UDC 621.777.01
DOI: 10.15587/1729-4061.2022.254867

ESTIMATING THE INITIAL STAGE IN THE PROCESS OF RADIAL-REVERSE EXTRUSION USING A TRIANGULAR KINEMATIC MODULE

Natalia Hrudkina
Corresponding author
Doctor of Technical Sciences, Associate Professor
Department of Mathematics and Modeling*
E-mail: vm.grudkina@ukr.net
Vladymyr Levchenko
PhD, Senior Researcher
Department of Radiowave Propagation in Natural Media
O. Ya. Usikov Institute for Radio Physics and Electronics of the National Academy of Sciences of Ukraine
Akademika Proskury str., 12, Kharkiv, Ukraine, 61085
Igramotdin Aliiev
Doctor of Technical Sciences, Professor, Head of Department
Department of Metal Forming*
Yurii Diachenko
PhD
Department of Technologies and Equipment of Foundry*
Roman Sivak
Doctor of Technical Sciences
Department of General Technical Disciplines and Labor Protection
Vinnytsia National Agrarian University
Sonyachna str., 3, Vinnytsia, Ukraine, 21008
Liudmyla Sukhovirska
PhD
Department of Fundamental Disciplines
Donetsk National Medical University
Pryvokzalna str., 27, Lyman, Ukraine, 84404
*Donbass State Engineering Academy
Akademichna str., 72, Kramatorsk, Ukraine, 84313

Those parts of solid or hollow blanks whose shape is complex should be produced by means of combined radial-longitudinal extrusion. However, the use of combined extrusion processes with several degrees of flow freedom requires a preliminary assessment of shape formation, which is true, taking into consideration the peculiarities of evolution of strain sites at different stages of deformation. When deforming high blanks, the presence of an intermediate rigid zone can be observed, separating two autonomous strain sites. When constructing an estimation scheme of the initial stage of the process of combined radial-backward extrusion of hollow parts with a flange, the presence of an intermediate rigid zone is taken into consideration. The need to improve the devised estimation scheme is caused by significant deviations in the projected growths of a part from its experimentally derived dimensions. As an alternative to the axial rectangular kinematic module of the lower deformation site, the use of an axial triangular module has been proposed, whose effectiveness is demonstrated in simulating the process of radial-longitudinal extrusion with expansion. The rationality of the proposed replacement was revealed, both for forecasting the forced mode of the deformation process and for the gradual part's shape formation. This has made it possible to reduce the projected estimates to 10 % in terms of the increase in the size of a part based on a comparative analysis with experimentally derived data. It is recommended to use the devised scheme for modeling the initial stage of the process for relatively high blanks at H_0/h_1>4...6; the limitation is the degeneration of the intermediate rigid zone. This will contribute to compiling recommendations for expanding the possibilities of using combined radial-backward extrusion of hollow parts with a flange during production

Keywords: combined extrusion, process modeling, energy method, kinematic module, forced mode, shape formation

Received date 21.02.2022
Accepted date 24.03.2022
Published date 28.04.2022

How to Cite: *Hrudkina, N., Levchenko, V., Aliiev, I., Diachenko, Y., Sivak, R., Sukhovirska, L. (2022). Estimating the initial stage in the process of radial-reverse extrusion using a triangular kinematic module. Eastern-European Journal of Enterprise Technologies, 2 (7 (116)), 51–59. doi: https://doi.org/10.15587/1729-4061.2022.254867*

1. Introduction

The modern development of solid medium mechanics and deformed solids enable solving a wide range of practical tasks related to material pressure forming (MPF). MPF methods are increasingly considered as an alternative to the classical techniques to form parts by removing chips. Most research tackles specific practical tasks to devise technology for the manufacture of articles with predefined characteristics [1–4]. Moreover, the variety of possibilities in terms of the use of a particular method of pressure treatment makes the choice of the most relevant one a priority task [1, 5]. Choosing it is primarily predetermined by the capabilities and features of production and the corresponding energy intensity and economic efficiency [2, 5]. The achievements of researchers in recent years, who resolved theoretical problems, contribute to extending the technological capabilities of plastic deformation processes [6, 7]. This applies primarily to the expansion of opportunities for the assessment and forecasting of energy-forced modes, phased shape formation, as well as defect formation in a semi-finished article [8–10]. The tendency to expand the range and materials of parts obtained by cold extrusion indicates the need to continue researching the processes of combined extrusion [10, 11]. These processes, on the one hand, reduce the number of stamping transitions of complexly profiled parts but, on the other hand, are the least investigated in terms of ensuring compliance of the semi-finished product with the size of the finished part. Thus, it is the construction of an adequate mathematical model of processes with several degrees of freedom of metal flow that will contribute to obtaining an assessment of the shape formation of a semi-finished article that corresponds to reality. And this, in turn, at the design stage would make it possible to determine the possibilities of combined extrusion to fabricate a quality part.

2. Literature review and problem statement

Currently, the most fully researched are the basic processes of extrusion and combined sequential extrusion (with one degree of freedom of metal flow). A study into various types of deviation of the shape of the part, defect formation, and the possibility of using radial extrusion processes is reported in [12]. A finite-element method was used to investigate the influence of structural parameters of stamps, the stressed-strained state in the manufacture of hollow brass parts by cold direct extrusion with expansion on a cone punch [13]. The possibilities of using the upper evaluation method to determine the geometric dimensions of the dead zone and energy parameters are investigated for the process of angular extrusion [14]. The studies into these processes made it possible to test the possibilities of theoretical methods and finite-element modeling in terms of obtaining adequate assessments of loads on the tool, the forces of matrix opening, the stress-strained state, and defect formation. However, from the point of view of investigating shape formation, of more interest is the processes of combined extrusion with several degrees of freedom of flow that make it possible to fabricate complexly profiled parts per a single run [11]. On the other hand, a new task becomes necessary for these processes – assessing the compliance of the projected dimensions of a semi-finished article with the size of the finished product.

