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ANALYSIS OF THE INFLUENCE OF DIRECT EXTRUSION BY THE STAMPING-ROLLING METHOD ON THE STRESS-DEFORMED STATE OF THE BLANKET MATERIAL

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The article presents a comprehensive analysis of the influence of direct extrusion by rolling stamping on the stress-strain state (SST) of the workpiece material with an emphasis on the formation of complex-profile end elements. The features of localized plastic deformation in the zones of contact with the tool are considered, as well as the mechanisms of material flow during the implementation of technological schemes with non-standard tool geometry. The study uses physical modeling using a copper workpiece of the M0b brand, on the surface of which a dividing grid was applied to fix the trajectories of material point movement. Microstructural analysis and microhardness measurements are performed in order to spatially localize the zones of maximum deformation intensity.

The results showed a clear localization of plastic deformations in the surface layers of the workpiece, which is accompanied by grain compaction and their orientation in the direction of the main deformation. In the central zones, the material retains a more homogeneous structure. The asymmetry of the NDS is established, caused by the asymmetric application of the load, which affects the geometry of the extruded profile. The dependence of the NDS characteristics on the tool shape, extrusion depth and friction conditions is revealed.

An approach to describing the stress state in the deformation zone is proposed, taking into account equilibrium equations, plasticity conditions and hardening curves. The deformation paths of material particles in critical zones are determined using coordinate grids and the theory of R-functions. The obtained data allow predicting limit states and optimizing process parameters. The study demonstrates the prospects of the direct extrusion method by rolling for the manufacture of high-precision complex-profile elements with controlled structural inheritance.

The findings provide a scientific basis for optimizing tool geometry and process parameters to achieve controlled stress–strain distribution and desired structural properties. The proposed approach enhances understanding of localized plastic deformation and supports the development of high-precision complex-profiled elements.

Key words: *rolling stamping, direct extrusion, stress-strain state, microstructure, localized plastic deformation, coordinate grid; microhardness, forming, profile blanks.*

Eq. 11. Fig. 9. Ref. 16.

1. Problem formulation

The processes of rolling stamping have developed significantly in recent years, in particular in the manufacture of complex-profile parts, where the radial flow of the material of cylindrical blanks is actively implemented. In scientific works [1–12], various technological schemes have been studied that allow for the effective formation of three-dimensional shapes due to localized plastic deformation, in particular during flanging, dispensing, crimping and other types of stamping. Such approaches provide not only high-precision reproduction of the shape, but also increased surface quality and mechanical characteristics of finished products.

A number of studies [1, 5, 6, 11] have paid attention to the formation of three-dimensional parts from thin-walled blanks, in particular tubular or cylindrical, by optimizing the rolling trajectory, load parameters and tool geometry. At the same time, the importance of a comprehensive analysis of the stress-strain state of the material is emphasized, which allows predicting zones of potential loss of plasticity and optimizing the design of the die. Studies [2, 12] also highlight the results of numerical modeling of the roll-forming process, in particular by finite element methods, which provides accurate prediction of the distribution of stresses and strains in the contact zone of the tool with the workpiece. Figure 1 presents far from all technological schemes for direct extrusion of a profile on the end face of the workpiece by the roll-forming method.

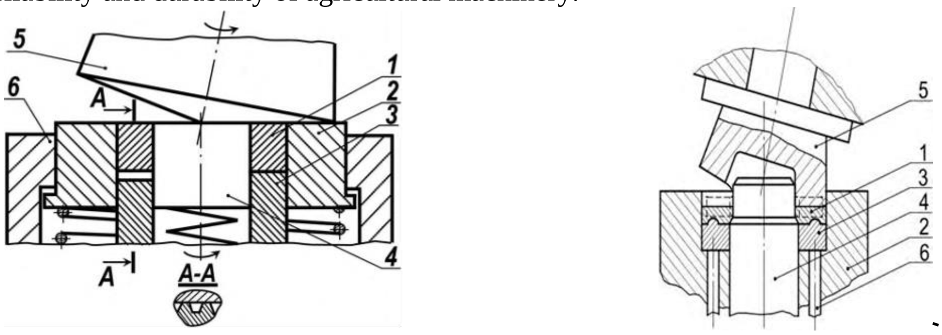
2. Analysis of recent research and publications

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.

