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To the Effective Properties Estimation of Materials

Gennady M. Zhuravlev[a], Aleksandr N. Sergeyev[a],
Aleksandr Y. Gvozdev[a], Dmitry A. Provotorov[a],
Nikolay N. Sergeyev[a] and Aleksandr N. Privalov[a]

[a]Tula State Pedagogical University named after L.N. Tolstoy, Tula, RUSSIA.

ABSTRACT

On the modern stage, the layer-by-layer production of components using additive technologies became possible. Such components do not require mechanical modifications, but can be deformed by plastic form change. Influence analysis of technological parameters, the degree of deformation, tool geometry, deformation velocity, friction coefficient on the kinematics of material flow, strain-stress state of the blank and the force conditions will help to optimize the process of components manufacturing. The studies were carried out using computer simulations according to multifactorial scheme, while the effect of each factor was estimated using the results of all experiments, which allows receiving more accurate results. The influence of deformation degree, the tool geometry (taper angle), the coefficient of friction, and deformation velocity on the value of technological strength was taken into account as the main technological factor. The influence of modeling of main technological parameters on the process of combined extrusion of thin-walled cylindrical components with the use of application programs reduces the time of process design and improves their accuracy.

KEYWORDS
Additive technologies, combined extrusion, computer simulation, increase of the deformation degree, regression equation

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Introduction

Recent advances in laser technology and computer technologies has led to the possibility of layer-by-layer manufacturing of objects according to electronic models based on so called additive technologies (Delhote et al., 2014; Mertens & Lecomte-Beckers, 2014; Gibson, Rosen & Stucker, 2014). Additive technologies are the technologies, which involve the manufacture of a product according to digital array data by the layer-by-layer addition of material (Kashapov et al., 2014; Sedlak et al., 2015).

Components produced in such a way can be subjected to plastic form change that do not require significant machining (Atzeni & Salmi, 2012; Krznar, Pilipović & Šercer, 2016).

CORRESPONDENCE Aleksandr N. Privalov ✉ privalov.61@mail.ru

Successful implementation of the plastic form change process depends on the correct choice of technological conditions of processing (Gibson, Rosen & Stucker, 2015; Vaidyanathan, 2015; Zhuravlev et al., 2015). In addition, while manufacturing the components, the formation of operational properties is often required (Gvozdev et al., 2016) along with obtaining the necessary geometric sizes and shapes (Isiksal-Bostan, Sahin & Ertepinar, 2015). Consider the effect of technological parameters on plastic form change of thin-walled cylindrical component from aluminium alloy A7– All-Union State Standard 21631-7 (Figure 1) at the combined extrusion by computer simulation using finite element methods of solving static problems, developed and adapted program complex DEFORM-3D® V6.1, simulation and planning method for multifactorial experiment (Novik & Arsov, 1980; Gvozdev, 2015).

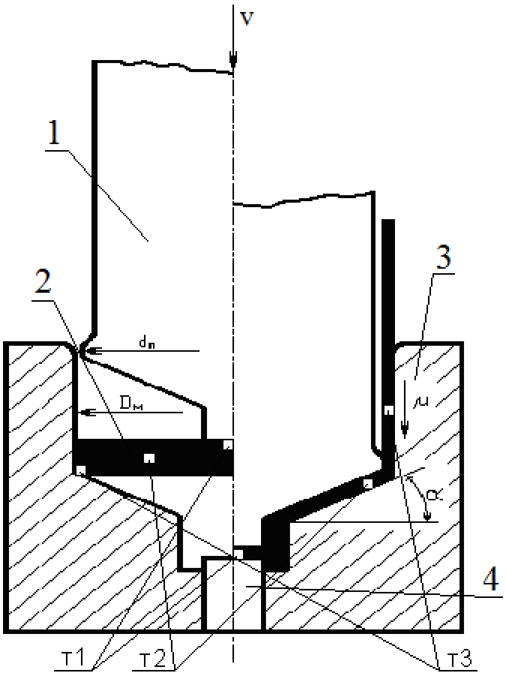

Figure 1. The scheme of the combined process of cold backward extrusion: 1 - plug; 2 - blank; 3 - matrix; 4 - ejector.

The influence of deformation degree, the matrix taper angle, friction coefficients, deformation velocity on the possibilities of the forming process by calculating the numerical values of the technological strength, stress intensity, and deformation with visualization of the obtained values in the form of graphic dependencies of their change from the steps were taken into account as the basic technological parameters (Dmitriev & Vorontsov, 2002 & 2004; Zhuravlev et al., 2016).

