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DETERMINATION OF THE WORKING PRESSURE FOR HOLLOW AL-PROFILES EXTRUSION IN HALF-SUNK BRIDGE TOOLS

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Abstract. *The working pressure, that is, the extrusion force represents the most important parameter for the choice of the machine (press), tool design and determination of energy expenditure (work of deformation). A complex formula for calculating the working pressure for Al-profile extrusion is derived in the paper, namely, the formula that ensures, if computer-aided, an analysis of the effects of all the process factors (geometric, tribological, reological and technological). The derived formula adequately takes into consideration the effects of the mentioned factors, in the quantitative and qualitative sense, as confirmed by an experiment realized under the production conditions. Regarding the applied calculation methodology, the derived formula in its original form can also be used for calculating the working pressure for extrusion of hollow profiles of other materials (titan, titan alloys and the like) if it is the same technology of profile making.*

Key Words: *Extrusion Working Pressure, Hollow Profiles, Al-alloys, Bridge Tools*

1. INTRODUCTION

Aluminium and Al-alloys belong to the most versatile and widely spread materials, which makes them perfect for a wide range of applications [1], [2], [3]. Having one-third of the weight of most other metals, aluminium allows design flexibility; therefore, it can be manufactured with tensile strength approaching that of steel. It can be readily fabricated and it accepts a wide range of finishes, making it ideal for applications in many industries, including electronics, linear motion, marine, medical, office imaging, recreational, telecommunications, test and measurement, transportation, window, door, display and trim, furniture and construction.

Complex (solid and hollow) profiles of wide application are mostly made of aluminium and aluminium alloys. That is why great efforts are made for the sake of perfecting

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and developing new technological procedures of extrusion and tools, introduction of new Al-alloys in profile production, as well as application of modern computer-aided procedures of design and simulation [4-15].

Modern industry requires increasingly complex and elaborated forms of Al-profiles with very narrow walls, narrow tolerances and a high surface quality. To meet such demanding requirements means to expand the field of Al-profile application in general, especially in car and aircraft industry in which the so-called Lightweight Construction Concept (Leichtbaukonzept) has become a reality at the end of the twentieth century.

The making of hollow Al-profiles is done in special tools (bridge tools, spider tools, porthole tools) that provide for a stable position of the mandrel tip, that is, constant clearance between the mandrel tip and the die during the extrusion process. In this way, in one press stroke and with one billet, hollow profiles of practically constant cross sections over several dozen meters in length are obtained. The extrusion represents not only a productive and effective technology that provides for a relatively low price of the product, but also the only possible technology for making hollow Al-profiles of complex geometry.

In practice the bridge tools are most often applied. These tools are made in several variants (namely, with a protruding bridge, with a half-sunk bridge and a full sunk bridge [16]). The half-sunk bridge tools have found the widest application in practice.

For the design of the forming process, for the tool design and proper choice of the existing technological equipment, the most important parameter that should be known is the extrusion force, that is, the working pressure of the extrusion process. The above-mentioned parameter represents the basic criterion for purchasing new (expensive) equipment for extrusion technology. That is why the problem of determining the extrusion force is given special attention in the referential literature.

2. Determination of the Extrusion Working Pressure

The process of extruding hollow profiles in bridge tools represents one of the most complex ones in the plasticity theories in general. A great number of authors have dealt with this problem regarding its theoretical or merely practical aspects. In their analyses the tool geometry and the material flow kinematics are treated in quite a simplified way and the problem is mostly reduced to the well-known solutions. However, it is well known that the shape of the bridge with a mandrel tip, as well as its position essentially affect the flow kinematics including the resistances that set up during the plastic metal deforming.

The analysis done in this paper refers to the process of extruding hollow profiles in the half-sunk bridge tools. The bridge geometry that is most often found in practice and that best approximates the so-called symmetrical air-profile (Fig. 1) is adopted. The material flow kinematics has been steadily analyzed while the emergence of "dead' zones is taken into consideration. In that sense the plastic deformation zone (PDZ) is divided in nine precisely defined segments. In each segment of the PDZ the tribological conditions are adequately defined as well as metal work hardening [4], [16-19]. In view of the fact that the material in the PDZ is exposed to a high "comprehensive" (three-dimensional) pressure, E. Siebel's assumption for contact friction stresses is adopted.

