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Influence of Variable Blank Holding Force and Nonmonotonous Process of Deep Drawing on Formability of Coated Sheets

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Preliminary note

The results of the research of influence of the blank holding force and nonmonotonous process of deep drawing on the formability of low-carbon steel sheet with one-side galvanic coating of zinc are presented in this paper. Identification and influence assessment was done by monitoring: forming force, the distribution of the principal strains in the sheet plane and their relationship to the forming limit diagram, changes of thinning strain and drawing depth as the most significant technological indicator. Based on the analysis of test results, it was concluded that the blank holding force has a significant influence in terms of intensified friction in the flange. Also, in terms of a single-phase monotonous process, the applied type of variable blank holding force had a beneficial effect on the results of forming. A nonmonotonous two-phase process with uniaxial tension in the first stage greatly affects the behaviour of materials. During the first phase, there is an increase of sheet anisotropy, which affects the formability decrease. The applied variable holding force shows favourable effects, especially when friction was increased, but they were not dominant.

Utjecaj promjenjive sile držanja i nemonotonosti procesa dubokog vučenja na obradivost limova s prevlakama

Prethodno priopćenje

Istraživan je utjecaj promjenljive sile držanja i nemonotonosti procesa dubokog vučenja na obradivost niskougljičnog čeličnog lima s jednostranom galvanskom prevlakom od cinka. Identifikacija i procjena utjecaja izvršena je praćenjem: sile vučenja, distribucije glavnih deformacija u ravnini lima te njihovog odnosa prema dijagramu granične deformabilnosti, promjene deformacije stanjenja i dubine izvlačenja kao najznačajnijeg tehnološkog pokazatelja. Na temelju analize rezultata pokusa zaključeno je da sila držanja pokazuje značajniji utjecaj u uvjetima pojačanog trenja na obodu. Također, u uvjetima jednofaznog monotonog procesa primijenjeni tip promjenljive sile držanja povoljno djeluje na rezultate oblikovanja. Dvofazni nemonotoni proces s jednoosnim zatezanjem u prvoj fazi suštinski utječe na ponašanje materijala. Tijekom prve faze dolazi do povećanja anizotropije lima, što doprinosi padu deformabilnosti. Primjenjena promjenjiva sila držanja pokazuje povoljne efekte, naročito pri pojačanom trenju, ali oni nisu dominatni.

1. Introduction

Deep drawing of thin sheets represents one of the dominant technologies in the modern industrial processing of metals. There is a number of procedures that can be studied from various aspects [1-3]. Different materials are used, but most often low carbon steel sheets are used (due to the good combination of strength, formability, ability of recycling and the price). Their main disadvantage is low corrosion resistance. Therefore, a series of sheet metals, with the same basic material and different non-corrosion coatings on one or both sides, were developed. The electrochemical coatings based on zinc have the greatest application.

During the past 15 years, significant research and professional effort, in addition to purely scientific knowledge, was made to achieve concrete technological results concerning the management of the process of deep drawing of thin sheets. The main motives lie in the increasing application of new materials with difficult formability [4].

Symbols/Oznake

q	- specific blank holding pressure, MPa - specifični pritisak držača
F_D	- blank hoding force (BHF), N - sila držanja
F_{DC}	- constant BHF, N - konstantna sila držanja
F_{Dt}	- variable BHF as function of time, N - sila držanja u funkciji vremena
F_{Dh}	- variable BHF as function of punch stroke, N - sila držanja u funkciji hoda izvlakača
R_m	- ultimate tensile strength, MPa - vlačna čvrstoća
R_e	- yield stress, MPa - granica razvlačenja
A_{80}	- elongation, at break, % - istezanje pri prekidu
r	- r factor - r faktor
n	- n factor - n faktor
K	- equivalent stress in plastic field, MPa - ekvivalentni napon u plastičnoj oblasti
d, D	- diameter, mm - promjer
r	- radius, mm - polumjer
s	- sheet thickness, mm - debljina lima
A	- area, mm^2 - površina
T	- period of time, s - vremenski period
φ	- natural strain in sheet plane - prirodna deformacija u ravnini lima

Indices/ Indeksi

1	- major principal strain in sheet plane; final value - prva glavna deformacija u ravnini lima; završna vrijednost
2	- minor principal strain in sheet plane - druga glavna deformacija u ravnini lima
3	- thinning strain, third principal strain - stanjenje, treća glavna deformacija
0	- initial value - polazna vrijednost
M	- die - matrica
D	- flange - držač

It turned out that it is very difficult to influence the process during its duration. In fact, it is possible only to influence the friction in the flange in two ways. The first way is through the holding force, and the other is through the default ribs of variable geometry [5]. Various devices have been developed, often very complex and expensive, in order to achieve adaptive control and autonomous operation, regardless of changes in the machining system [6-8]. The connection of this research with the previously mentioned is in the use of variable blank holding force.

