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Mathematical and Computer Simulation for the Appearance of Dimple Defect by Cold Combined Extrusion

The article is considered a comparative analysis for predicting defect such as dimple by energy method of power balance, upper bound method and finite element method. The upper bound method takes into account the geometrical position and dimension of the dimple, the criterion for the formation in dimple by energy method of power balance is the presence of a minimum point in the function of relative pressure on the relative velocity of metal outflow in the vertical direction. New engineering calculations for the relative pressure are developed in combined radial-backward extrusion process by using a kinematic module with fillet. A comparative analysis of the obtained data has been carried out by energy method of power balance, upper bound method, computer simulation by Qform 2/3D program and experimental data. Rationality of using the energy method of power balance in view of its efficiency and the possibility of taking into account various friction conditions and the presence of fillet on the matrix, as well as smaller deviations from the results of finite element simulation and experimental data have been defined. Providing more conditions that are favorable for friction in the bottom of the billet and in the flange area in comparison with the friction conditions on the glass wall contribute to delay in the dimple appearance. It was found that the radius of fillet makes it possible to delay the dimple appearance by the approximately (0,4 ÷ 0.5R) mm for the entered radius of fillet R. This allows us to expand the possibilities of obtaining parts with a flange by combined radial-backward extrusion without the formation of a defect such as dimple.

Keywords: energy method of power balance; upper bound method; Finite element method; kinematic module; combined extrusion; dimple.

1. INTRODUCTION

In modern conditions, mechanical engineering has one of the key roles in ensuring the development of the economic. In this context, the priorities are determined by the development of over-modern science-intensive technologies as opposed to the classical methods of forming parts by removing shavings [1, 2]. The avai–lability of different methods by metal forming, it is possible to solve the actual problem based on economic rationality [1, 3-6]. In recent years, investigation has been carried out in the direction of solving specific practical problems [3, 5-9] and the development of theoretical foundations by different methods such as energy method of power balance and upper bound method based on modeling of plastic deformation processes, finite element methods and statistical data analysis [10-13]. Areas of theoretical investigations including such as methods for describing the shape of bodies, components of design schemes, effective techniques for simplifying the assessments of power modes, predicting the phased shaping of a semi-finished product, determination of the optimal shape of the tool and techniques to avoid defect formation [11, 12, 14-17]. Cold forging extrusion process is considered such as perspective process of metal forming that allows us to use different billets and to make parts with different dimensions and qualities [1, 2, 18-21]. However, the limiting factors of more active implementation for cold forging extrusion processes in production are the failure of recommendations for predicting power and defor–mation mode. On the other hand, for cold extrusion forging processes according to basic schemes such as combined extrusion processes with several metal flow freedom degrees, additionally need to solve the problems of predicting the step by step and limiting shaping of the semi-finished product and also under certain conditions to appear and avoid defect formation processes [12, 13, 22-27]. The main ones are the non-fulfillment of the shape and size in the finished product, ruptures (separation) of the flange, the formation of cracks and various types of defects such as walls

Received: August 2021, Accepted: October 2021
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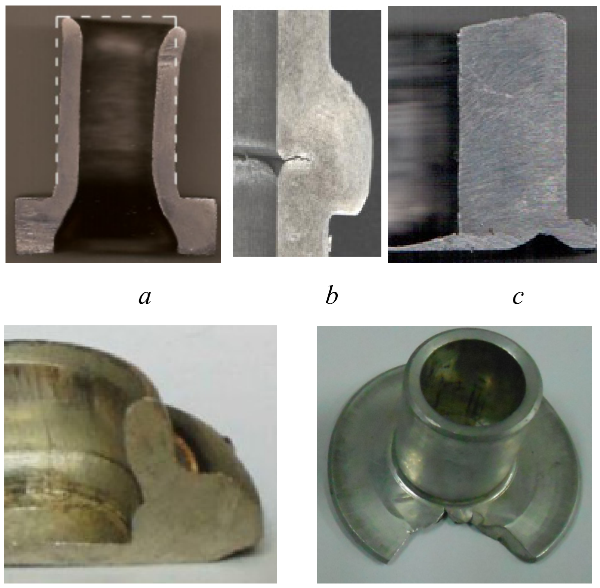
doi: 10.5937/fme2201090H

curvature, squeeze, folder and dimple [28-31]. Therefore, the actual problems are determination of ratios that are critical from the viewpoint of possible defect formation and technological factors that allows us to avoid the appearance of a defect. This will significantly expand the scope of application in cold forging extrusion technologies, including for combined extrusion with several metal flow freedom degrees.

