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THE DEVELOPMENT OF TRIANGULAR KINEMATIC MODULE TO CALCULATE THE DEFORMATION PRESSURE IN THE EXTRUSION PROCESSES

The article presents the universal kinematic module developed on the basis of the energy upper bound method, designed for use in mathematical simulations of combined processes of cold forging. In particular, this module can be used for force regime simulating and tool loads analyzing at radial-forward extrusion of hollow products with blind hole of continuous workpieces to describe deformation zones during metal flow to the center and turn zones from radial flow to backward one. The kinematically possible velocity field for convex curvilinear (parabolic) triangular module and the equations of its parabolic inclined boundary are given. Analytical dependencies for power of deformation forces, friction and shear at the boundaries of the module, as well as for the reduced pressure in a parametric form are obtained. The developed curvilinear kinematic module, the use of which makes it possible to increase the efficiency of the upper bound method for studying the processes of combined extrusion, has been tested and described. It is shown that value of reduced pressure for the curvilinear turn module is most affected by the relative thickness of the flange, its radius, the thickness of the wall of the tubular workpiece, as well as friction conditions. The possibility of correct using of curvilinear triangular module for the analysis of complex schemes of processes with several zones is demonstrated. The simulation for calculation schemes of radial-forward workpiece extrusion with variable flange height was carried out. It has been determined that the developed curvilinear triangular module due to the reducing the value of the velocity jump at its boundaries, makes it possible to reduce the upper estimate of the tool loads in comparison with the variants of simulations that were previously based on rectangular modules.

Key words: *energy upper bound method, curvilinear kinematic module, modular approach, radial-forward extrusion, tool load, simulation.*

In the range of forged workpieces, the significant volume is occupied by hollow parts with blind hole such as cups and sleeves, which are usually obtained using longitudinal backward and forward extrusion. Typical for longitudinal extrusion processes limitations are associated with the limiting tool loads and the losing tool life, which forces to introduce several serial operations with lower degrees of deformation and additional calibration operations of workpieces before extrusion respectively.

The combined extrusion methods including traditional longitudinal extrusion schemes with transverse (radial and cross side) extrusion schemes can serve as promising methods for stamping hollow parts. Combined extrusion processes can significantly reduce the energy-power parameters of deformation and manufacturing time, improve quality of parts and life of the stamping tool.

The widespread using of combined extrusion, especially in the production of hollow parts, is limited by the development of calculation apparatus for designing technological deformation modes, as well as insufficient knowledge of the stress-strain state of workpieces during deformation using new methods of sequential combined extrusion.

Using modular approach makes it possible to simplify the creating mathematical simulations for complex combined schemes by use of already existing set of tested and implemented modules. This approach requires further research to create universal kinematic modules (including ones with curved surfaces), which allow to more adequately describe the kinematics of metal flow in the deformation zone for combined processes due to the choice of velocity fields of more complex configurations and the analysis of which can be performed separately from other related modules.

For cold deformation technologies high unit and total deformation forces are characteristic limitations that reduce the stability of the process and the life time of the stamping tool [1, 2]. In the existing deformation methods, that remove these limitations, the reduction of loads on the tool occurs due to the creation of different sign scheme of the stress-strain state [3, 4], expansion [4, 5], decreasing contact area of tool with workpiece [1, 6], and also with the help of additional combined force and kinematic effects on the workpiece [5, 7].

Methods of combined extrusion, which combine schemes of transverse and longitudinal (backward and forward) extrusion, make it possible to obtain parts of the most complex shapes by just one operation [3, 5, 8]. The feature of the methods of sequential combined extrusion is that the direction of metal flow during the deformation process changes from radial (flow with expansion) to forward one. According to the results of the analysis of the stress-strain state of the workpieces, it was established that the process is limited by the action of tool force loads [8].

According to the results of experimental studies, the authors of works [2–5] claim that in the case of forward extrusion with expansion the deformation force is reduced by 16–40 % compared to longitudinal extrusion. The greatest decreasing deformation forces due to the greatest degree of freedom of the metal flow can be achieved if the turning flow of the workpiece material occurs immediately after the metal leaves the volume of the workpiece simultaneously from the side surface of the lower zone of the workpiece and the lower end surface or from direction of the lower zone of side surface. In the process of free (without die) extrusion deep hollow containers are produced, the specific force in this case decreases by 1.5–1.8 times [5, 9]. Free forming in the methods discussed above does not allow obtaining the required shape and dimensions of parts, therefore, for these semi-finished products, drawing on mandrel or direct extrusion are further provided.

