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Using Numerical Flow Analysis to Predict the Efficiency of a Francis Turbine

2. Analiza raznosa tlaka pri uporabi prilagodljivega pridrževala z možnostjo nadzora pridrževalne sile med globokim vlekom
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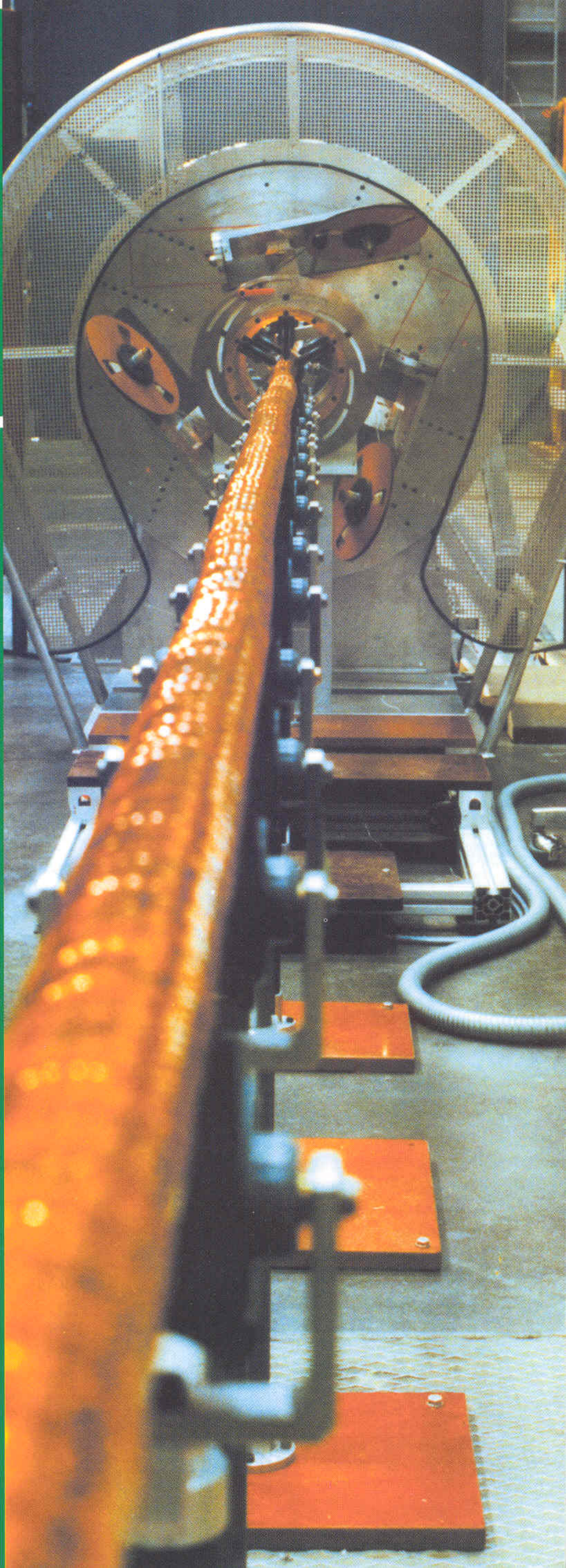

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Napoved izkoristka francisove turbine z numeričnim izračunom toka

Using Numerical Flow Analysis to Predict the Efficiency of a Francis Turbine

Dragica Jošt - Leopold Škerget

V prispevku je predstavljena numerična analiza toka v francisovi turbini. Osredotočili smo se na napoved energijskih izgub v toku in napoved izkoristka turbine. Rezultate, dobljene z ločeno analizo toka v vsakem delu turbine, smo primerjali z rezultati ločenega izračuna toka v spirali in skupnega izračuna toka skozi preostalo turbino. Nato smo izračunali tok v francisovi turbini v večjem številu obratovalnih točk, narisali školjčni diagram izkoristka in ga primerjali z izmerjenim. Enak izračun je bil narejen še za primer, ko nimamo izmerjenih vstopnih podatkov. V prispevku je predstavljen tudi vpliv gostote mreže in izbire turbulentnega modela na rezultate.

(Ključne besede: turbine francisove, izkoristek turbin, analize toka, modeli turbulentni)

This paper presents a numerical analysis of flow in a Francis turbine. We concentrate on flow-energy losses and efficiency prediction. The results, obtained by a separate analysis of each turbine component, are compared with the results of a separate analysis of flow in a spiral casing and a simultaneous calculation of the flow through the other turbine parts. After this we analysed flow in a Francis turbine at several operating points, an efficiency hill-chart diagram was drawn and compared with the measured one. The same calculation was made for a case where no measured inlet conditions were avaible. The effect of the grid density and turbulence models on the results is also presented.

