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Research into the Processes of Rolling Stamping of Ring and Flange Billets with a Complex Profile

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This article analyses the features of local deformation, which determine rolling stamping as an independent type of metal processing by pressure. Examples of the most complete realization of the advantages of stamping by rolling, which ensures the efficiency of industrial use, are given. In the priority directions of the development of science and technology, a special role is given to energy- and resource-saving. Modern national industries of mechanical engineering and metal processing, which are designed to increase the competitiveness of own products, are still largely based on the energy- and metal-intensive technological processes. The reduction of the energy and material costs is facilitated by the development and implementation of new metal processing by pressure in metalworking. This circumstance determines the priority of the development of agro-industrial production. The development of the agricultural sector and the need to increase its efficiency require improvement of technical support.

Key words: rolling stamping, metal pressure processing, cold three-dimensional stamping, deformation, forming, workpieces, yielding of metal.

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У роботі проаналізовано особливості локального деформування, які визначають прокатне штампування як самостійний вид оброблення металу тиском. Наведено приклади найбільш повної реалізації переваг штампування обкочуванням, що забезпечує ефективність промислового використання. У пріоритетних напрямах розвитку науки та техніки особливу роль відводять енерго- та ресурсозбереженню. Сучасні вітчизняні галузі машинобудування та металооброблення, які покликані підвищити конкурентоспроможність власної продукції, все ще значною мірою базуються на енерго- та металомістких технологічних процесах. Пониженню енергетичних і матеріяльних витрат сприяє розроблення та впровадження в металооброблення нових технологій оброблення металу тиском. Ця обставина зумовлює пріоритетність розвитку агропромислового виробництва. Розвиток аграрного сектора та необхідність підвищення його ефективности потребують вдосконалення технічного забезпечення.

Ключові слова: штампування обкочуванням, оброблення металу тиском, холодне тривимірне штампування, деформування, формування, заготівки, плинність металу.

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1. INTRODUCTION

Approaches based on the concept of multistage technological processes are increasingly used in the study of a wide range of production processes. Examples can be the processes of chemical, atomic energy, aircraft and automobile manufacturing, *etc.* [1].

Mechanical engineering mass manufactures and uses axisymmetric parts of various designs such as rings, bandages and flanges. The annual demand, including Ukraine's, for details of this type varies widely and can reach tens of millions of pieces. According to foreign companies, when cutting, the material utilization factor (MMF) is 40–50%, and when using cold stamping, it is 75–80%. If we take into account the energy consumption for the production of steel and its processing per unit weight of the finished part, it is 66–82 mJ/kg during cutting, and 41–49 mJ/kg during cold plastic deformation [2, 3].

There are methods of processing metals by pressure, based on the action of the technological load in the conditions of a localized plastic cell. The essence of these methods is that the shape change at each moment of time is performed only over a portion of the volume of the workpiece, and when the centre of deformation is moved, it covers the entire volume. These are well studied and widely used in production operations of free forging, rotary forging, rolling, *etc.* (Fig. 1).

The technological processes of end rolling and the sphere of mobile stamping, to combine into rolling stamping, rolling of rings and discs, *etc.*, can be attributed to relatively new ones that have an insignificant level of application [4].

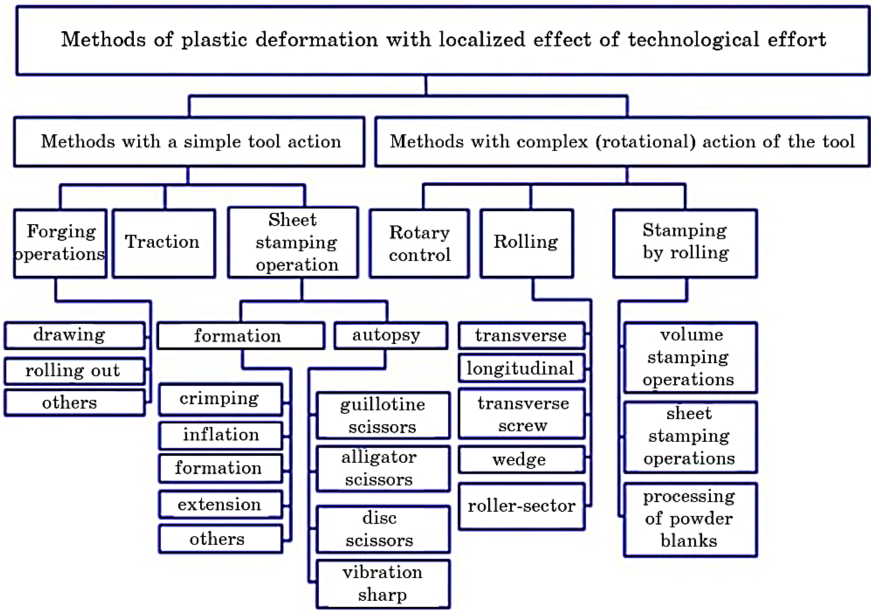

Fig. 1. Methods of plastic moulding and dissection with localized effect of technological force.

The problem of the limited level of production application of local methods is due to the fact that each of the listed technological processes has its own set of parts inherent in the form of which the process shows the highest efficiency.

Despite the fact that rolling stamping technologies have numerous advantages compared to traditional methods, as well as high economic and technological indicators, they have not been widely used today. National and foreign scientists pay considerable attention to the creation and development of resource-saving metalworking processes. These works have a relatively narrow spectrum of defining criteria and recommendations for the industrial use of rolling stamping.

