Analysis of forming properties during the isothermal upsetting of cylindrical workpieces in the viscous-plasticity mode

S N Larin [1]**, A A Pasynkov** [1]

[1] Tula State University, 92, Lenina ave., Tula, 300012, Russia

E-mail: mpf-tula@mail.ru

Abstract. In the manufacturing of axisymmetric parts made of high-strength alloys, slow hot deformation is widely used, which makes it possible to increase significantly the plasticity properties of the material and to reduce the deformation force, as well as to achieve greater deformation. However, currently there are few studies discussing the issues of high-strength materials formation theory. This article considers the isothermal upsetting of cylindrical workpieces made of hard-to-deform alloys in the viscous-plasticity mode. The article introduces isothermal upsetting models regarding the short-term creep mode. The article reveals the influence of technological parameters and friction conditions existing on the contact surfaces of the working tool and workpiece on the material flow kinematics, stressed and deformed states, and the force conditions. The results obtained during their development can be used to create design methods for innovative, science-intensive, competitive technological processes of next generation for manufacturing axisymmetric geometrically-complex parts by means of isothermal deformation methods.

1. Introduction
The main problem facing engineering nowadays is to increase the efficiency and competitiveness of products manufacturing of high-strength metals and alloys by pressure-processing methods that provide the maximum possible performance characteristics. In the manufacturing of axisymmetric parts from high-strength alloys, slow hot deformation is widely used, which makes it possible to increase significantly the plasticity properties of the material and to reduce the deformation force, as well as to achieve greater deformation. The pressure processing of hard-to-deform alloys in the short-term creep mode opens great prospects for the creation of new technological processes. Despite the large number of works devoted to theoretical and experimental studies of isothermal die forging of bar stocks, the problems of high-strength materials forming theory in short-term creep mode have not been fully discussed at present.

2. Materials and methods
Upsetting is a typical operation for the processing of metals by pressure [1]. The upsetting of high-strength materials workpiece is carried out under isothermal conditions on hydro-press equipment. The forging modes are determined by the temperature-speed conditions, as along as with deformation hardening of the material, there is a creep condition, depending on the processing speed [2,3]. In addition, the upsetting is non-stationary, which also affects the technology in terms of operating

pressure and the limiting degree of deformation. Thereupon let's consider a variant of upsetting properties calculation. We will use the energy calculation method based on the upper bound theorem of plasticity theory with respect to the discontinuous axisymmetric displacement velocity field [4].

Figure 1 schematically shows the upsetting process. The scheme also demonstrates the displacements velocity field, consisting of hard blocks "0" and a block of deformations "1". The blocks represent the rotation factors and the limited surfaces of discontinuity velocity.
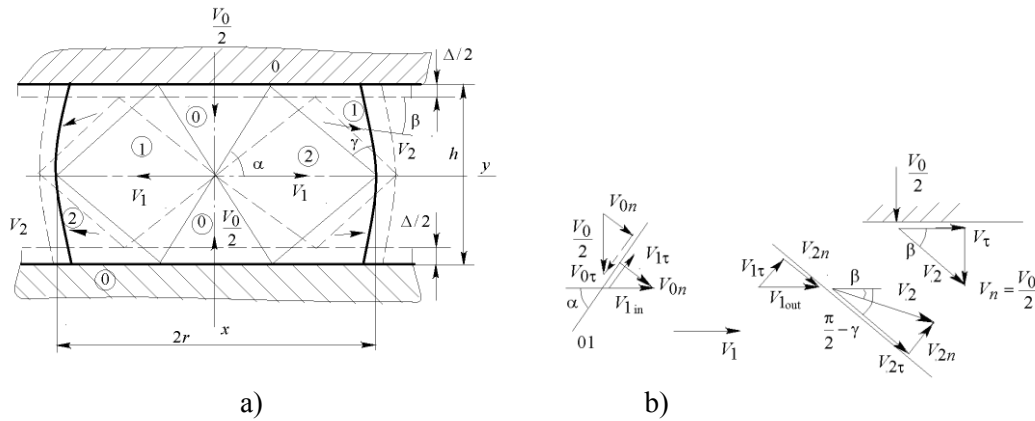