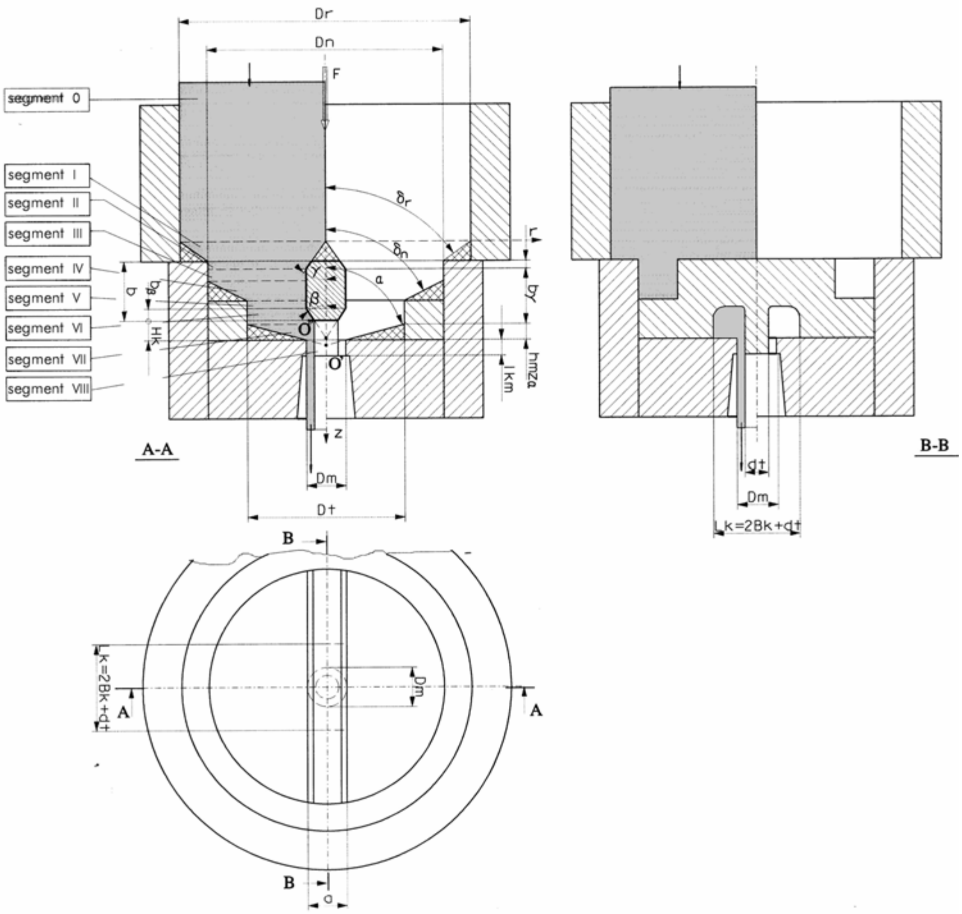


Fig. 1. Presentation of the Hollow Profile Extrusion Process in half-sunk Bridge Tool

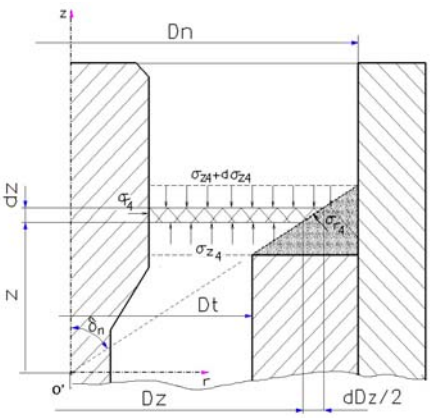


Fig. 2. Scheme of the Metal Stress State in IV Segment of the PDZ

2.1. Calculation Methodology

The overall hollow profile extrusion force can be expressed by the following relation:

$$F_{tot} = \sum_{i=1}^{n} F_{di} + \sum_{j=1}^{m} F_{tj} \tag{1}$$

where: F_{di}, F_{tj} - partial forces of plastic deformation and friction force in the segments of the plastic deformation zone[1].

The extrusion working pressure is determined in the well-known way:

$$p = F_{tot} / A_r = 4F_{tot} / \pi D_r^2 \tag{2}$$

2.1.1. Determination of the Plastic Deformation Forces

The force of ideal (frictionless) plastic deformation can be determined by applying the so-called engineering method, that is, by solving a system of equations consisting of equilibrium equation and plasticity conditions (yield criterion).

In accordance with the denotations given in Figs. 1 and 2 it is obtained for the segment IV of the PDZ:

$$-(\sigma_{z4} + d\sigma_{z4}) \cdot (A_{z4} + dA_{z4}) + \sigma_{z4} \cdot A_{z4} + [\sigma_r (\pi D_z - 2a) \cdot dl] \sin \delta_n = 0 \tag{3a}$$

$$\sigma_{r4} = \sigma_{z4} + \beta' K_{m4} \tag{3b}$$

Here the following relations are valid:

$$dl = \frac{dD_z}{2 \sin \delta_n} \; ; \; A_{z4} = \frac{\pi D_z^2}{4} - a \cdot D_z \quad ; \; dA_{z4} = \left(\frac{\pi}{2} D_z - a \right) dD_z \tag{4}$$

