The simulation of the process of combined radial reverse extrusion of hollow parts with a flange has established two fundamentally different, in terms of the components of the kinematic modules, calculation schemes CDZ-1.i and CDZ-2.j, taking into consideration the possible shape of the boundary of the section of a metal flow inside a workpiece. The comparison of the dependences of the optimal relative rate of metal outflow in the opposite direction for different schemes indicates significant differences in the resulting values in the course of the deformation process. The relevance of this study is due to making it easier to evaluate the use of the combined extrusion process to produce hollow parts with a flange while maintaining the required dimensions compared to simple deformation schemes. We have identified the lack of detailed studies into the technologies for the introduction of combined extrusion schemes, as well as the absence of technological recommendations for determining the force regime and the shape formation of a semi-finished article.

The process of the combined extrusion of hollow parts with a flange was investigated, thereby selecting different types based on the nature of the metal flow depending on the geometric ratios of the deformation process. We have obtained experimental data on the gradual shape formation of a semi-finished product in the process of deformation at different geometric ratios. The limits of using estimation schemes of the process have been defined to obtain data on the increments in a semi-finished product, including in terms of predicting the formation of a shrinkage cavity in the bottom part. It is recommended that a condition of selecting the appropriate scheme should be the condition for a minimum value of the reduced pressure of deformation $\bar{p}_i<\bar{p}_j$*. The resulting recommendations make it easier to predict the shape formation and the force mode of extrusion (a deviation from experimentally obtained data can be reduced to 10 %), which would contribute to evaluating the rationality of the combined extrusion processes while ensuring the required dimensions of a part*

Keywords: energy method, combined extrusion, parts with a flange, shape formation, deformation process

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PREDICTING THE SHAPE FORMATION OF HOLLOW PARTS WITH A FLANGE IN THE PROCESS OF COMBINED RADIAL-REVERSE EXTRUSION

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1. Introduction

A variety of materials processing methods include research into the possibilities of improving the performance of products in layered execution (ballistic durability of the design) [1], hot forging and stamping processes [2], rolling on rolling mills with hot stripes [3]. The use of explosive processing techniques for the manufacture of powdered materials products was demonstrated in work [4], the development of theoretical methods of describing the shape of bodies and their shape formation in the manufacture of sheet and bulk blanks was addressed in paper [5]. In turn, the intensive development in recent decades of precision volume stamping technology contributes to the increase in production volumes and the expansion of the range of stamped parts with the use of cold extrusion processes [6–8]. This allows the production of articles with the lowest energy and labor-intensive indicators, the highest metal utilization rate, and high surface quality. Studies in recent years relate to the traditional methods of cold extrusion (longitudinal and transverse) [9, 10] and the processes of combined extrusion with several degrees of freedom of metal flow [11]. At the same time, the analysis of force and deformation regimes and the shape formation of parts is often performed on the basis of finite-element modeling and experimentally. Promising are the studies of cold extrusion processes based on the use of various modifications of the energy method. In this case, the processes of combined extrusion with several degrees of freedom of the metal flow proceed in a self-regulating mode, which requires a preliminary assessment of the correspondence between the resulting semi-finished product and the required dimensions. The elimination of these difficulties is possible based on determining the optimal kinematic parameter (a metal outflow rate) and deriving estimation formulae for the reduced pressure and increments in a semi-finished product in the analytical form.

Currently, the range of products made at the enterprises of engineering and instrumentation contains a large number of hollow parts with flanges. However, when they are made by combined extrusion, there may occur, under certain conditions, a defect, including the distorted shape and size of the finished product. Thus, solving the tasks of effective forecasting of the shape formation of a workpiece in the processes of combined extrusion with several degrees of freedom of the flow could make up for the lack of recommendations on the use of combined extrusion processes in production and would contribute to their more active implementation.

2. Literature review and problem statement

Based on the analysis of literary data of recent years, it is possible to outline a range of major issues in the study of basic cold extrusion schemes and combination extrusion processes with several degrees of metal flow [9–19].