At the present time investigation of cold forging extrusion processes based on schemes and with several metal flow freedom degrees are devoted to investigation [11, 12, 15, 17-31]. Most of the investigation in mode–ling combined extrusion processes including the deter–mination of the force regime, estimates in increments of semi-finished product and carried out based on finite element modeling and experimental investigations [18, 19, 23, 25]. The authors [12, 13, 23-26, 28] has determined the influence of the tool design features, geometric relationships for shaping and energy power parameters in combined radial-longitudinal extrusion processes, however, the question of the possible appe–arance of defect formation has not been put. Inves–tigation can be considered a separate area by defor–mability of billets, calculations of the plasticity resource for the processes of combined radial-longitudinal extrusion [14, 16]. This makes it possible to assess the expansion of the technological capabilities in the inves–tigated plastic deformation processes. On the other hand, the promising application of various modifications in the energy method of power balance and upper bound method such as for determining energy-power parameters, and for predicting the formation of a semi-finished product and defect formation are considered [27, 30, 31].

Major defects in the processes of cold forging extrusion can be attributed such as walls curvature (Fig. 1, a), squeeze and dimple (Fig. 1, b, c, d), non-adherence and rupture of the flange (Fig. 1, e) [16, 27, 29, 30]. Defects in the form of the end lateral curvature occur due to insufficient fixation of the punch in the deformation process, which also causes a difference in the thickness of the glass wall (Fig. 1, a). Defect formation such as flange rupture is typical, usually for low plastic materials or with a small flange thickness for more plastic materials (Fig. 1, e). This type of defect formation is facilitated by a rather complex stress-strain state diagram, since in the flange formation zone circumferential tensile stresses prevail on the peripheral part and so the stress state is close to linear tension. Shape deviation in the form of dimple defect, depending on the extrusion schemes, can occur at different stages of the process and in different zones of the semi-finished product. For combined radial-backward extrusion in hollow parts with flange in the final stage of the process, with the overwhelming flow of metal in the opposite direction, dimple defect is formed in the bottom section (Fig. 1, c). For the same process, under the condition of the overwhelming metal flow in the radial direction (glass wall does not change) dimple defect is formed on the inner wall of the glass. (Fig. 1, d). The works [27, 29, 30] have been demonstrated the possibilities of using the energy method of power balance, upper bound method and finite element method for predicting defect formation in the processes of combined radial-longitudinal extrusion. Previously reported investigations [27, 30] have been demonstrated the capabilities of the upper bound method for pre–dicting dimple defect by comparative analysis with experimentally obtained data. However, the upper bo–und method has been given overestimated data in the moment of dimple formation and has been used for a simple case without taking into account the influence of friction conditions and the presence of chamfers or fillets on the matrix. In investigation [29], an analysis of experimental data in the deformation force for a process without and with dimple formation has been presented. However, the die design features with the form of a chamfer or fillet on the die tools and the right choice with friction conditions are very important in the ext–rusion processes to delay in the defect appearance. The energy method of power balance, which has been developed in recent years, is aimed at solving axisym–metric processes and is more flexible to quickly change the configuration of the tool and take into account the friction conditions. The development of the energy method will expand the understanding of the conditions for the appearance of a defect and determining the factors of effective control in the shaping of a semi-finished product for a more complex configuration.



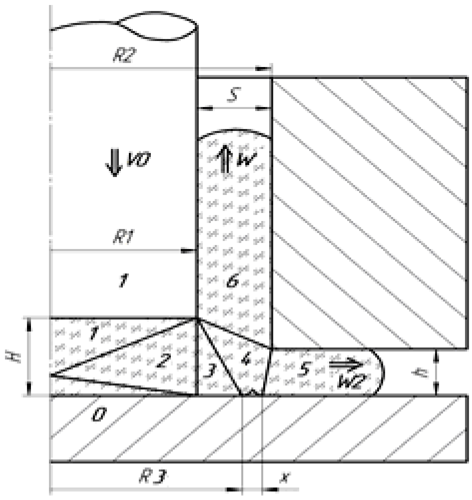
d *e*

Figure 1. Flange defects with the form of walls curvature(a), squeeze (b) dimple (c), (d) and rupture (e) [27, 29]

