Results of calculation of pressure distribution along the gap for the hydrostatic extrusion scheme with an uncompressed shank

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Abstract. Hydrostatic extrusion implemented in the fluid friction regime creates the most favorable stress state of the billet in the deformation zone, which ensures its improved mechanical properties: increased yield strength and strength with a high margin of plasticity, and greater uniformity. In order to implement the fluid friction regime throughout the entire process, a hydrostatic extrusion scheme with an uncompressed shank is proposed with the working chamber structurally divided into two cavities – radial and axial ones, and process design schemes are developed. The paper presents the results of calculation of pressure distribution along the shank for this scheme with regard to non-isothermal fluid flow in a thin annular gap, their graphical interpretation (pressure distribution diagrams along the shank at pressure drops ΔP), and data analysis. The pressure calculation results obtained can be used to determine the gap along the shank with regard to elastic deformation of the working chamber walls and the shank, and to adjust the calculation of other process parameters.

1. Introduction
At present, the development of technical solutions undoubtedly allows improvement of topical issues of science and technology [1–7]. Hydrostatic extrusion of materials is one of the most advanced methods to process brittle and difficult to deform materials by plastic deformation in a cold state. As a result of hydrostatic extrusion, an increased hydrostatic pressure is created in the deformation zone of materials [8–15]. Implementation of hydrostatic extrusion in the fluid friction regime enhances, other conditions being equal, a positive effect of high hydrostatic pressure of the working fluid directly in the deformation zone.
To implement the fluid friction regime throughout the entire process, three conditions must be met:

a) high speed of movement of the billet;
b) a small taper angle of the tool;
c) high viscosity of the working fluid.

However, even a combination of these conditions does not always yield positive hydrostatic pressing results, and fulfillment of one of the conditions causes negative effects. Thus, increased speed can cause extrusion of the most part of the billet in a regime different from the fluid one and, as a result, strong heating of the material (undesirable effect); decreased taper angle of the tool increases the tool size, which significantly increases the dry friction force at the beginning of the process; increased viscosity of the working fluid limits the range of working pressure, and the product surface often becomes wavy.

This problem can be solved through constructive division of the working chamber into two cavities, and required pressure is built therein to ensure higher working fluid pressure at the inlet to the deformation zone compared to the contact stresses between the billet and the tool. Figure 1 shows a hydrostatic extrusion scheme with an uncompressed shank. Division of the cavity into radial (1, figure 1) and axial (2, figure 1) parts provides hydrostatic pressing in the fluid friction regime: the pressure drop $\Delta P = P_1 - P_2$ required in cavities 1 and 2 is created during hydrostatic extrusion by throttling the working fluid in a thin annular gap between the chamber walls and the shank (3, figure 1).

![Figure 1. Scheme of hydrostatic extrusion with an uncompressed shank: 1 – radial cavity of the working chamber; 2 – axial cavity of the working chamber; 3 – shank; 4 – billet; $d_b$ – billet diameter; $d$ – shank diameter; $\ell$ – shank length; $V$ – speed of movement of the shank with the billet; $P_1$ – fluid pressure in the radial cavity; $P_2$ – fluid pressure in the axial cavity; $x$, $r$ – fixed cylindrical coordinate system.](image)

Viscous fluid flowing in a thin annular gap inevitably causes its heating [1], and in this case, accurate mathematical models to calculate hydrostatic extrusion parameters should be developed with regard to non-isothermal fluid flow.

During hydrostatic pressing, high pressures are built in the working chamber of the container, therefore elastic deformation of the chamber walls and the shank should be considered. It should be noted that technological processes typically employ autofretted containers; as a result, the material of the container and the shank undergo only elastic deformation throughout the process.

In order to evaluate the conditions and techniques to consider these deformations during hydrostatic extrusion with an uncompressed shank with regard to non-isothermal fluid flow, the first step of the
mathematical model designed for calculating the process parameters should include determination of pressure distribution along the shank. The analysis of the calculated pressure data allows calculation of the gap along the shank with regard to elastic deformation and adjustment of the calculation of other process parameters. Thus, it can be argued that the topic is relevant; the aim of the study and problems to be solved can be formulated.