Therefore, there are problems in the availability of available methods of typical technological design and development of national industrial equipment. The task of this work is a justification and demonstration of this direction, which, as a result of the improvement of the rolling deformation technology and the creation of specialized equipment, is gradually being formed into an independent production method of processing metals by pressure [5, 6].

Formulation of the problem. The purpose of the work is to study the rolling stamping processes of flat ring and flange blanks and to determine the ways of developing technological capabilities. Analysis of the nomenclature of parts in mechanical engineering showed (Fig. 2) that

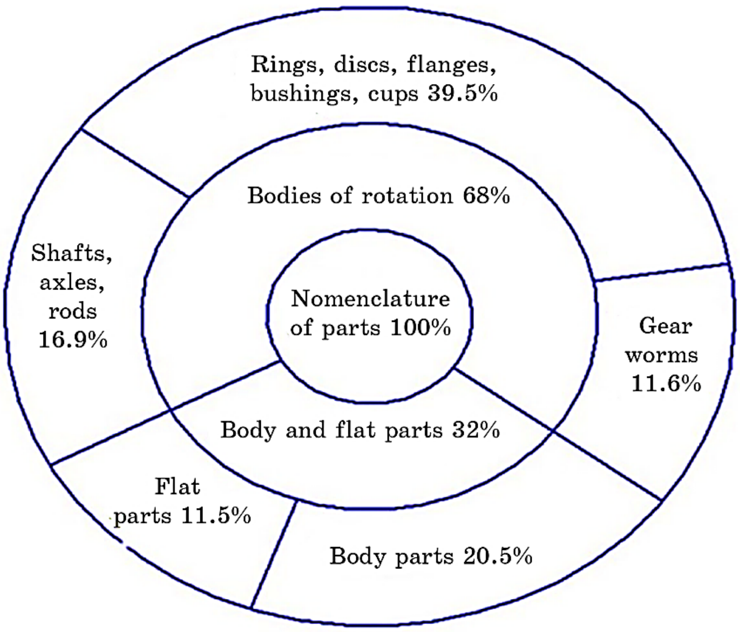

Fig. 2. Diagram of the distribution of the nomenclature of parts by structural features.

the vast majority of them are bodies of rotation (68%).

A large number of bodies of rotation include axisymmetric parts such as rings, disks, flanges, *etc*. In the production of these parts, mainly carbon, alloyed steel and non-ferrous metals are used. The main difficulties in the production of such parts by traditional methods consist in a sharp increase in the deformation force due to the closing of zones of hindered metal's flow.

To obtain such parts, methods are used in which the shape change is carried out by a tool that rolls over the surface of the workpiece. The production of parts under local loading allows achieving a plastic state in the deformation zone with a lower value of the technological effort.

For the preparation of blank parts such as rings, disks, flanges and bushings from plastic materials, the application of SHO processes can be effective. The main technological schemes of SHO are presented in Fig. 3 [2, 15].

Special development of SHO was achieved by the creation of such a direction as cold mechanical rolling (CMR). CMR processes make it possible to obtain axisymmetric, solid and hollow products of a complex profile with thin-walled elements of significant size by cold deformation [1, 16]. The shape change of workpiece can be implemented according to the following schemes (Fig. 4): deposition, landing of out-

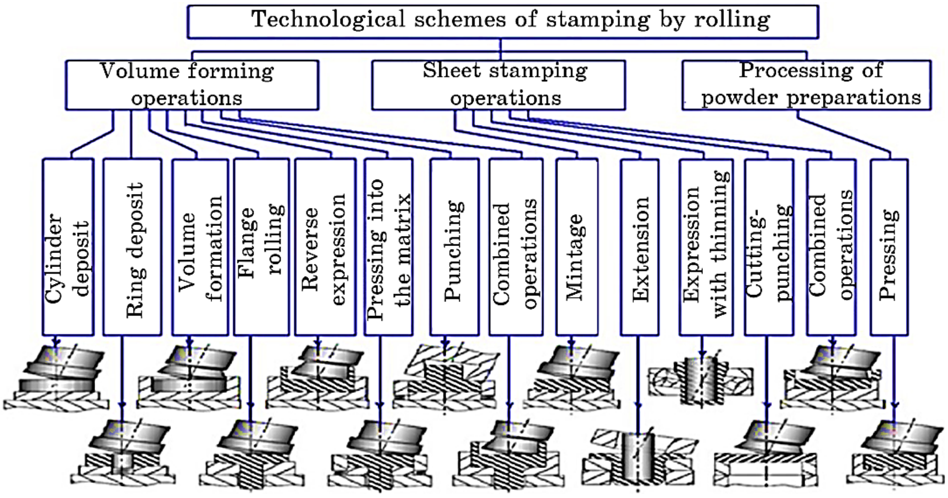

Fig. 3. Technological schemes of rolling stamping.