Figure 1. Upsetting scheme, field (a) and velocity plan (b)

3. Results and Discussion

The velocity field is non-stationary, because it changes during the upsetting (shown in dotted lines). The line "01" rotates relative to "no". The lines "01", "12" move along the coordinate axes "x", "y" respectively, which causes additional normal velocities on discontinuity velocity surfaces. The deformations occur on these surfaces and in the deformation block.

Equivalent stresses are expressed on the basis of the equality of the state of the material being deformed. On the surface of the discontinuity velocity is

$$\sigma_{\mathfrak{z}} = A\varepsilon_{\partial}^{m}\xi_{n}^{n} = A\left(\frac{V_0}{\Delta h}\right)^{n}\varepsilon_{\mathfrak{z}}^{m+n}; \tag{1}$$

In the deformation block

$$\sigma_{\partial} = A\left(\frac{\Delta h}{V_0}\right)^{m}\cdot\xi_{\mathfrak{z}}^{m+n}. \tag{2}$$

Expressions (1) and (2) take into account the stress relaxation in connection with creep. The power of the internal forces on the surface of the velocity discontinuity is expressed using $N_p = \frac{1}{V_3}\sigma_{\mathfrak{z}}V_{\tau}S$, where $\sigma_{\mathfrak{z}}$ are the equivalent stresses (9); $V\tau$ - tangential velocities; S - velocity discontinuity areas. We obtain the following expressions:

$$N_{01} = \frac{\pi A h^2}{2\sqrt{3}\sin\alpha}\left(\frac{1}{\Delta h}\right)^{n}V_0^{1+n}\left(1 + ctg^2\alpha\right)\varepsilon_{\mathfrak{z}01}^{m+n}; \tag{3}$$

$$N_{12} = \frac{\pi A h^2}{2\sqrt{3}\cos^2\gamma}\left(\frac{2r}{h}\cos\gamma - 1\right)\left(\frac{1}{\Delta h}\right)^{n}V_0^{1+n}\frac{\cos(\alpha+\beta)}{\sin\beta}\left[tg(\beta+\gamma) - tg\gamma\right]\varepsilon_{\mathfrak{z}12}^{m+n}; \tag{4}$$

$$N_{02} = \frac{\pi A h^2 tg^2\gamma}{2\sqrt{3}tg\beta}\left(\frac{1}{\Delta h}\right)^{n}V_0^{1+n}\varepsilon_{\mathfrak{z}02}^{m+n}. \tag{5}$$

In the deformation block, the powers are determined using expressions (4) and (5) by the following equation:

$$N_1 = \int_w \sigma_э \xi_э \mathrm{dw} = \pi A r h y_{\text{H.T.}} \left(\frac{\Delta h}{V_0}\right)^m \int_{y_{01}}^{y_{12}} dy \int_0^h \xi_э^{m+n} dx \qquad (6)$$

Here w- is the power of the deformation block; $y_{\text{H.T}}$ is the ordinate of block's longitudinal section on the velocities' plan (triangular ones with sides x=0, y_{01}, y_{12}). Upsetting pressure at any stage follows from the balance equation for the powers of the upper and internal forces. Using the expressions (3) - (6), we obtain

$$q \le 2\left(N_{01} + N_{12} + N_{02} + N_1\right) / \pi r^2 V_0. \qquad (7)$$

The pressure depends on the initial workpiece dimensions, upsetting degree, its speed and deformation's non-stationarity. It can be calculated for any stage of the operation for a given Δh. The lower value of the upper bounded pressure is determined by minimizing expression (7) with respect to angle α. When forging on crank presses, creep does not appear in formula (7) n = 0 as well.

