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THE WALL DEFORMATION AND THE DIAMETER REDUCTION IN THE PROCESS OF TUBE DRAWING WITH A FLOATING PLUG

ODKSZTAŁCENIE ŚCIANKI I REDUKCJA ŚREDNICY W PROCESIE CIĄGNIENIA RUR NA TRZPIENIU SWOBODNYM

The existing methods of analysis of drawing with a floating plug stated the most favourable angle differences between the drawing die and the plug. In the paper the theoretical analysis is made enabling achieving the possibly minimal diameter reduction at the stated wall thickness reduction. There is discussed tool geometry and a state of stress, which enable stable guidance of the process. The experimental studies with drawing of OF-Cu copper and CuZn37 brass tubes confirmed the results of theoretical consideration.

Dotychczasowe metody analizy procesu ciągnienia na trzpieniu swobodnym prowadziły do wyznaczania optymalnej różnicy kątów ciągadła i trzpienia. W pracy opracowano teoretycznie zależności pozwalające na uzyskanie jak najmniejszej redukcji średnicy rury w procesie przy założonej redukcji ścianki rury. Uwzględniono wpływ geometrii narzędzi oraz stanu naprężenia na uzyskanie stabilnych warunków prowadzenia procesu. Badania eksperymentalne przeprowadzone poprzez ciągnienie rur z miedzi OF-Cu i mosiądzu CuZn37 potwierdziły wyniki rozważań teoretycznych.

1. Introduction

One of the methods used most frequently in tube manufacture with the reduction of tube diameter and the wall thickness, is the process of drawing with a floating plug.

The important problem encountered during tube manufacture is how to obtain large wall thickness reduction at the lowest possible reduction in the diameter. This requires

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performing calculations of the dimensional range for the tools used, enabling stability of the drawing process. Therefore, extensive research should be made on tool geometry, deformation scheme and on how the process parameters affect the degree of tube deformation. This paper describes results of such research carried out for copper and brass tube drawing with a floating plug.

2. The methods of an analysis of the tube drawing process with a floating plug

There are some methods describing the phenomena taking place in the zone of tube deformation during the process, namely the method of analysis of the plug position in the deformation zone, the method employing differential equations for the state of equilibrium, power models and the method of evaluation of the redundant strains. These methods aim at obtaining the minimum drawing force at the specific initial and final dimensions of a tube.

The results reported by Avitzur [1], Bramley and Smith [2], as well as Pawelski and Amstroff [3] show that the position of the floating plug, n_r, is very important for the process.

It can be expected that there is the most optimal plug position, for which the relative drawing stress reaches its minimum [1].

The results of investigations show that in the process the minimum drawing stress may be obtained when using drawing dies with a semi-angle α in range of 16°–18° and adopting plugs ensuring $(\alpha - \beta)$ difference of an order between 2° and 3°.

In the paper the problem to be discussed is achieving minimal diameter reduction enabling process to the required reduction of the tube wall.

3. Theoretical characteristic of the process

To obtain the assumed reduction of the tube wall with minimal reduction of the tube diameter may be obtained by determining the minimal diameter of a starting tube $D_{0\min}$ according to the following formula:

$$D_{0\min} = kd_r + 2g_0 + \Delta, \tag{1}$$

where:
d_r — the start value of plug diameter before tube wall deformation,
Δ — the plug clearance in the starting tube,
k — coefficient of boundary operating conditions.

The published studies show, that it is reasonable to determine the position of the floating plug in the process [4, 5, 6]. The problem is difficult because of the difference in radii of curvatures between the working conical and cylindrical surfaces of tools (both in a die and in a plug). In the study, it is assumed that the position of the plug is determined by the diameter d_r of the plug conical surface, on which the process of wall deformation begins.

Moreover, it is found that in the part of sinking in the deformation zone, variation of wall thickness takes place, expressed by the angle ω. Both the diameter d_r and the angle ω are shown in Fig. 1.