The processes of combined extrusion are currently studied using finite-element analysis, theoretically (by the upper assessment method and the energy method of capacity balance (EMCB), and experimentally. The basics and procedure of using theoretical methods of research and calculation of cold extrusion processes are given in fundamental works.

In [15], a new presentation of the mechanics of absolutely solid and deformed bodies, and energy interpretation of the concept of “force” is proposed. The proposed defining equations contribute to improving the accuracy of kinematic and dynamic analysis, and the development and optimization of technological processes of pressure forming. Manual [16] gives examples of solving problems for calculating the force and kinematic parameters of metal pressure forming EMCB, including using the Mathcad software package. This is an effective tool for the application of EMCB for more complex tasks, including the analysis and modeling of combined extrusion processes.

Many scientists addressed various aspects of the processes of combined reverse-direct extrusion, which are widely implemented in the manufacture of automotive parts. Paper [17] provides recommendations for avoiding defect formation in the process of combined reverse-direct extrusion of the piston pin. It was established that the defect is characteristic of processes with a small thickness and adversely affects the quality of the resulting part. The authors proposed techniques to adjust the kinematics of the process based on moving tools. Their results of finite-element modeling and conclusions are consistent with the experimental results but are limited to the studied parameters.

Work [18] examines one of the stages in the production of hexagonal and trochoidal-like bolts using combined reverse-straight extrusion. New kinematically permissible velocity fields for determining the shape-forming load, extrusion course, and the nature of deformation relative to the run of the punch are proposed. The theoretically obtained data make it possible to define the pattern of deformation based on the punch run, the force of extrusion, and the shape formation of a semi-finished article.

The effect of deformation temperature and lubricants on the plastic properties of magnesium alloy (AZ61A) in the process of combined extrusion of a cup with axial protrusion is examined in [19]. The cited work complements and expands the practice and application of magnesium alloy treatment using plastic forming techniques.

Work [20] addresses the issues of determining the strain force and shape formation with simultaneous radial extrusion of external and internal flanges from a tubular article [20]. Theoretical calculations of the value of the reduced pressure of deformation on the punch and the gradual shape formation of growths of external and internal flanges were carried out on the basis of EMCB. However, there are no results to match the projected data on the phased increments of the part with the experimentally obtained data, which significantly reduces the weight of the reported results.

Various aspects of the peculiarities of the process of combined radial-backward extrusion have been investigated. In work [21], EMCB is used to determine the forced mode of the process of combined radial-backward extrusion. However, no appropriate calculation formulas were derived for the phased shape formation of a part. In [22], finite-element modeling was employed to analyze the influence of friction conditions and the radius of curvature of the matrix on the force parameters of deformation. The authors of [23] investigated, based on modeling using Deform 2D, the peculiarities of the metal flow, taking into consideration the influence of the angle of the end of the punch in the processes of reverse and combined radial-backward extrusion of blanks from hardened steel. However, the cited studies are limited in nature because of the set of parameters for the simulation conducted. Of interest is the analysis of extending the possibilities of using EMCB to predict the forced mode and the shape formation of a semi-finished article. Work [24] substantiates the need to use estimation schemes in the presence of an intermediate rigid zone at the initial stage for relatively high blanks. Paper [25] defines the conditions for ensuring the possibility of optimization according to the kinematic parameter in various estimation schemes and provides relevant recommendations. In [26], the authors proposed an algorithm for calculating the processes of combined extrusion that simplifies compiling technological recommendations. This applies to determining the forced mode of extrusion and preliminary assessment of the shape formation of a part with the ability to control the leakage of the metal in the process of deformation. Recommendations for the use of constructed mathematical models according to different geometric ratios of the radial-backward extrusion process are provided, which significantly enhances the value of the reported results. The defect formation in the form of a deflection in the bottom part is investigated in [27] with the construction of a diagram of the region of defect formation and the provision of recommendations for the prevention of this type of defect. This demonstrates the capabilities of EMCB in terms of assessing the forced mode and shape formation. The ability to control the shape formation of a semi-finished article both in terms of ensuring the required size and delaying the appearance of a defect in the form of deflection is demonstrated in [27]. This confirms the efficiency of EMCB and its capabilities related to the transformation of the basic estimation scheme of the process, taking into consideration the introduction of design features (rounding, chamfers, etc.). However, additional research is required as regards the initial stage of the deformation process for relatively high blanks, which are characterized by the presence of an intermediate rigid zone, which could reduce the deviation of the projected estimates of the growths of semi-finished articles from the experimentally obtained ones.

The process of trilateral direct-reverse-radial extrusion of hollow parts was investigated experimentally and using finite-element analysis. The finite-element analysis was applied in work [28] to examine the effect of geometric parameters on the forced mode and shape formation. Study [29] built on the research to determine the effect of friction conditions on the course of the deformation process. In further studies [30], attention was paid to determining the influence of geometrical parameters of the stamp design, as well as friction conditions, on the shape formation of a semi-finished article and the formation of defects. The validity of the simulation results was confirmed by experimental data on the forced mode and shape change. However, the influence of geometric ratios and friction conditions, which are the main factors in controlling the flow of metal, was investigated within the parameter variance, which indicates the limited nature of the results obtained.

Thus, studies in recent years indicate the prospects for using EMCB as an effective theoretical method for studying the processes of combined extrusion. Therefore, advancing this method from the point of view of devising clear recommendations for the construction of calculation schemes of the process according to the peculiarities in the formation of strain sites, the process stages, and possible changes in the structural features of the tool is a relevant task. This could provide an opportunity to control the flow of metal (the shape formation of a semi-finished article) in the processes of combined extrusion, as well as more actively employ these processes in the industry.

3. The aim and objectives of the study

The aim of this work is to predict an increase in the size of a part corresponding to a real one, based on devising an estimation scheme of the initial stage in the process of combined radial-backward extrusion. This will reveal the possibilities of using combined extrusion in terms of ensuring that the size of the flange and the wall of the cup meet the required dimensions of the finished part.

