Determination of parameters of the clearance with consideration to elastic deformations in various schemes of hydroextrusion

L S Prokhasko1, R V Zalilov2, E V Terenteva3, M P Timoshenko3 and I V Sokolov3

1 South Ural State University (national research university), 76, Lenin Avenue, Chelyabinsk, 454080, Russia
2 Nosov Magnitogorsk State Technical University, 38, Lenin Street, Magnitogorsk, 455000, Russia
3 K G Razumovsky Moscow State University of technologies and management (the First Cossack University), 73, Zemlyanoy Val, Moscow, 109004, Russia

E-mail: prokhaskols@mail.ru

Abstract. The scheme of all-around (triaxial) compression of the deformable material in the deformation center is the most favorable and desirable scheme from the point of view of giving the material high values of its physical and mechanical properties. The intention to bring real technological processes closer to implementation of this scheme led to development of range of technologies for processing materials with a high-pressure fluid and, in particular, hydroextrusion of materials. The hydroextrusion process in the most comprehensive way meets the requirement of all-around compression scheme of material when it is compressed in the hydrodynamic friction mode, which stable nature of flow depends on flow rate of a working fluid entering through the annular clearance between the plunger and the chamber. The flow rate is determined by pressure differential and the parameters of the clearance itself. Therefore, there is a need for analytical study of clearance parameters for various hydraulic extrusion schemes. This article analyzes the work motion pattern of an uncompacted plunger in a solid container and for hydroextrusion with an uncompressed shank. For these hydroextrusion schemes the mathematical equations are proposed in order to determine the parameters of the clearance, taking into account the elastic deformations of the container and the plunger (shank).

1. Introduction
Numerous scientific researches have been devoted to study of hydroextrusion both in our country and abroad [1-4]. Some scientific researches contain theoretical developments, while others also present the results of practical application of the process based on developed mathematical models [5-7].

The hydroextrusion method of processing, despite the complexity of implementation, has a number of undeniable advantages in comparison with other technologies for processing solid materials. The main advantage of the hydroextrusion process is the favorable stress state of a material in the deformation zone, which allows, for example, pressing materials which are hard to deform and which are brittle under normal conditions. This is a technology that allows reducing the loss of material, in particular, metal. Being exposed to high hydrostatic pressure the plasticity of solid materials...
significantly increases. Due to this circumstance, it becomes possible to extrude (press) many materials with large degrees of deformation, which is impossible, for example, when drawing. This advantage is particularly efficient if a fluid lubricating layer is formed between the tool (matrix, draw die) and the blank during the hydroextrusion process. Under these very conditions a high-quality extrusion of the blank is implemented, while the speed of pressing (extrusion) is determined by the flow rate of a working fluid from the source of pressure. The flow rate depends on change in the pressure of a working fluid in the thin annular clearance between the plunger (shank) and the container, as well as the size of the clearance itself.

This problem shall be addressed taking into account the nonisothermicity of a working fluid in the annular clearance. This fact is stated by row of authors of scientific researches. Thus, the article [5] presents a mathematical model for determination of the velocity of the plunger movement (shank) depending on change in pressure of a working fluid, taking into account the nonisothermal nature of its flow, as well as experimental data of laboratory research, calculated on basis of this mathematical model. The high matching of theoretical and experimental data proves the correctness of the formulation and solution of the problem, taking into account the nonisothermal nature of a working fluid flow during hydroextrusion.

The correctness of formulation of a problem of the nonisothermal flow of a working fluid and the necessity to take this aspect into account is also confirmed by the data specified in [6] on calculation of the pressure change along the shank, taking into account the nonisothermal flow of a working fluid in a thin annular clearance, as well as the results of calculation of the parameters of a viscous fluid flow during the process of continuous hydroextrusion of materials [7].

This way the high-quality hydroextrusion processes implementation is determined by the rate of extrusion or the flow rate of a working fluid through the annular clearance, so the problem of finding the parameters of the clearance is an interesting and relevant issue that should be solved taking into account hydrodynamics laws, theory of elasticity and etc.

The purpose of the research is to conduct an analytical study in order to determine the parameters of the annular clearance for various hydraulic extrusion schemes.