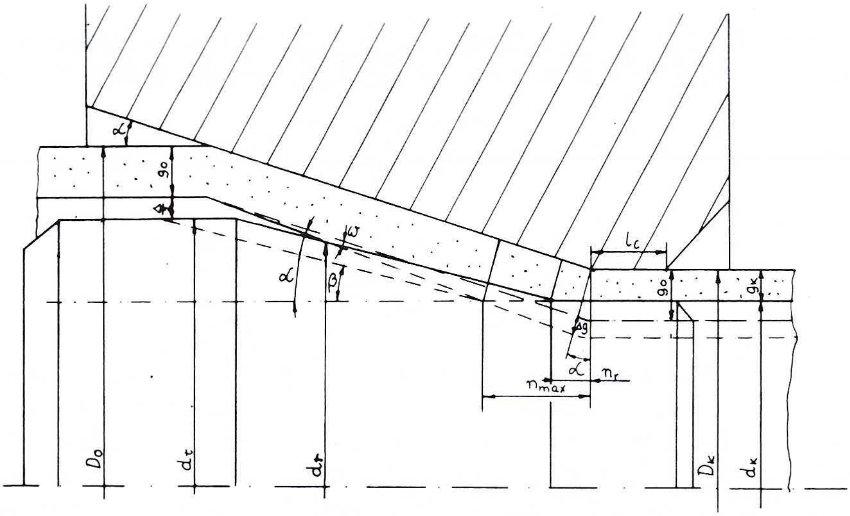

Fig 1. A schematic of tube drawing with a floating plug with the marked the angle ω describing wall thickness variation in the sinking zone and diameter d_r describing the start value of plug diameter before tube wall deformation

When adopting the notations as in Fig. 1 it is possible to obtain the following relationship, which is the equilibrium equation of the forces acting on the floating plug:

$$p_s \frac{(n_{\max} - n_r)\sin(\alpha + \omega)}{\sin(\alpha + \omega - \beta)} (d_r + d_k)(\sin\beta - \mu_2 \cos\beta) = 2\mu_2 d_k (l_c p_c + n_r p_w), \tag{2}$$

where:

$$n_r = n_{\max} \frac{(d_r - d_k)\sin(\alpha + \omega - \beta)}{2\sin(\alpha + \omega)\sin\beta},$$

$$n_{\max} = g_k tg\alpha + \frac{\left(g_0 + \Delta g - \dfrac{g_k}{\cos\alpha}\right)\cos\omega}{\sin(\alpha + \omega)},$$

p_s, p_w , p_c — unit pressures on the working surfaces of a plug (Fig. 2),
μ_2 — coefficient of friction on working surface of a plug.
The angle ω (Fig. 1) could be obtained from the formula:

$$\omega = \operatorname{arc\,tg} \frac{2\Delta g \sin\alpha}{2g_0 \cos\alpha + D_0 - D_k - 2g_0}. \tag{3}$$

Solving the equation (2) a formula can be obtained for the diameter d_r describing the beginning of tube wall deformation on the plug conical surface, the form of which will be as follows:

$$d_r = \sqrt{d_k^2 + R^2 \frac{\sin^2(\alpha+\omega-\beta)}{\sin^2(\alpha+\varpi)} + 2Rd_k \frac{\sin(\alpha+\omega-\beta)}{\sin(\alpha+\varpi)} + 4R\left(l_c \frac{p_c}{p_w} + n_{\max}\right)\sin\beta} -$$

$$-R\frac{\sin(\alpha+\omega-\beta)}{\sin(\alpha+\varpi)}, \qquad (4)$$

where:

$$R = \frac{\mu_2 d_k p_w}{(\sin\beta - \mu\cos\beta)\, p_s}.$$

Knowing the geometrical parameters, there are some difficulties connected with calculating the values of unit pressures p_s, p_w , p_c on the working surfaces of the tools.

To determine these values of the unit pressures, the method of equilibrium differential equations of the infinitesimal element of a tube in the particular zones of the deformation field was used. The scheme of tube drawing shown in Fig. 2 allows us to state that the deformation field may be divided into four zones [4,7].