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

– to identify the features in the formation of strain sites at the initial stage for constructing an effective estimation scheme of the process of combined radial-backward extrusion;

– to obtain an assessment of the forced mode and shape formation of a part according to the estimation scheme of the process in the presence of an axial triangular module of the lower deformation unit of the initial stage in the radial-backward extrusion process;

– to establish the correspondence between the theoretically obtained data (using axial triangular and rectangular kinematic modules) on the force parameters and shape formation of a part in the process of radial-backward extrusion and the experimental data.

4. The study materials and methods

An effective tool for using EMCB is the method of kinematic modules (MKM). Its application makes it possible to consider an estimation scheme of the process in the form of a set of separate unified elements (or whole systems) whose estimations are known. The bank of unified kinematic modules or their entire systems with a complete set of calculations of the reduced deformation pressure makes it possible to quickly respond to all changes in the estimation scheme caused by a change in the shape of a part or the configuration of a tool. In this case, constructing a new kinematic module typically allows it to be used not only for one particular estimation scheme or process but for a suite of different schemes where it can serve as their element. At the same time, an important role belongs to the peculiarities of MKM application for modeling the processes of combined extrusion in accordance with the classification of basic strain sites (SSs): sequential, connected, combined, transit, and combined [16, 21, 24, 31, 32].

The proposed categorization is useful in terms of the possibilities of further use of new kinematic modules or their sets for the construction of improved estimation schemes for other processes that may include them.

The simplest are the processes of combined extrusion in the presence of a sequential SS with one degree of freedom of metal flow. When calculating such processes, adjacent kinematic modules are sequentially added, taking into consideration the full component of the power of cut forces at the contact boundary [32] (Fig. 1, left pattern).

For processes with connected SS, the main task is to find the position of the boundary of two adjacent SSs with one degree of freedom of flow of metal [31] (Fig. 1, right pattern, SS-II-1 and SS-II-2). When analyzing processes with transit SS (disconnected SS), the presence of an intermediate rigid zone between autonomous SSs is taken into consideration. The optimal speed of the intermediate zone is determined subject to the equilibrium of forces acting on both sides of the surface separating two SSs [24] (Fig. 1, right pattern in the presence of rigid one). For processes with multidirectional metal flows originating in one combined SS, it is necessary to use kinematic modules with two degrees of freedom of flow. Further optimization is carried out according to the kinematic parameter in the form of the speed of metal flow in the longitudinal direction [24–26] (Fig. 1, right pattern in the absence of a rigid zone). Processes with combined SS are a combination of SSs from the first four groups while the calculation procedure is more complicated. Devising recommendations regarding the shape of kinematic modules and their sets, their construction, and expediency of application in new estimation schemes of combined extrusion processes in accordance with the peculiarities of SS formation could improve the efficiency of EMCB.

The experimental part of our studies is based on the physical modeling of cold extrusion processes using full-time experiments and a strain gauge method. For experimental studies, the test machine MS-500 with a force of 500 kN was used, which has the necessary capacities for implementing the processes of combined radial-longitudinal extrusion, a sufficient amount of interstamp space to host an experimental stamp with the registering sensors. The matrices and punches were made of the steel X12M, GOST 5950-73, hardened in oil, and strengthened to HRC 56...60; the working surface was polished to R_a0.4. Samples from AD1 were made of rods with subsequent heat treatment, which ensures the same properties at any randomly taken point of the sample when maximum plasticity is reached. Heating mode: heating, 350–400 °C, cooling in the air. To take into consideration the strengthening of AD1, a curve of true stresses was used, built on the results of mechanical tests for compression of cylindrical samples: $\sigma_s=131e^{0.28}$. We treated statistically the results of experimental studies of the force of extrusion.

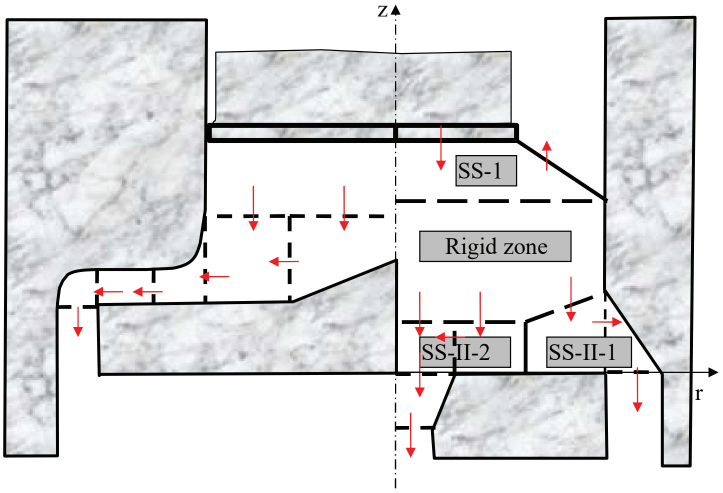


Fig. 1. Generalized estimation scheme of combined sequential (left pattern) and combined (right pattern) extrusion

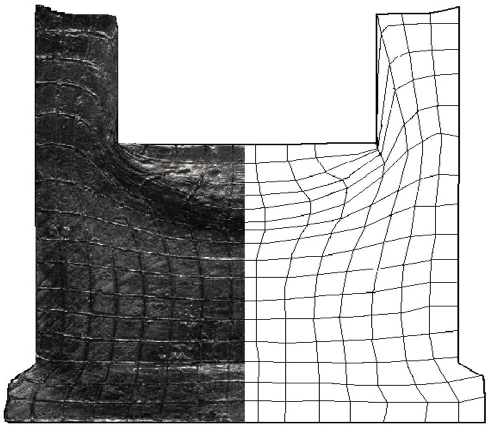


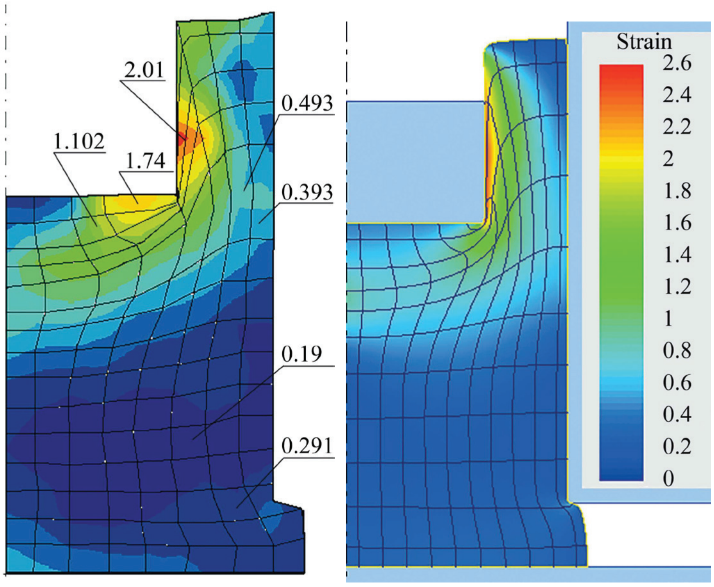
Fig. 2. Curvature of the divisional mesh of the lead C1 sample

