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SIMULATION OF THE PROCESS OF TRANSVERSE-FORWARD EXTRUSION WITH EXPANSION

Combined extrusion methods are a competitive solution for the production of complex-profiled and hollow parts in optimal power mode. By simulation of the combined transverse-forward extrusion process with using the energy method of kinematic modules, calculated correlations were obtained and an assessment of the influence of technological parameters on the deformation pressure was given. The possibility of considering the process of combined extrusion as sequentially composed one of two plane modules with the addition of normalized pressures of transverse and forward extrusion with expansion has been confirmed.

For the transverse extrusion module the correlations obtained by the upper bound method and showing results close to experimental data and similar solutions for problems of plane upsetting (final stage of die forming) and differing in two types of discontinuous velocity field were used. For a rectangular module of forward extrusion with expansion, a discontinuous velocity field was constructed and the correlation for calculating the pressure components on the velocity discontinuity lines was obtained. It has been found that there is an optimal value for the angle of the triangular module in the range of 42–45°, according to which it is recommended to tilt the semi-die wall. A graphical analysis of the dependence of the normalized combined extrusion pressure has allowed to identify that the relative parameters have the greatest influence on the pressure level: the height of the transverse extrusion deformation zone h/R_0 and the thickness of the ledge h/s, which characterize the degree of metal deformation.

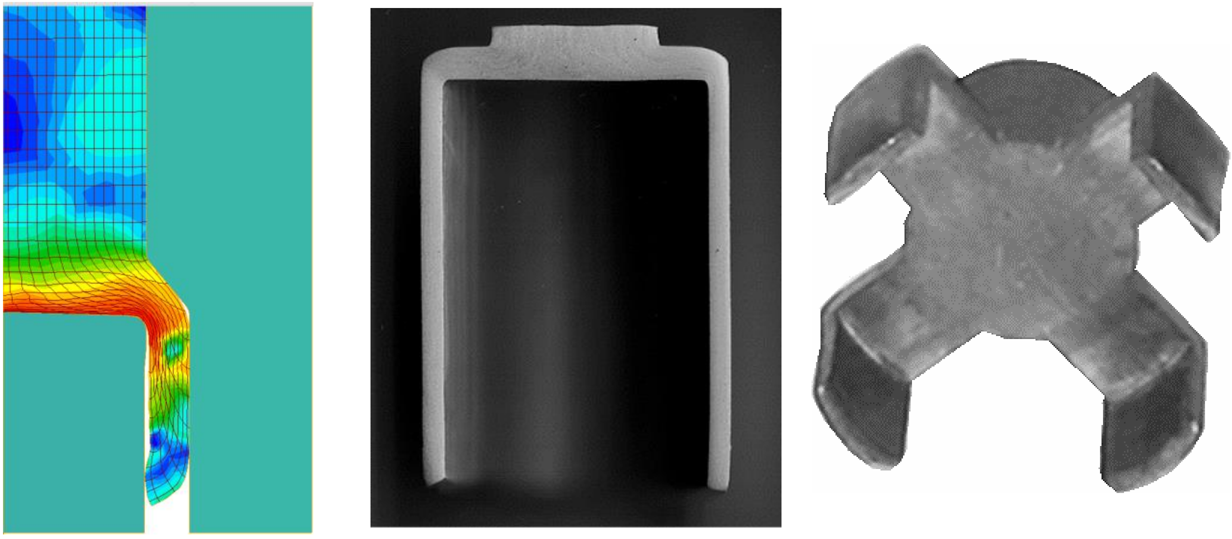
The correlations that make it possible to evaluate the influence of the relative wall thickness of a hollow product h/s on the normalized deformation pressure were experimentally confirmed on workpieces made of aluminum alloy AA1135.

Key words: *transverse-forward extrusion with expansion, method of kinematic modules, normalized pressure, hollow parts, parts with ledges.*

Modern tasks of machine building, in particular workpiece production, are the design of new technologies for working by pressure that make it possible to increase the productivity, complexity and quality of manufactured parts, including those made from new materials [1, 2]. Ensuring the necessary law of forming and the quality of parts of a complicated design with the required performance properties is possible with optimization and active control of plastic deformation modes [3, 4]. The creating and researching new methods of extrusion and simulations for calculating the processes of deformation of parts under complicated loading conditions are important directions in the development of precision die forming technologies [5]. At the same time, the prospects for the improvement of these technologies are associated with the development of deformation methods that are formed by combining longitudinal and transverse extrusion schemes and make it possible to obtain complex-profile hollow and rod parts in one operation [4, 6]. This is especially true for precision complicated parts such as crosspieces and deep sleeves (Fig. 1, *a*). A variation of transverse-forward extrusion with elements of radial metal flow is the method of sequential forward extrusion combined with expansion (Fig. 1, *b*), the use of which may lead to decreasing deformation forces on the punch and an increasing its stability [7, 8].