(Keywords: Francis turbine, turbine efficiency, flow analysis, turbulence models)

0 UVOD

Od rezultatov numerične analize toka v turbini pričakujemo natančno informacijo o toku, primerno točen izračun tokovnih izgub in izkoristka in napoved kavitacije. Pri oblikovanju novih gonilnikov in drugih delov turbinskih strojev je numerična analiza toka nepogrešljivo orodje. Mnogo laže je oblikovati veliko število lopatic gonilnika na računalniku in na podlagi numerične analize izbrati najboljšega, kakor pa izdelati številne modele in z meritvami izkoristka izbrati najboljšega. Pomembno pa je, da na podlagi numeričnih rezultatov res izberemo najboljši gonilnik. Bolj kot absolutna vrednost numerično dobljenega izkoristka nas zanimata lega optimalne točke obratovanja in oblika diagrama izkoristka.

V preteklosti smo računali vsak del turbine posebej. Rezultate analize toka skozi en del turbine smo uporabili za vstopne pogoje pri analizi naslednjega dela. Tak izračun ne upošteva vpliva

0 INTRODUCTION

Numerical results are expected to give detailed information about the flow in a turbine; to predict flow-energy lossses and efficiency with reasonable accuaracy; and to foresee the cavitation. In the design process of runners and other turbine components CFD is a useful tool: it is much easier to design a number of runner blades on a computer and numerically choose the best one than to do several models and model tests. But it is essential to choose the best runner. More than the absolute value of efficiency, it is important to accurately obtain the position of the best-efficency point and the shape of the efficiency diagram.

In the past, each part of a turbine was analysed separately. The results of the flow through one part of a turbine were used as inlet boundary conditions for the analysis of the next part. However, such a flow calculation does not take into account the influence of one turbine component on the previene komponente turbine na poprejšnjo. Tako izgubimo vpliv gonilnika na tok v dvojni kaskadi in vpliv sesalne cevi na tok v gonilniku. Kljub temu pa so bili rezultati ločene analize toka pogosto uspešno uporabljeni pri izboljšanju hidravličnih oblik vseh delov turbine ([1] in [2]).

V zadnjih letih je bil v numeričnem obravnavanju toka tekočin dosežen izreden napredek. Eden najpomembnejših dosežkov je skupni izračun toka v rotirajočih in nerotirajočih delih stroja. Tako je zdaj mogoče skupaj računati tok od vstopa v spiralo do izstopa iz sesalne cevi z vsemi predvodilnimi, vodilnimi in gonilnimi lopaticami. Tako upoštevamo medsebojni vpliv statorja, gonilnika in sesalne cevi in se izognemo nenatančnim robnim pogojem med komponentami. Slaba stran takega izračuna je veliko število vozlov, počasna konvergenca in dolgi računski časi. Kompromisna rešitev je ločen izračun toka v spirali in skupen izračun toka od vstopa v predvodilnik do izstopa iz sesalne cevi, območja računanja pri kaskadah predvodilnika, vodilnika in gonilnika pa so skrčena na en perodični del ([3] in [4]). Pogosto pa je tudi tak izračun prezamuden in se moramo odločiti za ločeno analizo toka. Zanesljivost numeričnih rezultatov je odvisna tudi od gostote mreže. V primeru premajhnih računalniških zmogljivosti je vprašanje, ali je bolje računati celotno turbino na redki mreži ali pa vsak del turbine posebej na zgoščeni mreži. Rezultati so odvisni tudi od izbire turbulentnega modela.

V tem prispevku skušamo prikazati razlike med rezultati ločenega in skupnega izračuna, vpliv gostote mreže in izbire turbulentnega modela na rezultate in zanesljivost numeričnega izračuna izkoristka turbine.

1 LOČENA, DELNO SKLOPLJENA IN SKLOPLJENA ANALIZA TOKA

Numerična analiza toka je bila narejena za model francisove turbine s specifično vrtilno frekvenco n_S=300 (n_s=3.65 $n\ Q^{1/2}\ H^{-3/4}$), ki je bila izmerjena na Turboinštitutu. Turbina sestoji iz spirale z 12 predvodilnimi lopaticami, 24 vodilnih lopatic, iz 13-lopatičnega gonilnika in kolenaste sesalne cevi z navpičnim rebrom v izstopnem delu.

Numerična analiza toka je bila narejena s programskim paketom CFX-TASCflow s standardnim modelom k - ε.