Evaluation of the effect of process parameters on:

- the deformation degree;
- the geometry of the tool;
- the deformation velocity;
- the friction coefficient on the kinematics of material flow;
- strain-stress state of the blank.

Will help to unlock the potential of additive technologies while obtaining products with high mechanical properties.

Methods

The research was carried out with the help of computer simulation using multifactor scheme when the assessment of each factor effect was based on the results of all experiments, which allows receiving more accurate results. The influence of deformation degree, tool geometry (taper angle), the friction coefficient, deformation velocity on the value of technological strength were taken into account as the main technological factors.

Data, Analysis, and Results

Modeling According to the Scheme of the Single-Factor Experiment.

Figure 2 presents correspondence graphs of the technological strength on the deformation degree, friction coefficient, deformation velocity, and the taper angle of the matrix.

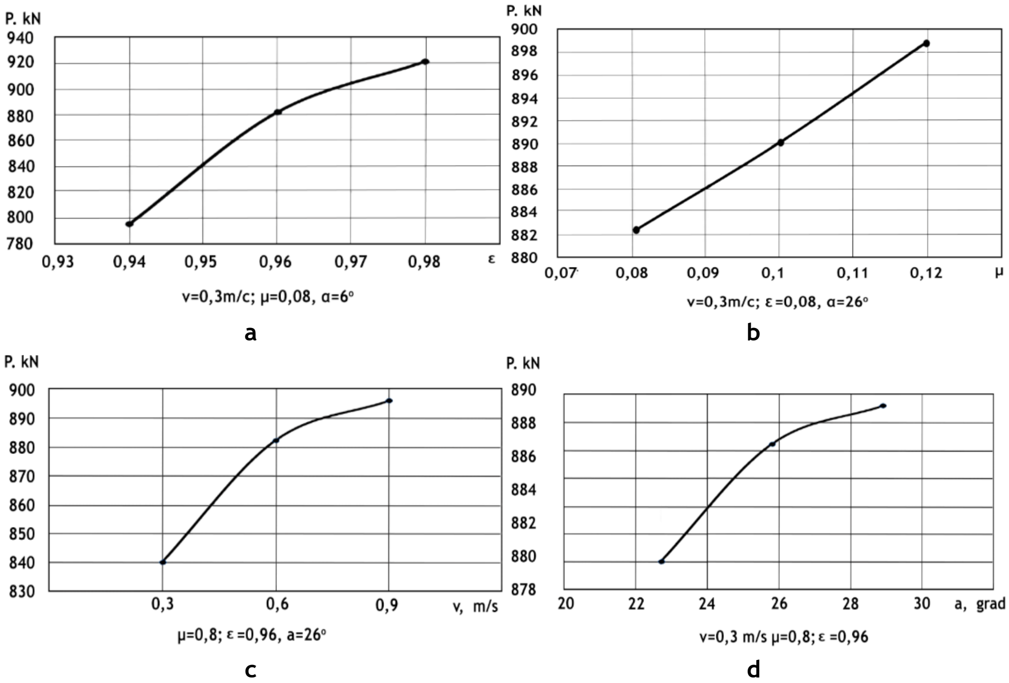

Figure 2. Correspondence graphs of technological strength on the degree of deformation (a), friction coefficient (b) deformation velocity (c), matrix taper angle (d).

Results analysis has shown that the technological strength increases with increasing deformation degree ε=0,94...0,98, deformation velocity v=0,3...0,9 m/s and friction at the contact surface of the plug and matrix μ = 0,08...0,12; and with the increasing taper angle of the matrix α=22...30^0 is reduced. The parameters $\alpha = 30^{\circ}; \mu = 0{,}08; v = 0{,}3$ м/с$; \varepsilon = 0{,}94$ give the minimum value of technological strength.

The influence of main technological parameters on the distribution of strain-stress intensity is studied.

Figure 3 shows the influence of deformation degree, the taper angle of the matrix, deformation velocity and the coefficient of contact friction on the stress intensity at the combined extrusion for 3 points.

