Determination of the parameters of viscous fluid flowing in an annular gap during continuous hydrostatic extrusion

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Abstract. The study of deformation of solids by high-pressure liquid (hydrostatic extrusion) is not only an interesting research problem, but an applied one. Hydrostatic extrusion method is currently widely used in various sectors of industry – from mechanical engineering to the food industry. This field of research seems relevant and promising. The paper presents the calculation results for some parameters of continuous hydrostatic extrusion of materials, shows graphs of the dependence of the axial stress in the billet on the total pressure drop along the length and graphs of the dependence of the total pressure drop along the length on the working fluid flow rate in the annular gap. The calculations were performed for the adiabatic fluid flow and for the flow with partial heat transfer. Analysis of the calculation results showed that for fixed flow rates of the working fluid and specified heat transfer conditions, maximum axial stresses can be obtained by optimal values taken for the ratios of the working chamber and the billet diameters.

1. Introduction

Advanced technical solutions help to improve topical issues of science and technology [1–7]. The main advantage of the hydrostatic extrusion process is a favorable stress state of the material in the deformation zone to press hard-to-deform brittle materials under normal conditions. Under high hydrostatic pressure, ductility of these materials significantly increases. Increased ductility facilitates extrusion of many highly deformed materials. This advantage is particularly effective if a liquid lubricant layer is formed between the tool (die, die) and the billet during hydrostatic extrusion. The mode of the hydrodynamic lubrication formed between the pressed billet and the tool depends on correct calculation of the main process parameters. These parameters should be calculated using a mathematical model adequate to the real physical process. In [8], the mathematical model implies movement of the plunger during hydrostatic extrusion with regard to the non-isothermal fluid flow in the annular gap. Comparison of the theoretical curves plotted using the determined parameters and their experimental
values showed that the calculated theoretical model is in agreement with actual process. Therefore, we use this mathematical model for calculations.

The aim of the study is to calculate the parameters of continuous hydrostatic extrusion and their graphical representation using a mathematical model of the non-isothermal fluid flow in the annular gap in conditions of large pressure drops.

Tasks to be fulfilled:
- to develop a practical scheme of the method to generate axial force and to determine the parameters of the viscous fluid flow;
- to implement a mathematical model of the non-isothermal flow of viscous fluid in a thin annular gap to calculate the parameters of the working environment;
- to plot a dependency graph: axial stress in the billet on the total pressure drop, and the total pressure drop on the working fluid flow in the annular gap.

2. Calculating the parameters of viscous fluid for the scheme of continuous hydrostatic extrusion of materials

The flow of viscous fluid in a thin gap in conditions of large pressure drops and fixed walls has been considered in many studies, for example, in [8–12]. Analysis of these studies shows that viscous fluid heats up when it flows in a thin gap in conditions of large pressure drops [11–12]. A change in the temperature field of the working fluid, that is, consideration of the non-isothermal nature of its flow, seems to be correct, since it allows us to understand the real nature of hydrostatic extrusion and create a valid mathematical model of the viscous fluid flow in a thin gap in conditions of large pressure drops. In [8], the authors suggest a mathematical model for hydrostatic extrusion with regard to the non-isothermal nature of the fluid flow in the annular gap in conditions of large pressure drops. Consistency of theoretical curves (change in fluid pressure in the chamber against the speed of the uncompressed plunger) with experimental data proves the correctness of the developed mathematical model. Therefore, take the equations obtained by the authors in [8] and use them to determine the characteristics of continuous hydrostatic extrusion of materials. Given the non-isothermal nature of flow of a viscous fluid in a thin annular gap, we thereby set the rheology of the working medium most closely approximated to the real physical process.

Figure 1 presents a scheme for generating an axial force, where $d$ is the diameter of the billet; $D$ is the diameter of the working chamber; $\ell$ is the estimated length of the working chamber; $V$ is the speed of movement of the billet; $\sigma$ is axial stresses in the billet at the outlet from the working chamber; $Q$ is the flow rate; $P_1$ is pressure at the inlet to the working chamber; $P_2$ is pressure at the outlet from the working chamber; $x, r$ is the cylindrical coordinate system. We assume that the die is an absolutely rigid body.