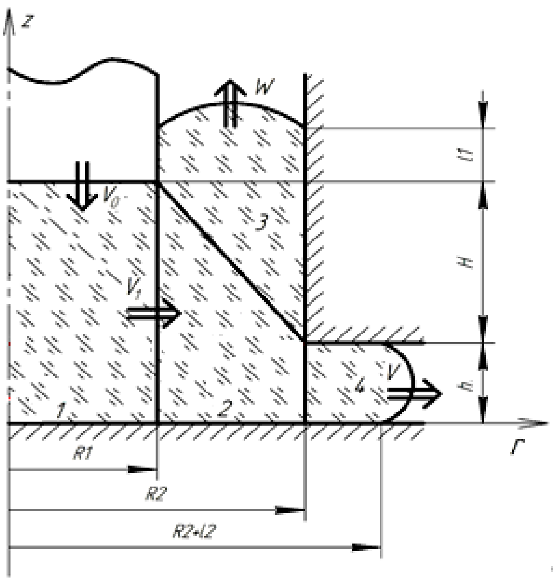
2. PRESENTATION OF THE MAIN MATERIAL

2.1 Mathematical modelling of the defect formation process by the energy method of power balance and upper bound method

The energy method of power balance and upper bound method are currently presented in two of the most The most common forms: upper bound method (plane strain problem) and energy method of power balance (axisymmetric problem) [32-40]. Approaches to solve problems for determining conditions, position and main factors in extrusion processes with the presence of defect formation are as follows. When using the upper bound method, appearance dimple defect in the bottom section in the final stage of the deformation process with combined radial-backward extrusion (Fig. 2, a), based on geometrical parameters, without affecting kinematical parameters has been shown. (the metal flow velocity in the vertical W and radial W_2 directions) [30]. On the other hand to analyze the problem of predicting defect in combined radial-backward extrusion can be used with the assumption of transition from combined to backward extrusion ($W_2 \rightarrow 0$). Metal flow in the radial direction that is defined as a condition to delay the moment of the dimple defect appearance. Thus, the geometrical parameters for predicting defect in combined radial-backward extrusion process as follows: H_0 – the height of billet, R_1 – the radius of the punch R_2 – the radius of matrix, R_3 – the geometrical position of the dimple, R – the radius of the fillet, h – the thickness of the flange, x – the width of the dimple, H_{cr} – the critical value of the bottom thickness in dimple appereance [30].



a



b

Figure 2. The calculated scheme of radial-backward extrusion process for predicting defect such as dimple: plane strain problem (a), axisymmetric problem (b)

Determination of the bottom thickness is the most valuable in the investigation of the defect solution process in the form of dimple and accordingly, calculating the stroke of deformation process to define the moment of the dimple defect appearance. To determine the limiting bottom thickness will be used the solution of the equation as follows:

$$\left[\begin{array}{l} (H_{cr}+G)^2 \cdot \left[\begin{array}{l} (H_{cr}-G)(3H_{cr}+2G)+ \\ +2\mu_s G^2 \end{array} \right] + \\ +GH_{cr} \cdot \left(\begin{array}{l} 3Gh+H_{cr}^2+ \\ +(H_{cr}-h)^2 \left(1-\dfrac{h}{R_2-R_1}\right) \end{array} \right) \end{array} \right] = 0 \quad (1)$$

where $G = R_2 - R_1 - h$.

The graphical dependence calculated by (1) makes it possible to determine the critical bottom thickness, to define the moment of the dimple defect appearance (Fig. 3) under the same as conditions of friction on the contact surface of the billet and the tool. Influence of friction conditions within the limits $\mu_s = 0 \div 0.16$ for cold extrusion process with $R_1 = 10$ mm, $R_2 = 20$ mm, in fig. 3 have been shown.

Different friction conditions and increase in flange thickness can be considered favorable factors to reduce the critical bottom thickness, i.e. different factors allow us to obtain dimple appearance after more time during deformation process. The obtained data must be compared with the investigation of the axisymmetric problem, finite element modeling results and experi–mental data.

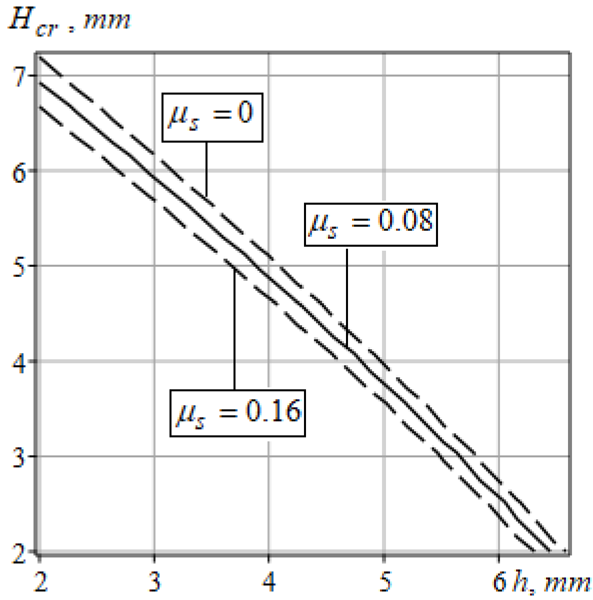


Figure 3. Dependence of the bottom thickness H_{cr} from the flange thickness h under various friction conditions based on the upper bound method

When using the energy method of power balance, an approach for obtaining the critical values of the bottom thickness, which corresponds to the appearance of dimple defect (Fig. 2, b) [20, 29].