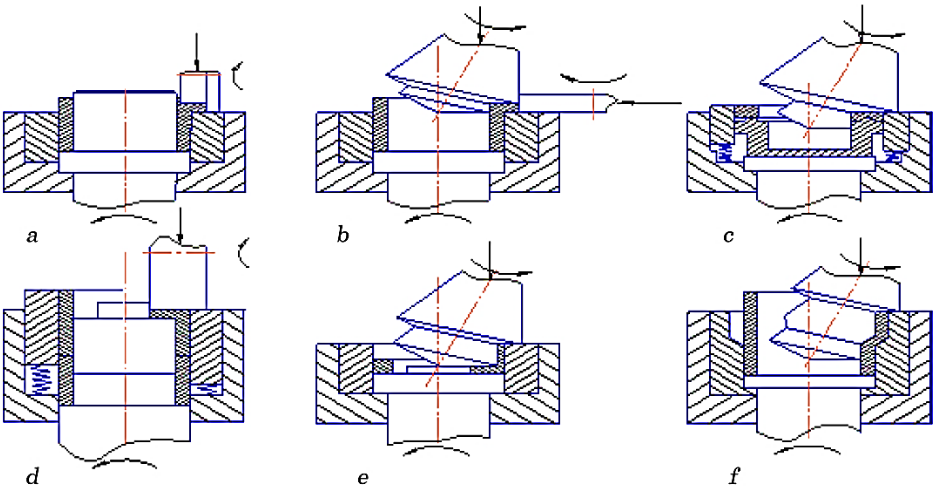

Fig. 4. Schemes of CMR: *a*, *b*—landing of the outer side; *c*—minting; *d*—landing of the inner side; *e*—reverse extrusion; *f*—distribution.

er and inner edges on tubular blanks; direct and reverse squeezing; dispensing, turning away, rotary hood, minting, *etc*.

Cylindrical or conical rolls are used as the main deforming tool in CMR. The cylindrical roll forms the inner and profiled outer edges according to the landing scheme.

A deforming tool in the form of a conical roll located at an angle to the axis of rotation of the part provides significantly greater technological capabilities. The conical roll makes it possible to form the part according to the schemes of disembarkation, direct and reverse extrusion, distribution, deposition, embossing [1]. When deforming with a conical roll, in some cases it is possible to refuse of using the mandrel, which simplifies the design of the equipment. The disadvantages of the conical tool are the complexity of the roll shape and the dependence of the tool size on the part size.

As blanks for rolling, you can use pieces of pipes and rods, stamped blanks and rings obtained by bending strips or rods with subsequent welding. The material of the blanks can be steel: structural steel—Art. 3, steel 20, steel 40; structural alloys—20X steel, 18XHT steel; ball bearings—SHKH15 steel; tool steel—steel 9XC, steel 4X13 and others, as well as non-ferrous metals and alloys.

The amount of single crimping is determined by the required degree of deformation, power parameters of the equipment, dimensions of the workpiece and mechanical characteristics of its material and can vary from 1–3 mm at the initial stage of deformation to 0.05–0.1 mm at the calibration stage. The final deformation of the part occurs, in most cases, in 10–30 revolutions or within 0.1–0.25 min. The shape and dimensions of the product are determined by the rolling scheme and the design of the equipment.

The main parameter that evaluates the suitability of metals for processing by the mechanical rolling method is sufficient plasticity.
The main factors that limit the technological possibilities of CMR processes are the destruction of the material, distortion and folding of the workpieces.

Deformability of workpieces in a real technological process depends on the shape change scheme, plasticity of the material, parameters of the process and the workpiece. The most dangerous schemes due to destruction are the landing of the outer edge, distribution and removal of tubular blanks.

When the outer edges are planted, the deformation limit before failure decreases with an increase in the ratio of the height of the part of the workpiece exposed to rolling to the wall thickness.

The stress state of the workpieces was evaluated using the indicator $\eta = (\sigma_1, \sigma_2, \sigma_3)/\sigma_u$, where σ_1, σ_2, σ_3 are the main stresses, σ_u—stress intensity [7]. The processing of the obtained results by the method of least squares made it possible to determine the ways of deformation of metal particles on the free surface of the edge in the co-ordinates ‘intensity of deformation (ε, u)–stress state indicator’ in the form of a dependence

$$\eta = k\varepsilon_u - n\,. \quad (1)$$

It was experimentally established that the angle of inclination of the

TABLE 1. Technological characteristics of semi-automatic machines for CMR.

Parameters	Dimensionality	Model		
		KO9013	CO424	CAO424
Strain force	[kN]	125	250	630
Matrix rotation speed	revolutions per wave	125	200	200
The power of the rotation drive	[kWt]	6	18.5	30
Productivity	details per hour	240	150	100
The diameter of the initial workpiece	[mm]	60	125	250
The edge width of the finished part	[mm]	15	25	40
The height of the edge of the finished part	[mm]	10	15	25
Overall dimensions of the machine				
Length	[mm]	2000	3500	4600
Width	[mm]	2000	1240	2000
Height	[mm]	1200	1240	1500
The weight of the machine	[kg]	3000	3600	15000

roll and the displacement of its top from the axis of the workpiece have a significant influence on the deformation path. With a constant angle of inclination of the roll $\alpha = 10°$ and the absence of its displacement, the main influence is exerted by factors h_0/b_0 and δ/b_0 (Fig. 5);

$$d_p/d_0 = \\ = \exp\{0.865\varepsilon_{*c}(\eta = 0)\exp(-\eta_к \ln\lambda)w - 0.14[\varepsilon_{*c}(\eta = 0)\exp(-\eta_к \ln\lambda)w]^2\}. \quad (2)$$

The limiting diameter of the outer edge of the rolled blank can be determined from the ratio, where is the value of the indicator at the point of intersection of the deformation path of the material particles of the dangerous zone of the workpiece with the plasticity diagram; coefficient of influence of deformation history on plasticity. When by rolling out, the outer sides $w = 1.2–1.35$.

