

РОЗДІЛ II ПРОЦЕСИ ОБРОБКИ ТИСКОМ У МАШИНОБУДУВАННІ

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PROMISING METHODS OF FORMING COMPLEX PROFILED PARTS BY PRECISE VOLUME EXTRUSION

An effective way to increase the competitiveness of engineering products is to develop resource-saving technologies for forming by precise volume extrusion. Extrusion methods are characterized by the possibility of active control of metal working modes and allow obtaining precise workpieces with dimensions and quality nearing the parameters of finished parts. There is currently a tendency to increase the capabilities of extrusion processes by adding new transverse (radial and lateral) extrusion methods to traditional longitudinal extrusion ones, aimed at producing more complex parts of previously inaccessible shapes. Further development of these technologies is associated with designing methods for combining longitudinal and transverse extrusion schemes, which allows optimizing the modes for manufacturing complex-profile hollow and rod parts in one operation. The kinds of technological schemes of transverse (radial) and combined transverse-longitudinal extrusion were systematized. The groups of combined, sequential and staged combined extrusion were defined, which combine schemes carried out sequentially along the path and time of execution. The features of forming and development of the deformed state of hollow and solid parts with flanges and thickenings in radial and combined extrusion were studied experimentally and using the finite element method. An assessment of the possibilities and limitations of new technological methods for controlling metal flow and the quality of a deformed workpiece was given. The conditions for the occurrence of characteristic defects in parts, as well as methods for eliminating defects and deviations in the shape of parts, were considered.

Key words: radial extrusion, combined transverse and longitudinal extrusion, forming, parts with flange, hollow parts, shape defects.

Design and development of new high-tech technological processes is one of the most important directions to intensify mechanical engineering, in particular, workpieces production. A significant reserve for increasing the competitiveness of mechanical engineering can be resource-saving technologies, which include processes of volumetric plastic deformation making it possible to obtain workpieces with regulated quality [1]. Currently, processes of volumetric deformation with additional force and kinematic effects are becoming widespread, which allows to provide an optimal mode of deformation and regulation of metal flow in the deformation centre, control of the stress-strain state of the workpiece, and, consequently, the quality of the obtaining part [2]. There are also known alternative processes of combined loading: deformation with torsion, local deformation, vibration deformation, deformation with counter pressure, deformation with tension, alternating deformation, deformation with the beneficial use of active, reactive and reverse friction forces, and others [3–5].

Methods of precise volume forming by extrusion are characterized by the possibility of active control of pressure working modes and allow obtaining workpieces with dimensions and quality that are close to the parameters of finished parts, due to which finishing by mechanical working is reduced or completely eliminated [1, 6]. Traditional methods of longitudinal (forward and backward) extrusion have shown the advantages of precise volume forming processes in the production of high-quality parts, but they do not cover the entire range of products [7].

Recently, there has been a steady trend towards improvement of the capabilities of the precise volume forming processes by increasing the complexity of the design of obtained parts. In addition to traditional extrusion methods, new methods of transverse (radial and lateral) extrusion are increasingly being used, aimed at producing complex parts with a flange or with one or more lateral ledges [8, 9]. New extrusion methods are used to produce parts of previously inaccessible shapes: hollow parts of complex configurations [10, 11], with flanges [2, 6], with steplike and hollow ledges of round (ring) and rectangular cross-section [12]. A review by the Forging Industry Association (FIA) [13] shows the evolution of the production process of the steel crosses from ordinary hot die deforming to cold extrusion, which brought the workpiece and finished part closer in shape and led to a significant reduction in laboriousness.

Prospects for further improvement of precise volume forming technologies are associated with the development of deformation methods that are provided by combining longitudinal and transverse extrusion schemes and allow the production of complex-profile hollow and rod parts in one technological operation in split dies [14, 15]. This is especially relevant for the production of precise parts with complex shape such types as crosses, cups with flanges, profiled bushings and deep sleeves. Combined extrusion with elements of radial flow (expansion) of metal is also a method of reducing deformation forces and increasing the durability of the deforming tool [16, 17].

The variability of technological modes, part and tool configurations, deformation schemes and metal flow kinematics requires adequate prediction of the results of forming precise parts, preliminary assessment of technological modes and capabilities of the deformation methods. For example, researches today are aimed at studying the influence of geometric parameters such as die radii, gap and diameter sizes, as well as friction conditions on the formation and fluctuations of loads in processes such as radial extrusion [8], lateral extrusion [12], backward extrusion of cups [7], combined extrusion of hollow parts [16], sequential radial-forward extrusion of hollow parts such as sleeves [18, 19], radial-longitudinal extrusion of bushing-type parts [10], three-sided backward-radial-forward extrusion of hollow bushing-type parts with a bridge [20] and transverse- backward extrusion of cups with a flange at the bottom [2, 21].

Ensuring the required law of forming and quality of complex design parts with the needful performance properties is possible under the condition of optimization and active control of plastic deformation modes [6, 22]. The development and study of new methods of extrusion and models for calculating the processes of deformation of parts under complex load conditions are important directions of development of precise volume forming technologies [15]. Generalization and analysis of the varieties of such methods, techniques, modes and tools of plastic deformation are the necessary conditions for increasing their efficiency and expanding the scope of use.

The purpose of the work is to systematize and generalize information on new methods of precise volume forming by extrusion.

In order to determine promising processes and research directions, it is necessary to compare and generalize technological schemes of deformation. The identification of the maximum number of new methods of volumetric deformation can be ensured by using specialized methods of directed synthesis, given in the literature on system design [15]. To generate technological schemes of combined deformation, it is desirable to conduct a more detailed analysis of the features related to the kinematic and force effects on the deformed workpiece. The study of the internal structure of the forming process, the relationship between the influence and movements of the tool and the directions of metal flow can lead to the identification of a number of possible solutions with better technical effects [2, 15].

The DSEA has developed number of methods for transverse and combined extrusion in various kinematic variants which using movable and composite tools [2, 8, 14, 23]. Kinematic impact techniques are an effective way to improve the quality of formed parts in precise volume forming processes by extrusion. It becomes possible for transverse extrusion processes to control deformation with regulation of product quality [8].

A feature of the transverse radial extrusion technology is the ability to actively regulate the deformation and force parameters of the process by changing the kinematics of the forming tool

movement. Fig. 1 shows some methods (kinematic variants) of radial extrusion [2, 8]. The simplest kinematic variants of radial extrusion (Fig. 1, scheme 1) are carried out with one-sided supply of metal into the working cavity of a stationary die. Extrusion with combined two-sided metal supply is performed by counter movement of punches or forced movement of the die at a speed that is approximately 2 times slower than the speed of the punch (scheme 2) [24]. In the third variant, extrusion is performed with sequential two-sided supply, which ensures better filling of the radial cavity [8].