To analyze technological (force and deformation) modes, computer (numerical) and analytical simulating methods are used. In particular, the finite element method (FEM) made it possible to study the patterns of the stress-strain state of parts, evaluate the unevenness of the deformed state of the workpiece and heat dissipation during plastic flow, and predict the deformability and form changing of workpieces in extrusion [9, 10].

To obtain engineering formulas needed for operative design calculations of power modes of processes, energy methods are most often used [2, 11]. At the same time, operative and approximate analysis of the patterns of process parameters influence on the power mode can be provided using the energy upper bound method (UBM) [12]. The modular approach in the energy method of kinematic modules (MKM) is aimed at increasing the efficiency of analysis and obtaining engineering correlations for calculating energy-power parameters [13]. By constructing kinematically possible velocity fields of various configurations, namely triangular or trapezoidal modules with curved surfaces of discontinuity, it is possible to obtain calculated correlations that take into account the features of the geometry of the part, the method, kinematics and stages of deformation [2, 6]. Using the MKM method, approximate correlations were obtained for the force mode of extrusion in a plane-deformed state, including for combined extrusion [14, 15]. In [15], a simulation of transverse-corner extrusion process was carried out, the design scheme of which was composed of autonomous modules for upsetting and corner deformation.



a *b*

Fig. 1. Scheme of the process of combined transverse-forward extrusion with expansion (based on the results of FEM simulation) (*a*) and typical parts obtained experimentally (*b*)

The purpose of the study is to create a mathematical model of the process of sequential transverse-forward extrusion combined with expansion and to determine the influence of the tool geometry on the value of the normalized deformation pressure.

The design scheme of the process (Fig. 2, *a*) for the case of plane deformation according to the MKM method is composed of two kinematic modules for the characteristic plastic zones of the part: in the central zone (with rigid elements 2, 3–6), where compression and transverse extrusion of the metal occur, and in the transition zone (with elements 7 and 8), where the metal is turned on the inclined section of the semi-die towards the forward direction.

We believe that the friction of the semi-finished product on the tool occurs along the contact surfaces of the central zone with the lower semi-die and the transition zone with the upper semi-die, as well as within the input and output zones 1 and 8.

In module I of transverse extrusion (elements 2–6), the height of the deformation zone does not exceed the height of the output hole h. In addition to the height of the central module h, the main process parameters include the angle of inclination of the semi-die β, as well as the thickness of the ledge or the wall thickness of the hollow product s.

To find the upper estimate of the normalized (dimensionless) deformation pressure of the metal in module I $\overline{p} = p/(2 \cdot k)$ applying the UBM method, the formula [12] was used:

$$\overline{p} = \frac{1}{2 \cdot h \cdot V_1} \cdot \left(\sum_{1}^{n} V_{i,j} \cdot l_{i,j} + 2 \cdot \mu \cdot \sum_{1}^{n} V_{i,k} \cdot l_{i,k} \right), \qquad (1)$$

where V_0 – the velocity of translational movement of the punch;

$V_{i,j}$ and $V_{i,k}$ – velocities on the contact surfaces (boundaries) of module;

$l_{i,j}$ and $l_{i,k}$ – lengths of the velocity discontinuity lines;
μ – friction coefficient (Siebel's), $0 \le \mu \le 0.5$.

