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METHOD FOR POCKET DIE DESIGN ON THE BASIS OF NUMERICAL INVESTIGATIONS OF ALUMINIUM EXTRUSION PROCESS

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The paper considers dependences of metal forming characteristics on dimensionless geometrical parameters of flat pocket die design at direct extrusion of aluminium thin-walled solid profiles. The theoretical analysis of plastic metal flow is carried out by means of the 2-D FEM model. The new method for flat pocket die design is proposed in the paper. The die design example is given for non-symmetrical U-shape profile.

Key words: *finite elements method (FEM), direct extrusion, die design, pocket flat die, aluminium alloy*

Metoda programiranja džepne matrice na osnovi numeričkih istraživanja procesa istiskivanja aluminijskih legura. Članak razmatra ovisnost karakteristika oblikovanja metala na bezdimenzionalne geometrijske parametre ravne džepne matice u izravnom istiskivanju tankih Al-profila. Teorijska analiza plastičnog tečenja metala je provedena primjenom 2-D FEM modela. nova metoda je predložena za izradbu ravne džepne matrice. Odnosi se na nesimetrični U-profil.

Ključne riječi: *metoda konačnih elemenata, izravno istiskivanje, projektiranje matrice, džepna ravna matrica, aluminijska legura*

INTRODUCTION

A typical extrusion of low and medium strength aluminium alloys solid shapes is performed with flat pocket dies. The pocket allows realising the extrusion as "billet-to-billet" process, and also facilitates filling-up die channel deadlocks and thin-walled elements of profile [1]. In addition it serves as an instrument for shape geometry control.

The scientific literature contains a variety of rules, formulas and methods for calculation of geometrical parameters of flat pocket dies design for extrusion of solid shapes of aluminium alloys [2 - 5]. However, a set of important die design parameters, such as bearing length [2, 3, 5], displacement of the channel from the centre of die [4], as displacement of median of the channel from median of pocket [2 - 5], etc. is often not taken into account, in general case it does not allow to calculate all necessary outcome values.

Because of the above reason the goal of the paper is the development of a flat pocket die design method for aluminium alloys solid shapes extrusion. Thus in order to reach this aim it is necessary to find the quantitative dependence between extrusion tool geometry and deforming parameters. Recently FEM simulations were used for solving similar problems [5, 6].

NUMERICAL ANALYSIS BY FEM

Despite the great interest for three-dimensional simulation, it is reasonable to research two-dimensional models where multiple computations are required due to their greater flexibility, lower computation time at the same precision, and the possibility of selection of a limited number of separate factors that have an effect on metal forming. On this basis, the two-dimensional mathematical model for reaching extrusion process has been developed [7].

The mathematical model is based on the following assumptions: the strain state at extrusion of metal from container is flat; process of direct extrusion is considered as quasistationary and isothermal; a deformed material is nonlinear-viscous and incompressible; deformation stress depends on strain, strain rates and temperature. The problem of plastic flow is solved by finite element method discretization of the Markov's variational principle functional. Real fields of velocities and average hydrostatic stress are defined on the strength of condition of a stationarity of a functional when variations of a functional on nodal velocities and average hydrostatic stress on element are equal to null.

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The usage of two-dimensional mathematical model has limited applicability of considered die design method only to shapes with thin-walled elements (the ratio of length of channel element to its thickness should be more than 12), that is shown in work [8].

The analysis of extrusion tools geometry allows to select seven characteristic dimensions that have an influence on metal flow (Figure 1.): the cross size of the container, D; distance from axis of the container to median of the channel (eccentricity), e; depth H and width B of the pocket; displacement of median of the channel from median of pocket, Δb; channel width (wall thickness of shape), s; bearing length, h. Six dimensionless die design parameters: $2e/D$, B/H, $\Delta b/B$, h/s, B/s, D/s were selected.