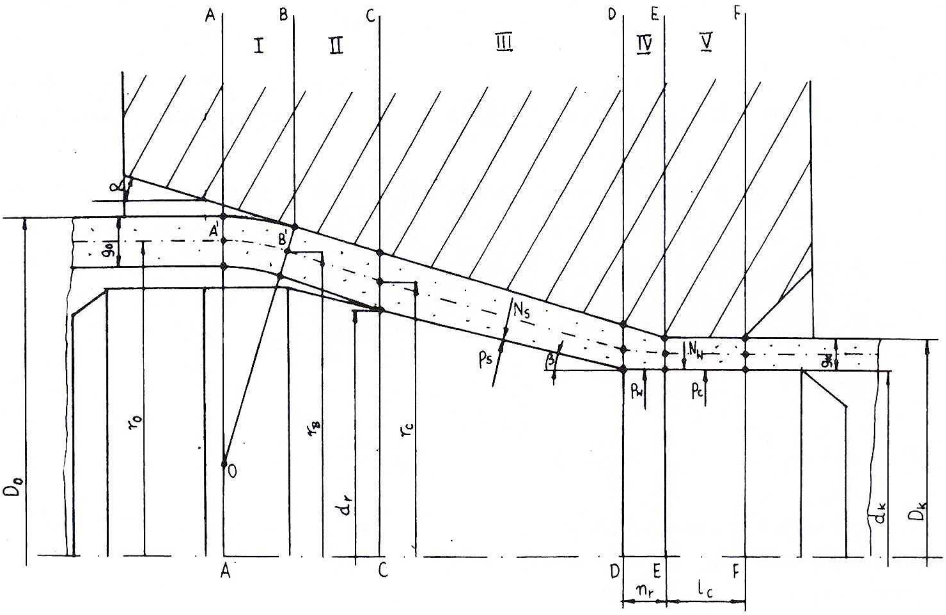

Fig.2. The scheme of tube drawing with deformation zone divided into zones

The equilibrium differential equation of the infinitesimal element should be determined separately for each zone [7] and after calculations we may get the following relationship describing the individual stress in the any cross section of the tube [8]:

$$\sigma_X = \sigma_{X-1}\left[\frac{S_X}{S_{X-1}}\right]^{B_x-1} + \frac{MB_X}{4-B_X}\left(\left[\frac{S_X}{S_{X-1}}\right]^{B_x-1}\cdot S_{X-1}^3 - S_X^3\right) + \frac{NB_X}{3-B_X}\left(\left[\frac{S_X}{S_{X-1}}\right]^{B_x-1}\cdot S_{X-1}^2 - S_X^2\right) +$$

$$+\frac{PB_X}{2-B_X}\left(\left[\frac{S_X}{S_{X-1}}\right]^{B_x-1}\cdot S_{X-1} - S_X\right) + \frac{TB_X}{1-B_X}\left(\left[\frac{S_X}{S_{X-1}}\right]^{B_x-1} - 1\right). \qquad (5)$$

In calculations, the influence of the strain on the flow stress is used, according the following equation [8];

$$f(S_X) = \sigma_{pX} = MS_X^3 + NS_X^2 + PS_X + T, \qquad (6)$$

where: M, N, P, T are the factors of the formula approximating the dependence of flow stress on the strain in form [8]:

$$f(S_X) = \sigma_{pX} = A\left(\frac{S_0 - S_x}{S_0}\right)^3 + B\left(\frac{S_0 - S_x}{S_0}\right)^2 + C\,\frac{S_0 - S_x}{S_0}\,D. \qquad (7)$$

where:
S_X — current cross section of the tube in a deformation zone,
S_0 — cross section of an initial tube.

The other parameters are different in the zones and can be determined using the following relationships:
in zone I: the Bisk and Schwejkin formula [6]
in the zone II:

$$B_X = \frac{\delta g\left(d_r + \dfrac{g_0 - \delta g}{\cos a}\right)}{\delta g\left(d_r + \dfrac{g_0 + \delta g}{2\cos a}\right) + (g_0 + \delta g)\left(\dfrac{D_0 - \delta g}{2\cos a} - d_r\right)}\;\frac{(\mathrm{tg}\alpha + \mu_1)\cos\alpha\cos(\alpha+\omega)}{(1-\mu_1\,\mathrm{tg}\alpha)\sin\omega}, \qquad (8)$$

where:

$$\delta g = \frac{(D_0 - 2g_0)\cos a - d_r}{2\mathrm{tg}(\alpha+\omega)}\,[\mathrm{tg}(\alpha+\overline{\omega}) - \mathrm{tg}\alpha]\cos\alpha$$

