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Analize kakovosti pridrževanja pločevine pri globokem vleku

Analysing the Quality of Sheet-Metal Holding during Deep Drawing

Tomaž Pepelnjak - Zlatko Kampuš

Preoblikovalni postopki postajajo zaradi zapletenosti izdelkov iz dneva v dan zahtevnejši. Pridrževanje pri globokem vleku se zaradi tega vedno bolj prilagaja poteku preoblikovalnega postopka, za kar se uporabljajo različni optimizacijski prijemi. V prispevku so predstavljeni sodobni načini optimizacije pridrževanja s poudarkom na časovni optimizaciji sile držala, elastičnih in segmentnih pridrževalih.

(Ključne besede: globoki vlek, pridrževanje pločevine, optimiranje, metode končnih elementov (MKE), simuliranje)

Due to the increasing complexity of products, forming procedures are becoming ever more demanding. As a consequence, the holding procedure is becoming better adapted to the forming process through the use of various optimisation concepts. This paper presents the modern methods for the optimisation of holding, with an emphasis on the temporary optimisation of the blankholder force and the use of elastic and segmented blankholders.

(Keywords: deep drawing, sheet metal holding, optimisation, final elements methods (FEM), simulations)

0 UVOD

Pri globokem vleku se pojavlja natezno-tlačno napetostno stanje, ki ob neustreznih preoblikovalnih pogojih povzroča gubanje pločevine. V izogib gubanju pločevine se pri globokem vleku, pri katerem je relativni premer pestiča d_p/s_0 večji od 30, pločevina pridržuje z držalom. Slednje prepreči gubanje preoblikovanca v prirobnici. Sila, potrebna za pridrževanje pločevine, se običajno določa za sam začetek vleka, pri čemer se najpogosteje uporablja Sieblov obrazec [1]:

0 INTRODUCTION

Deep drawing causes a stress-strain state in the workpiece that results in the wrinkling of the sheet metal if the forming conditions are not right. In order to avoid this wrinkling the sheet metal is held with a blankholder if the relative punch diameter d_p/s_0 is greater than 30 to prevent wrinkling in the flange. The required blankholder force is usually determined for the initial stage of deep drawing by the use of Siebel's formula [1]:

$$F_{\mathrm{d}} = A_{\mathrm{d}} \cdot p_{\mathrm{d}} \;,\; p_{\mathrm{d}} = \frac{R_m}{400}\left[\left(\beta_0 - 1\right)^3 + \frac{d_{\mathrm{p}}}{200 \cdot s_0}\right] \qquad (1).$$

Enačba popisuje vplive vlečnega razmerja in geometrijske oblike orodja ter natezno trdnost materiala vlečenca. Sila držala se računa za sam pričetek vleka, vendar so raziskave pokazale, da je tako izračunana pridrževalna sila prevelika za celoten potek preoblikovalnega postopka. Silo pridrževala lahko zato med vlekom tudi zmanjšujemo. Sodobni načini preoblikovanja pločevine se nagibajo k optimiranju preoblikovalnega postopka ([2] do [5]). S tem se povečuje tehnološka varnost, zmanjšujejo

The above equation describes the influences of the drawing ratio and the tool geometry as well as the tensile strength of the workpiece material. The blankholder force is calculated for the initial stage of deep drawing, however, research has shown that this results in forces which are too large for the later stages of the forming procedure. As a result, the blankholder force can be reduced during deep drawing. Modern concepts of sheet-metal forming include: optimisation of the forming procedure ([2] to [5]), which results in increased preoblikovalne sile in povečujejo dosegljiva vlečna razmerja. Za boljši nadzor preoblikovalnega procesa so v zadnjih letih razvili različne nove pridrževalne sisteme stiskalnic, s katerimi lahko krajevno in časovno spreminjajo silo pridrževanja med samim globokim vlekom. Preskusi in numerična računalniška simuliranja so pokazali, da sile pridrževala ne smemo preveč zmanjšati, sicer se tudi pri najmanjši prirobnici lahko pojavijo gube [6].

V članku predstavljamo numerične simulacije optimizacije pridrževanja pločevine. Za preprečevanje prevelikih lokalnih tlakov pridrževala smo poudarek optimizacije usmerili na krajevno in časovno prilagajanje pridrževanja s segmentiranimi pridrževali.

1 OPTIMIRANJE PRIDRŽEVANJA PLOČEVINE

Pri globokem vleku neokroglih preoblikovancev se natezno-tlačno napetostno stanje pojavlja samo na nekaterih odsekih vlečenca, drugje pa se lahko pojavlja npr. le upogibanje preko polmera matrice. Zaradi neenakomernega napetostnega stanja spreminjanje debeline preoblikovanca po obodu ni več nespremenljivo. Prav tako dobimo neenakomerne hitrosti gibanja materiala med samim preoblikovanjem. Posledica omenjenih nesimetričnosti so hitrejše gibanje pločevine na ravnih delih vlečenca ter počasnejše na vlečenih vogalih. Nadzor preoblikovalnega procesa z običajnim pridrževalom je v takem primeru zaradi neenakomerne debeline vlečene prirobnice preoblikovanca zelo zapleten.

Raziskave so pokazale [4], da lahko dvojno delujoče mehanske stiskalnice uspešno zamenjujemo z enojno delujočimi sitskalnicami z ustreznim računalniško številsko krmiljenim (CNC) zadrževalnim sistemom. Sodobni zadrževalni sistemi, ki se običajno uporabljajo, delujejo v veliki večini po dveh načelih:
– z elastičnimi pridrževali,
– s segmentiranimi pridrževali.

Zamenjava pridrževalne blazine s štiritočkovnim pridrževalnim sistemom za velika preoblikovalna orodja je bil prvi korak k izboljševanju nadzora pridrževanja zahtevnih vlekov v avtomobilski industriji. Rezultati kažejo pri pridrževanju z več medsebojno neodvisnimi hidravličnimi valji kakovostnejše preoblikovanje kakor v primeru običajne uporabe dvojno delujoče stiskalnice [4]. S povečevanjem števila hidravličnih valjev se lahko predvsem pri orodjih z osnovno ploščo večjo od 1000x1000 mm poveča nadzor nad potekom pridrževanja, pri čemer je število uporabljenih valjev odvisno od konstrukcije preoblikovalnega orodja in same stiskalnice [4].

Izkušnje na področju optimizacije pridrževanja srečamo tudi v slovenski industriji preoblikovalnih strojev, kjer podjetje Litostroj I.E. že nekaj časa vgrajuje za optimizacijo pridrževanja večtočkovne pridrževalne sisteme v svoje hidravlične stiskalnice [7]. Posebnost teh sistemov je pridrževalni

technological safety, reduced forming forces; and increased attainable drawing ratios. For better control of the forming process various new holding systems for presses have been developed in recent years that enable the spatial and temporary variation of the blankholder force during deep drawing. Experiments and numerical computer simulations have shown that the blankholder force should not be reduced excessively, or wrinkles will appear even for a minimal flange [6].

This paper presents a numerical analysis of the holding optimisation where the emphasis was given to the spatial and time adaptation of the blank holding with segmented blankholders in order to prevent the holding pressures being to high on particular segments.

