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MODELING THE PROCESS OF RADIAL-DIRECT EXTRUSION WITH EXPANSION USING A TRIANGULAR KINEMATIC MODULE

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Запропоновано у якості осьового використовувати розроблений трикутний кінематичний модуль 2а з криволінійною похилою межею, що дозволяє описувати характер течії металу в зоні розвороту до радіального видавлювання. На основі енергетичного методу отримано величини потужності сил деформування всередині побудованого кінематичного модуля 2а, потужності сил тертя на межі контакту заготовки з інструментом та потужності сил зрізу із суміжними кінематичними модулями. В результаті отримано аналітичний вираз приведеного тиску деформування осьового трикутного кінематичного модуля 2а з похилою межею, форма якої залежить від параметра α. Проаналізовано можливості оптимізації приведеного тиску деформування за параметром α за різних співвідношень геометричних параметрів модуля та умов тертя. З урахуванням форми суміжного кінематичного модуля 3а запропоновано використання отриманих залежностей приведеного тиску для розрахунків силових режимів процесів комбінованого послідовного радіально-поздовжнього видавлювання з розвиненою радіальною складовою течії металу.

Здійснено порівняльний аналіз розрахункових схем ЕМ-2а з розробленим осьовим трикутним кінематичним модулем 2а та ЕМ-2 із використанням осьового прямокутного кінематичного модуля 2 та експериментальними даними моделювання процесу комбінованого радіально-прямого видавлювання з роздачею. Перевищення даних за зусиллям деформування, отриманих на основі схеми ЕМ-2а (із розробленим трикутним модулем з криволінійною межею 2а) та ЕМ-2, від експериментально отриманих складає 12–15 % та 15–20 % відповідно. Це підтверджує раціональність використання розробленого осьового кінематичного модуля 2а з криволінійною межею замість осьового прямокутного кінематичного модуля при моделюванні процесів послідовного радіально-прямого видавлювання з розвиненою радіальною складовою течії металу.

Отримані залежності приведеного тиску деформування модуля 2а можуть бути вбудовані у інші розрахункові схеми процесів послідовного радіально-поздовжнього видавлювання. Завдяки цьому зниження отриманих силових параметрів процесу може становити 7–10 % по відношенню до схем, що містять осьовий прямокутний кінематичний модуль 2

Ключові слова: моделювання процесів комбінованого видавлювання, кінематичний модуль, енергетичний метод, процес деформування

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1. Introduction

Under current conditions, the role of effective resource-saving methods of metal forming, such as cold bulk stamping, is increasing. This is primarily due to the decrease in the indicators of energy and labor intensity of production and the increase in the metal utilization coefficient, as well as the increase in its mechanical properties. A steady trend towards increasing the production of precise blanks and expanding the range of stamped parts and materials using cold extrusion processes requires in-depth research and evaluation of the capabilities of these processes [1, 2]. The most common methods of cold extrusion at present are the techniques of longitudinal (reverse and direct) and traverse (radial and lateral) extrusion, as well as their combinations [3–5]. Components of complex shape should be extruded by using the combined (joint or sequential) extrusion, which has sufficient advantages over simple deformation schemes [4, 5]. However, there are a series of problems related, first of all, to the issues of metal plasticity under conditions of a complex stressed-strained state. In addition, there are relevant issues of assessing the power regimes of deformation and predicting shape-change and defect-formation [4, 6, 7]. Resolving these issues would help expand the possibilities of the combined cold extrusion processes and their active implementation in production.

2. Literature review and problem statement

In recent years, many researchers have shown interest in the processes of combined longitudinal-transverse extrusion. However, studies mainly include an analysis of force and deformation regimes of these processes performed experimentally or by finite-elements methods (FEM) and, therefore, are limited.