The construction of the estimation scheme of the processes of combined extrusion is based on the analysis of the stressed-strained state, the curvature of the dividing grids for the lead C1 with an applied coordinate mesh with a base of 3 mm. The data on forecasting the energy-forced mode and shape formation of a part are verified experimentally.

5. Results of studying the initial stage in the combined extrusion process

5. 1. Investigating the features in the formation of strain sites during the process of combined extrusion of hollow parts with a flange

It is advisable to make complex profiled parts from solid or hollow blanks by means of combined radial-longitudinal extrusion. However, the introduction of combined extrusion processes with several degrees of freedom of flow instead of basic processes requires a preliminary assessment of the true shape formation, taking into consideration the peculiarities in the formation of strain sites at different deformation stages. In the processes of radial-backward extrusion for fairly high blanks (at $H_0/h_1>4...6$) at the beginning of deformation, the presence of an intermediate rigid zone was established [24]. Additionally, the components of blanks made of the material C1 with an applied coordinate mesh with a base of 3 mm, the punch diameters and blanks of 28 mm and 45 mm with a chamfer thickness of 6.5 mm, a height of 47 mm were used. The working stroke of the slider was 12 mm (Fig. 2). The resulting data were used in the Mathcad 7 programming environment, which allowed us, based on the Renne procedure, to derive a quantitative assessment of the deformed state (Fig. 3, *a*). According to the modeling data from the software Qform 2/3D, the patterns of strain distribution inside a workpiece were obtained, which also confirm the presence of an intermediate rigid zone and a transit SS (Fig. 3, *b*). Pre-used estimation schemes of the process indicate the need to refine the height and speed of the rigid zone separating two autonomous SSs. Additionally, the resulting data on the shape formation of a semi-finished article indicate significant (up to 15–20 %) deviations of the data obtained theoretically from those acquired experimentally [24].



a *b*

Fig. 3. Analysis of strain distribution data: *a* – based on Renne procedure; *b* – acquired from Qform 2/3D

The nature of the curvature of the dividing grid and the distribution of strains has made it possible to determine the possibility of using the devised triangular kinematic module instead of a rectangular one in the turn zone to the radial flow in the lower autonomous SS. Such a replacement could be effective in terms of the demonstrated decrease in the deformation force for SS of the radial flow, which would affect determining the full force of deformation in the process and a change in the projected estimates of the growths of a semi-finished article.

5. 2. Devising an estimation scheme for determining the forced mode and shape formation at the initial stage of the process

According to the recommendations substantiated above, the generalized estimation scheme of the process takes the following form (Fig. 4).

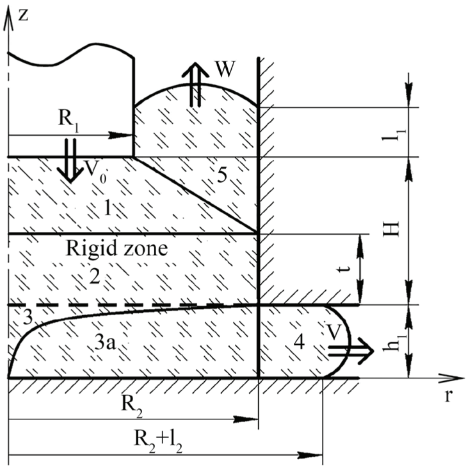


Fig. 4. Generalized estimation scheme of the process with two types of autonomous lower SS of radial extrusion

Hereafter, we denote SS-1 the estimation scheme of the process with the presence of rectangular kinematic modules of zones 2 and 3. The improved SS-1*a* includes trapezoidal rigid zone 2 and triangular axial module 3*a* (Fig. 4) with the possibility of further optimization according to the parameter $\alpha\in(0,\,1)$, which determines the shape of the curve.

In the simplest version of SS-1, in the presence of a rectangular boundary of trapezoidal module 1 and axial module 3 of rectangular shape, the expression for the reduced deformation pressure was derived [24]. Those calculations can be applied for the subsequent comparative analysis while using the reduced pressure of deformation of the upper strain site in the following form:

$$\bar{p}_{\uparrow}=\begin{bmatrix}\dfrac{2\bar{C}_1}{9\bar{k}^2}\ln\bar{R}_2\left(\left(4+3\bar{k}^2\right)^{3/2}-8\right)-\\-\dfrac{2\bar{k}\bar{C}_1}{3\sqrt{3}}+\dfrac{2}{\sqrt{3}}\dfrac{1+\bar{k}^2}{\bar{k}}\bar{C}_1\ln\dfrac{1}{\bar{R}_2}-\\-\dfrac{4\mu_1}{3\sqrt{3}}\cdot\dfrac{\bar{R}_2^2}{\bar{R}_2^2-1}\bar{k}+\dfrac{4\mu_1}{\sqrt{3}}\bar{C}_1\left(\Delta\bar{H}_X+\bar{l}_1\right)\end{bmatrix},\tag{1}$$

$$\Delta\bar{H}_X=\frac{\Delta H_X}{R_1},\ \bar{H}=\frac{H}{R_1},\ \bar{R}_2=\frac{R_2}{R_1},\ \bar{l}_1=\frac{l_1}{R_1},$$

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

In the new SS-1*a* estimation scheme, the differences relate to the lower strain site; no axial modules of complex shape were used. It is advisable to employ an axial triangular module whose calculations were carried out only for a process with one degree of flow. For the proposed variant of the axial kinematic module 3*a* triangular at the intersection, the inclined curvilinear boundary takes the form [32]:

$$z(r)=\frac{h_1r^2}{R_2^2(1-\alpha)+\alpha r^2},\tag{2}$$

where $\alpha\in(0,\,1)$ is a parameter that determines the shape of the curve.