Obratovalna točka turbine je določena s padcem, pretokom in vrtljaji. Namesto pretoka in padca raje uporabljamo pretočno število φ ($\varphi=Q/(\pi\omega r^3)$) in tlačno število ψ ($\psi=2gH/(\omega r)^2$). Tu sta φ in ψ brezdimenzijski števili in sta neodvisni od velikosti stroja. Numerična analiza toka je bila narejena za pet obratovalnih točk pri nominalnem ψ. Pretok pri določenem odprtju vodilnika in vrtljajih je bil dobljen iz meritev.

ous one. So the influence of a runner on the flow through the distributor and the influence of a draft tube on the flow in the runner were lost. In spite of this, results of separate analyses were used successfully to improve the hydraulic shapes of all turbine parts ([1] and [2]).

Recently, there has been a rapid development in CFD and one of the most important achievements is simultaneous calculation of the flow in rotating and non-rotating parts. It is now possible to calculate the flow from the spiral casing inlet to the draft-tube outlet with all the stay and guide vanes and the runner blades, simultaneously. In this way we take into account the interaction of the stator, the rotor and the draft tube and avoid inaccurate boundary conditions between the turbine components. The disadvantages of such a calculation are the large number of nodes, the slow convergence and the long CPU time. The compromise solution is a separate analysis of the spiral casing and a simultaneous calculation of the flow from the stay-vanes inlet to the draft-tube outlet, while the domain for the stay and guide vanes and the runner-blades cascades is reduced to one periodic part ([3] and [4]). Often, even this kind of calculation is too time consumming and a separate analysis has to be performed. The reliability of the numerical results also depends on the grid density. In the case of insufficient computer capacity there is a question as to whether it is better to calculate the whole turbine on a coarse grid or to calculate each part individualy on a fine grid. The results also depend on the turbulence model.

In this paper the difference between the results of separate and coupled analysis, the effect of grid density and the turbulence model on the results and the reliability of numerically predicted efficiency are presented.

1 SEPARATED, PARTLY COUPLED AND COUPLED-FLOW ANALYSIS

A numerical analysis was made for a model of a Francis turbine with specific speed n_S=300, (n_s=3.65 $n\ Q^{1/2}\ H^{-3/4}$), which was tested on the test rig at the Turboinstitute. The turbine consists of a spiral casing with 12 stay vanes, 24 guide vanes, a 13-blades runner and an elbow draft tube with a vertical pier.

The numerical analysis was made with the CFX-TASCflow computer code using the standard k - ε model.

The turbine operating point is determined by head, discharge and speed. Often, instead of discharge and head, a discharge coefficient φ ($\varphi=Q/(\pi\omega r^3)$) and a pressure coefficient ψ ($\psi=2gH/(\omega r)^2$) are used. Here φ and ψ are dimensionless numbers independent of the turbine dimensions. The numerical analysis was made for five operating points for a nominal ψ. A discharge corresponding to a certain-guide vane opening and speed was obtained from measurements.

Najprej je bila narejena analiza toka v spirali s predvodilnimi lopaticami. Območje računanja je razširjeno do izstopa iz gonilnika, vendar brez vodilnih in gonilnih lopatic. V mreži je 280 000 vozlov (sl. 1). Iz rezultatov izračuna toka v spirali smo dobili vstopne pogoje za nadaljnje izračune. Izračunali smo tudi izgube v spirali.

Numerična analiza toka v dvojni kaskadi, gonilniku in sesalni cevi je bila narejena na tri načine. Prvi način je bil ločen izračun toka v kaskadi, gonilniku in sesalni cevi. Območje računanja za dvojno kaskado je del med dvema predvodilnima in tremi vodilnimi lopaticami in med vencem in pestom, toda brez lopatic gonilnika. V mreži je 114 000 vozlov. Območje računanja za gonilnik je med dvema lopaticama, v mreži je 72 000 vozlov. Mreža za sesalno cev vsebuje 170 000 vozlov. Vstopni pogoji so dobljeni iz analize prejšnje komponente. Območja računanja se prekrivajo, ker smo želeli zmanjšati vpliv nenatančnih izstopnih robnih pogojev. Drugi način je delno sklopljena analiza toka. Tok skozi predvodilne in vodilne lopatice ter gonilnik računamo skupaj (166 000 vozlov), tok v sesalni cevi pa posebej (170 000 vozlov). Tretji način je skupen izračun toka od vstopa v predvodilnik do izstopa iz sesalne cevi. Mreža vsebuje 332 000 vozlov (sl. 2). Mreže za sklopljeno analizo so bile dobljene z združevanjem mrež ločenega izračuna, izpuščeni so bili le deli, ki se prekrivajo. Zato je struktura in gostota mreže enaka za ločen in sklopljen izračun.

Iz rezultatov numeričnega izračuna lahko izračunamo izgube v toku, navor na os turbine in izkoristek. V nerotirajočih delih turbine razlika med totalnim tlakom na vstopu in izstopu pomeni izgube:

First, a numerical analysis of the spiral casing with stay vanes was performed. The computational domain was extended to the runner outlet, but the guide vanes and runner blades were not modeled. The grid consisted of 280 000 nodes (Fig. 1). The results were used as the inlet conditions for subsequent calculations. At the same time the flow-energy losses in the spiral casing were calculated.

