PREDICTING THE SHAPE FORMATION OF PARTS WITH A FLANGE AND AN AXIAL PROTRUSION IN THE PROCESS OF COMBINED ALIGNED RADIAL-DIRECT EXTRUSION

Using the calculation schemes CS-1 (with the presence of a trapezoid module) and CS-1a (with rectangular kinematic modules) has been proposed for the process of the combined radial-direct extrusion of parts with a flange and an axial protrusion. The application of a trapezoidal kinematic module allows the description of the characteristic regions of metal flow, close to the actual course of the process based on the distorted coordinate grids. On the basis of the energy method, the values of the reduced deformation pressure have been obtained using the upper estimate of the power of deformation forces inside the trapezoidal kinematic module. The optimization involved the parameter Rk that determines the position of the surface of the interface of metal flow into an axial protrusion and a flange zone. We have performed a comparative analysis of the theoretical calculations of the magnitude of the reduced deformation pressure and the influence of geometric ratios and friction conditions on the qualitative and quantitative differences in the character of the change in the resulting curves. The overestimation of data on assessing the force mode based on the CS-1a scheme relative to the calculations based on the CS-1 scheme can be as high as 50 % and indicates the rationality of using the latter. This is due to the limitation in the use of the optimization (the absence of the optimization of the height of the deformation site) for the scheme containing elementary rectangular kinematic modules. The deviation from the experimentally obtained increments in an axial protrusion does not exceed 7–10 %, which indicates the validity of the use of the CS-1 estimation scheme with a trapezoidal kinematic module. Thus, it can be argued that it is correct to determine the position of the boundary of the surface of the interface of metal flow into an axial protrusion and a flange zone and the resulting assessment of the formation of a semi-finished product

Keywords: simulation of combined extrusion processes, kinematic module, energy method, semi-finished product shape formation

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1. Introduction

At present, the availability of a variety of methods for processing metals by pressure renders relevance to the task of choosing the most rational and economical method [1–5].

Studies of recent years have tackled both the solving of specific practical tasks [1–3] and the development of theoretical foundations for modeling the deformation processes. The areas of theoretical research relate to the methods that describe the shape of bodies, the techniques that simplify the

assessment of the force regimes and the shape formation of a semi-finished product, etc. [4, 5]. Special emphasis is also on the role of resource-saving methods of treating metals with pressure, based on cold plastic deformation, allowing for the production of billets with exact dimensions and high surface quality [6]. A steady trend towards expanding the range of stamped parts and materials involving cold extrusion processes necessitates in-depth research and evaluation of the possibilities of expanding the technological capabilities of these processes. In this case, studies of recent years have been related to processes that employ both the conventional longitudinal and transverse extrusion schemes and the combined (aligned or sequential) extrusion [7, 8]. The attention has also been paid to the issues of assessment of the deformability of blanks, extreme shape formation, and defect formation [9, 10].

Parts of the complex shape with flanges and appendages made from alloys of non-ferrous metals are widely used in various branches of engineering and instrumentation, specifically in the aviation industry. The gradual obtaining of the elements of such parts in different stamps over several runs is ineffective [6]. The processes of combined extrusion, obtained by a combination of the longitudinal (direct and reverse) and transverse (radial and lateral) extrusion, differ in great variety and the possibility of making hollow and solid parts with a profiled outer or internal surface in a single operation [7, 11]. The combined aligned extrusion processes also have advantages in reducing energy costs, as increasing the degree of freedom of metal outflow in several directions requires fewer deformation forces [11–15]. However, for the same reason, the calculation of such extrusion processes, which take place under an optimal self-regulating mode, as well as the assessment of the shape formation of parts, are not easy due to the difficulty of predicting the direction of the predominant metal flow.

Thus, a set of studies aimed at developing the procedures for calculating the force regime and predicting the shape formation and defect formation of parts in the processes of combined aligned extrusion is needed. This could encourage their more active industrial implementation.

2. Literature review and problem statement

The techniques of the combined extrusion that involve the longitudinal (direct and reverse) and transversal (radial or lateral) extrusion schemes make it possible to fabricate parts of the complex configuration in a single operation. A series of studies [8, 11, 12] analyzed processes of the lateral and consistent radial-longitudinal extrusion processes. Work [8] used a method of the upper assessment to investigate patterns in the character of the metal flow (the presence of a dead zone) in the reversal zone at lateral extrusion and estimated the force regime. Paper [11] examines the impact of the structural parameters and friction conditions on the force mode of the process of the consistent radial-longitudinal extrusion. It is possible to obtain large-diameter pipes from small cylindrical blanks by the radial-direct extrusion [12]. The use of additional hydrostatic pressure at the deformation site and the introduction of the sign-alternating deformation character ensures a significant increase in strength; however, no issues related to calculating the increased loads on the tool were considered. The analysis of techniques for part extrusion out of a solid blank as a result of the processes of the sequential

radial-longitudinal flow is reported in works [13, 14]. At the same time, the deformation process based on the scheme of radial-direct extrusion with expansion makes it possible to reduce the forces of deformation. However, this is accompanied by a significant increase in the specific loads on the tool, which is a limiting factor in the use of these processes. For the processes with a single degree of freedom of the flow of metal, most research is aimed at assessing the force regime. In this case, the features in shape formation are tackled only in terms of analyzing the impact of the characteristic zones on the deformed state of the blank and the occurrence of defects.