In the researches of authors [9-13] there is the effort to analyze the combined effect of the following factors: the regimes of friction, workpiece material, workpiece geometry, changes in the blank holding force, etc., with the realization of single-operation monotonous and two-phase nonmonotonous process of forming. The main aim is finding ways to apply the variable blank holding force, where the control system should be simpler, more accessible and with smaller industrial shops. Simplification of process control requires a detailed preliminary survey of all important influences on the forming process.

The basic scheme of the deep drawing in the tool with rigid elements is given in Figure 1. The process is characterized by a number of characteristics [2-4]: contact pressures are significantly below the yield point, friction is not always and everywhere harmful, there is always the new surface of sheet in contact with the tool, etc.

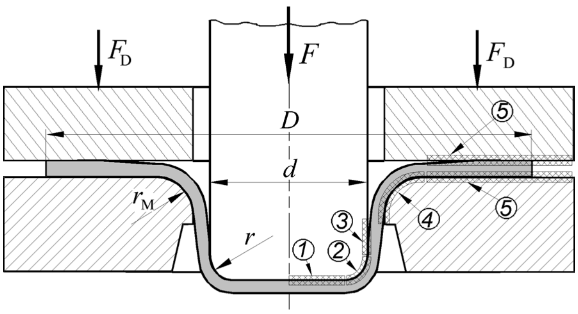


Figure 1. Basic scheme of deep drawing

Slika 1. Osnovna shema dubokog vučenja

In Figure 1, the most important zones of friction are presented. If almost complete elimination of friction in the zone 4 (zone of die radius) were performed, forming force of drawing could be reduced by 20 %. If you add zone 5 to zone 4, the force can reduce up to 50 % [4]. In this paper, a special attention is paid to the flange zone (5), and the conclusion that the contact of flat surfaces is maintained during the process, was adopted.

A contact at the micro-level is the object of many studies [e.g. 4, 14, 15]. It should be emphasized that the real value of macro-contact pressure at the flange area is up to 10 MPa compared to the theoretical value of pressure at the micro-level of more than 300 MPa. The friction regime (for rigid tools) in practice is almost always mixed or boundary.

2. Description of experiment and equipment

The essence of the conducted experiment is the realization of the combined effects of friction factors with the monotonous and nonmonotonous process of plastic forming.

The following factors of friction are varied: two variants of the normal force i.e. the blank holding force (constant and variable intensity during the process) and three regimes of friction (dry, oil use and simultaneous application of oil and foil). The approximate dry friction is realized by detailed cleaning of all contact surfaces with acetone. In the represented results, the mark D (dry) refers to the conditions of dry friction. Another type of friction is achieved by the mineral oil lubrication of the following characteristics: kinematic viscosity at 40 °C 45 mm^2/s, dynamic viscosity 42 mPas and density of 0,93 g/cm3. The oil is abundantly applied on all 4 surfaces of the flange (Figure 1). The mark *O* (oil) is used. The third type of friction is achieved by applying the mentioned oils and polyethylene foil simultaneously, which completely separates the contact surfaces during the process. The mark is *O* + *F* (oil + foil).

Monotonous process implies one operation of forming. The blank cuts from the unformed sheet and then deep drawing is done. Nonmonotonous process is two-phased. In the first phase, the uniaxial tension of sheet stripes (width of 130 mm and nominal length of 500 mm) up to the elongation of 10 % (Figure 2) is performed.

From such a deformed stripe, the blanks for the second phase, i.e. deep drawing, are stamped.

The following factors stay unchanged: forming speed, the conditions of friction in the zones outside of the flange, materials, tools and workpiece geometry. The performed experiments and the equipment used represent a relatively complex system [8-10] and they are shown in quite a small volume.

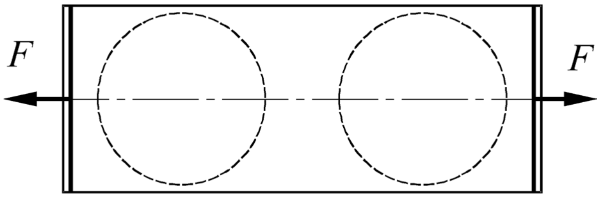


Figure 2. Scheme of uniaxial tension – the first phase of nonmonotonous process

Slika 2. Shema zatezanja – prve faze nemonotonog procesa

The first operation of the forming process - previous uniaxial tension, was carried out on a classical device for mechanical testing (max force of 100 kN) with the appropriate special tool for tightening the wide strip of sheet [8]. The permanent elongation of 10 % was chosen so as not to significantly reduce the formability, but still to be in the field of plasticity.