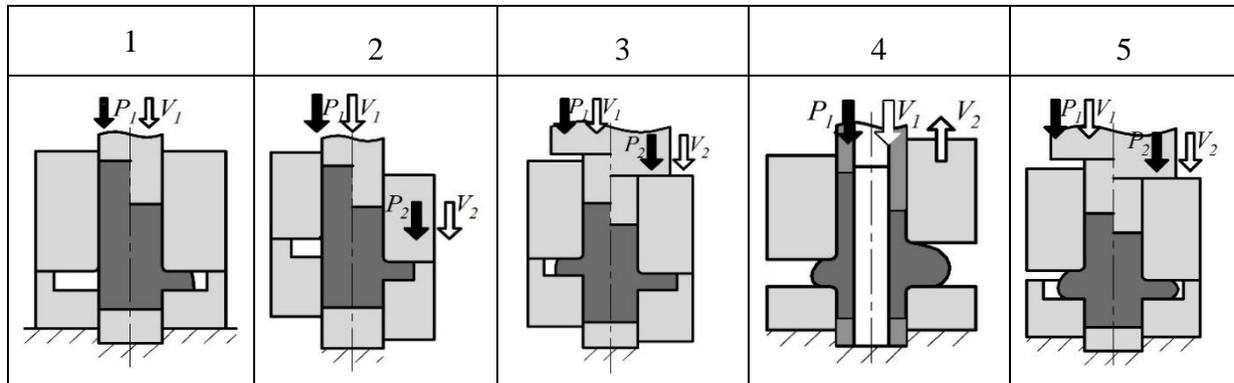


Fig. 1. Methods of adjusting the kinematics of metal flow during extrusion

The differences in the deformed state of parts obtained by extrusion with one-sided metal supply (one-sided extrusion) and two-sided extrusion can be demonstrated using the example of distortion of the dividing grid applied to the part before transverse extrusion (Fig. 2). In case of one-sided transverse (both lateral and radial) extrusion, the intense deformation center has an asymmetrical shape. The zone of maximum deformation and, accordingly, the zone of maximum hardening shift to the lower boundary of the deformation center, where a sharp increase in the degree of metal deformation occurs. Such uneven with a significant gradient deformation causes the danger of exhaustion of the resource of plasticity of the metal along the boundary of the intense deformation center. In lateral extrusion of thickenings and ledges, cracks appear even during deformation of highly plastic aluminum alloys (Fig. 3, *a*). This also reduces the performance reliability of cold extruded products. Flanges (for example, on parts of insulator suspensions made of 1020 steel), obtained by one-sided radial extrusion, can separate under load along a practically smooth surface [22]. To improve the performance properties of loaded products, it is necessary to control the formation of the structure of transition zones in order to prevent the formation of texture or the exhaustion of the plasticity resource.

In double-sided extrusion in a movable die (see Fig. 1, scheme 2) [24], the deformation center has symmetrical shape, smaller height and volume, which is a disadvantage, since the metal may not be sufficiently hardened in the transitional most loaded areas (see Fig. 2, *b*).

In sequential double-sided extrusion (see Fig. 1, scheme 3) [8], the receiving cavity of the die is filled with metal, supplied first from the upper part and then from the lower part of the workpiece. This allows to increase the volume of metal for forming the flange and to shift the zone with a high deformation gradient within the deformation center (Fig. 2, *c*).

A number of other technological methods have also been proposed to regulate the position of the zone of maximum metal hardening along the height of the deformation center, the degree of filling of the die receiving cavity, and the shape of extruded flange. These methods include extrusion with a combined supply of metal into the cavity of a movable die, which allows to control of flow and location of the hardened zone along the height of the deformation center; extrusion supplemented by preliminary or subsequent upsetting of the flange [2, 8].

To eliminate the risk of fracture of the part in zone of the transition to the flange and simultaneously to ensure sufficient strength, it is proposed to supplement one-sided extrusion with two-sided deformation at the final stage [25]. Elimination of defects such as mushroom-shaped flange is facilitated by combined radial extrusion, which includes preliminary metal loading into the cavity of a

movable die and subsequent flange upsetting (see Fig. 1, scheme 5) [8]. The method allows controlling the trajectory (history) of deformation and avoiding a dangerous rigid zone of stress state. In general, this leads to an increase of 1.5–2 times in the limit diameters of flanges obtained on rod workpieces.

The process of radial extrusion of flanges on hollow workpieces is characterized by defects such as sink marks that appear on the inner surface of the hollow workpiece when the height of the receiving cavity exceeds the wall thickness of the tubular workpiece (Fig. 3, *b*). To prevent such defect, the height of the receiving cavity of the die is gradually increased by raising the half-die (see Fig. 2, scheme 4) [8], which makes it possible to manufacture parts with flange thicknesses up to 4–5 thickness of workpiece wall. A gradual increase in the cavity height can cause the appearance of a sink mark on the outer side surface of the high flange (see Fig. 3, *d*).

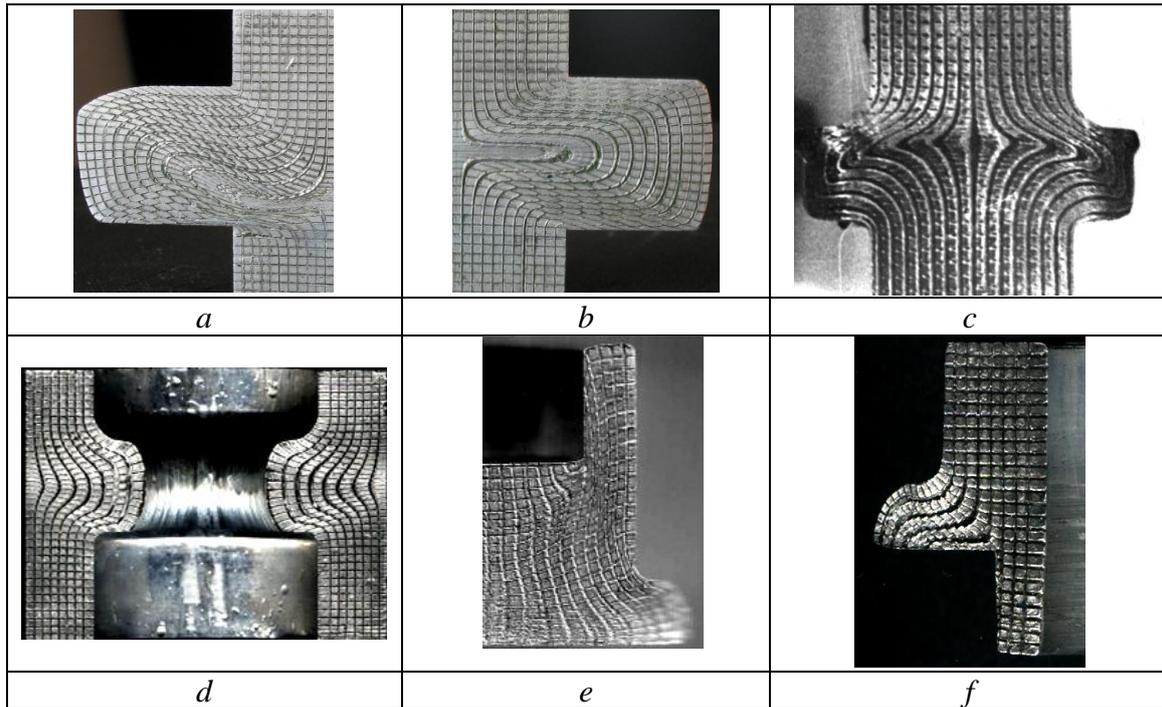


Fig. 2. Parts with a dividing grid obtained by radial extrusion with one-sided (*a*, *d*), two-sided (*b*) and sequentially two-sided (*c*) supply, as well as combined radial-backward (*e*) and radial-forward (*f*) extrusion