Works [9, 10] applied an upper assessment method using rigid blocks to confirm the existence of a dead zone in the reversal zone and to obtain estimates of the energy parameters of the lateral extrusion process. Paper [12] reported formulae for calculating the energy force parameters of the process of equal channel angular pressing, taking into consideration the properties of the material, the geometric parameters of the matrix, and the friction conditions. However, the proposed modification of the energy method is used in solving non-symmetric problems. The issues of deformability of blanks, assessment of extreme shape formation, and defection during combined extrusion were tackled in [13–18]. Work [13] modeled the combined extrusion process in order to assess the extreme shape formation of blanks made from different materials. Study [14] addressed the calculation of plasticity resource based on various criteria for the process of combined radial-direct extrusion, which makes it possible to assess the technological capabilities of a given process. Paper [15] assesses the stressed-strained state at a deformation site at the combined radial-reverse extrusion of a cup with a flange. That provided information about the resource of exhaustion of plasticity in the flange area for various materials. Work [16] investigated the estimation scheme of the combined radial-reverse extrusion process in terms of the occurrence of a shrinkage cavity in the bottom part of the cup. However, the terms of its use have not been studied for a wider range of process geometric ratios, which significantly narrows the scope of its application. A series of papers addressed the development of phenomenological approaches to assessing the complex strained-stressed state (SSS) and the utilized resource of plasticity in the processes of pressure treatment [17, 18]. Thus, studies [13–18] are aimed at assessing the technological possibilities of the combined extrusion processes in terms of SSS research, exhaustion of the resource of plasticity, and defection. However, the issues of predicting the mismatch in the shape and the required size of the extruded workpiece were not tackled.

The analysis of the influence of geometric and technological parameters in the process of direct-reverse-radial extrusion based on finite-element modeling in ABAQUS is reported in works [19, 20]. However, no analytical dependences were derived for the evaluation of the force regime and the shape formation of a workpiece, which significantly reduces the value of the reported results.

Paper [21] used Deform-2D-based simulation to determine the force parameters and the shape formation of hollow parts in the process of combined extrusion. Work [22] applied an energy method using the simplest velocity fields of a parallel flow to investigate the force mode in the process of radial-direct extrusion. An analytical expression for the magnitude of pressure at extrusion was obtained; the validity of the theoretical results was confirmed experimentally. However, no issues of assessment of the step-by-step and extreme shape change of a workpiece during the deformation process were addressed.

Thus, the issues related to obtaining general recommendations for the evaluation of shape change in the considered combined extrusion processes have not been resolved.

3. The aim and objectives of the study

The aim of this study is to establish the limitations and conditions of the preferred use of estimation schemes for predicting the shape change in a semi-finished product in the processes of combined radial-reverse extrusion of hollow parts with a flange.

To achieve the set aim, the following tasks have been solved:

– to analyze patterns in the course of the combined radial-reverse extrusion process at different process ratios;

– to conduct a comparative analysis of the dependences of the reduced pressure and increments of a semi-finished product, obtained on the basis of various estimation schemes;

– to identify the conditions of preferred use of the developed estimation schemes for predicting the shape change in a semi-finished product in the processes of combined radial-reverse extrusion of hollow parts with a flange.

4. Development of estimation schemes of the combined radial-reverse extrusion process

4. 1. Energy method for calculating the force regime and increments in a semi-finished product in the simulation of combined extrusion processes

To calculate the processes of combined extrusion based on the energy method [23–25], the deformable volume of a workpiece is split into the axisymmetric kinematic elements (modules), the flow of the material within which is described by the system of functions that determine the kinematically possible velocity field (KPVF). The calculation scheme of the process should be based on preliminary experimental studies and analysis of a metal flow's features that meet the boundary conditions, the condition of material incompressibility, and the continuity condition. The kinematic modules are considered in the r, θ, z cylindrical coordinate system taking into consideration the axial symmetry and that the circular velocity component equals zero $v_\theta = 0$.

In the analysis of the possible breakdown of the calculation scheme of the combined extrusion process into a set of kinematic modules within the framework of the use of the energy method, the size and configuration of the deformation site play a decisive role. The application of well-known elementary rectangular modules does not cause difficulties because of their good integration with more complex schemes. However, to describe the flow of a material in the kinematic elements with curved boundaries, which adequately describe the surfaces of the section of the material flow inside a part or the shape of the contact surfaces of the tool, it is necessary to develop modules with sloping and curved boundaries [11, 16, 26]. In constructing estimation schemes of combined extrusion, the main difficulties relate to cumbersome calculations of the amount of the reduced pressure and often the impossibility to derive this value in an analytical form. This entails difficulties in determining the optimal kinematic parameters of the process and obtaining, in the form of ready formulae, an estimate of the gradual shape change in a semi-finished product. One of the effective techniques to eliminate the specified difficulties is to use the upper estimate of the components of the amount of reduced pressure (mainly, the power of deformation forces). Another way to make it easier to assess the force parameters of the process and data on the shape change in a semi-finished product is to select «suitable» functions that describe the boundaries of the section of the flow within the workpiece. However, when modeling the processes of combined extrusion with several degrees of freedom of the metal flow, one should control the correspondence between the theoretically obtained calculations and experimental data. At the same time, special attention should be paid to the reliability of the resulting assessment of the shape change in a semi-finished product as the processes of combined extrusion occur under a self-regulating mode [16, 27]. And it is the search for the conditions of the preferred choice from the set of the developed estimation schemes, restrictions, and boundaries of their use which is one of the main tasks for the researcher within the framework of the energy method.