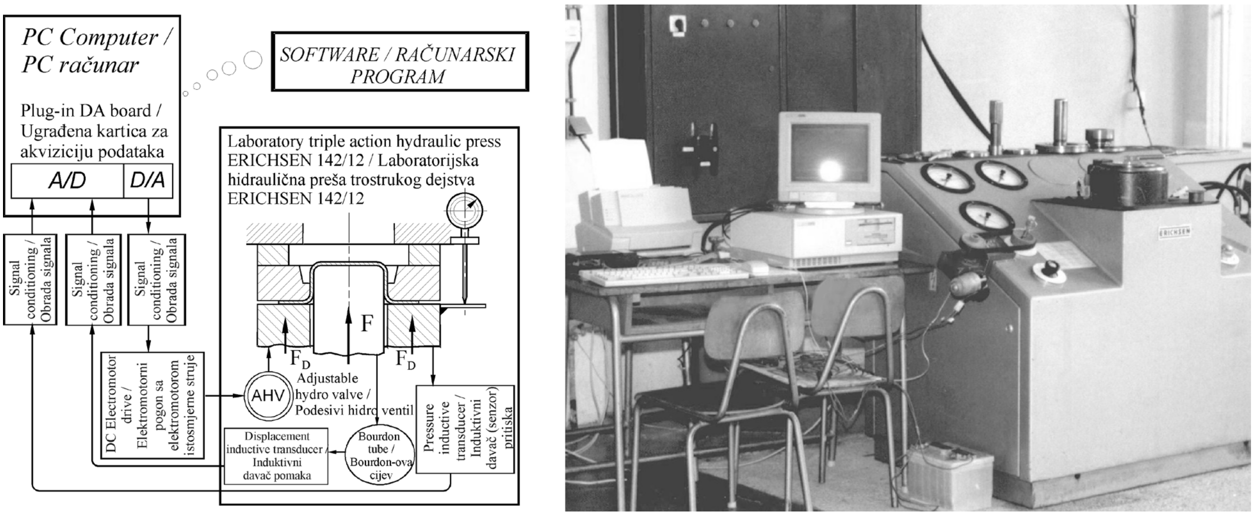
For deep drawing of previously prepared samples, the enhanced laboratory triple action hydraulic press Erichsen 142/12 (Figure 3) was used. The maximum force of the main activity is 130 kN, the maximum blank holding force is 34 kN and the extent of forming speed is 0-250 mm/min. The basic version of the press is improved by the computerized system for data acquisition which enables the following during the process: measuring of forming force, measuring of normal force (blank holding force), control of the blank holding force, i.e. the operation of the variable intensity according to a pre-defined dependence in the analytical form. The drawing was carried out at constant punch speed of 20 mm/min. The wrinkling in the flange was monitored mechanically. Figure 3. shows a block diagram of the most important parts of the control system.

To measure the strains of sheet, the classical method of grid pattern measuring (that includes deposition of circles of the nominal diameter of 3 mm) was used. The depositing of the grid pattern was done by using the electrochemical device Erichsen (power 1,5 kW). The measuring of the deformed grid is carried out optically.

3. Defining the blank holding force

In the preparation of this experiment, it was necessary to define the process of determining the blank holding force (normal force), i.e. contact pressure on the flange.

The intensity of the constant blank holding force is defined based on empirical recommendations. They usually give the value of specific holder pressure (*q*, MPa), depending on the type of material, thickness of sheet, drawing ratio, the dimensions of the blank, etc. The pressure q is multiplied by the initial area of the flange which gives the value of blank holding force. The side effect of the constant blank holding force is the



a) b)

Figure 3. Scheme of experimental equipment (a) and its view (b)

Slika 3. Shema eksperimentalnog uređaja (a) i izgled uređaja (b)

unnecessary large increase of the actual contact pressure on the flange at the end of the process, due to the reduction of the area of the flange. In this specific case, the mean value of several recommendations was adopted and the value $q = 2.046$ MPa [9] was acquired. The blank holding force is obtained by multiplying the pressure q and the initial flange surface. To determine the initial size of the flange, it is necessary to know the appropriate dimensions of the pieces and tools according to Figure 1. Diameter of piece: $d = 50$ mm, die radius : $r_M = 3.5$ mm, diameter of the blank: $D_0 = 110$ mm, sheet thickness: $s_0 = s = 0.8$ mm. The initial flange area:

$$A_{D0} = \frac{D_0^2 - \left(d_M + 2r_M\right)^2}{4}\pi, \text{ mm}^2. \quad (1)$$

Diameter of the die: $d_M \approx d + 2\,s$. The constant holding force is:

$$F_{DC} = q \cdot A_{d0}, \text{ N}. \quad (2)$$

According to mentioned numerical values and expressions 1 and 2, the following is derived: A_{D0} = 6806.3 mm^2 and F_{DC} = 13925.7 N.

The variable blank holding force is defined by the condition of specific pressure constant during the process. This means that the blank holding force is proportional to the area of the flange and it decreases during the process. To simplify control, it is possible to express the change of diameter (Figure 4) and the area of the flange in a function of time.