Expanding the possibilities of the combined aligned extrusion is impossible without assessing the shape formation of a part and matching the required size and the finished product. This, in turn, necessitates the development of theoretical methods for evaluating these techniques for different deformation sites (DS): uniform, aligned, disconnected, or combined. In this case, the combined longitudinal-transverse extrusion from a solid blank with an axial protrusion is characterized by a variety of possible implementation options. Depending on the character of the combination of simple schemes in one combined process, the division is primarily into the aligned and consistent processes. The most labor-intensive in predicting the shape formation of a part are the techniques of the combined aligned radial-longitudinal extrusion with two degrees of freedom of the metal flow. The basic schemes and received parts with an axial protrusion for the combined longitudinal-transverse extrusion are given in Table 1. We highlight among the techniques of the aligned combined longitudinal-transverse extrusion the scheme of a three-way radial-reverse-direct extrusion (Table 1, scheme A) as the most universal one to obtain a hollow part with a flange and an axial protrusion. The effect of geometric parameters and friction conditions in the direct-reverse-radial extrusion process was investigated by the finite-element method in the software package ABAQUS (ABAQUS Inc., USA) in work [15].

The technique of the aligned radial-reverse extrusion can produce parts of the rod type with appendages or a flange (scheme B) [16]. The radial-direct exhaustion can be used to fabricate parts with a flange from solid and tubular blanks (scheme C) [17].

Table 1

Schemes of the aligned longitudinal-transverse extrusion and the obtained parts with an axial protrusion
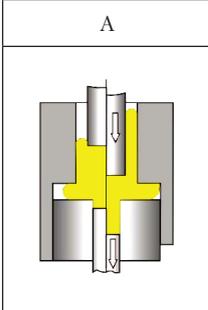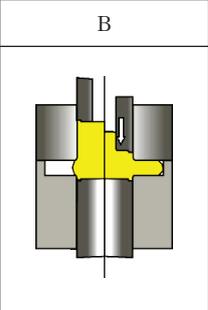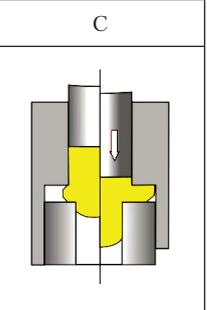
Work [17] reported modeling the process of the radial-direct extrusion of parts with a flange and a rod appendage (scheme B) by the method of finite elements using QForm2D/3D («KuantorForm», Russia). The method of planning the experiment was applied to derive the dependence of the reduced pressure of extrusion on the geometric parameters of the resulting part. However, the work does not define the boundary of the interface of the metal flow to an axial protrusion and into the flange area; the data obtained are limited. Paper [18] addressed the construction of a mechanism to control the force extrusion regime in order to prevent the destruction of the metal. The solution was obtained by the method of finite elements (MFE); it includes recommendations to prevent cracks in the axial zone of a rod part via optimizing the geometric parameters. However, the cited works do not report any analytical dependences to account for the influence of individual geometric parameters on the force and deformation modes of the process. Papers [9, 19] studied the stressed-strained state, the assessment of the resource of the plasticity, and the technological capabilities of the processes of the combined extrusion of parts from various materials. Work [19] reports the ways for the deformation of the material's particles, which makes it possible to assess the resource of the plasticity and technological capabilities of the process of the combined radial-direct extrusion process for different materials. Features of the process of the combined radial-reverse extrusion of hollow parts with a flange with the formation of a shrinkage cavity in the bottom part are described in paper [4]. Thus, the shape formation of parts was investigated from the position of possible defect formation in the form of a shrinkage cavity. The possibilities of obtaining data on the increments in a semi-finished product in an analytical form were demonstrated in studies [20, 21]. They report the results of modeling the force regime and the shape formation of a semi-finished product by the energy method. The authors gave recommendations for choosing the estimation schemes depending on the ratios of the process. However, the process of the combined radial-reverse extrusion was considered for the combined DS; the optimal value of the reduced pressure was determined by optimizing the kinematic parameters and the shape of deformation sites. As regards the process of the combined radial-direct extrusion of parts with the flange and axial protrusion, a given process is characterized by the presence of the combined DS. Determining the position of the surface of the interface of a metal flow makes it possible to establish the dimensions of the formed elements of the part in the course of the process. The accuracy of determining the position of this surface of the flow interface is a prerequisite for the success of solving the task of predicting the shape formation of a part. It depends on how close the flow velocity fields in the autonomous zones of DS to the actually observed pattern of metal flow in the combined process.