To carry out the theoretical analysis of effect of these parameters on a plastic metal flow the following basis initial conditions of calculations are accepted: $D = 160$ mm; billet length is 190 mm; $s = 2$ mm; $H = 10$ mm; $B = 12$ mm; $\Delta b = 0$; $e = 40$ mm; $h = 0$; the ram speed is 10 mm/s; the temperature of metal is equal 480 °C, an extruded aluminium alloy is 6063. At investigation, relationship of metal forming with displacement of median of the channel and median of pocket was combined with the axis of container ($2e/D = 0$).

It is necessary to note, that the profile going out from die orifice is bent on radius. Therefore the most objective parameter of curvature of the shape is its radius (r). The other conventional parameter for an estimation of the curvature is deviation from extrusion axis per unit of length (ζ), it can be calculated with known radius.

The theoretical analysis by mathematical simulation for each of the indicated dimensionless geometrical parameters was carried out [9 - 12]. The generalized results of theoretical investigations are shown in Figure 2.

BACKGROUNDS AND ALGORITMUS OF FLAT POCKET DIE DESIGN METHOD

Distance from the axis of the container to median of the channel (eccentricity) e tends to be bend the profile or its element in direction opposite to the axis of the container. At the same time, displacement of a die channel from axis of the container always takes place at multi-channel extrusion. At single-channel extrusion of solid profiles the lay-out of elements of channel (rectilinear sections into which all channel nominally is divided) with an eccentricity is normal practice.

It is noted in work [13], that assurance of linearity of metal outflow on different channel elements ensures lack of curvature of profile as a whole. On the ground of given concept - to provide a linearity of metal outflow from die orifice on its different elements - the method for flat pocket die design is developed.

From the above listed dimensionless geometrical parameters of extrusion tool only one can compensate the bending of output profile dependent on an eccentricity e. It is displacement of median of the channel from median of pocket Δb. Residuary factors (H/B, D/s, B/s, h/s) influence only an absolute value of this curvature.

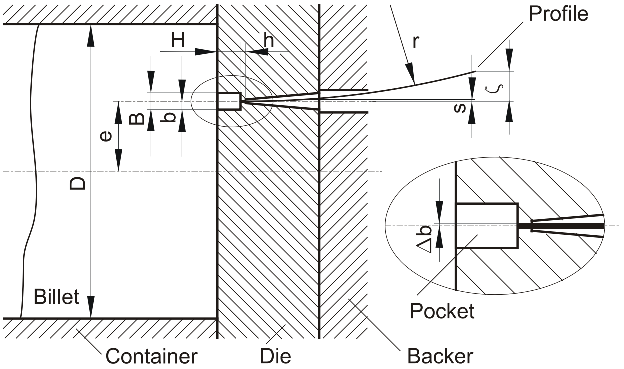

Figure 1. **Geometrical parameters of extrusion process with eccentricity**

Slika 1. **Geometrijski parametri procesa istiskivanja s ekscentricitetom**

In addition it is necessary to note some limitations which should be taking into consideration.

I. Diameter of container D and the width of channel elements (wall thickness of shape) s are fixed and are defined by available tool and profile order.
II. It is difficult to regulate the value of the eccentricity e of considered channel element because it depends on the profile form and its layout on the die face.
III. According to traditions that are grounded on principles of fabricability and efficiency of die manufacture, the pockets are produced with variable width on channel elements B and constant depth H.

The suggested method of flat pocket die design includes the following basic steps:

1. Definition of overall die dimensions.
2. Calculation of channel dimensions.
3. Lay-out of the channel on the die face.

These three steps are particularly described in the literature [14, 15, etc.] and do not require modifications.

4. Bearing length calculation.
4.1. Partition of the channel on elements. Such elements are, naturally, separate walls, webs, ribs, legs and flanges of a profile.

However, if the element of the channel has significant length, it results in essential difference of flow speeds along the element. Therefore, long walls or legs should be divided into some nominal parts. As criterion of necessity of partition it is suggested to use the ratio of distance from centroid of a profile element to die center ρ to container radius R_C. If this ratio along a leg varies more than 15 - 20 %, it is necessary to divide the channel into smaller elements.