Materials with a gentle plasticity diagram $(\varepsilon_p(\eta = -1)/\varepsilon_p(\eta = 0) < 1.5)$ can be destroyed not on the free surface of the edge, but in the zone with maximum deformations at a distance from the inner surface of the original pipe blank. In this case, the admissible degree of deformation must also be checked by the marginal degree of burst deposition [1–3];

$$h_0/h_p = \exp[\varepsilon_{*c}(\eta = 0)\exp(1.5\ln\lambda)]. \quad (3)$$

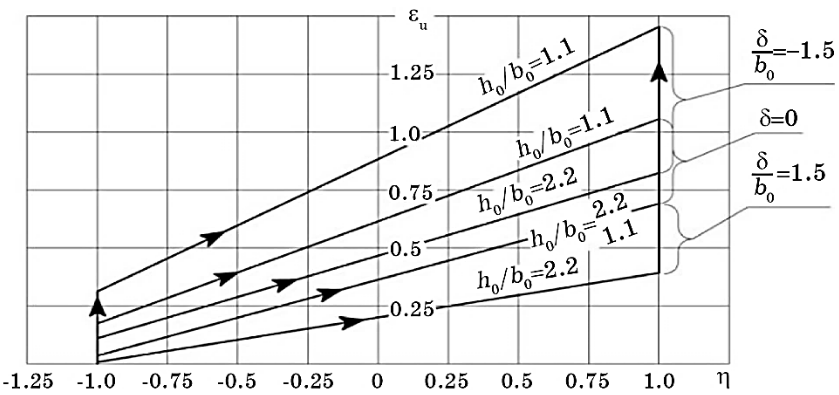

Fig. 5. Ways of deformation of the free surface of the outer side during landing.

In Figure 6, workpieces are shown with their external and internal edges, obtained according to the landing scheme for a blank with $2 < h_0/b_0$ when using a purposeful displacement of the top of the roll from the centre of the workpiece.

When rolling tubular blanks according to the scheme of landing the outer sides, in case $h_0/s_0 > 2-2.5$, the wall is curved and a fold is formed; this is a technological limitation of the process due to the loss of stability of the workpiece. To avoid the formation of folds when rolling blanks with a relative wall thickness $s_0/d_0 < 0.1-0.12$ and the relative initial height $h_0/s_0 > 3$ of the formation of the outer sides can be carried out according to the deburring scheme. The workpieces deburred by the CMR method are shown in Fig. 7.

$$\delta = \frac{s_0}{(1,5\ldots 2)\mu}, \tag{4}$$

where μ is the coefficient of friction on the surface of the rolls-workpiece.

Unrolling of workpieces according to the deburring scheme is accompanied by the appearance of significant tensile stresses, so this type of unrolling can be subjected to materials with high plasticity,

Fig. 6. Blanks with an outer and inner edge, obtained by landing with a purposeful displacement of the top of the conical roll.

Fig. 7. The workpiece obtained by debarring: at the intermediate and final stages.

a b c

Fig. 8. Scheme of direct extrusion–calibration and the appearance of the obtained blanks: *1*—blank, *2*—clamp, *3*—matrix, *4*—mandrel, *5*—roll, *6*—ejector.

which is characterized by the value of the relative narrowing of the neck when the sample is stretched $\psi_{\varnothing} = 60...65\%$.

The production of parts from steels 10, 20, 12X18N10T and copper M0b showed that deburring of rolling allows obtaining high-quality edges of significant sizes, including and with a thickness significantly less than the wall thickness of the original workpiece.

Technological schemes of direct extrusion–calibration and combined deformation with deposition and reverse extrusion are more favourable from the point of view of metal deformability [7]. According to the first scheme, thrust bearing rings and parts of cam clutches were obtained (Fig. 8).

The workpiece in this case is a ring obtained by cutting from a sheet on a stamp or cut from a pipe. The material of the bearing ring is bearing steel. Application conical roll with $\alpha < 10°$ allows reducing the centrifugal flow of the material and the intensity of the formation of external burr. In the rolling process, a track of the rolling elements, end surfaces with chamfers, outer and inner diameters of 8–9 accuracy quality are formed. The surface roughness of the raceway is $R_a = 0.2$–0.4 μm; the other surfaces are $R_a = 0.8$–2.5 μm. The rolling time is of 4–5 seconds.

Figure 9 shows the products obtained according to the technological scheme of deposition with reverse extrusion.

Thus, by purposefully applying various technological schemes of SR, it is possible to obtain high-quality products of various shapes, and

a *b*

Fig. 9. Complicated profiled products obtained by rolling with a cylindrical roll: *a*—flange with a collar; *b*—element of the body of the electrovacuum device.

using an approach based on deformability criteria, determine the suitability of the material for processing and the final dimensions of the products.

2. PRESENTATION OF THE MAIN RESEARCH MATERIAL

Rounded flat workpieces are quite common in the manufacturing industry. Traditionally, such workpieces are obtained by cutting or cutting from a sheet, which is accompanied by significant waste in the form of jumpers. Therefore, the issue of effectively obtaining thin workpieces for subsequent MRM operations is quite relevant [8].

Despite the development of stamping processes with improved contact friction conditions [9, 10], the main operation for obtaining thin round workpieces remains their cutting from a sheet. At the same time, the quality of the blanks does not always meet the requirements due to the initial anisotropy and different sheet thicknesses.

In the further extraction of products from such blanks, the main factor limiting technological possibilities is the destruction of blanks in the most dangerous local zones. Ruin is preceded by a loss of deformation resistance or a local thinning of the workpiece in the form of a neck, from the moment of its formation, an increase in the degree of extraction becomes impossible.