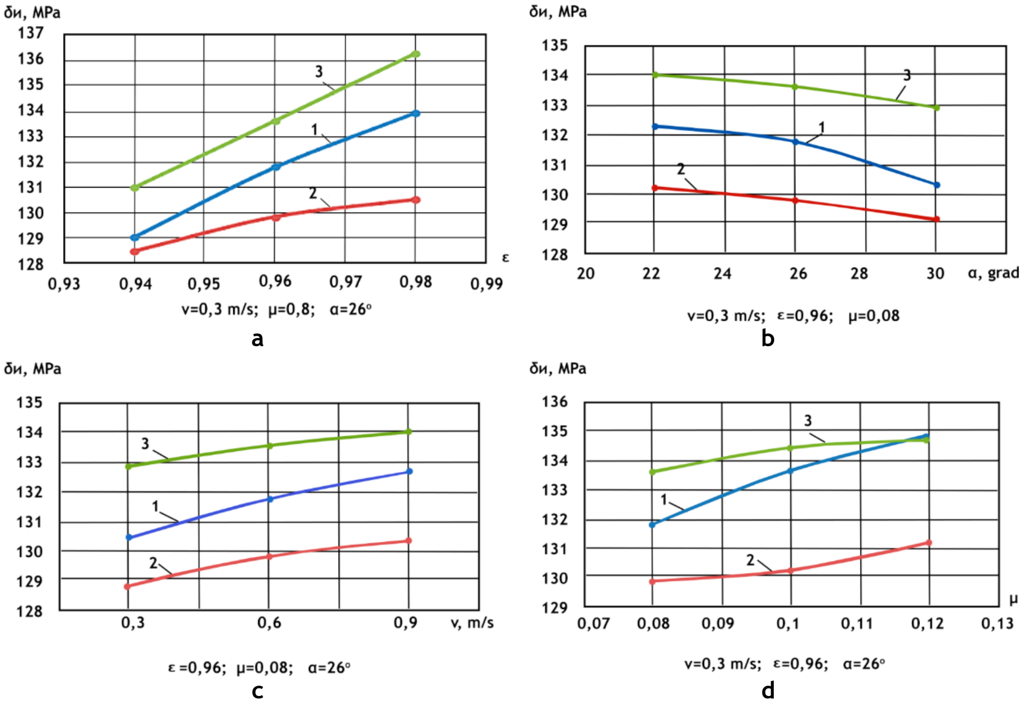

Figure 3. A graph of the effect of the deformation degree (a), the taper angle of the matrix (b), deformation velocity (c), and coefficient of contact friction (d) on the stress intensity.

Results analysis has shown that the stress intensity increases with increasing degree of deformation, deformation velocity and friction at the contact surface of the plug and the matrix and decreases with increasing taper angle of the matrix. Unevenness in the intensity of tension at different points is observed. The stress intensity reaches the largest numerical value at points 1 and 3 in zones of components contact with tools. The stress intensity reaches the maximum value in the contact zone “tool- blank” $\sigma_u = 136{,}28\,\text{МПа}$ (MPa) (point 3), but for all time of the process it does not exceed the limit values.

Figure 4 illustrates the dependence of the influence of the deformation degree, the taper angle of the matrix, deformation velocity and the coefficient of contact friction on the intensity of deformation.

Results analysis has shown that the intensity of deformation increases with increasing degree of deformation, deformation velocity, friction at the contact surface of the plug and matrix, and the taper angle of the matrix. There is a sharp unevenness in the intensity of deformation at different points. The intensity of deformation reaches its highest value at point 3. The deformation intensity in the process of extrusion reaches a maximum value ε_u=3,62 (point 3) with increasing the degree of deformation to 0.98.

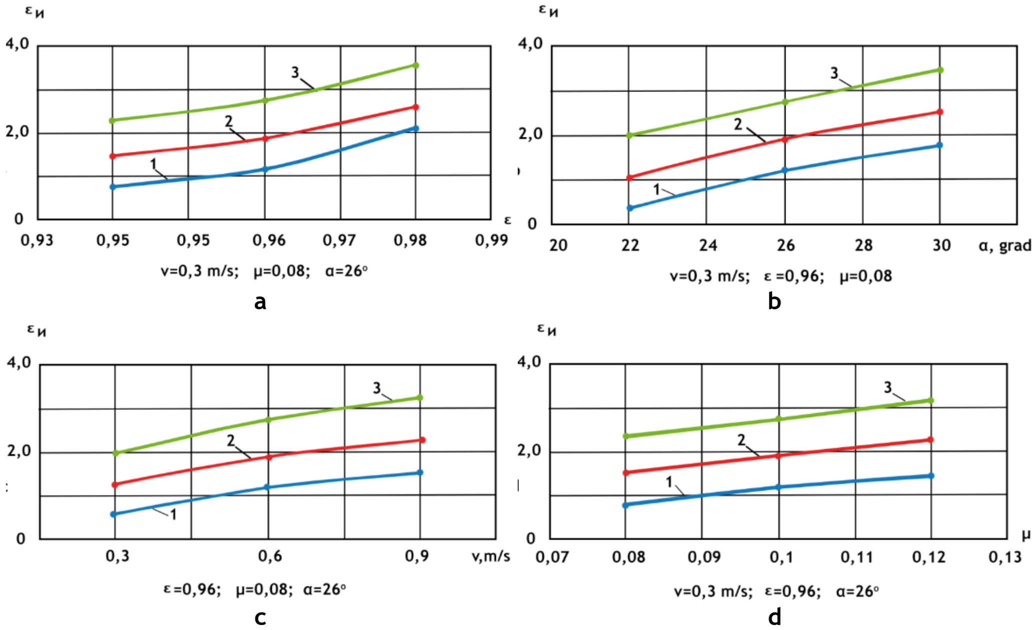

Figure 4. A graph of the effect of the deformation degree (a), the taper angle of the matrix (b), deformation velocity (c) and coefficient of contact friction (d) on the deformation intensity.