1 OPTIMISATION OF SHEET-METAL HOLDING

When deep drawing noncircular workpieces, the stress-strain state only appears in certain workpiece parts, while others may only be bent over the die radius. Due to the nonuniform stress-strain state, the variation in workpiece thickness along its circumference is no longer constant. In addition, parts of the material move at a nonuniform speed during forming. These asymmetric conditions result in the faster movement of sheet metal in the straight parts of the workpiece and slower movement on the drawn edges. Due to the nonuniform thickness of the drawn workpiece flange, the control of the forming process with a conventional blankholder is very complex.

Research has shown [4] that double-stroke mechanical presses can be successfully replaced with single-stroke presses by using an appropriate computer numerically controlled (CNC) holding system. The commonly used modern holding systems are mainly based on two principles:
– with elastic blankholders,
– with segmented blankholders.

The replacement of the holding cushion with a four-point holding system for large forming tools was the first step towards improving the holding control for demanding deep-drawing processes in the automotive industry. By using several independent holding cushions better quality forming than that obtained with conventional double-stroke presses has been obtained [4]. With an increase in the number of hydraulic cylinders, control over the course of the holding can be improved, primarily in tools with a base plate greater than 1000 x 1000 mm where the number of cushions used depends on the design of the forming tool and the press [4].

Experience with the optimisation of holding can also be found in the Slovenian forming-machines industry. For some time now, Litostroj I.E. has been using multipoint blankholder systems in its hydraulic presses in order to optimise sheet-metal holding [7]. A special feature of these systems is that they sistem, ki je izveden v pehalu stiskalnice. Ker se omenjene stiskalnice uporabljajo predvsem kot transfer stiskalnice, je pomembna tudi izvedba strege izdelkov med stiskalnicami [8].

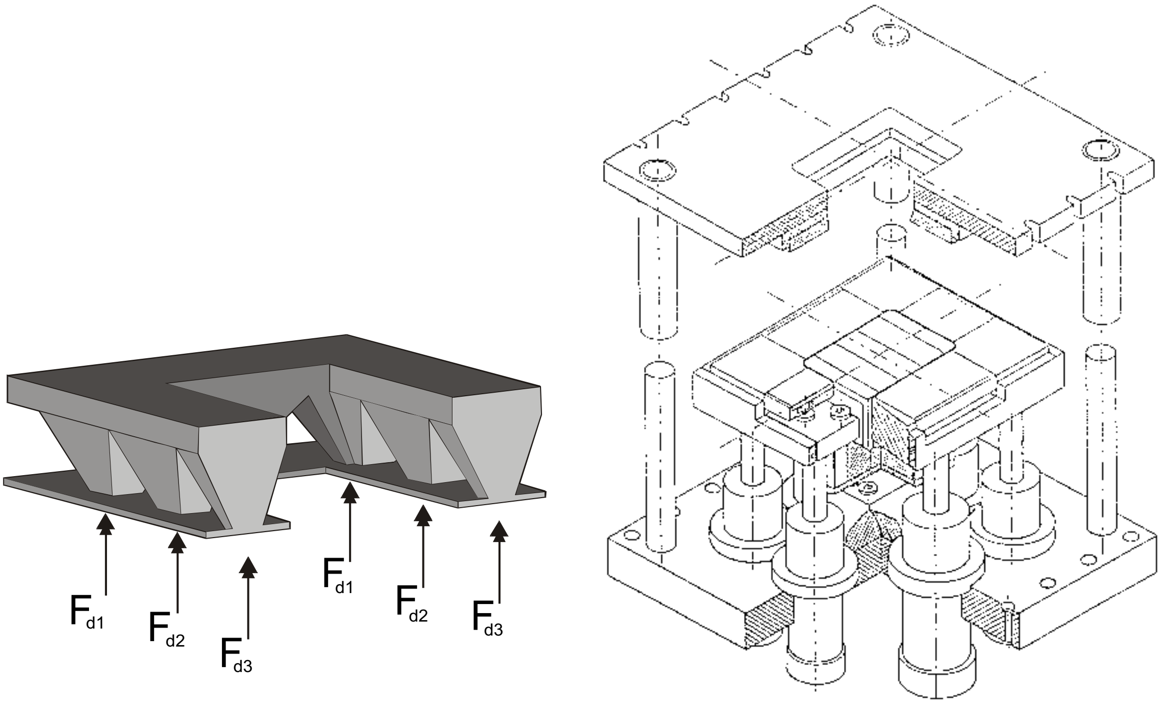
Vsi našteti sistemi optimiranega pridrževanja temeljijo na osnutku elastičnega prilagajanja pridrževala površini pločevine, ki je večje od elastičnih deformacij običajnih pridrževalnih plošč (sl.1). Konstrukcijsko se problematika povečevanja elastičnosti pridrževala rešuje s posebnimi oblikami pridrževalnih plošč [4]. Za vse doslej naštete pridrževalne sisteme uporabljamo specializirane prirejene stiskalnice z zahtevnim nadzorom preoblikovalnega postopka.

V primeru preoblikovanja krojenih prirezov različnih debelin žal tudi s povečano elastičnostjo pridrževala ne moremo kakovostno pridrževati geometrijsko zapletenih preoblikovancev. Za optimizacijo pridrževanja krojenih prirezov so se zaradi tega razvila posebna segmentirana pridrževala, pri katerih različne debeline krojenega prireza pridržujemo z medsebojno ločenimi segmenti [2]. Optimizacija pridrževanja v tem primeru ni izvedena v samem stroju preko posebnih pridrževalnih sistemov, temveč kar v samem orodju (sl. 1). Posamezne segmente krmilimo s plinskimi vzmetmi. Tako lahko segmente obremenjujemo medsebojno popolnoma neodvisno. Takšen način pridrževanja omogoča tudi pridrževanje z lokalno popolnoma različnimi silami pridrževanja, kar je najbolj uporabno predvsem pri preoblikovanju krojenih prirezov. S segmentiranimi pridrževali je mogoče zelo učinkovito

are integrated in the press ram. Since these presses are primarily used as transfer presses, the handling of products between the presses is also important [8].

All of the above-mentioned systems for optimised holding are based on the concept of elastic adjustment of the blankholder in relation to the surface of the sheet metal, which is greater than the elastic deformations of conventional holding plates (Figure 1). In terms of design, the problem of increasing the elasticity of the holder is solved with the use of specially shaped holding plates [4]. All of the above holding systems require specialised presses with complex control of the forming process.

When forming tailored blanks of various thicknesses, however, even elastic blankholders cannot ensure high-quality holding of workpieces with complex geometry. In order to optimise the holding of tailored blanks, special segmented holders have been developed with different thicknesses of tailored blanks held with separate holder segments [2]. In this case, the optimisation of holding is not performed in the machine with the use of special holding systems, but in the tool itself (Figure 1). Individual segments are controlled with the use of gas springs, which load each individual workpiece segment independently of the others. This method also enables holding with locally different blankholder forces, which is most useful in the forming of tailored blanks. Segmented blankholders very effectively solve the problem of



Sl. 1. *Pridrževalna plošča s povečano elastičnostjo [4] (levo) in orodje s segmentiranim pridrževalom [2] (desno)*

Fig. 1. *Holding plate of increased elasticity [4] (left) and tool with a segmented blankholder [2] (right)*

reševati tudi problematiko naleganja pridrževala na različno debele dele pridrževane prirobnice preoblikovanca, ki nastanejo zaradi preoblikovalnega postopka ali uporabljane platine (npr. krojenega prireza).