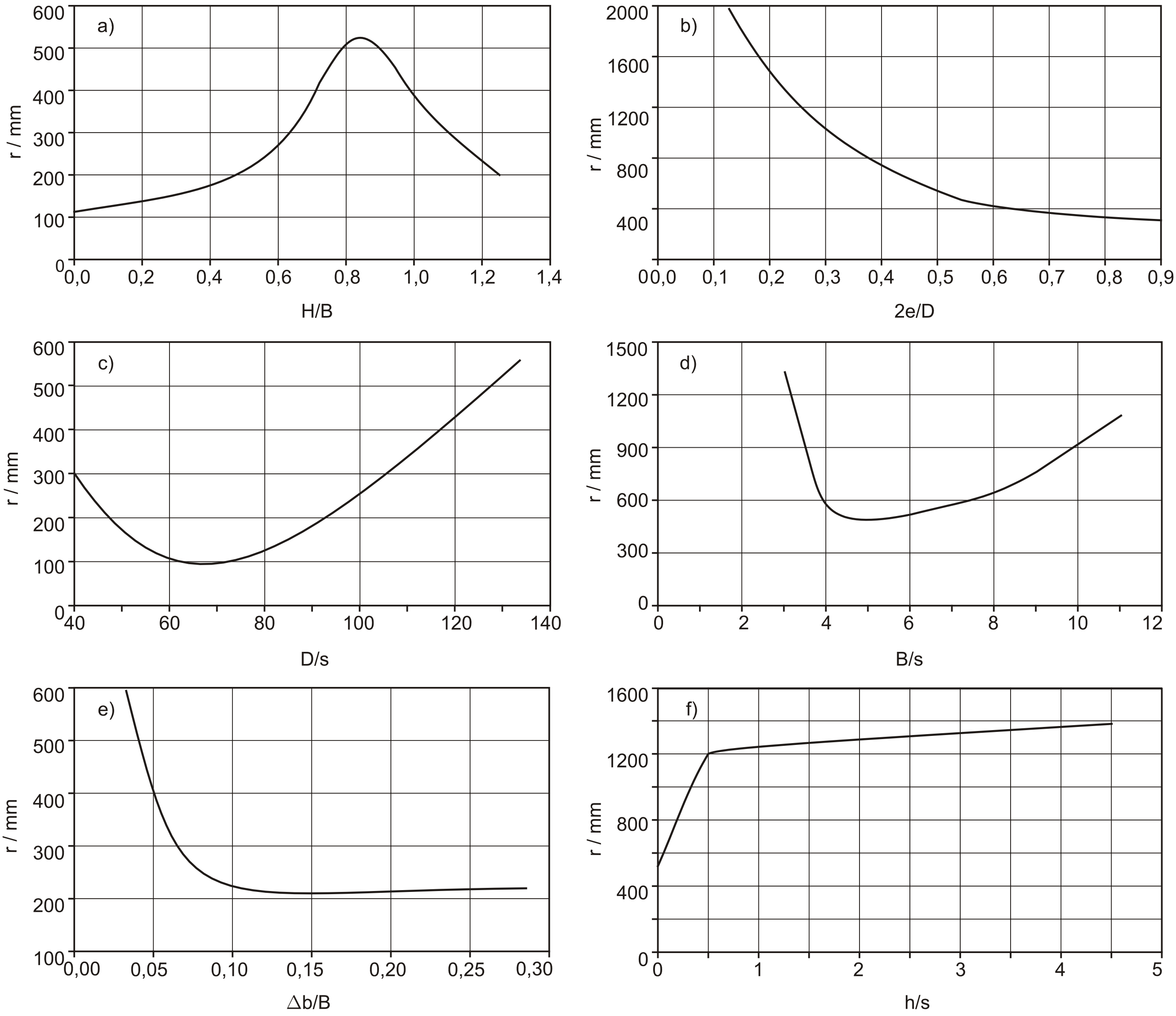

Figure 2. **Dependence of curvature radius of profile on dimensionless parameters: a) *H*/*B*, b) 2*e*/*D*, c) *D*/*s*, d) *B*/*s*, e) Δ*b*/*B*, f) *h*/*s***

Slika 2. **Ovisnost radijusa zakrivljenja profila o bezdimenzionalnim parametrima: a) *H*/*B*, b) 2*e*/*D*, c) *D*/*s*, d) *B*/*s*, e) Δ*b*/*B*, f) *h*/*s***

Besides deadlock elements of the channel should be selected. The length of such elements is accepted equal to local channel width, and between elements passes with length 2 - 5 channel width are executed.