Modeling According to the Scheme of the Multifactor Experiment

The following values were taken as independent factors:

x_1– the degree of deformation ε; x_2– the taper angle of the tool α; x_3– the friction coefficient μ; x_4 – the rate of deformation ν.

When carrying out computer simulation, the change of mechanical properties of the material was used as a random variable, which was taken from the recommended interval of numerical values $\sigma_B = 68\ldots72$ МПа (MPa) using randomization.

To describe the process, the grid plan of the I-th order was adopted, designed to estimate the unknown parameters of the model (when *n*=4) of the following form

$$y = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 + a_{12}x_1x_2 + a_{13}x_1x_3 + a_{14}x_1x_4 + a_{23}x_2x_3 +$$
$$+ a_{24}x_2x_4 + a_{34}x_3x_4 + a_{123}x_1x_2x_3 + a_{124}x_1x_2x_4 + a_{234}x_2x_3x_4 + a_{134}x_1x_3x_4 +$$
$$+ a_{1234}x_1x_2x_3x_4.$$

We use a full factorial experiment of 2^4 type.

When establishing the scope of factors, the technological features of combined extrusion were taken into account. The levels of factors and variation intervals are given in Table 1.

Table 1. The levels of factors and variation intervals.

Levels	Factors			
	x_1	x_2	x_3	x_4
	ε	α	μ	ν
+	0,98	30	0,12	0,9
0	0,96	26	0,10	0,6
-	0,94	22	0,08	0,3

Coded values of factors (x_i) are associated with genuine ratios

$$x_i = \frac{X_i - X_{io}}{\Delta X_i},$$

where x_i– a coded value; X_1– natural value; X_{i0}– natural value of the ground level factor; ΔX_i – the interval of variation,

$$x_1 = \frac{\varepsilon - 0{,}96}{0{,}02}; \quad x_2 = \frac{\alpha - 26}{4}; \quad x_3 = \frac{\mu - 0{,}1}{0{,}02}; \quad x_4 = \frac{\nu - 0{,}6}{0{,}3}.$$

The matrix type for the four factors is presented in Table 2.

Table 2. The planning matrix type for the four factors.

№	x_1	x_2	x_3	x_4
1	+	+	+	+
2	-	+	+	+
3	+	-	+	+
4	-	-	+	+
5	+	+	-	+
6	-	+	-	+
7	+	-	-	+
8	-	-	-	+
9	+	+	+	-
10	-	+	+	-
11	+	-	+	-
12	-	-	+	-
13	+	+	-	-
14	-	+	-	-
15	+	-	-	-
16	-	-	-	-

For the research, the adapted software package and the following dimensions of blank were used: diameter of the circle D_{KP}=39,8 ММ (mm); the thickness of the circle T_{KP}=5 ММ. The dimensions of the tool (see Figure 2.1): the diameter of the plug $d_{П}$ =39,66 ММ, which was changed by varying the degree of deformation and the diameter of the matrix D_M=40 ММ that remained constant. In the process of computer simulation the following values have changed: the taper angle of the matrix α, the rate of deformation and the coefficient of friction on the tool μ that was the same on the plug and the matrix.

To eliminate the influence of systematic errors caused by external conditions, the experiments were randomized in time. Plan of experiment in the natural scale and the results are shown in Table 3.

Duplication of experiments allowed us to verify the accuracy of the calculations, and to determine the error. Error of experiment, or, as it is often called the reproducible error in parallel experiments, was tested by the Cochran's criterion

$$G = \frac{S^2_{\max}}{\sum S^2} \leq G_T,$$

where $S^2_{\max}$ – the largest dispersion of the experiment; $S^2_{\max}$ – the dispersion of the experiment $S^2 = \dfrac{\left(y_1 - \bar{y}\right)^2 + \left(y_2 - \bar{y}\right)^2}{n}$;

y_1 – the value in the first experiment;

y_2 – value in the second experiment;

$\overline{y}$ – average value,

$\overline{y} = \frac{y_1 + y_2}{n}$;

n=2 – the number of parallel experiments;

$G_T = G_{(0,05;1;16)} = 0,455$ – the table value of Cochran's criterion at the 5% significance level.