Due to the direction of the metal flow into the radial cavity at the beginning of the process, it is possible to increase the outer diameter of the cup. Further, in the turn zone, the flow of the workpiece material will occur in the forward (predominantly) or backward direction. Further development of extrusion methods with intensive expansion led to the emergence of sequential combined radial-forward extrusion (Fig. 1). In this process the developed radial flow of the material contributes to significant increasing in the transverse dimensions of the hollow part [2, 8].

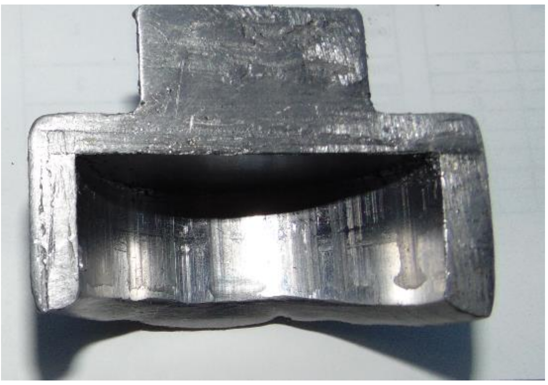


Fig. 1. The part obtained by sequential radial-forward extrusion

At present the most widespread methods for studying the processes of volumetric deformation among the traditional theoretical ones are the analytical energy method of power balance, the upper bound method (UBM) and the finite element method. The main advantages of analytical methods of theoretical analysis include the possibility of developing experimentally observed calculation schemes of metal flow pictures and obtaining analysis results in the form of engineering calculation formulas.

The modular approach used and developed in the Donbass State Engineering Academy (DSEA) can serve to increase the efficiency of the energy method. It is based on the selection and use of pre-developed kinematically possible velocity fields (KPVF) in the form of separate areas [1] or kinematic modules [5, 10–12], which are designed to more accurately describe various prevailing deformation schemes in plastic zones. Most often, rectangular or quadrangular (rhombic) and triangular modules are used as elementary zones. Their using does not cause problems when obtaining solution, as well as when embedding them in the construction of discontinuous velocity field, but for fields with more complex configuration it is necessary to use modules of complex shapes, including those with curvilinear generatrixes. Therefore, design of new kinematic modules with non-linear geometric characteristics, checking the possibility of using them as components for models of combined radial-forward extrusion processes and determining the limits of parameters that provide acceptable level of tool loads of these processes is the relevant task.

The purpose of the work is to expand the possibilities of the energy method for the theoretical analysis of combined processes of radial-forward extrusion through the creating and using of universal curvilinear kinematic modules.

Calculation schemes of radial-forward extrusion processes are characterized by the presence of the turn area (zone 5) in the deformation zone, where the metal changes the radial direction of the flow to the longitudinal one. For this zone, it is advisable to use curvilinear triangular module for description (Fig. 2). We solve the problem by analogy with the solution for the triangular module used to describe the metal flow to the center of the tubular workpiece [13]. The difference is that in this case, the flow of metal occurs in the backward direction – from the center with turning the direction from radial to forward one. In addition, in this problem, one of the sides of the module is the surface contacting with the die, that is, instead of the power of shear forces, it is necessary to calculate the power of friction forces on this surface.

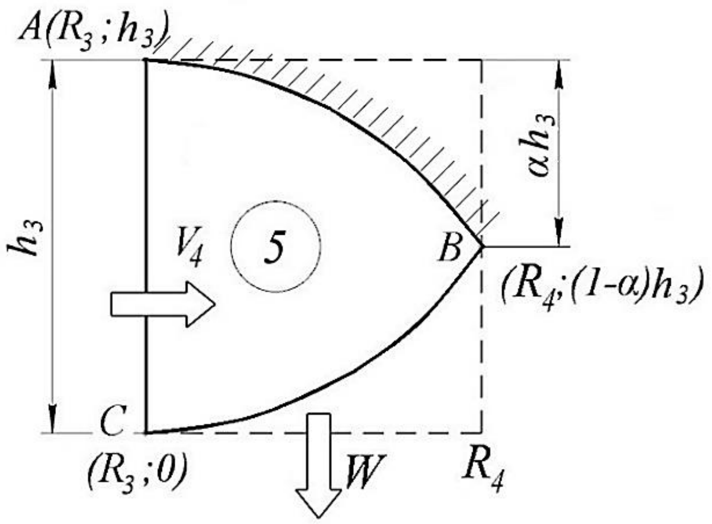


Fig. 2. Scheme of metal flow in the angular curvilinear module

It was found that in the reduction problem, the kinematic field in the form of curvilinear triangle gives the smallest value of the reduced pressure [13]. Thus, a convex (parabolic) triangular module was chosen as the most suitable for solving the problem of radial-forward extrusion with expansion.