Pomanjkljivost orodij s segmentiranimi pridrževali je njihova zelo visoka cena, ki je odvisna od vgrajenih plinskih vzmeti in tlačnih sistemov za zagotavljanje pridrževalnih sil. S tega vidika je zamisel izvedbe povečane elastičnosti pridrževanja že v sami stiskalnici boljša, saj omogoča prilagodljivost pridrževanj za vsa uporabljana orodja brez dodatnih osnutkov optimizacije pridrževanja v samem orodju.

2 OPTIMIRANJE PRIDRŽEVANJA GLOBOKEGA VLEKA KORITA

Iz pregleda raziskav optimizacij pridrževanja v svetu smo prišli do sklepov, da je smiselno analizirati kombinacijo sistema elastičnih in segmentiranih pridrževal. Za primerjavo rezultatov optimizacijskih strategij z ostalimi avtorji ([2] do [6]) smo analizirali sile pridrževanja za konvencionalno in segmentirano pridrževalo. Glavni cilj pri tem je bil določitev sistema za časovno in krajevno optimizacijo pridrževanja s segmentiranim pridrževalom.

Analizirali smo tri različne zasnove pridrževalnih konceptov na primeru globokega vleka korita:

- običajno pridrževanje z nespremenljivo pridrževalno silo,
- običajno pridrževanje s spreminjanjem pridrževalne sile,
- pridrževanje s segmentiranim pridrževalom.

Izdelek je bil izbran v sodelovanju s podjetjem Litostroj E.I., ki je tehnologijo preoblikovanja podobnega izdelka s transfer stiskalnicami že uporabilo za naročnika v tujini [7]. Za testni izdelek smo izbrali pločevinastemu koritu podoben izdelek (sl. 2) z izmerami 400x400 mm, s polmeri zaokrožitve 80 mm na vogalih in 45 mm na dnu korita. Material testnega izdelka je nerjavno jeklo, katerega materialne lastnosti, potrebne za simuliranje z MKE, so zbrane v preglednici 1.

Uporabljani program za simuliranje preoblikovanja pločevine računa s togimi lupinskimi elementi orodja ([9] do [12]), zaradi česar smo za izračune elastičnega pridrževanja najprej analizirali segmentirano pridrževanje. Izračuni potrebnih pridrževalnih sil segmentiranega pridrževala in

fitting the blankholder to the held workpiece flange parts of various thicknesses resulting from the forming procedure or the used blank (e.g. tailored blank).

The disadvantage of tools with segmented blankholders is that they are very expensive because they contain gas springs and a pressure system which provides the blankholder forces. For this reason, the idea of increasing the elasticity of holding in the press is better, since it enables holding to be adapted for all the used tools without additional optimisation of holding in the tool.

2 OPTIMISATION OF HOLDING IN THE DEEP DRAWING OF SINKS

After reviewing the present situation with regard to blankholder optimisation, we can conclude that it is reasonable to analyse a holding system consisting of a combination of elastic and segmented blankholders. To compare the results of the optimisation strategies for holding force to the research work from other authors ([2] to [6]), the variable blankholder forces have been analysed for conventional and segmented blankholders. The main objective was to determine the system for the spatial and time optimisation of the segmented holding of the blank.

Three different holding concepts used for deep drawing a metal sink were analysed:

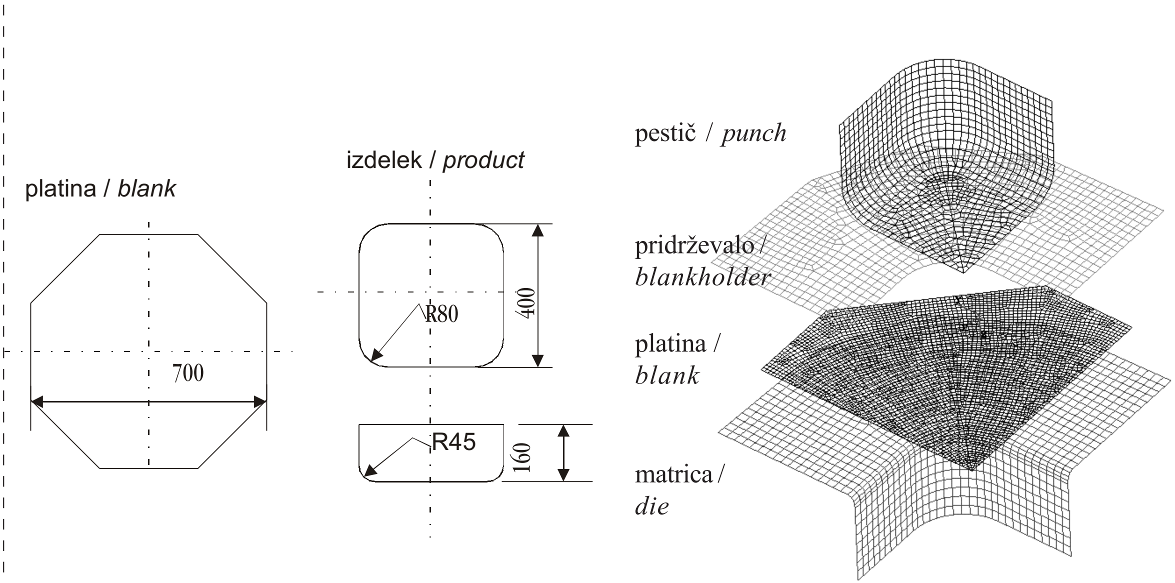
- conventional holding with constant blankholder force,
- conventional holding with varying blankholder force,
- holding with segmented blankholder.

The product was selected in cooperation with Litostroj E.I., which has used this technology for forming a similar product with transfer presses for a foreign client [7]. A product similar to a sheet-metal sink was chosen for testing (Figure 2) with dimensions 400 x 400 mm, rounding radius 80 mm on edges and 45 mm at sink bottom. The material chosen for the test product was stainless steel. Its characteristics, which were used in the FEM simulations, are presented in Table 1.

