналіз, механіка, формоутворення, напружено-деформований стан, сили, виробництво сільськогосподарської техніки.*

Ф. 7. Рис. 8. Літ. 14.

INFORMATION ABOUT THE AUTHORS

Vitalii YANOVYCH – Doctor of Technical Sciences, Professor of the Department of Agricultural Machinery and Equipment of Vinnytsia National Agrarian University (St. Soniachna, 3, Vinnytsia, Ukraine, 21008, e-mail: yanovichvitaliy@gmail.com, https://orcid.org/0000-0002-8152-7124).

Andrii SHTUTS - Candidate of Technical Sciences, Senior Lecturer, Department of Electric Power Engineering, Electrical Engineering and Electromechanics, Vinnitsa National Agrarian University (3, Soniachna st. , Vinnitsa, 21008, Ukraine, email: shtuts1989@gmail.com, https://orcid.org/0000-0002-4242-2100).

Iryna HUNKO – Candidate of Technical Sciences, Professor of the Department of General Technical Disciplines and Labor Protection of Vinnytsia National Agrarian University (3 Sonyachna St., Vinnytsia, 21008, Ukraine, e-mail: irynagunko@vsau.vin.ua, https://orcid.org/0000-0001-5470-7413).

Ludmila SHVETS – Candidate of Technical Sciences, Associate Professor, Department of Agricultural Engineering and Technical Service Vinnytsia National Agrarian University (3 Sonyachna St., Vinnytsia, Ukraine, 21008, e-mail: shlv0505@i.ua, https://orcid.org/0000-0002-4364-0126).

ЯНОВИЧ Віталій Петрович – д.т.н., професор, кафедри «Машин та обладнання сільськогосподарського виробництва» Вінницького національного аграрного університету (вул. Сонячна, 3, м. Вінниця, 21008, Україна. yanovichvitaliy@gmail.com, https://orcid.org/0000-0002-8152-7124).

ШТУЦЬ Андрій Анатолійович – к.т.н. старший викладач кафедри «Електроенергетики, електротехніки та електромеханіки» Вінницького національного аграрного університету (вул. Сонячна, 3, м. Вінниця, 21008, Україна, email: shtuts1989@gmail.com, https://orcid.org/0000-0002-4242-2100).

ГУНЬКО Ірина Василівна – кандидат технічних наук, доцент, кафедри загальнотехнічних дисциплін та охорони праці Вінницького національного аграрного університету (вул. Сонячна, 3, м. Вінниця, 21008, Україна, e-mail: irynagunko@vsau.vin.ua, https://orcid.org/0000-0001-5470-7413).

ШВЕЦЬ Людмила Василівна – кандидат технічних наук, доцент кафедри агроінженерії і технічного сервісу Вінницького національного аграрного університету (ВНАУ, вул. Сонячна, 3, м. Вінниця, Україна, 21008, e-mail: shlv0505@i.ua, https://orcid.org/0000-0002-4364-0126).