By introducing relations (4) in equation system (3) it is obtained that:

$$\int_{\sigma_{z4,1}}^{\sigma_{z4,2}} d\sigma_{z4} = 2\beta' K_{m4} \left[\int_{D_t}^{D_n} \frac{dD_z}{\pi D_z - 4a} - 2a \int_{D_t}^{D_n} \frac{dD_z}{D_z (\pi D_z - 4a)} \right] \tag{5}$$

By solving integral (5) and by writing the expression, the formula for deformation force in segment IV of the following form is obtained:

$$F_{d4} = \beta' K_{m4} \frac{\pi D_r^2}{4} \left(\frac{\pi D_n^2}{4} - a D_n \right) \ell n \frac{(\pi D_n - 4a) D_n}{(\pi D_t - 4a) D_t} \tag{6}$$

In the above-described way the other formulae for partial ideal deformation forces are obtained (Table 1).

[1] Other denotations are given in the denotation nomenclature at the end of the paper

Table 1. Partial deformation forces

Segment	Formula
0	$F_{d0} \cong 0$
I	$F_{d1} = \beta' K_{m1} \dfrac{\pi D_r^2}{4} \ell n \left(\dfrac{D_r}{D_n} \right)^2$
II	$F_{d2} = \beta' K_{m2} \dfrac{\pi D_r^2}{4} \left[\left(\dfrac{D_n}{D_r} \right)^2 - \dfrac{4D_n}{\pi D_r^2}(a - 2b_\gamma \, tg\gamma) \right] \ell n \dfrac{\pi D_n - 4a + 8b_\gamma \, tg\gamma}{\pi D_n - 4a}$
III	$F_{d3} = 0$
IV	$F_{d4} = \beta' K_{m4} \dfrac{\pi D_r^2}{4} \left(\dfrac{\pi D_n^2}{4} - aD_n \right) \ell n \dfrac{(\pi D_n - 4a)D_n}{(\pi D_t - 4a)D_t}$
V	$F_{d5} = 0$
VI	$F_{d6} = \beta' K_{m6} \dfrac{\pi D_r^2}{4} \left[\left(\dfrac{D_t}{D_r} \right)^2 - \dfrac{4aD_t}{\pi D_r^2} \right] \ell n \dfrac{\pi D_t - 4a + 8b_\beta \, tg\beta}{\pi D_t - 4a}$
VII	$F_{d7} = \beta' K_{m7} \dfrac{\pi D_r^2}{4} \left[\left(\dfrac{D_t}{D_r} \right)^2 - \left(\dfrac{d_t}{D_r} \right)^2 \right] \ell n \dfrac{D_t^2 - d_t^2}{D_m^2 - d_t^2}$
VIII	$F_{d8} = 0$

2.1.2. Determination of the Contact Friction Forces

Partial contact friction forces can be determined by applying an energy equation that can be written for segment IV in the following form:

$$N_{t4} = \int_{z_1}^{z_2} dN_{t4} = \int_{z_1}^{z_2} (dA'_{t4} \cdot \tau_{t4} + dA'_{m4} \cdot \tau_{m4}) V_{z4} = F_{t4} \cdot V_0 \tag{7}$$

On the basis of Fig. 1 and Fig. 2 the following relations are obtained:

$$dA'_{t4} = (\pi D_z - 2a)\, dl = \frac{\pi D_z - 2a}{2 \sin \delta_n} dD_z \, ; \; dA'_{m4} = 2 \frac{D_z + (D_z + dD_z)}{2} dz = \frac{D_z}{tg\delta_n} dD_z \tag{8a}$$

$$V_{z4} = V_0 \frac{A_r}{A_{z4}} = V_0 \frac{\pi D_r^2}{4} \frac{4}{D_z (\pi D_z - 4a)} \tag{8b}$$

$$\tau_{t4} = \mu_{t4} K_{m4} \; ; \; \tau_{m4} = \mu_{m4} K_{m4} \tag{8c}$$

By introducing relations (8) into equation (7) and after integrating and writing the formula for the partial contact friction force in segment IV of the PDZ is obtained:

$$F_{t4} = K_{m4} \frac{\pi D_r^2}{4} \frac{1}{\sin \delta_n} \left[\left(\mu_{t4} + \frac{4}{\pi} \mu_{m4} \cos \delta_n \right) \ell n \frac{\pi D_n - 4a}{\pi D_t - 4a} - \mu_{t4} \ell n \frac{D_t}{D_n} \right] \tag{9}$$

In the above-described way the other formulae for partial contact friction forces are obtained (Table 2).