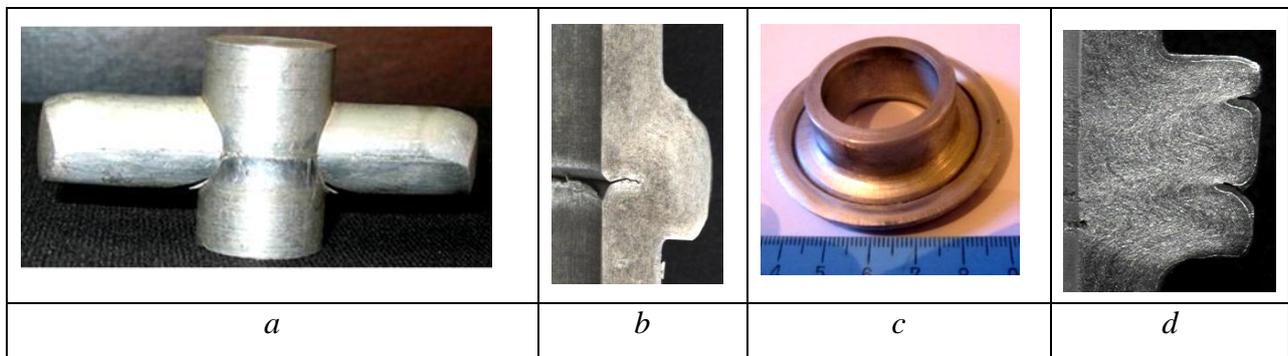


Fig. 3. Fracture of the ledge (*a*) and distortion of the flange shape (*b–d*)

The method of preliminary formation of a technological (temporary) flange shoulder in the flange formation zone is also aimed at preventing the appearance of sink marks [26]. FEM simulation and experimental research confirmed the possibility of manufacturing parts without such defects (Fig. 4).

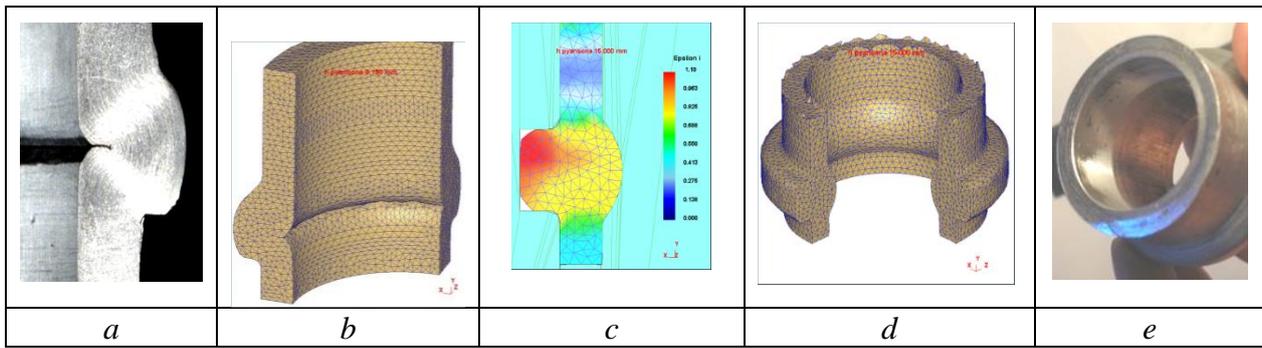


Fig. 4. Elimination of sink mark by formation of a technological shoulder [26]

Characteristic defects of the processes of flange radial extrusion are deviations in the shape of the flanges [8, 22]. During radial extrusion of metal into a circular cavity of constant height, the thickness of the extruded flange continuously decreases with distance from the rod. Typical types of deviation in the shape of parts observed in radial extrusion of flanges on a workpiece are shown in Fig. 5.

Parts with relatively thin flanges (at $\bar{h} = h/R_0 = 0.3...0.4$) and small dimensions ($\bar{R}_1 = R_1/R_0 \leq 1.3$) can be obtained without noticeable distortion of shape. At smaller and larger values \bar{h} , thinning of the flange leads to distortion of its shape and a decrease in the degree of working cavity filling with metal. In extrusion with one-sided supply, the lower part of the cavity is filled faster, and the resulting flange takes a mushroom-like shape (see Fig. 5, row A). The upper curved end face of the flange or thickening can be approximately described by a parabolic curve.

For one-sided deformation of thickenings (flanges in the middle part of the rod), a typical deviation in shape is the lag of the lower edge of the thickening in the radial flow, caused by the braking effect of the lower part of the deformed workpiece. The area of contact between the thickening and the end face of the half-die is, at any value, less than the area determined by its maximum diameter. The size of the relative radius of separation R_n/R_1 depends on the thickness of the thickening \bar{h} in extrusion solid parts, and for tubular parts it depends also on the thickness of the workpiece wall.

The extrusion of relatively thin wide flanges can be accompanied by the phenomenon of loss of stability and the distancing of the flange peripheral sections from the end face of the lower half-die. The bending of the flange is greater, the softer the deformed material (see Fig. 5, row B).

In extrusion with combined two-sided supply, the thickenings have a symmetrical wedge shape with a thickness at the edge that decreases as the flange diameter increases.

The surface roughness of parts obtained by radial extrusion is uneven. With one-sided supply, the extruded metal contacts only the end face of the lower half-die, which significantly improves the surface quality ($R_a \leq 0.32$ micron). At the upper curved end face of the flange, the surface quality deteriorates, which is especially noticeable when deforming soft aluminum alloys. An increase in roughness on both surfaces of the forming wedge-shaped flanges is observed in double-sided extrusion. With sequential two-sided supply, the roughness of the flange end faces is lower, but on one of its end faces, formed by a broken line, the metal flow, which entered at the second stage from the lower part of the workpiece, is layered on the obtained flange in the form of a noticeable bump. Uneven distribution (anisotropy) of the roughness of the end faces of the half-dies can lead to such a deviation in shape as ovality of the flanges, which is especially significant in the absence of a lower undeformed part of the workpiece and high plasticity of the material of the part. Deviation from the roundness of the flanges can also be observed with small values of the radii of the transition edges of the dies, as well as with non-parallelism of the end faces of the half-dies that form the radial receiving cavity. Under such conditions, uneven metal flow in the radial direction is observed, which leads to the formation of local thickenings of the flange (bumps) due to the reduction of its radius. In this case,

the softer the deformed material, the more unstable the workpiece and the more likely such defects are to appear. When the values of the receiving cavity height increase ($\bar{h} \geq 2,0$), there is a risk of uneven flow or loss of stability of the workpiece. The extruded flanges at the end of the rod workpiece acquire an asymmetrical (one-sided) shape. The thickenings in the middle part with a thickness of more than 3.0 take the form of a double barrel, it is similar to how such a distortion occurs during upsetting between flat plates.