The value of the relative pressure is obtained in the equation:

$$\bar{p} = \bar{p}_{1-3} + \Delta\bar{p}_{c2-4} + \Delta\bar{p}_4, \quad (2)$$

where $\bar p_{1-3}$ and $\Delta\bar p_4$ — relative pressures of modules 1-3 and 4, respectively, without taking into account the power of shear forces between modules 2 and 4;

$\Delta\bar p_{c2-4}$ — relative pressures of shear forces between modules 2 and 4.

The components of equation (2) are defined as follows:

$$\bar p_{1-3}=\left(\begin{array}{l} 1+\frac{1}{\sqrt3}\left(\bar H_0-\Delta\bar H_X\right)\left(1+\bar W+\bar a\bar V_1\right)+\bar p_2+ \\ +\frac{1+\bar a^2+2\mu_{s\to}}{\sqrt3 \bar a}\left(\begin{array}{l}\left(\bar M+\bar W(1-\bar b^2)\right)\ln\left(\frac{\bar R_2+\bar b}{1+\bar b}\right)- \\ -\frac{\bar W}{2}\left[(\bar R_2-\bar b)^2-(1-\bar b)^2\right]\end{array}\right)+ \\ +\frac{2(\mu_{s\uparrow}+\mu_{s\to})}{3\sqrt3\left(\bar H_0-\Delta\bar H_X\right)}+\frac{4\mu_{s\uparrow}}{\sqrt3}(1+\bar W)(\Delta\bar H_X+\bar l_1)+ \\ +\frac{4\mu_{s\uparrow}\bar R_2}{\sqrt3}\bar W\left(\bar H_0-\bar h+\bar l_1\right)\end{array}\right) \quad (3)$$

$$\bar p_2\le\frac{2}{\sqrt3}\sqrt{\begin{array}{l}\bar a\left(\frac{\bar R_2^3-1}{3}+\bar b\,\frac{\bar R_2^2-1}{2}\right)\times \\ \times\left(4\left(1+\frac{\bar a^2}{3}\right)\left(\bar U_1+\bar U_2\right)+\left(4+\frac{\bar a^2}{3}\right)\bar U_3\right)\end{array}} \quad (4)$$

$$\Delta\bar p_{c2-4}=\bar p_{c2}=\frac{\bar R_2\bar h}{\sqrt3}\left(\bar W+\frac{\bar M+\bar W(1-\bar R_2^2)}{2\bar R_2\bar h}\bar a\right) \quad (5)$$

$$\Delta\bar p_4=\left[\begin{array}{l}\frac{2}{\sqrt3}\left[\bar M+\bar W(1-\bar R_2^2)\right]\ln\left(\frac{\bar R_2+\bar l_2}{\bar R_2}\right)+ \\ +\frac{4\mu_{s\to}}{\sqrt3}\left(\bar M+\bar W(1-\bar R_2^2)\right)\frac{\bar l_2}{\bar h}\end{array}\right] \quad (6)$$

where $\Delta\bar H_X=\frac{\Delta H_X}{R_1}, \bar H=\frac{H}{R_1}, \bar H_0=\frac{H_0}{R_1},\ \bar R_2=\frac{R_2}{R_1}$,

$\bar h=\frac{h}{R_1},\ \bar l_1=\frac{l_1}{R_1}, \bar l_2=\frac{l_2}{R_1},\ \bar b=\frac{\bar h}{\bar a}-\bar R_2, \bar a=\frac{\bar H}{1-\bar R_2}$,

$\bar W=\frac{W}{V_0}, \bar V_1=\frac{1}{2\left(\bar H_0-\Delta\bar H_X\right)}, \bar M=2\bar V_1\left(\bar H_0-\Delta\bar H_X\right)$.

In this case, the geometric position of dimple is not taken into account, the function of the relative pressure is investigated (2) from the relative velocity of metal outflow in the vertical direction .

The character of the change in the kinematic parameter (metal outflow rate in the vertical direction) is the criterion that, in the presence of a minimum point, make a conclusion about the possibility of a defect solution. The moment of defect formation corresponds to the presence of a minimum parameter $\bar W$ depending on the bottom thickness *Hcr* (Fig. 4). For a process without formation of dimple, is characterized by a monotonic fall over punch displacement (stroke), (growth relative to bottom thickness *Hcr*) the whole deformation process that is, the absence of a minimum point (fig. 4, lower curve with $\mu_{s\uparrow}$ = 0.16, $\mu_{s\to}$ = 0). We will carry out a comparative analysis of theoretical result by upper bound method (1), and energy method of power balance (2) from the viewpoint of investigation in the critical value of the bottom thickness, which corresponds to appearance of dimple defect. Using the range of variation in friction conditions for cold extrusion with h_1=3 mm and critical values range in the bottom thickness H_{cr} from 3.5 mm to 7.5 mm are considered. However, a comparative analysis with the upper bound method (Fig. 3) can be carried out only for the same as friction conditions on all contact surfaces of the billet and the tool, i.e. $\mu_s=\mu_{s\uparrow}=\mu_{s\to}$.