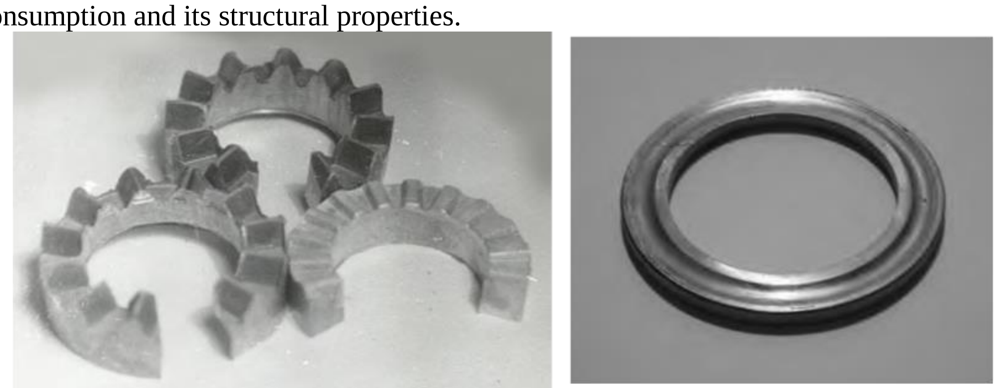


a *b*

Fig. 1. Schemes of direct shaping of the workpiece end face by the rolling stamping method: a – in a spring-loaded matrix-mandrel system; b – in a profile tool gauge.

Of particular note are works that consider the possibility of implementing complex material flow patterns in the formation of end profiles. Some types of parts are characterized by the presence of a complex relief on the end part of the workpiece, which is difficult to obtain using traditional rolling patterns. In such cases, the use of direct extrusion by the rolling stamping method is promising, when the shaping occurs on the opposite end of the workpiece to the one in contact with the deforming roll.

Fig. 2 shows typical examples of the implementation of such technological patterns - in particular, the formation of a half-coupling (Fig. 2a) and a thrust bearing ring (Fig. 2b). As can be seen, the use of a rolling die with a given end profile allows you to achieve the required geometry of the elements by extruding metal from the central part to the periphery. This approach allows you to reduce the number of technological transitions and increase the accuracy of reproducing a given shape, and also provides better control over the material consumption and its structural properties.



a *b*

Fig. 2. Blanks obtained by the rolling stamping method: a – cam coupling halves, at different stages of rolling; b – thrust bearing ring.

In particular, the insufficient level of research into forming processes complicates the development of effective technological schemes with controlled material flow and ensuring a given geometry of finished elements. One of the key problems is the limited data on the stress-strain state (SSS) of the workpiece material during deformation. This, in turn, makes it impossible to comprehensively assess deformability, predict fracture initiation zones, and determine technological process limits taking into account the tool life and the limiting state of the material.

In addition, the technological heredity of the resulting products remains uncertain, in particular the influence of the deformation method on the structure, mechanical properties, and durability of the final parts. Such uncertainty limits the introduction of new high-performance roll-forming techniques into serial production.

Research into the SSS of workpieces during localized plastic deformation is an important direction for further improvement of roll-forming processes. In order to study the influence of technological parameters on the stress-strain state of the material at the initial stage of research, experimental methods were used. Among them are the hardness measurement method for assessing the strengthening zones, the dividing grid method for determining the deformation pattern, and the analysis of the microstructure of the material, which allows assessing the nature of structural changes in different zones of the workpiece.

Thus, the analysis of recent studies indicates the high efficiency of rolling stamping methods for forming complex-profile workpieces, especially when using non-standard deformation schemes. Further research in this direction should focus on optimizing the design of dies, increasing the accuracy of stress state modeling, and reducing energy consumption while maintaining the quality of finished products.

3. The purpose of the article

The aim of the work is to analyze the process of forming blanks using the rolling stamping method with direct extrusion, to establish the regularities of the stress-strain state and microstructural changes in the material, and to investigate the influence of technological parameters on the quality of forming complex geometric profiles.