4. 2. Development of estimation schemes for the process of combined radial-reverse extrusion of hollow parts with a flange

For relatively low workpieces, they use estimation schemes with a combined site of deformation. In this case, special attention is paid to the splitting into constituent blocks (modules) and their configuration, taking into consideration the nature of the line of the section of the metal flow inside the workpiece and the features of the tool configuration. The use of curved-border modules instead of straight-line modules expands their application by making it possible to vary the shape and volume of the respective modules. This makes it possible to derive relevant valid solutions where the module with a straight-line boundary cannot handle the task. However, given the possibility of constructing the infinite set of KPVF for a given process, it is necessary to consider the possibility of building the solutions by the energy method for balancing the capacities based on various splitting into elementary modules, followed by comparative analysis.

Consider the developed estimation schemes of the process of combined radial-reverse extrusion of hollow parts with a flange using the axial trapezoidal kinematic module 1 (scheme CDZ-1.i, Fig. 1, *a*) and the trapezoidal kinematic module 2 (scheme CDZ-2.j, Fig. 1, *b*).

KPVF of the axial trapezoidal kinematic module 1 in a generalized form for the scheme of the process CDZ-1.i [27]:

$$\begin{cases} V_{z1} = -V_0 \dfrac{R_1^2}{T_i^2(z)} + W_2\left(1 - \dfrac{R_1^2}{T_i^2(z)}\right), \\ V_{r1} = -\dfrac{r \cdot R_1^2}{T_i^3(z)} T_i'(z)\left(V_0 + W_2\right), \end{cases} \tag{8}$$

where i is responsible for the shape of the boundary section of the flow of kinematic modules 1 and 3 in the form:

$$T_1(z) = k \cdot \left(z - \left(H + h_1\right)\right) + R_1, \quad k = T_1'(z) = \frac{R_1 - R_2}{H};$$

$$T_2(z) = \frac{1}{\sqrt{C_1 \cdot z + C_2}}, \quad C_1 = \left(R_2^2 - R_1^2\right) / \left(R_1^2 R_2^2 H\right),$$

$$C_2 = 1 / R_2^2 - C_1 h_1;$$

$$T_3(z) = \frac{A}{\sqrt{B - C \cdot e^{2M \cdot (z - h_1)}}}, \quad A = R_1 R_2 \sqrt{1 - e^{2MH}},$$

$$B = R_2^2 - R_1^2 e^{2MH}, \quad C = R_2^2 - R_1^2,$$

$M \in (-\infty, 0) \cup (0, +\infty)$ – optimization parameter.

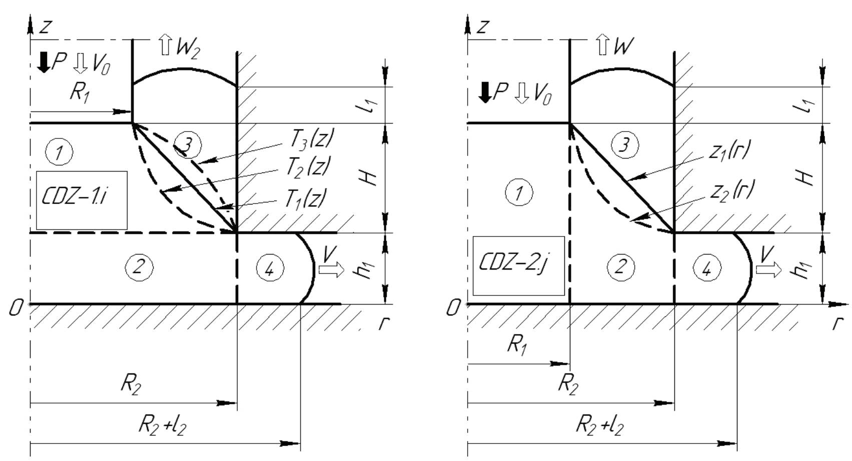


Fig. 1. Estimation schemes of the process of combined radial-reverse extrusion of hollow parts with a flange: *a* – CDZ-1.i; *b* – CDZ-2.j

A feature of the use of the estimation schemes CDZ-1.1,2 is the possibility of deriving ready calculation formulae for the increment in a semi-finished product in the vertical direction (forming the wall of the cup) and a flange area. The optimal value of the kinematic parameter is found from the conditions of equality to zero of the power of cut forces at the boundaries of kinematic modules 1 and 2. This is achieved by selecting those functions that are «suitable» in terms of subsequent calculations, describing the sloping boundary of module 1, with the possibility of obtaining the power of deformation forces in an analytical form. Using a boundary shape in the form $T=T_3(z)$ yields a possibility to vary the $M\in(-\infty,0)\cup(0,+\infty)$ parameter and to a significant complication of subsequent calculations, which is a limiting factor in its use [27].

