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A Computer Assisted Process Design of Multi-Step Deep Drawing

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It is well-known from practice that only some cups whose height is smaller than diameter can be successfully drawn in one step. Many steps require more tools and larger total manufacturing costs. The main objective of this study was to minimize the number of deep-drawing steps. The paper presents the application of software DDCP developed for designing the multi-step deep-drawing processes in manufacturing of cylindrical cups. The analysis of the computing results obtained by this software shows that the number of drawing steps is decisively affected by relative height of the given part, while the impact of relative radius is smaller. In the paper a diagram for determining the number of deep-drawing steps is given, which is very suitable for engineers in practice.
Also, various very useful approaches for reducing the number of deep-drawing steps are recommended.

Računalno potpomognuto projektiranje procesa višefaznog dubokog vučenja

Izvornoznanstveni članak

Iz prakse je poznato da se samo neke posude s visinom manjom od promjera mogu uspješno izvlačiti u jednoj operaciji. Više operacija podrazumijeva i više alata i veće ukupne troškove proizvodnje. Glavni cilj ovog istraživanja bio je smanjiti broj koraka dubokog vučenja. Prikazana je primjena softvera DDCP koji je razvijen za izradu cilindričnih komada procesom dubokog vučenja u više operacija. Analiza računalnih rezultata ovog softvera pokazuje da na broj koraka vučenja presudno utječe relativna visina komada, dok je utjecaj relativnog radijusa manji. U radu je prikazan dijagram za određivanje broja koraka dubokog vučenja, koji je vrlo pogodan za inženjere u praksi. Također, preporučeni su razni vrlo korisni pristupi za smanjenje broja koraka dubokog vučenja.

1. Introduction

Generally, deep drawing is a method of forming under compressive and tensile conditions whereby a sheet metal blank is transformed into a hollow cup, or a hollow cup is transformed into a similar part of smaller diameter without any intention of altering the sheet thickness [1].
The deep-drawing of cylindrical cups is done, as a rule, in many steps. When more than one drawing step is used, the subsequent steps often are referred to as re-drawing.
It is well-known from practice that only some cups whose height is smaller than diameter can be successfully drawn in one step (single drawing). The re-drawing process is used frequently to produce cups with very deep geometry. Many steps imply more tools for each step. Along with the increasing number of steps, the time needed for designing the technological process and tools also increases, along with the total costs for manufacturing such parts.
It is clear that productivity and economic benefits of steel elements manufacturing can be, to a great extent, increased by reducing the number of drawing steps. On the other hand, the prior knowledge of the needed number of steps reduces the design efforts and shortens the whole procedure. The usual procedure for determining the number of steps for deep-drawing of cups without a flange is given in Reference [2].
Some recommendations for the choice of the number of steps that are not sufficiently precise can be found in the literature. Many of the multi-step deep-drawing process have been carried out with trial-and-error experimental work in the factory without the fundamental understanding of the complicated deformation mechanism and plasticity theory [3].
The aim of paper is to offer, to engineers-designers, a reliable way of determining minimal number of deep-drawing steps practically with no prior calculations.

Symbols/Oznake

D_0	- blank diameter, mm - promjer pripremka	f	- unilateral clearance, mm - zazor
d_i	- cup diameters by redrawing steps, mm - promjeri vučenih dijelova po operacijama	φ_m	- logarithmic uniform strain (elongation) - logaritamsko jednoliko izduženje
N	- number of drawing steps - broj operacija dubokog vučenja	σ_e	- flow stress - naprezanje plastičnog tečenja
m_i	- draw-reduction ratio (DRR) - koeficijent redukcije	C	- constant of flow curve - konstanta krivulje tečenja
m^t_i	- tabulated draw-reduction ratio - tablični koeficijent redukcije	n	- strain hardening coefficient - eksponent očvršćivanja
t	- blank (sheet) thickness, mm - debljina pripremka (lima)	R	- coefficient of anisotropy - faktor plastične anizotropije
t_r	- blank (sheet) relative thickness, % - relativna debljina pripremka	$R_{0.2}$	- yield stress (strength), N/mm^2 - granica razvlačenja
H	- height of drawing part, mm - visina vučenog dijela	R_m	- ultimate tensile strength, N/mm^2 - rastezna čvrstoća materijala
r	- drawn cup radius, mm - radijus na vučenoj posudi	p_{bh}	- blank holding pressure, MPa - pritisak tlačnog prstena
r_p	- punch nose radius, mm - radijus zaobljenja žiga		**Greek letters/Grčka slova**
r_d	- die profile radius, mm - radijus zaobljenja matrice	β	- deep-drawing ratio - koeficijent dubokog vučenja
Δh	- trimming allowance, mm - dodatak za obrezivanje	φ	- logarithmic strain - logaritamski stupanj deformacije

2. Method for determining the number of deep-drawing steps

Figure 1 gives a cylindrical cup without a flange obtained in many deep-drawing steps.