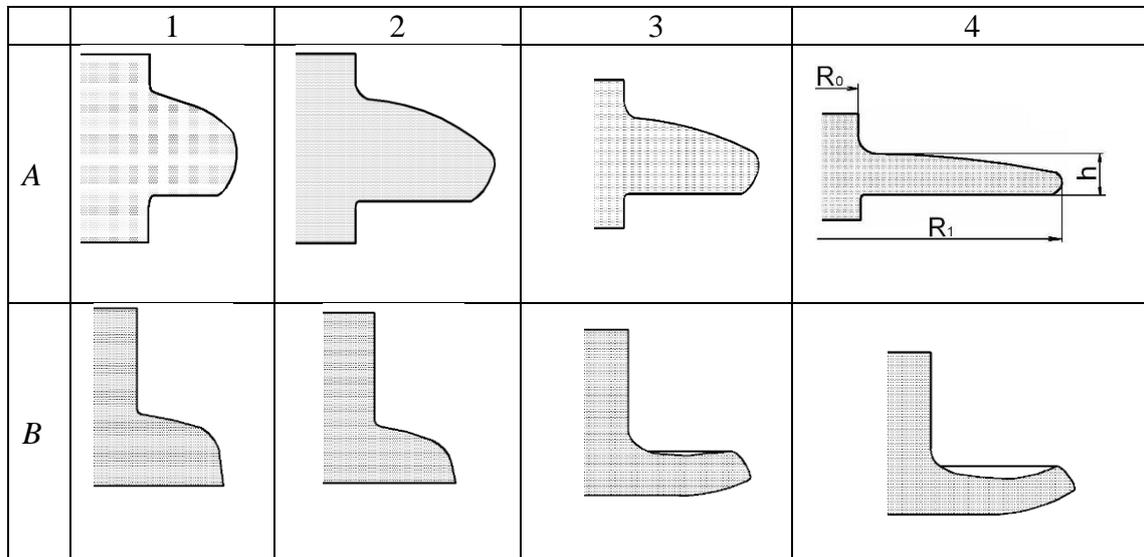


Fig. 5. Deviation of the shape of thickenings and flanges in radial extrusion

A comparison of the shapes of thickenings (flanges on the middle of parts) and flanges on the part end faces, formed on hollow workpieces by one-sided deformation, is shown in Fig. 6. A quite convenient and clear criterion for assessing the extruded deviations of the shape of thickenings from the correct cylindrical shape can be the indicator λ , equal to the ratio of the extruded volume of metal to the calculated volume of the circular transverse cavity, determined by the maximum diameter of the thickening (Fig. 3, b) [3, 9]. For cases of extrusion with single- and double-sided supply, the degree of cavity filling and the value of the indicator are significantly reduced at $\bar{h} \geq 0.5$.

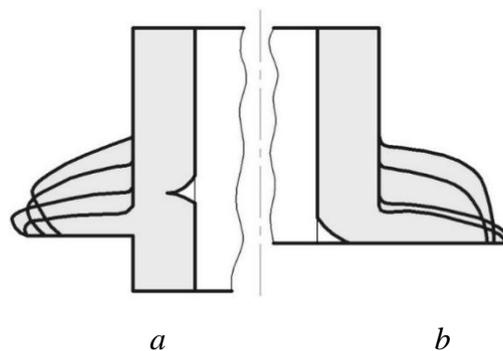


Fig. 6. Contours of thickenings (a) and flanges (b) on a tubular workpiece

The greatest filling of the circular cavity can be achieved by extrusion with sequential two-side supply. The value of the rate is determined by the relationship:

$$\lambda = B_0 - B_1 \cdot (h/R_0). \tag{1}$$

The values of the empirical coefficients B_0 and B_1 must be determined depending on the extrusion scheme:

Schemes of extrusion with supply	B_0	B_1
one-sided	1.037	0.185
double-sided	1.010	0.220
sequentially double-sided	1.025	0.088

It is advisable to use these data when calculating the dimensions of the initial workpiece, the height of which should be greater than the height of the finished part by the value of the working stroke S , set by the expression:

$$S = \lambda \cdot h \cdot (\bar{R}^2 - 1). \quad (2)$$

It should be mentioned that the influence of the material grade on the patterns of forming is insignificant and was noted only in spatial bending of thin flanges and in their local thinning and the appearance of bumps.

Forming flanges on tubular workpieces has some differences compared to extrusion of flanges on solid workpieces. This also concerns the qualitatively new shape of the obtained flanges, formed both in the middle part and at the end of the tubular workpieces (see Fig. 5, row B and Fig. 6). The non-adherence of the flanges to the supporting surface – the end face of the lower half-die, is greater for hollow parts than that observed for flanges formed on a solid workpiece. This is caused by the spatial bending of the periphery of the relatively thin flange. The end face flange, by its maximum diameter, is adjacent precisely and over its entire surface to the end face of the lower half-die at average values of the relative thickness of the flange $0.4 \leq \bar{h} \leq 0.8$. Below these values there is a region of relatively thin flanges, for which a separation of the flange periphery from the end face of the half-die is observed (starting from the relative radius of the flange $R_1/R_0 \geq 1.3$). This non-adherence is not yet accompanied by spatial eversion of the entire flange, and the upper end face of the flange retains its usual mushroom-like or curvilinear shape. But the non-adherence caused by spatial bending becomes noticeable even with sufficiently thick flanges (0.4 and higher); the flange periphery breaks away from the supporting surface, i.e. from the end face of the half-die, and the flange in section takes the shape of a “boot toe” (see Fig. 3, c). At values $\bar{h} \leq 0.2$ the entire flange is turned out and in the absence of support from the end face of the upper half-die the flange can acquire a hemispherical hollow shape.

Any process can be considered as combined one if, in addition to the main action (impact, flow, technique), it uses or is supplemented by an additional influence on the workpiece, either the direction of the flow or the additional movement of the tool. The formation of product properties is associated with external kinematic and force effects on the workpiece and depends on the prevailing deformation scheme. New possibilities of intensifying the forming processes and ensuring the best working of the structure are opened up by the processes of combined deformation: reduction with shear, die deforming with expansion, die deforming with torsion, using friction forces, etc. Additional influence on a given operation and on a given workpiece may be a force and/or kinematic effect. The main force impact is usually carried out by one active (movable) deforming tool. This can be a punch, a striker or a roller. At the same time, the forming tool – a die with a receiving (forming) cavity, as a rule, is stationary. The use of additional force effects by means of tension, counter pressure, directed friction forces, support, twisting, etc., usually requires the provision of additional energy and additional movement to other parts of the technological tooling (equipment, dies) [15, 26].

Kinematic influence should be understood as the influence on the kinematics of the process of the deformed workpiece material flow by targeted regulation (control) of the flow direction, the deformation nature, the type of deformed state, ensuring freedom of flow, changing the direction of flow, the type of deformation, the direction of supply. This may also sometimes require the use of a

special (generating) force impact. But in many cases, the kinematics of the deformation process is not unambiguously related to the force effect, but is determined by the design (geometry) of the tool, the degree of freedom of its mobility, compliance, constant and step-by-step switching-on [15, 2]. Kinematic influence can contribute to a sharp improvement in the working of the structure of the deformed metal, level out the unevenness of deformation, and eliminate stagnation zones. For cold deformation processes with characteristic high total and specific loads, one of the main goals of kinematic influence is to increase the degree of freedom of the deformed metal flow. This combined flow, occurring in an optimal self-regulating power mode, helps to increase the stability of the tool, expanding the possibilities due to the complexity of the shape and accuracy of the obtained parts.