Table 2. Partial friction forces

Segment	Formula
0	$F_{t0}=\mu_{r0}K_0\pi D_r(L_{0x}-h_{mzr})=\mu_{r0}K_0\pi D_r[L_0-(\Delta L_s+\Delta L_m)-h_{mzr}]\cong$ $\cong\mu_{r0}K_0\frac{\pi D_r^2}{4}\left[\frac{4L_0}{D_r}\left(\frac{D_0}{D_r}\right)^2+1{,}2\frac{D_n}{D_r}-2\right]^{*)}$; $\Delta L_s=L_0[1-(D_0/D_r)^2]$; $\Delta L_m\approx 0{,}2D_r$, $h_{mzr}\approx 0{,}29(D_r-D_n)$, $\delta_r\approx 57{,}5^0$
I	$F_{t1}=F_{t1r}+F_{t1m}=K_{m1}\frac{\pi D_r^2}{4}\frac{1}{\sqrt{3}}\left[\frac{1}{\sin\delta_r}\ell n\left(\frac{D_r}{D_n}\right)^2+\frac{1}{\sin\gamma}\ell n\frac{\pi D_r}{\pi D_r-4a+8b_\gamma\, tg\gamma}\right]$
II	$F_{t2}=K_{m2}\frac{\pi D_r^2}{4}\left[\frac{\pi\mu_{n2}\cos\gamma+4\mu_{m2}}{4\sin\gamma}\ell n\frac{\pi D_n-8h_{mzr}tg\gamma}{\pi D_n-8(h_{mzr}+b_\gamma)tg\gamma}+\frac{2\mu_{n2}b_\gamma}{D_n}\right]$
III	$F_{t3}=K_{m3}\frac{\pi D_r^2}{4}\left[\left(\pi-2\frac{a}{D_r}\right)\mu_{n3}+2\mu_{m3}\right]\frac{4(H_t-b_\gamma+H_{tt}-h_{mzn})}{\pi D_n-4a}$
IV	$F_{t4}=K_{m4}\frac{\pi D_r^2}{4}\frac{1}{\sin\delta_n}\left[\left(\mu_{t4}+\frac{4}{\pi}\mu_{m4}\cos\delta_n\right)\ell n\frac{\pi D_n-4a}{\pi D_t-4a}-\mu_{t4}\ell n\frac{D_t}{D_n}\right]$; $\mu_{t4}=\frac{1}{\sqrt{3}}$
V	$F_{t5}=K_{m5}\frac{\pi D_r^2}{4}\left[\left(\pi-2\frac{a}{D_t}\right)\mu_{t5}+2\mu_{m5}\right]\frac{4(H_{tt}-H_t-b-b_\beta)}{\pi D_t-4a}$
VI	$F_{t6}=K_{m6}\frac{\pi D_r^2}{4}\left\{\left(\frac{\pi}{2}-\frac{a}{D_t}\right)\mu_{t6}+\right.$ $\left.+\left[\frac{\xi}{\cos\beta}+(1-\xi)\right]\mu_{m6}\right\}\frac{1}{\xi\, tg\beta}\ell n\frac{4D_t-4\xi(a-2b_\beta\, tg\beta)+4\eta}{\pi D_t-4\xi a+4\eta}$; $\xi=L/D_t$; $\eta=a(D_t-L)$
VII	$F_{t7}=K_{m7}\frac{\pi D_r^2}{4}\frac{1}{\sin\delta}\left[\mu_{t7}\,\ell n\frac{D_t^2-d_t^2}{D_m^2-d_t^2}-\mu_{tj7}\cos\alpha\,\ell n\frac{(D_t+d_t)\cdot(D_m-d_t)}{(D_t-d_t)\cdot(D_m+d_t)}\right]$ $\mu_{t7}=1/\sqrt{3}$
VIII	$F_{t8}=K_8\frac{\pi D_r^2}{4}4\lambda\, l_{km}\frac{\mu_{m8}D_m+\mu_{tj8}d_t}{D_r^2}$; $\lambda=D_r^2/(D_m^2-d_t^2)$

*) *While extruding the n^{th} billet the current billet length in the recipient should be calculated according to the formula:* $L_{0x}=L_0(D_0/D_r)^2+L_{po}$

On the basis of formulae (1) and (2) and expressions given in Table 1 and Table 2 the formula for calculating the working pressure of the hollow profile extrusion process is obtained in the following form:

$$
\begin{aligned}
p = {} & K_0\mu_{r0}\left[\frac{4L_0}{D_r}\left(\frac{D_0}{D_r}\right)^2 + 1{,}2\frac{D_n}{D_r} - 2\right] + \\
& K_{m1}\left\{\frac{1}{\sqrt{3}}\left[\frac{1}{\sin\delta_r}\ell n\left(\frac{D_r}{D_n}\right)^2 + \frac{1}{\sin\gamma}\ell n\frac{\pi D_r}{\pi D_r - 4a + 8b_\lambda tg\gamma}\right] + \right. \\
& \left. + \sqrt{3}\beta'\ell n\left(\frac{D_r}{D_n}\right)^2\right\} + K_{m2}\left\{\beta'\left[\left(\frac{D_n}{D_r}\right)^2 - \frac{4D_n}{\pi D_r^2}(a - 2b_\gamma tg\gamma)\right]\ell n\frac{\pi D_n - 4a + 8b_\gamma tg\gamma}{\pi D_n - 4a} + \right. \\
& \left. + \frac{\pi\mu_{n2}\cos\gamma + 4\mu_{m2}}{4\sin\gamma}\ell n\frac{\pi D_n - 8h_{mzr}tg\gamma}{\pi D_n - 8(h_{mzr} + b_\gamma)tg\gamma} + \frac{2\mu_{n2}b_\gamma}{D_n}\right\} + \\
& + K_{m3}\left[\left(\pi - 2\frac{a}{D_r}\right)\mu_{n3} + 2\mu_{m3}\right]\frac{4(H_t - b_\gamma + H_{tt} - h_{mzn})}{\pi D_n - 4a} + \\
& K_{m4}\left\{\beta'\left(\frac{\pi D_n^2}{4} - aD_n\right)\ell n\frac{(\pi D_n - 4a)D_n}{(\pi D_t - 4a)D_t} + \right. \\
& \left. + \frac{1}{\sin\delta_n}\left[\left(\mu_{t4} + \frac{4}{\pi}\mu_{m4}\cos\delta_n\right)\ell n\frac{\pi D_n - 4a}{\pi D_t - 4a} - \mu_{t4}\ell n\frac{D_t}{D_n}\right]\right\} + \\
& + K_{m5}\left[\left(\pi - 2\frac{a}{D_t}\right)\mu_{t5} + 2\mu_{m5}\right]\frac{4(H_{tt} - H_t - b - b_\beta)}{\pi D_t - 4a} + \\
& + K_{m6}\left\{\beta'\left[\left(\frac{D_t}{D_r}\right)^2 - \frac{4aD_t}{\pi D_r^2}\right]\ell n\frac{\pi D_t - 4a + 8b_\beta tg\beta}{\pi D_t - 4a} + \left\langle\left(\frac{\pi}{2} - \frac{a}{D_t}\right)\mu_{t6} + \left[\frac{\xi}{\cos\beta} + (1-\xi)\right]\mu_{m6}\right\rangle\right. \\
& \left. \cdot\frac{1}{\xi tg\beta}\ell n\frac{4D_t - 4\xi(a - 2b_\beta tg\beta) + 4\eta}{\pi D_t - 4\xi a + 4\eta}\right\} + K_{m7}\left\{\beta'\left[\left(\frac{D_t}{D_r}\right)^2 - \left(\frac{d_t}{D_r}\right)^2\right]\ell n\frac{D_t^2 - d_t^2}{D_m^2 - d_t^2} + \right. \\
& \left. + \frac{1}{\sin\delta}\left[\mu_{t7}\ell n\frac{D_t^2 - d_t^2}{D_m^2 - d_t^2} - \mu_{tj7}\cos\alpha\,\ell n\frac{(D_t + d_t)\cdot(D_m - d_t)}{(D_t - d_t)\cdot(D_m + d_t)}\right]\right\} + K_8 4\lambda l_{km}\frac{\mu_{m8}D_m + \mu_{tj8}d_t}{D_r^2}
\end{aligned} \tag{10}
$$

The manual calculation of the working pressure of the extrusion force by applying formula (10) can be weary and time-consuming. In such cases some authors turn to simplifying formulae at the expense of their accuracy.

However, in view of very large computer application in industry, the authors of this paper have developed an adequate program (ALFORCE), whose algorithm is shown in Fig. 3. The program ensures the maximal working pressure calculation as well as the calculation of variable working pressure (force) in the "steady state" extrusion. Namely, this extrusion phase is characterized by a constant drop of the working pressure due to the billet length reduction, that is, reduction of contact friction between the billet and the recipient. In this way a theoretical diagram of the extrusion force – stem travel can be formed; on the basis of all this it is possible to calculate in a sufficiently accurate way the deformation energy (work) expenditure for each concrete extruded profile.