A numerical analysis of the flow in the tandem cascade, the runner and the draft tube was made in three stages. The first stage was a separate analysis of the flow through the tandem cascade, the runner and the draft tube. The computational domain for the tandem cascade is the region between two stay vanes and three guide vanes and between the hub and crown, but without runner blades. The domain consists of 114 000 nodes. The computational domain for the runner analysis is the region between two blades, it consists of 72 000 nodes. In the draft tube there are 170 000 nodes. The inlet conditions were obtained from numerical results of the upstream component. In order to minimize the influence of the inaccurate outlet boundary conditions the computational domains overlapped. The second stage was a partly coupled analysis. Flow through the stay vanes, the guide vanes and the runner were calculated simultaneously (166 000 nodes), while the draft tube was analysed separately (170 000 nodes). Finally, the flow from the stay-vanes inlet to the draft-tube outlet was analysed simultaneously. The grid consisted of 332 000 nodes (Fig. 2). The grids for the coupled analysis were obtained by attaching the grids of separate analyses and omitting the parts which overlapped, so the grid structure and grid density were the same for the separate and coupled analyses.

From the numerical results the flow-energy losses, the torque on the shaft and the efficiency can be calculated. Flow-energy losses in the non-rotating turbine parts are calculated as the difference between the total pressure at the domain inlet and outlet

$$\Delta E = \frac{1}{\rho.Q}\left(\int_{S_1} p_{tot} v_t dS - \int_{S_2} p_{tot} v_t dS \right) \qquad (1),$$

pri čemer je

where

$$p_{tot} = \frac{1}{2}\rho.v^2 + p \qquad (2),$$

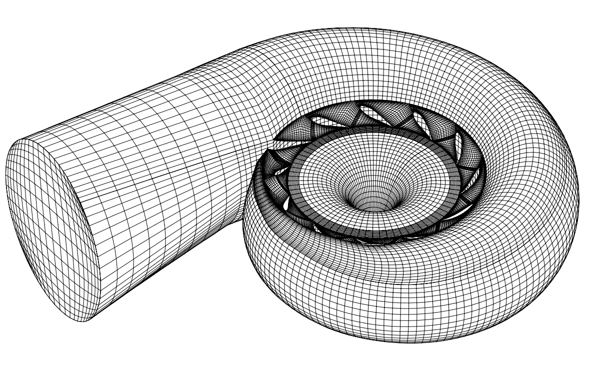
v_t je transportna komponenta hitrosti, S_1 in S_2 pa vstopni in izstopni prerez. Če ΔE delimo s težnostnim pospeškom g, dobimo izgube, izražene kot del padca, ki ni bil izkoriščen. V gonilniku večino razlike v totalnem tlaku pomeni delo gonilnika, majhen del pa izgube v toku. Izkoristek gonilnika izračunamo po obrazcu:

v_t is transport velocity component, S_1 and S_2 are the inlet and outlet cross-sections. If ΔE is divided by the acceleration due to gravity g, the flow-energy losses can be expressed as a head, which was not utilized. In the runner most of the difference in total pressure is converted to runner work, while a small part represents flow-energy losses. The turbine efficiency can be calculated by:

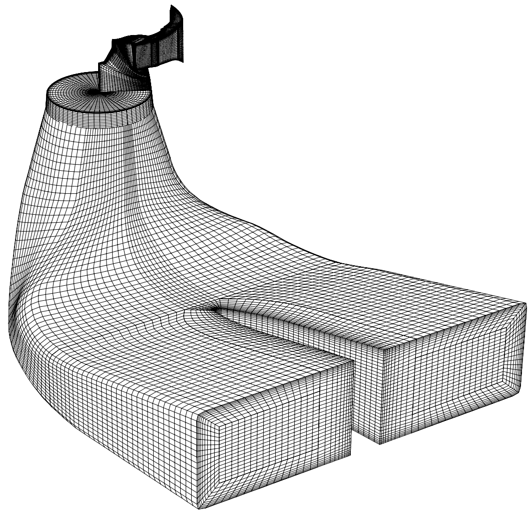
$$\eta = \frac{M.\omega}{\rho.Q.\Delta E} \qquad (3),$$

pri čemer je M navor na os turbine, ω pa kotna hitrost. V primeru ločene numerične analize dobimo ΔE kot vsoto prispevkov posameznih komponent.

where M is the torque on the shaft, and ω is the angular velocity. In the case of a separate numerical analysis ΔE is obtained as the sum of the contributions of all the turbine parts.