Table 3. Experiment plan.

№	Implementation order	ε	α	μ	ν	y_1	y_2	$\overline{y}$	S^2
1	9	0,98	30	0,12	0,9	96,36	96,33	96,345	0,0002
2	2	0,94	30	0,12	0,9	83,55	83,02	83,285	0,0703
3	7	0,98	22	0,12	0,9	89,10	88,77	88,935	0,1089
4	1	0,94	22	0,12	0,9	79,79	78,68	79,235	0,3080
5	13	0,98	30	0,08	0,9	94,29	93,41	93,850	0,1936
6	3	0,94	30	0,08	0,9	76,99	77,44	77,215	0,0506
7	14	0,98	22	0,08	0,9	85,58	85,49	85,535	0,0022
8	6	0,94	22	0,08	0,9	77,30	76,97	77,135	0,0273
9	11	0,98	30	0,12	0,3	96,35	96.34	96,345	0,0001
10	16	0,94	30	0,12	0,3	78,99	79,31	79,150	0.0256
11	10	0,98	22	0,12	0,3	87,27	86,55	86,910	0,1296
12	12	0,94	22	0,12	0,3	75,76	75,67	75,715	0,0021
13	5	0,98	30	0,08	0,3	95,74	95,53	95,635	0,0113
14	8	0,94	30	0,08	0,3	77,45	77,02	77,235	0,0463
15	4	0,98	22	0,08	0,3	86,65	86,61	86,633	0,0005
16	15	0,94	22	0,08	0,5	73,39	73,41	73,400	0,0001

Thus,

$$G = \frac{0,308}{0,9767} = 0,315 \le G_T,$$

this means that the experiment is replicable.

In further results treatment, $l(t)$ is taken as an estimate of the noise dispersion

$$S_y^2 = \frac{\sum S^2}{N},$$

where N – the number of plan experiments,

$$S_y^2 = 0,396;$$

$$S_y = 0,63.$$

The value of the regression coefficients was determined by the least-squares method:

$$a_0 = \frac{\sum \overline{y_i}}{N};\ a_i = \frac{\sum \overline{y_i} x_i}{N};\ a_{ij} = \frac{\sum \overline{y_i} x_i x_j}{N};\ a_{ijk} = \frac{\sum \overline{y_i} x_i x_j x_k}{N};\ a_{ijk} = \frac{\sum \overline{y_i} x_i x_j x_k x_l}{N}.$$

The resulting regression coefficients were assessed according to statistical significance using t_i – the Student's t-test

$$t_i = \frac{|a_i|}{S_{ai}} \geq t^T_{\alpha,f},$$

where $S_{ai} = \frac{S_y}{\sqrt{nN}} = \frac{0,63}{\sqrt{2.16}} = 0,111$ – the dispersion of the estimated coefficients; $t^T_{\alpha,f}$ = 2,02 – the Student's t-test, taken from tables depending on the significance level of α=0,05 and the number of degrees of freedom f=32.

Therefore, $|a_i| = S_{ai} t^T_{\alpha,\ f} = 0,224$; and the regression coefficients should be $|a_i| \geq 0,224$. The other coefficients are statistically insignificant and can be omitted in the model.

Thus, the following regression equation is obtained

$$y = 84,5 + 6,53x_1 + 2,61x_2 + 1,81x_3 + 1,26x_4 + 1,46x_1x_2 - 0,386x_1x_3 -$$
$$-0,805x_1x_4 + 0,55x_2x_3 + 0,845x_3x_4.$$

In the natural scale, the equation has the following form

$$P = 67,85 + 2,91\varepsilon - 1,17\alpha + 83,80\mu + 0,79\nu + 1,83\varepsilon\alpha - 96\varepsilon\mu + 0,69\alpha\mu - 0,81\varepsilon\nu.$$

The dispersion of adequacy for the derived equations is determined by the formula

$$S^2_{\text{неад}} = \frac{\sum\left(y_{\text{ур}} - y_{\text{рас}}\right)^2}{f_2},$$

where $y_{\text{ур}}$ and $y_{\text{рас}}$ – the values of the response in the experiment, respectively calculated in accordance with regression equation and obtained during the simulation (Table 4); and f_2 is the number of degrees of freedom, f_2 = N – K, K is the number of retained coefficients, including a_0 in the regression equation f_2 = 16 – 10 = 6.

Table 4. The table of statistical values.