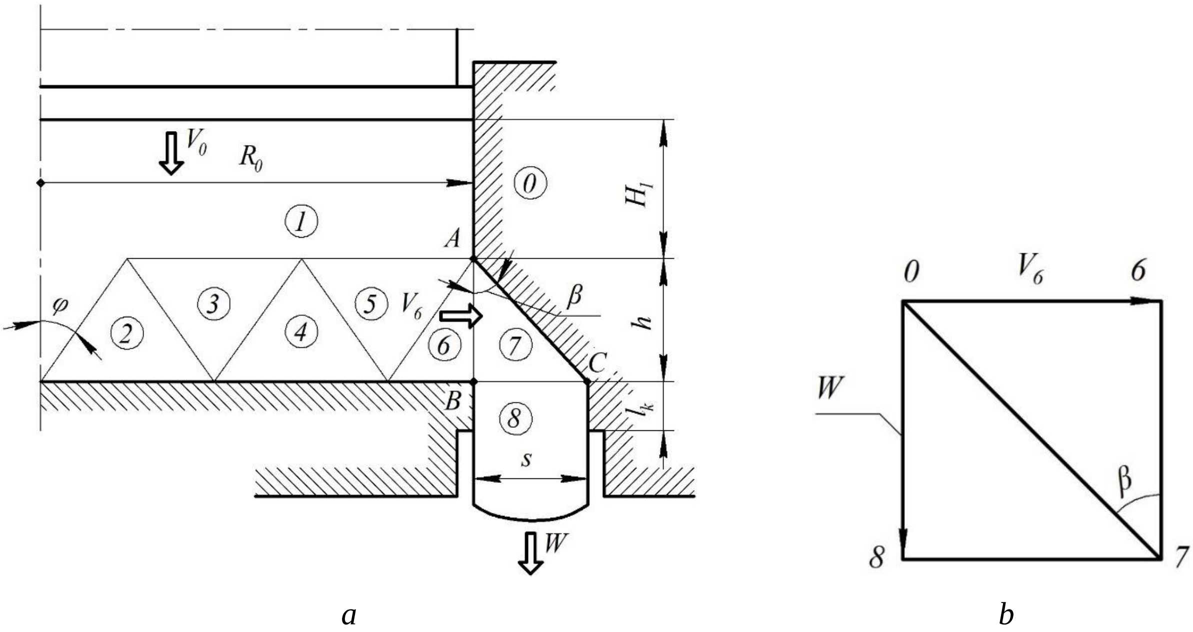


Fig. 2. Design scheme of the transverse-forward extrusion process with expansion (*a*) and velocity hodograph for the reversal zone of the metal flow direction (*b*)

For extrusion with small values h/R_0 (≤ 0.6), the shape of the deformation area in zone 1 is similar to a strip, and the number of rigid elements increases (see Fig. 2, *a*). Thus, for the central module I of transverse extrusion, we have taken as a basis the kinematically possible field developed for the bilateral symmetrical upsetting of a strip (disk) by counter-moving punches and consisting of several rigid elements [12].

The difference is that it is necessary to use different values of the contact friction coefficients on the upper and lower boundaries of the zone, and on the upper boundary with zone 1, moving at velocity V_0, the friction coefficient will take the limit value μ_1 = 0.5, since the upper limit of the upsetting zone (2–6) is the shear boundary. The formula for the normalized deformation pressure will take the form:

$$\bar{p}_1 = 1 + \frac{1}{2} \cdot \left(\frac{1}{2 \cdot \bar{h}} + \mu \cdot \frac{1}{\bar{h}} \right), \quad (2)$$

where $\bar{h} = h/R_0$.

A graphical analysis of the obtained correlation (2) for the normalized transverse extrusion pressure vs the geometric parameters of the process is given in Fig. 3.

As the parameter $\bar{h} \le 0.6$ decreases, the value of the normalized pressure increases rapidly, which is expected, since the degree of deformation increases. When $\bar{h}$ decreases threefold, the pressure increases almost fourfold. The increase in deformation pressure with increasing friction coefficient is not as intense as for strip upsetting. This is explained by the fact that boundary friction is observed only on one boundary (1–2) of the deformation zone.

The solution was separately obtained for the reversal module II (zones 7 and 8) also by the upper bound method by constructing a discontinuous field and a velocity hodograph. Zone 7 is a triangle with a friction surface on a generatrix semi-die inclined at an angle β. This design scheme of the process corresponds to the plane problem of a hollow part extrusion with wall thickness *s* and bottom thickness *h*. The calculation of a triangular module is simplified because it is rectangular one. The velocity hodograph for the triangular zone was constructed, according to the known rules [12], under the condition that the figures of field and hodograph are similar (see Fig. 2, *b*). The parameters of boundary lines and shear velocities are given in Table. 1.

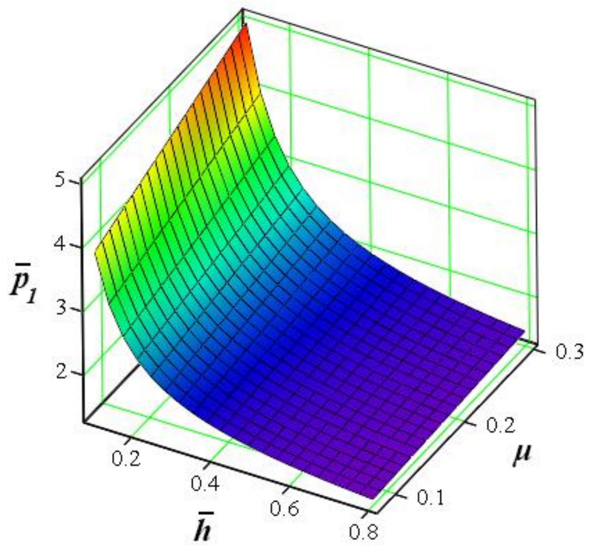


Fig. 3. Graph of dependence of the normalized transverse extrusion pressure $\bar{p}_1$ vs parameters $\bar{h}$ and μ