Combined extrusion methods are developed on the basis of simple methods of longitudinal (forward and backward) and transverse (radial and lateral) extrusion. United combined schemes are obtained by integrating methods of the same type. For example, bushings with flanges (thickenings) on both the outer and inner side surfaces can be obtained by combined radial extrusion [15]. Methods of combined longitudinal-transverse extrusion differ by their multi-variant implementation and involve a combined, sequential or staged combination of simple deformation schemes. In addition to the characteristic advantages of combined schemes (optimal and self-regulating power mode, large degrees of deformations, increased tool life), the inclusion of transverse extrusion in combined schemes leads to a noticeable increase in the complexity of the resulting shapes of parts. Increasing the complexity of the shape of parts obtained in this way contributes to a sharp growth in technical and economic indicators and the competitiveness of new technologies.

United combine extrusion involves the use of a split die and the simultaneous flow of the workpiece metal from a single zone (Fig. 7). Among the methods of combined radial-longitudinal extrusion, we will single out, as the most universal, the scheme of three-sided radial-backward-forward extrusion (schemes of group A) for obtaining hollow parts with a flange and a ledge. The method of radial-backward extrusion (schemes of group B) can be used to obtain both hollow parts of the “cup with a flange at the bottom” type and parts of the “rod with a flange” type from initial hollow and solid workpieces. The methods of the combined radial-backward extrusion group occupy a preferential place in a number of analyzed processes due to low working loads and therefore can be recommended for materials with increased resistance to deformation. The characteristic restrictions of the group processes are related to the different-sign stress state in the flange zone, which reduces the degree of deformation. Depending on the parameters of the part, the deformation centers in these processes can be united or attached one. And when using high workpieces, the deformation centers (radial and backward directions) can be separated with an intermediate rigid zone between them. In general, this causes difficulties in predicting the preferred direction and sequence of metal flow, and therefore, in finding the pattern of manufactured part forming.

The schemes of combined radial-forward extrusion are shown in Fig. 8. Radial-forward extrusion can be used to produce parts with a flange from solid and tubular workpieces. Methods of combined (associated by time and deformation centers) radial-forward extrusion (group C) are the most difficult schemes to implement. The restriction of the processes is that high shear deformations occur at the flow dividing up boundary, which cause the risk of separation of the parts of the workpiece along this boundary. In this case, geometric parameters and adjustment of the metal supply by counter pressure or friction forces can be used to regulate the flow. A method of extrusion in a movable die (scheme 4) is proposed, in which the deformation centers related to the metal flow to the forward and radial directions are separated from the very beginning of the extrusion process [2].

Sequential combined radial-longitudinal extrusion (RLE) is free from this restriction and is very effective for forming elongated tubular parts with a large difference in the diameter of the stepped parts and changing wall thickness. In this case, the RLE methods are fundamentally different, and therefore two groups are distinguished according to the predominant flow and nature of deformation: RLE with expansion (Fig. 9, row D) [2, 17] and RLE with reduction (Fig. 9, row E) [10]. The forward extrusion scheme is used predominantly in the combination of RLE methods, but it is also possible that after radial extrusion, the metal flows in the backward direction (see Fig. 9, scheme D4). RLE with expansion has advantages in reducing deformation forces, and RLE with reduction can be

used to manufacture parts with profiled outer and inner surfaces. The classification of sequential combined extrusion methods is based on the analysis of kinematic structures, according to the extended generalized extrusion scheme [8].

