Розроблено розрахункові схеми процесу комбінованого радіально-зворотного видавлювання деталей з фланцем. На основі енергетичного методу отримані формули для розрахунку наведеного тиску деформування і поетапного збільшення розмірів напівфабрикату. Актуальність дослідження ґрунтовано на забезпеченні спрощення оцінки використання даного процесу деформування для отримання деталей необхідної конфігурації. Крім того, підтверджено ефективність визначення межі використання отриманої розрахункової схеми для співвідношень $2h_1R_2/(R_2^2-R_1^2)<1$.

Проаналізовано номенклатура виробів, що випускаються на підприємствах машинобудування й приладобудування та містить значну кількість порожнистих деталей з фланцями і відростками різної форми. Обґрунтовано, що використання комбінованих схем видавлювання при виготовленні деталей типу «стакан з фланцем», у порівнянні з використанням простих схем деформування, підвищує технологічні можливості процесу. Це відбувається за рахунок зниження енергетичних витрат, скорочення кількості технологічних переходів, а також підвищення складності форми одержуваних деталей. Підтверджено недостатню вивченість технологій впровадження комбінованих схем видавлювання та брак відповідних технологічних рекомендацій. Визначено силовий режим видавлювання, що відповідає дійсності, та оцінка можливості керування витіканням металу в процесі деформування. Проведено дослідження процесу холодного комбінованого видавлювання порожнистих деталей з фланцем та запропоновані розрахункові схеми процесу. Здійснено моделювання процесу комбінованого видавлювання за допомогою використання експериментально-аналітичного методу та встановлено закономірності формоутворення деталей з фланцем від геометричних і технологічних параметрів. Отримано дані про поетапне формозміння напівфабрикату в процесі деформування. Підтверджено, що запропоновані моделі спрощують розробку технологічних рекомендацій щодо визначення силового режиму видавлювання і керування витіканням металу в процесі деформування

Ключові слова: комбіноване видавлювання, деталі з фланцем, поетапна формозміна, процес деформування

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DEVELOPMENT OF CALCULATION SCHEMES FOR THE COMBINED EXTRUSION TO PREDICT THE SHAPE FORMATION OF AXISYMMETRIC PARTS WITH A FLANGE

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1. Introduction

Development of modern machine building engineering is impossible without the development of new resource-saving technologies that make it possible to manufacture high-quality products at the lowest indicators for energy consumption and complexity of production and with the highest coefficient of the utilization of metal. Given this, the role of effective resource-saving methods for metal machining by pressure, based on the cold plastic deformation, is more and more important [1, 2]. Note that the processes of cold extrusion allow obtaining billets with accurate dimensions, high surface quality.

However, there are several problems related primarily to the issues of metal plasticity under conditions of the complex stressed-strained state and to the processes of its strengthening [3, 4]. Of great importance in this case is the design and calculation of tools, as well as investigating its durability, since the cost of punches and matrices may amount to about 25 % of the cost of resulting articles.

At present, the range of products manufactured at the enterprises of machine-building and instrument industries includes a large number of hollow parts with flanges and branches of various shapes. This necessitates studying and implementation of new processes for obtaining parts of such type. One of the major challenges in this field is the development and implementation of the cold forging process using combined extrusion that has sufficient advantages over simple deformation techniques [5, 6]. Combining the processes of backward and radial extrusion when manufacturing parts with a flange improves technological possibilities of forging processes through the reduction of energy costs and the number of transitions. At extrusion with several degrees of freedom for a metal flow it is required to preliminary estimate the phased and resulting change in shape of a semi-finished product. The lack of comprehensive recommendations on shape-forming parameters under industrial conditions requires the development of estimation schemes of changes in the shape of a part in the process of combined extrusion.

2. Literature review and problem statement

At present, the most promising methods for improving the efficiency of cold forging include the design, research, and implementation of new effective technological techniques of extrusion. The use of combined extrusion processes when manufacturing hollow parts with a flange improves technological possibilities of a given process, compared to the application of simple deformation processes. This is achieved by bringing down energy costs, by reducing the number of technological transitions, by making the shape of obtained parts more complex.

All the techniques for simultaneous extrusion in different directions can be categorized depending on the patterns in the deformation zone (DZ) formation. The categories include techniques with the attached, connected, disconnected, and combined DZ [7]. The simplest ones in terms of their application with respect to the energy method are the techniques with an attached deformation zone. The deformation of low billets for techniques with a connected DZ is characterized by multidirectional metal flows that emerge in a single combined deformation zone. In contrast to the previous group of processes, an analysis of techniques with a combined DZ becomes possible when using kinematic parameters as the variable ones.

Investigating extrusion techniques with disconnected deformation zones poses the greatest difficulty. A given group is characterized by the presence of an intermediate rigid zone.

This case is observed at deformation of relatively high billets. The optimal value for a kinematic parameter (motion speed of the rigid zone) was proposed to determine from the condition of equality of powers, acting on both sides of the plane that divides two independent deformation zones [8]. Such an approach to determining an optimal kinematic parameter was chosen as an alternative due to the impossibility of applying the required condition of optimality of the pressure magnitude for a given parameter n in the form $\partial p/\partial \nu = 0$.

Analysis of techniques with a combined DZ implies the use of all previously considered approaches. Research into processes related to this group comes down to establishing a position of a certain surface in the flow division, which would subsequently make it possible to determine without any difficulty the magnitudes of phased increments in the dimensions of a part.

Of particular interest are also papers [9–15] based on various modifications of the energy method aimed at investigating basic and combined extrusion processes. Thus, paper [9] reports analysis of the process of setting-extrusion of an axisymmetric billet using flat strikers, one of which has a central circular opening. The authors paid special attention to the character of a metal flow in different directions. Theoretical analysis of the study is based on a comparison of different velocity fields; recommendations are proposed for choosing an optimal technique for the considered technological parameters. However, there are no general recommendations on the prospects of applying the proposed velocity fields for other techniques of combined extrusion.