Taking into consideration the power components of the deformation, cut, and friction forces, for the triangular kinematic module 3a, taking into consideration the boundary of kinematic module 4, the reduced deformation pressure of the lower autonomous SS-1*a* was derived:

$$\bar{p}_{1a\to}=\begin{bmatrix}\dfrac{2A}{\alpha\sqrt{3}}\begin{bmatrix}\sqrt{3}\ln 3-\sqrt{3}+\\+\dfrac{\sqrt{3}}{1-B^2}-\dfrac{3}{2}\ln\left|\dfrac{1+B}{1-B}\right|-\\-\sqrt{3}\ln\left|\dfrac{\sqrt{3}B-3}{\sqrt{3}B+1}\right|\end{bmatrix}+\\+\dfrac{\bar{R}_2\bar{h}_1}{\sqrt{3}}\begin{bmatrix}\dfrac{\bar{R}_2^2(3-2\alpha)}{3\bar{h}_1^2}+\dfrac{1}{2C\alpha}\cdot\operatorname{arctg}C+\\+\dfrac{(1-\alpha)(2\alpha-1)}{2\alpha}\end{bmatrix}+\\+\dfrac{2}{\sqrt{3}}\bar{R}_2^2\ln\left(\dfrac{\bar{R}_2+\bar{l}_2}{\bar{R}_2}\right)+\dfrac{\alpha\bar{R}_2\bar{h}_1}{\sqrt{3}}+\dfrac{4\mu_1\bar{R}_2\bar{t}}{\sqrt{3}}+\\+\dfrac{2\mu_2\bar{R}_2^3}{3\sqrt{3}\bar{h}_1}(3-2\alpha)+\dfrac{4\mu_2\bar{R}_2^2\bar{l}_2}{\sqrt{3}\bar{h}_1}\end{bmatrix},\tag{3}$$

where $A=\dfrac{\bar{R}_2^2(1-\alpha)}{\sqrt{3}},\ B=\dfrac{\sqrt{(1-\alpha)^2+3\alpha^2}+\alpha-1}{\alpha\sqrt{3}},\ C=\sqrt{\dfrac{\alpha}{1-\alpha}}.$

In this case, the full value of the reduced pressure $\bar{p}_{1a}$ of the new SS-1*a* estimation scheme using the triangular kinematic module 3a takes the following form:

$$\bar{p}_a=\frac{4\mu_1\bar{R}_2}{\sqrt{3}\left(\bar{R}_2^2-1\right)}\left|1-\lambda\bar{R}_2^2\right|\left(\bar{H}-\bar{t}+\bar{l}_1\right)+$$
$$+(1-\lambda)\bar{p}_{\uparrow}+\lambda\,\bar{p}_{1a\to},\tag{4}$$

where the movement speed of the rigid zone is determined from the ratio:

$$\lambda=\frac{\bar{p}_{\uparrow}}{\bar{p}_{\uparrow}+\dfrac{\left(\bar{R}_2^2-1\right)\bar{R}_2^2}{2\bar{h}_1\bar{R}_2}\bar{p}_{1a\to}},\tag{5}$$

where $\bar{p}_{\uparrow}$ is the reduced deformation pressure for the reverse extrusion process;

$\bar{p}_{1a\to}$ is the reduced deformation pressure for the radial extrusion process in the form of SS-1*a*.

Having determined from (4) the optimal value of the flow rate in the vertical direction *W*, one can obtain data on the increments of the part in the process of deformation.

To obtain data on the forced mode, the average strain value *e* is used in the form e^*_{iave}:

$$e^*_{iave} = \left(1-\frac{t}{H_0}\right)\cdot \bar{p}_{\uparrow} + \frac{t}{H_0}\cdot \bar{p}_{1a\rightarrow}, \qquad (6)$$

where *t* is the height of the rigid zone, H_0 is the initial height of a workpiece.

In this case, the reduced pressure is a criterion value, which makes it possible to calculate, regardless of the grade of the material, for a certain deformation scheme, the amount of strain pressure *p* and the strain force *P*:

$$p = \bar{p}\cdot\sigma_s, \qquad (7)$$

$$P=p\cdot F,$$

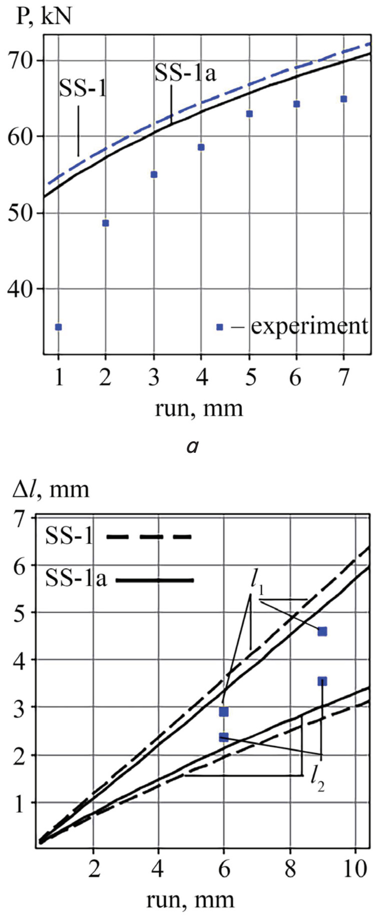
where *F* is the cross-sectional area of the active deforming tool.

Thus, we determined the forced mode according to (7) based on (4) and (6), and acquired data for assessing the shape formation of a part based on the newly developed SS-1*a* scheme at the initial stage of the radial-backward extrusion process.