4. Results and discussion

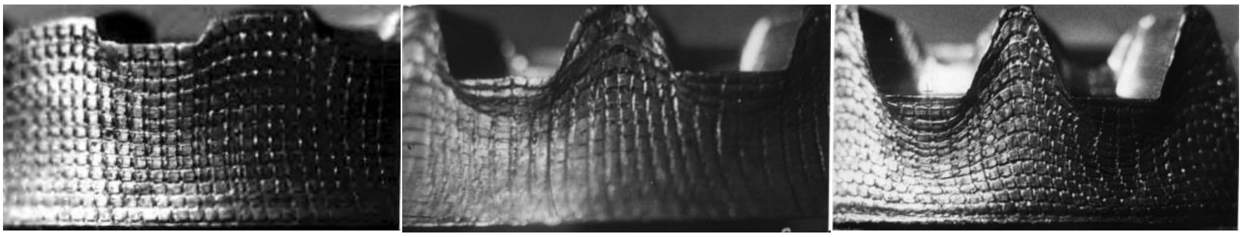
For physical modeling of the direct extrusion process by the roll-forming method, a combined ring blank was used, consisting of two parts: the inner and outer rings. In order to study the deformation features, a rectangular dividing grid was applied to the outer cylindrical surface of the inner ring, which served as an indicator of local material displacements and the distribution of deformations during the loading process.

Figure 3 shows a general view of the deformed rings after the roll-forming process, with part of the outer ring removed to visualize changes on the surface of the inner part of the blank.

Fig. 3. General view of the deformed ring

Figure 4 also shows the deformation of the dividing grid on the surface of the inner ring, recorded at different stages of the direct extrusion process: initial (a), intermediate (b) and final (c). These images allow analyzing the nature of the material flow and the localization of the zone of intense plastic deformation.

Figure 4 shows a deformed mesh applied to the outer surface of the cam, which allows us to assess the influence of the tool shape on the formation of the product profile and the features of the contact interaction between the workpiece and the deforming element.



a ***b*** ***c***

Fig. 4. Deformation of the mesh on the outer surface of the inner ring at different stages of direct extrusion by rolling stamping

In the course of physical modeling of direct extrusion processes by rolling stamping, copper of the M0b grade was chosen as the material for manufacturing blanks. This choice is due to a number of important characteristics of this material, which are critical for studying the regularities of plastic deformation. In particular, copper has high plasticity and good workability under pressure, which allows for high-quality formation of complex geometric shapes even under conditions of localized deformations.

The key feature of M0b copper is its high sensitivity to mechanical action, which is manifested in the variability of the microstructure depending on the degree of deformation. This makes it possible to analyze with high accuracy local changes in the intensity of deformations in the internal zones of the blank. It is thanks to this property that it is possible to reliably trace the features of the material flow and assess its reaction to variable technological parameters, such as the shape of the tool, the depth of extrusion and the speed of the process.

In addition, copper is characterized by a pronounced, albeit heterogeneous initial microstructure, which is valuable for studying the processes of structure formation during plastic deformation. The presence of zones with different density and grain size of the material allows us to assess the heterogeneity of the distribution of deformations within one workpiece and to identify critical areas prone to stress accumulation or microdamage.

The study of changes in the microstructure of the material during deformation is an important element of the analysis of the stress-strain state and metal flow mechanisms during the formation of elements of complex geometry. Fig. 5 shows the appearance of the deformed microstructure of the M0b copper workpiece material in the cross section of the cam at the intermediate (a) and final (b) stages of direct extrusion by the rolling stamping method. The change in the structure at different stages of the process allows us to establish the patterns of deformation effects across the thickness of the workpiece and identify local zones of the greatest influence of the contact interaction of the tool with the material.