The aim of the study is to calculate pressure distribution along the shank using the developed mathematical model of the non-isothermal fluid flow in a thin annular gap.

Objectives:
- to develop a design scheme for hydrostatic extrusion with an uncompressed shank;
- to analyze the calculated pressure data for different diameters of the billet (4, Figure 1), to obtain graphical interpretation of the data (graphs of pressure distribution along the shank for different pressure drops $\Delta P$);
- to draw conclusions about the effect of the data obtained on calculation of the gap along the shank and other process parameters.

2. Design schemes. The main relationships

For hydrostatic extrusion of materials, installations typically used are supplied with containers that have a through hole of constant cross section and, therefore, constant stiffness along the length. As can be seen in Figure 1, the scheme of hydrostatic extrusion of materials consists of the working chamber divided into two cavities during the working cycle – radial cavity $1$ and axial cavity $2$, which are under different hydrostatic pressures $P_1$ and $P_2$.

To calculate the elastic deformation of the working chamber surface, an exact solution can be used with respect to the loading system presented in figure 2.

![Figure 2. Pressure distribution along the gap between the shank and the working chamber.](image)

When calculating the elastic deformation of the shank surface, the scheme shown in figure 3 (a) can be taken as the design scheme, while the real nature of the pressure distribution is shown in figure 3 (b).
Figure 3. Pressure diagrams on the shank: $P(x)$ – pressure distribution in the liquid layer; $P_1$ and $P_2$ – fluid pressure in the radial and axial cavities, respectively; $\sigma_x$ – axial stresses in the billet.

The pressure drop in cavities 1 and 2 (figure 1) required for implementation of the fluid friction regime, is created during hydrostatic extrusion by throttling the working fluid in a thin annular gap between the walls of the container and shank 3. The increased pressure $P_1$ compared to $P_2$ leads to a decrease in axial compressive stresses $|\sigma_x|$. This decrease in $|\sigma_x|$, provided it remains sufficient for subsequent pressing of the billet, and an increase in pressure $P_1$ create the conditions for formation of a liquid lubricant layer at the inlet to the deformation zone, that is, hydrostatic extrusion is implemented in the fluid friction regime.

To calculate the gap along the shank, it is necessary to determine the pressure in the gap on the assumption that it is a constant cross-section. The resulting pressure distribution will be the first approximation which is to be made more precise if the gap noticeably changes along the shank.

The pressure along the gap is determined using the following equation [1]:

$$
\frac{1}{\alpha + \frac{k}{\rho c}} \exp \left[ -\frac{kV}{Q \rho c} \pi \left( \frac{NV}{BQ + AV} - d^2 \frac{G}{K} \right) (P_1 - P(x)) \right] \cdot \left\{ \exp \left[ (\alpha + \frac{k}{\rho c})(P_1 - P(x)) \right] - 1 \right\} = \mu_0 \exp(\alpha P_1)(BQ + AV)x
$$

where $\alpha$ is the piezoelectric coefficient of the fluid viscosity; $\lambda$ is the temperature coefficient of the fluid viscosity; $\rho$ is the density of the fluid; $c$ is the heat capacity of the fluid; $k$ is the coefficient characterizing the dissipation of energy, $k = 1$; $\Psi = (D_{\text{sh}}/d)^2$ is dimensionless gap parameter between the container and the shank; $Q$ is the fluid flow in the gap between the shank and the working chamber walls; $\mu_0$ is fluid viscosity under normal conditions; $V$ is the speed of movement of the shank with the billet; the coefficients $A$ and $B$ have the form:

$$
A = \frac{32}{d^2} \frac{c}{1 - \Psi (1 - \Psi) + \ln \Psi (1 + \Psi)} \left( 1 + \frac{1 - (1 - \Psi)}{\Psi \ln \Psi} \right)
$$

$$
B = \frac{128}{d^4} \frac{\Psi}{1 - \Psi (1 - \Psi) + \ln \Psi (1 + \Psi)}
$$

Some results of solution (1) are presented in the form of graphs in Figures 4–5. The following values were used for the calculations:

$\mu_0 = 0.10^{\circ}$ Pa·s – the fluid viscosity that consists of a mixture of 50% glycerol and 50% ethylene glycol under normal conditions;
\( \rho = 1300 \text{ kg/m}^3 \) – the fluid density;
\( \alpha = 0.42 \cdot 10^{-8} \) – the piezoelectric coefficient of the fluid viscosity;
\( d_b = 1.8 \) and 3.0 mm – the billet diameter;
\( D_{ch} = 10.1 \) mm – the working chamber diameter in the initial state (the graphs show the current diameter value at working pressure);
\( d = 9.8 \) mm – the shank diameter in the initial state (the graphs show the current diameter value);
\( \ell = 25 \) mm – the shank length;
\( P_2 = 1.5 \cdot 10^8 \) Pa – the working fluid pressure in the axial cavity during the process;
\( \Delta P = P_1 - P_2 = 0.25 \cdot 10^8 \ldots 9 \cdot 10^8 \) Pa – the pressure drop along the shank;
\( D_c = 0.174 \) m – the outer diameter of the container;
\( \nu = 0.3 \) – the Poisson’s ratio;
\( E = 2.1 \cdot 10^{11} \) – the Young’s modulus of elasticity.

Figure 4. Graph of pressure distribution along the shank: \( D_{ch} = 10.19 \) mm; \( d = 9.77 \) mm;
\( d_b = 3.0 \text{ mm}: 1 \) – \( V = -51.15 \cdot 10^{-3} \) m/s; \( 2 \) – \( V = -39.67 \cdot 10^{-3} \) m/s; \( 3 \) – \( V = -29.70 \cdot 10^{-3} \) m/s;
\( 4 \) – \( V = -20.97 \cdot 10^{-3} \) m/s; \( 5 \) – \( V = -13.24 \cdot 10^{-3} \) m/s; \( 6 \) – \( V = -6.30 \cdot 10^{-3} \) m/s;
\( d_b = 1.79 \text{ mm}: 1 \) – \( V = -47.95 \cdot 10^{-3} \) m/s; \( 2 \) – \( V = -37.21 \cdot 10^{-3} \) m/s; \( 3 \) – \( V = -27.87 \cdot 10^{-3} \) m/s;
\( 4 \) – \( V = -19.69 \cdot 10^{-3} \) m/s; \( 5 \) – \( V = -12.43 \cdot 10^{-3} \) m/s; \( 6 \) – \( V = -5.92 \cdot 10^{-3} \) m/s.
3. Results and their analysis

Analysis of the data on the pressure distribution along the shank in the range of pressure drop $\Delta P = 0.25 \times 10^3 \ldots 1.5 \times 10^3$ atm for two billet diameters $d_b = 1.79$ and 3.0 mm revealed insignificant difference between them. The graphs of pressure distribution along the shank actually coincide, and the pressure change along the gap is close to linear with insignificant pressure drops (Figure 4).

Figure 5 shows that at large pressure drops in the range $\Delta P = 3 \times 10^3 \ldots 9 \times 10^3$ atm the curves exhibit a pronounced nonlinear pattern, and the pressure values along the shank differ for different billet diameters $d_b = 1.8$ and 3.0 mm (curve 6 is close to linear with a small pressure drop $\Delta P = 1.5 \times 10^3$ atm for $d_b = 3$ mm and $\Delta P = 1 \times 10^3$ atm for $d_b = 1.79$ mm).

The obtained data on the pressure distribution at small pressure drops $\Delta P$ can be used as a first approximation in calculating the gap along the shank using exact elementary methods for determining elastic deformation of the walls of the container and the shank. At pressure drops of the order of $\Delta P = 6 \times 10^3 \ldots 9 \times 10^3$ atm, the main pressure drop falls on about 20% of the shank length $\ell$. In this case, it is necessary to use other methods for calculating elastic deformation, for example, variational ones.

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