Table 1

Length of boundary lines and values of velocity discontinuities

i, j	$l_{i,j}$	$V_{i,j}$
6–7	h	$V_1 \cdot h/s$
0–7	$\sqrt{h^2+s^2}$	$V_1 \cdot \sqrt{h^2+s^2}/s$
7–8	s	V_1
0–8	l_k	$V_1 \cdot h/s$

Using the data from Table 1 and the energy balance formula (1), after transformations we have found the correlation for the metal deformation pressure in the reversal module (without taking into account the influence of contact friction within zone 8):

$$\bar{p}_2 = \frac{1}{2} \cdot \left[\frac{h}{s} + \frac{s}{h} + 2 \cdot \mu_s \cdot \left(\frac{h}{s} + \frac{s}{h}\right)\right]. \quad (3)$$

At $\frac{s}{h} = tg\beta$, expression (3) through the angle β has the form:

$$\bar{p}_2 = \frac{1}{2} \cdot \left[tg\beta + ctg\beta + 2 \cdot \mu_s \cdot (tg\beta + ctg\beta)\right]. \quad (4)$$

At β = 45°, tgβ = 1, and

$$\bar{p}_2 = 1 + 2 \cdot \mu_s. \quad (5)$$

At maximum friction μ = 0.5:

$$\bar{p}_2 = 2.0. \quad (6)$$

When studying the mathematical model (4), the values of the relative geometric parameter *s/h* of module, corresponding to certain values of the angle β ($tg\beta = s/h$), were used. In the normalized pressure formula (4), the value β is an optimizing one. The optimization criterion is the minimum normalized pressure. Optimization was carried out using a computer in the MathCAD environment by enumerating the numerical values of the optimizing parameters from the minimum to the maximum possible ones with a certain specified step. The optimization results for parameter β are presented in the form of graphs in Fig. 4.

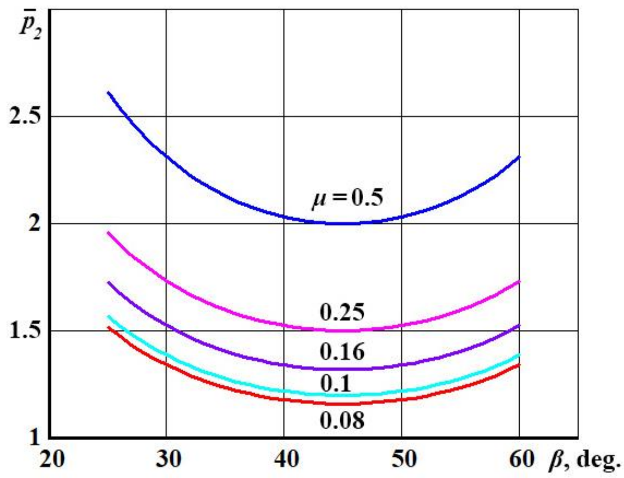


Fig. 4. Correlations of the normalized deformation pressure of the metal in a triangular module $\bar{p}_2$ vs the value of the angle β for different values of the friction coefficient μ

The *h/s* parameter, on which the degree of deformation for metal flow within the module depends, has the greatest influence on the force mode of extrusion. Doubling the value of *h*/*s* from 1.0 to 2.0 (and, corresponding, decrease in β) leads to increasing deformation pressure by 30–40 %. At the same time, it was found from graphs the presence of a stable minimum of normalized pressure values, regardless of friction conditions, at optimal values of the *h/s* parameter close to 1.0. That is, there is a certain value of the optimal angular parameter β, at which the normalized pressure of the process is minimal one and the lower points of the curves correspond to these values. Apparently, the optimal value of the inclination angle of the generatrix of the semi-die β from the point of view of the minimum normalized pressure is in the range of 42–45°.

The influence of contact friction on the force parameters is significant, since the friction surface is almost equal to the shear surfaces in this module. Increasing the friction coefficient values from 0.08 to 0.16 leads to a corresponding increase in deformation pressure by 17 %, and from 0.08 to 0.5 – by 60 % (see Fig. 4).