The program used for the simulation of the sheet-metal forming involves rigid-shell tool elements ([9] to [12]), and so the segmented holding was analysed first for the calculations of elastic holding. The calculation of the required blankholder forces for a segmented blankholder and the thicknesses of the held flange in

Preglednica 1. *Materialne lastnosti analizirane nerjavne pločevine*
Table 1. *Material characteristics of the analysed stainless- steel sheet metal*

C MPa	1345	E MPa	210000	r_0 1	0,9
n 1	0,376	ν [1]	0,3	r_{45} 1	1,41
R_p MPa	300	ρ kg/m^3	7800	r_{90} 1	1,005
R_m MPa	640	s_0 mm	0,7		



Predprocesor / *Preprocessor*	CAD: I-Deas
Simulacija / *Simulation*	Pam-Stamp
Pregledovalnik / *Postprocessor*	Pam-View

ŠTEVILO ELEMENTOV / *NUMBER OF ELEMENTS*:	
Pestič / *Punch*:	836
Pridrževalo / *Blankholder*:	925
Matrica / *Die*:	1292
Platina / *Blank*:	3568

ROBNI POGOJI / *BOUNDARY CONDITIONS*:
simetrija v X osi / *symmetry X-axis*
simetrija v Y osi / *symmetry Y-axis*

TRENJE / *FRICTION*: COULOMBOV ZAKON / *COULOMB LAW*
Petsič - platina / *Punch-Blank*: $\mu = 0,1$
Pridrževalo - platina / *Blankholder-Blank*: $\mu = 0,1$
Matrica - platina / *Die-Blank*: $\mu = 0,1$

HITROST PESTIČA / *PUNCH SPEED*:
v_p = 7500 mm/s

Sl. 2. *Geometrijska oblika testnega izdelka in plošče (levo) in model za simuliranje z MKE (desno)*
Fig. 2. *Geometry of the test product and blank (left) and FEM simulation model (right)*

debeline pridrževane prirobnice v analiziranih časovnih korakih so pomenili vhodne podatke za analize elastičnega obnašanja pridrževala in preračune izmer elastične pridrževalne plošče ([7] in [13]).

2.1 Model globokega vleka na osnovi MKE z običajnim držalom

Simuliranja globokega vleka smo izvajali s programom Pam-Stamp® [9]. Program je prirejen za preoblikovanje pločevine in računa po eksplicitni numerični metodi z lupinskimi elementi.

RPK (CAD) model plošče in orodja ter mrežo MKE (vozlišča in elemente) smo pripravili v programu I-DEAS, pri čemer smo upoštevali osno simetričnost modela in analizirali le 1/4 celotnega modela. V predprocesorju Pam-Stamp-a smo modelu po MKE dodali podatke o materialu, robnih pogojih, pogojih trenja med orodjem in ploščo in preostale za simuliranje potrebne podatke (sl. 2). Pločevina je bila popisana z

the analysed time intervals were used as the input data for the analyses of the elastic behaviour of the blankholder and the calculations of the dimensions of the elastic holding plate ([7] and [13]).

2.1 FEM model of deep drawing with a conventional blankholder

The simulations of the deep drawing were performed using the Pam-Stamp® program [9]. This is a specialised program for sheet-metal forming which uses an explicit numerical method and shell elements.

A CAD model of the blank, the tool and the FEM mesh (nodes and elements) were prepared in the I-DEAS program. Since the model is axisymmetric, only one quarter of the model was analysed. Data on the material, the boundary conditions and the friction conditions between the tool and the blank, as well as other data required for the simulations were added to the FEM model using the Pam-Stamp pre-processor (see

Preglednica 2. *Analizirani načini pridrževanja in pojavi okvar preoblikovanca*
Table 2. *Analysed holding methods and defects on the workpiece*

Način pridrževanja *Holding*	Spreminjanje sile *Variation of the force*	Kakovost preoblikovanja in izbrani odločitveni kriterij *Quality of forming and the selected criterion*
$F_d = F_{d,sie}$ (po Sieblu /*due to Siebel*)	nespremenjeno *unchanged*	v redu (KMD, gube, F_p, tanjšanje) *good (FLC, wrinkles, F_p, thinning)*
$F_d = 1{,}5\ F_{d,sie}$	nespremenjeno *unchanged*	v redu (KMD, gube) slabše (F_p, tanjšanje) *good (FLC, wrinkles)* *worse (F_p, thinning)*
$F_d = 2\ F_{d,sie}$	nespremenjeno *unchanged*	slabo - trganje (KMD) *bad - tearing (FLC)*
$F_d = 0{,}75\ F_{d,sie}$	nespremenjeno *unchanged*	boljše (KMD, gube, F_p, tanjšanje) *better (FLC, wrinkles, F_p, thinning)*
$F_d = 0{,}5\ F_{d,sie}$	nespremenjeno *unchanged*	slabo - gubanje (pomiki prirobnice) v redu (F_p, tanjšanje) *bad - wrinkles (flange displacements)* *good (F_p, thinning)*
$F_d = 1{,}5\ F_{d,sie} \searrow F_{d,sie} \nearrow 1{,}5\ F_{d,sie}$	pada - raste *decreases-increases*	v redu (KMD, gube, F_p) boljše (tanjšanje) *good (FLC, wrinkles, F_p)* *better (thinning)*
$F_d = F_{d,sie} \searrow 0$ N	pada *decreases*	boljše (KMD, gube, F_p, tanjšanje) *better (FLC, wrinkles F_p, thinning)*
Opomba: $F_{d,sie}$ je pridrževalna sila, izračunana po Sieblovem obrazcu. Kakovost preoblikovalnega postopka smo vrednotili glede na referenčen vlek s silo pridrževanja $F_d = F_{d,sie}$. *Note:* *$F_{d,sie}$ is the blankholder force calculated according to Siebel's formula. The quality of forming has been evaluated according to the reference blankholder force of $F_d = F_{d,sie}$.*		

elasto-plastičnim zakonom, orodje pa je bilo togo. V elastičnem področju velja Hookov zakon (popis z E, ν) ter Holomonov zakon utrjevanja v plastičnem področju.

V prvi fazi raziskav smo analize preoblikovanja najprej naredili z običajnim pridrževalom z različnimi velikostmi pridrževalnih sil. Nespremenljiva sila pridrževala $F_{d,sie}$, izračunana po Sieblovem obrazcu, pomeni referenčno vrednost, s katero smo primerjali različne načine pridrževanja - preglednica 2. Rezultate simuliranj po MKE preoblikovanja korita smo vrednotili s kriteriji:

- velikost preoblikovalne sile;
- tanjšanje materiala, ki ne sme preseči 20 % debeline pločevine;
- diagram krivulj mejnih deformacij (KMD) iz katerega preberemo pojave lokalnih tanjšanj in trganja materiala;
- pomiki vozlišč v smeri *'z'*, s katerimi vrednotimo gubanje ravne površine (prirobnice).

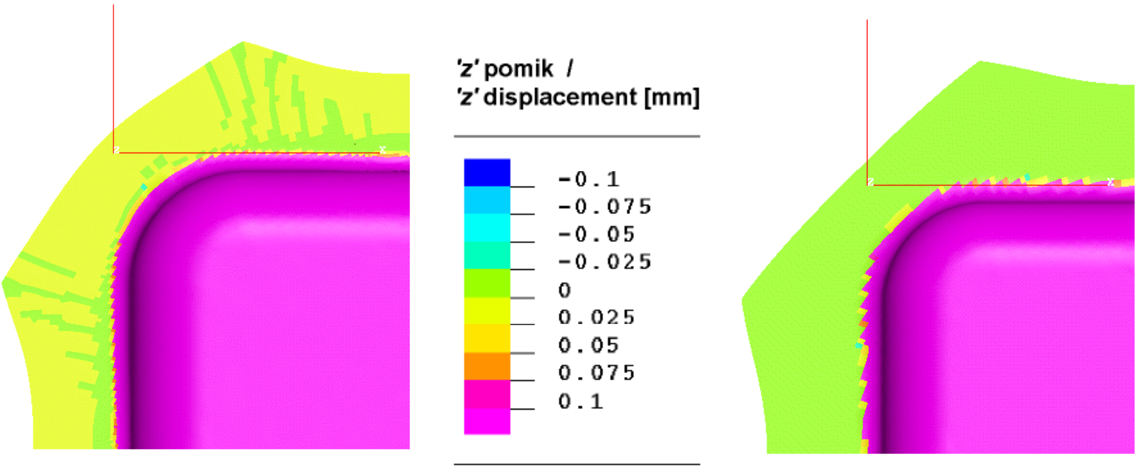
Za najuspešnejše vrednotenje gubanja prirobnice preoblikovanca se je izkazalo določevanje pomikov pridrževane prirobnice v smeri *'z'*. Za kriterij smo vzeli Δz=0,05 mm, znotraj katerega smo lahko zelo dobro določili mejo velikosti sile pridrževanja,

Figure 2). Sheet metal is described using the law of elasto-plasticity and the tool is rigid. Hook's law applies in the elastic zone (description with E and ν) and Holomon's law of hardening in the plastic zone.