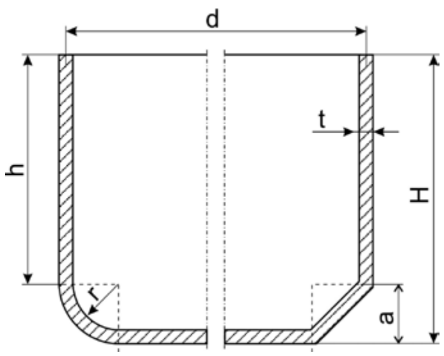


Figure 1. Cylindrical cup without flange: Variant I (left), Variant II (right)

Slika 1. Cilindrična posuda: varijanta I (lijevo), varijanta II (desno)

The given geometric parameters affect the blank diameter size and thus the number of drawing steps since draw-reduction ratio (DRR) is defined as:

$$m_1 = \frac{d_1}{D_0};\ m_2 = \frac{d_2}{d_1};\ ....m_N = \frac{d_N}{d_{N-1}} \tag{1}$$

where d_i is the cup diameters by steps, D_0 is the blank diameter, N is the number of drawing steps.

Total draw-reduction ratio is defined as:

$$m_{tot} = m_1 \cdot m_2 \cdot m_3 ....m_N \tag{2}$$

The values of draw-reduction ratios are given in Table 1 taken over from Reference [4].

Table 1. Draw-reduction ratio for the cylindrical cup without flange

Tablica 1. Koeficijent redukcije za cilindrične posude

DRR$_s$ m_i	Blank relative thickness/Relativna debljina pripremka t_r=100 t/D_0 (%)				
	2.0-1.50	**1.5-1.0**	**1.0-0.5**	**0.5-0.2**	**0.2-0.06**
$m_1=d_1/D_0$	0.46-0.50	0.50-0.53	0.53-0.56	0.56-0.58	0.58-0.60
$m_2=d_2/d_1$	0.70-0.72	0.72-0.74	0.74-0.76	0.76-0.78	0.78-0.80
$m_3=d_3/d_2$	0.72-0.74	0.74-0.76	0.76-0.78	0.78-0.80	0.80-0.82
$m_4=d_4/d_3$	0.74-0.76	0.76-0.78	0.78-0.80	0.80-0.82	0.82-0.84
$m_5=d_5/d_4$	0.76-0.78	0.78-0.80	0.80-0.82	0.82-0.84	0.84-0.86

The problem in question can be simplified by introducing relative geometric parameters H/d and r/t. Thus, on the basis of formula for blank diameter of cylindrical cup with flat bottom the theoretically maximal relative height of the drawn cup in one drawing step can be determined:

$$\frac{H}{d}=\frac{1}{4}\left[\left(\frac{1}{m_1}\right)^2+1.72\frac{r}{d}+0.57\left(\frac{r}{d}\right)^2-1\right] \qquad (3)$$

$(0 \le r/d \cong a/d \le 0.5d)$

If the limit value of the draw-reduction ratio in the first step is $m_1 \cong 0.48$, from relation (3) is obtained that $H/d \cong 0.84 \div 1.09$.

A very detailed analysis of the effects of the above-given parameters can help to determine the sufficient number of drawing steps, only on the basis of the drawing of a finished part.

For this purpose, the computer-assisted deep-drawing process design was carried out using the DDCP (Deep Drawing of Cylindrical Parts, [5]) program for over 100 shapes of the finished part. DDCP program was developed with the aim of obtaining the designers and engineers who work in production planning, in a quick manner, with reliable information about the deep-drawing process of cylindrical parts, with and without a flange, with the implementation of the transition radius or with taper transition.

Input data to the program (Fig. 2) are: the dimensions of the finished part, type and mechanical properties of the workpiece material, type and coefficients of flow curve, friction coefficient, part tolerance and others.