An alternative generalized estimation scheme is CDZ-2.j with the presence of the trapezoidal kinematic module 2 with different shapes of the sloping boundary in the form $z=z_j(r)$.

KPVF of the trapezoidal kinematic module 2 in a generalized form for the scheme of the process CDZ-2.j [12]:

$$\begin{cases} V_{z2}=\dfrac{W+z_j'(r)V_{r2}}{z(r)}z, \\ V_{r2}=\dfrac{V_0R_1^2+W\left(R_1^{\,2}-r^2\right)}{2r\,z_j(r)}, \end{cases}$$

where j is responsible for the shape of the boundary section of the flow of kinematic modules 2 and 3 in the form:

$$z_1(r)=a(r+b),\quad a=\frac{H}{R_1-R_2},\quad b=\frac{h_1}{a}-R_2.$$

A distinctive feature of a given estimation scheme is the impossibility to derive the reduced pressure in an analytical form. The use of different techniques to linearize the intensity of deformation rates has proven its ineptitude because of the inability to choose the corresponding linear function axial that is unique for the entire volume of the axial trapezoid module. It is possible to simplify calculations for the case $z=z_1(r)$ based on the use of the upper estimate of the power of deformation forces by Cauchy-Bunyakovsky [16]. In this case, the use of numerical calculations and the corresponding upper estimate showed a slight discrepancy (up to 1–3 %). This applies to the resulting calculation of the amount of the reduced pressure, as well as the correspondence of the nature of change in the optimal kinematic parameter (the speed of metal outflow in the vertical direction). It is possible to use a sloping boundary between kinematic modules 2 and 3 in the form of some non-linear function $z=z_2(r)$, but this leads to a significant complication of subsequent calculations; the issue of the rationality of such a replacement remains open at this stage.

5. Comparative analysis of shape change in a semi-finished product in the process of combined radial-reverse extrusion for various estimation schemes

The character of the metal flow during the combined radial-reverse extrusion of hollow parts with a flange depends on the ratio of the process geometric parameters, including the features of the tool configuration, as well as the friction conditions. In this case, an experimental study involving the workpieces made from aluminum alloys AA6061, AA6063, from lead Pb and brass C46400 revealed significant differences in the process of deformation. This applies to the peculiarities of shape change in a semi-finished product for different ratios of the geometric parameters of the deformation process. For ratios within $0.5<2h_1R_2/(R_2^2-R_1^2)<1.5$, the flow of metal occurs in the radial (forming a flange zone) and reverse (forming the wall of a cup) directions. In this case, the flow of the metal in the vertical direction is opposite to the direction of the punch movement (Fig. 2, *a, b*). For the predominantly radial flow at $2h_1R_2/(R_2^2-R_1^2)>1.5$ for sufficiently low workpieces, it is possible to capture the metal in the contact area with the punch, followed by the movement of metal, co-directed with the punch, in the wall of the cup (Fig. 2, *c, d*). In this case, the height of a semi-finished product decreases during the process of deformation, in fact, there is a formation of the flange zone, the wall of the cup is formed only due to the difference in the speed of movement of the active tool and the metal of the wall of the cup in the same direction. For ratios $2h_1R_2/(R_2^2-R_1^2)<0.5$ at the final stage of the deformation process, it is possible to form a shrinkage cavity in the bottom part of the cup (Fig. 2, *e, f*). In this case, the stage of shrinkage cavity formation corresponds to the predominantly reverse flow of the metal, the formation of the wall of the cup occurs with the involvement of the metal from a zone adjacent to the flange area [16].