Sl. 1. *Območje računanja in mreža za izračun toka v spirali*
Fig. 1. *Computational domain and grid for flow analysis in the spiral casing*



Sl. 2. *Območje računanja pri skupnem izračunu toka skozi predvodilnik, vodilnik, gonilnik in sesalno cev*
Fig. 2. *Computational domain for simultaneous calculation of the flow through the stay and guide vanes, the runner and the draft tube*

Podroben prikaz rezultatov ločene, delno sklopljene in sklopljene analize je prikazan v [5]. Pokazalo se je, da ločena analiza toka napove prevelike izgube v vseh delih turbine, izračunani navor na os turbine pa je skoraj enak pri ločeni, delno sklopljeni in sklopljeni analizi toka. Zato ločena analiza toka napove bistveno manjši izkoristek, kakor je bil izmerjen. Tudi lega optimalne točke obratovanja je pomaknjena k večjemu pretoku. Rezultati delno sklopljenega izračuna so nekoliko bliže izmerjenim. Oblika diagrama izkoristka, dobljenega s sklopljenim izračunom, se dobro ujema z izmerjenim, vrednosti izkoristka pa so za okoli 3% manjše od izmerjenih (sl. 3).

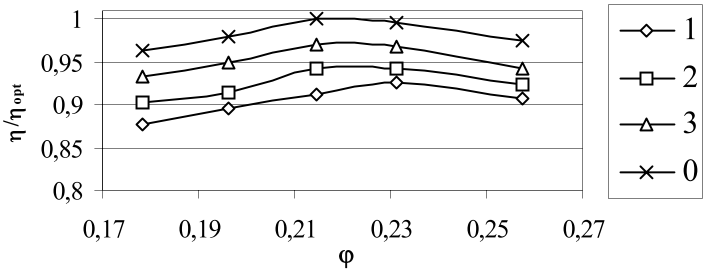
A detailed comparison of the results of the separate, the partly coupled and the coupled analysis is presented in [5]. We found that the separate flow analysis overestimates the flow-energy losses in all the turbine parts, while the calculated torque on the shaft is nearly the same for the separated, the partly coupled and the coupled calculations. In other words, the separate analysis predicts a much lower efficiency than the measured value. Also, the position of the best-efficiency point is shifted to a higher discharge. The results of the partly coupled calculation are closer to the measured values. The shape of the efficiency curve obtained with the coupled analysis is in good agreement with the measured value, but the calculated efficiency is about 3% lower than the measured values (Fig. 3).

2 ŠKOLJČNI DIAGRAM IZKORISTKA

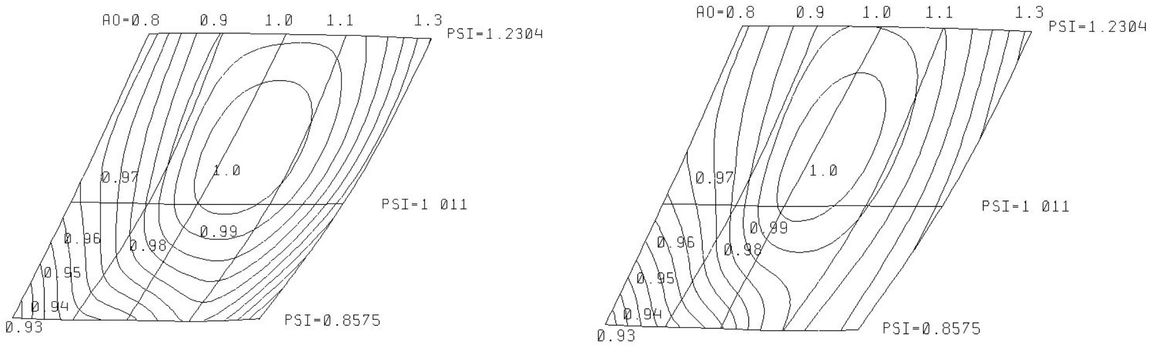
2 HILL-CHART DIAGRAM

Na podlagi rezultatov za nominalno tlačno število smo ugotovili, da je le sklopljena analiza primerna za izračun izkoristka turbine. Zato smo s sklopljeno analizo izračunali izkoristek v naslednjih

On the basis of the results for the nominal pressure coefficient it was concluded that only the coupled analysis is suitable for the prediction of turbine efficiency. Therefore, only the coupled analysis was



Sl. 3. *Diagram izkoristka za nominalno tlačno število ψ=1,011*
1 - ločen izračun, 2 - delno sklopljen izračun, 3 - sklopljen izračun, 0 - meritve
Fig. 3. *Efficiency diagram for the nominal pressure coefficient ψ=1.011*
1 - separated calculation, 2 - partly coupled calculation, 3 - coupled calculation, 0 - measurement



Sl. 4. *Školjčna diagrama izkoristka na temelju izračunanih in izmerjenih vrednosti v 15 točkah*
Fig. 4. *Hill-chart efficiency diagram based on the calculated and measured efficiency at 15 points*

desetih točkah obratovanja, pet za nižje in pet za višje tlačno število. Izračunane in izmerjene krivulje izkoristka se po obliki dobro ujemajo, izračunani izkoristek je za okoli 3% manjši, le pri velikem pretočnem številu in majhnem tlačnem številu (φ=0,2336, ψ=0,8575), smo dobili odstopanje okoli 5%.