In the first phase of the research work, the analyses of forming were performed with a conventional blankholder using different magnitudes of the blankholder force. A constant blankholder force $F_{d,sie}$ calculated according to Siebel's formula was used as a reference value for the comparison of the different holding methods (Table 2). The results of the FEM simulations of forming the sink were evaluated using the following criteria:

- magnitude of the forming force;
- thinning of the material, which must not exceed 20% of the sheet-metal thickness;
- diagrams of the forming limit curves (FLC), in which localisation and tearing of the material can be seen;
- displacements in the *'z'* axis, which are used to evaluate the wrinkling of the flat surfaces (flange).

The determination of the displacements of the held flange in the *'z'* axis proved to be the most successful method for the evaluation of the wrinkling of the workpiece flange. Δz=0.05 mm was taken as a criterion, and within this interval it was possible



$F_d = 0{,}50\,F_{d,sie}$ $F_d = 0{,}75\,F_{d,sie}$

Sl. 3. *Napoved gubanja prirobnice*
Fig. 3. *Prediction of flange wrinkling*

pri kateri se je material pričel gubati. Slika 3 prikazuje analizo gubanja prirobnice pri dveh različnih silah pridrževanja.

Primerjave simuliranj običajnega pridrževanja s togim držalom so pokazale, da dajejo spreminjajoče (padajoče - naraščajoče) sile pridrževanja boljše rezultate kakor pridrževanje z enako veliko nespremenljivo silo. Tudi vlečna sila na pestiču je zaradi tega manjša, s čimer se zmanjša tudi potrebna energija za globoki vlek. To je pomembno predvsem pri izdelkih z velikimi površinami, pri katerih pridrževalna sila pomeni pomemben delež celotne preoblikovalne sile. Kljub zelo velikim tlakom na pridrževani preoblikovanec proti koncu globokega vleka se izkaže, da sile ne smemo preveč zmanjšati (npr. na vrednost $F_d = 10\,\%\,F_{d,sie}$ ali celo $F_d = 0$ N), saj se v teh primerih pričnejo proti koncu vleka pojavljati gube v prirobnici.

2.2 Model globokega vleka na osnovi MKE s segmentiranim pridrževalom

Iz osnov preoblikovanja je znano, da je pri globokem vleku izdelkov z ravnimi deli na teh mestih potrebna večja pridrževalna sila, ki zavira prehiter tok materiala preko vlečnega polmera. V primeru običajnega pridrževala v ta namen uporabljamo zadrževalne letve, preko katerih mora drseti pločevina, preden vstopi v vlečni del matrice. V analizah z MKE smo namesto pridrževalnih letev uporabili segmentirano pridrževalo. Z njim dosegamo boljšo in enakomernejšo porazdelitev tlakov po prirobnici preoblikovanca ter se s tem približamo željenemu stanju pridrževanja z elastičnim pridrževalom. Pri pritisku p_d=3,6 MPa (F_d =0,75 $F_{d,sie}$) na ravne dele prirobnice smo že v prejšnjih raziskavah ugotovili, da se material na prirobnici ne guba, vendar smo pregled z enakim tlakom izvedli tudi za segmentirano pridrževanje.

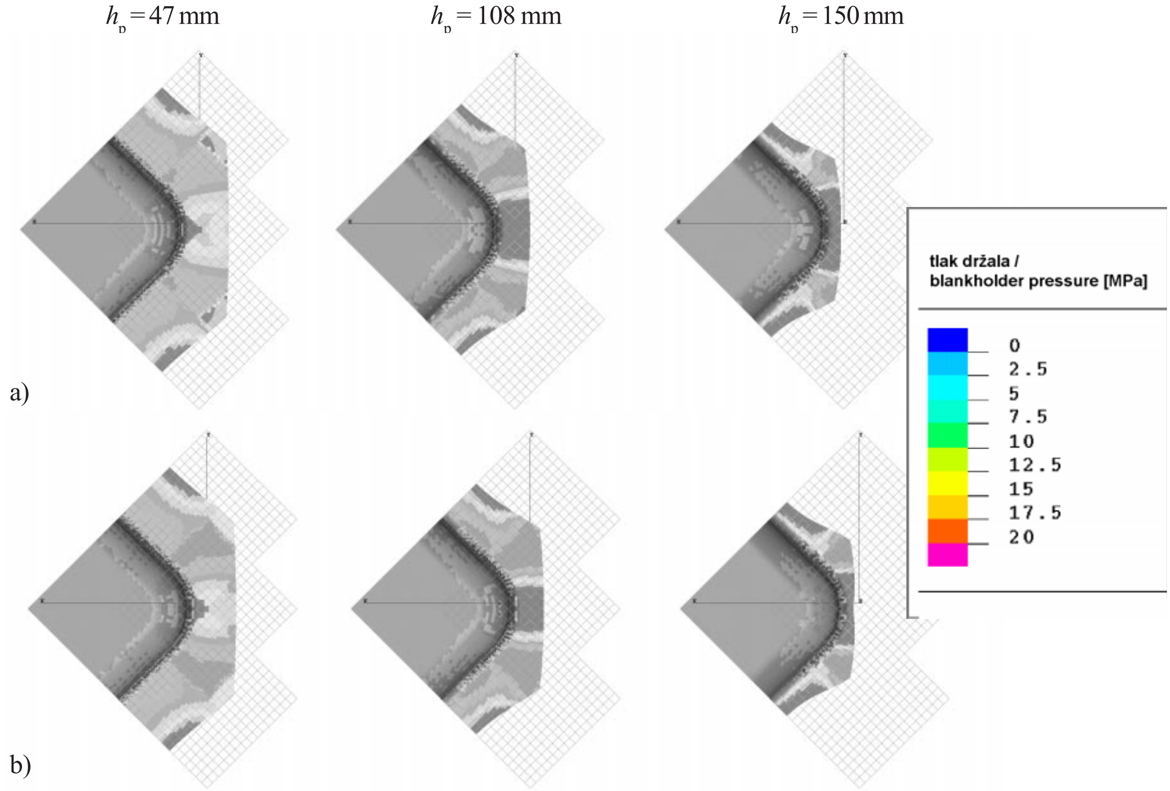
to accurately determine the upper blankholder force limit at which the material began to wrinkle. Figure 3 shows the analysis of the flange wrinkling for two different blankholder forces.