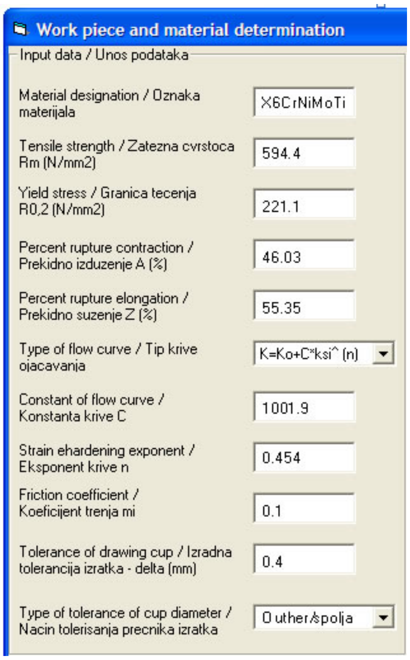


Figure 2. Screenshot of program's data input

Slika 2. Ulazni podaci u program

After defining the input data, the program offers a range of output values, such as: blank diameter, the number of required deep-drawing steps, the dimensions of workpieces by drawing operations (Fig. 3), the value of the blank holding force, drawing forces, and deformation works by multi-step deep-drawing process, consistent with the known equations from the literature [4], [6], [7].

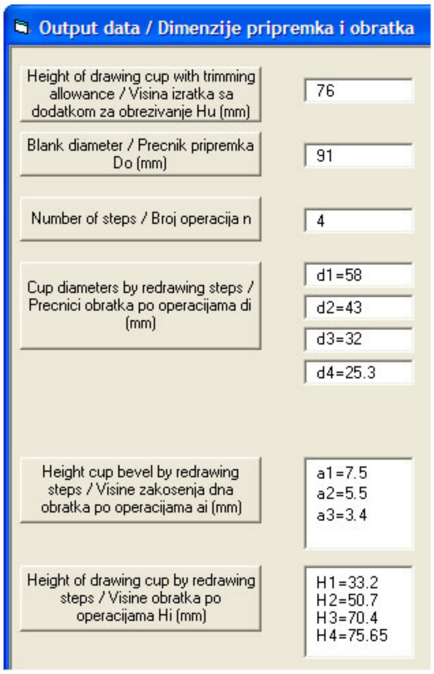


Figure 3. Screenshot of program's output data

Slika 3. Izlazni podaci programa

The analysis of the calculation results shows that the most decisive effect upon the number of deep drawing steps is that of the cup's relative height H/d while the impact of relative radius r/t is smaller.

For engineers in practice the most suitable way of presenting these results is a diagram (Fig. 4) [2].

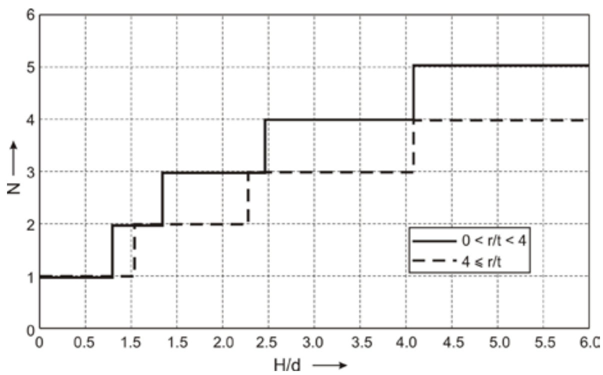


Figure 4. Number of deep-drawing steps vs. relative cup height

Slika 4. Broj operacija dubokog vučenja ovisno o relativnoj visini posude

3. A case study

The cylindrical cup manufactured in real deep-drawing process in industry is shown in Fig. 5.

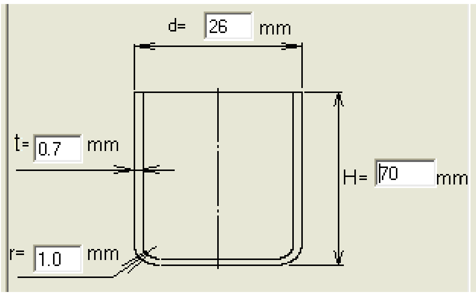


Figure 5. Cylindrical cup after deep-drawing process

Slika 5. Cilindrična posuda nakon procesa dubokog vučenja

The sheet metal material was SPCC (a kind of cold forging steel). The total number of drawing steps was four, with the trimming process inserted between the first and the second drawing step [8].
The same result was obtained by applying the DSS (Design Support System) program [8].
After running the DDCP program for the given cup, the sequence of steps and the cup dimensions by the drawing steps are shown in Fig. 6. The DDCP program suggests four drawing steps with added trimming process.