Rounded parts with a relatively small height are difficult to manufacture; $h/d < 0.3$ with a diameter of no more than 300–350 mm. In this case, high-power and high-rigidity hot stamping press equipment is required, and highly alloyed, expensive steels are required for the production of stamping equipment.

In this regard, the article examines the technological process of stamping by rolling (SR) of flat annular and flange workpieces.

SR allows obtaining blanks of the required shape by reshaping them from square, round and ring. According to the proposed technology, the sheet is cut into square blanks without waste, which are reshaped

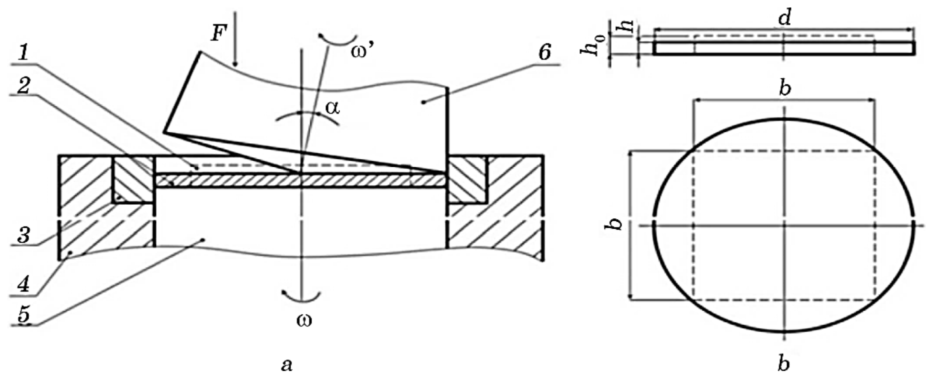

Fig. 10. Scheme of reshaping of workpieces by the SR method (*a*), view of the original square and rolled round workpiece (*b*): *1*—workpiece, *2*—product, *3*—matrix, *4*—spindle, *5*—ejector, *6*—roll.

by the SR method (Fig. 10.) into flat round ones or with the required thickness profile. Thus, the reshaping of the workpiece is carried out according to the scheme of precipitation by the SR method.

In the case of reshaping of workpieces by the SR method, the possibility of controlling the intensity and direction of the metal`s flow by shifting the roll is practically excluded, since it is impossible to ensure the shift of the top of the roll due to the use of a die-gauge. In this case, centrifugal drawing of the metal is preferred. At the same time, the maximum flow intensity is observed at a distance $r < 0.2R$.

The debugging scheme shown in Fig. 11 according to the classification of rolling stamping processes [11, 12] should be classified in the first group - waste-free production of flat workpieces.

When the metal flows in different axial directions of the workpiece, three stages of forming are observed.

At the first stage, there is an intensive redistribution of the volume of metal [12] (in the reverse direction from the applied force P) and in the radial (along the line H–H) directions (Fig. 12). In the tangential direction, the redistribution of the volume of metal is slowed down, which is confirmed by the difference in the values of a_i and b_i (Fig. 4). The resistance to deformation throughout the volume of the part is also different, on the surface of the interaction of the initial blank with the punch I, the outer layers move more intensively than the inner layers due to the high friction of the initial workpiece along the surface of its interaction with matrix II (this is obvious when considering the contact area of the tool with the original workpiece).

Because of this, additional loads appear: on the outer compressive surface (since each inner layer restrains the movement of the adjacent outer one) and on the inner one—tensile ones (since each outer layer moving faster than the neighbouring one captures it with itself).

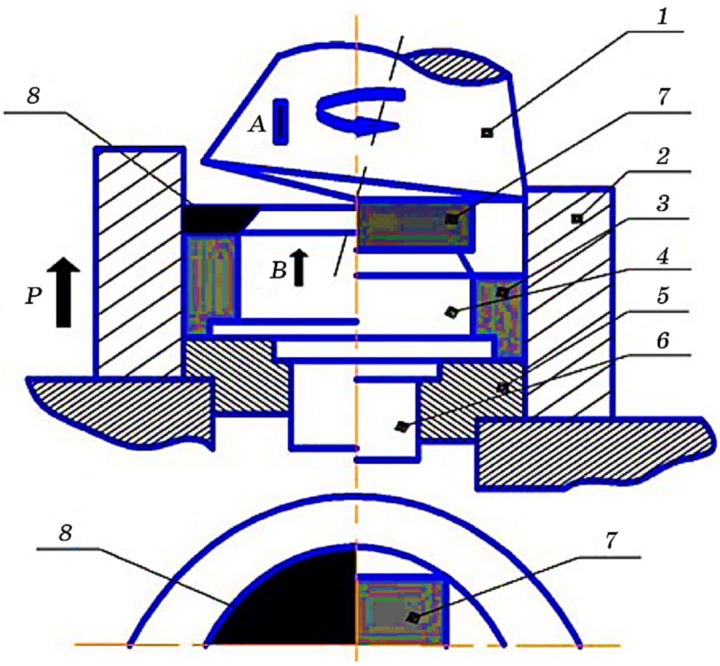

Fig. 11. Setup scheme for rolling stamping of flanged parts and blanks: *1*—punch; *2*—container; *3*, *4*—matrix; *5*—ring; *6*—ejector; *7*—starting workpiece; *8*—finished part.

As a result of equalizing the load, there is a zone of the inner layers with additional radial load, which increases to the outer surface. The fact that the surface layers of the metal move more intensively than the lower layers is confirmed by examining the cross section of the workpiece in the first stage of the process (Fig. 13).