Comparisons of simulations of conventional holding using a rigid holder showed that varying the blankholder forces yielded better results than holding with a constant force. As a result, the drawing force on the punch is also smaller, which reduces the energy required for deep drawing. This is important mainly in products with a large surface area, where the blankholder force represents a significant percentage of the total forming force. In spite of very large pressures on the held workpiece which occur towards the end of the deep drawing, it turns out that the forces must not be reduced excessively (e.g. to F_d = 10% $F_{d,sie}$ or even to $F_d = 0$ N), because this causes wrinkling of the flange towards the end of the drawing.

2.2 FEM model of deep drawing with a segmented blankholder

It is well known from the theory of forming that when deep drawing products with flat sections a greater holding force is required in such sections to prevent a too rapid flow of material over the drawing radius. In the case of conventional blankholders, draw-beads are used for this purpose, over which the sheet metal slides before entering the drawing zone of the tool. In the FEM analyses, a segmented blankholder was used instead of draw beads. Such a blankholder gave a better, more uniform, distribution of pressures along the workpiece flange and thus enabled to approximate the desired state of holding with an elastic blankholder. It was already observed during previous research that at a pressure of p_d=3.6 N/mm^2 ($F_d = 0.75\,F_{d,sie}$) on flat sections of the flange, the flange material did not wrinkle. A reference simulation was also performed for segmented holding, using the same pressure. The selected blankholder segment size was 100 x

Gib pestiča / *Punch travel:*



Sl. 4. *Porazdelitve tlakov po prirobnici za različne začetne tlake pridrževanja: a) p_d =3,6 MPa na vseh segmentih ter b) p_d = 3,6 MPa na ravnih delih in p_d = 2,4 MPa v vogalih*

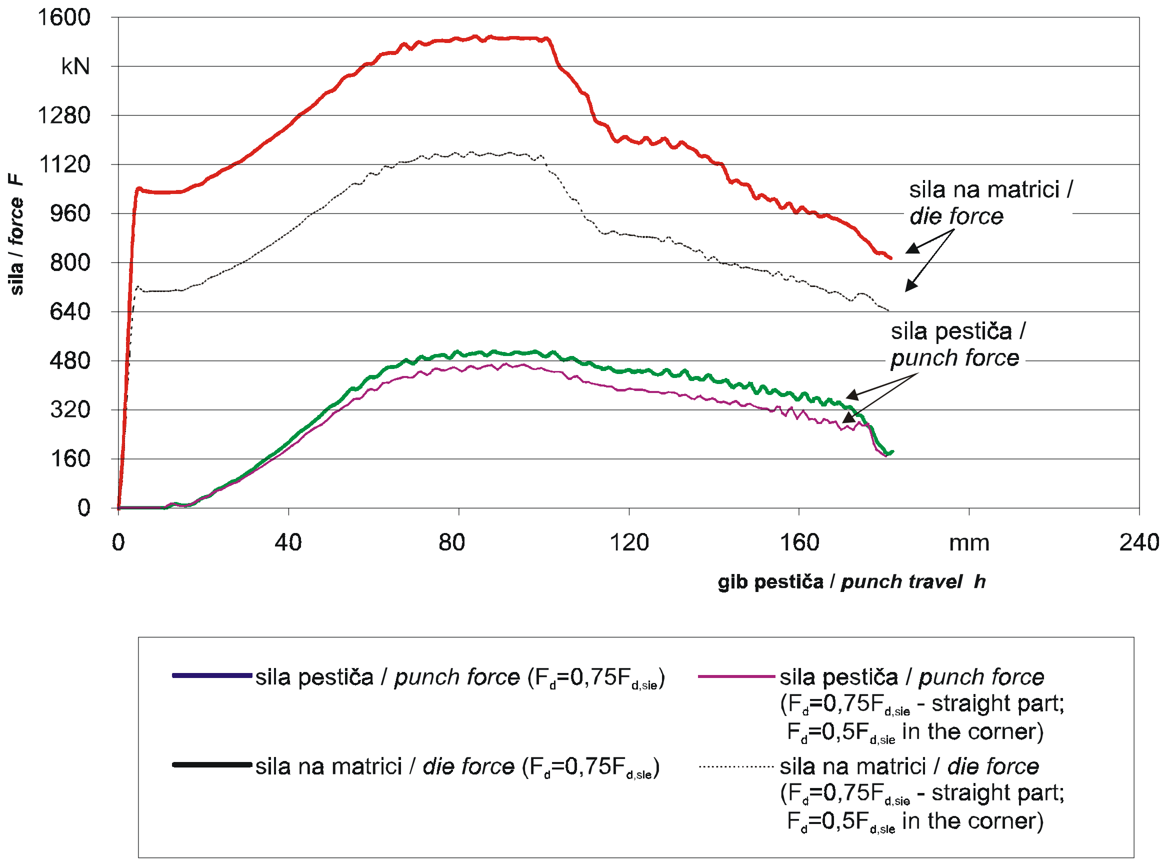
Fig. 4. *Distribution of pressures on the flange for different initial holding pressures: a) p_d =3.6 MPa on all segments and b) p_d = 3.6 MPa on the straight parts and p_d = 2.4 MPa on the edges*

Izbrana velikost segmentov držala je 100x100 mm. V naslednji fazi smo na ravnih delih prirobnice ohranili tlak p_d =3,6 MPa, na vogalih pa smo znižali pritisk na p_d = 2,4 MPa (F_d =0,5 $F_{d,sie}$). Kljub zmanjšanju pridrževalne sile v vogalih vlečenca z vrednotenjem pomikov vozlišč mreže MKE nismo zaznali gubanja prirobnice. Kriterij ugotavljanja gubanja je pomik vozlišč, večji od Dz=0,05 mm. Slika 4 prikazuje tlake na prirobnici med vlekom preoblikovanca v treh fazah vleka. Zmanjšanje pritiska držala vpliva tudi na zmanjšanje pridrževalne sile in s tem tudi silo merjeno na matrici (sl. 5). Kot je razvidno iz slike 5, se z zmanjševanjem pridrževalne sile na posameznih segmentih na F_d = 0,5 $F_{d,sie}$ občutno zmanjša celotna sila preoblikovalnega postopka. Energijski izračun preoblikovanja ob pridrževanju z nespremenljivo silo F_d = 0,75$F_{d,sie}$ in krajevno optimirano silo kaže na 35,8 odstotno zmanjšanje porabe energije v slednjem primeru.

Rezultati globokega vleka z uporabo segmentiranega držala so namenjeni za analize elastičnega pridrževanja [13]. Zaradi različnih debelin pločevine, ki so posledica različnih napetostno deformacijskih stanj po prerezu neokroglega vlečenca ter anizotropije materiala, se

100 mm. In the next phase, the pressure of p_d =3.6 MPa was maintained on the straight parts of the flange of the sink circumference, while on the edges it was reduced to p_d = 2.4 MPa (F_d =0.5 $F_{d,sie}$). In spite of a reduced blankholder force on the workpiece edges, the evaluation of the FEM mesh-node displacements did not reveal any wrinkling of the flange. A node displacement in excess of Δz=0.05 mm was used as the criterion for establishing the wrinkling. Figure 4 shows the pressures on the flange during three phases of deep drawing the workpiece. A reduction of the blankholder pressure also reduces the holding forces and the force measured on the die (see Figure 5). As Figure 5 shows, with decrease of blankholder force on particular segments down to F_d =0.5 $F_{d,sie}$, significant decrease in total force used for forming procedure can be achieved. The calculated energy for particular forming process performed with unique holding force of F_d = 0.75 $F_{d,sie}$ and with the spatial optimised one reveals 35.8 % reduction in energy consumption.