The obtained correlations for the deformation pressure within the considered modules were used in the general scheme of combined extrusion with expansion. Assembling a general design scheme involves summing up the normalized pressures of the component modules and does not cause difficulties. It should be noted that the combination of modules is possible not only according to the variant shown in Fig. 2, although it is the main one. In the first main variant, the pressures calculated using formulas (2) and (3) are summed up.

When calculating the normalized combined extrusion pressure, the energy consumption for contact friction in zones 1 and 8 was additionally taken into account, using the following summands:

$\bar{H}_1 \cdot \mu$, where $\bar{H}_1 = H_1/R_0$;

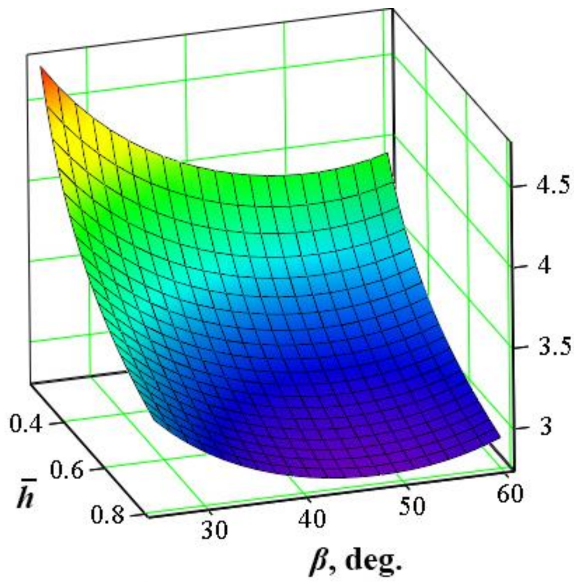
$\mu \cdot 2 \cdot \bar{l}_k/\bar{s}$, where $\bar{l}_k = l_k/R_0$ and $\bar{s} = s/R_0$.

In calculations, the value $\bar{l}_k$ according to experimental data is taken equal to 0.25.

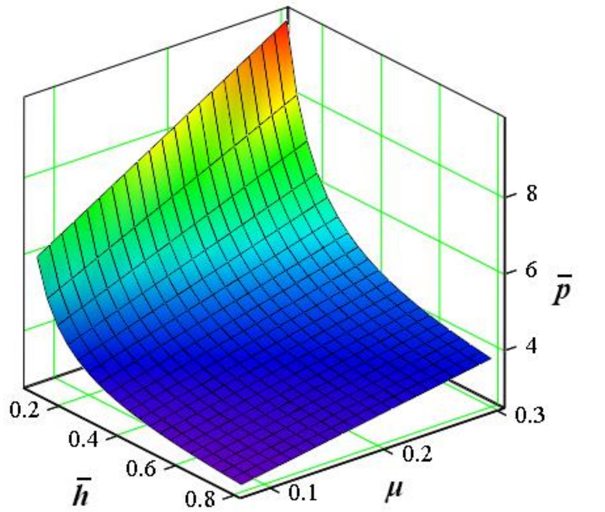
As a result, the correlation was obtained for the normalized pressure of combined extrusion with expansion:

$$\bar{p} = \bar{p}_1 + \bar{p}_2 + \bar{H}_1 \cdot \mu + \mu \cdot 2 \cdot \bar{l}_k/\bar{s}. \quad (7)$$

The nature of the change in the normalized pressures of plane sequential extrusion according to the described variant can be considered using the graphs shown in Fig. 5.



a



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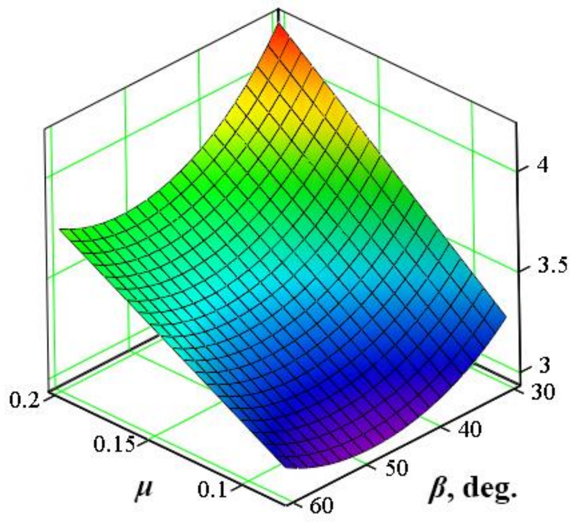