μ_1 — coefficient of friction on working surface of a die,

$$p_{sx} = \frac{f(S_X) - \sigma_X}{\cos\beta + \mu_2\sin\beta},$$

where:
p_{sx} — current unit pressure on the working surface of a plug in the zone II
in the zone III:

$$B_X = \frac{1}{\eta_1}\left[\frac{(\sin\alpha+\mu_1\cos\alpha)\cos\alpha\cos\beta}{(\cos\alpha-\mu_1\sin\alpha)\sin(\alpha-\beta)}\left(1+\frac{g_k+n_r\mathrm{tg}\alpha}{d_k+g_k+n_r\mathrm{tg}\alpha}\right)-\right.$$

$$\left.-\frac{(\sin\beta-\mu_2\cos\beta)\cos\alpha\cos\beta}{(\cos\beta+\mu_2\sin\beta)\sin(\alpha-\beta)}\left(1-\frac{g_k+n_r\mathrm{tg}\alpha}{d_k+g_k+n_r\mathrm{tg}\alpha}\right)\right], \tag{9}$$

where:

$$\eta_1 = 1+\frac{(g_k+n_r\mathrm{tg}\alpha)\left(d_r+\dfrac{g_0+\delta g}{\cos\alpha}-d_k-g_k-n_r\mathrm{tg}\alpha\right)}{(d_k+g_k+n_r\mathrm{tg}\alpha)\left(\dfrac{g_0+\delta g}{\cos\alpha}-g_k-n_r\mathrm{tg}\alpha\right)},$$

$$p_{wx} = f(S_X)-\sigma_X,$$

where:
p_{wx} — current unit pressure on the working surface of a plug in the zone III
in the zone IV:

$$B_X = \frac{(\sin\alpha+\mu_1\cos\alpha)\cos\alpha}{(\sin\alpha-\mu_1\cos\alpha)\sin\alpha}+\frac{d_k\mu_2\mathrm{ctg}\beta}{d_k+2g_k},$$

$$p_{cx} = f(S_X)-\sigma_X, \tag{10}$$

where:
p_{cx} — current unit pressure on the working surface of a plug in the zone IV.

When inserting parameters characterising the process of tube drawing with a floating plug it is possible to obtain the following formula for the total stress of drawing [8]:

$$\sigma_c = \left[\sigma_E+\frac{f(S_E)-2\sigma_E\left(1+\dfrac{\mu_1}{\mu_2}\right)}{1+\dfrac{D_k\mu_1}{d_k\mu_2}}\right]\cdot e^{\frac{\left(1+\frac{D_k\mu_1}{d_k\mu_2}\right)\mu_2 d_k l_c}{d_k g_k+g_k^2}}-\frac{(f(S_E)-2\sigma_E)\left(1+\dfrac{\mu_1}{\mu_2}\right)}{1+\dfrac{D_k\mu_1}{d_k\mu_2}}, \tag{11}$$

where:
σ_E — individual stress in the cross section E of the tube (Fig. 2)
S_E — cross section E of the tube (Fig. 2)

Knowing the values of stresses in each deformation zone, the unit pressures in the zones can be obtained according to the following formulae:

$$p_{ouX} = \frac{f(S_X)-\sigma_X}{\cos\alpha_x-\mu_1\sin\alpha_x} \qquad p_{inX} = \frac{f(S_X)-\sigma_X}{\cos\beta_x-\mu_2\sin\beta_x}, \tag{12}$$

where:

p_{ouX} — current unit pressure on the working surface of a die,

p_{inX} — current unit pressure on the working surface of a plug.

As we may see the values of the unit pressures influence the value of d_r and n_r and vice-versa the values of the unit pressures in the deformation zone are depended on the values of d_r and n_r. The values are incoherent but the equation may be solved by iteration: the values determined when successive iterations are adequately close.