A series of works study the force parameters and shape-changes in combined extrusion processes. In [8], based on a finite element method, employing the ABAQUS software (ABAQUS Inc., USA), the influence of geometric parameters and friction conditions in the process of direct-inverse-radial extrusion was analyzed. Paper [9] studied the force parameters and shape change of hollow parts during combined extrusion based on simulations using Deform-2D (Scientific Forming Technologies Corporation (SFTC), USA). However, there are no analytical dependences of the force regimes and increments of semi-finished products, which limits the application of the reported results. Work [10] conducted a comparative analysis of the theoretically (based on the upper estimate using rigid triangular elements) and experimentally obtained data on the force parameters of the process and the shape change of blanks. Studies [11, 12] applied an upper estimate method (hard blocks) to confirm the emergence of a dead zone in the reversal zone and to obtain estimates of the energy parameters of the lateral extrusion process. However, the proposed modification of the energy method is used to solve flat non-axisymmetric problems. Paper [13] investigated the effect of structural parameters and friction conditions on the deformation forces in the process of consistent radial-longitudinal extrusion, but no analytical dependences of energy-force parameters were obtained. Radial direct extrusion [14] is an effective method for producing large diameter pipes from small cylindrical blanks. At the same time, the use of additional hydrostatic pressure at the deformation site and the introduction of the sign-alternating character of deformation ensures, along with a very low loss of plasticity, a significant increase in strength. However, the issues of calculating the increased energy costs and loads on the tool in the cited study remained unresolved.

To obtain an assessment of force regimes and shape changes in the processes of combined radial-longitudinal extrusion, an effective theoretical method is the energy method, in particular, a power balance method [15]. As part of its application, special attention should be paid to expanding the base of unified modules of complex shape (triangular or trapezoidal with curvilinear boundaries [16]). That would make it possible to build the estimation schemes of a deformation process taking into consideration the relevant (to experimental data) boundaries of the metal flow interface within a semi-finished product, as well as the boundaries of the contact between a tool and a workpiece [16, 17]. At the same time, the possibility to obtain analytical dependences of the reduced pressure makes it possible to optimize the force mode, determine the optimal configuration of the tool and, for the case of combined joint extrusion, to predict the shape change and defect formation in a component [18].

However, the techniques of building analytical solutions, reported in [17, 18] relate to the kinematic modules of the trapezoidal shape. The axial triangular kinematic modules with curvilinear boundaries must be developed, which describe the line of the flow interface when moving from the longitudinal to the transverse (radial) flow.

Thus, the increasing complexity of the tool geometry and the character of a metal flow inside a blank requires the development of new kinematic modules of triangular and trapezoidal shapes with different types of borders.

3. The aim and objectives of the study

The aim of this study is to expand the base of unified kinematic modules by developing a new axial triangular kinematic module with a curvilinear boundary, allowing more complete and accurate modeling of the processes of combined sequential radial-longitudinal extrusion.

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

– to develop an axial triangular kinematic module with a curvilinear boundary, making it possible to describe the boundary of a metal flow interface in the reversal zone to the radial extrusion;

– to analyze a possibility to integrate the developed axial triangular kinematic module into the estimation schemes of the combined sequential radial-longitudinal extrusion process;

– to conduct a comparative analysis of the force parameters of the radial-direct extrusion process with expansion, obtained theoretically (using the developed module and based on previously used axial modules), with experimentally obtained data.

4. Calculating the reduced pressure of an axial triangular kinematic module with a curvilinear boundary

4. 1. Development of an axial triangular kinematic module with a curvilinear border

For a theoretical analysis of axisymmetric cold extrusion processes, modifications of the energy method [19–22] are used. As part of the application of a power balance method, the deformable volume of the workpiece is split into kinematic modules with corresponding kinematically possible velocity fields (KPVF). Calculating the power of plastic deformation forces inside the kinematic module, the forces of cutting with the adjacent modules and friction forces on the surface of the tool make it possible to obtain the reduced pressure in an analytical form [20, 21]. Such calculations are required by the triangular modules with a sloping boundary of a curvilinear or straight shape [23, 24] or curvilinear modules of different configurations as components of schemes of combined sequential longitudinal-radial extrusion with expansion. At the same time, when selecting the shape and building the kinematic module KPVF, it is necessary to ensure not only the correspondence of its boundaries to experimental data but also the possibility of obtaining analytical expressions of the reduced pressure [17, 18, 23, 24]. That would make it possible to take full advantage of the energy method and optimize the force mode of the deformation process for the selected variable parameters. A new triangular module 2a with a curvilinear boundary (Fig. 1) is proposed as an axial kinematic module describing the transition from direct to radial flow.