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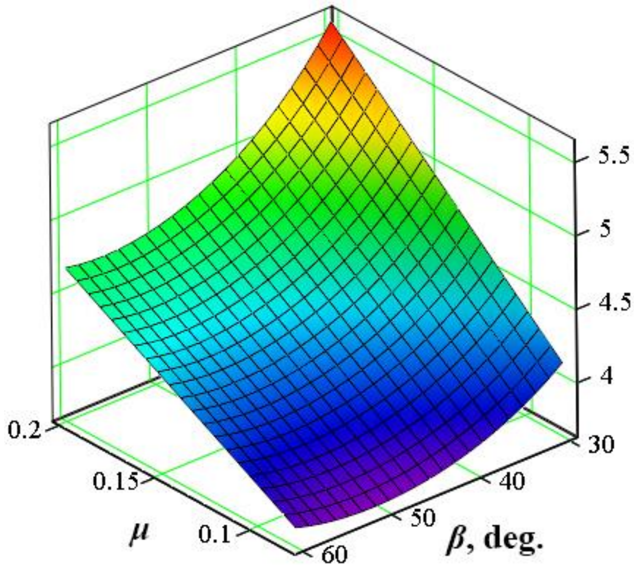

d

Fig. 5. Graphs of the correlation of normalized extrusion pressure vs the process parameters at $\overline{H}_1 = 1.0$; $\bar{l}_k = 0.25$ and for μ = 0.1 (*a*); β = 45° (*b*); $\bar{h} = 0.5$ (*c*); $\bar{h} = 0.25$ (*d*)

The parameter $\bar{h}$ has a significant influence on the normalized pressure even at small values of the friction coefficient μ (see Fig. 5, *a*–*d*). Decreasing the parameter $\bar{h}$ in the combined process causes a sharp increase in the required values of the normalized pressure. As for the influence of such parameters as the coefficient of friction μ and the thickness of the wall (process) *s* (within *h/s* = 0.5–1.0), no significant changes were seen in the combined process compared to the pressure characteristic of the modules separately. However, when calculating the process of combined extrusion in an extended range of thicknesses *s*, the influence of the parameter *h/s*(β) on the force parameters is significant (see Fig. 5, *a*, *c*). Thus, decreasing β from 40° (*h*/*s* = 0.84) to 10° (*h*/*s* = 0.176) leads to a twofold increase in the pressure of sequential combined transverse-forward extrusion. The angle β (and the parameter *s/h*) is thus a more significant parameter, especially for friction coefficients μ approaching 0.2 (see Fig. 5, *c*), and its optimal value is close to 45° (see. Fig. 5, *c*, *d*).

It should be noted that for extrusion with a large value of the parameter $\bar{h}$ ($h/R_0 \geq 0.6$), the shape of the deformation area in zone 1 is similar to a lens, and the number of rigid elements decreases. In this case, for the transverse extrusion module, the expression obtained for transverse extrusion in [15] can be used:

$$\bar{p}_1 = \frac{1}{2} \cdot \left(\frac{1}{\bar{h}} + \bar{h} \right) + \mu_s \cdot \left(2 - \bar{h} + \bar{H}_1 \right), \quad (8)$$

where $\bar{h} = h/R_0$.

At this value $\bar{p}_1$ in formula (7), the pressure of combined extrusion with expansion also depends on $\bar{h}$ and *h/s* (Fig. 6). This variant of combining modules with relatively large values of h/R_0 is characterized by increasing the influence of the degree of compression in the zone of the reversal-forward extrusion module. As the relative height h/R_0 increases from 0.6 to 1.0, the normalized pressure decreases from 2.7 to 2.48 units. This trend continues when the ratio of height to wall thickness of the product (ledge) *h/s* changes. It is also clear that the smaller the wall thickness *s* of the extruded part, the higher the normalized process pressure, which is explained by increasing the degree of deformation. As the *h/s* parameter increases from 1.0 to 1.4 ($\bar{h} = 0.6$), the pressure increases from 2.7 to 2.82 (see Fig. 6).

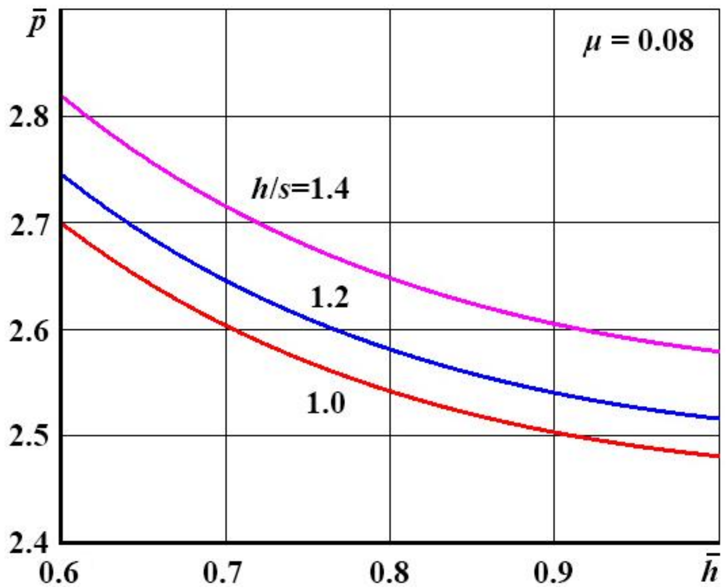

Fig. 6. Graph of the correlation of the sequential extrusion normalized pressure vs the process parameters