4. The own investigations results

Proof of the calculation results was performed by drawing of tubes from copper OF-Cu and brass CuZn37. The nominal dimensions of the tubes were as follows; initial diameter D_0 = 18.0 mm, initial wall thickness g_0 = 0.8 mm and length of about 2 m, The tubes were drawn to final diameter D_k = 16.0 mm and final wall thickness g_k = 0.6 mm in tools with various geometry; plug angles β in the range of 10°–18° (0.1745–0.3142 rad) and dies with the following angles and lenghts of die calibrating zone; α = 15.5° (0.2075 rad) l_c = 2.00 mm, α = 15.5° (0.2075 rad) l_c = 4.25mm, α = 19° (0.3316 rad) l_c = 2.25 mm and α = 19.2° (0.3374 rad) l_c = 4.25 mm.

Mechanical properties of the tube materials used in the investigations and factors of the formula (6), which were obtained from process of sink drawing of initial tubes, are shown in Tab.1.

TABLE 1

Properties of initial tubes

Material of a tube	Mechanical properties			Factors of the formula (6)		
	R_m [MPa]	$R_{0.2}$ [MPa]	A_{100} [%]	A [MPa]	B [MPa]	C [MPa]
OF-Cu	235.5	49.9	32.8	0.000584	–0.16850	11.273
CuZn37	379.2	177.6	45.5	0.000221	–0.18003	14.115

Trefil 1780 lubricant was used to lubricate the working surfaces of the drawing dies and the plugs. The drawing tests were carried out using chain drawbench with maximum drawing force of 40 kN and at drawing speed of 4 m/min.

The investigation's results are shown in Fig. 3, 4, 5, 6 as the dependence of both calculated drawing stress σ_c and true drawing stress σ_{rz} on the plug angle β.

It could be seen that the results of the described mathematical model, as well as character of the curves, are close to true values obtaining from the process.

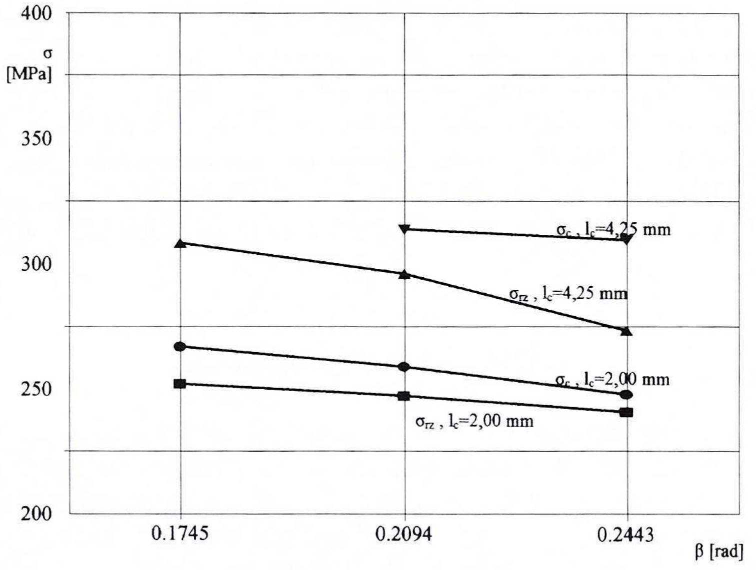

Fig. 3. The relationship between calculated drawing stresses σ_c as well as true drawing stresses σ_{rz} and the plug angle β for dies α = 15.5° (0.2705 rad) l_c = 2.00mm, and α = 15.5° (0.2705 rad) l_c = 4.25mm, tube material OF-Cu