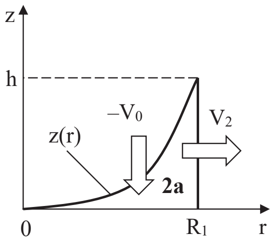

Fig. 1. The axial triangular kinematic module 2a with a curvilinear border

A given module can be used with the kinematic module bordering the sloping boundary, adjacent to the right, of different configurations, and rigid. At the same time, the shape of the sloping face reflects the character of a metal flow when reversing from direct to radial extrusion during the deformation of blanks by successive combined extrusion with expansion.

Consider a KPVF of the kinematic module 2a in the following form:

$$\begin{cases} V_z = -\dfrac{\alpha V_0}{h} z, \\ V_r = \dfrac{V_0}{2h} \cdot \dfrac{R_1^2(1-\alpha)+\alpha r^2}{r}. \end{cases} \tag{1}$$

The shape of the curve, which describes the curvilinear upper boundary, is determined from the continuity conditions of the normal speed component on the surface of the cut on either side of it and the conditions of metal incompressibility. If the boundary is defined as some continuous function between the curvilinear rigid module 1 and the proposed triangular module 2a, the continuity condition takes the following form:

$$[\Delta V_z]\mathrm{d}r - [\Delta V_r]\mathrm{d}z = 0, \tag{2}$$

where $[\Delta V_z]$ and $[\Delta V_r]$ are the magnitudes of a speed gap at the border between the kinematic modules 1 and 2a.

Upon solving the appropriate differential equation (2) and by using boundary conditions in the form $z(0)=0$ and $z(R_1)=h$, we obtain the curve in the final form:

$$z(r) = \frac{hr^2}{R_1^2(1-\alpha)+\alpha r^2}, \tag{3}$$

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

Calculations during the modeling of the processes of sequential radial-direct extrusion with expansion are carried out in dimensionless quantities, attributed to the outer radius of matrix R_2. Thus, in the following calculations, we use $\bar{R}_1 = R_1 / R_2$ and $\bar{h} = h / R_2$. The curve configuration, depending on the α parameter, makes it possible to describe a kinematic module with a convex or concave sloping boundary and then use the α parameter as an optimization parameter (Fig. 2). This would make it possible to take full advantage of the energy method's capabilities in terms of obtaining a minimum of the magnitudes of power and the deformation reduced pressure.

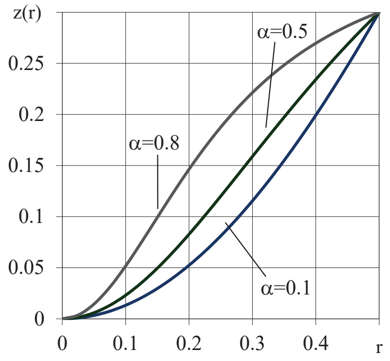

Fig. 2. Configuration $z = z(r)$ depending on the α parameter at $\bar{R}_1 = 0.5$ and $\bar{h} = 0.3$

Using expressions (1) and (3), we obtain the magnitude of the power of the deformation forces in the analytic form:

$$N_{\partial 2a} = \frac{2A\pi\sigma_S V_0}{\alpha\sqrt{3}} \left[\begin{array}{l} \sqrt{3}\ln 3 - \sqrt{3} + \dfrac{\sqrt{3}}{1-B^2} - \\ -\dfrac{3}{2}\ln\left|\dfrac{1+B}{1-B}\right| - \sqrt{3}\ln\left|\dfrac{\sqrt{3}B-3}{\sqrt{3}B+1}\right| \end{array} \right], \tag{4}$$

where

$$A = \frac{R_1^2(1-\alpha)}{\sqrt{3}},$$

$$B = \frac{\sqrt{(1-\alpha)^2 + 3\alpha^2} + \alpha - 1}{\alpha\sqrt{3}}.$$

A given kinematic module 2a can be combined exclusively with an upper rigid module 1 ($V_z=-V_0$, $V_r=0$), so, considering (2), the magnitude of the power of the cutting forces takes the form:

$$N_{c1\_2a} = \frac{\pi\sigma_S R_1 h V_0}{\sqrt{3}} \left[\begin{array}{l} \dfrac{R_1^2(3-2\alpha)}{3h^2} + \dfrac{1}{2C\alpha} \times \\ \times \operatorname{arctg} C + \dfrac{(1-\alpha)(2\alpha-1)}{2\alpha} \end{array} \right], \tag{5}$$

where

$$C = \sqrt{\frac{\alpha}{1-\alpha}}.$$

The magnitude of the power of friction forces with the tool takes the form:

$$N_{t2a} = \frac{2\pi\sigma_S \mu_S R_1^3 V_0}{3\sqrt{3}h}(3-2\alpha). \tag{6}$$

The proposed triangular curvilinear module 2a is internal, so consider it in a combination with the right adjacent module of type 3a (Fig. 3). In subsequent calculations, we assume the speed at the boundary of entry to module 3a takes the form $V_2 = V_0 R_1 / (2h)$.