№	$y_{\text{ур}}$	$y_{\text{рас}}$	$y_{\text{ур}} - y_{\text{рас}}$	$\left(y_{\text{ур}} - y_{\text{рас}}\right)^2$
1	96,10	96,345	0,245	0,060
2	83,77	83,285	0,485	0,235
3	89,12	88,935	0,185	0,035
4	78,06	79,235	-0,175	0,030
5	93,08	93,850	-0,771	0,593
6	78,12	77,215	0,885	0,783
7	84,68	85,535	-0,855	0,731
8	77,72	77,135	0,585	0,342
9	95,52	96,345	-0,825	0,680
10	78,84	79,150	-0,311	0.096
11	85.93	86,910	-0,982	0,961
12	76,67	75,715	0,955	0,912
13	96,14	95,635	0,505	0,255
14	78,05	77,235	0,815	0,664
15	85,68	86,633	-0,953	0,908
16	73,27	73,400	-0.131	0,017

$$\sum 7{,}302$$

Therefore,

$$S^2_{\text{неад}} = \frac{7{,}302}{6} = 1{,}22.$$

The adequacy of the equation was checked using the F – criterion (Fisher criterion)

$$F = \frac{S^2_{\text{неад}}}{S^2_y} \le F_{(0{,}05, f_{\text{ад}}, f)},$$

where $F_{(0{,}05, f_{\text{ад}}, f)} \le F_{(0{,}05{,}6{,}32)}$, table value of F – criterion for the accepted 5% level of significance is equal to 2,34,

$$F = \frac{S^2_{\text{неад}}}{0{,}63} = \frac{1{,}22}{0{,}63} = 1{,}94.$$

Since the calculated value of the F – criterion does not exceed the table value, then the model is adequate. Analyzing the regression equation, it can be concluded that a taper angle matrix, that is, the geometry of the tool has the greatest influence on the value of technological strength in the combined cold extrusion in this variation interval.

The received equation allows constructing the characteristic curves:

- technological strength on the deformation degree and taper angle of a matrix at constant values of deformation velocity and the coefficient of contact friction (Figure 5);
- technological force on the contact friction coefficient and the taper angle of the matrix at constant values of the deformation degree and deformation velocity (Figure 6);
- technological force on the deformation degree and the coefficient of contact friction at constant values of the taper angle of the matrix and deformation velocity (Figure 7);
- technological force on the deformation degree and deformation velocity at constant values of the contact friction coefficient and the taper angle of the matrix (Figure 8).

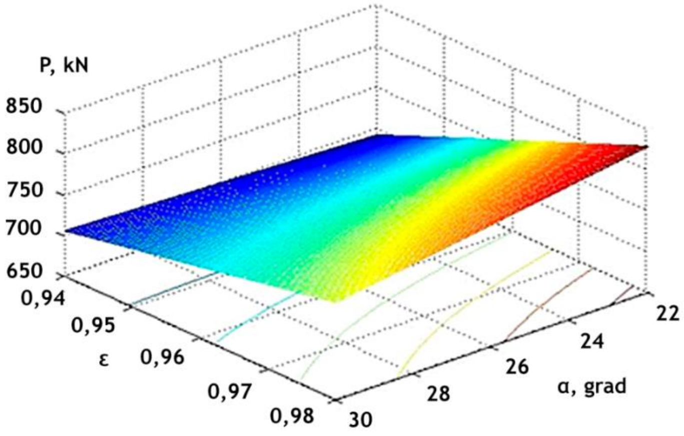

Figure 5. A graph of the influence of the deformation degree, the taper angle of a matrix on the technological force at constant values of deformation velocity and the contact friction coefficient.

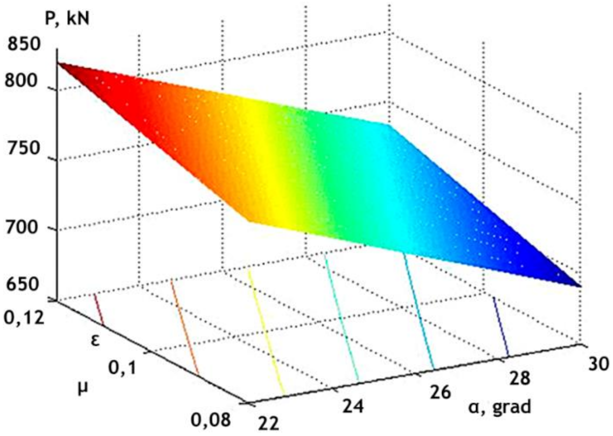

Figure 6. Influence graph of the matrix taper angle, and the friction coefficient on the technological strength at constant values of deformation velocity and deformation degree.