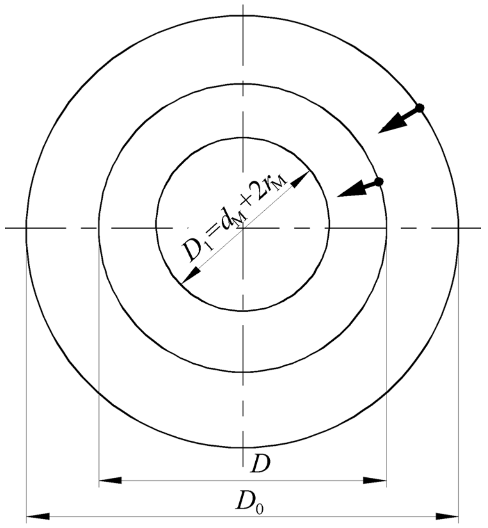


Figure 4. Change of flange area during the process

Slika 4. Promjena površine oboda tijekom procesa

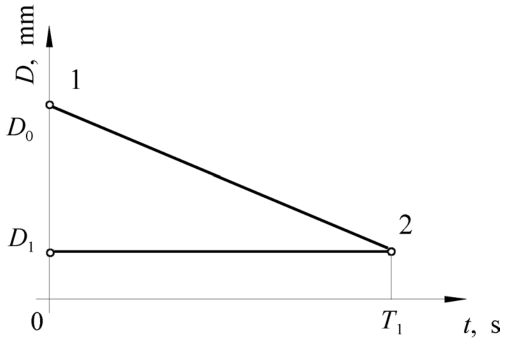


Figure 5. Flange diameter dependence on time

Slika 5. Ovisnost promjera oboda o vremenu

Through the experiment, it was determined that for time $T_1 = 150$ s the initial diameter $D_0 = 110$ mm decreases to $D_1 = 58{,}6$ mm at constant speed of the punch stroke (20 mm/min). Furthermore, linear dependence of the flange diameter on time can also be adopted (according to Figure 5).

According to Figure 5:

$$D = D_0 - \frac{D_0 - D_1}{T_1} t, \text{ mm.} \tag{3}$$

Flange area is:

$$A_D = \frac{\pi}{4}\left(D^2 - \left(d_M + 2r_M\right)^2\right), \text{mm}^2. \tag{4}$$

A_D as a function of time (according to Figures 3 and 4) is given by the following equation:

$$A_D = A_{DP} - \frac{\pi}{2} D_0 \frac{D_0 - D_1}{T_1} t + \frac{\pi}{4}\left(\frac{D_0 - D_1}{T_1}\right)^2 t^2. \tag{5}$$

The function of blank holding force, in accordance with the expression 2, is given as:

$$F_{Dt} = q \cdot A_D, \text{ N.} \tag{6}$$

Based on the actual numerical values, the following is obtained:

$$F_{Dt} = 13925.7 - 121.12 \cdot t + 0.1886 \cdot t^2 \tag{7}$$

In expression 7, time is expressed in *s*.

Sometimes it is useful to express F_{Dt} according to equations 7 in the function of punch stroke. In order to determine the required dependence, a linear relation between the punch stroke and time is adopted (as in Figure 5). The error is negligible if the velocity of punch stroke is constant, and if there is no break of sheet sliding on the flange. Both conditions are practically always fulfilled. The dependence is shown in Figure 6.

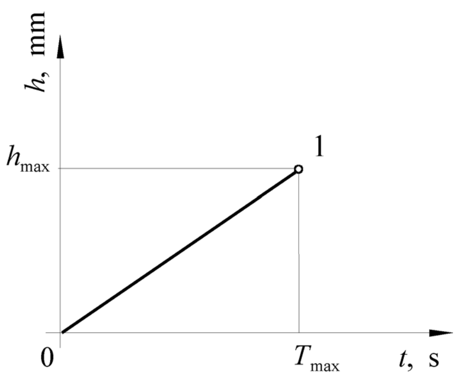


Figure 6. Punch stroke dependence on time

Slika 6. Ovisnost hoda izvlakača o vremenu

In this example, the total depth of pieces, i.e. stroke $h_{max} = 54$ mm is achieved in T_{max}=165 s. According to Figure 6 the following applies:

$$h = \frac{h_{max}}{T_{max}} t, \text{mm.} \tag{8}$$

Application of numeric values:

$h = 0.3273 \cdot t$, mm; and $t = 3.0553 \cdot h$, s; and thus:

$$F_{Dt} = 13925.7 - 370.06\, h + 1.76 \cdot h^2, \text{ N} \tag{9}$$

At $T = 150$ s, i.e. $h \approx 49.1$ mm, $F_{Dt} = F_{Dh} \approx 0$

The graphical representation of functional dependence of the blank holding force on time is given in Figure 7. The constant value of the specific blank holding pressure *q* is also shown.