As can be seen from the microstructure images, during the deformation process, there is a densification of grains, a decrease in their size and an orientation of the structure in the direction of the main deformation. This is especially clearly manifested in the zones adjacent to the end surface, where the maximum stress gradient is realized. In the central areas, a more uniform structure is observed, which indicates a less intense effect of the deforming tool in these areas. For a more detailed analysis of the nature of microstructural changes, Fig. 6 presents an enlarged view of the microstructure of copper M0b at characteristic points of the formed profile, according to the designations in Fig. 5b. This allows us to establish the spatial localization of zones with different deformation intensities, identify the directions of metal flow and assess the efficiency of profile formation at a given rolling stamping mode.

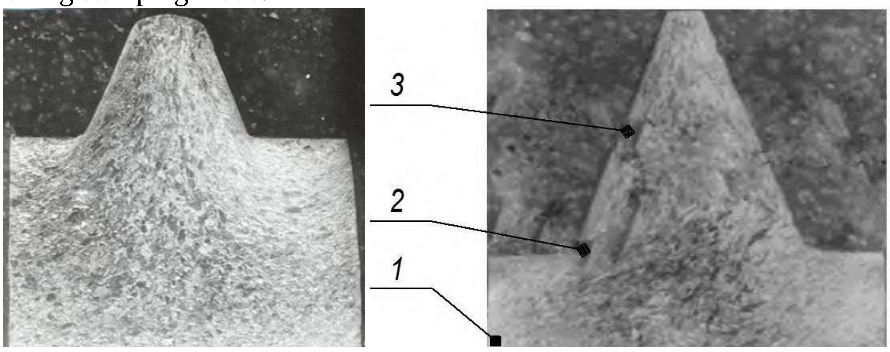


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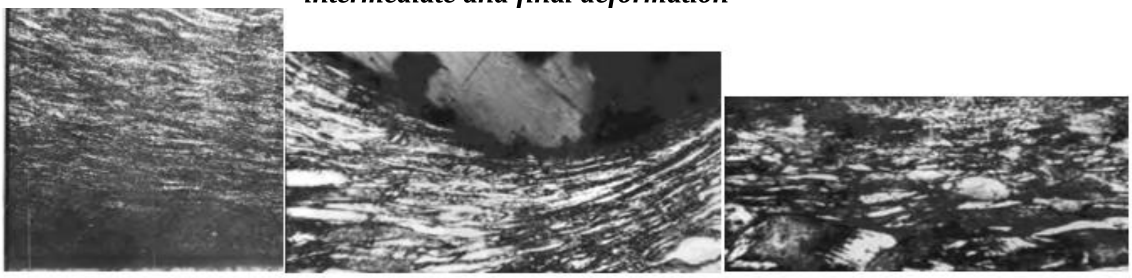
Fig. 5. Cross-section of a cam with a deformed microstructure of copper M0b at the stages of intermediate and final deformation



a *b* *c*

Fig. 6. Fragments of the microstructure of copper M0b at selected points of the profile (Fig. 5b): a – contact zone (point 1); b – point 2; c – point 3.

The study of the stress-strain state (SS) of the workpiece material was also carried out using the microhardness measurement method, which allows to assess the level of accumulated plastic deformations in different zones of the formed element. The measurement methodology was based on the principles outlined in previous studies, with adherence to a single scheme for placing measurement points along the cross-section of the deformed area.

Based on the obtained hardness values, a deformation intensity distribution map was constructed, which reflects the change in the mechanical state of the material depending on the distance to the contact zone with the roll and the shape of the tool. In particular, the results indicate the presence of pronounced deformation gradients in the direction from the outer surface to the inner layers of the workpiece, which confirms the localization of the main plastic deformation in the surface zones.

Fig. 7 presents the nature of the distribution of deformation intensity in the zone of the extruded element, obtained on the basis of microhardness measurements. Analysis of this diagram allows to determine the most loaded areas that experience maximum material displacement during the forming process.