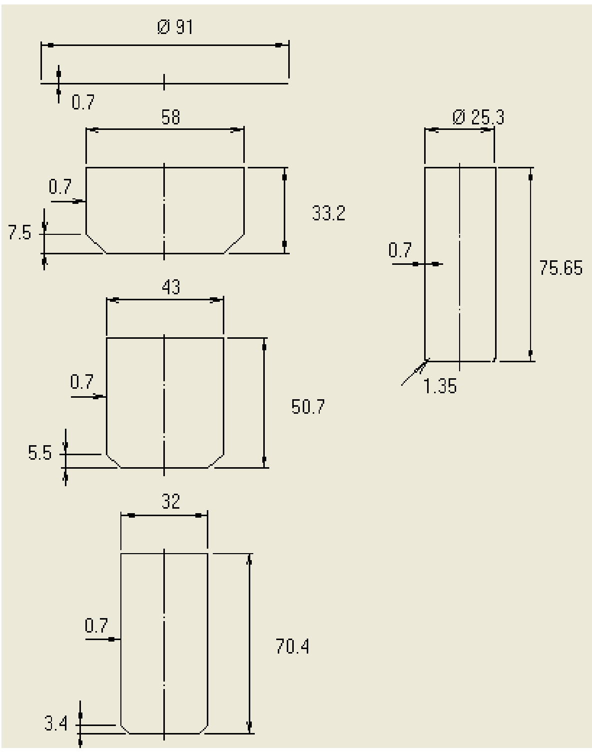


Figure 6. Deep-drawing process displayed in the DDCP

Slika 6. Proces dubokog vučenja prikazan u DDCP

Here, it should also be mentioned that some deviations of the theoretical values of the relative drawing heights, for the first deep-drawing step, according to equation (3), from the values given in Fig. 4, are a consequence of the real prior calculation that takes into consideration the allowance for trimming as well.
The comparison between the DRR of real process and the output from the DSS and DDCP is given in graphical form in Fig. 7, which shows that the DRR in the first drawing step is the lowest in the real process and vice versa; in the other drawing steps, DRR is the highest in the real process.

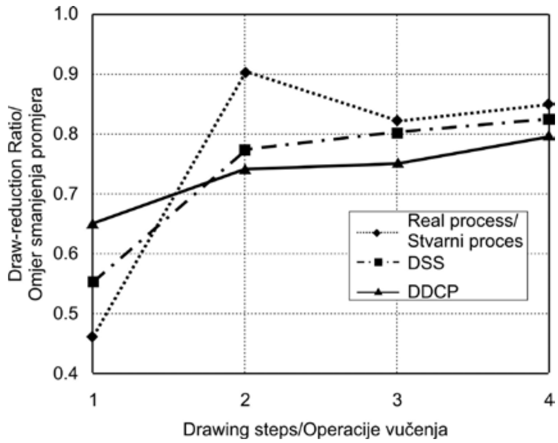


Figure 7. Graphical comparison between the DRR of the real process and output from the DDCP and DSS: D_0 = 91.9 mm (real process), D_0 = 91.0 mm (DDCP), D_0 = 92.4 mm (DSS)

Slika 7. Grafička usporedba koeficijenta redukcije stvarnog procesa i dobivenih rezultata iz programa DDCP i DSS: D_0 = 91.9 mm (stvarni proces), D_0 = 91.0 mm (DDCP), D_0 = 92.4 mm (DSS)

It is known that the first drawing step is a critical one due to a higher possibility for failure (breakage) and wrinkling [9]. In that sense we could expect the DDCP designed deep-drawing process to be the most successful (with the least scrap).

4. Results and discussion

A successful deep-drawing process depends on numerous influential factors. However, regardless of the many influential factors involved, the following are the most important and each of them must be considered when designing the deep-drawing process:

1. Type of sheet metal (mechanical properties; heat treatment; strain hardening coefficient; coefficient of anisotropy; material thickness);
2. Stamping tool (punch and die radii; type and shape of blank holder; holder pressure; clearance);
3. Drawn part and blank geometry;
4. Deep drawing ratio;
5. Multi-step procedure;
6. Other influential factors (die surface quality; die temperature; lubricant; press speed).