Paper [10] develops approaches and a procedure for constructing different kinematically possible velocity fields; however, possibilities to employ the proposed modules for extrusion techniques with disconnected DZ are not demonstrated. Authors of [11], in order to analyze the forging of axisymmetric parts, isolated 4 different types of elementary modules with characteristic features and respective limits of application; the process was simulated. Papers [12, 13] explore the process of a combined backward-forward extrusion by the upper bound element technique using arbitrarily oriented triangular elements, combined with the method of finite elements (UBET).

An analysis of changes in shape and a defect formation in the processes of forward, radial, and radial-reverse extrusion is addressed in paper [14]. The authors proposed a diagram of regions that are critical in terms of the formation of a defect in the form of a shrinkage cavity at the bottom part at a combined extrusion of parts with a flange. The study, however, focused on the prediction of defect formation and did not imply the derivation of estimation formulae for determining the increments of a semi-finished product during deformation. Paper [15] reports analysis of the process of combined radial-reverse extrusion in a conical die. In this case, three distinctive stages in the process were defined, depending on the position of the punch and patterns in a metal flow in the deformation zone; however, only the second stage was considered. It should also be noted that the value for the boundary of flow division h^* and the values for the total power are found numerically; they were not obtained in the explicit form.

Thus, the research into the processes of combined radial-reverse extrusion is limited to solving the problems on flat deformation and intermediate stages of the process. The need to study such processes is predetermined by their possible use in metal machining industries and agriculture. Given this, of greatest interest are the processes of obtaining hollow parts with branches of varying shape and cross-section (casing with a different form of the external surface and a flange, a union, a latch-housing assy, etc.). The lack of studies into such processes has led to the absence of comprehensive recommendations for the assessment of technological modes and possibilities of the cold deformation process. In addition, still insufficiently examined are the issues related to phased and marginal changes in shape, to analysis of the formation of various types of defects. It is required to create complete and more precise estimation techniques to predict shape-formation, technological methods to ensure effective control over a metal flow. The designs and recommendations to be created would contribute to expanding the possibilities of the combined extrusion processes and their broader application in industry.

3. The aim and objectives of the study

The aim of present study was to identify patterns in the processes of cold combined radial-reverse extrusion, to develop estimation schemes for the prediction of shape forming of hollow parts with a flange. The result would make it possible to determine the rational technological regimes and would improve technical-economic efficiency of these deformation processes.

To accomplish the aim, the following tasks have been set:

– to construct mathematical models for the process of combined extrusion of hollow parts with a flange that would make it possible to determine the force mode of deformation and obtain data on the phased change in shape of a semi-finished product;

– to model, using an experimental-analytical method, the process of combined extrusion, and to establish patterns in the shape formation of parts with a flange due to the geometrical and technological parameters;

– to define conditions for the application of the developed estimation schemes, and to estimate, based on them, technological possibilities of the method of combined extrusion of hollow parts with a flange.

4. Energy method for studying the processes of combined extrusion of parts with a flange

When solving tasks on die forging, the most commonly used method is the energy method. It is based on the application of extreme principles of the theory of plasticity and makes it possible to evaluate an effort of the deformation from above by a direct construction of solutions with no need for the integration of differential equations of equilibrium [16]. The energy method also applies to the analysis of combined extrusion processes.

At present, there are two known basic modifications of the energy method:

– an energy method (a method of balance of power or work), based on modeling a metal flow in the deformation zone using continuously deformed modules;

– an upper bound method (UBM), based on the simulation of a metal flow in the deformation zone using rigid (non-deformable), typically triangular blocks.

Key assumptions for the energy method of power balance:

– deformed material is homogeneous, isotropic, rigidly plastic (σ_s=const);

– rates of plastic deformation are proportional to the stresses that cause them;

– velocity discontinuities are possible in the material in infinitely thin layers if the continuity of normal components of velocities is maintained in this case;

– the forces of contact friction do not depend on the normal stresses and are defined by the Siebel friction law: $\tau_k=\mu_s\sigma_s$ (μ_s is a friction coefficient, $0\leq\mu_s\leq 0.5$);

– thermal stresses and deformations, forces of inertia and other mass forces are negligible.

In order to calculate axisymmetric process of change in shape, the deformed volume of a billet is split into axisymmetric kinematic elements (modules). The flow of a material inside each module is described using the functions that define the kinematically possible velocity field (KPVF). These modules are considered in the cylindrical coordinate system with respect to axial symmetry and to that a circular velocity component equals zero, $\nu_\theta=0$. Kinematically possible velocities are set based on the preliminary conducted experimental research and analysis of the patterns in a metal flow [17]. In this case, for the axisymmetric kinematic elements with a rectangular cross-section the simplest technique for constructing KPVF is based on the assumption about a parallel flow of metal. If the velocity components along each coordinate direction do not depend on the coordinates along other directions, that is $\nu_z=\nu_z(z)$, $\nu_r=\nu_r(r)$, the components of velocity in a general form are derived from formulae (1):

$$v_z = C_1 z + C_2;\ \ v_r = -0.5C_1 r + \frac{C_3}{r};\ \ v_\theta = 0, \tag{1}$$

where C_1, C_2, C_3 are the arbitrary constants.

The constants are determined based on the kinematic boundary conditions in speeds and the conditions of continuity of a normal velocity component at the surface of a velocity discontinuity.

In a general case, the KPVF that was built to describe the flow of material of a billet should satisfy the following conditions:

– kinematic boundary at speeds (KBC);

– incompressibility;

– continuity, which is continuity of a normal velocity component on the surface of the cut, on both sides of it.