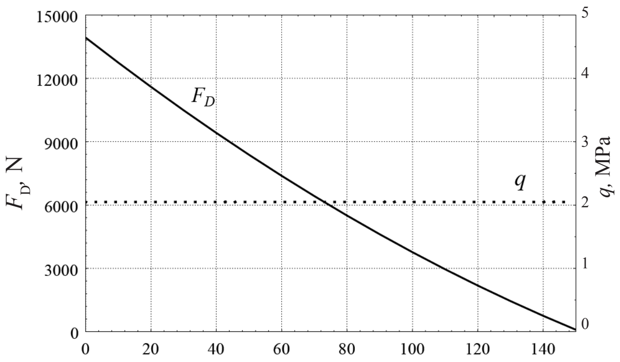


Figure 7. Functional dependence of the blank holding force on time

Slika 7. Ovisnost sile držanja o vremenu

4. Results, analysis and discussion

The material used in this experiment is low-carbon steel sheet with one-side galvanic coating of zinc. The designation according to DIN EN 10152 is DC04 + ZE; mat. No. 1.0338. Thickness is 0.8 mm. The basic mechanical properties and some formability characteristics of the material are shown in Table 1.

All values in Table 1 are given with respect to the planar anisotropy in directions of 0°, 45° and 90° to the rolling direction of sheet. The mean values are given in the last row. The strengthening curves are shown in the form of two exponential approximations.

The effects of three regimes of lubrication, two types of blank holding force and two types of progress of forming process are monitored through the following indicators: forming force of drawing, the distribution of the main surface strains and their relationship to the limit formability curves diagram (forming limit diagram - FLD), the distribution of thinning strain, and change of drawing depth.

The side of sheet with the coating is facing the punch and it remains on the inner surface of the workpiece, which is most often the case in practice.

Table 1. Properties of coated sheet metal DC04+ZE

Tablica 1. Svojstva prevučenog lima DC04+ZE

DC04+ZE − s_o=0,8 mm							
	R_m, MPa	R_p, MPa	R_p/R_m	A_{80}, %	n	r	Strengthening curve approximation / Aproksimacija krivulje ojačanja
0°	304.4	190.0	0.62	36.1	0.245	1.309	K=190+394.4$\varphi^{0.485}$ K=552.9$\varphi^{0.245}$
45°	319.7	205.8	0.644	30.7	0.21	0.98	K=205.8+364.3$\varphi^{0.42}$ K=538.4$\varphi^{0.21}$
90°	303.5	197.5	0.65	34.75	0.22	1.454	K=197.5+355.3$\varphi^{0.445}$ K=520.8$\varphi^{0.22}$
Medium value / Srednja vrijednost	311.8	199.8	0.64	33.1	0.221	1.181	K=199.8+369.5$\varphi^{0.443}$ K=537.6$\varphi^{0.221}$

R_m – ultimate tensile strength, R_e – yield stress, A_{80} – engineering strain, elongation, at break, n- strain hardening exponent, r – coefficient of normal anisotropy (r-factor).

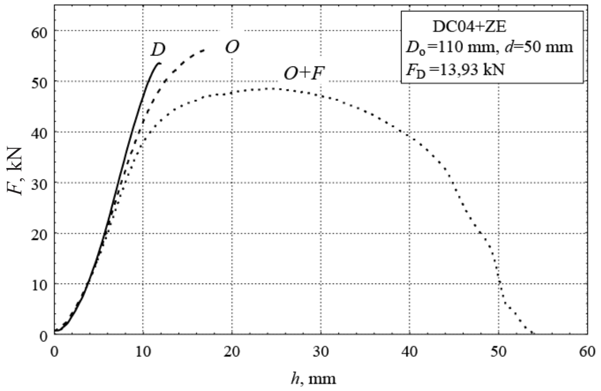


Figure 8. Forming force dependence on stroke at FD=const. and one-phase process

Slika 8. Ovisnost sile izvlačenja o hoda pri FD=const. i jednofaznom procesu

Figure 8 shows that at dry (D) friction, the process has the adverse flow and destruction of pieces takes place at the depth of 13.1 mm. The use of oil (O) leads to an increase in the depth to 17.2 mm. Only with the use of full lubrication (O + F), this intensity of the blank holding force can enable the full depth of the workpiece.

Figure 9 shows very unfavourable distribution of deformations at dry friction. The strains are in the zone of plane deformation state with distinctive thinning, which is clearly illustrated in Figure 10. The deformation field, when using the oil, is more favourable, but thinning and destruction are present in the critical zone. At complete separation of contact surfaces, the influence of the blank holding force was significantly reduced, and with such intensity, the distribution of deformation is acceptable.

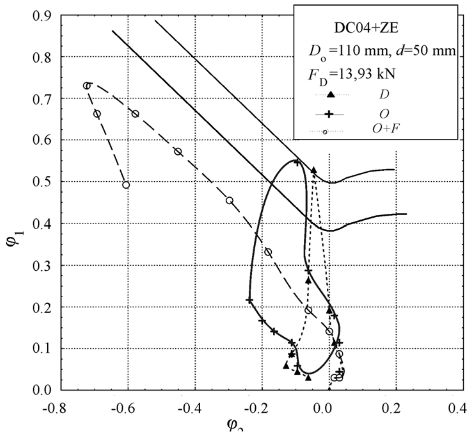


Figure 9. Strain distributions in sheet plane at F_D=const. and one-phase process

Slika 9. Distribucije deformacija u ravnini lima pri F_D=const. i jednofaznom procesu

In Figure 10, the location 1 applies to the bottom centre of piece and locations 8 and 9 correspond to the critical zone above the bottom radius (according to the scheme in Figure 1).