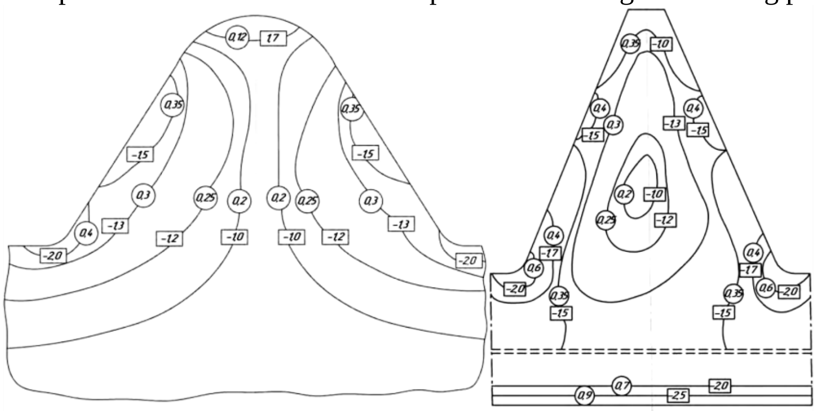


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Fig. 7. Maps of the distribution of the stress-strain state in the formed element of the workpiece during direct extrusion by the SH method:
a – intermediate stage; b – final stage: $(\bigcirc)\eta = const$ **and** $(\square)\varepsilon_i = const$

To study the NDS of the plastic zone of the workpiece during direct extrusion by the SH method, the method of coordinate dividing grids is also used, built on the use of a technique based on the theory of R-functions. In this case, the element was extruded stepwise (see Fig. 4) - a flat problem. The nature of the distribution of isolines $\varepsilon_i = const$ in the area of the extruded element, obtained from the results of the measurement of the coordinate dividing grid, is presented in Fig. 7.

The stressed state of the element in the bending zone is volumetric, while the deformed state is considered as flat ($\varepsilon_z = 0$). To describe the mechanics of workpiece deformation during direct extrusion by the SH method, the general equation of equilibrium of the element of the workpiece zone of constant thickness under conditions of axisymmetric deformation taking into account the action of friction forces on the contact surfaces is used:

$$\rho \frac{d\sigma_\rho}{d\rho} + \sigma_\rho - \sigma_\theta - \frac{\mu\rho}{\sin\alpha}\left(\frac{\sigma_\rho}{R_\rho} + \frac{\sigma_\theta}{R_\theta}\right) = 0, \quad (1)$$

where σ_ρ – meridional tension; σ_θ – latitudinal stress; μ – coefficient of friction; ρ – distance from the axis of symmetry; R_ρ, R_θ – radii of curvature in the meridional and latitudinal sections.

In the case of neglecting friction, equation (1) has the following form:

$$\rho \frac{d\sigma_\rho}{d\rho} + \sigma_\rho - \sigma_\theta. \quad (2)$$

Given the equation with two unknowns, we introduce the energy condition for plasticity:

$$\sigma_i = \frac{1}{\sqrt{2}}\sqrt{(\sigma_\rho - \sigma_\theta)^2 + (\sigma_\theta - \sigma_z)^2 + (\sigma_z - \sigma_\rho)^2} = \sigma_s. \quad (3)$$

With flat deformation:

$$\sigma_z = \frac{\sigma_\rho + \sigma_\theta}{2}. \quad (4)$$

Then, taking into account (4), the plasticity condition (3) can be written as:

$$\sigma_\rho - \sigma_\theta = \frac{2}{\sqrt{3}}\sigma_s. \tag{5}$$

To obtain solutions that allow determining the analytical distribution of the stress field taking into account the hardening of the material, it is first necessary to specify the analytical expression of the hardening curve - that is, the dependence of the yield stress on the magnitude of the deformation. In most cases, this dependence is nonlinear, which significantly complicates the construction of accurate mathematical models.

The use of the hardening curve in the "stress-strain" coordinates in the analysis of metal processing processes by pressure causes significant difficulties, even when this dependence is presented in the form of a simple analytical function. This is explained by the complex interaction between the individual deformation components, which are nonlinear and interdependent in nature. As a result, the integration of the equations of equilibrium and compatibility of deformations often requires the use of numerical methods or simplification of the physical and mechanical model of the material.