We write KPVF for the triangular curvilinear module 5 as follows:

$$\begin{cases} V_{z5} = -\alpha \cdot W; \\ V_{r5} = \dfrac{V_3 \cdot R_3}{r}, \end{cases} \tag{1}$$

where $W = \frac{2 \cdot R_3 \cdot h_3}{R_4{}^2 - R_3{}^2} \cdot V_3$.

Taking into account the velocity field represented by these formulas and the condition of continuity of the normal velocity component, the equation for parabolic inclined boundary between the zones is obtained.

Equation of curvilinear boundaries of module 5:

$$Z'_{AB}=\frac{-\alpha\cdot W}{\frac{V_3\cdot R_3}{r}}=-\frac{\alpha\cdot W}{V_3}\cdot\frac{r}{R_3};\quad Z_{AB}=-\frac{\alpha\cdot W}{V_3}\cdot\frac{r^2}{2\cdot R_3}+C_1;\quad \Leftarrow A(R_3;h_3);$$

$$C_1=h_3+\frac{\alpha\cdot W}{V_3}\cdot\frac{R_3}{2};\quad Z_{AB}=\left(1-\alpha\cdot\frac{r^2-R_3{}^2}{R_4{}^2-R_3{}^2}\right)\cdot h_3; \tag{2}$$

$$Z'_{BC}=\frac{-\alpha\cdot W+W}{\frac{V_3\cdot R_3}{r}}=\frac{W\cdot(1-\alpha)\cdot r}{V_3\cdot R_3};\quad Z_{BC}=\frac{W\cdot(1-\alpha)\cdot r^2}{2\cdot V_3\cdot R_3}+C_2;\quad \Leftarrow C(R_3;0);$$

$$Z_{AB}=(1-\alpha)\cdot\frac{r^2\cdot R_3{}^2}{R_4{}^2-R_3{}^2}\cdot h_3. \tag{3}$$

For module 5, where the flow is turned from radial to forward, based on the accepted KPVF, the friction and shear powers are calculated using the known formulas [1]:

$$N_m=\iint\limits_{F_K}\tau_\kappa\cdot|V_\kappa|dF_k;\quad N_c=\iint\limits_{F_c}\tau_s\cdot|V_c|dF_c.$$

The value of the velocity discontinuity at the boundary AB is:

$$|V_z|=-\alpha\cdot C\cdot V_3;\quad C=\frac{2\cdot R_3\cdot h_3}{R_4{}^2-R_3{}^2}.$$

The power of friction forces on the surface AB is calculated as:

$$N_{C_{AB}}=\frac{\sigma_s}{\sqrt{3}}\cdot\frac{2\cdot\mu_s}{\sqrt{3}}\cdot 2\cdot\pi\cdot\int\limits_{R_3}^{R_4}\left|\frac{|V_z|}{f'_{AB}(r)}\cdot r\cdot(1-f'_{AB}(r))^2\right|dr=$$
$$=\frac{2\cdot\pi\cdot\sigma_s}{\sqrt{3}}\cdot\frac{2\cdot\mu}{\sqrt{3}}\cdot\int\limits_{R_3}^{R_4}\left|\frac{-\alpha\cdot C\cdot V_3}{\frac{\alpha\cdot C\cdot V_3}{R_3}}\cdot r\cdot\left(1+\left(\frac{-\alpha\cdot C\cdot}{R_3}\right)\right)^2 dr=\right| \tag{4}$$
$$=\frac{2\cdot\pi\cdot\sigma_s\cdot V_3}{\sqrt{3}}\cdot R_3\cdot\frac{2\cdot\mu_s}{\sqrt{3}}\cdot\left(R_4-R_3+\alpha^2\cdot C^2\cdot\frac{R_4{}^2-R_3{}^2}{3\cdot R_3{}^2}\right).$$

At the BC boundary, the value of the velocity discontinuity is:

$$|V_z|=-\alpha\cdot W+W=(1-\alpha)\cdot\frac{2\cdot R_3\cdot h_3}{R_4{}^2-R_3{}^2}\cdot V_3=(1-\alpha)\cdot C\cdot V_3;$$

$$N_{C_{BC}} = \frac{2\cdot\pi\cdot\sigma_s}{\sqrt{3}}\cdot\int_{R_3}^{R_4}\left|\frac{(1-\alpha)\cdot C\cdot V_3}{\frac{(1-\alpha)\cdot C}{R_3}\cdot r}\cdot r\cdot\left(1+\frac{(1-\alpha)\cdot C}{R_3}\cdot r\right)^2\right|dr = \tag{5}$$
$$= \frac{2\cdot\pi\cdot\sigma_s\cdot V_3\cdot R_3}{\sqrt{3}}\cdot\left(R_4 - R_3 + \frac{(1-\alpha)^2\cdot C^2}{R_3^2}\cdot\frac{R_4^2-R_3^2}{3}\right).$$