Most types of material can be drawn from a flat blank into a cup. However, due to the level of stress which the material is subjected to during this process, some types of material which are less deformable, may require an annealing operation before being taken through any further reduction after the initial stages. Furthermore, thicker materials tend to be stiffer. It can be gripped better during the deep-drawing process. Thicker materials have more volume, meaning they can stretch for longer distances during the deep-drawing process.

Also, it is known that, the effectiveness of the deep-drawing process depends on the ratio between the yield strength ($R_{0.2}$) and ultimate tensile strength (R_m). Starting from the flow curve in the form $\sigma_e = \sigma_0 + C\varphi^n$, the following relation is obtained [7]:

$$\frac{R_{0.2}}{R_m} = e^{\varphi_m}\left(1 - \frac{\varphi_m}{n}\right) ;\ \sigma_0 \cong R_{0.2} \qquad (4)$$

where φ_m is the logarithmic uniform elongation, n is the strain hardening coefficient.

Theoretically and practically it was proved that the sheet metals with a higher coefficient of anisotropy (R) are suitable for deep-drawing. The effect of this coefficient on deep-drawing ratio (DDR) for some materials is shown in Fig. 8 [10].

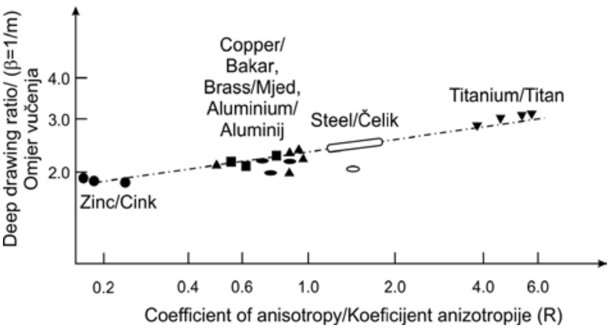


Figure 8. Influence of normal anisotropy on DDR

Slika 8. Utjecaj koeficijentaplastične anizotropije na koeficijent dubokog vučenja

The quantification of the impact of coefficient of anisotropy on the DDR can be done using semi-empirical formula [7]:

$$m_1 = 0.624 - 0.02828 \cdot t_r - (0.039 + 0.00928 \cdot t_r)\,R \qquad (5)$$

Other important factors for successful deep-drawing are the size, accuracy, and surface finish of the stamping tool. Decisions regarding the die radius should be based on material type and thickness. If a die radius is too small, material will not flow easily, resulting in stretching and, most likely, fracturing of the cup. If a die radius (r_d) is too large, particularly when deep-drawing thin-gauge stock, material begins to wrinkle after it leaves the pinch point between the draw ring surface and the blank holder.

Designing the blank geometry to minimize excess material can reduce the potential for wrinkling. Blank sizes and shapes that are too large can restrict metal flow, and the geometry of parts affects the ability of metal to flow during the deep-drawing process. The sheet metal blank has an inherent grain structure, so the stresses can vary depending on the design of the die and the orientation of the grain. Adjusting the grain in an asymmetrical design to minimize the compound of grain stresses and the general stresses of the deep-drawing process is something to take into consideration.

The blank holding force, as an important parameter, shows a significant influence on the process only in conditions of intensified friction [11]. To control metal flow, sufficient blank holding force must be present. If blank holding force is inadequate, the material wrinkles during compression. The wrinkles then cause the blank holder to further separate from the draw ring surface, and control of the material will be lost.

The DRR ratio is among the most important elements to be considered when attempting to deep-drawing a cylindrical cup. In accordance with relation (2), the total DRR and therefore the number of drawing operations, affect both partial DRR. However, based on the data from Tab. 1, it is apparent that the greatest reduction in diameter was achieved in the first drawing operation. It is therefore necessary to choose the smallest possible value for DRR in the first drawing operation. One possible approach is the choice of material with higher coefficient of anisotropy. Note that in Tab. 1 this parameter is not directly taken into account.

By analyzing relation (5) it can be concluded that in Tab. 1 lower values of DRR in the first operation are related to the sheet metal with large anisotropy. In selecting the DRR this fact should be kept in mind.