5. 3. Comparative analysis of theoretically and experimentally obtained data on forced mode and shape formation

Our comparative analysis of the forced mode and shape formation shall be carried out for the simplest case of SS-1 [24] and according to the newly developed SS-1*a* scheme with an axial triangular kinematic module of the lower site of radial extrusion. For the material AD1, at parameters R_1=7.5 mm, R_2=10.6 mm, h_1=3 mm, H_0=20 mm, the theoretical and experimental data were compared. The extrusion force calculated for SS-1*a* using a triangular module according to (4) and (6), (7) is closer to experimental data (point data, Fig. 5) relative to SS-1 using a rectangular module. Deviations in the SS-1*a* scheme from the experimentally obtained data do not exceed 3–10 %, starting with a run of 3 mm compared to the SS-1 scheme, for which the deviation can reach 12 % or more (Fig. 5, *a*). Based on comparing the increments in a part in the process of deformation using experimental data, a diagram with the lower site SS-1*a* was also more rational. The deviation in the increments in the vertical direction for SS-1*a* does not exceed 10 % at the final stage of deformation; according to the SS-1 scheme, it reaches 18 % or more (Fig. 5, *b*).

The introduction of triangular axial module 3*a* instead of a rectangular one affected the increase in the rigid intermediate zone 2, the reduction of plastic zone 3*a*, and the corresponding changes in the nature of the metal flow in this zone. According to expression (3), the deformation pressure in the lower strain site SS-1*a* decreased, which, in turn, caused changes in determining the movement of the rigid zone according to (5), and reducing the total value of the reduced pressure according to (4). The comparative analysis of the height of the rigid zone *t* and parameter λ calculated according to the schemes SS-1*a* and SS-1 indicates the following (Fig. 6, *a, b*). For the improved estimation scheme SS-1*a*, there is a slight increase in the height of the rigid zone (Fig. 6, *a*) and more significant for the parameter λ, which is responsible for moving through the rigid intermediate zone 2 (Fig. 6, *b*). At the same time, an increase in the parameter λ causes a more rapid filling of the flange zone and a less rapid formation of the cup wall, which is consistent with comparing the growths above (Fig. 5, *b*). These differences, together with a decrease in the value $\bar{p}_{1a\rightarrow}$ relative to the corresponding $\bar{p}_{1\rightarrow}$ for the lower SS scheme with rectangular modules and provide more accurate predictive data on the forced mode and shape formation of a semi-finished article.

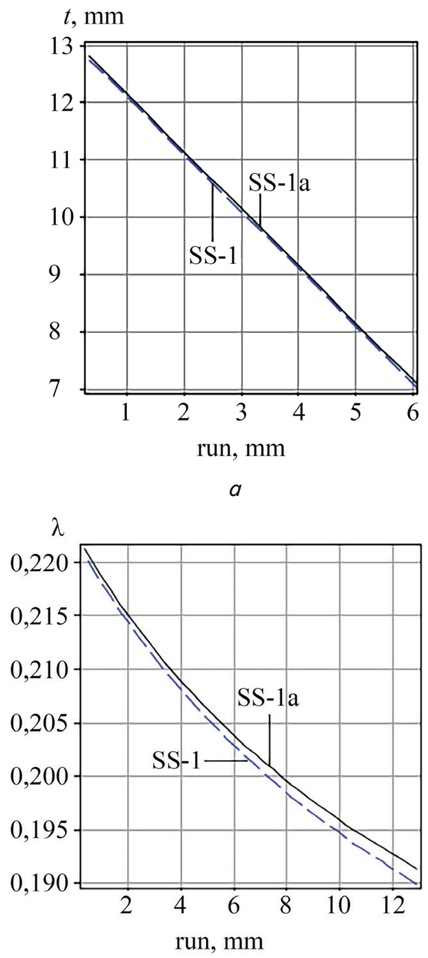


a

b

Fig. 5. Comparative analysis of SS-1 and SS-1*a* schemes with the point data acquired experimentally: *a* – extrusion forces; *b* – increase in the size of a part

Thus, the use of the previously devised axial kinematic module instead of the simplest rectangular one in the new estimation scheme SS-1*a* is rational for the application in modeling the combined extrusion processes with a transit SS. The criterion of optimality based on the reduced pressure has been met; the introduction of a new kinematic module has made it possible to obtain an assessment of shape formation, which is more consistent with experimental data relative to the SS-1 scheme. The use of a given SS-1*a* estimation scheme is recommended for modeling the process initial stage for relatively high blanks at H_0/h_1>4...6 and is limited to degeneration of the intermediate rigid zone when *t*=0. After the degeneration of the intermediate rigid zone, it is necessary to switch the estimation schemes corresponding to the combined SS.



a

b

Fig. 6. Comparative analysis of the estimation schemes SS-1 and SS-1*a*: *a* — the height of the rigid zone; *b* — parameter λ

6. Discussion of results of modeling the initial stage of the process of combined extrusion of parts such as a cup with a flange