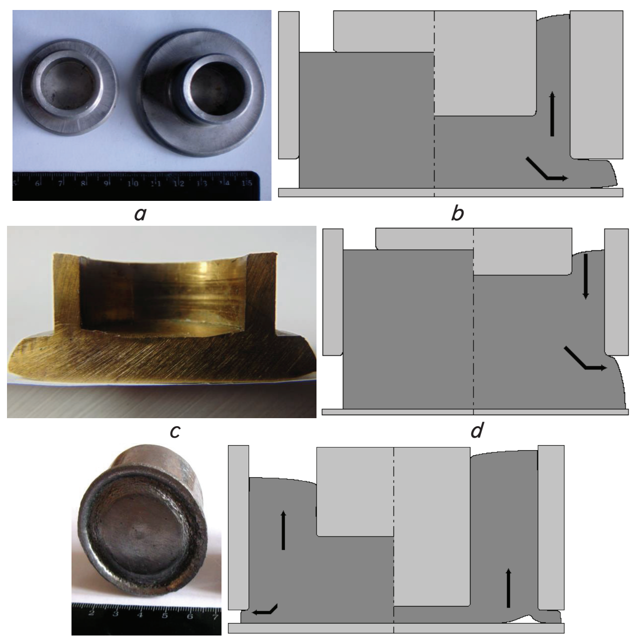


Fig. 2. Patterns of shape change in a semi-finished product in the process of combined radial-reverse extrusion: *a, b* – with the presence of radial and reverse flow; *c, d* – with the predominantly radial flow; *e, f* – with the formation of a shrinkage cavity in the bottom part of the cup

The character of change in the kinematic parameter – the outflow rate of a metal onto the wall of the cup for each type of the scheme of the process of combined radial-reverse extrusion – is also different. In this case, it is necessary to identify the limitations and conditions of preference for the use of the above-proposed estimation schemes CDZ-1.i and CDZ-2.j for different ratios of the deformation process. To this end, we shall conduct a comparative analysis of the character of change in the relative optimal kinematic parameter $\bar{W} = W/V_0$ – the flow of the metal in the opposite direction. For ratios $0.5 < 2h_1R_2/(R_2^2 - R_1^2) < 1.5$, it is necessary to analyze the behavior of the metal outflow rate functions in the opposite direction for schemes CDZ-1.1,2 and CDZ-2.1 and to determine the conditions of their preferred use to assess the shape change in a semi-finished product. The estimation scheme CDZ-2.1 was used to predict the occurrence of a shrinkage cavity in the bottom of the cup at $2h_1R_2/(R_2^2 - R_1^2) < 0.5$. The moment of the defect occurrence corresponds to the presence of a minimum of the parameter $\bar{W}$ depending on the magnitude of run H_x. A process that proceeds without the formation of a shrinkage cavity is characterized by the monotonous decline $\bar{W}$ during the entire process of deformation, which is the absence of a minimum point. A given scheme has made it possible to obtain, as a preliminary estimate, a diagram of the size of the parts that can be obtained by combined extrusion without the formation of shrinkage cavities [16]. We shall conduct a comparative analysis of the $\bar{W}$ function behavior for the case of the experimentally obtained data for a part made from lead with the resulting shrinkage cavity at R_1=10.5 mm, R_2=22.5 mm, h_1=4.5, H_0=17 mm (Fig. 3).

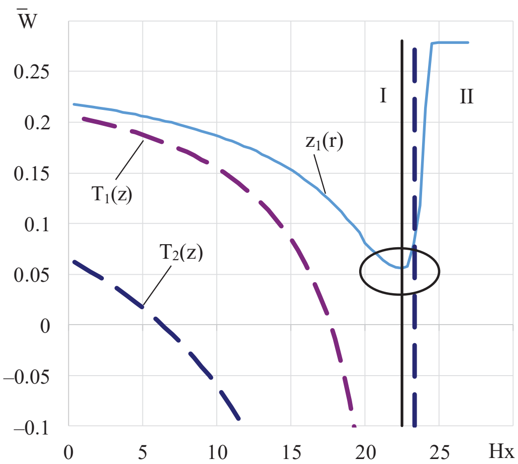


Fig. 3. Comparative analysis of changes in the relative rate of metal outflow $\bar{W}$ during the process for different estimation schemes

The estimation schemes CDZ-1.1,2 are characterized by the decline in the function of the relative outflow rate in the opposite direction throughout the entire deformation process; in this case, the lower values of magnitude $\bar{W}$ are typical of the estimation scheme with the curvilinear boundary of the T=$T_2(z)$ type. The character of change in the amount of reduced pressure during the process for the various estimation schemes for the case of the occurrence of a shrinkage cavity is shown in Fig. 4. In this case, the optimal scheme, based on a minimum of the reduced pressure, is CDZ-2.1, which corresponds to the theoretical provisions of the energy method. The highest value is acquired by the amount of reduced pressure according to CDZ-1.2, which is explained by a larger deviation of the magnitude $\bar{W}$ from the corresponding reality.