The beginning of the second stage of the process is determined at the moment of contact of the initial workpiece with the matrix on surface III. Although the movement of the volume of metal does not change its character in relation to the first stage, it occurs with increasing resistance to deformation, which is explained by the intensive formation of the lower part of the workpiece. In the directions along the line H–H, the radial flow of metal increases, and at the moment of filling the outer diameter of the container, it changes its direction, at the same time, in the direction along the line S–S, the tangential flow of metal prevails, and at the moment of changing the direction of the flow of metal along H–H, an increased hydrostatic pressure, the increase of which determines the filling of the lower part of the flange [13].

A characteristic feature of the first two stages of forming is the presence of internal circular steps when the initial and final stages of the process are formed, and the height difference $H2 - H1 = S$ gives

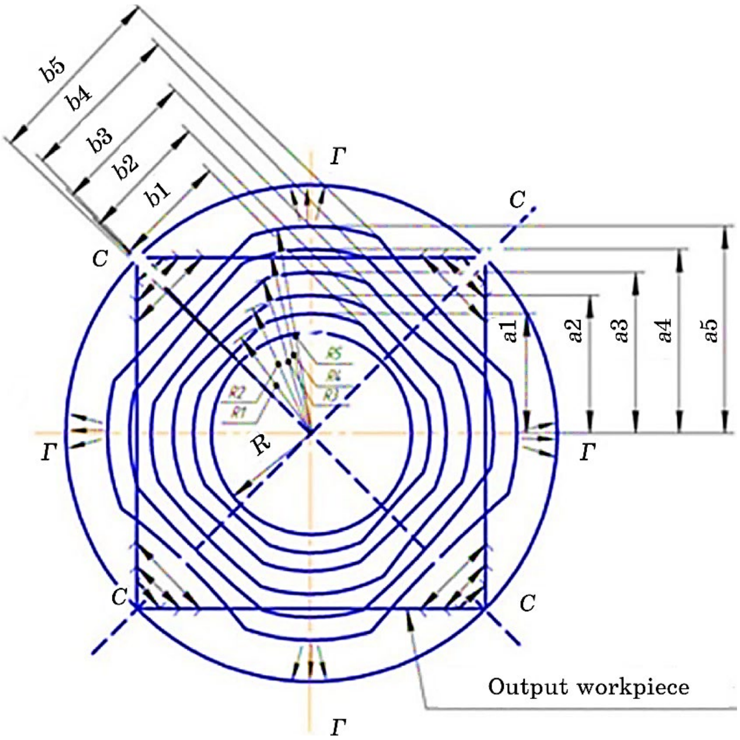

Fig. 12. Scheme of metal flow in the flange part of the part during rolling stamping from a ring blank. *H–H*—radial metal flow conversion line *S–S*—tangential metal flow conversion line.

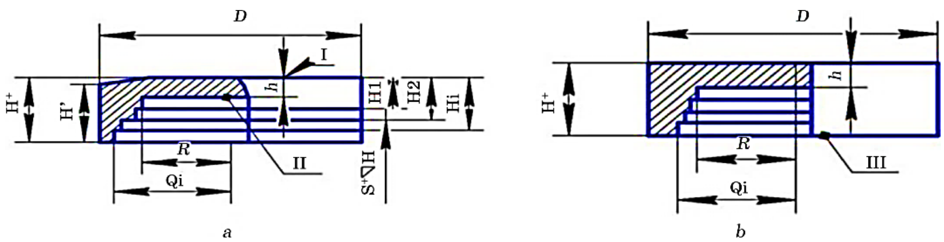

Fig. 13. Cross-section of the workpiece at the stage of the process: *a*—along the *G–G* plane, *b*—along the *S–S* plane.

the feed value for one rolling cycle.

The formation of straight sections on the *S–S* line is a consequence, the distortion forms rings due to the support at the point of contact of the workpiece with the diagonal direction.

The third stage of the process is the calibration of the canvas and the inner diameter of the workpiece. The process occurs without a signifi-

TABLE 2. Dimensions and parameters of the rolling stamping process of ring and flange workpieces.

№	Parameter names	Marking	Unit of measurement	Parameters
1.	Diagonal of the original workpiece	L_d	[mm]	186 ± 240
2.	The thickness of the original workpiece	H_{sum}	[mm]	16
3.	Angle of inclination of the axis of the punch	θ	(degree)	2
4.	Axial feed of the tool	S	[mm/turn]	1.7
5.	Heating temperature	T	[°C]	740
6.	The maximum force of the stamp	P	[kN]	2300

cant increase in deformation force [14].

In the analysis stage of the study, a device for the production of blanks and parts by the rolling stamping method is proposed [15].

The device for implementing the method contains a matrix *1*, a rolling punch *2* and an ejector *3*. The punch *2* receives a rolling motion from a special drive. The matrix *1* and the ejector *2* are mounted on the press table and can move vertically from their drives.

Research of the obtained products in terms of accuracy corresponds to 10–11 quality, the surface roughness is 3.2 µm [16].

Calculation of the workpiece during rolling stamping.