The wider introduction in the industry of combined extrusion processes of complex profiled parts should employ an adequate preliminary assessment of not only the forced mode but also the compliance of a semi-finished article with the size of the finished part. This requires the improvement of EMCB as an effective theoretical method for calculating cold extrusion processes, taking into consideration the peculiarities in the formation of strain sites at different deformation stages. The least investigated are the processes with a transit (disconnected) strain site in the presence of an intermediate rigid zone separating two autonomous SSs. The identified features in the formation of strain sites (the presence of an intermediate rigid zone and the shape of zone 3*a*) according to the curvature of the dividing grid (Fig. 2) and the distribution of strains (Fig. 3) are taken into consideration when constructing the scheme of the radial-backward extrusion process. Based on that, the use of an axial triangular module in the turn zone to the radial flow is proposed, to replace the simplest rectangular deformation in the lower strain site (Fig. 4). We have derived estimates of the forced mode in form (4) and (7) and the shape formation of a part according to the estimation scheme of the process in the presence of an axial triangular module of the lower deformation site at the initial stage of the radial-backward extrusion process. In contrast to [24] where significant deviations in estimates of parts increments from experimentally obtained sizes were found, the new estimation scheme SS-1*a* managed to reduce them. This became possible due to the consideration of the more complex shape of the reversal zone 3*a* (Fig. 4) of the triangular shape, which influenced determining the main characteristics of the process. More accurate data on the height of the rigid zone and the parameter λ were acquired from (5), which is responsible for moving through the rigid intermediate zone 2 (Fig. 6). A comparative analysis of the forced mode of deformation and the shape formation of a part according to the proposed (with an axial triangular module) and basic (with the simplest axial rectangular module) and experimental data was carried out. The rationality of the proposed replacement was revealed, both in terms of forecasting the forced mode of the deformation process (Fig. 5, *a*) and the step-by-step shape formation of a part (Fig. 5, *b*); the deviation is up to 10 % in size increases according to the comparative analysis with experimentally obtained data. Thus, it is recommended at the initial stage of combined extrusion processes to take into consideration in the estimation diagrams the presence of a rigid zone and the complex shape of strain sites. This makes it possible to expand the capabilities of EMCB and address the task of obtaining more accurate estimates of both the force characteristics of the deformation process and the growth of a part. It is recommended to use the SS-1*a* scheme with a triangular axial module to simulate the initial stage of the process for relatively high blanks at $H_0/h_1>4...6$; the limitation is the degeneration of the intermediate rigid zone at $t=0$. The introduction of structural features of the tool (the presence of chamfers or rounding) would affect the replacement of value (3) of the reduced pressure of deformation of the lower autonomous SS-1*a*. At the same time, the calculation algorithm is identical to the calculated scheme in question and may be recommended for further research in terms of the possibilities of controlling the shape formation of a part.

7. Conclusions

1. It is advisable to make complex profiled parts from solid or hollow blanks by means of combined radial-longitudinal extrusion with several degrees of freedom of metal flow. It is necessary to ensure forecasting the shape formation of a true part for the possibility of assessing the rationality of the use of combined extrusion from the point of view of ensuring the required dimensions of the part. Taking into consideration the peculiarities in the formation of strain sites at different stages of the deformation process within the framework of EMCB would contribute to devising effective estimation schemes for the process.

2. We have managed to obtain an assessment of the forced mode and shape formation of a part based on the devised estimation scheme of the initial stage in the radial-backward extrusion process with the presence of an axial triangular module of the lower strain site. The application of a given estimation scheme is recommended for modeling the initial stage of the process for relatively high blanks at $H_0/h_1>4...6$ and is limited to degeneration of the intermediate rigid zone when $t=0$.

3. The influence of change in the set of kinematic modules of the lower strain site on the height and speed of movement of the rigid zone has been analyzed. It was established that an increase in the height and speed of the rigid zone along with a decrease in the reduced value of deformation pressure of the lower strain site compared to the previously devised scheme entails a decrease in the projected assessment of the forced mode. It was also possible to reduce to 10 % the deviation of the projected shape formation of a part from the experimentally obtained data, which indicates the prospect of using a triangular module instead of a rectangular module in the axial zone.