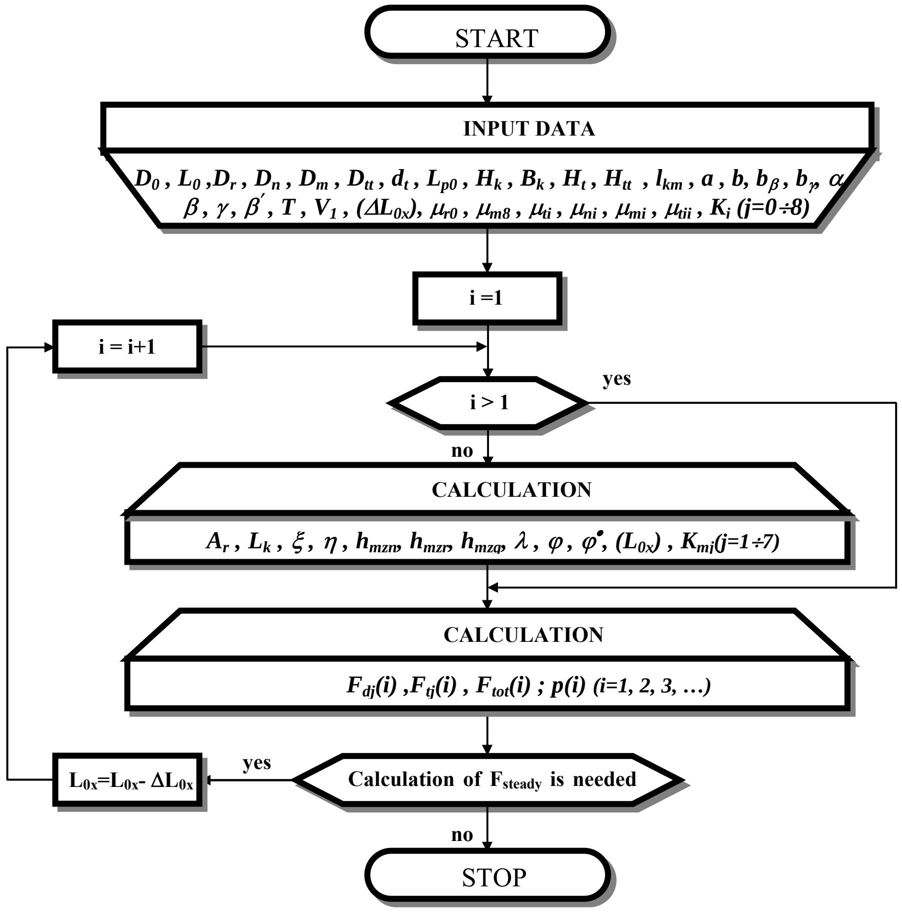
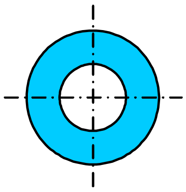
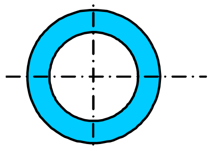
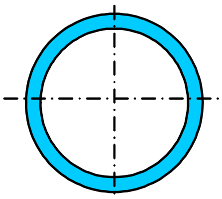
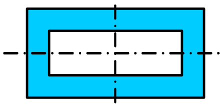
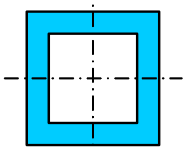
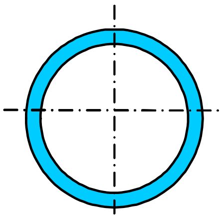
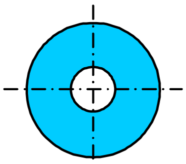


Fig. 3. Flow Chart of the ALFORCE Software

3. EXPERIMENT

In order to verify the above-presented methodology a comprehensive experiment has been carried out under production conditions upon the direct extrusion press of capacity of 27,5 (MN) and recipient (container) diameter of 238 (mm) [19]. The representational aluminium alloy AlMgSi0.5 is selected. The other basic parameters referring to the experiment and calculation are given in Table 3.

Table 3.

Tools No.	Profiles	A (mm^2)	s (mm)	λ (-)
T1		500	8	88,93
T2		500	5	88,93
T3		500	3	88,93
T4		500	5	88,93
T5		500	5	88,93
T6		400	3	111,16
T7		400	5	111,16

$T \cong 500$ (^oC) , $T_{rec} = 450 \div 460$ (^oC) , $T_{tool} = 440 \div 450$ (^oC) ; $L_0/D_0 = 200/220\text{-}600/220\text{-}820/220$ (mm/mm); $L_{p0} = 40$ (mm) ; $V_0 = 8 \div 10$ (m/min) ; $\dot{\varphi} = 0{,}4 \div 0{,}5$ (s^{-1}) ; $\mu_{r0} = 0{,}45$, $\mu_{ni} \cong 0{,}5$, $\mu_{kmi} = \mu_{tji} = 0{,}2$ [4], [16], [20] $K_0 = 30$, $K_1 = 29$, $K_3 = 27$, $K_4 \cong K_5 = 26$, $K_6 \cong K_7 \cong K_8 = 25$ (N/mm^2) [21].