At the input speed V_4 according to the energy balance equation at known power of external active forces:

$$N_{\partial 5} = 2\cdot\pi\cdot R_3\cdot h_3\cdot\sigma_s\cdot V_4\cdot\overline{p}_5,$$

the reduced deformation pressure $\overline{p}_5$ is determined as the sum of components that take into account the plastic deformation of module 5, as well as the values of shear and friction on its boundaries:

$$\overline{p}_{cA-B} = \frac{1}{\sqrt{3}\cdot h_3}\cdot\frac{2\cdot\mu_s}{\sqrt{3}}\cdot\left(R_4 - R_3 + \alpha^2\cdot C^2\cdot\frac{R_4^2-R_3^2}{3\cdot R_3^2}\right); \tag{6}$$

$$\overline{p}_{c5-6} = \frac{1}{\sqrt{3}\cdot h_3}\cdot\left(R_4 - R_3 + \frac{(1-\alpha)^2\cdot C^2}{R_3^2}\cdot\frac{R_4^2-R_3^2}{3}\right). \tag{7}$$

To simplify the calculated dependencies for module 5, based on the results of calculating the rates of relative linear deformations, it is recommended to determine the highest absolute value of the rate $|\dot{\varepsilon}_{\max}|$ and use the linearized dependence of the type $\dot{\varepsilon}_i = 1{,}08\cdot|\dot{\varepsilon}_{\max}|$ [14, 15] to calculate the intensity of the strain rate in the zone. As a result, the following expression for the pressure of deformation forces was proposed:

$$\overline{p}_{d5} = \frac{2}{\sqrt{3}}\cdot\left[\left(\frac{\overline{R}_3^2}{\overline{R}_4^2-\overline{R}_3^2}+1\right)\cdot\ln\frac{\overline{R}_4}{\overline{R}_3}-\frac{1}{2}\right]. \tag{8}$$

The share of pressure that takes into account the shear on the boundary is [13]:

$$p_{c4-5} = \frac{2\cdot R_3\cdot h_3\cdot\alpha}{\sqrt{3}\cdot\left(R_4^2-R_3^2\right)}. \tag{9}$$

After calculating the powers of the deformation, shear and friction forces, substituting into the power energy balance equation:

$$p\cdot F\cdot V_0 = \sum N_{di} + \sum N_{fj} + \sum N_{sk},$$

where N_{di} – the power of deformation forces expended on forming,

N_{fj} – the power of friction forces,

N_{sk} – the power of shear force,

all the found values and reducing by factor $2 \cdot \pi \cdot \sigma_S \cdot V_4 \cdot h_3 \cdot R_3$, we obtained dependence for determining the reduced pressure (relative unit force):

$$\overline{p}_5 = \left[\begin{array}{l} \dfrac{2}{\sqrt{3}} \cdot \left[\left(\dfrac{R_3{}^2}{R_4{}^2 - R_3{}^2} + 1 \right) \cdot \ln \dfrac{R_4}{R_3} - \dfrac{1}{2} \right] + \dfrac{4 \cdot \mu_s}{\sqrt{3}} \cdot \dfrac{l_k}{R_4 - R_3} + \dfrac{2 \cdot R_3 \cdot h_3 \cdot \alpha}{\sqrt{3} \cdot \left(R_4{}^2 - R_3{}^2 \right)} + \\ + \dfrac{1}{\sqrt{3} \cdot h_3} \cdot \left[\left(1 + \dfrac{2 \cdot \mu_s}{\sqrt{3}} \right) \cdot \left(R_4 - R_3 \right) + \left(\dfrac{2 \cdot \mu_s}{\sqrt{3}} \cdot \alpha^2 + (1 - \alpha)^2 \right) \cdot \dfrac{4 \cdot h_3{}^2}{\left(R_4{}^2 - R_3{}^2 \right)^2} \cdot \dfrac{R_4{}^2 - R_3{}^2}{3} \right]. \end{array} \right] \tag{10}$$