Fig. 11 shows the change of punch force and blank holding force depending on the punch stroke. Gradually decreasing dependence shows what real blank holding force can be acquired by the control system of the experimental device. The dashed line corresponds to the previously defined parabolic function of the blank holding force. DEC designation refers to the decreasing character of the blank holding force.

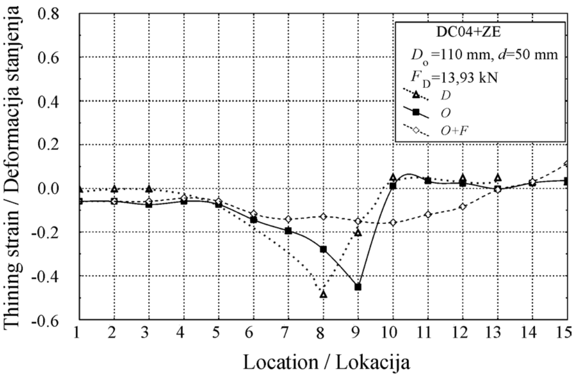


Figure 10. Strain of thickness distributions at F_D=const. and one-phase process

Slika 10. Distribucije deformacije debljine pri F_D=const. i jednofaznom procesu

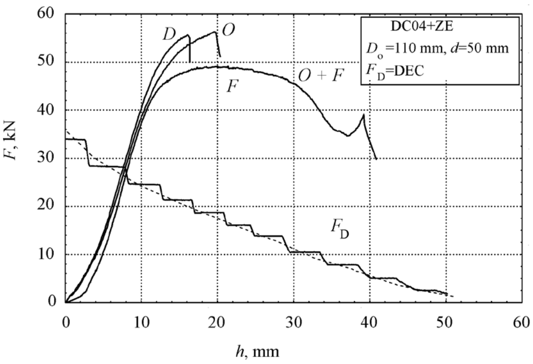


Figure 11. Forming and holding force dependence on punch stroke, F_D≠const., one-phase process

Slika 11. Ovisnosti sile izvlačenja i sile držanja od hoda izvlakača, F_D≠const, jednofazni proces

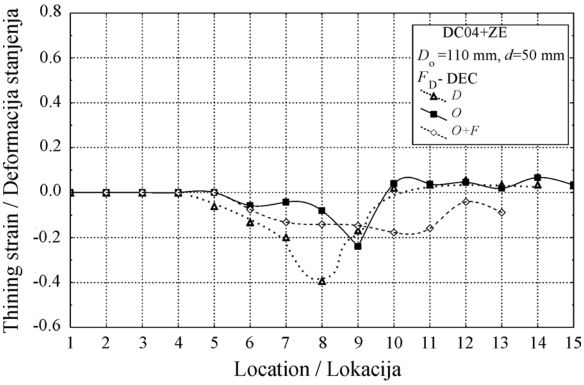


Figure 13. Strain of thickness distributions at F_D≠const., one-phase process

Slika 13. Distribucije deformacije stanjenja pri F_D≠const., jednofazni proces

From Figure 11, it is possible to find out the following drawing depth:

- at dry friction 16.1 mm (increase of 22.9 % compared to Fig. 8),
- with application of oil 19.7 mm (increase of 14.5 %),
- with application of oil and foil at a depth of 34 mm, the wrinkles are registered on the flange and the process is terminated at a depth of 41 mm.

Curves in Figure 12 very illustratively show the real effects of the constant pressure on the holder, i.e. the decreasing blank holding force. The loop distribution at the dry friction and at the oil lubrication is lower compared to the unstable forming zone in FLD. The unloading of the workpiece was achieved, which is resulting in macro effect – increase of the drawing depth. A similar observation applies when thinning strain changes are compared to Figure 10 and Figure 13.