The development of new kinematic modules of complex shapes could make it possible to build such estimation schemes that would adequately describe the velocity fields of the characteristic zones inside the deformable part. This, in turn, could help obtain a more accurate assessment of the position of the surface of the metal flow interface for the case of a combined deformation site. Thus, the task of predicting the shape formation of a semi-finished product would be solved, which could contribute to the development and implementation of the new techniques of extrusion of parts with the complex configuration in production.

3. The aim and objectives of the study

The aim of this study is to develop an estimation scheme for the process of the combined radial-direct extrusion of parts with a flange and an axial protrusion, which could make it possible to effectively predict the shape formation of a semi-finished product.

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

– to determine, on the basis of MFE and experimental data, the form of the kinematic modules for an estimation scheme, which would qualitatively describe the set of the characteristic zones and the boundary of the flow surface interface to the direct and centrifugal radial extrusion;

– to analyze the impact of the ratios and conditions of the deformation process on the possibility of optimizing the magnitude of the reduced pressure, derived from the energy method;

– to conduct a comparative analysis of the increments in a semi-finished product and the force parameters of the process of the combined radial-direct extrusion, obtained theoretically and experimentally.

4. Modeling the process of the combined radial-direct extrusion of parts with a flange and an axial protrusion

4. 1. Development of an estimation scheme of the process of the combined radial-direct extrusion of parts with a flange and an axial protrusion

The schemes of simultaneous extrusion in several directions are typically categorized depending on the characteristics of the formation of a deformation site (DS). The schemes with the uniform, connected, disconnected, and combined deformation sites are distinguished [22, 23]. The use of the schemes with a connected DS within the energy method [23–26] requires the simplification of calculations and determining the boundary of the interface between two autonomous deformation sites. This makes it possible to obtain data on the force mode and the gradual shape change in a semi-finished product in the process of combined extrusion. In this case, dividing each autonomous deformation site into a set of unified kinematic modules has a significant role for subsequent calculations. The base of the developed unified kinematic modules makes it possible to consider various variants of estimation schemes, including the use of kinematic modules with sloping boundaries [4, 10, 20–23, 27]. In the case of the combined radial-direct extrusion of parts with an axial protrusion, the CS-1 calculation scheme containing trapezoidal module 4 (Fig. 1) was proposed. A given division into a set of kinematic blocks corresponds to the data on the distortion of the dividing grid (Fig. 2). The boundary of the flow interface to the direct extrusion, forming the axial protrusion, is matched by a set of modules 1–3, 6, and the radial extrusion, for modules 1, 4, 5, is determined by the position R_k of the junction of modules 3 and 4. In this case, a special case of degeneration of trapezoidal kinematic module 4 into a rectangular 4a (at $h_k=h$) can be used as an alternative calculation scheme CS-1a for the comparative analysis of the process. In [17], for the process of the radial-direct extrusion of parts with a flange and a rod appendage, experimental and finite-element studies of the force regime and the stressed-strained state were carried out. However, the authors did not determine the boundary of the metal flow interface to the axial protrusion and the flange area, which significantly reduces the value of the cited work and requires additional research.
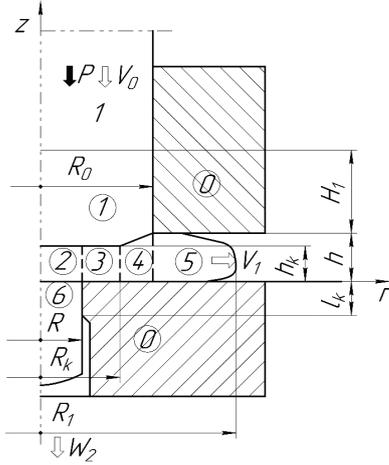
Fig. 1. The estimation scheme of the process of the combined aligned radial-direct extrusion of parts with a flange and an axial protrusion
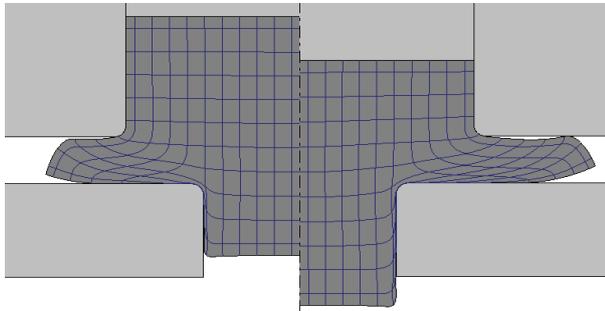