Na temelju izračunanega izkoristka v 15 obratovalnih točkah narišemo školjčni diagram izkoristka. Za primerjavo narišemo še diagram na podlagi izmerjenega izkoristka v 15 obratovalnih točkah (sl. 4). Numerične vrednosti izkoristka so deljene z največjim izračunanim izkoristkom, izmerjene vrednosti pa z največjim izmerjenim izkoristkom. Obravnavane točke obratovanja so na presečiščih krivulj, ki pomenijo nespremenljivo odprtje vodilnika in vodoravnih črt, ki pomenijo stalen ψ. Lega optimalne točke obratovanja se dobro ujema z meritvami, prav tako tudi oblika krivulj s stalnim izkoristkom. Izračunani diagram je v okolici optimalne točke obratovanja nekoliko bolj položen, dlje od optimalne točke obratovanja pa bolj strmo pade kakor izmerjeni. Razlika je največja v desnem spodnjem delu diagrama, zaradi večjega odstopanja med izmerjenim in izračunanim izkoristkom pri φ=0,2336, ψ=0,8575.

made for the additional ten operating points, five for the lower and five for the higher pressure coefficient. The calculated and measured efficiency curves have the same shape, however, the calculated efficiency is about 3% lower. The exception is the operating point, with a large discharge coefficient and a small pressure coefficient (φ=0.2336, ψ=0.8575), where the discrepancy is 5%.

On the basis of the calculated efficiency for the 15 operating points a hill-chart diagram was drawn. For comparison, a diagram based on the measured efficiency at 15 operating points was also drawn (Fig. 4). The numerically obtained values were divided by the highest calculated efficiency, while the experimental values were divided by the highest measured efficiency. The treated operating points were at the cross-sections of the curves of constant guide-vane opening (A_0) and the lines of constant ψ. The position of the best-efficiency point was quite accurately predicted. The shape of the efficiency contours was also in quite good agreement. Near the best-efficiency point the calculated diagram is flatter than the measured one, but further from the best-efficiency point the efficiency decreases quickly. The descrepancy is largest at the bottom right-hand part of the diagram, because of the larger disagreement between the measured and calculated efficiency at point φ=0.2336, ψ=0.8575.

3 VPLIV GOSTOTE MREŽE IN TURBULENTNIH MODELOV NA REZULTATE

Diagram izkoristka za nominalno tlačno število je bil dobljen iz rezultatov numerične analize, izvedene s standardnim modelom k-ε na precej redki mreži. Da bi preučili vpliv gostote mreže in turbulentnega modela na rezultate, je bila ločena analiza toka v optimalni točki obratovanja narejena z različnimi turbulentnimi modeli na redki in zgoščeni mreži.

Porazdelitve tlaka in hitrosti, dobljene na mrežah različne gostote, so kakovostno zelo podobne. Pri redkih mrežah so energijske izgube v toku večje predvsem na račun precenjenih izgub zaradi trenja na stenah. Z zgostitvijo mrež se izgube zmanjšajo, zlasti v dvojni kaskadi in v gonilniku, medtem ko je vpliv zgostitve mreže v sesalni cevi manjši. Vpliv zgostitve mreže je enak za vse uporabljene turbulentne modele.

3.1 Turbulentni modeli

Pri izbiri turbulentnih modelov smo se omejili na dvoenačbna modela k-ε in k-ω. Poleg standardnega modela k-ε smo računali tudi z modelom RNG. Ta model je dobljen s teorijo renormalizacijskih grup (RNG), uporabljeni na Navier-Stokesovih enačbah. Transportni enačbi za k in ε sta enaki kakor pri standardnem modelu k-ε, razlikujejo se le koeficienti, s katerimi sklenemo sistem [6].

Turbulentni model k-ω je bil razvit z namenom, da bi bolj natančno napovedali odlepljanje toka na gladkih stenah. V CFX-TASCflow so vključeni trije modeli k-ω: standardni Wilcoxov model k-ω [7], model BSL (Baseline model) in model SST (Shear Stress Transport model). Standardni model k-ω je zelo občutljiv za vstopne pogoje za ω. Model BSL skuša ohraniti prednosti modelov k-ε in k-ω. Pri tem modelu je Wilcoxov model pomnožen s funkcijo F_1, model k-ε pa je najprej transformiran v obliko k-ω, nato pa pomnožen s $(1-F_1)$. F_1 je definirana tako, da imamo zunaj mejne plasti standardni model k-ε, ob steni pa preidemo na model k-ω [8]. Model SST upošteva prenos turbulentnih strižnih napetosti in najbolje popiše odlepljanje toka na stenah [9].