For the tensile zone:

$$\sigma_\rho = \frac{2}{\sqrt{3}} \cdot \left[\sigma_m \cdot \ln\left(\frac{\rho}{R}\right) + \frac{2^n}{\sqrt{3^n}} \cdot \frac{A}{n+1}\left[\left(\ln\frac{\rho}{\rho_н}\right)^{n+1} - \left(\ln\frac{R}{\rho_н}\right)^{n+1}\right]\right], \tag{6}$$

$$\sigma_\theta = \frac{2}{\sqrt{3}} \cdot \left[\begin{array}{l} \sigma_m + A\cdot\left(\frac{2}{\sqrt{3}}\cdot\ln\frac{\rho}{\rho_н}\right)^n + \sigma_m\cdot\ln\frac{\rho}{R} + \\ + \frac{2^n}{\sqrt{3^n}}\cdot\frac{A}{n+1}\cdot\left[\left(\ln\frac{\rho}{\rho_н}\right)^{n+1} - \left(\ln\frac{R}{\rho_н}\right)^{n+1}\right] \end{array}\right], \tag{7}$$

$$\sigma_z = \frac{2}{\sqrt{3}} \cdot \left[\begin{array}{l} \frac{1}{2}\cdot\left[\sigma_m + A\cdot\left(\frac{2}{\sqrt{3}}\cdot\ln\frac{\rho}{\rho_н}\right)^n\right] + \sigma_m\cdot\ln\frac{\rho}{R} + \\ + \frac{2^n}{\sqrt{3^n}}\cdot\frac{A}{n+1}\cdot\left[\left(\ln\frac{\rho}{\rho_н}\right)^{n+1} - \left(\ln\frac{R}{\rho_н}\right)^{n+1}\right] \end{array}\right] \tag{8}$$

For the compression zone:

$$\sigma_\rho = \frac{2}{\sqrt{3}} \cdot \left[\begin{array}{l} \sigma_m\cdot\ln\left(\frac{r}{\rho}\right) + \frac{2^n}{\sqrt{3^n}}\cdot \\ \cdot\frac{A}{n+1}\left[\left(\ln\frac{\rho_н}{\rho}\right)^{n+1} - \left(\ln\frac{\rho_н}{r}\right)^{n+1}\right] \end{array}\right], \tag{9}$$

$$\sigma_\theta = \frac{2}{\sqrt{3}} \cdot \left[\begin{array}{l} -\sigma_m - A\cdot\left(\frac{2}{\sqrt{3}}\cdot\ln\frac{\rho_н}{\rho}\right)^n + \sigma_m\cdot\ln\frac{r}{\rho} + \\ + \frac{2^n}{\sqrt{3^n}}\cdot\frac{A}{n+1}\cdot\left[\left(\ln\frac{\rho_н}{\rho}\right)^{n+1} - \left(\ln\frac{\rho_н}{r}\right)^{n+1}\right] \end{array}\right], \tag{10}$$

$$\sigma_z = \frac{2}{\sqrt{3}} \cdot \left[\begin{array}{l} -\frac{1}{2}\cdot\left[\sigma_m + A\left(\frac{2}{\sqrt{3}}\cdot\ln\frac{\rho_н}{\rho}\right)^n\right] + \sigma_m\cdot\ln\frac{r}{\rho} + \\ + \frac{2^n}{\sqrt{3^n}}\cdot\frac{A}{n+1}\cdot\left[\left(\ln\frac{\rho_н}{\rho}\right)^{n+1} - \left(\ln\frac{\rho_н}{r}\right)^{n+1}\right] \end{array}\right] \tag{11}$$

As follows from formulas (6) and (9), the values of the stresses σ_ρ increase in modulus in the direction from the outer surface of the workpiece to its inner layers.

The characteristic features of the deformation process should also include the asymmetry of the stress-strain state (SSS) with respect to the geometry of the extruded profile, revealed in Fig. 4 and 7. This is due to the asymmetric application of the load during the rolling of the workpiece. Such a feature of the material flow can be technologically appropriate in cases where the side surfaces of the element have different angles of inclination. At the same time, if it is necessary to ensure symmetry of the SSS, it is advisable to use the reversal of the position of the workpiece during deformation.

Changing the parameters of the element profile, in particular the geometric characteristics shown in Fig. 8, leads to certain changes in the values of the intensity of deformations and the stress state index. However, the general nature of their distribution remains stable. A similar stability of the spatial distribution of the specified values is observed when the workpiece material varies, provided that the friction parameters on the contact surfaces remain unchanged.