Formula (12) was converted into dimensionless form, that is, related to the inner radius R_3, by dividing all geometric parameters by this radius:

$$\overline{p}_5 = \left[\begin{array}{l} \dfrac{2}{\sqrt{3}} \cdot \left[\left(\dfrac{1}{\overline{R}_4{}^2 - 1} + 1 \right) \cdot \ln \overline{R}_4 - \dfrac{1}{2} \right] + \dfrac{4 \cdot \mu_s}{\sqrt{3}} \cdot \dfrac{\bar{l}_k}{\overline{R}_4 - \overline{R}_3} + \dfrac{2 \cdot \cdot \bar{h}_3 \cdot \alpha}{\sqrt{3} \cdot \left(\overline{R}_4{}^2 - 1 \right)} + \\ + \dfrac{1}{\sqrt{3} \cdot \bar{h}_3} \cdot \left[\left(1 + \dfrac{2 \cdot \mu_s}{\sqrt{3}} \right) \cdot \left(\overline{R}_4 - 1 \right) + \left(\dfrac{2 \cdot \mu_s}{\sqrt{3}} \cdot \alpha^2 + (1 - \alpha)^2 \right) \cdot \dfrac{4 \cdot \bar{h}_3{}^2}{\left(\overline{R}_4{}^2 - 1 \right)^2} \cdot \dfrac{\overline{R}_4{}^2 - 1}{3} \right]. \end{array} \right] \tag{11}$$

For the convenience of analysis, we also introduce the parameter of the relative wall thickness of the hollow part s/h_3, where $s = R_4 - R_3$.

For curvilinear triangle, the position of the triangle point B is optimized. The optimal value of the parameter α is found from the condition of the minimum reduced pressure $\overline{p}_5$ ($\partial \overline{p}_5 / \partial \alpha$) in the form of calculation formula:

$$\alpha = \frac{\sqrt{3}}{2 \cdot \left(\sqrt{3} + 2 \cdot \mu_s \right)} \cdot \left(2 - \frac{3}{2} \cdot \overline{R}_3 \cdot \frac{\overline{R}_4{}^2 - \overline{R}_3{}^2}{\overline{R}_4{}^3 - \overline{R}_3{}^3} \right). \tag{12}$$

The graphic representation of the expression for optimal value of the parameter α is shown in Fig. 4. It can be seen that in the range of 0.45...0.55, the parameter α has minimum value. But if we deviate from the optimal value upwards, for example, to values α = 0.9…0.8, then the pressure increasing is insignificant (see Fig. 4). The practical use of module 5 follows from this statement. It can be applied to other deformation schemes in which the outer border of the parabolic shape can be the surface of the forming tool.

Based on the results of the calculations, plots of the dependence of the reduced pressure vs the geometric parameters and friction conditions of the metal deformation process in the turn zone of the metal flow from the radial to the direct direction were plotted (Fig. 5–7).

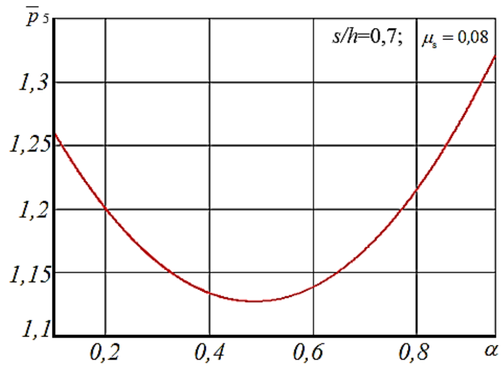


Fig. 4. Dependence of the reduced pressure vs the parameter α in the curvilinear turn module

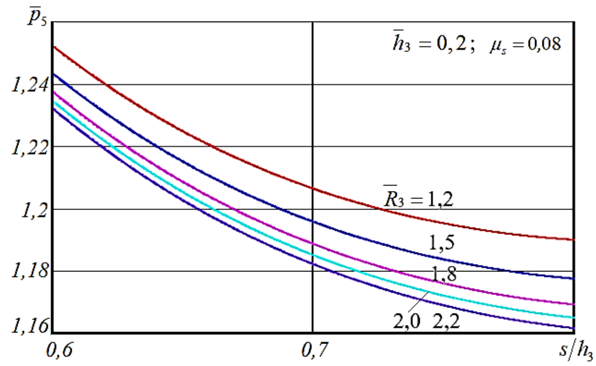


Fig. 5. Dependence of the reduced deformation pressure of the triangular module vs the relative parameter s/h_3

It has been established that the relative thickness of the flange $\bar{h}_3$, flange radius $\bar{R}_3$, parameter s/h_3, as well as the friction conditions expressed in terms of the friction coefficient μ have the greatest influence on the value of the reduced pressure $\bar{p}_5$. When decreasing the wall thickness of the tubular workpiece, the minimum values of the reduced pressure are characteristic of smaller values of the relative geometric parameter $\bar{h}_3$ (see Fig. 6).