4.2. Definition of ρ and ρ/R_C for each channel element.

4.3. Calculation of cross section area *F* and perimeter of contact with bearing *P* for each channel element and ratio *P*/*F*.

4.4. Definition of bearing length for each channel element by improved Matveev-Zhuravsky formula [16]. It permits to take into account a gradient of metal velocity with removing an element from die center [1]:

$$h_i = h_0 \frac{P_0 F_i}{P_i F_0}\left[1 - k_\rho \left(\frac{\rho_i}{R_C}\right)^2\right], \qquad (1)$$

where:

h_i and h_0 - bearing length of *i* and base element respectively;

k_ρ - coefficient that takes into account the distance between element centroid and die center.

The element with greatest ratio *P*/*F* as a base is chosen.

5. Partition of a die face into elements.

5.1. Definition of flow boundaries position is carried out similarly to the method of Yu. P. Glebov for relief die design [17].

For the neighboring walls and legs the flow boundary is the line which divides internal angle between them in direct ratio to their thickness. Similarly, for shapes such as U-profiles with legs of different thickness the flow boundary lies parallel way to them and also divides distance between wings proportionally to their thickness. The example of dead zones forming and flow boundaries in Figure 3. is shown. The areas within the flow boundaries and container as die face field are named.

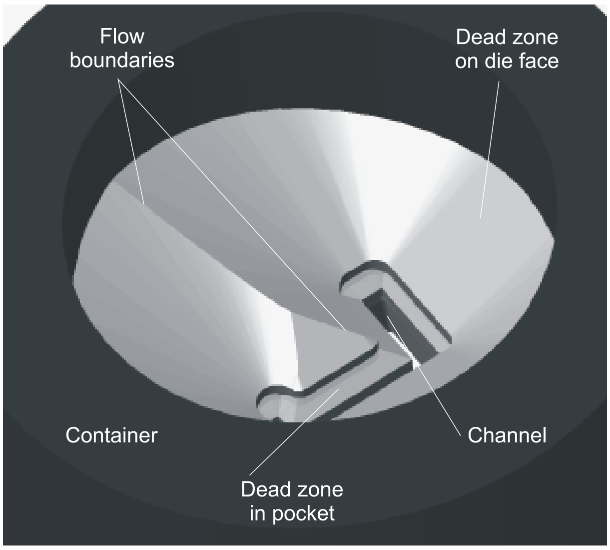

Figure 3. **Example of dead zones forming and flow boundaries**
Slika 3. **Primjer mrtvih zona oblikovanja i krivulje tečenja**

These fields are shared on die face regions by lines which are perpendicular to channel median.

5.2. Determination of these regions centroids and distances from them to a median of corresponding channel element (an eccentricity *e*).

5.3. Definition of average size of die face region *D*. For calculation procedure simplification it is offered to determine it as perpendicular to channel median through the channel element centroid between region boundaries.

5.4. Calculation of ratio $2e/D$ and D/s.

6. Definition of pocket width *B*.

Under data [18], it is offered to determine the width of the pocket by formula:

$$B = \frac{C_B}{s} + s, \tag{2}$$

where: C_B is coefficient equal to 0,05 … 0,1 of container diameter.

As a matter of manufacture convenience a constant pocket width along a separate profile leg should be accepted.

7. Specifying of pocket depth and parameter H/B for each element of the channel. Since it is desirable to have constant pocket depth along the channel and due to results of mathematical simulations the minimum curvature of profile is ensured at $H = (0,8 - 0,9)\,B$. Thus, the pocket depth is set constant along all channel and equal to 0,8 - 0,9 of maximum pocket width.