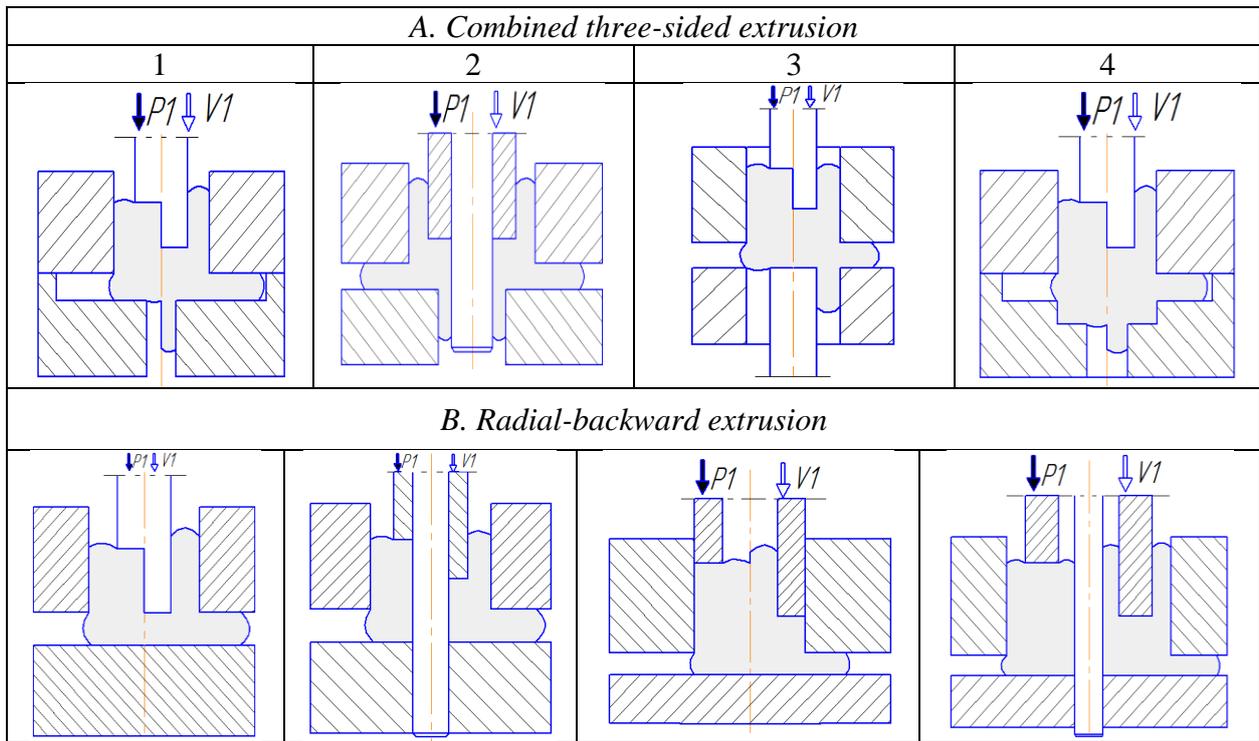


Fig. 7. Methods of combined radial-longitudinal extrusion

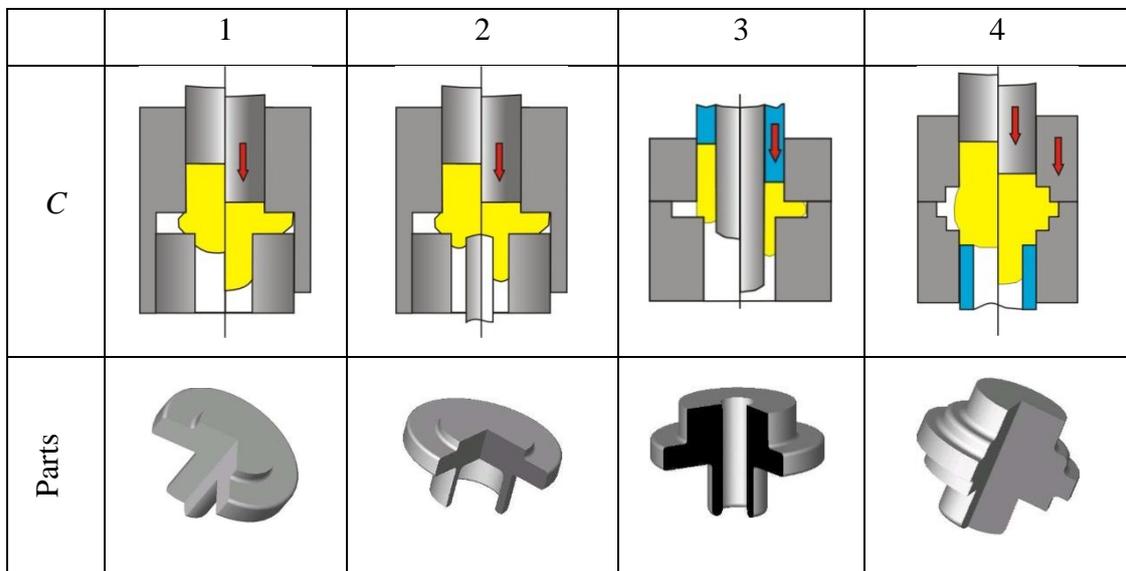


Fig. 8. Methods of united combine radial-forward extrusion

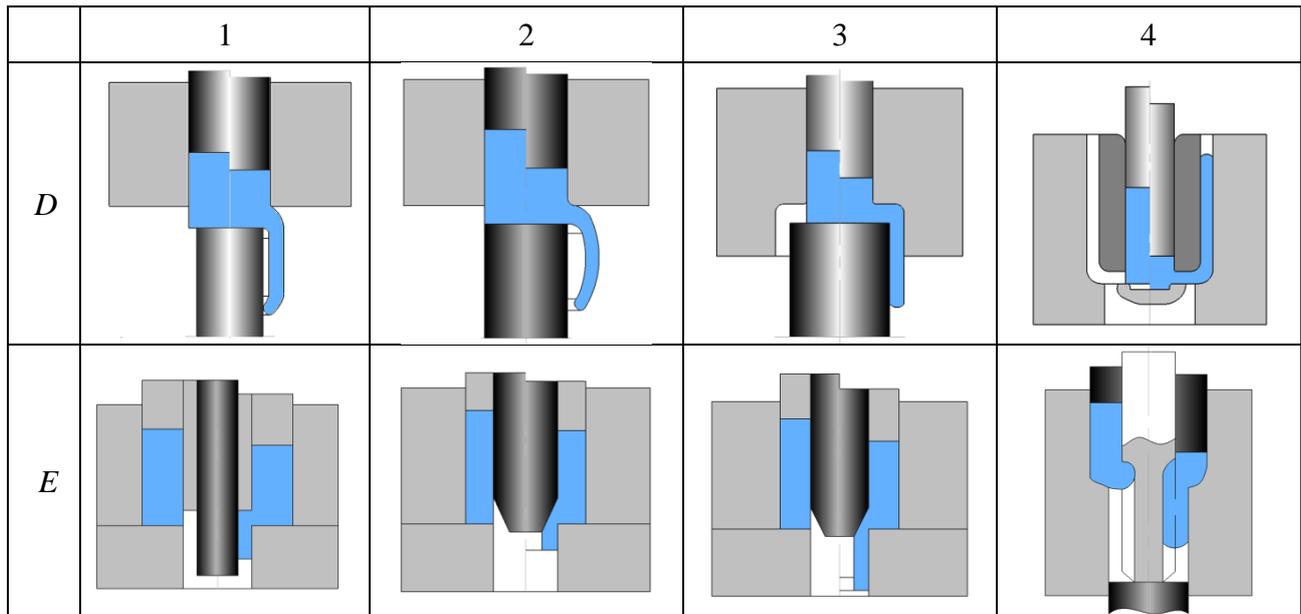


Fig. 9. Methods of sequential combined radial-longitudinal extrusion

A number of schemes of sequential radial-forward extrusion differ by the fact that during the deformation process the values of technological gaps between the forming tools are regulated and thus ensure the production of parts of complex configuration with a variable wall thickness and profiled side surfaces. The extrusion process is carried out on rotary equipment with rotation of the workpiece and tools. According to the method of local deformation, the radius of the flow reversal zone from radial to forward flow is variable and adjustable depending on the required diametrical dimensions of the steps of the hollow part [27].

The methods of staged combined transverse-longitudinal extrusion are characterized by more complex kinematics of tool movement (Fig. 10, group F). But they allow obtaining parts of complex spatial shapes and with lower specific and total loads on the tool [26]. Such possibilities are also inherent in a group of deformation schemes with complex kinematics of deforming tools movement. These combined methods require the design of special dies, in which one active movable deforming tool – a punch is not enough. Also mobility must also be in additional parts, both the deforming (active) and the forming tool. These dies differ by the complexity of kinematics and require active control and can be a prototype of specialized pressing equipment, which means a qualitative leap in the development of forging and pressing production. The advantages of methods for extrusion of complex-profile parts are the increase in the technological capabilities of extrusion processes. Staged methods for extrusion of hollow parts are also used for the production of complex-profile parts with a complex external or internal profile and a variable wall thickness in the dies with a movable tool. To produce hollow parts with a profiled external surface, a method of deformation in movable dies has been proposed (see Fig. 10, scheme F1) [28].

In extrusion by this method, at the moment of contact between the end faces of the punch and the workpiece, its deformation by piercing begins with a predominantly free flow of metal into the cavity of the expanded zone and an upper annular thickening is formed on the side surface of the product. Then the next stage of deformation is carried out – closed piercing by reverse flow (backward extrusion) of metal, and the hollow part of the product (between the thickenings) is formed.

Let us also separately consider modern methods aimed specifically at increasing the efficiency of manufacturing hollow parts of sleeve and cup types. It is known that hollow parts such as cups can be manufactured from initial workpieces in the form of solid and hollow semi-finished products using simple longitudinal extrusion schemes. However, in this case, controlling the metal flow, the force mode of deformation and the quality of the products causes significant difficulties.