Fig. 2. Distortion of the dividing grid in the combined aligned radial-direct extrusion of parts with a flange and an axial protrusion

For informative information about the calculation schemes CS-1 and CS-1a, we shall give the kinematically possible velocity fields (KPVF) for the different forms of kinematic module 4 in Table 2. In this case, the KPVF of kinematic modules 5 and 6 are completely identical, and the KPVF of kinematic modules 2 and 3 in the calculation scheme CS-1a requires the replacement of quantity h_k with h.

Table 2

KPVF of kinematic modules 4 and 4a

Estimation scheme CS-1	Estimation scheme CS-1a
Trapezoidal module 4: $$\begin{cases} V_{z4} = -\dfrac{V_0 + kV_{r4}}{z(r)}z, \\ V_{r4} = \dfrac{V_0\left(r^2 - R_k^2\right)}{2rz(r)}, \end{cases}$$ $z(r) = k(r - R_k) + h_k$ – sloping boundary at $k = \dfrac{h - h_k}{R_0 - R_k}$	Rectangular module 4a: $$\begin{cases} V_{z4a} = -\dfrac{V_0}{h}z, \\ V_{r4a} = \dfrac{V_0\left(r^2 - R_k^2\right)}{2hr} \end{cases}$$

The trapezoidal kinematic module 4 is a special case of the kinematic module with two degrees of freedom of the flow considered in work [4]. To obtain the power of the deformation forces, it is rational to use the Cauchy – Bunyakovsky upper assessment in the following form:

$$N_{d4} \le \sqrt{V_4 \cdot \iiint\limits_{V_4} \dot{\varepsilon}_{i4}^2 \, dV_4},$$

where

$$V_4 = 2\pi\left(\frac{k}{3}\left(R_0^3 - R_k^3\right) + \frac{h_k - kR_k}{2}\left(R_0^2 - R_k^2\right)\right)$$

is the volume of the region of kinematic module 4; $\dot{\varepsilon}_{i4}$ is the intensity of deformation rates.

We move to the dimensionless quantities relative to R_0 for all geometric parameters of the process and in $\bar{p}_{N_{d4}} = N_{d4}/(\pi\sigma_s V_0 R_0^2)$, and obtain the amount of the reduced pressure for the CS-1 scheme:

$$\bar{p} = \begin{bmatrix} \bar{R}_k^2 - \bar{R}_1^2 + \bar{p}_{N_{d4}} + \dfrac{2\left(1 - \bar{R}_k^2\right)}{\sqrt{3}}\ln\left(1 + \Delta\bar{l}_1\right) + \\[2mm] + \dfrac{\bar{R}_k^2 \bar{h}_k}{\sqrt{3}\bar{R}_1} + \dfrac{1}{\sqrt{3}}\left(\begin{array}{c} 2\bar{R}_k^2 - \sqrt{3\bar{R}_1^4 + \bar{R}_k^4} + \\ + \bar{R}_k^2\ln\left(\dfrac{\bar{R}_k^2 + \sqrt{3\bar{R}_1^4 + \bar{R}_k^4}}{3\bar{R}_1^2}\right) \end{array}\right) + \\[2mm] + \dfrac{1 + k^2 + 2\mu_s}{\sqrt{3}k}A + \dfrac{\bar{h}}{\sqrt{3}}\left(1 - k\dfrac{1 - \bar{R}_k^2}{2\bar{h}}\right) + \\[2mm] + \left(1 + 2\mu_s\right)B + 2\dfrac{\left(\bar{R}_k^2 - \bar{R}_1^2\right)\bar{R}_1}{3\sqrt{3}\bar{h}_k} + \\[2mm] + \dfrac{4\mu_s}{\sqrt{3}}\left(\bar{H}_0 - \Delta\bar{H}_x + \dfrac{\left(1 - \bar{R}_k^2\right)\Delta\bar{l}_1}{\bar{h}} + \dfrac{\bar{R}_k^2 \Delta\bar{l}_2}{\bar{R}_1}\right) \end{bmatrix}, \quad (1)$$

where

$$A = \frac{1 - \bar{R}_k^2}{2} + \left(\bar{R}_k - \frac{\bar{h}_k}{k}\right)\left(1 - \bar{R}_k\right) + \\ + \left(\frac{\bar{h}_k^2}{k^2} - 2\frac{\bar{R}_k \bar{h}_k}{k}\right)\ln\left(1 + \frac{k\left(1 - \bar{R}_k\right)}{\bar{h}_k}\right),$$

$$B = \frac{3\bar{R}_k^2\left(\bar{R}_k - \bar{R}_1\right) - \left(\bar{R}_k^3 - \bar{R}_1^3\right)}{3\sqrt{3}\bar{h}_k},$$

$$\bar{h}_k = \frac{\bar{h}}{\bar{R}_0 - \bar{R}_1}\left(\bar{R}_k - \bar{R}_1\right)$$

is the relative height of kinematic module 4.