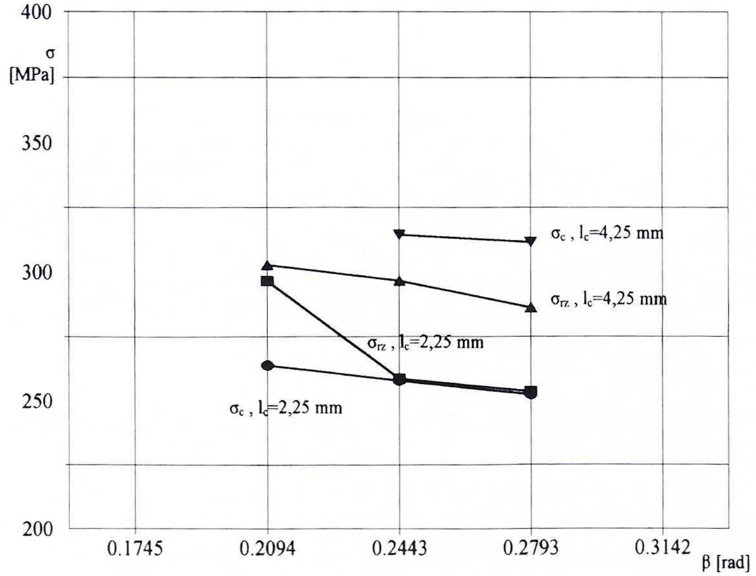

Fig. 4. The relationship between calculated drawing stresses σ_c as well as true drawing stresses σ_{rz} and the plug angle β for dies α = 19° (0.3316 rad) l_c = 2.25mm and α = 19.2° (0.3374rad) l_c = 4.25mm, tube material OF-Cu

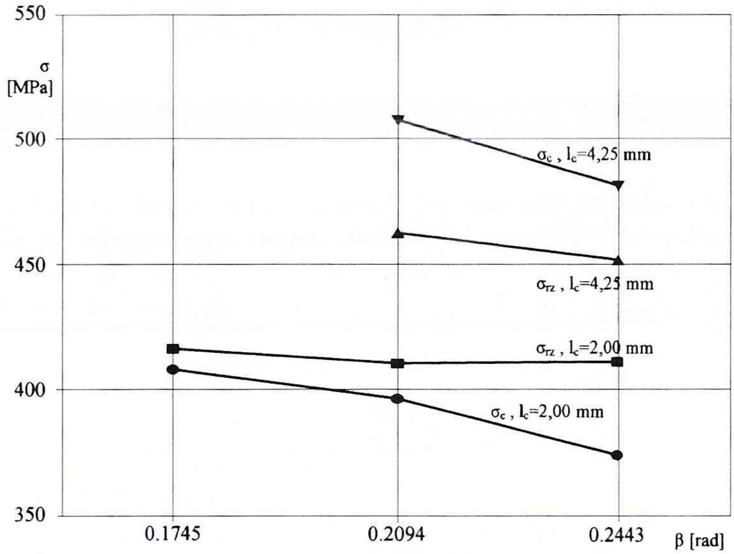

Fig. 5. The relationship between calculated drawing stresses σ_c as well as true drawing stresses σ_{rz} and the plug angle β for dies α = 15.5° (0.2705 rad) l_c = 2.00mm, and α = 15.5° (0.2705 rad) l_c = 4.25mm, tube material CuZn37

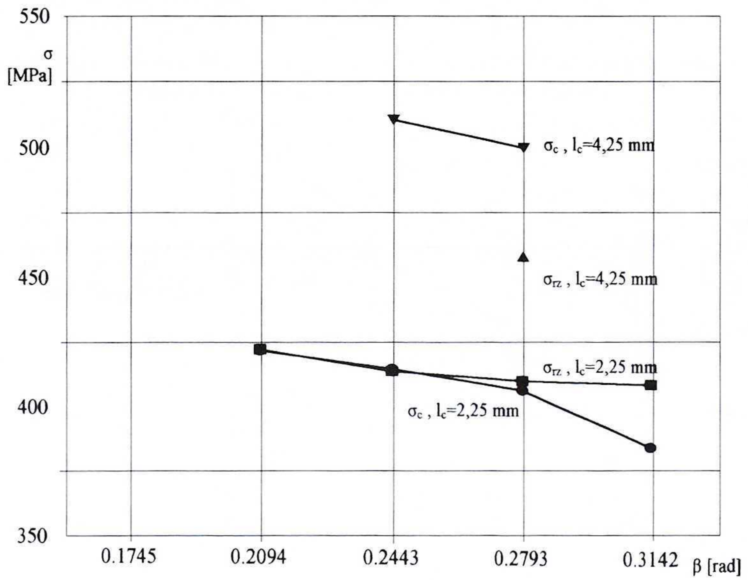

Fig. 6. The relationship between calculated drawing stresses σ_c as well as true drawing stresses σ_{rz} and the plug angle β for dies α = 19° (0.3316 rad) l_c = 2.25mm and α = 19.2° (0.3374 rad) l_c = 4.25mm., tube material CuZn37