The rates of relative linear and shear deformations for the modules considered in a cylindrical coordinate system are calculated from formulae (2):

$$\dot{\varepsilon}_z = \frac{\partial v_z}{\partial z};\ \ \dot{\varepsilon}_r = \frac{\partial v_r}{\partial r};\ \ \dot{\varepsilon}_\theta = \frac{v_r}{r};\ \ \dot{\gamma}_{rz} = \frac{\partial v_z}{\partial r} + \frac{\partial v_r}{\partial z}. \tag{2}$$

A condition for incompressibility can be used in the form of equality (3):

$$\dot{\varepsilon}_z + \dot{\varepsilon}_r + \dot{\varepsilon}_\theta = 0. \tag{3}$$

If a boundary is set using a certain continuous function T=$f(r)$, a condition for continuity at the interface between modules, its elements, and the tool, takes the following form (4):

$$\left[\Delta v_z\right]dr - \left[\Delta v_r\right]dz = 0, \tag{4}$$

where $\left[\Delta v_z\right]$ and $\left[\Delta v_r\right]$ are the magnitudes of a velocity discontinuity at the interface between modules, its elements, and the tool.

The next step following the selection of the appropriate set of KPVF for a given process is the construction of the basic equation of energy balance for power, linking the power of external active forces $N_a=pF\nu_0$ to the power of internal forces:

$$pFv_0 = \sum N_{d\,i} + \sum N_{ci-j} + \sum N_{t\,j-n}, \tag{5}$$

where $N_{d\,i}$ is the power of forces for the plastic deformation of module i; N_{ci-j} is the power of forces of the cut between adjacent modules i and j; $N_{t\,j-n}$ is the power of friction forces, occurring at the surface of contact between module j and tool n.

The power used for plastic deformation:

$$N_d = \iiint_V \sigma_S \dot{\varepsilon}_i \mathrm{d}V, \tag{6}$$

where σ_s is the yield point, MPa; $\dot{\varepsilon}_i$ is the intensity of deformation rates in the elementary volume dV.

For the axisymmetric deformation, the intensity of deformation rates (7):

$$\dot{\varepsilon}_i = \frac{\sqrt{2}}{3}\sqrt{\left(\dot{\varepsilon}_z - \dot{\varepsilon}_r\right)^2 + \left(\dot{\varepsilon}_z - \dot{\varepsilon}_\theta\right)^2 + \left(\dot{\varepsilon}_r - \dot{\varepsilon}_\theta\right)^2 + \frac{3}{2}\dot{\gamma}_{rz}^2}, \tag{7}$$

where the rates of relative linear $\dot{\varepsilon}_z$, $\dot{\varepsilon}_r$, $\dot{\varepsilon}_\theta$ and shear $\dot{\gamma}_{rz}$ deformations.

The power of the cut forces N_{ci-j} at the cut surfaces F_c between adjacent modules i and j:

$$N_{ci-j} = \iint_{F_A} \tau_C \left[\Delta v_c\right] \mathrm{d}F_c, \quad (8)$$

where $\left[\Delta v_c\right]$ is the magnitude of the velocity function discontinuity; $\mathrm{d}F_c$ are the discontinuity surfaces F_c; $\tau_C = \frac{\sigma_S}{\sqrt{3}}$ is the shear stress at the boundary of the cut; σ_s is the yield point, MPa.

The power of friction forces produced at the contact surface between module j and tool n:

$$N_{t\,j-n} = \iint_{G_t} \tau_k \left[\Delta v_t\right] \mathrm{d}G_t, \quad (9)$$

where $\left[\Delta v_t\right]$ is the magnitude of friction speed of billet surface G_t relative to the working surface of the tool; $\tau_k = 2\mu_S \frac{\sigma_s}{\sqrt{3}}$ is the contact tangential friction stress; μ_S is a coefficient of friction $(0 \le \mu_S \le 0.5)$.

Upon the substitution of equation (5) with (6), (8), and (9), by dividing both parts of the resulting equality by a multiplier FV_0, we obtain a formula for reduced pressure $\bar{p} = p/\sigma_s$:

$$\bar{p} = \frac{\sum_i N_{di} + \sum_k N_{ci-j} + \sum_j N_{t\,j-n}}{FV_0 \sigma_s}. \quad (10)$$

In this case, the resulting pressure is a criterial magnitude, which makes it possible to calculate, regardless of the grade of a material, for a particular deformation technique, the magnitude of deformation pressure p and deformation force P:

$$p = \bar{p} \cdot \sigma_s, \quad p = \bar{p} \cdot \sigma_s, \quad (11)$$

where F is the cross-sectional area of the active deforming tool.

As mentioned above, the size and configuration of a deformation zone plays a pivotal role in constructing KPVF and, consequently, leads to the simplification or complication of a mathematical apparatus of calculations. It is not always that one is able to obtain analytic expressions in the disclosure of integrals, which assign the power of plastic deformation, friction forces and the cut forces, due to the need to integrate the bulky, including irrational, functions.

The possibility of obtaining the reduced pressure in the analytical form makes it possible to make full use of the extreme properties of KPVF, determining a parameter value from the condition of a minimum of the function of the reduced pressure (in the simplified form):

$$\frac{d\bar{p}}{da} = 0, \quad \frac{d^2 \bar{p}}{da^2} > 0. \quad (12)$$

It is worth noting that (as a necessary condition for the existence of an extremum) critical points of the first kind for the reduced pressure function are found in the general case from conditions:

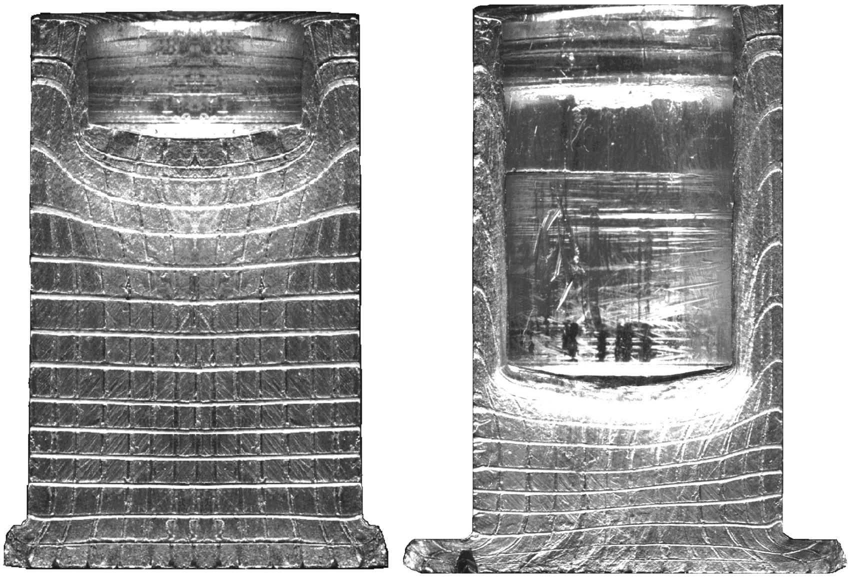
$$\frac{d\bar{p}}{da} = 0 \text{ or } \frac{d\bar{p}}{da} \text{ does not exist.}$$

It is worth noting that regarding the processes of materials forming (MF), the optimal parameters are mostly those values that are derived from equality (12). In this case, all obtained critical values, which do not contradict the essence of geometrical and kinematic parameters of the process, are checked whether they include a minimum of the function based on a sufficient condition for the existence of an extremum.

5. Experimental research into the process of combined radial-reverse extrusion

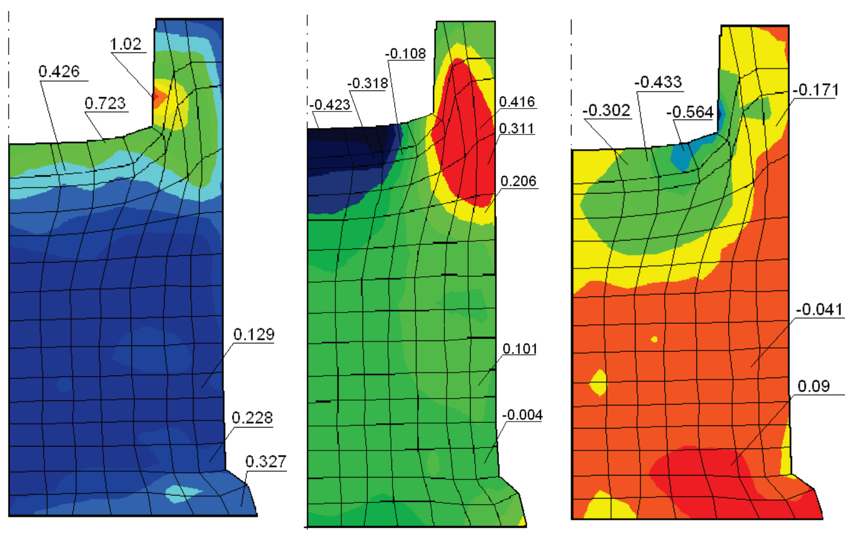
Evaluation of form change patterns, as well as analysis of the stressed-strained state (SSS) of the extruded sample during deformation process, is an important research stage. That makes it possible to obtain information needed to predict the quality of stampings, conformity to the requirements related to sizing, evaluation of deformability, estimation of the deformation processes energy-power mode. At present, research into a billet's SSS in the combined extrusion processes is reported in several papers [10, 18]; however, in the context of combined radial-reverse extrusion, the data obtained earlier require additional, a more detailed, investigation. To acquire information on SSS of the billet's material one can apply methods of experimental research and mathematical modeling, as well as their combination. To study the deformed state, we employed method of coordinate grids. To conduct experimental analysis, we used composite billets made from material C1 with an overlaid coordinate grid o with a base of 2 mm for D_p=21 mm, D_m=28 mm, H_f=3 mm, H_0=37 mm. A slider's working stroke was 5 mm for the first stage and 17 mm for the second process of deformation (Fig. 1). Based on the pattern of a coordinate grid deformation at the initial stage, one may assume the presence of an intermediate rigid zone in which material almost does not deform. Metal escapes into the gap between the punch and the die and into a cavity of the flange from two deformation sites separated by a zone. A characteristic feature of a given process is that the heights of these deformation zones remain practically unchanged over the course of the process that comes at the expense of consuming metal from the intermediate rigid zone. Upon further deformation, there comes a moment of complete degeneration of the intermediate zone when the upper and lower deformation zones merge.

Analysis of the pattern of change in the dividing grid allowed us to draw certain conclusions about the course of a given process of deformation. We note that the greatest distortion of the dividing grid is characteristic of the section under a punch and between a punch and a matrix in the created wall of the cup. Grid elements adjacent to the matrix wall undergo compression in the radial direction, that is, they are pulled upwards. There is almost no distortion of the grid in the intermediate zone (the height of this zone reduces over the course of the process). After scanning the deformed grid and processing the image using the software package Grafula we identified coordinates of the grid cell nodes. The data obtained were employed in the compiled program in the programming environment Mathcad 7 that enables the calculation of a deformation component increment in line with an I. P. Renne procedure, as well as obtaining the quantified estimation of a phased change in the deformed state at each stage (Fig. 2, 3). Data on the pattern of deformations distribution confirm the existence of an intermediate rigid zone and a disconnected DZ in the course of a given deformation process [18].