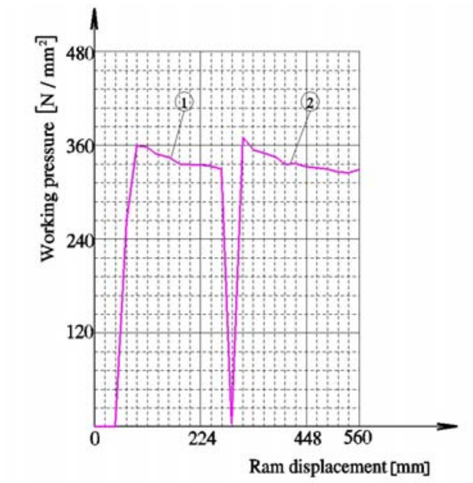
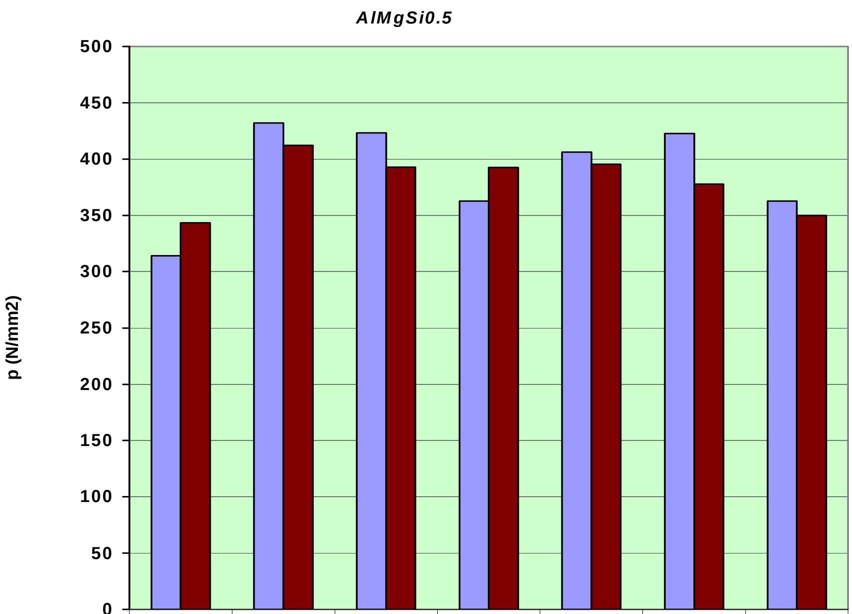


Fig. 4. Typical Diagram of the Working Pressure Change during the Extrusion Process

Fig. 4. gives a diagram of the extrusion process working pressure changes at successive (billet-to-billet) extrusion of two billets (in the tool denoted with T7), while Fig. 5 gives comparative values of the working pressure of extrusion obtained by the experiment and calculation.

It should be noted that the authors tried really hard to make the experimental tools identical in their geometry with respect to the extruded profiles. However, for technical reasons, slight deviations are allowed and this has to be taken into consideration while analyzing experimental results.



	T1	T2	T3	T4	T5	T6	T7
Measured	314.2	432	423.3	362.8	406.2	422.5	362.8
Calculated	343.4	412.2	392.8	392.4	395.4	377.8	349.8

Fig. 5. Comparison of the Measured and the Calculated Extrusion Working Pressures

By analyzing the experimental and the calculation results the following conclusions can be made:

- deviations of calculations and experiment are within the range ± 10%, which confirms the validity of the written formula for calculating the working pressure of the hollow Al-profile extrusion in the half-sunk bridge tool. It should be stressed that the above-mentioned deviations are affected to the largest extent by the experiment error, the technical condition variations during the experiment, errors in determining the flow stress ($\delta K \approx 5 \div 10$ %) [22], and the error occurring while determining friction coefficient ($\delta\mu \approx 5 \div 15$ %) and the like,
- by increasing a reduction degree (deformation degree), while all the other conditions remain the same, the extrusion working pressure also increases,
- by reducing profile wall thickness, while all the other conditions remain the same, the extrusion working pressure increases,
- by increasing the billet length, the extrusion working pressure is significantly increased since only friction in the recipient takes about 40 % of the overall extrusion force, and,
- designs of technology and experimental tools are made correctly as confirmed by many examples from practice as well as by data given by other authors ($p < 450$ N/mm^2, for $\lambda > 60$ [23]).

Formula (10) in the given form refers to the round tube extrusion. The above-given experimental data show that the same formula can be used for calculating tubes of other simple forms. For tubes and profiles of random cross-section the same can be reduced to the basic profile form - a round tube - by introducing the following relations:

$$D_m = O_m / \pi = \sum L_{mi} / \pi \; ; \; d_t = O_t / \pi = \sum l_{ti} / \pi \quad \text{[for forces } F_{t7} \text{ and } F_{t8}] \tag{11a}$$

$$D_m = 2\sqrt{A_m / \pi} \; ; \; d_t = 2\sqrt{A_t / \pi} \quad \text{[for force } F_{d8}] \tag{11b}$$

4. CONCLUSION

The general formula for calculating the working pressure of the hollow profile extrusion process in the half-sunk bridge tools that takes into consideration, in an adequate way, geometric, tribological and reological factors of the technological process is derived.