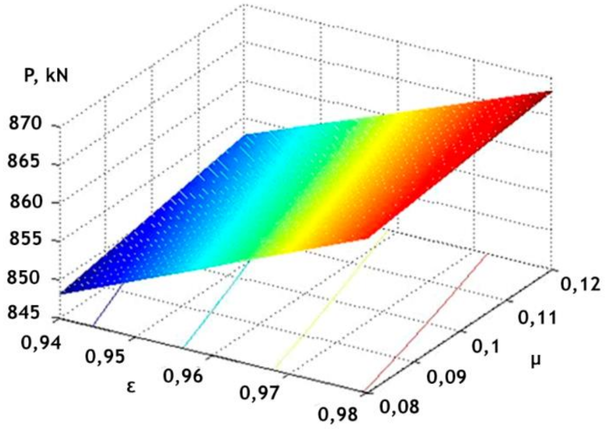

Figure 7. A graph of the influence of the deformation degree, and the friction coefficient on the technological strength at constant values of deformation velocity and taper angle of the matrix.

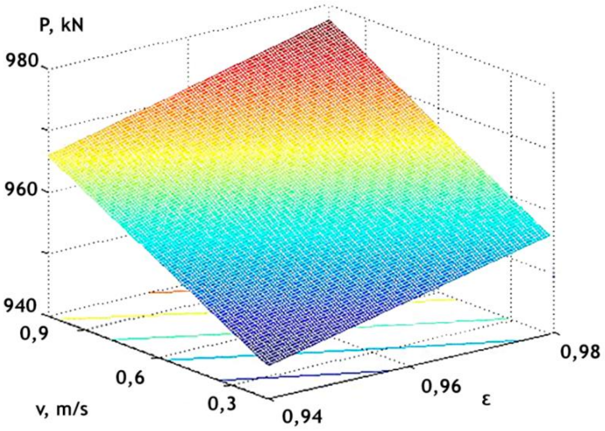

Figure 8. A graph of the influence of deformation velocity, and deformation degree on the technological strength at constant values of the friction coefficient and the matrix taper angle.

The process simulation of combined extrusion allowed establishing the correspondences of process parameters influence: deformation degree, the matrix taper angle, the friction coefficients of tool, and deformation velocity on the kinematics of material flow, strain-stress state of the blank, and the force conditions. It is shown that at the deformation degree ε=0,96 it is possible to use the friction coefficient on the tool μ=0,08…0,12, the taper angle of the matrix α=26…30°, the deformation velocity ν=0,3…0,9 м/с (m/s).

Discussions

The obtained regression equation and graph correspondences between the influence of basic operation parameters and the magnitude of the technological forces allow determining the importance of technological force depending on the basic factors without using sophisticated computer technology, which significantly reduces computation time. The obtained power value can be used to select the processing equipment, to predict the tool power and to choose the material for its manufacturing.

The influence of technological parameters, the degree of deformation, the tool geometry, deformation velocity and friction coefficient on the kinematics of material flow, strain-stress state of the blank and force conditions is determined. It is shown that the operation of combined extrusion of thin-walled components made of aluminum alloy A7 may be held at the deformation degree of the extrusion ε= 0,96 with wall thickness S=0.17 mm. Further increase in deformation degree leads to the destruction of the semi-product. The coefficients of friction on the matrix and plug μ= 0,08...0,12 and the taper angle of the matrix α=26...30^0, the deformation velocity ν = 0,3 … 0,9 м/с (m/s) are optimal, which give the optimal values of stresses and deformation.

Adapted software package allows simulating the influence of main technological parameters on the ability of the combined extrusion process of thin-walled cylindrical components with the visualization of calculations results in the form of charts, graphs, drawings of deformable semi-product, which allows reducing the computing time, providing clarity of results and reducing terms of new products development. In addition, this method assumes increased accuracy in contrast to the design scheme of L.I. Aliyev & N.S. Grudkina (2013) where there is a 15-20% disparity increment of semi-product during the process.

Conclusion

Analysis of the obtained regression equations showed that a taper angle matrix that is, the geometry of the tool has the greatest impact on the value of technological strength in the combined extrusion of thin-walled cylindrical components in the variation interval of these factors.