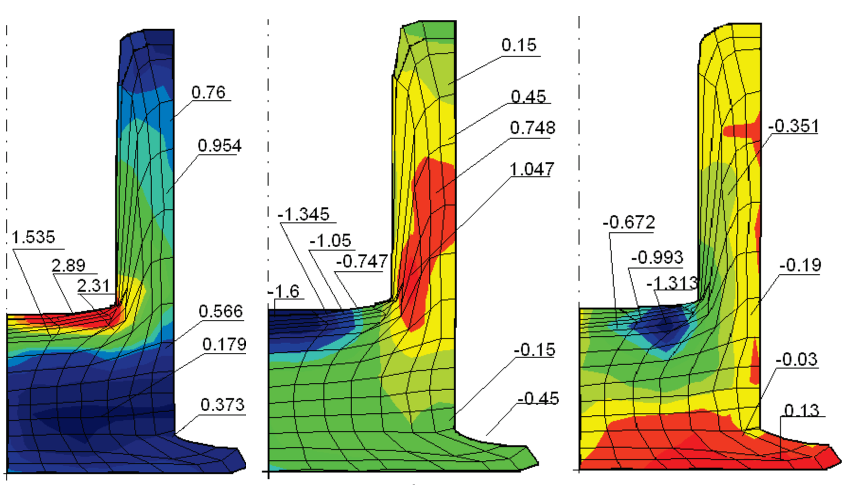
a *b*

Fig. 1. Pattern of a phased change in the dividing grid with a base of 2 mm: *a* — first stage; *b* — second stage



a *b* *c*

Fig. 2. Pattern of the first stage of change in the deformed state: *a* — ε_i; *b* — ε_z; *c* — ε_{rz}



a *b* *c*

Fig. 3. Pattern of the second stage of change in the deformed state: *a* — ε_i; *b* — ε_z; *c* — ε_{rz}

We shall note several regions with a characteristic trend of a phased change in the deformed state pattern. The most intense deformation is experienced by a section located directly under the punch and which captures a gap between it and the matrix. The magnitude of deformation intensities ε_i reaches values of 0.8÷1.1 at the first stage (Fig. 2), and 2.3÷3 at the second stage (Fig. 3) in the process of deformation. This region is characterized by the negative values, the greatest for modulus, for deformation components ε_z and ε_{rz}.

There is almost no growth in the deformation intensity inside an intermediate zone (ε_i is within 0.1÷0.2, ε_z and ε_{rz} do not exceed the values of −0.1 and −0.19, respectively, for the second stage of deformation). Grid elements adjacent to the matrix wall undergo compression in the radial direction (ε_z and ε_{rz} are within 0.2÷1 and −0.17÷−0.3, respectively).

For a flange region, the pattern of change in the intensity of deformations is similar (ε_i is within 0.4), ε_{rz} grows within 0.09÷0.13 over the course of the process, ε_z reaches values of 0.45 for the second stage. The greatest positive values of shear deformations at the outer surface of the flange at the bottom of the cup indicate the plasticity of the zone, dangerous in terms of running out of resource.

An analysis of results on the exploration of the state, deformed in the processes of combined radial-reverse extrusion, for rather high billets, allows us to distinguish three characteristic stages in the process:

1) an initial (stationary) stage of the process – with a disconnected deformation zone;

2) an intermediate (nonstationary) stage – with a connected deformation zone;

3) the final stage of the process.

As noted above, the disconnected deformation zone is characterized by that the heights of the upper and bottom deformation zones remain almost unchanged in the course of the process that comes at the expense of using a metal from the intermediate rigid zone. Upon further deformation, at a time point of complete degeneration of the intermediate zone and a merge of the upper and lower deformation zones, there starts the second (intermediate) stage of the process. During this stage of the process, flows of metal originate in a single deformation zone, with the predominant division into the radial and reverse flow occurring dependent on the height of the flange and the cup's wall thickness [18]. At the final stage of the process, when a punch reaches position corresponding to the height of the flange, there happens a sharp increase in the extrusion force through a preferential course of the process in line with the technique «setting+extrusion». Analysis of experimental data allowed us to draw conclusions that were considered in the theoretical study into the process of combined extrusion of parts with a flange:

– dimensions of deformation zones, separated by an intermediate rigid area, at the initial stage of the process remain almost unchanged until their merging and depend only on the geometrical parameters of the process;

– the most intense deformation is experienced by a section located directly under the punch that captures the gap between it and the matrix;

– grid elements adjacent to the wall of the matrix undergo compression in the radial direction;

– directly at the butt of the punch at the initial stage a shift of metal in the radial direction is negligible while being enhanced as the process progresses;

– the greatest positive values for shear deformations are observed in a flange zone (at the outer surface) at the bottom of the cup.

6. Analysis of the combined radial-reverse extrusion process of parts with a flange using the energy method

Theoretical analysis, using the energy method, of the combined process of radial-reverse extrusion of parts with a flange is based on the estimation scheme CDZ-1.1 (Fig. 4, *a*). A given scheme includes an improved kinematic module and makes it possible to derive formulae for calculating energy-power parameters and a size increment of a semi-finished product. At the same time, the application of the scheme CDZ-1.1 differs from those considered earlier in the scientific literature by the simplicity of expression for the reduced pressure, derived in the analytical form, the optimal value for kinematic parameters $\bar{W}_{opt}\uparrow$ and a possibility to estimate a part's form change in the course of the process using readily applicable formulae.

We have defined boundaries for using a given estimation scheme for the preferential backflow of metal to the wall of the cup, corresponding to ratios $2h_1R_2/\left(R_2^2-R_1^2\right)<1$.