For contact friction conditions characteristic of cold plastic deformation processes (μ_s = 0.08) with different ratios of geometric parameters of the deformation process, the value of the normalized deformation pressure has an optimal value at the angle β = 44°. Based on this value, it should be recommended to tilt the generatrix of the semi-die wall.

If excluding in formula (7) the friction at the exit (at a length $\bar{l}_k = l_k/R_0$) from the deformation zone, then we obtain a formula for an approximate calculation of the upper estimate of the pressure in the process of “die-free” extrusion. At the same time, on an inclined boundary it is also advisable not to take into account the influence of friction forces on the force regime of the process. A comparison of experimental and theoretical values of force parameters under such conditions was made for hollow parts made of alloy AA1135 with parameters R_0 = 21.2 mm; $\bar{h} = 0.28$; $\bar{s} = 0.188$ (Fig. 7). The degree of deformation is determined by the amount of material upsetting in the zone of the first module (2–6) with a maximum stroke of the counter punch S = 17 mm.

The excess of the calculated data in deformation forces over the experimental ones is 3–5 % for die-free extrusion (*A*) and 15–17 % for sequential transverse-forward extrusion with expansion (*B*), which confirms the possibility of using the developed models for technological and design calculations.

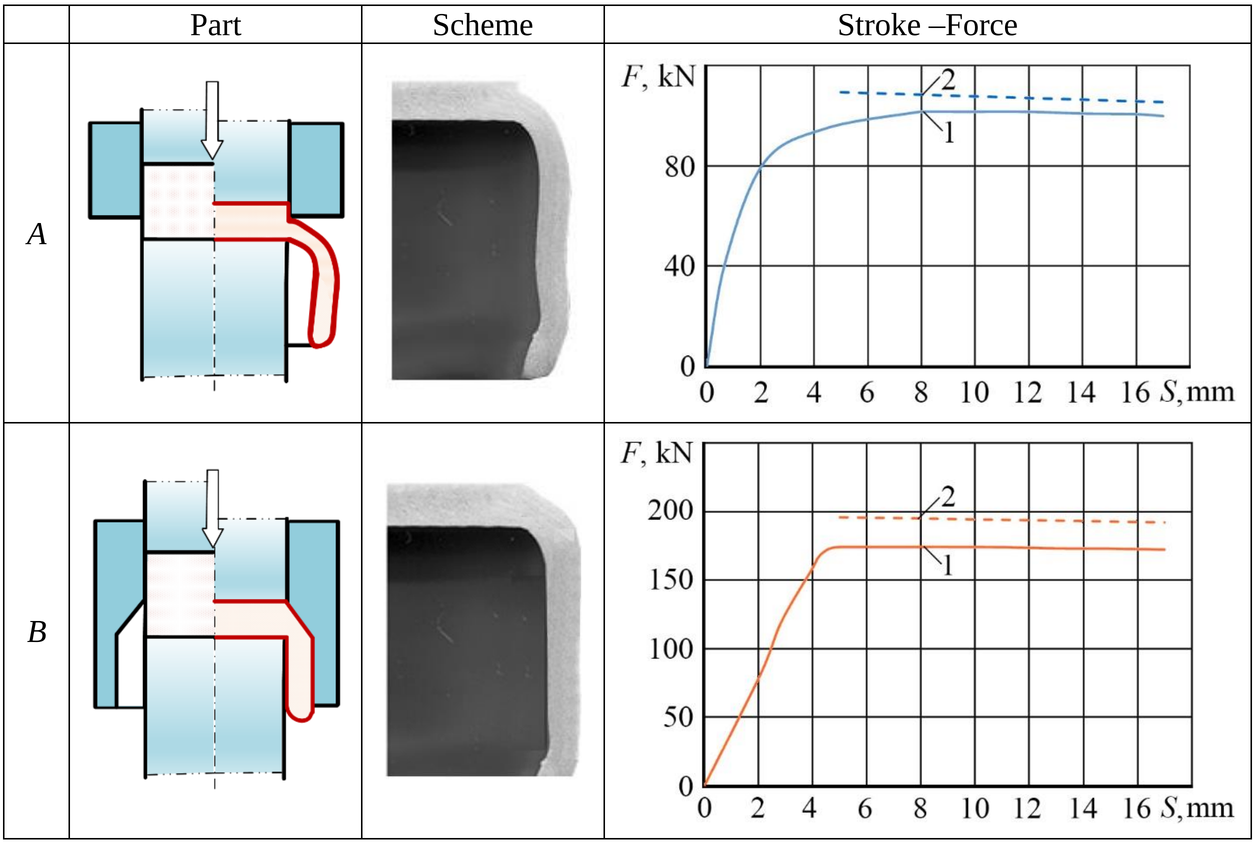

Fig. 7. Comparison of calculated results (curve 2) with experimental data (curve 1) on deformation forces for die-free (*A*) and transverse-forward (*B*) extrusion with expansion

The use of triangular kinematic modules in the design schemes of the process of sequential transverse-forward extrusion with the expansion helps to simulate the process of deformation of hollow parts or parts of complicated shape with ledges in the die (see Fig. 1, *b*).

CONCLUSIONS

By simulating the force mode of the combined transverse-forward extrusion process using the energy method of kinematic modules, calculated correlations were obtained and an assessment of the influence of technological parameters on the deformation pressure was given.

The possibility of considering the process of combined extrusion as sequentially composed of two plane modules with the addition of the normalized pressures of transverse and forward extrusion with expansion has been confirmed.

For the transverse extrusion module, expressions were used, which has been obtained by the upper bound method and show results that are close to experimental data and similar solutions for problems of plane upsetting (final stage of die forming) and differ in two types of discontinuous velocity field.

For the second rectangular module of forward extrusion with expansion, a discontinuous velocity field was constructed and the correlation for calculating the pressure components on the velocity discontinuity lines was obtained. It has been found that there is an optimal value for the angle of the triangular module in the range of 42–45°, according to which it is recommended to tilt the semi-die wall.