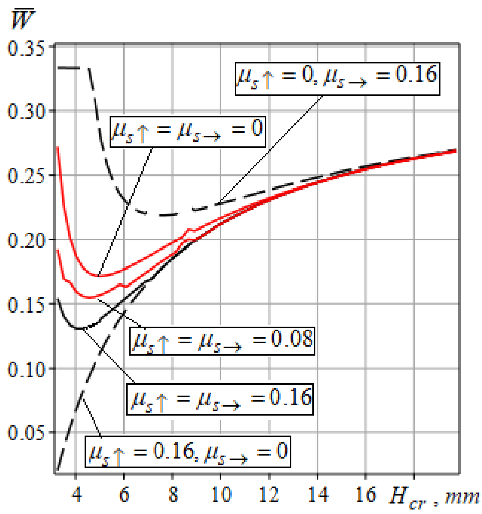


Figure 4. Change in the optimal value for the relative velocity of metal outflow in the vertical direction during the process punch displacement t from the bottom thickness

For values h=3 mm, the critical bottom thickness H_{cr} is determined by the upper bound method (1) with is approximately 5.93 mm (Fig. 3, the curve with μ_s = 0.08) and in comparison by energy method of power balance H_{cr} is approximately 4.5 mm (solid curve with $\mu_{s\uparrow}=\mu_{s\to}$ = 10, fig. 4). Similarly, for by equation (1) will be determined a critical bottom thickness is approximately 6.17 mm in comparison to 5 mm by the equation (2), and for the corresponding critical values reach 5.68 mm and 4.22 mm. Thus, the predicted value of H_{cr}, which is obtained by equation (1), can be used as a preliminary estimate of the same as friction conditions on all contact surfaces of the billet and the tool. In this case, the analysis of any other friction conditions ranges or changes in the configuration of the tool is impossible, however, the advantages of using (1) can definitely be attributed to the elementary nature of obtaining the necessary information. Comparative analysis with experimental data for the material lead is shown in the rationality of using equation (2), deviations of the predicted bottom thickness values with the beginning of dimple appearance from experimental result does not exceed 1-1.5 mm, and according to equation (1) it can reach 2.5 mm and higher [29]. Previously obtained results in this investigation were additionally compared with the upper bound method that which showed more significant deviations from the experimentally obtained data. Thus, calculations by equation (2) are closer to reality and more informative from the viewpoint of taking into account various friction conditions and the possibility of promptly replacing the shape of the flange zone (configuration of the kinematic module 4, Fig. 2, b).

2.2 Computer simulation of the defect formation process with finite element method by QForm 2/3D program

A comparative analysis of the experimental result with obtained part from lead for the formation of dimple and simulation by QForm 2/3D in different parameters such as R_1=10.5 mm, R_2=22.5 mm, h=3.5 mm and H_0=20.5 mm and bottom thickness H_{cr}=1,0 mm are considered (Fig. 5). The obtained results in the shaping of the part are identical. This allows us to make more extensive use of simulation results by QForm 2/3D as an analogy a natural experiment for comparative analysis with obtained data by energy method of power balance. In this investigation the theoretical result according to equation (2) in the form H_{cr} =4.5 mm (fig. 4, curve with $\mu_{s\uparrow} = \mu_{s\rightarrow} = 0.08$) confirms with experimental result 4 mm for mate–rial such as lead (fig. 5) for the moment of defect appearance.

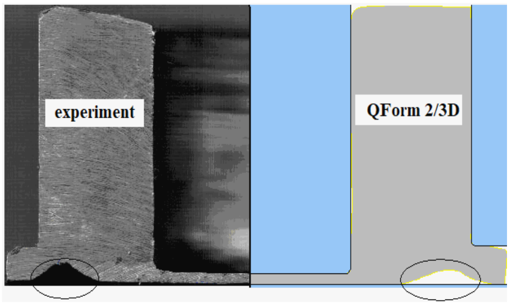


Figure 5. Analytical report and models by QForm2D/3D for appearance of dimple

According to simulation by QForm 2/3D, significant influence of friction conditions with the possibility of a defect such as dimple that is consistent with the result of theoretical investigations based on the calculation equation (2) are confirmed. Analysis of friction condi–tions as a technological factor in the shaping control of semi-finished product with lead material are carried out for parameters R_1 = 10.5 mm, R_2 = 22.5 mm, h=3 mm and H_0=20 mm and bottom thickness H_{cr}= 4 mm (Fig. 6) and partially higher when using equation (2) (Fig. 4). Thus, the conditions of contact friction can be attributed to significant factors affecting the possibility of defect formation in the process of combined radial-backward extrusion. It should be borne in mind that the deteri–oration of the friction conditions in the bottom section of the billet make it possible to reduce the size of the flange zone, and the deterioration of friction conditions on the glass wall, which are formed, against, will contribute to the increased dimen–sions of the flange and long-time delay for dimple appearance during deformation process.