Eden od problemov dvoenačbnih modelov je obnašanje v okolici zastojnih točk. Pogosto opazimo pred zastojnimi točkami zelo visok nivo turbulence, ki se nato porazdeli okoli telesa. Problem sta rešila Kato in Launder s spremembo produkcijskega člena v enačbi za turbulentno kinetično energijo [10].

Pri turbulentnem modelu k-ε tok ob stenah najpogosteje modeliramo s standardnimi stenskimi funkcijami z logaritmičnim profilom. Da bi se izognili nedoslednosti pri zelo gostih mrežah, so razvili stenske funkcije s fiksnim y^+ [11]. Pri modelu k-ω je

3 THE EFFECT OF GRID DENSITY AND TURBULENCE MODELS ON THE RESULTS

The efficiency diagram for a nominal pressure coefficent was obtained from the results of a numerical analysis performed by the standard k-ε model on coarse grids. In order to study the effect of the grid density and the turbulence model on the results, a separate numerical analysis at the best-efficiency point (BEP) was performed using different turbulence models for the coarse and refined grids.

The pressure and velocity distribution obtained for grids of different density are qualitatively similar. For the case of coarse grids the flow-energy losses are too high, mostly due to overprediction of the friction losses. With grid refinement the flow-energy losses decrease, especially in the tandem cascade and the runner, while in the draft tube the effect is small. The same effect of grid refinement was obtained with all the turbulence models.

3.1 Turbulence models

The calculations were made with two-equational models k-ε and k-ω. Besides the standard k-ε model the RNG model was also used. This model is obtained from Renormalized Group Theory applied to Navier-Stokes equations. The transport equations for k and ε are the same as for the case of the standard k-ε model, but the closure coefficients are different [6].

The k-ω turbulence model was developed to predict the onset of separation on a smooth surface more accurately. In CFX-TASCflow three k-ω models are available: the standard Wilcox model [7], the BSL (Baseline) model and the SST model (Shear Stress Transport model). The standard k-ω model is very sensitive to the inlet conditions for ω. The BSL model combines the advantages of the k-ε and k-ω models. The Wilcox model is multiplied by a blending function F_1. The k-ε model is at first transformed to the k-ω formulation and then multiplied by $(1-F_1)$. F_1 is defined in such a way that outside the boundary layer the standard k-ε model is used, while inside the boundary layer the k-ω model is used [8]. The SST model accounts for the transport of the turbulent shear stress and therefore predicts the separation most accurately [9].

One of the problems with the two- equational models is the behavior near stagnation points. It is frequently observed that very high turbulence levels are predicted upstream of a stagnation point and then transformed around the body. This problem was solved by Kato and Launder, who changed the production term in the equation for the turbulent kinetic energy [10].

When the k-ε turbulence model is used, the flow in the near-wall region can be modeled by standard log-law wall functions. To avoid inconsistencies for the case of fine grids, fixed y^+ wall functions were developed [11]. For the k-ω model problem nedoslednosti rešen s formulacijo, ki pri zgoščenih mrežah avtomatično preide iz stenskih funkcij za visoka Re števila na model za nizka Re števila [12].

V CFX-TASCflow je vključen tudi dvoslojni turbulentni model. Pri tem modelu tok dovolj stran od sten modeliramo z modelom k-ε, tok ob stenah pa z enoenačbnim modelom. Za visoka Reynoldsova števila mora biti ob stenah mreža zelo zgoščena [12]. Zaradi premajhnih računalniških zmogljivosti tega modela nismo uporabili.