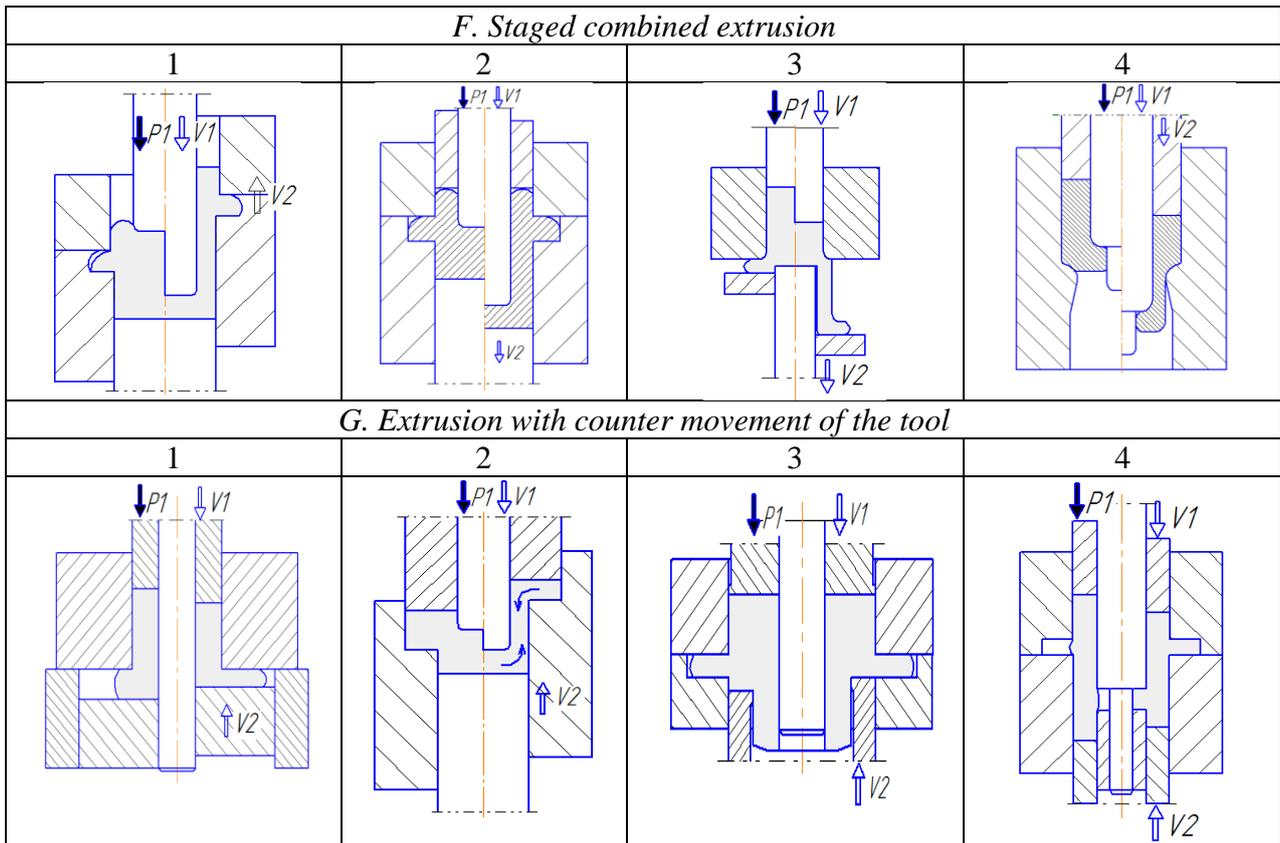


Fig. 10. Schemes of staged combined extrusion with complex kinematics of tool movement

Combined extrusion methods are more attractive from the point of view of controlling the deformation and flow mode of metal in order to obtain complexly profiled and high-quality hollow parts with lower energy costs. Sequential radial-forward extrusion is quite effective for forming elongated tubular parts with varying wall thickness and a large size difference in stepped parts. In addition, the methods for manufacturing hollow parts such as deep sleeves (cups) differ by a combination of alternating deformation schemes and deformation schemes with an increased degree of freedom of metal flow.

The method for manufacturing hollow parts with a blind hole and with a shaped inner surface (Fig. 11, scheme 1) [29] includes the manufacture of a semi-finished product from a solid workpiece by longitudinal (backward or forward) and radial extrusion, which are alternately carried out in a die that is capable of longitudinal movement. To perform the next operation, the resulting semi-finished product is installed in the dies with a reduction die and drawing along the outer surface of the semi-finished product. In this case, the metal from the shoulders A and B is transferred (shifted to the axis of symmetry) with the formation of shoulders on the inner surface of the cup. The production of hollow parts by this method allows obtaining parts with an internal stepped surface, which significantly expands the possibilities of extrusion processes and the range of extruded parts.

The essence of another method for manufacturing hollow parts such as sleeves (see Fig. 11, scheme 2) [30] consists of two operational deformations of the workpiece by combined extrusion and drawing, while at the first transition of the process, the semi-finished product is manufactured in the shape of a conical cup by a method of combined backward-forward extrusion, and then a cylindrical sleeve is obtained from it by reduction and drawing. The use of this method allows obtaining hollow parts with high-quality metal working in the zone of the sleeve wall and a high-quality outer surface, which significantly expands the technological capabilities of the process. Ensuring a combined nature of metal flow in the wall zone of a semi-finished product leads to the appearance of active friction forces and a shear component of deformation, which makes it possible to obtain deep products from a hollow part with a well- and uniformly worked metal structure.

Methods for eliminating defects such as sink marks in the extrusion of sleeves and cups are based on controlling the kinematics of metal flow and the forces of contact friction. According to the method of manufacturing hollow parts such as sleeves by transverse-forward extrusion (scheme 3), in extrusion of a part, a technological ledge in its bottom part is formed by forward extrusion, which is removed in the final stage of the process by reverse movement of the metal into the deformation center and the body of the part [31]. The use of this method allows for the production of hollow parts such as deep sleeves without the appearance of shape deviations in the form of sink marks in the bottom of the part cavity, which significantly expands the technological capabilities of the process and the quality of the parts produced.

Improving the technological capabilities and products quality by eliminating defects such as sink marks and transverse cracks is achieved by applying contact friction forces to the side surface of the workpiece, placed in the die, reversibly directed along the axis of symmetry of the cup (scheme 4). The non-unidirectional changing influence of friction forces on the side surface can contribute to the reorientation, alignment, healing and complete elimination of transverse cracks [32]. The task of decreasing or eliminating external retraction at the bottom of the cup can be solved by forming an external annular protrusion (shoulder) on the side surface in the bottom area or on the bottom of the cup by filling the notch provided in the die [33] or on the end face of the counter punch. Such a shoulder on the side surface has a braking effect on the outer layers of the extruded wall of the cup, thereby preventing the bottom of the cup from moving away from the end face of the counter punch and creating a sink mark.