The magnitude of the power of cutting forces between modules 2a and 3a takes the form:

$$N_{c2a\_3a} = \frac{\alpha\pi\sigma_S R_1 h}{\sqrt{3}} V_0. \tag{7}$$

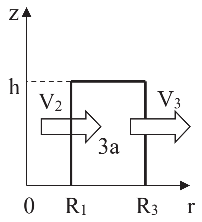

Fig. 3. Configuration of the adjacent kinematic module 3a

In terms of studying the possibility of using the α parameter as a variable, it is necessary to consider the magnitude of the reduced pressure, taking into consideration the power of deformation forces, cutting forces, and friction forces, for the combination of module 2a and module 3a. Considering (4) to (7), examine the reduced pressure magnitude in the form:

$$\bar{p}_{2a\_3a}=\frac{N_{\partial 2a}+N_{c1\_2a}+N_{t2a}+N_{c2a\_3a}}{\pi\sigma_s V_0 R_1^2}. \qquad (8)$$

Thus, all the components of the combination of these modules, depending on the α parameter, have been taken into consideration.

4. 2. Analysis of the magnitude of the reduced pressure of the axial triangular kinematic module with a curvilinear boundary

We shall analyze the character of change in the optimal value of variable parameters at different ratios of the geometric parameters of the deformation process and friction conditions (Fig. 4). The character of the reduced pressure curves, according to formula (8), under different friction conditions is similar with the presence of a minimum point, which indicates the possibility of optimization for the α parameter.

At the same time, the deterioration of friction conditions leads to a shift towards an increase in the optimal value of α. However, for the conditions of friction typical of cold extrusion in the range from $\mu_S=0.08$ to $\mu_S=0.16$, this change is insignificant and corresponds to the limits from 0.87 to 0.9 (Fig. 4).

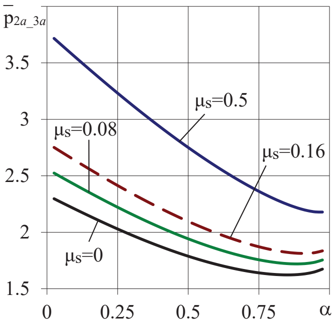

Fig. 4. Dependences of reduced pressure $\bar{p}_{2a\_3a}$ on the α parameter at $\bar{R}_1=0.5$, $\bar{h}=0.2$ and different friction conditions

We shall investigate the effect of the thickness of a flange area and the punch radius on the optimal value of α based on formula (8) (Fig. 5). The character of the resulting curves at different geometric ratios is similar with the presence of a minimum point. As a primary dependence, to be more informative, consider the line at $\bar{R}_1=0.5$, $\bar{h}=0.2$ (solid line). Reducing the relative thickness of the flange area $\bar{h}$ results in an increase in the magnitude of the deformation reduced pressure and in a shift, towards growth, of the optimal value of the α parameter (blue dotted lines).

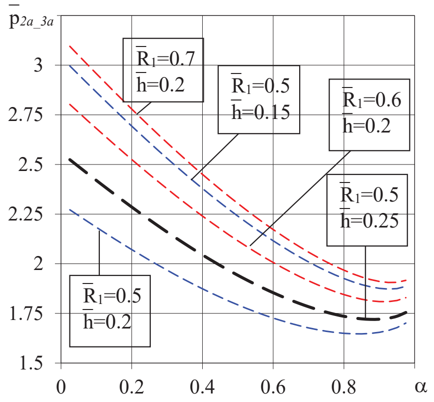

Fig. 5. Dependences of reduced pressure $\bar{p}_{2a\_3a}$ on the α parameter when $\mu_S=0.08$ at different geometrical ratios

Reducing the relative radius of an active deforming tool $\bar{R}_1$ at a fixed thickness of the flange zone also increases the magnitude of the optimal value of parameter α. However, with these geometric ratios, a change in the optimal parameter is insignificant and varies from 0.81 to 0.93 under friction conditions $\mu_S=0.08$.