The calculated and technological results are obtained with reference to the upsetting of cylindrical workpieces with dimensions 2r=50 mm, h0 – 40 mm made of aluminum alloys at 450 ° C and titanium alloys at 950 ° C. Upsetting pressure, as follows from the table and figure 2, decreases with increasing operation time.
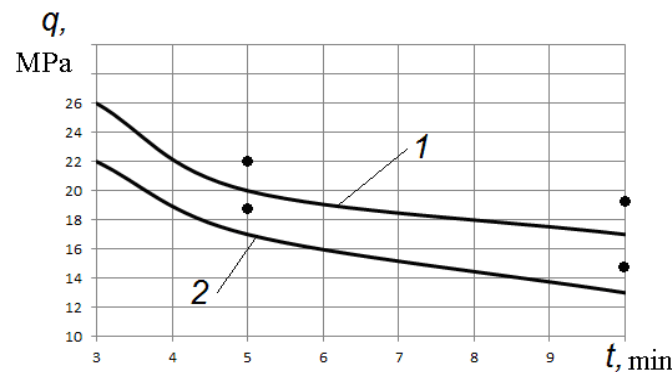

Figure 2. Dependence of the specific upsetting pressure from the deformation time: 1 - AMg6 alloy; 2 - alloy VT14

Therefore, for one group of materials the upsetting degree can be increased by increasing the duration of the operation. For another group, there is no such dependence. Taking into account the non-stationary nature of the process during the calculations corrects the deformation values, surface stresses and, consequently, affects the pressure estimates and the critical degree of deformation.

In order to take into account the influence of the deformation rate, friction and workpiece dimensions on the quality of the products obtained, strain and deformation forces, this process was studied with the QFORM software. Its use is justified by the qualitative compliance of the results obtained in the course of the study based on the upper boundary plasticity theorem with the results obtained in the QFORM studies. Studies were carried out for the titanium alloy VT14, since its deformation is the most difficult one. For a more complete picture of the study, workpieces with a length of 40; 60; 80 mm and with a diameter of 40 mm were used. The proportions of these sizes are 1; 1.5 and 2, respectively. Friction varied in the range between 0.1 and 0.3, which corresponds to the real type of lubrication, that is to the liquid glass (with friction coefficient value being 0.1), as well as a mixture of graphite and oil (in this case the friction coefficient is 0.3).

Figure 3 shows the dependence of the change in the force during the upsetting on the deformation rate for different dimensions of workpieces at $\mu = 0{,}1$.
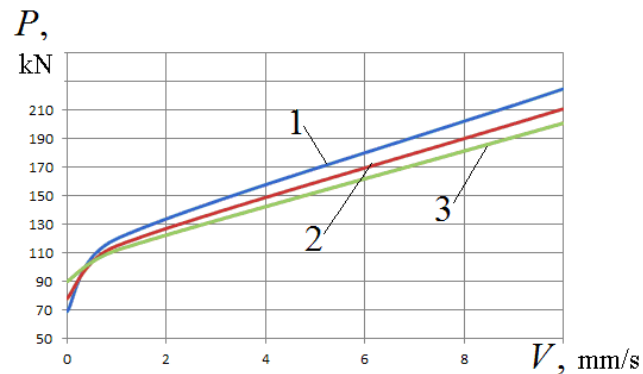
3

Figure 3. Dependence of forces under isothermal upsetting from deformation rate ($D_b = 40\ mm$;
$\mu = 0{,}1$): 1 - $H_b = 40\ mm$; 2 - $H_b = 60\ mm$; 3 - $H_b = 80\ mm$