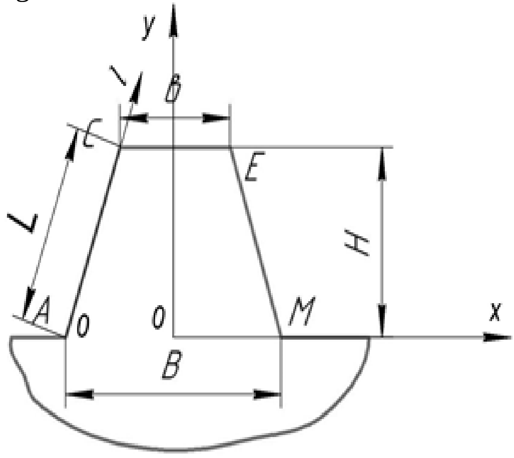

Fig. 8. Typical shape parameters of an element formed by the rolling stamping method

To assess the deformability of the workpiece material, as well as determine the limiting deformations taking into account the criteria for preventing destruction or ensuring the required level of mechanical properties of the finished product, it is important to analyze the deformation trajectories of material particles in critical zones. Such analysis allows us to establish the regularities of the plastic flow of the material, the nature of overstresses and the formation of potentially dangerous areas.

Fig. 9 shows the results of determining the deformation paths of material particles in the most loaded areas of the workpiece, obtained by the method of coordinate dividing grids using the theory of R-functions. This method allows us to track the movement of material points with high accuracy throughout the deformation process, which is critically important for building correct models of the NDS.

A feature of the established deformation paths is the nature of the material flow at the initial stages of extrusion. In particular, in the zone adjacent to the conditional OM line, the dominance of tensile stresses is observed under the condition of a practically constant value of the stress state indicator. At the same time, the magnitude of the deformation intensity at the initial stage is relatively small. However, at the final stage of forming, the free surface of the workpiece undergoes a significant complication of the structure of the NDS, and the deformation intensity in this zone reaches limit values, which may indicate an approach to the plasticity limit or the beginning of deformation localization.

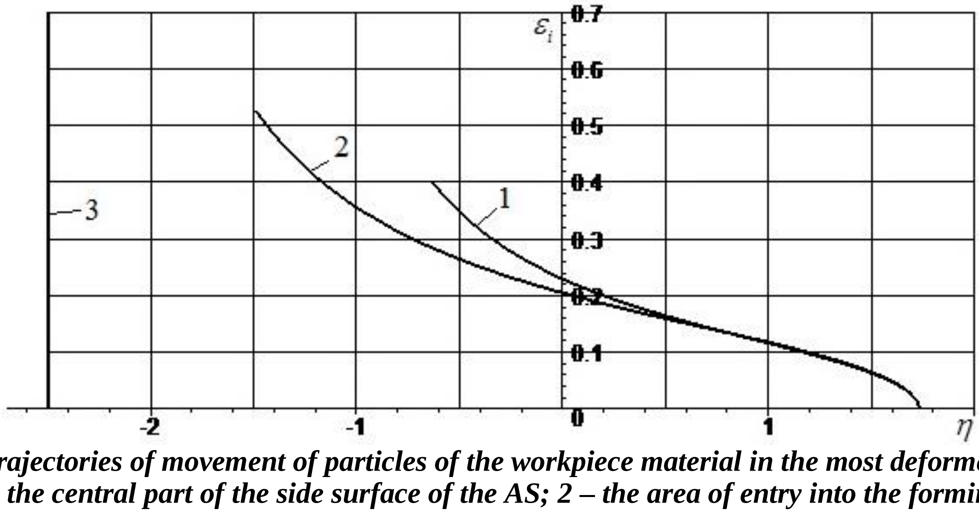

Fig. 9. Trajectories of movement of particles of the workpiece material in the most deformed zones: 1 – the central part of the side surface of the AS; 2 – the area of entry into the forming channel (near point A); 3 – the zone of contact of the workpiece with the roll.