Thus, for a comparative analysis of the increment in the size of a semi-finished product, we consider schemes CDZ-2.1 and CDZ-1.1 (Fig. 5). The increments of a flange zone during the process of deformation are characterized by the overestimated calculated dimensions of a semi-finished product for scheme CDZ-1.1; this discrepancy acquires more weight during the process of deformation. It is more legitimate to use the forecasting results according to scheme CDZ-2.1; the deviation from the experimentally obtained data does not exceed 10 %. In this case, since the formation of a shrinkage cavity, a given scheme has demonstrated the possibility of an adequate description of the change in the size of a flange (namely, the absence of increments l_2, starting from the run of 24.5 mm, Fig. 5).

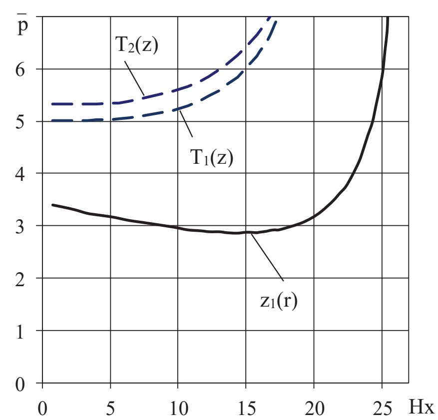


Fig. 4. Comparative analysis of reduced pressure in the course of the process for various estimation schemes

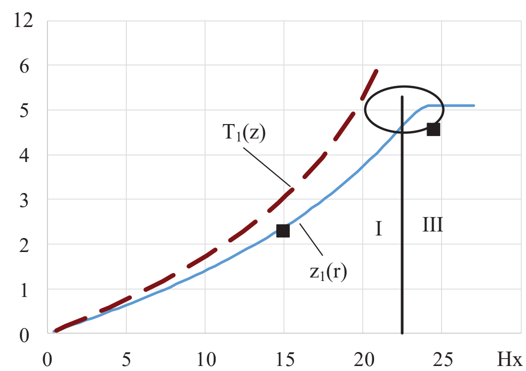


Fig. 5. Data on the increments in a semi-finished product in the radial direction

Thus, the condition $\bar{p}_i < \bar{p}_j$ is a criterion for choosing the preferred estimation scheme. However, the monotonous descending throughout the entire process of deformation of the relative outflow rate of the metal $\bar{W}$, corresponding to schemes CDZ-1.i, does not allow them to be used for predicting a shrinkage cavity. Thus, uniquely recommended for the ratios $2h_1R_2/(R_2^2 - R_1^2) < 0.6$ with possible defect formation in the form of a shrinkage cavity in the bottom part is the estimation scheme CDZ-2.1 and the diagram based on it. For ratios $0.5 < 2h_1R_2/(R_2^2 - R_1^2) < 1.5$, one needs to use CDZ-1.1,2 and CDZ-2.1 with the choice according to the lowest reduced pressure.

For the process of combined radial-reverse extrusion with a predominantly radial flow (Fig. 2, *c*, *d*) at ratios $2h_1R_2/(R_2^2 - R_1^2) > 1.5$, a comparative analysis for all varieties of CDZ-1.i was carried out. These schemes were used as the most rational ones in terms of the possibility of obtaining the optimal value $\bar{W} < 0$, characteristic of a given process of deformation. We shall carry out a comparative analysis of the increments in the cup's wall l_1 for the case of the experimentally obtained data on a part made from C46400 at $R_1=10.5$ mm, $R_2=14$ mm, $h_1=5.7$, $H_0=17$ mm (Fig. 6).

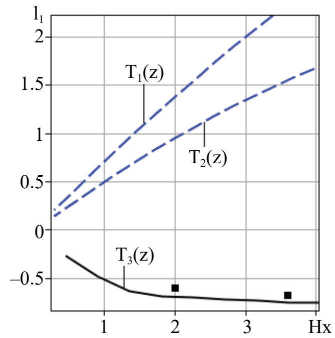


Fig. 6. Data on the increment in a semi-finished product in the vertical direction

A negative increment (the height of a semi-finished product, as a result, is less than the initial height of the workpiece) corresponds to experimental data only for the type of scheme CDZ-1.3 with a boundary in the form $T=T_3(z)$, the remaining calculations are not true.

The use of CDZ-1.3 for the process of a predominantly radial flow is possible due to the variation in $M\in(-\infty,0)\cup(0,+\infty)$ and the directionality of the curve convex, which more adequately describes the boundary of the metal flow section inside the workpiece but leads to a significant complication of calculations.