However, the observance of the necessary friction conditions in the entire deformation process and constant for the entire contact surface of the billet and the tool are a rather controversial issue in the real process of extrusion.

As known, that combined extrusion processes with several freedom degrees of metal flow have the self-regulation property in the shaping of a semi-finished product. The presence of a complex configuration in the tool as chamfer and fillet forms are also factors for the control in the shaping of a semi-finished product. The results of shaping simulation in the extrusion process of combined radial-backward by Qform 2/3D indicate differences in the design of the flange zone (Fig. 7) and the possibility of correction with the provision of the defect appearance such as dimple. Varying the friction boundary conditions make it possible to obtain corrections of the filling in the flange zone up to 10% for the given parameters of the deformation process.

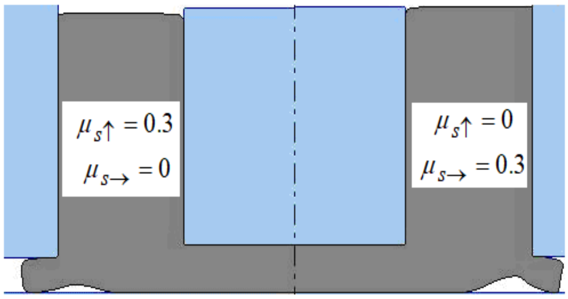


Figure 6. Process simulation by QForm 2/3D with defect appearance such as dimple under various conditions of friction

More favorable factor from the viewpoint of uni–formity for filling the flange zone is the fillet selection factor that it is possible to form a uniform flange without defects. However, the primary task should be considered precisely the comparison in the shapes of the semi-finished product with the identification for the moment of defect appearance in the dimple form in billet (Fig. 1, c). In the process simulation by Qform 2/3D have been used additionally fillet radius dimensions such as 2 mm and 5 mm for R_1=10.5 mm, R_2=22.5 mm, h=3 mm and H_0=20 mm and friction conditions $\mu_1 = \mu_2 = 0.08$ for the lead material.

A delay in the dimple appearance can be reached approximately up to (0.4 ÷ 0.5R) using the radius of fillet R. For a process without fillet in given geometric relationships we have the dimple appearance for a bottom thickness of approximately 4.4 mm, with the radius fillet 2 mm and 5 mm, it is possible to reduce this critical value by 3.231 mm and 2.023 mm, respectively.

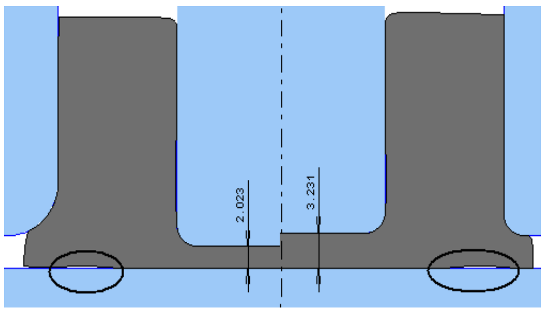


Figure 7. Comparative analysis of glass bottom thickness that corresponds to the dimple appearance in R = 5 mm (left half) and R = 2 mm (right half)

Thus, for the tool design features fillet dimension is a favorable factor in terms of flange design and it is possible to avoid dimple appearance. However, the possibility of correcting defect formation due to the design features of the tool by using champers and fillets with different dimensions on the tools such as matrix that before by energy method of power balance were not used, calculation models did not take into account these features.

2.3 Improvement of mathematical models for pre–dictting defect formation process

The energy method of power balance allows us to use different schemes with the presence of kinematic modules with various configurations [33, 36-39].

Development of a kinematic module with fillet (Fig. 8) provides operational analysis capabilities to determine the optimal radius of fillet from viewpoint dimple appearance by the required amount in punch displacement (stroke) or bottom thickness [40]. The die and tool design to predict the defect formation such as dimple with the determination of the optimal fillet radius to make the production of quality parts will be main practical investigations.