8. Definition of curvature of profile element depending on parameters $2e/D$, H/B, D/s, B/s, h/s. In connection with the better convenience in practical use and the additively of value of profile curvature on length unit ζ this factor, instead of radius r, further is used.

The curvature of profile element in dependence on eccentricity and other parameters is determined as:

$$\zeta' = \zeta_0' k_e k_H k_D k_B k_h, \tag{3}$$

where ζ_0' is the basic value of curvature defined theoretically under basis initial conditions, mm/m; k_e, k_H, k_D, k_B, k_h are the factors which are taking into account influence of dimensionless parameters $2e/D$, H/B, D/s, B/s, h/s respectively.

The factors which are taking into account influence of dimensionless parameters are calculated as:

$$k_e = a_0 + a_1\left(\frac{2e}{D}\right); \tag{4}$$

$$k_H = a_0 + a_1\left(\frac{H}{B}\right) + a_2\left(\frac{H}{B}\right)^2; \tag{5}$$

$$k_D = a_0\left(\frac{D}{s}\right)^2 \exp\left[\frac{a_1\left(\dfrac{D}{s}\right)^2}{a_2 + a_3\left(\dfrac{D}{s}\right)^2}\right]; \tag{6}$$

$$k_B = a_0\left(\frac{B}{s}\right)^4 \exp\left[\frac{a_1\left(\dfrac{B}{s}\right)^2}{a_2 + a_3\left(\dfrac{B}{s}\right)^2}\right]; \tag{7}$$

$$k_h = a_0 + \frac{a_1}{a_2 + \dfrac{h}{s}}. \tag{8}$$

Formulas (4) - (8) are obtained by statistical processing of results of above presented theoretical investigations.

Correlation index at definition of coefficient k_e is 0,991, k_H - 0,955, k_D - 0,971, k_B - 0,899, k_h - 0,999.

Factors in the equations (4) - (8) are given for a case of extrusion of the aluminum alloy 6063 and are shown in Table 1. The basic value of curvature ζ_0' for the considered alloy is 945 mm/m.

Table 1. **Values of factors to the equations (4) - (8) for the aluminum alloy 6063**
Tablica 1. **Vrijednosti faktora jednadžbi (4) - (8) za aluminijsku leguru 6063**

	a_0	a_1	a_2	a_3
k_e	–0,037	1,99	-	-
k_H	4,924	–8,147	4883	-
k_D	0,0005258	–0,0001359	0,7007	0,0001205
k_B	0,013253	–0,025832	0,03123	0,18
k_h	0,385	0,0375	0,061	-

9. Definition of curvature ζ'' in dependence on displacement of median of pocket from median of channel by formula:

$$\zeta'' = \zeta''_b k_H k_D k_B k_h, \tag{9}$$

where ζ''_b is a curvature that is given by displacement of pocket median from channel median of flat zero-bearing die;

$$\zeta''_b = \frac{a_0 + a_1 \cdot \frac{\Delta b}{B} + \left(\frac{\Delta b}{B}\right)^2}{1 + a_2 \cdot \frac{\Delta b}{B}}. \tag{10}$$

Factors in the equations (10) are equal to a_0 = –46,68; a_1 = 56930; a_2 = 19,762. Correlation index at definition of curvature ζ''_b is 0,978.

10. Selection of value of displacement of pocket median from channel median Δb is carried out so that

$$\zeta' - \zeta'' \rightarrow 0. \tag{11}$$

Displacement of pocket median should be made in direction from a centroid of die face field.

Usage of the factor k_H, k_D, k_B, k_h in formulas (3) and (9) is necessary for the estimation of the real value of curvature for a case when selection of value Δb can not satisfy the condition (11).

EXAMPLE OF USING OF FLAT POCKET DIE DESIGN METHOD

The profile has U-shaped form with lengths of legs 40, 70 and 15 mm and thickness 3,0; 1,8 and 1,0 mm respectively. Extrusion is realized from around container ∅ 125 mm (Table 2.).