Based on the energy method, in accordance with (6) to (10), we derived calculation formulae for determining the magnitude of reduced pressure (13) and a size increment of a semi-finished product (14). In this case, we managed to obtain the expression of the magnitude of reduced pressure in the explicit form and to determine the optimal value for a kinematic parameter $\bar{W}_{opt}$ based on condition (12). With respect to the possibility of representing the optimal value for kinematic parameter $W_{opt}\uparrow$ in the form of a function of the progress ΔHx, of the billet's size increment at the sequential stages of deformation, we determine, by integrating $W_{opt}(\Delta Hx)$ for a section of stroke $[0;\Delta Hx]$ and from the condition for equality of the volume of metal, pressed out by the punch, which forms the wall of the cup and a flange.

$$\bar{p}_{opt}=\left(\begin{array}{l} 2\bar{C}_{1opt}\ln\bar{R}_2\left(\frac{1}{9k^2}\left(\left(4+3k^2\right)^{3/2}-8\right)-\frac{1+k^2}{\sqrt{3}k}\right)+ \\ +\left(1+\bar{W}_{opt}\bar{R}_2^2\right)\left(\begin{array}{l} 1+\frac{2}{\sqrt{3}}\ln\left(\frac{\bar{R}_2+\bar{l}_2}{\bar{R}_2}\right)+ \\ +\frac{\bar{h}_1}{\bar{R}_2\sqrt{3}}+\frac{2\mu_2}{3\bar{h}_1\sqrt{3}}\left(\bar{R}_2+6\bar{l}_2\right) \end{array}\right)+ \\ +\frac{4\mu_1\bar{R}_2^3}{\sqrt{3}\left(\bar{R}_2^2-1\right)}\left|\bar{W}_{opt}\right|\left(\bar{H}+\bar{l}_1\right)+ \\ +\frac{4\mu_1}{3\sqrt{3}}k\left(-1+\bar{W}_{opt}\frac{\bar{R}_2^2}{\bar{R}_2^2-1}\right)+ \\ +\frac{4\mu_1}{\sqrt{3}}\left(\Delta\bar{H}_X+\bar{l}_1\right)\left(1-\bar{W}_{opt}\frac{\bar{R}_2^2}{\bar{R}_2^2-1}\right) \end{array}\right), \quad (13)$$

where

$$\bar{W}_{opt}=\frac{\left(\bar{R}_2+2k\bar{h}_1\right)\left(\bar{R}_2^2-1\right)}{\bar{R}_2^2\left(2k\bar{h}-\bar{R}_2\left(\bar{R}_2^2-1\right)\right)},\quad \bar{C}_{1opt}=1-\bar{W}_{opt}\frac{\bar{R}_2^2}{\bar{R}_2^2-1}.$$

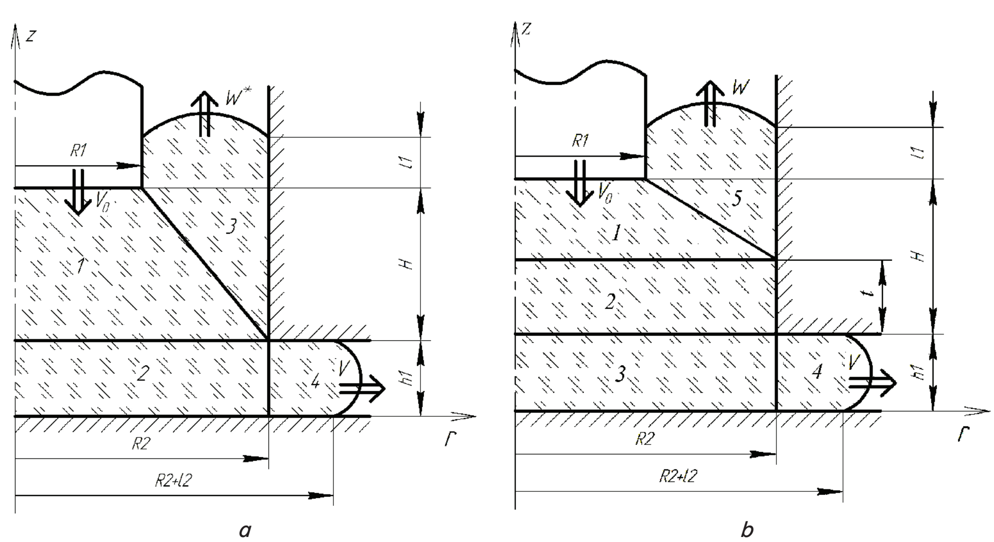


Fig. 4. Calculation schemes:
a – CDZ-1.1; *b* – DDZ-1.1 for the process of combined radial-reverse extrusion

$$\begin{cases} \Delta l_1 \uparrow = \dfrac{R_1^2}{R_2^2 - R_1^2}\left(\begin{array}{l} \Delta Hx + \dfrac{2h_1 R_2^2}{R_2 (R_1 + R_2)} \times \\ \times \ln\left| 1 - \dfrac{\Delta Hx R_2 (R_1 + R_2)}{(H_0 - h_1) R_2 (R_1 + R_2) + 2h_1 R_1^2} \right| \end{array} \right), \\ \Delta l_2 \to = \sqrt{\dfrac{R_1^2 \Delta Hx - (R_2^2 - R_1^2) l_1 \uparrow}{h_1} + R_2^2} - R_2, \end{cases} \quad (14)$$

where ΔHx is the punch stroke corresponding to the stage of deformation.

For sufficiently high billets (at $H_0/h_1>4...6$) the estimation scheme with a combined DZ can be improved through the introduction of an additional intermediate rigid zone, which would take into consideration the specificity of metal flow characteristic of the disconnected DZ, without causing significant complication of subsequent calculations. We shall employ, as an alternative estimation scheme, the modified scheme DDZ-1.1 with intermediate rigid zone 2 (Fig. 4, *b*).