6. Recommendations on using the estimation schemes CDZ-1.i and CDZ-2.j to predict the shape formation of a semi-finished product

A comparative analysis of the force regime and the shape formation of a semi-finished product in the process of combined radial-reverse extrusion has made it possible to devise recommendations on using the estimation schemes CDZ-1.i and CDZ-2.j.

It has been established that the lowest value of the reduced pressure is the criterion of the preference for the use of the estimation scheme for different ratios of the deformation process.

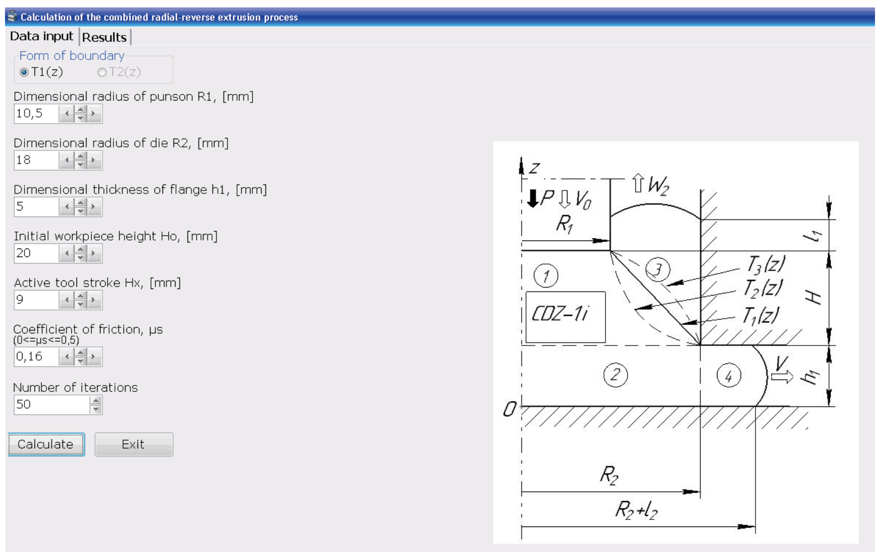
However, for processes with the possible occurrence of a shrinkage cavity in the bottom part of the cup $(2h_1R_2/(R_2^2-R_1^2)<0.5)$, the unambiguously recommended estimation scheme is CDZ-2.1.

For a predominantly radial flow at ratios $2h_1R_2/(R_2^2-R_1^2)>1.5$, it is preferable to use CDZ-1.3 with a boundary in the form $T=T_3(z)$.

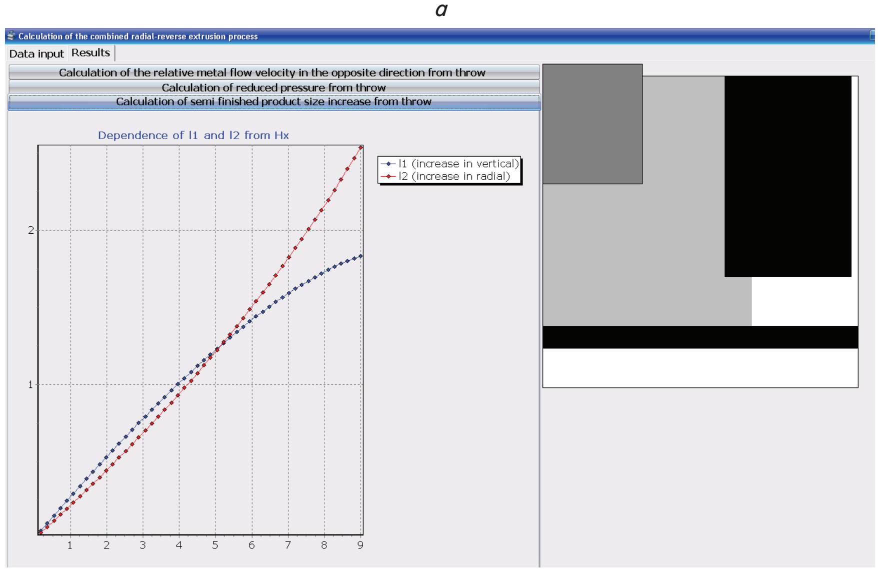
Thus, for a wide range of ratios $0.5<2h_1R_2/(R_2^2-R_1^2)<1.5$, it is necessary to develop software that includes the developed estimation schemes with the possibility of promptly selecting the most preferable one. A software module has been developed for calculating the force parameters and shape change in the process of combined radial-reverse extrusion based on CDZ-1.1 and CDZ-1.2.

The software module was developed in the Delphi Community Edition programming environment and it provides data on the increment in a semi-finished product during the process, on a change in the relative outflow rate $\overline{W}$, and the amount of the reduced pressure, as well as the shape of a semi-finished product (Fig. 7).