Analyzing the diagram from Fig. 4 the following conclusions can be drawn:

- the increase of H/d ratio brings about the increasing number of steps, at first rapidly and then much more slowly;
- there are transition intervals of H/d ratio when the number of steps is not unambiguously determined.

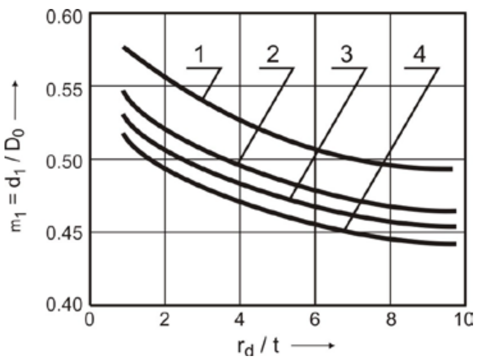
Since it is generally desirable for the number of deep drawing steps to be as small as possible, the diagram suggests that for the given sheet metal thickness the cup radius should be increased (when allowed).

Moreover, it is well known from practice that the DRR are also influenced by other (not only geometric) factors. In that sense, more favourable DRR, and thus a smaller number of drawing steps, can be realized by [12], [13]:

- choosing a larger die and/or punch radius (Figure 9) [4];
- reducing trimming allowance (Δh);
- choosing metal sheets with greater normal anisotropy and/or greater strain hardening coefficient [4];
- heat treatment of sheet metal and intermediate annealing;

- local heating blank flange in deep-drawing [4].

By applying one or more of the above suggested actions, the number of deep-drawing steps can be reduced and that should be especially kept in mind in the above mentioned situations of indecision. On the other hand, it is clear that some of the proposed actions cannot be always and everywhere applied for technical reasons or lack of economic benefits of such production.



1. $r_p / t = 1$; 2. $r_p / t = 6$; 3. $r_p / t = 2.5$; 4. $r_p / t = 10$

Figure 9. Influence of die and punch radii on the draw-reduction ratio in the first drawing step

Slika 9. Utjecaj radijusa matrice i žiga na koeficijent redukcije u prvoj operaciji dubokog vučenja

Improvements in technological procedures can significantly reduce the number of operations in deep-drawing of round parts with complex geometry [14].

Paper [15] shows how change of sequences in the deep-drawing process can reduce the number of operations. As it can be seen in Fig. 10, the first scheme requires three operations, but by the second scheme only two operations are sufficient. The check of the DRRs for both variants of the deep-drawing process is given in Table 2. These results indicate that the second variant is a valid alternative process design.

Among the so-called non-traditional forming processes, hydraulic deep-drawing is widely used in industry [16]. Hydroforming is the process of metal forming, where force is indirectly applied to workpiece by means of fluid pressure, as opposed to conventional metal forming processes [17]. There are numerous advantages, such as the possibility of production of very complex tubular parts, automatization of process, etc.

Other processes such, as fluid-pressure-assisted deep-drawing [18], deep-drawing with friction-actuated blank holding [18], deep-drawing with compressive loaded cup-rim [19], [20], deep-drawing with hydraulic counter pressure [21], and deep-drawing with compressive radial stress [21], have no industrial applications.