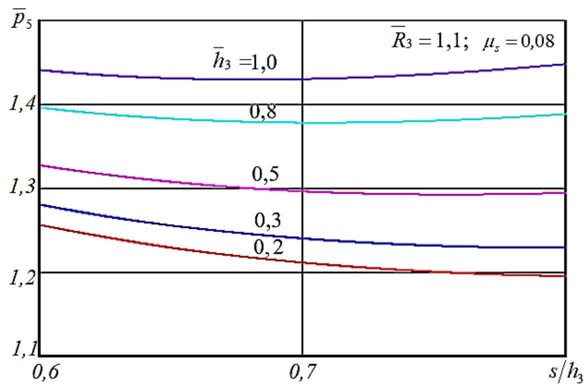


Fig. 6. Dependence of the reduced deformation pressure of the triangular module vs the relative parameter s/h_3 at variable height h_3

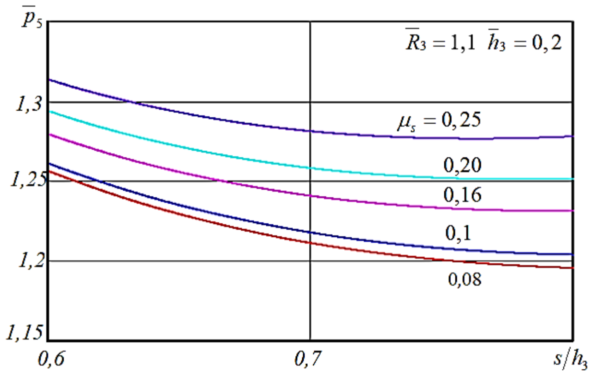


Fig. 7. Dependence of the reduced deformation pressure of the triangular module vs the relative parameter s/h_3 for different friction conditions

Reducing the relative radius of the flange $\bar{R}_3$ and increasing the friction coefficient μ leads to definite increasing the reduced flange extrusion pressure. With increasing the dimensionless geometric parameter $\bar{H}_1$, the reduced pressure increases intensively only at values of the friction coefficient close to the maximum (see Fig. 7).

Generalized calculation scheme for the process of sequential radial-forward extrusion with expansion with the curvilinear shape of kinematic module, close to the experimentally observed deformation field (the analysis of the flow picture was carried out according to installation experiments), are shown in Fig. 8.

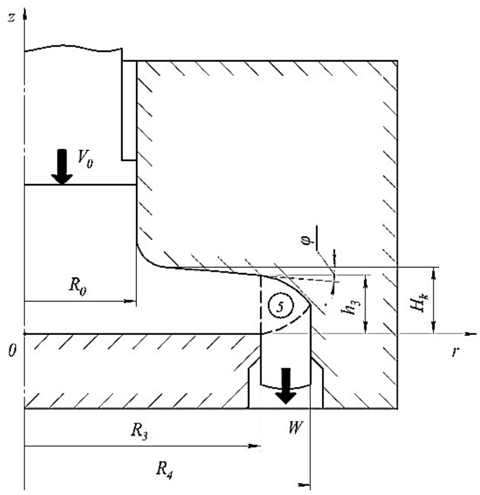
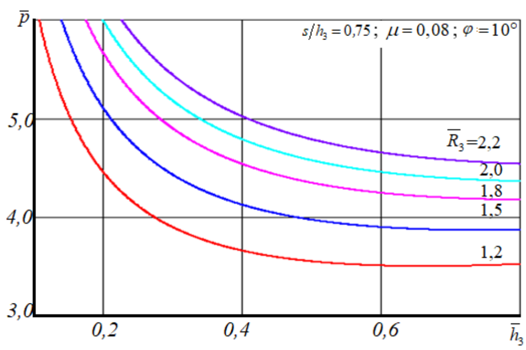


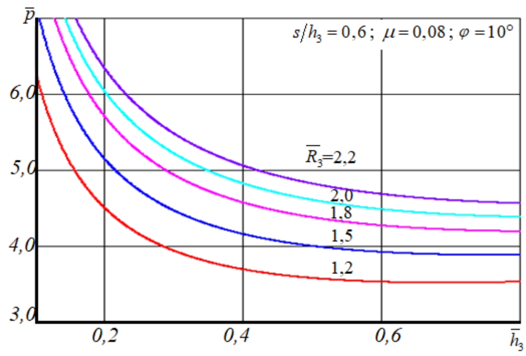
Fig. 8. Calculation scheme with curvilinear modules for the process of sequential radial-forward extrusion of hollow parts with flange of variable height