Thus, to ensure maximum deformability, the most favorable deformation paths are those in which the minimum ratio of the deformed height to the thickness of the workpiece wall is observed. In addition, an important factor is the negative displacement of the roll tip, which contributes to the improvement of the deformation process. Under these conditions, an optimal load distribution on the material is achieved, which ensures effective forming of the workpiece with minimal energy losses and a decrease in the probability of defects during plastic deformation.

5. Conclusion

The conducted study confirmed the effectiveness of the direct extrusion method by rolling stamping for forming complex-profile end elements from cylindrical blanks. It was found that during deformation the material demonstrates a clearly localized plastic flow in the zones adjacent to the contact surfaces of the tool, which is accompanied by intensive grain compaction, their orientation in the direction of the main deformation and a significant change in the microstructure. This allows for targeted control of the forming processes and optimization of the stress distribution in the blank.

The use of M0b copper as a model material made it possible to study in detail the patterns of localized plastic deformation due to its high plasticity and sensitivity to changes in the microstructure. It was found that the largest deformations are concentrated in the surface layers, and in the central parts of the blank the structure remains less changed. This is confirmed by both microstructural observations and the results of microhardness measurements.

The study revealed the asymmetry of the stress-strain state in the extrusion zone, caused by asymmetric loading. This effect can be used for directional shaping of profiles with non-uniform geometry, however, in cases where symmetry of the NDS is required, it is advisable to use reverse deformation. The use of coordinate grids and microhardness methods provided spatial localization of zones with maximum deformation intensity, which is important for the development of reliable tool schemes.

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АНАЛІЗ ВПЛИВУ ПРЯМОГО ВИТИСКУВАННЯ МЕТОДОМ ШТАМПУВАННЯ ОБКОЧУВАННЯМ НА НАПРУЖЕНО-ДЕФОРМОВАНИЙ СТАН МАТЕРІАЛУ ЗАГОТОВОК

У статті проведено комплексний аналіз впливу прямого витискування методом штампування обкочуванням на напружено-деформований стан (НДС) матеріалу заготовок з акцентом на формування складнопрофільних торцевих елементів. Розглянуто особливості локалізованої пластичної деформації в зонах контакту з інструментом, а також механізми плину матеріалу при реалізації технологічних схем з нестандартною геометрією інструменту. У дослідженні застосовано фізичне моделювання з використанням мідної заготовки марки М0б, на поверхню якої наносилась ділильна сітка для фіксації траєкторій переміщення матеріальних точок. Проведено мікроструктурний аналіз і вимірювання мікротвердості з метою просторової локалізації зон максимальної інтенсивності деформацій.

Результати показали чітку локалізацію пластичних деформацій у поверхневих шарах заготовки, що супроводжується ущільненням зерен та їх орієнтацією у напрямку головної деформації. У центральних зонах матеріал зберігає більш однорідну структуру. Встановлено асиметрію НДС, зумовлену несиметричним прикладенням навантаження, що впливає на геометрію витиснутого профілю. Виявлено залежність характеристик НДС від форми інструмента, глибини витискування та умов тертя.

Запропоновано підхід до опису напруженого стану в зоні деформації з урахуванням рівнянь рівноваги, умов пластичності та кривих зміцнення. Визначено шляхи деформування часток матеріалу в критичних зонах за допомогою координатних сіток і теорії R-функцій. Отримані дані дозволяють прогнозувати граничні стани та оптимізувати параметри процесу. Дослідження демонструє перспективність методу прямого витискування обкочуванням для виготовлення високоточних складнопрофільних елементів з керованою структурною спадковістю.

Результати забезпечують наукову основу для оптимізації геометрії інструменту та параметрів процесу для досягнення контрольованого розподілу напружень і деформацій та бажаних структурних властивостей. Запропонований підхід покращує розуміння локалізованої пластичної деформації та підтримує розробку високоточних складнопрофільних елементів.

Ключові слова: *штампування обкочуванням, пряме витискування, напружено-деформований стан, мікроструктура, локалізована пластична деформація, координатна сітка, мікротвердість, формоутворення, профільні заготовки.*

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