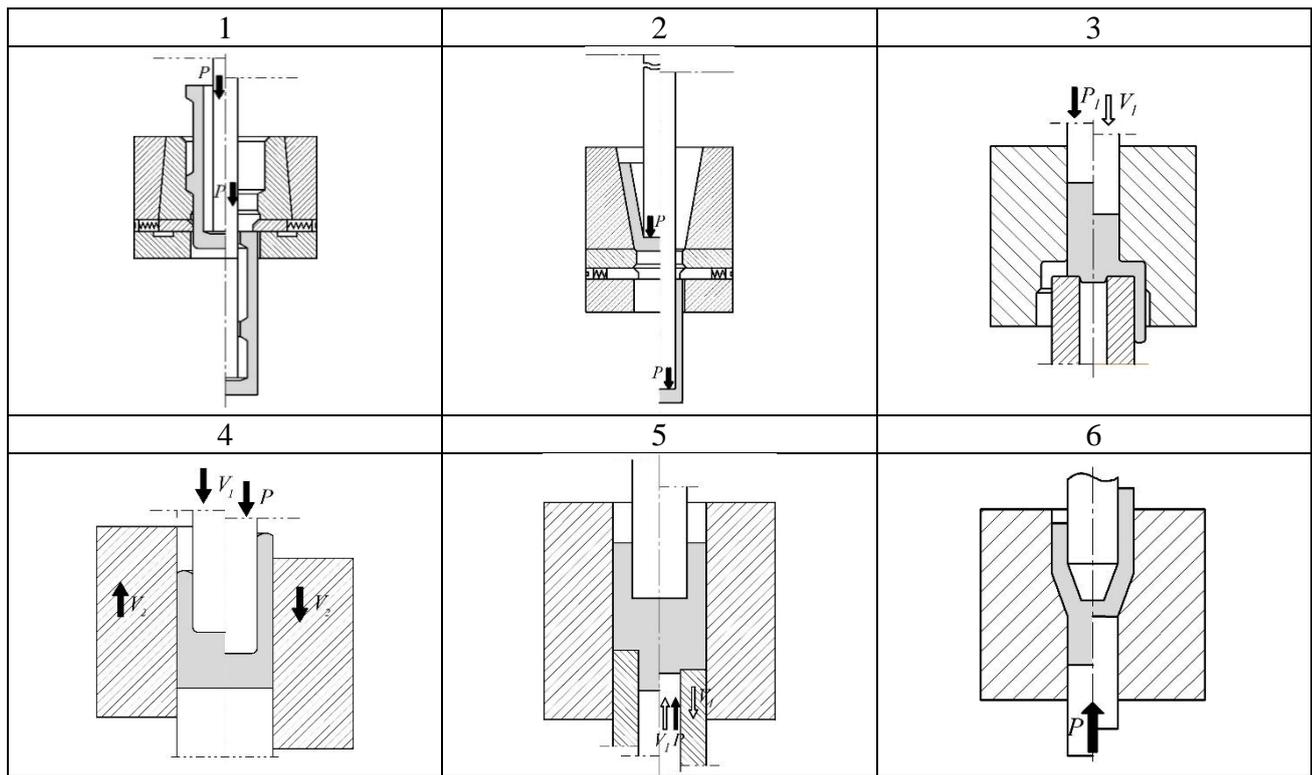


Fig. 11. Methods of extrusion of hollow parts

According to the method of extrusion of hollow parts (scheme 5), the task of improving quality is solved due to the fact that deformation occurs in two stages in such a way, that backward extrusion of the wall of the cup and forward extrusion with the formation of a technological ledge in the bottom of the cup are performed simultaneously at the first stage, and the metal is displaced at the second one [34]. The alternating deformation, to which the metal is subjected in the bottom part of the semi-finished product-cup due to first forward extrusion and then backward extrusion of the metal into the bottom part, ensures good working of the metal of this bottom zone [35].

Fig. 11 also shows a method with similar kinematics, presented in the works of other authors, namely in scheme 6 [36]. The originality and advantages of these methods in reducing power parameters and deviations from misalignment of the cavity of parts work in their favor.

Fig. 12–14 show photos of parts obtained by extrusion using the above-mentioned methods of combined deformation. The materials of the workpieces were aluminum alloys AA6061, AA3003, copper C14200, brass C46400. It can be noted such a feature of combined extrusion schemes as the possibility of obtaining a fairly clear complex contour of a part in one direction of extrusion without overloading the tool (see the cup with a hexagonal flange in Fig. 12). Of interest are also variable-thickness bushings, which were obtained using the RLE method with reduction (see Fig. 13, B3). Deviation of shape in the form of sink marks and fracture of the part in the flange zone or in the cup wall zone (after turning from the flange zone) are the main types of defects in products manufactured using combined extrusion. RLE with reduction is characterized by defects in the flange zone of the part due to the appearance of a stagnation zone (Fig. 14, e).



Fig. 12. Hollow parts produced by radial-backward extrusion

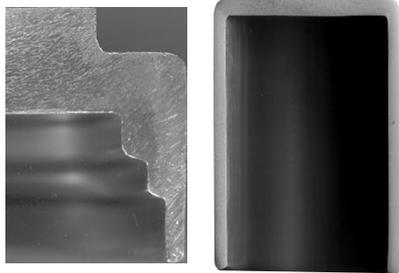
	1	2	3
A			
B			

Fig. 13. Parts obtained by combined three-sided (A1), radial-forward (A2) and radial-backward (A3) extrusion and sequential radial-forward extrusion with expansion (B1, B2) and with reduction (B3)



Fig. 14. Defects of parts obtained by combined radial-backward (*a–c*), radial-forward with expansion (*d*) and radial-forward with reduction (*e*) methods of extrusion

CONCLUSIONS

Increasing use of transverse (radial and lateral) extrusion methods in recent years in addition to the traditionally applied longitudinal (forward and backward) extrusion methods has been found. The varieties of technological schemes for radial extrusion have been systematized and the features of kinematic variants have been considered.

An assessment of the possibilities and limitations of new technological methods for controlling the flow of metal and the quality of the deformed workpiece was given (methods of supplying metal into the die cavity, additional movements of tools, and the use of contact friction forces). A number of technological methods were proposed that regulate the position of the zone of maximum metal hardening along the height of the deformation center, the degree of filling of the receiving cavity of the die and the shape of the obtained flange. These methods include extrusion with a combined supply of metal into the cavity of a movable die, extrusion supplemented by preliminary or subsequent upsetting of a flange, double-sided and sequential double-sided extrusion. Methods for preventing and eliminating defects in the shape of parts such as sink marks, as well as reducing the unevenness of the deformed state, have been found and proposed.

The application of new methods of combined deformation based on a combination of transverse and longitudinal extrusion schemes has led to the use of the advantages of their combination and the expansion of the range of parts that can be obtained by precise volume forming. Groups of combined, sequential and staged combined extrusion, differing in the kinematics of the process, the stress-strain state and the force mode of deformation, were distinguished. The possibilities of expanding the scope of using new methods of extrusion of hollow parts such as cups, sleeves and bushings have been found, related to solving the tasks of increasing the accuracy of the shape of parts, reducing the required forces and obtaining parts of a more complex design. The features of forming and development of the deformed state of hollow and solid parts with flanges and thickenings in extrusion for different kinematic variants were studied experimentally and using the finite element method.

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Левченко В. М., Алієва Л. І., Абхарі П. Б., Малій О. Г. Перспективні способи точного об'ємного штампування видавлюванням складнопрофільованих деталей.

Ефективним шляхом підвищення конкурентоспроможності продукції машинобудування є освоєння ресурсозберігаючих технологій точного об'ємного штампування видавлюванням. Способи видавлювання відрізняються можливістю активного керування режимами обробки металів і дозволяють отримувати прецизійні заготовки із розмірами і якістю, які наближаються до параметрів готових деталей. Зараз спостерігається тенденція до розширення можливостей процесів видавлювання за рахунок додавання до традиційних способів поздовжнього видавлювання нових способів поперечного (радіального та бокового) видавлювання, які спрямовані на виготовлення більш складних деталей недоступних раніше форм. Подальший розвиток цих технологій пов'язано з розробкою способів комбінування схем поздовжнього та поперечного видавлювання, що дозволяє оптимізувати режими виготовлення складнопрофільованих порожнистих та стрижневих деталей за одну операцію. Систематизовано різновиди технологічних схем поперечного (радіального) та комбінованого поперечно-поздовжнього видавлювання. Виділено групи суміщеного, послідовного та поетапного комбінованого видавлювання, в яких об'єднано схеми, що здійснюються послідовно за шляхом і за часом виконання. Експериментально та за допомогою методу скінченних елементів досліджено особливості формоутворення та розвитку деформованого стану порожнистих та суцільних деталей з фланцями та потовщеннями при радіальному та комбінованому видавлюванні. Дана оцінка можливостей і обмеженням нових технологічних прийомів управління течією металу та якістю деформованої заготовки. Розглянуто умови виникнення характерних дефектів деталей, а також способи усунення появи дефектів і відхилень форми деталей.

Ключові слова: радіальне видавлювання, комбіноване поперечне-поздовжнє видавлювання, формоутворення, деталі з фланцем, порожнисті деталі, дефекти форми.

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TSTU – Tashkent State Technical University named after Islam Karimov, Tashkent