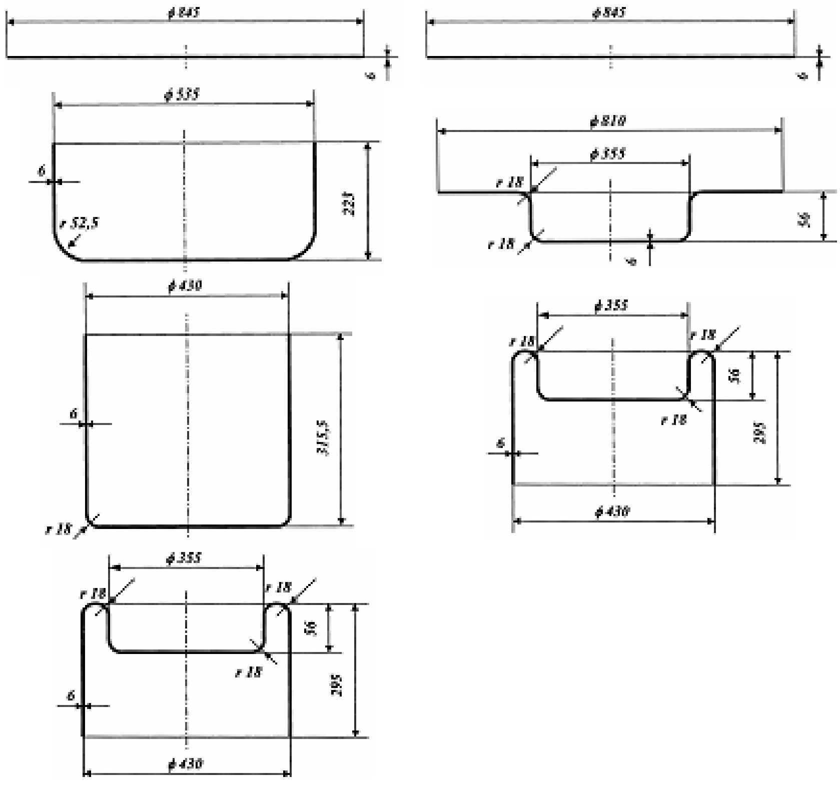


Figure 10. Variants of deep-drawing of the same cylindrical cup with a double wall:
a) in three operations, b) in two operations

Slika 10. Varijante dubokog vučenja iste cilindrične posude s dvostrukim zidom:
a) u tri operacije, b) u dvije operacije

Table 2. Draw-reduction ratios in deep-drawing double-wall cylindrical cup

Tablica 2. Koeficijent redukcije pri dubokom vučenju cilindričnih posuda s dvostrukim zidom

Variants / Varijante	First operation / Prva operacija	Second operation / Druga operacija	Third operation / Treća operacija	Remark / Napomena
a	m_1= 535/845= 0,633 m^t_1= 0,53 ÷ 0,55 (t_r = 100·6/845= 0,71) *direct deep-drawing / izravno duboko izvlačenje*	m_2= 430/535= 0,804 m^t_2= 0,74 ÷ 0,76 (t_r = 100·6/845= 0,71) *direct or indirect deep-drawing / izravno ili posredno duboko izvlačenje*	m_3= 355/430= 0,826 m^t_3= 0,76-0,78 (t_r = 100·6/845= 0,71) *indirect deep-drawing / posredno duboko izvlačenje*	The proposed variant of the forming process is acceptable because the following relations are valid / Predložena varijanta procesa oblikovanja je prihvatljiva, jer vrijede sljedeći odnosi: $m_1 > m^t_1$ $m_2 > m^t_2$ $m_3 > m^t_3$
b	m_1= 355/845= 0,420 m^t_1= 0,409 (t_r = 100·6/845= 0,71 ; D_v/d=810/355=2,28) *direct deep-drawing / izravno duboko izvlačenje*	m_2= 430/810= 0,531 m^t_2= 0,53 ÷ 0,55 (t_r = 100·6/810= 0,74) *direct deep-drawing / izravno duboko izvlačenje*	-	The proposed variant of the forming process is acceptable because the following relations are valid / Predložena varijanta procesa oblikovanja je prihvatljiva, jer vrijede sljedeći odnosi: $m_1 > m^t_1$ $m_2 > m^t_2$
m_i- calculated draw-reduction ratios / izračunati koeficijent redukcije; m^t_i – tabulated draw-reduction ratios / tablični koeficijent redukcije				

5. Conclusion

The results obtained in the present paper can be summarized as follows:

Deep-drawing of cylindrical cups without flange can be carried out in one operation only with the relative height being $H / d \leq 1$.

The diagram given in this paper may be very useful for engineers-designers in practice, since only two geometrical parameters are sufficient for determining the number of deep-drawing operations, practically without any calculation. In this diagram there are ''singular'' points where number of deep-drawing operations is not defined accurately. In the cases in which there is a dilemma about the number of deep-drawing operations, engineers should rely on their practical experience and/or results of the numerical simulation of the deep-drawing process.

For reducing the number of deep-drawing operations, first of all, it is necessary to choose, forming and geometrical parameters that do not affect the geometry of the cylindrical drawn cup, such as larger die profile radius and coefficient of anisotropy, adequate blank holder force, lower trimming allowance, etc.

The choice of some actions for reducing the number of drawing steps implies a comprehensive analysis.

It is assumed that the given recommendations in this paper are valid for optimal unilateral clearance ($1 \leq f \leq 1.3$ mm, [22]) and optimal blank holding pressure ($1 \leq p_{bh} \leq 3$ MPa).

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