The above-presented formula is used for calculating the maximal extrusion working pressure. With the computer aid and respective program (whose algorithm is given in the paper) it is easy to analyze the effect of each of the above-stated factors both upon the overall and the partial extrusion forces as well as the force changes in the so-called stationary extrusion phase.

Since the given formula refers to the extrusion of the basic hollow profile, namely, a round tube, the paper gives a procedure by which (to meet the demands of the calculation) complex hollow profiles are reduced to the basic one.

The experiment realized under production conditions shows that the above-given formula adequately takes into account the effect of the technological factors and that it is sufficiently accurate for practical needs.

Regarding the applied calculation methodology the derived formula can also be applied to the calculation of the working pressure for extruding other hollow profiles of other materials such as, for instance, titan, titan alloys and others.

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THE LIST OF USED SYMBOLS

D_r (mm)	- recipient diameter
D_0, L_0 (mm)	- billet diameter and length
A_0 (mm)	- billet cross-section ($A_0 \cong A_r$)
D_m, d_t (mm)	- die diameter and mandrel tip diameter at output channel
D_n, D_t (mm)	- tool holder diameter and mandrel inner diameter
L_{0x} (mm)	- variable billet length in recipient ($0< L_{0x} \le L_0$)
L_{p0} (mm)	- length of discard
h_{mzr} (mm)	- height of "dead " metal zone in recipient
h_{mzn}, $h_{mz\alpha}$ (mm)	- height of "dead" metal zone on mandrel and die
a, b (mm)	- size dimensions of bridge cross-section
γ, β (°C)	- bridge inclination angle at the head and at the bottom
b_γ, b_β (mm)	- bridge inclination height at the head and at the bottom
H_t, H_{tt} (mm)	- bridge height (measured from the die) and mandrel height
H_k, B_k (mm)	- tool welding chamber height and width
l_{km} (mm)	- mean length of die land
α, δ_n, δ_r (°C),	- inclination angle of "dead" zone on die, tool holder and recipient
A'_{ti}, A'_{mi} (mm^2)	- friction surfaces on mandrel and die (tool holder) and in the i-th segment of the PDZ
λ (-) , φ (-)	- extrusion ratio and logarithmic strain
$\varphi^\bullet$ (s^{-1})	- (mean) strain rate
V_0 , V (mm/s)	- ram (inlet) speed and extrusion (exit) speed
V_{zi} (mm/s)	- metal flow velocity in the i-th segment of the PDZ
T, T_{rec}, T_{tool} (°C)	- deformation, recipient and tool temperatures
μ_{r0} (-)	- contact friction coefficient on the recipient
μ_{ti} (-)	- contact friction coefficient on the mandrel (bridge) and the i-th segment of the PDZ
μ_{ni}, μ_{mi} (-)	- contact friction coefficient on the tool holder and mandrel and the i-th segment of the PDZ
μ_{tji} (-)	- contact friction coefficient on the mandrel tip (i=7,8)
μ_{m8} (-)	- contact friction coefficient on the die
μ (-)	- inner friction coefficient ($\mu = 1/\sqrt{3}$)
K_0 (N/mm^2)	- input flow stress (billet)
K_8 (N/mm^2)	- output flow stress (profile)
K_{mi} (N/mm^2)	- mean flow stress in the i-th segment of the PDZ
β' (-)	- Lode's coefficient ($\beta' \approx 1{,}1$)
z_{1i}, z_{2i} (mm)	- limits of the i-th segment of the PDZ in the direction of z-axis

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ODREĐIVANJE RADNOG PRITISKA PROCESA ISTISKIVANJA ŠUPLJIH AL-PROFILA U ALATU SA POLUUTOPLJENIM MOSTOM

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Radni pritisak, odnosno sila istiskivanja predstavlja najvažniji parametar za izbor mašine (prese), projektovanje alata i određivanje utrošene energije (deformacionog rada). U radu je izvedena kompleksna formula za proračun radnog pritiska istiskivanja šupljih Al-profila, koja uz pomoć računara omogućava analizu uticaja svih faktora procesa (geometrijskih, triboloških, reoloških, tehnoloških). Izvedena formula adekvatno uzima u obzir uticaje pomenutih faktora, u kvantitativnom i kvalitativnom smislu, što je potvrđeno eksperimentom, koji je realizovan u proizvodnim uslovima. S obzirom na primenjenu metodologiju proračuna, izvedena formula u izvornom obliku se može upotrebiti i za proračun radnog pritiska istiskivanja šupljih profila od drugih materijala (titana, titanovih legura i dr), ukoliko se radi o istovetnoj tehnologiji izrade profila.

Ključne reči: *radni pritisak istiskivanja, šuplji profili, Al-legure, mostni alati*