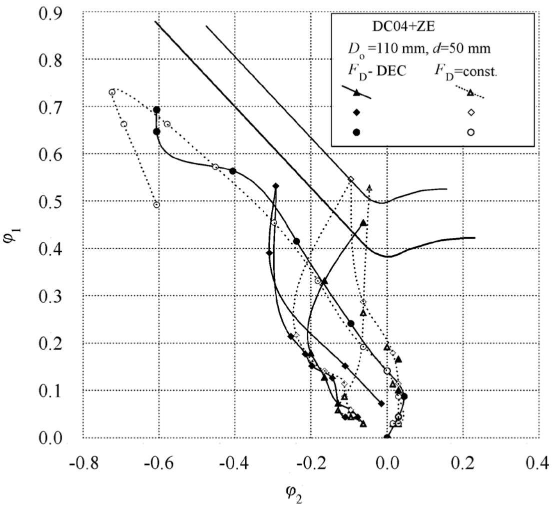


Figure 12. Comparative view of strain distribution at F_D=const. and F_D≠const., one-phase proces

Slika 12. Usporedni prikaz distribucija deformacija pri F_D=const. i F_D≠const., jednofazni proces

Based on the listed values, it can be concluded that the principle of applying the constant pressure on the flange gives good results in conditions of intensified friction. If the friction is very small, the wrinkling in the flange strongly increases and the higher blank holding force is needed for the prevention. In such conditions, there is practically no significant influence of the blank holding force on the punch force and so it is possible to use high-intensity FD without negative consequences.

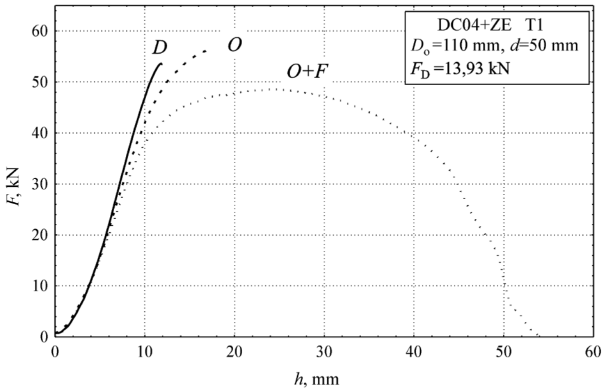


Figure 14. Forming forces at F_D=const., two-phase process

Slika 14. Sile izvlačenja pri F_D=const., dvofazni proces

Figure 14 gives an overview of the punch force depending on the punch stroke at nonmonotonous, two-phase process, which is suggested by the mark *T*1 (uniaxial tension). At increased friction (state *D* and *O*), less drawing depths were achieved (compared to the Figure 8). For dry friction, the depth is 11.7 mm, and for oil lubrication 15.1 mm.

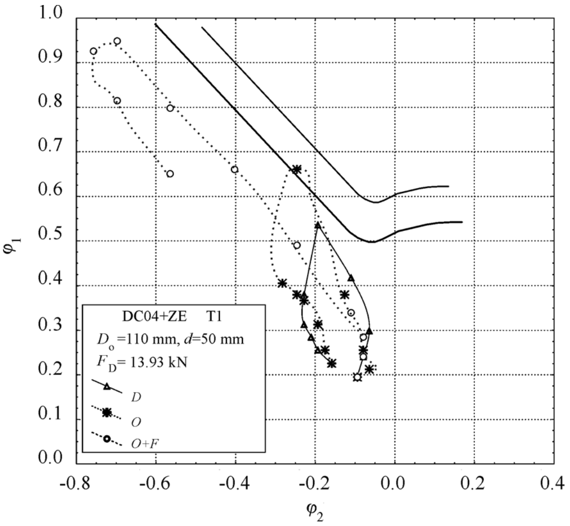


Figure 15. Distributions of strains in sheet plane, F_D=const., two-phase process

Slika 15. Distribucije deformacija u ravnini lima, F_D=const., dvofazni proces

Apparently, the combination of the previous tension and a relatively high intensity of the empirical blank holding force gives an unfavourable course of the process of forming. However, the reduction of friction in a contact condition of $O + F$, almost completely eliminates the side effects of both influences. The small wrinkles appear at the end of punch stroke but the process is successfully finished.

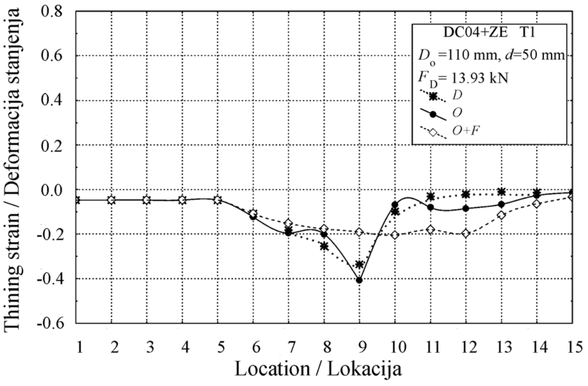


Figure 16. Strain of thickness distributions, F_D=const., two-phase process

Slika 16. Distribucije deformacije stanjenja, F_D=const., dvofazni proces

These observations confirm the distributions of strains which are shown in Figures 15 and 16. In this case, there is enhanced material sensitivity to thinning and destruction. Although the maximum deformations (as in Figure 15) are in the lower part of the unstable forming zone between the limiting curves FLD, the destruction still occurs.

The final part of the experiment includes the application of decreasing blank holding force in the two-phase nonmonotonous process. The two contact conditions with excessive friction (*D* and *O*) were used. The full lubrication is not applied, because it was clearly shown that there is practically no influence of the blank holding force under these conditions. The higher intensity of F_D is required in order to safely prevent the appearance of wrinkles.