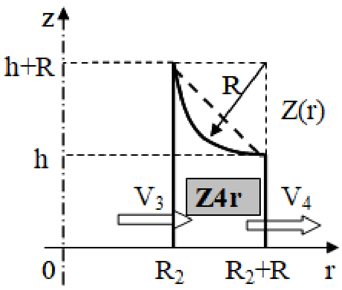


Figure 8 – Kinematic module with fillet

The calculation scheme of the deformation process with module 4 – kinematic module Z4r with fillet, for anticipation dimple appearance, allows us to get the fol–lowing results. According to equation (2) it is necessary to replace components (5) and (6) respectively (7) and (8) [40]:

$$\Delta\bar{p}_{c2-4r} = \left| \bar{p}_{c2} - \frac{2\pi^2 A}{\sqrt{3} R_2 R^2} \right|; \tag{7}$$

$$\Delta\bar{p}_{4r} = \left[\begin{array}{l} \dfrac{1}{2\pi V_3 R_2 (h+R)} \sqrt{S \cdot V} + \dfrac{A}{2\sqrt{3} C^2} + \\ + \dfrac{2\mu_S}{\sqrt{3}} \left[\begin{array}{l} \dfrac{2}{B} \left[R - \dfrac{A}{B} \ln \left| \dfrac{BC+A}{B \dfrac{R_2 R}{2\pi} + A} \right| \right] + \\ + A \left[\begin{array}{l} \dfrac{B^2}{A^2} \ln \left| \dfrac{(BR_2 R + 2\pi A) C}{R_2 R (BC+A)} \right| + \\ + \dfrac{B}{A} \left(\dfrac{1}{C} - \dfrac{2\pi}{R_2 R} \right) - \\ - \dfrac{1}{2} \left(\dfrac{1}{C^2} - \dfrac{4\pi^2}{R_2^2 R^2} \right) \end{array} \right] \end{array} \right] \end{array} \right] \tag{8}$$

where, $S = \iiint\limits_V \dot{\varepsilon}_i^2 dV$, $\dot{\varepsilon}_i$ – the intensity of defor–mation rates for the module Z4r;

$$V = 2\pi \left[\begin{array}{l} A \left(R + R_2 \left(1 - \dfrac{R}{2\pi} \right) \ln \left| \dfrac{2\pi C}{R_2 R} \right| \right) + \\ + B \dfrac{(R_2 + R)^2 - R_2^2}{2} \end{array} \right]$$

– the vol–ume of the module Z4r for the approximating curve;

$$z(r) = \frac{A}{r - R_2 \left(1 - \dfrac{R}{2\pi} \right)} + B$$

$$A = \frac{R^2 R_2}{2\pi} \left(1 + \frac{R_2}{2\pi} \right); \; B = h + R - \frac{2\pi A}{R_2 R};$$

$$C = R \left(1 + \frac{R_2}{2\pi} \right); \; V_3 = \frac{V_0 R_1^2}{2 R_2 (h+R)}$$

Thus, the value of the relative pressure with the presence of the kinematic module Z4r taking into account (2) and (7) and (8) takes the form:

$$\bar{p} = \bar{p}_{1-3} + \Delta\bar{p}_{c2-4r} + \Delta\bar{p}_{4r} \tag{9}$$

According to equation (9) the influence of fillet for the dimple appearance with R_1=10 mm, R_2 =20 mm, h=3 mm and H_0=16 mm is analyzed. For the basic calculation scheme of the process, the dimple appearance corresponds to the stroke ΔHx =10.4 mm (critical bottom thickness Hcr =5.6 mm, solid upper curve, Fig. 9), with the fillet it is possible to delay the dimple appearance with R=2 mm to ΔHx =11.41 mm (Hcr= 4.59 mm) and R=5 mm to reduce ΔHx=12.44 mm (Hcr = 3.56 mm). The obtained data correspond to the form of the semi-finished product, according to Qform2/3D (Fig. 7) and the oriented value of the delay in (0.4 ÷ 0.5R) mm.

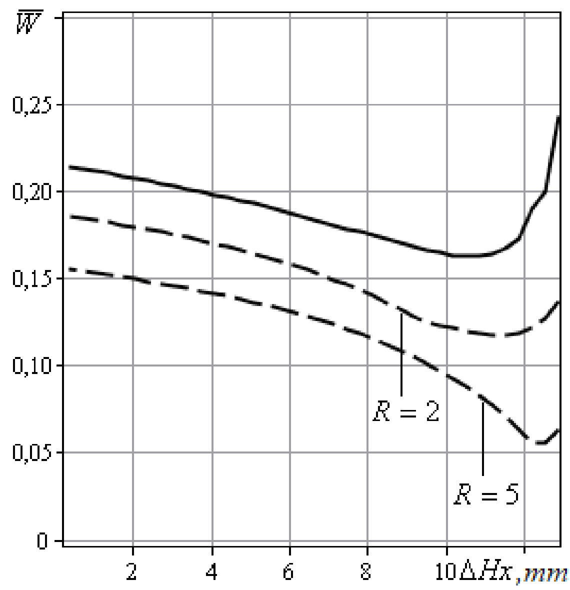


Figure 9. Fillet influence analysis for dimple appearance

Thus, based on the comparative analysis by using energy method as upper bound method (1) and energy method of power balance (2) and (9), theoretical results indisputable will been confirmed. The use of dimple appearance in accordance with (1) can be recommended due to the simplicity of calculations in the form of a preliminary stage for predicting a defect. A more complete analysis, taking into account the identification of control factors in the form of friction conditions and the possibility of fillet in the flange zone, is provided by energy method of power balance.