Determining the magnitude of the reduced pressure according to CS-1a does not cause difficulties given the presence of the elementary kinematic modules of the rectangular shape only.

4. 2. Analysis of the amount of the reduced pressure in the process estimation scheme

In order to analyze the magnitude of the reduced pressure in the developed calculation scheme CS-1, the position of the boundary of the flow interface $\bar{R}_k \in [\bar{R}_1, 1]$ should be considered as an optimizing parameter. In this case, the boundary positions of the magnitude $\bar{R}_k = \bar{R}_1$ and $\bar{R}_k = 1$ match the degeneration of the process of the combined radial-direct extrusion into direct or radial ones, respectively. We shall study a change in the amount of reduced pressure at the initial stage of the deformation process. Increasing the relative

thickness of the flange h while maintaining the remaining deformation process ratios reduces the amount of the reduced pressure (Fig. 3, a). In this case, the optimal value of the boundary of the flow interface in the relative dimensions $\bar{R}_k$ shifts to the left, that is, it corresponds to the increase in the size of module 4, which is responsible for the formation of the flange zone. The deterioration of contact friction conditions, on the contrary, entails an increase in the amount of the reduced pressure and a shift in the optimal value of $\bar{R}_k$ to the right, which indicates a more intense flow of the metal into an axial protrusion (Fig. 3, b). This can be explained by the more significant impact of friction conditions as they hinder the flow into the flange zone, given the larger area of the contact between a billet and the lower matrix (modules 4 and 5). It is possible to optimize the reduced pressure based on the $\bar{R}_k$ parameter for different values of the relative radius of the axial protrusion $\bar{R}_1$ while maintaining the remaining deformation process ratios. In this case, the increase in the relative radius of the axial protrusion leads to a decrease in the reduced pressure, and the deviation of magnitude $\bar{R}_k$ from $\bar{R}_1$, at the same time, slightly decreases (Fig. 3, c).
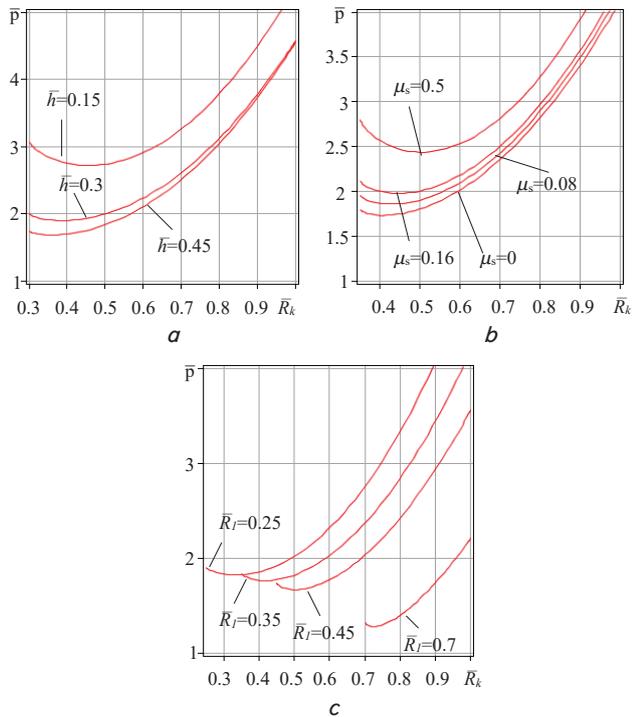

Fig. 3. Dependences of the reduced pressure $\bar{p}$ on the $\bar{R}_k$ parameter: a — at $\bar{R}_1=0.6$, $\mu_s=0.08$ and different $\bar{h}$; b — at $\bar{R}_1=0.35$, $\bar{h}=0.3$ and friction conditions; c — at $\bar{h}=0.35$, $\mu_s=0.08$ and different $\bar{R}_1$