1. Initial conditions (Fig. 14.):

$$C = D, \; V_d = V_z, \tag{5}$$

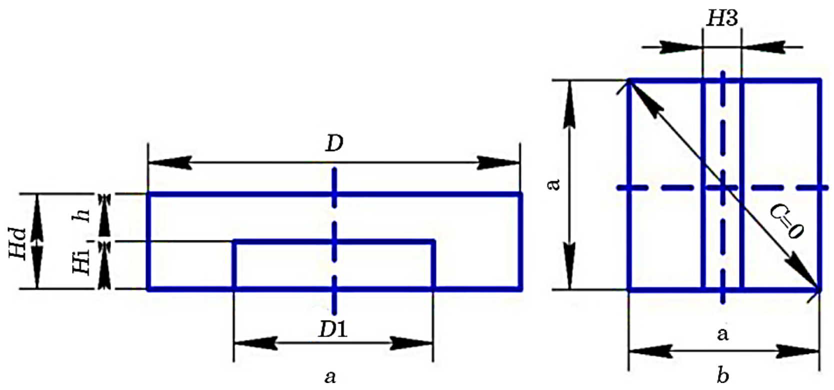

Fig. 14. Dimensions of the finished part (*a*) and the initial blank (*b*).

where C—diagonal of the workpiece; D—outer diameter of the part; V_d, V_z—the volumes of the part and workpiece.

2. Variation intervals:

$$D_1/D = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9,$$
$$\text{Sun} = 3.5, 10, 12, 14, 16, 20,$$
$$h = 0, 1.5, 4,$$

where D_1—inner diameter of the part; H_d—the height of the part; h—is the thickness of the jumper.

3. Conclusions of calculation formulas:

$$V_d = (\pi D^2 H - \pi D_1^2 H_1) / 4, \quad (6)$$

$$V_z = a^2 H_3, \quad (7)$$

where a—side of the workpiece:

$$a = \left(\frac{C}{\sqrt{2}}\right)^2; \quad (8)$$

but $C = D$, then,

$$a = \left(\frac{D}{\sqrt{2}}\right)^2. \quad (9)$$

From formula (7),

$$H_z = \frac{V_z}{a^2}. \quad (10)$$

However, according to condition (5), V_z is equal to V_d.

After transformation (10), we will get the original formula for calculating the height of the workpiece:

$$H_z = 1.57(H_d - B^2 H_1). \quad (11)$$

Power parameters and forming processes during rolling stamping of flat annular and flange blanks from a square workpiece. In the processes of three-dimensional rolling stamping, at each moment of time, the initial workpiece is in contact with the tool only with part of the end surface, thus forming a local centre of deformation [7].

The location of the centre of oscillations at the top of the conical (rolling) of the tool, which determines the dependence of the total stamping force on the angle of inclination of the tool axis θ, the feed of the workpiece S, the shapes and geometric dimensions of the initial workpiece.

Rolling stamping can be carried out in two ways:

- with constant effort, when the required shape change is achieved due to a certain number of rolling cycles under load [17];
- with constant axial feed of the tool (workpiece) in one rolling cycle.

In the latter option, the punching force will increase to a maximum by the end of the punching, but by this time the deformation will be over, the endurance under full load is not required, the rolling drive will not experience peak loads at the initial moment of punching, and the productivity will be higher.

As a rule, according to the first option, stamping is carried out on low-power equipment. In the initial stage of the press process, maximum effort is given, while the feed will inevitably decrease due to the increase in the size of the workpiece. When carrying out such a process, there is uneven deformation along the height and re-sticking of the surface layers of the workpiece, which are in contact with the rolling tool.

Pre-stamping, *i.e.*, the final operation of complete shaping of the workpiece, is carried out at very small feeds, the locality factor X increases, and the productivity at the same time decreases significantly.

In this regard, it is advisable to conduct a process with a constant supply. In this case, the force P_{os} is increasing with each run-in cycle, and the locality coefficient λ will keep a constant value.

The calculated feed at a constant number of running-in of the spherical moving mechanism is slightly less than the actual feed. Despite this, the effort is not observed, since the local feed does not have time to show itself during the rolling cycle.

As a result, productivity increases and the probability of defects detected in the case of conducting the process with constant effort decreases SR. In this case, the requirements for the equipment of the power press and the rolling mechanism change accordingly.

Researching [18] in this direction was carried out on low-power equipment and did not reveal all the advantages of rolling stamping.
Based on the above, we will consider the characteristic features of stamping round flanges from square and strip blanks with constant feed.

Figure 15 shows the diagrams of the established process of rolling stamping with square and strip workpieces.

To calculate the area of the local centre of plastic deformation of the spot of contact with the surface of the rolling tool, we use the formulas given in [19], where the stress-deformed state of the metal during this process is most accurately described.

It should be noted that the law of the smallest perimeter is not observed when stamping round workpieces from square or strip workpieces. In this regard, the boundaries of the square and strip workpieces remain practically straight. This allows you to determine the local centre of deformation of the contact spot in the direction perpendicu-