3. CONCLUSIONS

Analysis of the possibilities for controlling the shaping of complexly shaped parts in the design stage of com– bined extrusion processes are associated with the development of theoretical methods.

The article provides a comparative analysis of two theoretical methods for predicting defect such as dimple by using the main modifications of the energy method. It was found that, in comparison with the experimental result, the upper bound method shows large deviations. Therefore, the use of estimate (1) is recommended as a preliminary stage for assessing defect formation for the simplest case without taking into account the radius of fillet on the matrix. Based on the analysis of a semi-finished product shaping in Qform 2/3D, a significant effect with the radius of fillet on the matrix and various friction conditions for the formation of a dimple were determined. It was found that ensuring more favorable friction conditions in the bottom part of the billet and in the flange zone in comparison with the friction con– ditions on the nozzle wall contributes to a more late appearance of dimple. To take these factors into acco– unt, the authors obtained new engineering calculations of the relative pressures (2) in the combined radial-backward extrusion process using a kinematic module with a fillet. It was found that the introduction of the fillet radius allows to delay the appearance of the dim– ple by a stroke equal to approximately (0.4 ÷ 0.5R) mm for the entered radius of fillet R. This allow in the design stage, ensure that high-quality parts are obtained without the formation of a dimple by determining the required radius of fillet and friction conditions.

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NOMENCLATURE

V_0	Punch velocity, [mm/s]
V_3	Velocity of the metal flow for the module Z4r, [mm/s]
W	Velocity of the metal flow in the vertical direction on the glass wall, [mm/s]
h	The thickness of the flange, [mm]
H_{cr}	The critical value of the bottom thickness in dimple appereance, [mm]
ΔHx	Punch displacement (stroke), [mm]
R_1	The radius of the punch, [mm]
R_2	The radius of matrix, [mm]
R_3	The geometrical position of the dimple, [mm]
R	The radius of fillet
z(r)	Inclined boundary of the flow interface in module 2
μ_s	Coefficient of friction, $0 \le \mu_s \le 0.5$
$\bar{p}$	Relative pressure
$\bar{p}_r$	Relative pressure with radius of fillet
$\bar{p}_{1-3}$	Relative pressure in modules 1-3 and 4
$\Delta\bar{p}_4$	Relative pressure in modules 4
$\Delta\bar{p}_{4r}$	Relative pressure in modules 4 with radius of fillet
$\Delta\bar{p}_{c2-4}$	Relative pressure of shear force between modules 2 and 4
$\Delta\bar{p}_{c2-4r}$	Relative pressure of shear force between modules 2 and 4 with radius of fillet

МАТЕМАТИЧКА И КОМПЈУТЕРСКА СИМУЛАЦИЈА ПОЈАВЕ УДУБЉЕЊА ТОКОМ ХЛАДНОГ КОМБИНОВАНОГ ИЗВЛАЧЕЊА

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Овај чланак представља компаративну анализз за предвиђање дефекта као што је удубљење енер–гетским методом биланса снага, методом горње границе и методом коначних елемената. Метода горње границе узима у обзир геометријску позицију и димензију удубљења, критеријум за формирање у удубини енергетским методом биланса снаге је присуство минималне тачке у функцији релативног притиска на релативну брзину изливања метала у вертикални правац. Нови инжењерски прорачуни за релативни притисак су развијени у комбинованом процесу извлачења радијално-назад коришћењем кинематичког модула са углом. Урађена је упоредна анализа добијених података енергетским методом биланса снага, методом горње границе, комп–јутерском симулацијом Kform 2/3D програмом и експерименталним подацима. Утврђена је рационалност употребе енергетског метода биланса снага с обзиром на његову ефикасност и могућност узимања у обзир различитих услова трења и присуства заобљења на матрици, као и мањих одступања од резултата симулације коначних еле–мената и експерименталних података. дефинисано. Обезбеђивање више услова који су повољни за трење у дну гредице и у области прирубнице у поређењу са условима трења на стакленом зиду доприноси одлагању изгледа удубљења. Утврђено је да радијус угаонице омогућава одлагање појаве удубљења за приближно (0,4 ÷ 0,5Р) мм за унети радијус угаонице Р. То нам омогућава да про–ширимо могућности добијања делова са прируб–ницом за комбиновано извлачење радијално-назад без формирања дефекта као што је удубљење.