A graphical analysis of the correlation for the normalized combined extrusion pressure has shown that the relative parameters have the greatest influence on the pressure level: the height of the transverse extrusion zone h/R_0 and the wall thickness h/s, which characterize the degree of metal deformation. The influence of friction is especially significant within the reversal-forward extrusion module.

The adequacy of the calculated correlations, which make it possible to evaluate the influence of the relative wall thickness of the product h/s on the normalized deformation pressure, was experimentally confirmed on workpieces made of aluminum alloy AA1135.

Correlations for calculating the force parameters of combined transverse-forward extrusion with expansion can be used to design extrusion processes for both hollow cylindrical products and parts with lateral ledges.

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Левченко В. М., Алієв І. С., Чепеленко О. Ю., Картамишев Д. О., Малій О. Г. Моделювання процесу поперечно-прямого видавлювання з роздачею.

Способи комбінованого видавлювання є конкурентоспроможнім рішенням для виготовлення складнопрофільованих та порожнистих деталей в оптимальному силовому режимі. Моделюванням процесу комбінованого поперечно-прямого видавлювання енергетичним методом кінематичних модулів отримано розрахункові залежності і дана оцінка впливу технологічних параметрів на тиск деформування. Підтверджено можливість розгляду процесу комбінованого видавлювання як послідовно складеного з двох плоских модулів з додаванням приведених тисків поперечного та прямого видавлювання з роздачею.

Для модулю поперечного видавлювання використано залежності, що отримані методом верхньої оцінки і які показують результати, близькі до експериментальних даних і до аналогічних рішень для задач плоского осадження (доштампування) і відрізняються двома видами розривного поля швидкостей. Для прямокутного модуля прямого видавлювання з роздачею побудовано розривне поле швидкостей та отримано залежності для розрахунку компонентів тиску на лініях розриву швидкостей. Встановлено, що існує оптимальне значення для куту трикутного модулю в межах 42–45°, за яким рекомендовано виконувати нахил стінки напівматриці. Графічним аналізом залежності приведеного тиску комбінованого видавлювання встановлено, що найбільший вплив на рівень тиску мають відносні параметри: висота осередку поперечного видавлювання h/R_0 та товщина відростка h/s, які характеризують ступінь деформування металу.

Залежності, які дозволяють оцінити вплив відносної товщині стінки порожнистого виробу h/s на приведений тиск деформування, отримали експериментальне потвердження на заготовках з алюмінієвого сплаву АД1.

Ключові слова: *поперечно-пряме видавлювання з роздачею, метод кінематичних модулів, приведений тиск, порожнисті деталі, деталі з відростками.*

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