The analysis of the obtained dependence was carried out with the drawing plots shown in Fig. 9, in which such relative process parameters as the height h_3, the radius of the flange zone R_3 (the radius of the part cavity) and the ratio of the wall thickness of the part to the thickness of its bottom s/h are used as variables [16]. The effect of friction, as is known, is unambiguous; therefore, $\mu_s = 0.08$ was taken as the coefficient of friction, which is typical for cold extrusion processes.

If we consider the level of influence of the main parameters on the power mode of the process and the value of the reduced pressure, then we can see that the relative thickness of the wall of the hollow part s/h and the relative height of the flange cavity or, what is the same, thickness of the bottom of the part $\bar{h}$ have the greatest influence (see Fig. 9). On the effect in, the radius of the cavity of the part R_3 is in third place. In the general process at small values of h the effect is quite noticeable – the pressure $\bar{p}$ steadily increases with increasing $\bar{R}_3$. From the plots of the dependence of deformation pressures, taking into account s/h in the forward extrusion block (Fig. 10), it can be seen that the production of sleeve type parts with relatively thin walls requires significant energy values –up to $6\cdot\sigma_s$ and more [16]. The deformation pressure of combined extrusion is higher than the pressure of radial (centrifugal) extrusion by 1.5...2.1 times, depending on the size of the clearance for the forward flow of metal. But at $s/h = 0.5$ and more, the loads are quite acceptable. At the same time, the use of the optimal values of the specially introduced parameter α, which characterizes the geometry of the triangular module, makes it possible to prepare rational shape of the die and obtain significantly lower values of contact friction forces.



a



b

Fig. 9. Dependence of the pressure of sequential combined extrusion vs the parameter $\bar{h}_3$ for different values of the relative cavity radius $\bar{R}_3$ at relative thickness s/h_3 = 0.75 (*a*) and s/h_3 = 0.6 (*b*)

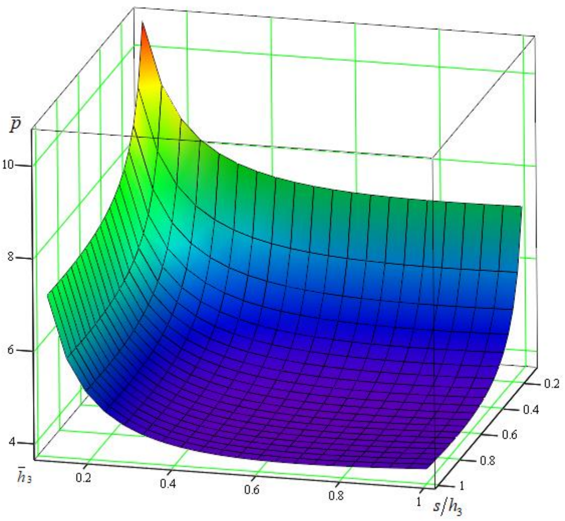


Fig. 10. Dependence of the pressure of sequential combined extrusion vs the relative wall thickness s/h_3 and the parameter $\bar{h}_3$ at $\mu_s = 0.08$; $\bar{R}_3 = 1.6$; $\varphi = 5°$

Thus, the developed module provides the possibility of simulating wide range of the processes with radial component of the metal flow.

CONCLUSIONS

It has been found that the velocity field containing curvilinear triangular kinematic elements better corresponds to the experimentally determined picture of radial extrusion deformations and metal flow kinematics and provides the lowest upper estimates of extrusion pressures. The simulations of the force regime and the analysis of the tool loads by the energy method of the upper estimate for radial-forward extrusion of hollow products with blind hole from continuous blanks using the developed curvilinear triangular kinematic module to describe the turn zone from the radial flow to the forward one were carried out. The kinematically possible velocity field for convex curvilinear (parabolic) triangular module and the equation for its inclined parabolic boundary are given. Analytical dependencies in parametric form are obtained for the powers of deformation forces, friction and shear on the boundaries of the module, as well as for pressure. For the parameter α, which characterizes the geometry of the module, optimization from the condition of the reduced pressure minimum was carried out and the analytical expression was obtained for its calculation. At the same time, the clarification of upper estimates of the axisymmetric deformation pressures due to their reduction is 18…30% compared to the known solutions based on axisymmetric modules with rectilinear contours. The nature of the influence of the main technological parameters (variable and constant value of the bottom thickness, cavity radius and part wall thickness) on the power mode of the process of sequential radial-forward extrusion of hollow parts is established. The deformation pressure during combined extrusion is higher than the pressure of radial (centrifugal) extrusion by 1.5...2.1 times, depending on the size of the clearance for the forward flow of metal. But at $s/h = 0.5$ and more, the loads are quite acceptable. At the same time, using the optimal values of the specially introduced parameter α, which characterizes the geometry of the triangular module, makes it possible to choose rational form of the die and obtain significantly lower values for contact friction forces.