Figure 4 shows the dependence of the change in the force during the upsetting from the deformation rate for different dimensions of the workpieces at $\mu = 0{,}3$.
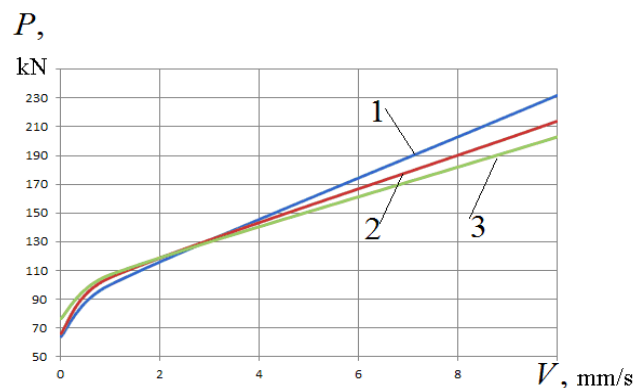

Figure 4. Dependence of forces during isothermal upsetting from deformation rate ($D_b = 40\ mm$;
$\mu = 0{,}3$): 1 - $H_b = 40\ mm$; 2 - $H_b = 60\ mm$; 3 - $H_b = 80\ mm$

According to the analysis of the dependencies presented in fig. 3 and 4 we can see that together with the increase of the deformation rate the force is also increasing, but the greatest intensity of force growth is achieved in the velocity intervals between 0 and 1 mm/s. Changes in the height of the workpiece with its constant diameter do not affect the force growth greatly. However, we can say that the smaller the ratio of the height of the workpiece to its diameter, with the same stroke of the punch, the greater the force is. An increase in the friction value from 0.1 to 0.3 evenly increases the force values by 10%.

Figure 5 shows the dependence of the change in the force during the upsetting from the deformation rate for different workpiece dimensions.
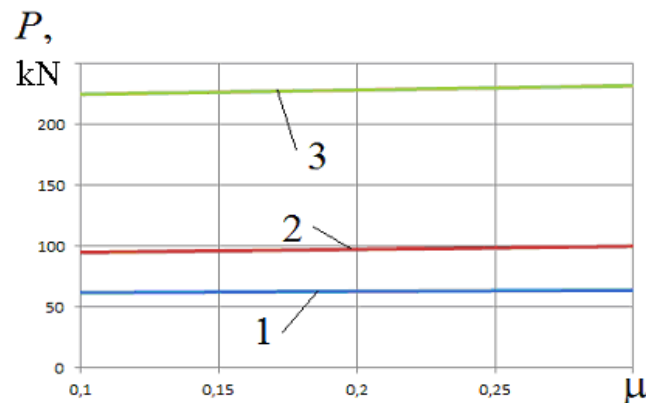
Figure 5. Dependence of forces during the isothermal upsetting from the friction coefficient ($D_b = 40\ mm; H_b = 40\ mm$):1 - $V = 0,01\ mm/\sec$; 2 - $V = 0,1\ mm/\sec$; 3 - $V = 10\ mm/\sec$

According to the analysis of the dependence shown in fig. 5 it is seen that the force increases with increasing deformation rate. The increase in the friction value leads to an even growth of the force value.

It has been established that during the upsetting, a defect arises for all workpieces, depending on the deformation rate, which manifests itself in the form of barrel or cavity formation in the central section of the part. In this connection, we carried out a study, the purpose of which was to determine the rate of deformation, at which such a defect does not arise. It can be seen that for workpieces made of titanium alloy at the deformation temperature $900°C$ the best value of the deformation rates for the height $H_b = 40\ mm$ is $V = 0,2\ mm/\sec$; for height $H_b = 60\ mm$ is $V = 0,5\ mm/\sec$; for height $H_b = 80\ mm$ is $V = 0,7\ mm/\sec$. According to the obtained data, we can construct the diagram shown in Fig. 6.
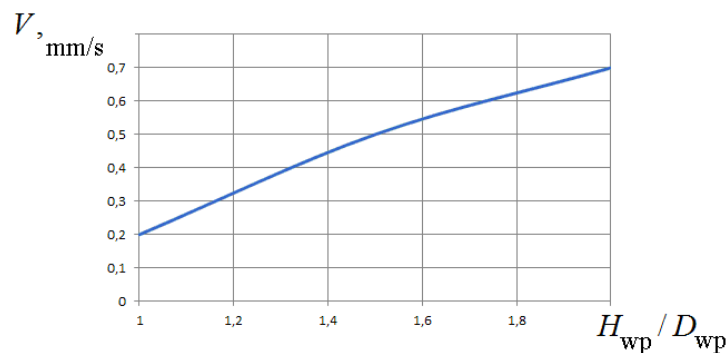