Thus, the developed axial triangular kinematic module 2a with a curvilinear boundary can be used in the general estimation schemes of the longitudinal extrusion processes with a possibility to optimize for parameter α.

5. Comparative analysis of theoretical and experimental data on the force mode of the combined radial-direct extrusion process with expansion

In order to test a possibility to embed into general estimation schemes, we conducted an experimental study into the extrusion of hollow components using the combined radial-direct extrusion with expansion (Fig. 6). The hollow components with an external diameter of 28 mm and 24 mm were obtained, manufactured during the radial-direct extrusion from aluminum alloys and copper M1. At the same time, the choice, as an adjacent one, of the kinematic module 3a makes it possible to use the results in form (8) for the developed radial flow. The assessment of the stressed-strained state of the workpiece made from the aluminum alloy AD31 in the process of deformations, obtained by using FEM, as well as the experimental data, are given in work [16]. At the same time, the character of the distribution of stress intensity and deformation in the deformed blank allows us to argue about the rationality of considering the developed kinematic module 2a as an axial one.

We acquired experimental data on the effort of the deformation of a blank made from the aluminum alloy AD1 at R_1=7.5 mm, R_3=12 mm, R_2=14 mm, and the initial height of the blank H_0=50 mm. At the same time, the thickness of the flange zone h ranged from 2.2 mm to 5.3 mm, the full working cycle of the punch was 43 mm. A comparative analysis was performed involving the theoretically calculated values based on two estimation schemes: including an elementary axial rectangular module 2 (EM-2) and including the developed axial triangular module 2a (EM-2a). The hardening curve of the material AD1 is approximated by the demonstration function

$\sigma_s = 138.4 \cdot e^{0.218}$ MPa, and the average intensity of the accumulated deformation was equated to the reduced deformation pressure, the friction factor value is equal to $\mu_S = 0.04$. The deviation of data derived from the estimation scheme EM-2a (Fig. 7, solid line) and EM-2 (Fig. 7, dotted line) from those experimentally acquired (Fig. 7, points), is, respectively, 15–20 % and 12–15 %.

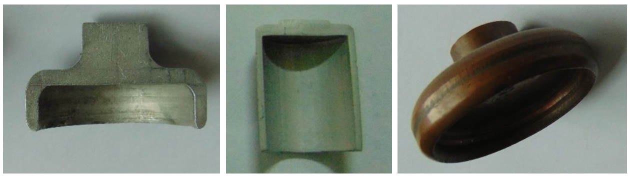

Fig. 6. Hollow components obtained by the radial-direct extrusion with expansion

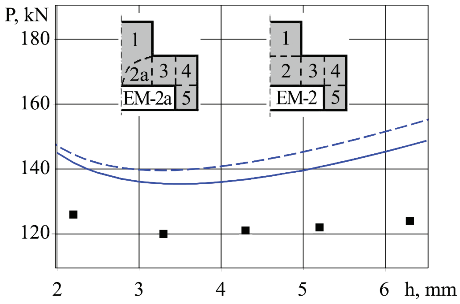

Fig. 7. Comparison of results from the theoretical and experimental studies into the manufacture of hollow components made from AD1 using radial-direct extrusion

Compare the reduced pressure for the developed kinematic module 2a (EM-2a) taking into consideration components (8) and for elementary module 2 $\overline{p}_{2\_3a}$ (EM-2) taking into consideration a part of the components from the previously developed process scheme [16]. These values are derived considering the power of deformation forces, friction forces, as well as cutting forces, on surfaces with adjacent modules 1 and 3 (Fig. 8). The comparative analysis of the reduced pressure $\overline{p}_{2a\_3a}$ (solid lines) and $\overline{p}_{2\_3a}$ (dotted lines) at $\overline{R}_1 = 0.5$ and $\mu_S = 0.04$ indicates the possibility of optimization for the parameter α for all ratios of geometric parameters. At the same time, the overestimation of the magnitude of the reduced pressure when using module 2 compared to using the proposed module 2a can reach 7–10 %, which indicates the rationality of its application.