The results of deep drawing with the segmented blankholder served for the analyses of the elastic holding [13]. Different sheet-metal thicknesses, which resulted from different stress-strain states across the cross-section of a noncircular workpiece and material anisotropy, caused the appearance of locally different



Sl. 5. *Sila na orodju pri enako veliki nespremenljivi sili pridrževanja vseh segmentov ter zmanjšani sili pridrževanja v vogalih izdelka*

Fig. 5. *Force on the tool at equal and constant holding forces for all segments and a reduced blankholder force on the product edges*

pojavljajo različni lokalni tlaki pridrževanja. Velikosti teh tlakov v različnih fazah vlečenja ter pripadajoče porazdelitve debelin po značilnih prerezih prirobnice vlečenca pomenijo vhodne podatke za analize elastične pridrževalne plošče. Z njimi lahko optimiramo prilagajanje pridrževala porazdelitvi debelin prirobnice vlečenca in lokalno uravnavamo tlake pridrževanja med samim vlekom.

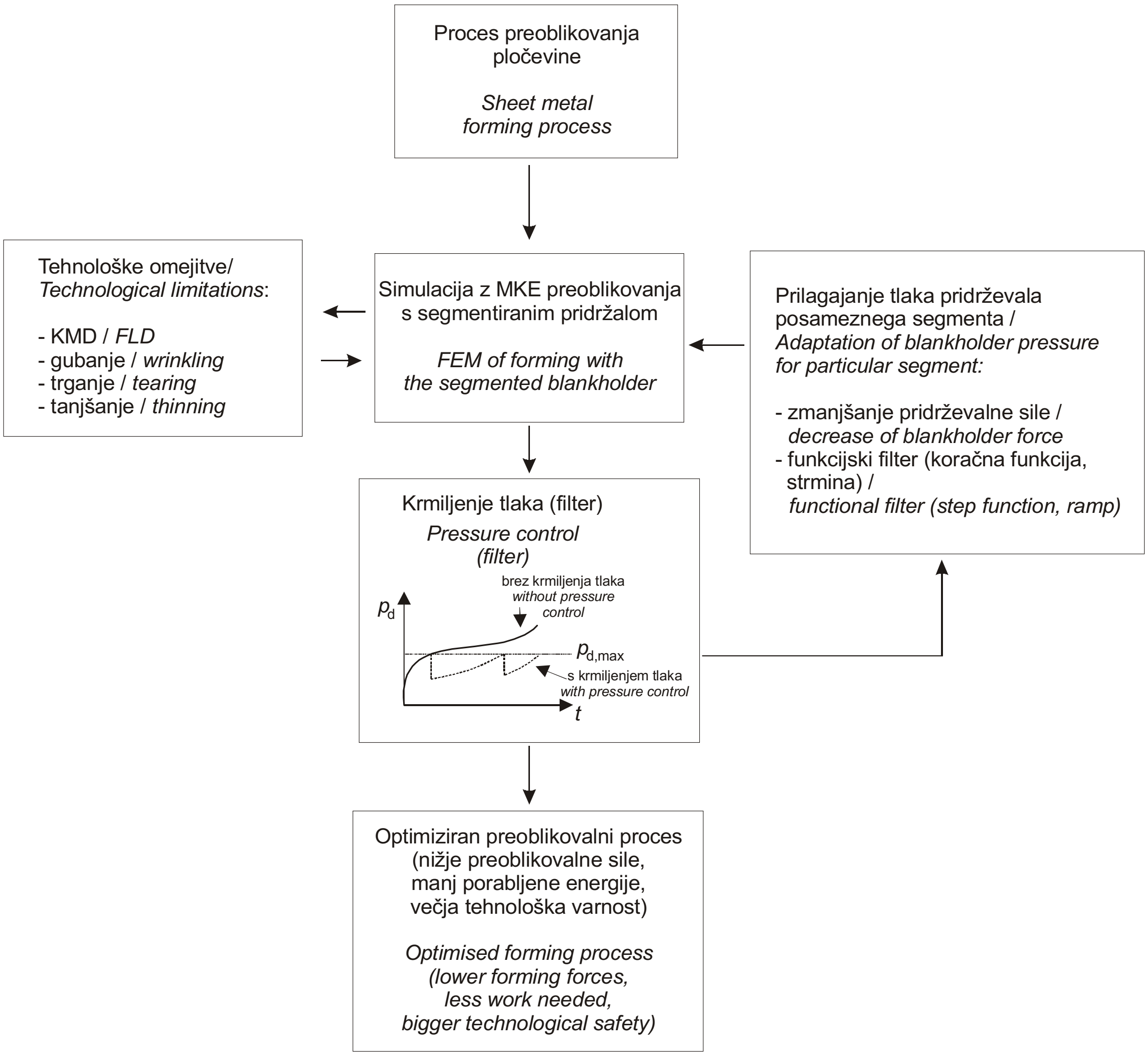
V zadnji fazi analiz smo pridrževalne sile posameznih segmentov časovno spreminjali glede na večanje tlaka na posameznem segmentu. Takšna optimizacija predstavlja nov koncept prilagajanja pridrževalne sile zahtevam preoblikovalnega postopka, ki do sedaj še ni bila izvedena. Zasnova časovne optimizacije pridrževalne sile posameznega segmenta temelji na prilagajanju tlaka pridrževanja glede na vnaprej predpisano največjo vrednost $p_{d,max}$ (sl.6). Ob prekoračitvi največjega tlaka držala na posameznem segmentu smo zmanjšali pridrževalno silo tega segmenta. S tem pridrževalni tlak ponovno pade pod dopustno vrednost. Simulacije z MKE s prilagajanim tlakom pridrževanja smo analizirali glede na opazovane tehnološke parametre kot so gubanje, trganje,

holding pressures. The magnitudes of these pressures in different phases of the deep drawing and the corresponding distributions of thicknesses across the characteristic cross-sections of the workpiece flange were used as the input data for the analyses of the elastic holding plate. Such analyses can be used to optimise the adjustment of the blankholder to the distribution of the workpiece flange thicknesses and locally control the holding pressures during deep drawing.