The reduced pressure magnitude $\bar{p}$ was derived analytically similar to (13) and is a function of geometrical parameters of the process and a factor λ, responsible for the motion speed of the rigid zone:

$$\bar{p} = \left(\begin{array}{l} \dfrac{4\mu_1 \bar{R}_2}{\sqrt{3}(\bar{R}_2^2 - 1)} \left| 1 - \lambda \bar{R}_2^2 \right| (\bar{H} - \bar{t} + \bar{l}_1) + \\ + \dfrac{4\mu_1}{\sqrt{3}} \bar{C}_1 (1 - \lambda)(\Delta \bar{H}_X + \bar{l}_1) + \\ + (1 - \lambda) \left[\begin{array}{l} \dfrac{2\bar{C}_1}{9\bar{k}^2} \ln \bar{R}_2 \left((4 + 3\bar{k}^2)^{3/2} - 8 \right) - \\ - \dfrac{2\bar{k}\bar{C}_1}{3\sqrt{3}} + \dfrac{2}{\sqrt{3}} \dfrac{1 + \bar{k}^2}{\bar{k}} \bar{C}_1 \ln \dfrac{1}{\bar{R}_2} \end{array} \right] + \\ + \dfrac{4\mu_1}{3\sqrt{3}} \cdot \dfrac{\bar{R}_2^2}{\bar{R}_2^2 - 1} \bar{k} (\lambda - 1) + \\ + \lambda \left[\begin{array}{l} \bar{R}_2^2 + \dfrac{2}{\sqrt{3}} \bar{R}_2^2 \ln \left(\dfrac{\bar{R}_2 + \bar{l}_2}{\bar{R}_2} \right) + \dfrac{\bar{R}_2^3}{3\sqrt{3}\bar{h}_1} + \\ + \dfrac{\bar{R}_2 \bar{h}_1}{\sqrt{3}} + \dfrac{4\mu_1 \bar{R}_2 \bar{t}}{\sqrt{3}} + \dfrac{2\mu_2 \bar{R}_2^3}{3\sqrt{3}\bar{h}_1} + \dfrac{4\mu_2 \bar{R}_2^2 \bar{l}_2}{\sqrt{3}\bar{h}_1} \end{array} \right] \end{array} \right), \quad (15)$$

where

$$\Delta \bar{H}_X = \frac{\Delta H_X}{R_1}, \quad \bar{H} = \frac{H}{R_1},$$

$$\bar{R}_2 = \frac{R_2}{R_1}, \quad \bar{h}_1 = \frac{h_1}{R_1}, \quad \bar{l}_1 = \frac{l_1}{R_1}, \quad \bar{l}_2 = \frac{l_2}{R_1},$$

$$\bar{k} = \frac{1 - \bar{R}_2}{\bar{H} - \bar{t}}, \quad \bar{C}_1 = \frac{\bar{R}_2^2}{\bar{R}_2^2 - 1}.$$

The value for coefficient λ is established from the equality of power, acting on rigid zone 2 on both sides; after basic transforms it takes the following form:

$$\lambda = \frac{\bar{p}_1}{\bar{p}_1 + \dfrac{(\bar{R}_2^2 - 1)\bar{R}_2^2}{2\bar{h}_1 \bar{R}_2} \bar{p}_2}, \quad (16)$$

where $\bar{p}_1$ is the reduced pressure for the process of reverse extrusion with respect to speed of zone 2; $\bar{p}_2$ is the reduced pressure for the process of radial extrusion.

Using expression (16) in order to determine coefficient λ one can obtain a reduced pressure for the process of combined extrusion in general. In this case, minimization of the derived magnitude $\bar{p} = \bar{p}(\bar{t})$ is achieved by varying the geometrical parameter $\bar{t}$, a relative height of rigid zone 2. To verify the acceptability of the obtained calculation expressions, we performed combined radial-reverse extrusion of an experimental batch of parts made of lead Pb, aluminum alloys AA1135, AA5654, C46400, at hydraulic presses in the universally-adjustable stamps. Friction coefficient was adopted at μ_s=0.08. Based on the results of research, we constructed a dependence chart of extrusion effort on the press slider stroke. We applied, as theoretical calculation models for relatively high billets ($H_0/h_1>4...6$), the scheme DDZ-1.1 for ratios $2h_1R_2/(R_2^2 - R_1^2) < 1$ and a scheme with a combined DZ.

To calculate the mean deformation degree e_i with respect to the R. Hill's assumptions, adapted to the process of combined radial-reverse extrusion for schemes with a disconnected DZ, we used expression:

$$e_{icp.} = \begin{cases} \bar{p} \uparrow, & (1), \\ \bar{p} \to, & (2), \end{cases} \quad (17)$$

where $\bar{p}\uparrow$ is the reduced pressure of the process of reverse extrusion; $\bar{p}\to$ is the reduced pressure for the process of radial extrusion of components of the combined extrusion schemes.

In this case, the magnitude $e_{icp.}$ in the form of (1) will be used for the components of the reduced pressure responsible for the reverse extrusion, while the magnitude $e_{icp.}$ in the form of (2) – for the reduced pressure components responsible for radial extrusion (with respect to the volume of a rigid zone).

For schemes with a combined DZ, we accepted:

$$1 - k = \frac{(R_2^2 - R_1^2)\Delta l \uparrow}{R_1^2 \Delta Hx}, \quad (18)$$

taking into consideration the ratio of the pressed-out volume of metal, corresponding to the reverse extrusion, to the total volume of pressed-out metal. Given this assumption for the calculation of the mean degree of deformation e_i at combined extrusion with a combined DZ, we obtain using (17):

$$e_{icp.} = (1 - k) \cdot \bar{p} \uparrow + k \cdot \bar{p} \to. \quad (19)$$

When calculating values of P for schemes with a disconnected deformation zone, the proposed expression for a mean deformation degree e_i allowed us to derive estimation data that correspond to reality. Overvaluation of the theoretically obtained results for the energy-power parameters of the process (R_1=10.5 mm, R_2=14 mm, h_1=3 mm, H_0=17 mm) does not exceed 10–15 % (Fig. 5).