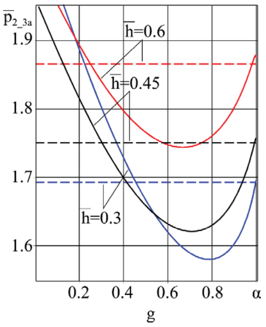

Fig. 8. Comparative analysis of reduced pressure $\overline{p}_{2a\_3a}$ (solid lines) and $\overline{p}_{2\_3a}$ (dotted lines) at $\overline{R}_1 = 0.5$ and $\mu_S = 0.04$

Thus, the developed axial triangular kinematic module 2a can be recommended as the basic one in the estimation schemes of the processes of combined sequential radial-longitudinal extrusion with the developed radial component of the flow.

6. Discussion of results of the triangular module's integration into the estimation schemes of the radial-direct extrusion process with expansion

The triangular kinematic module 2a with a curvilinear sloping boundary, proposed as an axial one (Fig. 1), makes it possible to describe the character of the flow of metal in the reversal zone to radial extrusion. The resulting analytical expression for the reduced deformation pressure of the axial triangular kinematic module 2a with a sloping boundary, according to (4) to (8), can be used in general calculation schemes. An analysis of the behavior of the reduced pressure function $\overline{p}_{2a\_3a}$ confirms the possibilities of optimizing a given quantity for parameter α at different ratios of the geometric parameters of the module and friction conditions. We have performed a comparative analysis of theoretical estimations in line with the scheme EM-2a (with the presence of the axial triangular kinematic module 2a considering the components (8)) and EM-2 (with the presence of the axial rectangular kinematic module 2) and experimental data on the force mode of the process of combined radial-direct extrusion with expansion. The data on the deformation effort, obtained from the scheme EM-2a and EM-2, exceed those experimentally acquired by 12–15 % and 15–20 %, respectively (Fig. 7). Thus, the rationality has been confirmed to use the developed axial kinematic module 2a with a curvilinear boundary instead of the axial rectangular kinematic module in the simulation of processes of sequential radial-direct extrusion with the developed radial component of metal flow. The resulting dependences of the deformation reduced pressure of module 2a in the form (4) to (8) can be built into other estimation schemes of successive radial-longitudinal extrusion processes. Such processes include processes with a developed radial flow (the presence of an adjacent kinematic module in the form of 3a) up to the degeneration of the kinematic module 1 in the triangular one. At the same time, the reduction in the estimated force parameters of the process can reach 7–10 % relative to the schemes containing the axial rectangular kinematic module 2.

It is promising to develop new curvilinear kinematic modules of different configurations, as well as additional research into the integration of the developed kinematic triangular module 2a into more complex calculation schemes of combined extrusion processes.

7. Conclusions

1. As an alternative to existing axial kinematic modules with a parallel flow describing the reversal of metal from the direct to radial flow, an axial triangular kinematic module 2a has been developed. A given kinematic module 2a makes it possible to describe the shape of the boundary of the metal flow interface in the reversal zone to the radial extrusion, based on the continuity condition and the boundary conditions, in the form of the α parameter function. The configuration of the curve depending on the α parameter allows us to describe the kinematic module 2a with both a convex and a concave inclined boundary and in the future use the α parameter as an optimization parameter.

2. We have analyzed a possibility to optimize the magnitude of reduced pressure $\overline{p}_{2a\_3a}$ for parameter α, responsible for the sloping boundary shape, as well as the impact exerted on the optimal value of parameter α by different geometric ratios within the scheme and friction conditions. Thus, the integration of the developed axial triangular kinematic module

into the calculation schemes of the process of combined sequential radial-longitudinal extrusion has been investigated.

3. We have performed a comparative analysis of the force parameters of the radial-direct extrusion process with expansion, obtained theoretically using the developed module 2a (the EM-2a scheme) and on the basis of previously used axial modules (the EM-2 scheme), with those experimentally acquired. The smallest deviation from the experimental data corresponds to the EM-2a scheme (it is 12–15 %), which confirms the rationality of using the developed axial kinematic module 2a with a curvilinear boundary. The resulting dependences of the reduced pressure of the deformation of module 2a can be built into other estimation schemes of successive radial-longitudinal extrusion processes. As a result, the reduction in the estimated force parameters of the process could reach 7–10 % relative to the schemes containing the axial rectangular kinematic module 2.

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