The obtained results can be used in a variety of additive technologies to obtain products with high mechanical properties using composite lubricants based on nanomaterial’s.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributors

Gennady M. Zhuravlev is Doctor of Engineering, Professor of Department of Building Materials, Technology and Service, Tula State Pedagogical University named after L.N. Tolstoy, Tula, Russia;

Aleksandr N. Sergeyev is Doctor of Pedagogy, Professor of Department of Technology and Service, Tula State Pedagogical University named after L.N. Tolstoy, Tula, Russia;

Aleksandr Y. Gvozdev is Doctor of Engineering, Professor of Department of Technology and Service, Tula State Pedagogical University named after L.N. Tolstoy, Tula, Russia;

Dmitry A. Provotorov is PhD, Research of Department of Technological Systems of Food, Printing, and Packaging Facilities, Tula State Pedagogical University named after L.N. Tolstoy, Tula, Russia;

Nikolay N. Sergeyev is Doctor of Engineering, Professor of Department of Technology and Service, Tula State Pedagogical University named after L.N. Tolstoy, Tula, Russia;

Aleksandr N. Privalov is Doctor of Engineering, Professor of Department of Technology and Service, Tula State Pedagogical University named after L.N. Tolstoy, Tula, Russia.

References

Alieva, L.I., & Grudkina, N. S. (2013). Theoretical Analysis of the Process of a Combined Radial-Backward Extrusion of Components with Flange. *Moscow State University of Mechanical Engineering (MAMI) Bulletin,* 2(2).

Atzeni, E., & Salmi, A. (2012). Economics of Additive Manufacturing for End-Usable Metal Components. *The International Journal of Advanced Manufacturing Technology, 62*(9), 1147-1155.

Delhote, N. et al. (2014). Inkjet Printing and Additive Technologies for the Fabrication of RF Components. International Microwave Symposium.

Dmitriev, A.M., & Vorontsov, A.L. (2002). Technology of Hammering and Matrix Forging. Part 1. Forging Pressing: the Textbook, 400 p. Moscow: *Vyschaya shkola*.

Dmitriev, A.M., & Vorontsov, A.L. (2004). Accounting of Heterogeneity of Mechanical Properties and Deformation Velocity in the Calculations of the Extruding Processes. *PF MWP, 8,* 3–10.

Gibson, I., Rosen, D., & Stucker, B. (2014). *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing,* 486 p. Springer.

Gibson, I., Rosen, D., & Stucker, B. (2015). *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing,* Ch. 10, 469 p.

Gvozdev, A.E., Starikov, N.E., Zolotukhin, V.I., Sergeev, N.N., Sergeev, A.N., & Breki, A.D. (2016). The Technology of Construction and Operating Materials: Textbook, 351 p. Tula: *Tula State University Press*.

Gvozdev, A.E., Zhuravlev, G.M., Sergeev, N.N., Zolotukhin, V.I., & Provotorov, D.A. (2016). Calculation of strain damage in the process of reverse extrusion of metal products. *Metal Technology*, 1, 21-33.

Gvozdev, A.E., Zhuravlev, G.M., Sergeev, N.N., Zolotukhin, V.I., & Provotorov, D.A. (2015). Statement of the Problem of Calculating the Deformation and Damage of Metals and Alloys. *The Production of Rolled Products, 10*, 18-26. ISSN 1684-257X.

Isiksal-Bostan, M., Sahin, E., & Ertepinar, H. (2015). Teacher Beliefs toward Using Alternative Teaching Approaches in Science and Mathematics Classes Related to Experience in Teaching. *International Journal of Environmental and Science Education*, *10*(5), 603-621.

Kashapov, R.N. et al. (2014). The Method of Manufacture of Nylon Dental Partially Removable Prosthesis Using Additive Technologies. *IOP Conference Series: Materials Science and Engineering. IOP Publishing, 69*(1), 012026.

Krznar, N., Pilipović, A., & Šercer, M. (2016). Additive Manufacturing of Fixture for Automated 3D Scanning–Case Study. *Procedia Engineering,* 149, 197-202.

Mertens, A., & Lecomte-Beckers, J. (2014). Processing Metallic Materials by Additive Technologies-Specificities of the Thermal History and Microstructures. *ORBI*, 1-12. Luxembourg.

Novik, F.S., & Arsov, Y.B. (1980). Optimization Process of Metal Machining Technology by Methods of Experiments Planning, 304 p. Sofia: *Tekhnika.*

Sedlak, J. et al. (2015). Study of Materials Produced by Powder Metallurgy Using Classical and Modern Additive Laser Technology. *Procedia Engineering*, 100, 1232-1241.

Vaidyanathan, R. (2015). Additive Manufacturing Technologies for Polymers and Composites. Additive Manufacturing, 19-64. Florida: *CRC Press.*

Zhuravlev, G.M., Gvozdev, A.E., Sergeev, N.N., Zolotukhin, V.I., & Provotorov, D.A. (2015). The Effect of Deformation Damage on the Formation of Mechanical Properties of Low Carbon Steels. *The Production of Rolled Products*, 12, 3-14.