In the last phase of the -presented analyses the blankholder forces of individual segments were varied with time, with respect to pressure increases on an individual segment. This is a new concept in the adjustment of holding to the requirements of the forming process, which has not been analysed yet. The optimisation concept of the blankholder pressure on each segment was based on the adaptation of the applied pressure according to the pre-defined value of maximum blankholder pressure $p_{d,max}$ - Figure 6. Once the maximum blankholder pressure on a particular segment was exceeded its blankholder force was decreased to decrease the pressure to less then the critical value. The FEM simulations with adopted blankholder pressures were analysed according to demanding technological parameters such as wrinkling criteria, tearing, thinning and FLD curve as well.

tanjšanje in diagram KMD. Analiza poteka preoblikovanja s tlaki pridrževanja 3,6 MPa na vseh segmentih držala pokaže, v katerih časovnih korakih vleka se tlak na posameznem segmentu zveča preko opredeljene dopustne vrednosti. Iz izkušenj smo določili, da sme biti zvečanje tlaka na segmentu do največ 10-kratne vrednosti tlaka na začetku vleka. Silo pridrževanja na posamezni segment smo nato zmanjšali na njeno polovično vrednost in jo tako obdržali, dokler tlak pridrževala ponovno ne prekorači mejne vrednosti. Optimizacija sil pridrževanja je pokazala pričakovano dodatno zmanjšanje potrebnih vlečnih sil, kar ugodno vpliva tako na potek vleka kakor tudi na porazdelitev debelin vlečenca. Vrednotenje za preoblikovanje porabljene energije je pokazalo 43,6 odstotno zmanjšanje glede na referenčen preoblikovalni proces z nespremenljivo silo $F_d = 0{,}75F_{d,sie}$ na vseh segmentih držala.

The analysis of the forming process with an initial holding pressure of 3.6 MPa on all blankholder segments shows those time intervals during deep drawing during which the pressure on an individual segment exceeds the predefined allowable value. On the expert basis, it was determined that the pressure increase on an individual segment may be up to 10 times the initial value. The blankholder force on each individual segment was then reduced to half its value and maintained at this level until the pressure on the particular blankholder segment reached the maximum level again. The optimisation of the blankholder forces showed the expected additional decrease in the required drawing forces, which has a favourable effect both on the deep-drawing process and on the distribution of workpiece thicknesses. The evaluation of the energy needed for the forming operation showed a decrease of 43.6 % in comparison with the reference forming process with a unique holding force of $F_d = 0.75\,F_{d,sie}$ on all segments of the blankholder.



Sl. 6. *Zasnova krajevne in časovne optimizacije tlaka pridrževala pločevine*
Fig. 6. *Optimisation concept for spatial and time adaptation of blankholder pressure*

3 SKLEPI

Analize preoblikovanja neokroglega izdelka so pokazale, da se s spreminjanjem in optimiranjem pridrževalne sile lahko zmanjšajo sile globokega vleka. Optimizacijo pridrževanja smo vrednotili s kriteriji zmanjševanja preoblikovalnih sil, tanjšanja preoblikovanca in vrednotenjem procesne varnosti. S tem prihranimo del potrebne energije preoblikovanja. S simulacijami po MKE se lahko napovejo izboljšave poteka sil pridrževanja, pri katerih se izdelek kakovostno preoblikuje. Razvili smo zasnovo krajevne in časovne optimizacije segmentiranega pridrževanja, s katero lahko s simulacijami po MKE dodatno izboljšamo preoblikovalni proces že v navideznem okolju.

Pri globokem vleku velikih preoblikovancev pogosto pomeni energija, porabljena za pridrževanje pločevine med preoblikovanjem, pomemben delež celotne porabljene energije. Sile pridrževanja so pri tem lahko celo večje od samih vlečnih sil. Vrednotenje rezultatov pridrževanja s segmentnim pridrževalom ob zmanjševanju sile pridrževanja na vogalu izdelka je pokazalo, da je potrebna celotna energija za vlek za 35 odstotkov manjša, kakor v primeru enakomernega pridrževanja vseh segmentov z enako silo. Pri vrednotenju časovno in krajevno optimirane pridrževalne sile smo ugotovili celo 43,6 odstotno zmanjšanje energije potrebne za preoblikovalni proces.

Nov način prilagajanja pridrževalnih sil posameznih segmentov je oprt na časovno analizo stičnega tlaka med orodjem in prirobnico preoblikovanca. Z njim se dodatno povečuje prilagodljivost pridrževalnega sistema. Z zmanjševanjem pridrževalne sile posameznega segmenta ob prekoračitvi kritične vrednosti stičnega tlaka se dodatno zmanjšuje za preoblikovalni proces porabljena energija. Hkrati se povečuje tehnološka varnost in izboljšuje porazdelitev debelin preoblikovanca.

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3 CONCLUSIONS

The presented analyses of forming noncircular workpieces showed that it is possible to improve the forming process with the optimisation of the blankholder force. The optimisation has been evaluated according to the reduction of the forces in deep drawing by varying and optimising the blankholder force, decreasing the local material thinning and evaluating the process safety. This can help reduce the energy required for forming. Using FEM simulations it is possible to predict improvements in the variation of blankholder forces which will result in high-quality forming. A concept for spatial and time optimisation of the blankholder force for a segmented holder has been developed for additional optimisation improvements of the forming process with FEM simulations in the virtual environment.

When deep drawing large workpieces the energy required to hold the sheet metal during forming frequently represents a significant portion of the total energy, and the blankholder forces may even exceed the drawing forces. An evaluation of the results of holding using segmented blankholders and reduced holding forces on product edges showed that the total energy required for deep drawing is reduced by 35 percent in comparison with the situation where all the segments are held uniformly, i.e. with equal force. The evaluation of spatial and time optimisation of the blankholder pressure has shown a reduction in the energy used by 43.6 percent in comparison with the reference forming process.

The described new approach to the adjustment of blankholder forces on individual segments is based on temporary analyses of the contact pressure between the tool and the workpiece flange. This also increases the adaptability of the holding system. By reducing the blankholder force on an individual segment at the time the critical limit for contact pressure is exceeded the energy required for forming can be further reduced. At the same time, the technological safety is increased and the distribution of thicknesses in the workpiece improved.

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4 OZNAKE SIMBOLOV
4 SYMBOLS

pridrževalna sila	F_d	blankholder force
sila držala izračunana po Sieblovem obrazcu	$F_{d,sie}$	the blank holder force calculated by Siebel's formula
pridrževana površina	A_d	holded surface
tlak pridrževala	p_d	blankholder pressure
mejni tlak pridrževala	$p_{d,mej}$	limit blankholder pressure
natezna trdnost	R_m	tensile strength
meja plastičnosti	R_p	yield strength
vlečno razmerje	β_0	drawing ratio
premer pestiča	d_p	punch diameter
začetna debelina pločevine	s_0	initial sheet thickness
konstanta materiala	C	material constant
eksponent utrjevanja	n	hardening coefficient
modul elastičnosti	E	elasticity modulus
Poissonovo razmerje	ν	Poisson's coefficient
gostota materiala	ρ	material density
Lankfordovi koeficient normalne plastične anizotropije v smereh 0°, 45° in 90° glede na smer valjanja	r_0, r_{45}, r_{90}	Lankford's coefficients of anisotropy in directions 0°, 45° and 90° according to the rolling direction

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Naslov avtorjev: dr. Tomaž Pepelnjak
doc.dr. Zlatko Kampuš
Fakulteta za strojništvo
Univerza v Ljubljani
Aškerčeva 6
1000 Ljubljana

Athors' Adress: Dr. Tomaž Pepelnjak
Doc.Dr. Zlatko Kampuš
Faculty of Mechanical Eng.
University of Ljubljana
Aškerčeva 6
1000 Ljubljana, Slovenia

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