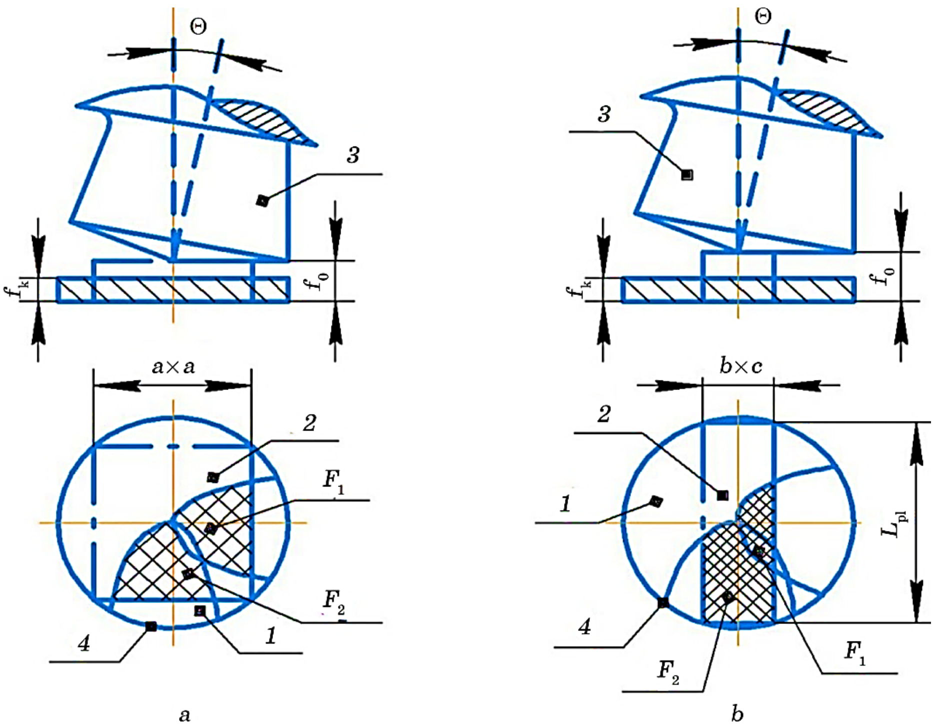

Fig. 15. Scheme of rolling stamping of flat workpieces (circles): *a*) punching from a sheet; *b*) punching from a strip. *1*—stamped circle; *2*—initial workpiece; *3*—punch; *4*—matrix.

lar to the border of the square or strip workpiece.

The ratio of the area of the contact spot in different directions is approximately 20% at the initial moment of stamping. As the stamp fills the circular cross-section of the stamped workpiece, the ratio decreases and when it is completely filled in all directions, it becomes equal (this is the final stage of stamping).

Correspondingly, the resistance of the metal and the contact pressure change due to the change in the contact areas in the local centre of plastic deformation, that is, the metal is easily stamped in the direction of the face. It explains that the appearance in the direction of the face, which is shown in work [20–23] based on the example of the loss of stability of the workpiece in the tangential direction perpendicular to the boundary.

The intensive flow of metal in the tangential direction in the corner zones of square or strip workpieces remained unclear.

In Figures 16–18, the nature of the flow of metal from its initial stage to the final output product is shown that shows how the metal is redistributed around the circle. Figure 17 shows the diagram of the

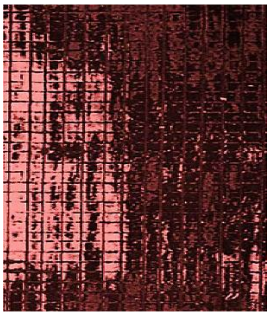

Fig. 16. Output blank from the strip.

Fig. 17. Intermediate shape of the blank when punching a circle from a strip in case of loss of stability (bend) in the region of the side face, parallel to the axis of the strips.

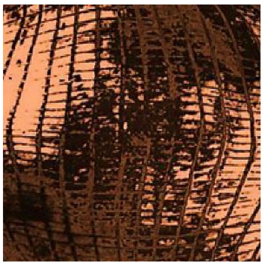

Fig. 18. The final shape of the workpiece.

areas of the contact spot during rolling stamping from a square blank, where their difference is clearly visible.

The difference in contact areas in the direction of the boundary and in the direction of the corner of the workpiece leads to an increase in the feed in the area of the faces, from which the tool already rolls onto the corner zone. This causes an intense tangential flow of metal in the corner zones of a square or strip workpiece, and sufficiently pronounced conditions perpendicular to the boundary disappear along stamp filling measures. The consequence of this is high accuracy in the thickness of the workpieces [24, 25]. It was previously shown that, even on thin workpieces, the ratio $N/D = 0.02$ corresponds to the accuracy of cold-rolled sheet without calibration.

3. CONCLUSIONS

The stress–strain state of workpiece material is an important characteristic necessary for assessing deformability and determining force parameters. Among the effective methods of NDS analysis are the grid method, hardness measurement, and microstructural analysis.

Direct extrusion by the SHO method was considered by us using the example of forming end teeth of a gear sleeve. To increase the accuracy of determining deformation intensity in cross-sections of workpieces, a highly strengthening material, namely, copper M0b, was chosen for physical modelling.

As a result of constructing graduation graphs and measuring hardness in workpiece cross-sections, as well as grids on workpiece surfaces, the distribution character of stress and strain intensity, as well as the stress state index in the plastic area, was obtained. The most rigid stress state scheme is observed at the apex of the extruded teeth, but here the least deformation occurs. The largest deformations are formed at the base of the tooth, but the stress state is close to uniaxial compression.

Reverse extrusion by the SHO method was also modelled on copper M0b. NDS analysis showed that the most deformed zone is the thin-walled element zone, which is formed because of metal flow from the contact plastic spot area of the roller with the workpiece. Maximum deformations are observed in this zone, gradually decreasing as you move away from the contact surface.

The flange part of the workpiece is a zone of relatively uniform deformation. Dependences of the growth of deformation intensity on the periphery of the flange from the relative increase in its length were constructed.

Based on the analysis results, paths of material particle deformation in dangerous zones due to possible workpiece destruction were constructed, which were then used to assess workpiece material deformability.

The possibilities of direct extrusion are limited by the complexity of force transmission from the roller to the opposite end face of the workpiece and significant contact stresses. Therefore, this operation is more suitable for calibration or forming of small-size workpiece elements, which should be taken into account when developing corresponding SHO technological processes.

Further research in this direction will expand knowledge of material deformation mechanisms during stamping by extrusion and develop new approaches to optimizing technological processes in the production of metal parts.

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