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Алієва Л. І., Левченко В. М., Алієв І. С., Картамишев Д. О. Розробка трикутного кінематичного модуля для розрахунку тиску деформування в процесах видавлювання

У роботі представлено розроблений на основі енергетичного методу верхньої оцінки універсальний кінематичний модуль, призначений для використання в математичних моделях комбінованих процесів холодного об'ємного штампування. Зокрема, цей модуль можна використовувати при моделюванні силового режиму та аналізі навантажень на інструмент при радіально-прямому видавлюванні порожнистих виробів з глухим отвором із суцільних заготовок для опису зон деформації при течії металу до центру та зон розвороту від радіальної течії до зворотної. Наведено кінематично можливе поле швидкостей для опуклого криволінійного (параболічного) трикутного модуля та рівняння його параболічної похилої межі. Отримано аналітичні залежності для потужностей сил деформування, тертя та зрізу на межах модуля, а також для наведеного тиску у параметричному вигляді. Розроблений криволінійний кінематичний модуль, застосування якого дозволяє підвищити оперативність методу верхньої оцінки для дослідження процесів комбінованого видавлювання, протестовано та описано. Показано, що на величину приведеного тиску для криволінійного модуля розвороту найбільший вплив мають відносні товщина фланця, його радіус, товщина стінки трубчастої заготовки, а також умови тертя. Продемонстровано можливість коректного використання криволінійного трикутного модуля для аналізу складних схем процесів із кількома зонами. Моделювання проведено для розрахункових схем радіально-прямого видавлювання заготовки зі змінною висотою фланця. Встановлено, що розроблений криволінійний трикутний модуль за рахунок зниження величини розриву швидкостей на його межах дозволяє знизити верхню оцінку навантажень на інструмент у порівнянні з варіантами моделей, які раніше базувалися на модулях прямокутної форми.

Ключові слова: *енергетичний метод верхньої оцінки, криволінійний кінематичний модуль, модульний підхід, радіально-пряме видавлювання, навантаження на інструмент, моделювання.*

Алиева Л. И., Левченко В. Н., Алиев И. С., Картамышев Д. А. Разработка треугольного кинематического модуля для расчета давления деформирования в процессах выдавливания

В работе представлен разработанный на основе энергетического метода верхней оценки универсальный кинематический модуль, предназначенный для использования в математических моделях комбинированных процессов холодной объемной штамповки. В частности, этот модуль можно использовать при моделировании силового режима и анализе нагрузок на инструмент при радиально-прямом выдавливании пустотелых изделий с глухим отверстием из сплошных заготовок для описания зон деформации при течении металла к центру и зон разворота от радиального течения к обратному. Приведены кинематически возможное поле скоростей для выпуклого криволинейного (параболического) треугольного модуля и уравнения его параболической наклонной границы. Получены аналитические зависимости для мощностей сил деформирования, трения и среза на границах модуля, а также для приведенного давления в параметрическом виде. Разработанный криволинейный кинематический модуль, применение которого позволяет повысить оперативность метода верхней оценки для *исследования процессов комбинированного выдавливания, протестирован и описан. Показано, что на величину приведенного давления для криволинейного модуля разворота наибольшее влияние оказывают относительные толщина фланца, его радиус, толщина стенки трубчатой заготовки, а также условия трения. Продемонстрирована возможность корректного использования криволинейного треугольного модуля для анализа сложных схем процессов с несколькими зонами. Моделирование проведено для расчетной схемы радиально-прямого выдавливания заготовки с переменной высотой фланца. Установлено, что разработанный криволинейный треугольный модуль за счет снижения величины разрыва скоростей на его границах позволяет снизить верхнюю оценку нагрузок на инструмент по сравнению с вариантами моделей, которые ранее базировались на модулях прямоугольной формы.*

Ключевые слова: *энергетический метод верхней оценки, криволинейный кинематический модуль, модульный подход, радиально-прямое выдавливание, нагрузка на инструмент, моделирование.*

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