The graphic interpretation of the result of a shape change in the form of the increments in a semi-finished product l_1 and l_2, as well as the shape of the semi-finished product (in the form of the right half), makes it possible to assess the correspondence between the resulting dimensions and appropriate parameters.



a



b

Fig. 7. The software module windows: *a* – dialog data entry; *b* – output of results

7. Discussion of results of studying the combined radial-reverse extrusion process based on estimation schemes

In order to obtain an assessment of the shape change in a semi-finished product in the process of combined radial-reverse extrusion, two estimation schemes CDZ-1.i and CDZ-2.j were distinguished, fundamentally different in the sets of the components of kinematic modules, taking into consideration the possible shape of the boundary of the metal flow section within a workpiece (Fig. 1). The comparison of the dependences of the optimal relative speed of metal outflow in the vertical direction indicates significant differences in the character of change in the magnitude during the deformation process. A set of the kinematic modules of estimation scheme CDZ-2.1 describes the process of deformation with a change in the monotonous decline $\bar{W}$ to an increase with the presence of a minimum point (Fig. 3). This corresponds to the occurrence of a defect in the form of a shrinkage cavity in the bottom of the cup at the final stage of the deformation process at the process ratios $2h_1R_2/(R_2^2-R_1^2)<0.5$ (Fig. 2, *e*, *f*, Fig. 3). On the basis of experimental data, we have confirmed the validity of the assessment of the shape-change obtained on the basis of a given estimation scheme and the inconsistency of the estimated data on the increment in a semi-finished product based on schemes CDZ-1.i. For the process of a predominantly radial flow of metal at $2h_1R_2/(R_2^2-R_1^2)>1.5$, the use of the CDZ-1.3 estimation scheme with a curved boundary in the form $T=T_3(z)$ is recommended, the rest of the calculations are not true (Fig. 6). The range $0.5<2h_1R_2/(R_2^2-R_1^2)<1.5$ requires the use of the CDZ-1.1,2 and CDZ-2.1 schemes with a comparative analysis of the force mode of deformation. The condition of the preferred choice of the scheme should be a condition of the minimum value of the amount of the reduced pressure of deformation (Fig. 4). The devised recommendations for the use of the proposed estimation schemes make it easier to define the shape-change and the force extrusion regime, which would help assess the possibilities of using the combined extrusion processes to ensure the necessary dimensions of a part.

The limitation on the use of the proposed software at present is the use of estimation schemes CDZ-1.i with a different kind of the sloping boundary for ratios $0.5<2h_1R_2/(R_2^2-R_1^2)<1.5$.

In the future, we plan to develop software that takes into consideration all the developed estimation schemes for modeling the process of combined radial-reverse extrusion.

8. Conclusions

1. We have analyzed patterns in the process of combined radial-reverse extrusion at different ratios $2h_1R_2/(R_2^2-R_1^2)$, which significantly affect the shape formation (the ratio of increments of the flange area and the wall of the cup) of a component. The varieties with a predominantly radial flow of metal have been highlighted at the negative increment in a semi-finished product in the vertical direction l_1 (the capture of the metal of the wall of the cup in the direction of the movement of the punch). For a predominantly reverse extrusion, it is possible that a defect may appear in the form of a shrinkage cavity in the bottom of the cup at the final stage of the deformation process at $2h_1R_2/(R_2^2-R_1^2)<0.5$.

2. A comparative analysis has been performed of the dependences of the reduced pressure, the rate of outflow of the metal in the vertical direction, and the increments in a semi-finished product, derived on the basis of estimation schemes CDZ-1.i and CDZ-2.j, taking into consideration the possible shape of the boundary of the metal flow section inside a workpiece. We have established a significant discrepancy in the projected increments of a semi-finished product in the vertical direction l_1 when using the proposed estimation schemes CDZ-1.i with a different shape of the boundary of the section of the flow. Preferred is the CDZ-1.3 scheme with a boundary in the form $T=T_3(z)$, which is due to the possibility of varying the parameter $M\in(-\infty,0)\cup(0,+\infty)$.

3. We have defined the conditions in the form of a range of the ratios $2h_1R_2/(R_2^2-R_1^2)$ for the preferred use of the developed estimation schemes for predicting the shape change in a semi-finished product in the processes of combined radial-reverse extrusion of hollow parts with a flange. At ratios $0.5<2h_1R_2/(R_2^2-R_1^2)<1.5$, selecting the preferred estimation scheme should be based on a minimum of the reduced pressure.

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