Tasks:

- for the scheme of an uncompacted plunger in a single-layer container, to determine the radial displacements of the container working chamber surface and the surface of the plunger;
- to present theoretically substantiated parameters for a hydroextrusion scheme with an uncompacted shank;
- to analyze the proposed mathematical models.

2. Materials and methods

For the accurate calculations of hydroextrusion parameters it is necessary to take into account the nonisothermicity of a working fluid flowing under a large pressure differential in a thin annular clearance between the container and the plunger (shank) [5-7]. It is equally important to take into consideration the elastic deformations of the walls around the clearance which are directly proportional to the fluid pressure in the layer, as well as the changes in the clearance size. The author of the research also states the necessity to take into account the changes in viscosity caused by pressure, as well as elastic deformations of the channel walls in various hydroextrusion processes [8].

This research is confined to considering the following schemes: the movement of an uncompacted plunger in a solid container and hydroextrusion with an uncompacted shank.

The diagram of the movement of an uncompacted plunger in a solid container is shown in the figure 1. The conditional notations shown in figure 1 are as follows 1: 1 – non-sealed plunger; 2 – container; d – diameter of the plunger; D – diameter of the container chamber; Dк – outer diameter of the container; ℓ – length of the working part of the plunger; d – diameter of the plunger; h – the clearance between the side surface of the plunger and the working chamber of the container; V – plunger movement velocity; P1 – fluid pressure in the working chamber.
For a non-sealed plunger scheme in a single-layer container the clearance is defined as follows:

\[ h = h_0 + U_k + U_n, \]  

where \( h_0 \) is initial clearance between the plunger and the container; \( U_k \) – radial displacement of the cylindrical surface of the working chamber of the container; \( U_n \) – radial displacement of the plunger surface.

Figure 1. Diagram of a non-compacted plunger in a single-layer cylinder.

Using the Lame ratios for the cylinders loaded with radial and axial pressures, the following ratios can be written down:

\[ U_k = \left(1 + k^2 \right) Pd \frac{1}{2E} \frac{1}{2E} \sigma_x d, \]  

where \( E \) and \( \nu \) – is modulus of elasticity and Poisson’s ratio of the container material; \( \sigma_x \) – is the axial tensions in the container;

\[ k = \frac{d}{D_k}, \]  

where \( D_k \) – is the outer diameter of the container.

If the container is not loaded axially, then the second term will be omitted from the equation (2).

The radial displacements of the plunger surface are determined by the following ratio:

\[ U_n = \left(1 - \frac{1}{\nu} \right) Pd \frac{1}{2E} \frac{1}{2E} \sigma_x d. \]
where \( P \) – is current pressure along the clearance; \( P_1 \) – fluid pressure under the butt-end of the plunger; \( E_1 \) – modulus of elasticity of the plunger material; \( \nu_1 \) – Poisson’s ratio of the plunger material.

The scheme of hydroextrusion with a non-compacted shank is shown in the figure 2. The conditional notations shown in figure 2: 1 – shank; 2 – container; 3 – matrix; 4 – blank; 5 – annular clearance; I and II – cavities; \( d \) – diameter of the shank; \( D \) – diameter of the working chamber of the container; \( D_c \) – outer diameter of the container; \( \ell \) – calculated length of the shank; \( d_1 \) – diameter of the blank; \( h \) – clearance between the side surface of the shank and the working chamber of the container; \( Q \) – flow rate of a working fluid; \( V \) – velocity of movement of the shank with the blank; \( P_1 \) – pressure of a working fluid in the radial cavity of the working chamber; \( P_2 \) – pressure of a working fluid in the end cavity of the working chamber.

This scheme is most efficient for hydro-pressing of blanks of small diameter (less than 5 mm). The idea of the scheme is simple: the shank 1 is tightly attached on the butt-end of the blank 4 (see Figure 2). When the blank moves during the hydroextrusion process, the fluid from the cavity I is throttled into the cavity II through the annular clearance 5 between the cavity 1 and the container 2. This creates a pressure difference in the cavities I and II, and \( P_1 > P_2 \). It is necessary to provide that during the process of movement (extrusion) this pressure difference \((P_1 – P_2)\) is sufficient to provide conditions to form fluid lubricant between the matrix 3 and the blank 4.