![Figure 1. Scheme for generating an axial force: billet (1); working chamber (2).](image-url)
Use the equation that determines the functional dependence of the pressure drop \((P_1 - P_2)\) and the flow rate \(Q\) [1]:

\[
\frac{1}{\alpha + \frac{\lambda k}{\rho c}} \exp \left[ -\frac{\lambda k V}{Q} \frac{P_1 - P_2}{BQ + AV} - d^2 E \right] \left( \exp \left[ \left( \alpha + \frac{\lambda k}{\rho c} \right) (P_1 - P_2) \right] - 1 \right) = \mu \exp (\alpha P_1) (BQ + AV) l,
\]

where \(l\) is the length of the working chamber (figure 1).

Transcendental equation (1) was solved using the Newton method. As a result, the flow rate characteristic for the liquid layer in the annular gap with one movable boundary was determined.

At the same time, the axial force generated by the liquid flow was determined using the following equation [1]:

\[
F = \pi NV \frac{P_1 - P_2}{BQ + AV} - \pi d^2 E (P_1 - P_2),
\]

where

\[
N = \frac{4}{\ln \psi}, \quad E = \frac{1}{4} \left[ \frac{1 - \sqrt{\psi}}{\psi / \ln \psi} + 1 \right].
\]

In equation (4), \(\psi = (d/D)^2\) (figure 1).

Then we determined the axial stress arising in the billet at the outlet from the working chamber. The calculations were performed using the following data: 1) the working fluid is glycerol; rheological characteristics of glycerin: \(\mu_0 = 1.460 \text{ H} \cdot \text{s/m}^2; c = 2304.5 \text{ J/(kg \cdot deg)}; \rho = 1290 \text{ kg/m}^3; \alpha = 0.565 \cdot 10^{-8} \text{ 1/Pa}; \lambda = 0.02 \text{ 1/deg}; 2) geometric parameters: \(d = 0.005 \text{ m}; \psi = 0.35\ldots0.95; l = 0.1 \text{ m}; 3) the speed of the billet movement \(V = 0.1 \text{ m/s} \).

Some calculation results obtained using this mathematical model are presented in Figures 2–5: graphs of the dependence of the axial stress in the billet \(\sigma\) on the total pressure drop along the length \(\Delta P\) (figures 2–3) and graphs of the dependence of the total pressure drop along the length \(\Delta P\) on the working fluid flow in the annular gap (figures 4–5).

The graphs are shown for the adiabatic flow \((K = 1)\) and for the flow with partial heat transfer \((K = 0.6)\).

3. Results and their analysis

Analysis of the graphs of the dependence of the axial stresses in the billet \(\sigma\) on the total pressure drop \(\Delta P = P_1 - P_2\), that is, \(\sigma = f(\Delta P)\) (figures 2–3), showed the following:

a) dependence of the axial stresses in the billet \(\sigma\) on the total pressure drop \(\Delta P\) is close to linear;

b) impact of the dissipation coefficient \(K\) on characteristics of the viscous fluid flow in a thin annular gap is insignificant;

c) the smaller \(\psi = (d/D)^2\), the greater value of \(\sigma\) is achieved in conditions of an equal total pressure drop \(\Delta P\).

Analysis of the flow characteristics presented in figures 4–5 showed that:

a) the coefficient \(\psi\) strongly affects the characteristics of the process;

b) the dissipation coefficient \(K\) has a significant effect on the flow characteristics.

There are optimal values of the parameter \(\psi\) for specified heat transfer conditions. Maximum axial stresses can be obtained for these values at fixed flow rates of the working fluid.
Figure 2. Graph $\sigma = f(\Delta P)$ $K = 1$.

Figure 3. Graph $\sigma = f(\Delta P)$ $K = 0.6$. 
Figure 4. Graph $\Delta P = f(Q)$ $K = 1$.

Figure 5. Graph $\Delta P = f(Q)$ $K = 0.6$.

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