5. Summary

In the plug drawing, with the tube cross-section reduction remaining constant, the drawing stress reduces slightly with a decrease of angle difference, whereas the fall in the value of the drawing stress with decreasing the length of calibrating zone is more pronounced. The sink zone increases with increasing of angle difference. The increasing amount of sinking will influence the actual proportional presence of sink in plug drawing. To assess this influence, the discussed sets of calculations were designed to keep minimal sink in the plug drawing, using formula (1) to determining the minimal

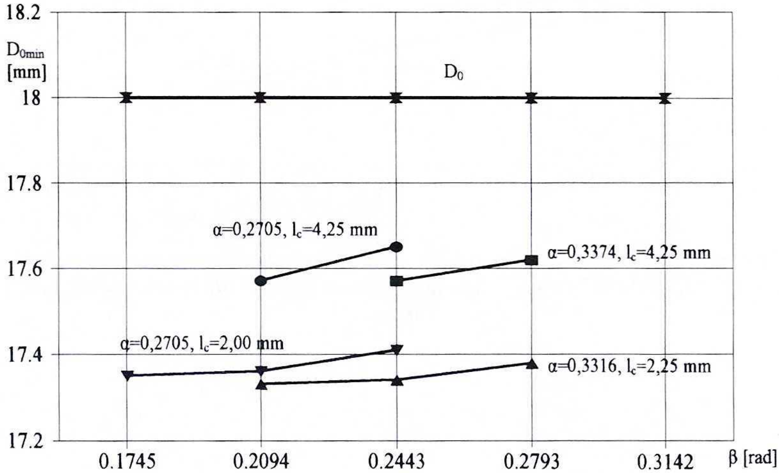

Fig. 7. The relationship between calculated minimal values of starting tube diameters D_{0min} and the plug angle β for tube material OF-Cu and different die geometry

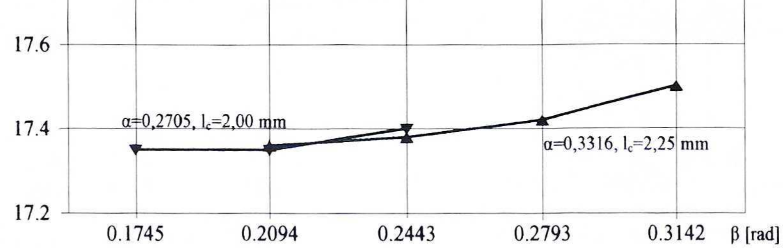

Fig. 8. The relationship between calculated minimal values of starting tube diameters D_{0min} and the plug angle β for tube material CuZn37 and different die geometry

diameter of a starting tube $D_{0\min}$. In Fig. 7 and 8, the calculated minimal values of starting tube diameters enabling leading the process at the established reduction of the tube wall g_0/g_k = k1,33 are shown. With reference to Fig. 7 and 8, we observe that the minimal values of starting tube diameters decrease with decreasing in the length of calibrating zone, whereas the increase of angle difference influences the value of $D_{0\min}$ to significantly decrease, when the effect of sink is minimised.

This observation is of importance, in view of the fact that in plug drawing, the wall thickness reduction is the essence of the process. It is clear that when intensive wall thickness reduction is required, the minimising of tube diameter reduction could be important.

6. Conclusions

1) The method of calculating the initial diameter of the plug d_r on which the process of wall reduction begins, is performed by analytical procedure that may be applied to determine the minimal starting tube diameter, enabling process to the required reduction of the tube wall. The procedure utilises the equilibrium differential equations of the infinitesimal element of a tube in the particular zones of the deformation field for the obtaining the drawing stress.

2) The closeness of the values of calculated and true drawing stresses confirm that the established geometrical parameters of deformation zone should not be neglected when designing the geometrical features of tools for drawing.

3) The method used in the investigations, leads to minimise the part of sinking in the tube drawing with a floating plug.

4) A further proof of the developed technique proposed by the authors, namely the mentioned analytical procedure, taking into consideration other metals and alloys that have higher hardness and wider range of reductions, is necessary.

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