![Figure 2. Hydroextrusion scheme with non-compacted shank.](image)

In practice the various designs of shanks are used: solid ones, shanks with holes on the rubber sleeve. For solid shank or for shank with holes assigned for the rubber sleeve, the displacements are determined by similar ratios, only coefficients are different.

Figure 3 shows the calculation scheme for determining the radial displacements of the cylindrical surface of a solid shank.

Here we write down the equation of displacement of the lateral cylindrical surface of a solid shank:

\[
U_{xa} = \frac{1-\nu_1}{E_1} \frac{Pd}{2} \frac{\nu_1 \sigma_x d}{E_1}.
\]  
(5)
where \( E_1 \) and \( \nu_1 \) – are the elastic modulus and Poisson’s ratio of the shank material; \( P \) – is the current pressure along the clearance; \( P_1 \) – is the fluid pressure under the end of the shank; \( d \) – диаметр of the shank (refer to the figure 2); \(|\sigma_x|\) – are the axial stresses in the container, which vary from \( P_1 \) to \( P_2 \) as well as the pressure along the clearance \( P \), so the assumption is: \(|\sigma_x| \approx P\).

![Figure 3](image)

**Figure 3.** Calculation scheme for determining the radial displacements of the cylindrical surface of a solid shank.

If the container is not loaded in the axial direction, then the second term in equation (5) can be omitted and it is converted to the following form:

\[
U_{xx} = \left(1-2\nu_1\right)\frac{Pd}{2E_1}.
\]  

(6)

The radial displacements of the surface of the working chamber of the container are recorded for the case when there are no axial stresses in it, in the following form:

\[
U_e = \frac{1+k^2}{1-\nu^2} + \nu \frac{Pd}{2E},
\]  

(7)

where \( k = d/D_k \) is the ratio of diameter of the shank to the outer diameter of the container (refer to the figure 2).

The clearance between the solid tank and the container in the general case, when the material of the container and the shank are different, is determined by the following ratio:

\[
h = h_0 + \left[\frac{1-2\nu_1}{E_1} + \frac{1+k^2}{E(1-k^2)} + \nu\right] \frac{Pd}{2E}.
\]  

(8)

Here \( h_0 \) – is the initial clearance.

In the case where the container and the shank are made of steel grades of the same constants, the clearance between the shank and the container can be determined as follows:

\[
h = h_0 + \left[\frac{2}{1-k^2} - \nu\right] \frac{Pd}{2E}.
\]  

(9)

3. Results and discussions

Usually the initial clearance between the uncompacted plunger does not exceed 5-10 microns, and for hydroextrusion schemes with uncompressed shank it is usually 10-200 microns. If the plunger or shank diameter is 10 mm or more, the ratio of the clearance thickness to the diameter is much less than one. Therefore, in contrast to the problem of continuous hydraulic compression, which is solved in an
axisymmetric formulation, this research presents a solution in a plane (flat) formulation without taking into account the transverse flow of the fluid.

In a scheme of hydroextrusion with a non-compacted shank for real processes the deviation of the clearance value from the constant value rarely exceeds 3-5 %. But this occurs at relatively low values of pressure differentials along the shank [6]. For these cases, methods of calculations that ignore the change in the clearance along its length are quite suitable. For large pressure differentials within the range $\Delta P = 3 \times 10^8...9 \times 10^8$ it is necessary to take into account the change in the clearance size due to the nonisothermal nature of viscous fluid flow in a thin annular clearance, which helps to correct the calculation of other parameters of the process [6]. In processes where the initial value of the clearance is of the same order as the value of the clearance change, the calculation method shall include the ratios (8)–(9).

4. Conclusions

For the hydroextrusion process the design scheme for a working fluid flow in the deformed clearance and a mathematical model for determining the parameters of the annular clearance, taking into account the elastic deformations of the walls that limit the clearance, were developed. On its basis the theoretically justified parameters of the clearance were proposed for the schemes of an uncompressed plunger in a single-layer container and hydroextrusion with an uncompressed shank, taking into account the elastic deformations of the walls of the working chamber and the shank.

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