References

1. Kukhar, V. V. (2015). Producing of elongated forgings with sharpened end by rupture with local heating of the workpiece method. Metallurgical and Mining Industry, 6, 122–132. Available at: https://www.metaljournal.com.ua/assets/Journal/MMI-6/016-Kukhar.pdf
2. Shapoval, A., Drahobetskyi, V., Savchenko, I., Gurenko, A., Markov, O. (2020). Profitability of Production of Stainless Steel + Zirconium Metals Combination Adapters. Key Engineering Materials, 864, 285–291. doi: https://doi.org/10.4028/www.scientific.net/kem.864.285
3. Markov, O., Kukhar, V., Zlygoriev, V., Shapoval, A., Khvashchynskyi, A., Zhytnikov, R. (2020). Improvement of upsetting process of four-beam workpieces based on computerized and physical modeling. FME Transactions, 48 (4), 946–953. doi: https://doi.org/10.5937/fme2004946m
4. Zhbankov, I., Aliieva, L., Malii, K. (2020). Simulation of microstructure changes of steel during the open die forging process. Journal of Chemical Technology and Metallurgy, 55 (3), 523–529. Available at: https://dl.uctm.edu/journal/node/j2020-3/4_19-278_p_523-529.pdf
5. Kukhar, V., Balalayeva, E., Hurkovska, S., Sahirov, Y., Markov, O., Prysiazhnyi, A., Anishchenko, O. (2019). The Selection of Options for Closed-Die Forging of Complex Parts Using Computer Simulation by the Criteria of Material Savings and Minimum Forging Force. Intelligent Communication, Control and Devices, 325–331. doi: https://doi.org/10.1007/978-981-13-8618-3_35
6. Gribkov, E. P., Malyhin, S. O., Hurkovskaya, S. S., Berezshnaya, E. V., Merezhko, D. V. (2022). Mathematical modelling, study and computer-aided design of flux-cored wire rolling in round gauges. The International Journal of Advanced Manufacturing Technology, 119 (7-8), 4249–4263. doi: https://doi.org/10.1007/s00170-022-08662-x
7. Kulagin, R., Beygelzimer, Y., Estrin, Y., Ivanisenko, Y., Baretzky, B., Hahn, H. (2019). A Mathematical Model of Deformation under High Pressure Torsion Extrusion. Metals, 9 (3), 306. doi: https://doi.org/10.3390/met9030306
8. Bhaduri, A. (2018). Extrusion. Springer Series in Materials Science, 599–646. doi: https://doi.org/10.1007/978-981-10-7209-3_13
9. Marini, D., Cunningham, D., Corney, J. R. (2017). Near net shape manufacturing of metal: A review of approaches and their evolutions. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 232 (4), 650–669. doi: https://doi.org/10.1177/0954405417708220
10. Ogorodnikov, V. A., Dereven'ko, I. A., Sivak, R. I. (2018). On the Influence of Curvature of the Trajectories of Deformation of a Volume of the Material by Pressing on Its Plasticity Under the Conditions of Complex Loading. Materials Science, 54 (3), 326–332. doi: https://doi.org/10.1007/s11003-018-0188-x
11. Alieva, L. I. (2018). Sovershenstvovanie protsessov kombinirovannogo vydavlivaniya. Kramatorsk: OOO «Tirazh - 51», 352.
12. Aliev, I. S. (1988). Radial extrusion processes. Soviet Forging and Sheet Metal Stamping Technology, 6, 1–4.
13. Kalyuzhnyi, V. L., Alieva, L. I., Kartamyshev, D. A., Savchinskii, I. G. (2017). Simulation of Cold Extrusion of Hollow Parts. Metallurgist, 61 (5-6), 359–365. doi: https://doi.org/10.1007/s11015-017-0501-1
14. Perig, A. (2015). Two-parameter Rigid Block Approach to Upper Bound Analysis of Equal Channel Angular Extrusion Through a Segal 2θ-die. Materials Research, 18 (3), 628–638. doi: https://doi.org/10.1590/1516-1439.004215
15. Alyushin, Yu. A. (2012). Mekhanika tverdogo tela v peremennykh Lagranzha. Moscow: Mashinostroenie, 192.
16. Shestakov, N. A. (1998). Energeticheskie metody rascheta protsessov obrabotki metallov davleniem. Moscow: MGIU, 125.
17. Hu, Y., Lai, Z., Zhang, Y. (2007). The study of cup-rod combined extrusion processes of magnesium alloy (AZ61A). Journal of Materials Processing Technology, 187-188, 649–652. doi: https://doi.org/10.1016/j.jmatprotec.2006.11.054
18. Lee, D. J., Kim, D. J., Kim, B. M. (2003). New processes to prevent a flow defect in the combined forward–backward cold extrusion of a piston-pin. Journal of Materials Processing Technology, 139 (1-3), 422–427. doi: https://doi.org/10.1016/s0924-0136(03)00515-6
19. Lee, H. I., Hwang, B. C., Bae, W. B. (2001). A UBET analysis of non-axisymmetric forward and backward extrusion. Journal of Materials Processing Technology, 113 (1-3), 103–108. doi: https://doi.org/10.1016/s0924-0136(01)00666-5
20. Aleksandrov, A. A., Evstifeev, V. V., Koval'chuk, A. I., Evstifeev, A. V. (2012). Matematicheskoe modelirovanie protsessa poperechnogo vydavlivaniya konicheskikh flantsev na trubnoy zagotovke. Vestnik SibADI, 6 (28), 93–98.
21. Golovin, V. A. et. al. (2005). Razrabotka i issledovanie protsessov kholodnoy obemnoy shtampovki polykh osesimmetrichnykh detaley slozhnoy formy. Kuznechno-shtampovochnoe proizvodstvo. Obrabotka materialov davleniem, 11, 35–38.
22. Lee, H. Y., Hwang, B. B., Lee, S. H. (2012). Forming load and deformation energy in combined radial backward extrusion process. Proceedings of the Int. Conf. "Metal Forming 2012". Krakow, 487–490.
23. Noh, J., Hwang, B. B., Lee, H. Y. (2015). Influence of punch face angle and reduction on flow mode in backward and combined radial backward extrusion process. Metals and Materials International, 21 (6), 1091–1100. doi: https://doi.org/10.1007/s12540-015-5276-y

24. Vlasenko, K., Hrudkina, N., Reutova, I., Chumak, O. (2018). Development of calculation schemes for the combined extrusion to predict the shape formation of axisymmetric parts with a flange. Eastern-European Journal of Enterprise Technologies, 3 (1 (93)), 51–59. doi: https://doi.org/10.15587/1729-4061.2018.131766
25. Hrudkina, N., Aliieva, L. (2020). Modeling of cold extrusion processes using kinematic trapezoidal modules. FME Transactions, 48 (2), 357–363. doi: https://doi.org/10.5937/fme2002357h
26. Hrudkina, N., Aliieva, L., Abhari, P., Kuznetsov, M., Shevtsov, S. (2019). Derivation of engineering formulas in order to calculate energy-power parameters and a shape change in a semi-finished product in the process of combined extrusion. Eastern-European Journal of Enterprise Technologies, 2 (7 (98)), 49–57. doi: https://doi.org/10.15587/1729-4061.2019.160585
27. Hrudkina, N. S., Markov, O. E., Shapoval, A. A., Titov, V. A., Aliiev, I. S., Abhari, P., Malii, K. V. (2022). Mathematical and computer simulation for the appearance of dimple defect by cold combined extrusion. FME Transactions, 50 (1), 90–98. doi: https://doi.org/10.5937/fme2201090h
28. Farhoumand, A., Ebrahimi, R. (2009). Analysis of forward–backward-radial extrusion process. Materials & Design, 30 (6), 2152–2157. doi: https://doi.org/10.1016/j.matdes.2008.08.025
29. Farhoumand, A., Ebrahimi, R. (2016). Experimental investigation and numerical simulation of plastic flow behavior during forward-backward-radial extrusion process. Progress in Natural Science: Materials International, 26 (6), 650–656. doi: https://doi.org/10.1016/j.pnsc.2016.12.005
30. Jafarzadeh, H., Barzegar, S., Babaei, A. (2014). Analysis of Deformation Behavior in Backward–Radial–Forward Extrusion Process. Transactions of the Indian Institute of Metals, 68 (2), 191–199. doi: https://doi.org/10.1007/s12666-014-0441-4
31. Hrudkina, N., Aliieva, L., Markov, O., Malii, K., Sukhovirska, L., Kuznetsov, M. (2020). Predicting the shape formation of parts with a flange and an axial protrusion in the process of combined aligned radial-direct extrusion. Eastern-European Journal of Enterprise Technologies, 5 (1 (107)), 110–117. doi: https://doi.org/10.15587/1729-4061.2020.212018
32. Hrudkina, N. (2021). Process modeling of sequential radial-direct extrusion using curved triangular kinematic module. FME Transactions, 49 (1), 56–63. doi: https://doi.org/10.5937/fme2101056h