In the context of using the energy method, the criterion for choosing the calculation scheme of the process as the most rational one is the condition of the lowest value of the reduced pressure. We shall conduct a comparative analysis of the magnitudes of the reduced pressure for $\bar{R}_k$, obtained for the CS-1 scheme, and its alternative CS-1a scheme, with a rectangular kinematic module 4a. The magnitude of the reduced pressure for the PC-1a calculation scheme is also optimized based on the boundary of the flow interface $\bar{R}_k \in [\bar{R}_1,1]$. The comparative analysis of the CS-1 and CS-1a calculation schemes has revealed a significant difference in both the quantification and the character of the change in the

reduced pressure (Fig. 4). The optimization based on the $\bar{R}_k$ parameter for the developed calculation scheme CS-1 is possible at the different process ratios (Fig. 3, 4). However, for the alternative scheme CS-1a, a monotonous increase in $\bar{p}$ is possible at all possible values of $\bar{R}_k \in [\bar{R}_1,1]$ for $\bar{R}_1=0.5$ at the initial stage of deformation, as well as the possibility of such optimization when increasing the relative radius of the axial protrusion. In this case, for different ratios, the amount of the reduced pressure according to the CS-1 scheme is definitely lower than the values obtained on the basis of the alternative CS-1a scheme; the deviation can reach 50 % and larger (Fig. 4).
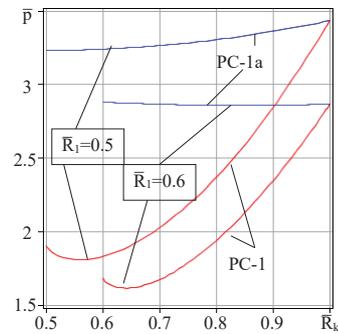

Fig. 4. Dependences of the reduced pressure $\bar{p}$ on the parameter $\bar{R}_k$ at $\bar{h}=0.6$, $\mu_s=0.08$, and different $\bar{R}_1$

Thus, the developed scheme CS-1 should be considered preferable at the stage of analyzing the reduced pressure as the magnitude characterizing the assessment of the force regime of the process of the combined radial-direct extrusion of parts with a flange and an axial protrusion.

4. 3. Predicting the shape change in a semi-finished product in the process of aligned radial-direct extrusion

As noted above, the main issue in assessing the technological capabilities of the combined extrusion processes with several degrees of freedom of the metal flow is to acquire data on the gradual shape change in a semi-finished product that correspond to reality. It is therefore necessary to control the adequacy of the assessment based on the increments in the size of a semi-finished product obtained on the basis of the developed estimation schemes. Experimental studies of the combined radial-direct extrusion of parts with a flange and an axial protrusion were carried out in order to verify the validity of assessing a shape change in a semi-finished product (Fig. 5).

Fig. 5. Parts with an axial protrusion obtained by the combined radial-direct extrusion

Experimental studies were conducted at the MS-500 test press using universally-reconfigurable equipment involving the application of methods of dividing grids, the macrostructure detection, as well as strain gauging. The combined radial-direct extrusion produced the parts made from the aluminum alloy AD1 with an external diameter of 42 mm and 28.2 mm and with an axial protrusion with a diameter of 25, 21, and 15 mm (Fig. 5). The technological lubricant used was lamb fat. In this case, attention was paid to obtaining data on the stressed-strained state, which determines the choice of the configuration of the modules of a calculation scheme, the evaluation of the force regime, and the peculiarities of shape change in a semi-finished product [17].

We shall analyze the possibilities of using the calculation scheme CS-1 to predict the shape formation during the deformation process at the different process ratios and their impact.

Taking into consideration the possibility of determining the optimal value of the boundary of the flow interface, the increments in a semi-finished product in the radial direction $\Delta l_1 \rightarrow$ and forming the axial protrusion $\Delta l_2 \downarrow$, take the following form:

$$\begin{cases} \Delta l_2 \downarrow = \Delta l_i \downarrow = \Delta l_{i-1} \downarrow + \Delta \cdot \dfrac{R_{ki}^2}{R_0^2}, \\ \Delta l_1 \rightarrow = \sqrt{\dfrac{R_0^2 \Delta Hx - R_1^2 \Delta l_2 \downarrow}{h} + R_0^2} - R_0, \end{cases} \quad (2)$$

where i is the iteration number; Δ is the step of the iteration.

These calculations are used for any calculation scheme CS-1 and CS-1a for the appropriate optimal values of the magnitude $R_k \in [R_1, R_0]$.