Figure 6. The diagram, estimating the rational deformation rate

4. Conclusion

It can be concluded that for the design of technological processes of isothermal forging, with upsetting being the main deformation scheme, the isothermal upsetting occurs under strain hardening conditions and stress relaxation in connection with the development of creep of the material being processed. This fact affects the punching mode; the operation pressure decreases as the upsetting rate decreases. At the same time, workpiece material damage is accumulated; for some materials the less the speed of the operation is, the less is the final damageability for a given upsetting degree, for other materials, the dependence from speed (time) does not appear; taking into account the non-stationarity of the

upsetting approximates the pressure estimation and the critical degrees of deformation to the actual ones. As a result, recommendations to ensure a defect-free upsetting in a viscous-plastic flow mode without barrel or cavity formation were provided.

5. Acknowledgments

References

[1]   Unksov E P Theory of plastic deformations of metals 1983 *M .: Mechanical Engineering* 598.

[2]   Romanov K I Mechanics of hot metal forming 1993 *Moscow: Mashinostroenie* 240.

[3]   Zhang H, Li X, Tang W, Deng X, , Reynolds A P, Sutton M A Heat transfer modeling of the friction extrusion process 2015 *Journal of Materials Processing Technolog*. **Volume 221** 21–30

[4]   Matthias Haase, Erman A, Tekkaya Cold extrusion of hot extruded aluminum chips 2015 *Journal of Materials Processing Technology* **Volume 217** 356–367

[5]   Peter Krizika, Martin Baloga, Emilia Illekovab, Peter Svec Sr.b, Igor Matkob, Matej Stepaneka, Martin Noskoa, Frantisek Simancika The oxidation behavior of gas-atomized Al and Al alloy powder green compacts during heating before hot extrusion and the suggested heating process 2014 *Journal of Materials Processing Technology* **Volume 214 Issue 6** 1165–1172.

[6]   Hong-ye Li, Min Xia, Zhen Zhao, Yu Zheng An experimental study on local thickening laws based on multi-plate extrusion 2013 Journal of Materials Processing Technology **Volume 213 Issue 7** 1213–1220

[7]   Marcus Engelhardt, Norbert Grittner, Hermann von Senden genannt Haverkamp, Wilfried Reimche, Dirk Bormann, Friedrich-Wilhelm Bach Extrusion of hybrid sheet metals 2012 *Journal of Materials Processing Technology* **Volume 212 Issue 5** 1030–1038.

[8]   Wenxiong He, Erde Wang, Lianxi Hu, Yang Yu, Hongfei Sun Effect of extrusion on microstructure and properties of a submicron crystalline Cu–5 wt.Cr alloy 2008 *Journal of Materials Processing Technology* **Volume 208, Issues 1–3** 205–210.

[9]   Nicolas Fiétiera, Yves Krähenbühlb, Matthieu Vialardb New methods for the fast simulations of the extrusion process of hot metals 2009 *Journal of Materials Processing Technology* **V**olume **209, Issue 5** 2244–2259.

[10]   Malinin N N Creep in metal processing 1986 *M .: Mechanical Engineering* 216.

[11]   Yakovlev S S, Yakovlev S P, Chudin V N, Tregubov V I, Chernyaev A V Isothermal shaping of anisotropic materials by a rigid tool in the regime of short - term creep 2009 *M .: Mechanical Engineering* 412.