Comparative analysis of increments in a semi-finished product based on the developed estimation schemes and experimentally acquired data (Fig. 6) allow us to draw a conclusion on the acceptability of results obtained theoretically. The difference between the predicted part's dimensions and those derived experimentally does not exceed 15–20 %.

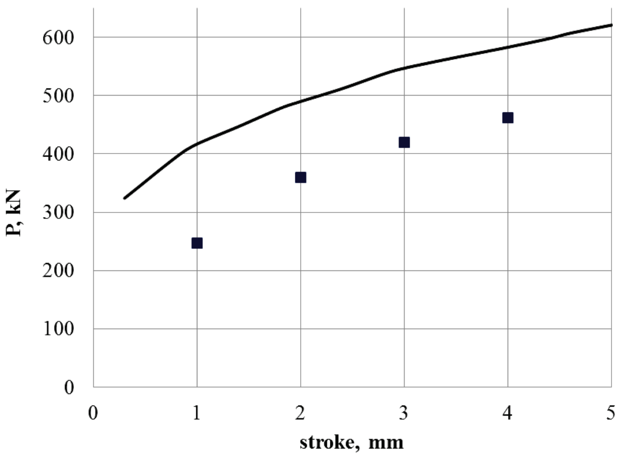
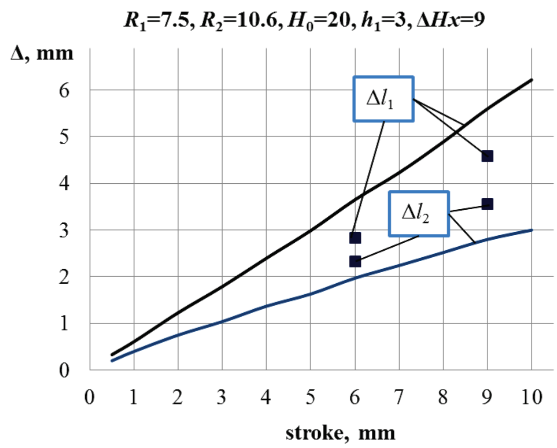
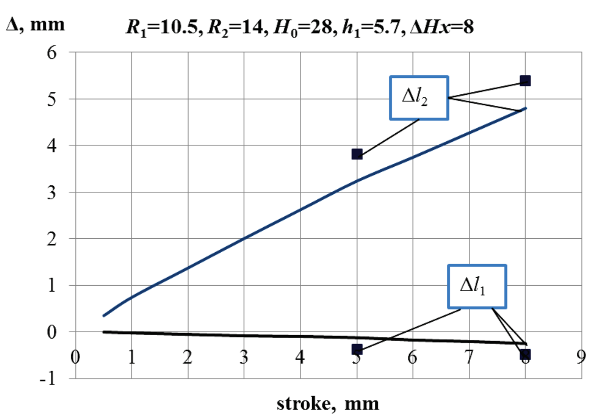


Fig. 5. Experimental and theoretical data on the extrusion effort due to a press stroke for material C46400



a



b

Fig. 6. Experimental and theoretical data on the size increment of semi-finished products made of aluminum alloys: *a* – AA1135; *b* – AA5654

7. Discussion of results of studying the process of combined radial-reverse extrusion of parts with a flange

Results of the experimental study into the power mode of the process of radial-reverse extrusion of parts made from lead Pb, aluminum alloys AA5654, AA5654, brass C46400, confirmed the validity of results of calculations of the accepted mathematical models. When calculating values for P, it is appropriate, for schemes with a disconnected DZ, to use the expression of the mean deformation degree e_i. We took into consideration a change in the height of an intermediate rigid zone during deformation process; overvaluation of the results derived theoretically does not exceed 10–15 %. A comparative analysis of the pattern in a phased form change of billets showed the validity of using the proposed estimation schemes to predict the phased and resulting form change of a semi-finished product. Deviation of the results, obtained theoretically, from experimental data does not exceed 15–20 % (Fig. 6). That confirms the possibility of employing the developed calculation models and the prospects for using the energy method when calculating processes of combined extrusion.

However, the schemes developed in the course of our research could not apply for the geometrical parameters of the process $2h_1R_2/(R_2^2-R_1^2)<1$ and would require a search for the new calculation schemes.

The aim of future study is to develop new calculation schemes with respect to their systematization for predicting the shape formation at different dimensions of hollow parts with a flange.

8. Conclusions

1. We have developed calculation scheme CDZ-1.1 and derived, based on the energy method, formulae for calculating the reduced pressure of deformation and phased size increments of a semi-finished product for the process of combined radial-reverse extrusion of parts with a flange. This has greatly simplified the estimation of a possibility to exploit a given process of deformation to obtain parts with required configuration, and to define the boundaries in the application of a given calculation scheme for ratios $2h_1R_2/(R_2^2-R_1^2)<1$.

2. We have developed calculation schemes for the process of combined radial-reverse extrusion of parts with a flange for the billets that are high enough (at H_0/h_1>4...6), with the existence of an intermediate non-deformable zone. The data that we acquired on a phased form change in a semi-finished product correspond to reality. It is recommended to use the calculation scheme DDZ-1.1 for the simulation of processes of combined extrusion of parts with a flange for ratios H_0/h_1>4...6 and $2h_1R_2/(R_2^2-R_1^2)<1$.

3. Based on the research into SSS of the billet at combined extrusion of parts with a flange for relatively high billets, we confirmed the existence of an intermediate non-deformable zone at the initial stage of deformation. This testifies to the relevance of appropriate theoretical assumptions, as well as application of calculation models that have a disconnected deformation zone.

Acknowledgements

Our study has employed, and further developed, approaches and a procedure for constructing different kinematically possible velocity fields, a modular approach, reported in paper [10]. Authors express their gratitude to L. I. Alieva for advice and recommendations when discussing the results of studying the process of combined radial-reverse extrusion of parts with a flange.

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