For the given conditions according to steps 1 and 2 of the method diameter and thickness of die is 160 and 30 mm respectively. Calculated values of channel dimensions are given in Table 3.

Table 2. **General parameters and references**
Tablica 2. **Općeniti parametri i referentni podaci**

Profile area, F_P / mm^2	253,8
Diameter of container, D_C / mm	125
Extrusion ratio, E_R	48,4
Die temperature, T_D / °C	440
Aluminium temperature, T_{Al} / °C	470
Minimal bearing length, h_0 / mm	2
Preset H/B_{max}	0,9
Base curvature, mm/m	945
Elongation at stretching, e_s	0,005
Thermal stretching coefficient for steel	1,19E–05
Thermal stretching coefficient for Al	2,55E–05
Temperature coefficient, k_T	0,0067

Table 3. **Channel dimensions**
Tablica 3. **Dimenzije kanala**

Profile dimension / mm	70,0	40,0	15,0	3,0	1,8	1,0
Channel dimension / mm	70,67	40,39	15,12	2,98	1,77	0,96
Coefficient k_P (puller)	0,0009	0,0011	0,0015	0,0021	0,0023	0,0025
Coefficient k_{FC} (flow in channel)	0,003	0,004	0,006	0,013	0,016	0,020
Additive from wearing and service / mm	–0,10	–0,10	–0,10	–0,09	–0,08	–0,07
Tolerance / mm	0,45	0,30	0,20	0,20	0,20	0,15

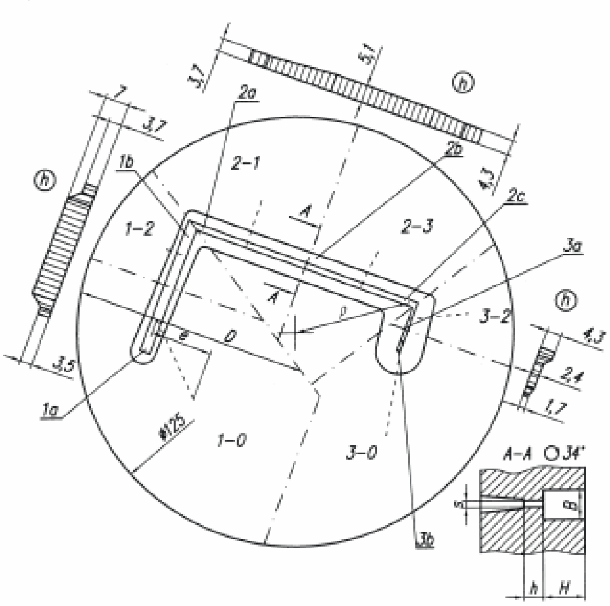

Figure 4. **Flat pocket die for U-shape extrusion**
Slika 4. **Ravna džepna matrica za istiskivanje U-profila**

Table 4. **Bearing length**
Tablica 4. **Nosiva dužina**

Number of channel element	1a	1b	2a	2b	2c	3a	3b
Wall thickness, s / mm	3	3	1,8	1,8	1,8	1	1
Length, l / mm	5	30	5	30	5	12	1
Area, F / mm^2	6	84,6	9	54	9	12	1
Perimeter, P / mm	7	56,4	10	60	10	24	3
Specified perimeter, P/F /(1/mm)	1,2	0,7	1,1	1,1	1,1	2,0	3,0
Preliminary bearing length, h_0 / mm	5,1	9,0	5,4	5,4	5,4	3,0	2,0
Distance from die centre, ρ / mm	42,5	34,8	41,7	19,0	33,2	32,0	30,0
Specified distance from die centre, ρ / R_C	0,68	0,56	0,67	0,30	0,53	0,51	0,48
Coefficient of specified distance, k_ρ	0,68	0,78	0,69	0,94	0,80	0,82	0,84
Bearing length, h / mm	3,5	7,0	3,7	5,1	4,3	2,4	1,7

The die channel is layed out quasi-tangentially to concentric die center circles; legs are directed downward so that bottom points lay on a horizontal line. The channel is divided into elements (are numbered from 1a up to 3b), as shown in Figure 4., and bearing length is calculated (Table 4.) by formula (1). Distribution diagrams of bearing length h along the channel are shown in Figure 4.