The effect of friction conditions on the growth of the flange area size is shown in Fig. 6. Favorable friction conditions ($\mu_s = 0$) contribute to a more intensive filling of the flange area. This indicates that friction as an unfavorable factor in terms of the radial component of the flow to the flange zone due to the large area of the contact between a billet and a tool in zones 4 and 5.
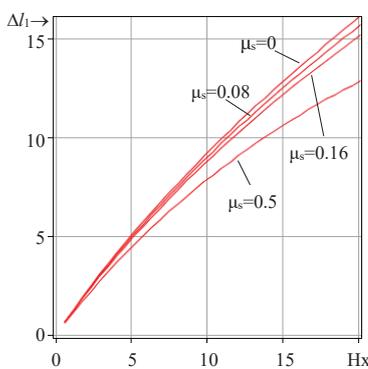

Fig. 6. Dependences of the increments in a semi-finished product in the flange zone during the process at $R_1 = 8$ mm, $R_0 = 20$ mm, $h = 7$ mm, $H_0 = 30$ mm for the CS-1 scheme under different friction conditions

The comparative analysis of a semi-finished product's increments during the process, derived from the CS-1 and CS-1a schemes, shows a significant difference in the quantitative and quantitative character of their change (Fig. 7). Under the conditions of friction $\mu_s = 0.08$, characteristic of cold extrusion, at the initial stage, when using the CS-1a

scheme, the optimal value is $R_k \rightarrow R_1$, which corresponds to the degeneration of module 3 and the predominant radial flow of the metal. Further, with the increase in the influence of the friction forces, the contact of the blank with the lower matrix (modules 4 and 5) undergoes a shift R_k to the right in the direction of the increase and a more intensive formation of an axial protrusion (Fig. 7, blue solid line). In this case, in the beginning, there is an underestimation of the incremental growth of the axial protrusion, along with an overestimation of the size of the flange area. For the increments $\Delta l_1 \rightarrow$ and $\Delta l_2 \downarrow$, derived from CS-1, the increase in the rate of an axial protrusion growth occurs more smoothly throughout the deformation process, which corresponds to reality (Fig. 7). The comparative analysis with the experimentally obtained data for increments $Dl_2 \downarrow$ (Fig. 7, point data) shows the validity of the CS-1a calculation scheme (the deviations do not exceed 7–10 %). In this case, there are significant deviations for CS-1a (the overestimation can reach two times in the final stage). Thus, the assessment of the form-changing, obtained on the basis of the CS-1 calculation scheme, has been confirmed.
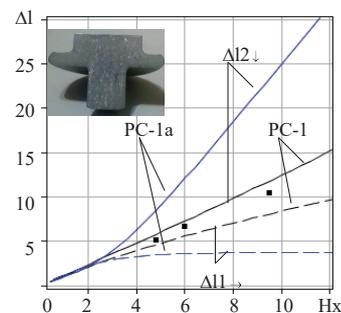

Fig. 7. Dependences of a semi-finished product's increments during the process at $R_1 = 7.8$ mm, $R_0 = 14.1$ mm, $h = 4$ mm, $H_0 = 20$ mm, $\mu_s = 0.08$ for the CS-1 (black) and CS-1a (blue) schemes

More informatively, in terms of assessing the change in the character of the metal flow during the deformation process, is the study of the change in the magnitude of $\delta = \bar{R}_k - \bar{R}_1$ – the deviations in the boundary of the flow interface of R_k from R_1 (in relative sizes) (Fig. 8). For the CS-1a calculation scheme, the factual impossibility of optimizing based on the $\bar{R}_k$ ($\bar{R}_k \rightarrow \bar{R}_1$) parameter is typical of the initial stage of the deformation process: Fig. 8, curves (2.1) and (2.2). Subsequent deformation is characterized by a sharp jump in the value of $\bar{\delta} = \bar{R}_k - \bar{R}_1$ up to the transition to direct extrusion – Fig. 8, curve (2.2).

For the CS-1 calculation scheme, the R_k-based optimization is possible throughout the entire deformation process; the increase in the share of direct extrusion in relation to the radial component (the increase in δ) proceeds more smoothly: Fig. 8, curves (1.1) to (1.4).

In this case, the deterioration of friction conditions entails the higher deviations $\bar{\delta}$ for different process ratios. This is due to the higher proportion of the metal forming the axial protrusion: Fig. 8, curves (1.1) and (1.3), (1.2) and (1.4). Thus, the comparative analysis of the assessment of the shape change in a semi-finished product derived from the proposed calculation schemes and those established experimentally suggests that the use of CS-1a that contains the trapezoidal kinematic module 4 is preferable.
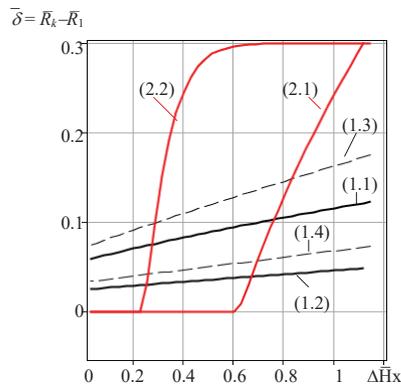
Fig. 8. Dependences of the deviation $\overline{\delta}=\overline{R}_k-\overline{R}_1$ in the course of the process at $\overline{h}=0.35$, $\overline{H}_0=1.5$ for schemes CS-1 (black) and CS-1a (red): scheme CS-1: (1.1) $-\overline{R}_1=0.4$, $\mu_s=0.08$; (1.2) $-\overline{R}_1=0.7$, $\mu_s=0.08$; (1.3) $-\overline{R}_1=0.4$, $\mu_s=0.16$; (1.4) $-\overline{R}_1=0.7$, $\mu_s=0.16$; scheme CS-1a: (2.1) $-\overline{R}_1=0.4$, $\mu_s=0.08$; (2.2) $-\overline{R}_1=0.7$, $\mu_s=0.08$