The results of Figure 17 can be compared with Figures 11 and 14. Compared to Figure 14, the difference is the application of decreasing dependency F_D. The achieved depth for dry friction is 12.4 mm (11.7 mm in Figure 14). For oil application, the depth is 13.7 mm (15.1 mm in Figure 14). It is evident that in the realized two-phase process, the beneficial effect of the variable force remains only at expressed friction (*D*). Even in the conditions of mixed friction (*O*), the favourable effects disappear. Previous deformation creates the increased sensitivity of materials and decrease of deformability.

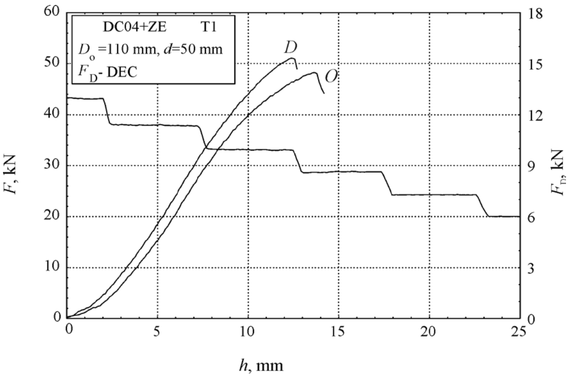


Figure 17. Forming forces at F_D≠const., two-phase process

Slika 17. Sile izvlačenja pri F_D≠const., dvofazni proces

Compared to Figure 11, the difference is the application of previous deformation. Smaller drawing depths are evident, which shows an adverse effect of tensions in the first phase.

Figure 18 provides an interesting view of the distributions of main deformations in the sheet plane. The maximum values of both distributions are practically under the curve of the beginning of unstable deformation, and there is a critical sheet thinning and destruction. This phenomenon confirms the increased material sensitivity to thinning as a result of the first phase of forming. The negative effect was not diminished by the decreasing blank holding force. The relation between the limiting curves FLD and the distribution curves (as in this case), imposes caution in the choice of methodology to determine the FLD.

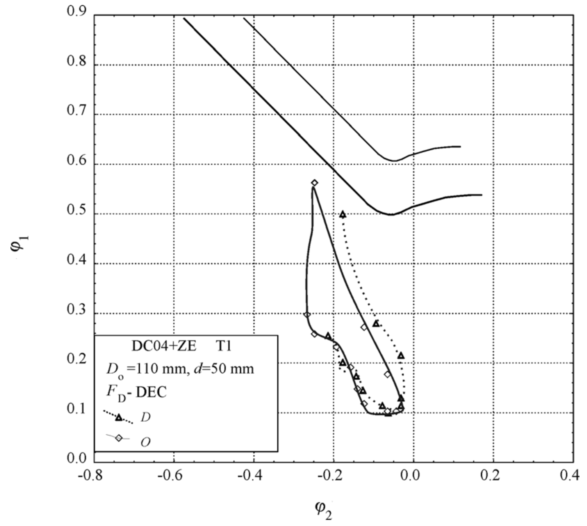


Figure 18. Strain distributions in sheet plane, $F_D \neq$const., two-phase process

Slika 18. Distribucije deformacija u ravnini lima, $F_D \neq$const., dvofazni proces

5. Conclusions

After the realized experimental research, the systematization and the analysis of results, it is possible to make the following conclusions.

The blank holding force, as an important parameter, shows a significant influence on the process only in conditions of intensified friction. The biggest influence is in the extreme case of dry friction. The influence is clear also in the conditions of mixed friction. In the extreme case of reduced friction by complete separation of the contact surfaces with lubricant and foil, the blank holding force has practically no influence, except that greater intensity should be used in order to prevent increased tendency to appearance of wrinkles.

In conditions of a single-phase, monotonous process of forming, the beneficial effect of the decreasing blank holding force (according to the principle of constant blank holding pressure throughout the process) has been proven. There comes to a certain unloading of the workpiece. Strain distributions are better and formability is higher. This results in greater drawing depths.

The two-phase, nonmonotonous process brings essential changes. Previous uniaxial tension increases sheet anisotropy. It is known that a deep drawing formability is very dependent on sheet anisotropy in the direction of sheet thickness, which increases the tendency to sheet thinning. The experiment results illustrate the mentioned adverse effects.

The effect of the decreasing blank holding force in terms of the two-phase process showed favourable effects at the increased friction, but these effects are not dominant. The previous deformation leads to difficult forming conditions that could be partially reduced with the variable blank holding force.

The process of deep drawing of cylindrical pieces greatly depends on the properties of the sheet anisotropy. With the process of nonmonotonous deformation, these properties deteriorate, which is clearly shown in the results. It is possible to expect different effects with pieces with different geometry, especially box type and asymmetric forms.

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