Die face is divided into 3 fields to define the shape and dimensions of the pocket (Figure 4.). Each of these fields is divided into 2 regions corresponding to half of channel element length. In Figure 4. the centroid of die face regions are marked and the dot line shows the distance from them up to the channel element center (projection of such a line to the perpendicular to the channel median is the eccentricity e). Through the channel element center perpendicularly to channel median the line representing dimension D is passed.

The maximum value of pocket width, calculated by formula (2) is 13,5 mm. At optimum ratio H/B = 0,9, the value of pocket depth is 12 mm.

Further, the curvatures of profile elements in dependence on parameters $2e/D$, H/B, D/s, B/s, h/s, is defined (formulas (4) - (8)), and also values $\Delta b/B$ necessary for compensating of these curvatures are selected (Table 5.). If values $\Delta b/B$ are known, it is possible to define the position of pocket walls. As each element of the channel was divided into 2 parts, pocket walls are straight and nonparallel to the channel (see Figure 4.).

Table 5. **Pocket geometry**
Tablica 5. **Geometrija džepa**

Number of pocket element	0-1	1-2	2-1	2-3	3-2	3-0
Thickness of channel element, s / mm	3,0	3,0	1,8	1,8	1,0	1,0
Length of channel element, l / mm	19,1	19,1	34,5	34,5	7,5	7,5
Area of channel element, F / mm^2	57,3	57,3	62,1	62,1	7,5	7,5
Cross dimension of die face region, D / mm	67	36,8	50	68,1	34	39,4
Extrusion ratio in region, D/s	22	12	28	38	34	39
Eccentricity of channel element, e / mm	17,8	15,5	13,3	10,8	15	5,3
Relative eccentricity, $2e/D$	0,53	0,84	0,53	0,32	0,88	0,27
Pocket width, B / mm	7,2	7,2	8,7	8,7	13,5	13,5
Pocket depth (constant), H / mm	12	12	12	12	12	12
Ratio B/s	2,4	2,4	4,9	4,9	13,5	13,5
Ratio H/B	1,70	1,70	1,39	1,39	0,90	0,90
Bearing length (average), h_{med} / mm	6,4	6,3	4,5	4,9	2,7	2,2
Relative bearing length, h/s	2,12	2,10	2,49	2,73	2,74	2,20
Coefficient of eccentricity, $k_{2e/D}$	1,02	1,64	1,01	0,59	1,72	0,50
Coefficient of relative pocket depth, $k_{H/B}$	5,15	5,15	3,03	3,03	1,55	1,55
Coefficient of extrusion ratio, $k_{D/s}$	0,32	0,11	0,46	0,71	0,62	0,74
Coefficient of extrusion ration in pocket, $k_{B/s}$	0,35	0,35	0,94	0,94	0,12	0,12
Coefficient of bearing length, $k_{h/s}$	0,40	0,40	0,40	0,40	0,40	0,40
Curvature from channel eccentricity, ζ_{CE} / mm	226	121	504	449	75	26
Curvature from pocket displacement, ζ_{PE} / mm	226	121	504	449	75	26
Relative pocket median displacement, $\Delta b/B$	0,027	0,060	0,026	0,013	0,067	0,011
Min. distance from channel to pocket wall, $b_{\min}$ / mm	1,9	1,7	3,2	3,4	5,3	6,1
Max. distance from channel to pocket wall, $b_{\min}$ / mm	2,3	2,5	3,7	3,6	7,2	6,4
Pocket - channel median displacement, Δb / mm	0,2	0,4	0,2	0,1	0,9	0,1

CONCLUSION

Within the framework of introduced work the flat pocket die design method for extrusion of shapes with thin-walled elements of aluminum alloys is developed.

Numerical value of the factors which take into account the influence on metal forming of set of dimensionless die geometry parameters for one of the most widely used at extrusion aluminum alloy 6063 are obtained.

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