5. Discussion of the results of forecasting the shape formation of parts with a flange and an axial protrusion

The proposed calculation scheme CS-1 that contains the trapezoidal kinematic module 4 (Fig. 1) makes it possible to describe the character of the metal flow in the region where the metal flow is divided into the direct and centrifugal radial extrusion. As an alternative, the calculation scheme CS-1a has been suggested, obtained as a special case of the degeneration of trapezoidal module 4 into the rectangular one, 4a. The resulting expression of the reduced pressure according to (1) allows the optimization of a given value based on the R_k parameter, which corresponds to the boundary of the flow interface. The analysis of the behavior of the reduced pressure function for CS-1 confirms the possibility of optimizing a given value based on the R_k parameter at the different ratios of the geometric parameters of the deformation process and friction conditions. The comparative analysis of the theoretical calculations of the optimal value of the reduced pressure according to the CS-1 and CS-1a schemes (with the presence of a rectangular kinematic module 4a) has been carried out. The overestimation data based on CS-1a relative to CS-1 can be as high as 50 % or larger, which suggests the benefits of using CS-1 to assess the force mode. This is because for the initial phase of deformation for CS-1a at the low values of the radius of the axial protrusion and the friction factor, the optimal value is $\overline{R}_k \to \overline{R}_1$. Thus, for a given set of kinematic modules of the simplest rectangular shape, it is not possible to use the optimization possibilities in full. The distortion of the dividing grid also confirms the preference for using the CS-1 estimation scheme with the trapezoid module 4 with a sloping boundary. The resulting dependences of a semi-finished product's increments in the flange area and the axial protrusion area make it possible to predict the shape formation of a part. The comparative analysis of a semi-finished product's increments during the process with experimental data also confirms the preference

for using the CS-1 calculation scheme. Thus, the developed CS-1 calculation scheme with the presence of the trapezoidal module 4 makes it possible to assess the possibilities of using the process of the combined radial-direct extrusion in terms of obtaining the required dimensions of a part.

A given calculation scheme is designed for the simplest shape of a tool (without edges, facets, rounds). A more complex configuration of the tool requires a correction of the magnitude of the reduced pressure (1), taking into consideration changes in the components for kinematic modules 5 and 6 of the new form.

It is promising to assess the possibility of using CS-1 as an autonomous deformation site in the simulation of the initial stage (the disconnected deformation site) of the trilateral radial-reverse-direct extrusion process (scheme A, Table 1).

6. Conclusions

1. We have considered, as alternatives to the schemes of the process of the combined aligned radial-direct extrusion of parts with a flange and an axial protrusion, the schemes CS-1 (containing a trapezoidal module 4) and CS-1a (containing elementary kinematic rectangular modules). The set of the kinematic modules used in CS-1 makes it possible to better describe the characteristic regions of metal flow to the axial protrusion and flange. The R_k optimization parameter used corresponds to the boundary of the interface of the metal flow to the axial protrusion (direct extrusion) and the flange (radial current).

2. The effect of the geometric ratios of the process and friction conditions on the optimal value of the reduced pressure and the position of the boundary of the flow interface has been analyzed. Significant differences in the character of change in the amount of the reduced pressure and the optimization possibilities based on the R_k parameter for the proposed estimation schemes have been revealed. According to the condition of the minimum reduced pressure, the preferred calculation scheme is PC-1 with the presence of the trapezoidal kinematic module 4; the divergence relative to calculations based on the CS-1a scheme can reach 50 % or higher.

3. A comparative analysis of the increments in a semi-finished product during the process of deformation, obtained on the basis of the considered calculation schemes and derived experimentally, has been performed. The presence of the trapezoidal kinematic module 4 in CS-1 has allowed us to better describe the form of the components of the kinematic modules and to more fully use the possibilities of optimizing the reduced pressure along the boundary of the flow interface R_k. The deviation from the experimentally obtained data does not exceed 7–10 %, which indicates the consistency of evaluating the shape change of a semi-finished product based on the CS-1 scheme.

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