3.2 Izračun toka z različnimi turbulentnimi modeli

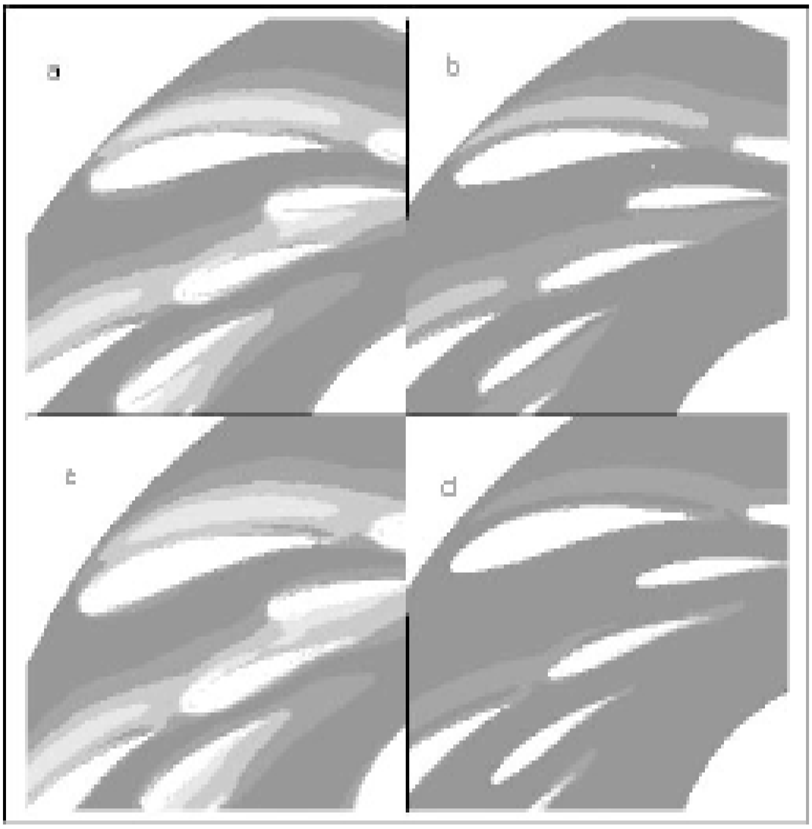
Tok v dvojni kaskadi smo računali s standardnim in z modelom RNG k-ε. Z modelom RNG dobimo nekoliko manjše energijske izgube v toku kakor s standardnim modelom. Izračun je bil ponovljen s standardnima modeloma k-ω in SST k-ω. S standardnim modelom k-ω dobimo predvsem zaradi nekoliko večje sence za lopaticani za malenkost večje izgube kakor s standardnim modelom k-ε. Na sliki 5 je prikazana porazdelitev turbulentne kinetične energije, dobljene z različnimi modeli na gosti mreži. S standardnima modeloma k-ε (sl. 5a) in k-ω (sl. 5c) modeloma dobimo veliko

the problem of inconsistencies in the case of fine grids is solved by a formulation which automatically switches from wall functions to a low-Re near-wall formulations as the grid is refined [12].

In CFX-TASCflow a two-layer turbulence model is also available. The standard k-ε model is used away from the wall, while the one-equation model is used near the wall. For high Reynolds numbers a very fine grid near the walls is required [12]. Due to insufficient computer capacity, we did not use this model.

3.2 Flow calculation with different turbulence models

Flow in the tandem cascade was calculated with the standard and the RNG k-ε models. With the RNG model, smaller flow-energy losses were obtained than with the standard k-ε model. The calculation was repeated with standard k-ω and SST k-ω models. With the standard k-ω model, due to larger wakes behind the vanes, slightly larger flow-energy losses were obtained than with the standard k-ε model. The distribution of turbulent kinetic energy, obtained with the different models on the refined grid is presented in Fig. 5. With the standard k-ε (Fig. 5a) and the standard k-ω (Fig. 5c) models, an increase in the turbulent kinetic energy near the stagnation



Sl. 5. *Porazdelitev turbulentne kinetične energije v dvojni kaskadi*
Fig. 5. *Distribution of the turbulent kinetic energy in the tandem cascade*
a – standardni model k-ε / standard k-ε model, b - model k-ε, Kato-Launder , c – standardni model k-ω / standard k-ω model, d – model SST k-ω, Kato-Launder

zvečanje turbulentne kinetične energije v okolici zastojnih točk in okoli lopatic. Pri obeh modelih s Kato-Launderjevim produkcijskim členom dobimo veliko bolj enakomerno porazdelitev turbulentne kinetične energije (sl. 5b in 5d). Zato dobimo tudi manjše izgube, in sicer pri modelu k-ε na redki mreži za 2,5%, na gosti mreži pa za 4%, pri modelu k-ω pa na redki mreži za 4%, na gosti mreži pa za 9,7%. Najmanjše izgube dobimo z modelom SST k-ω, tam je tudi porazdelitev turbulentne kinetične energije najbolj enakomerna (sl. 5d). Pri modelu k-ε se izgube nekoliko zmanjšajo še z uporabo stenskih funkcij s fiksnim y^+.

Pri izračunu toka v gonilniku smo primerjali navor na os turbine in izkoristek gonilnika. Razlike v navoru so majhne, pod 0,35%. Izkoristek gonilnika je najmanjši pri standardnem modelu k-ε in največji pri modelu SST k-ω. Z zgostitvijo mreže se pri vseh modelih izkoristek poveča za približno 1%.

Tok v sesalni cevi smo računali z obema dvoenačbnima modeloma. Primerjali smo izgube in koeficient rekuperacije tlaka C_p. Koeficient rekuperacije tlaka predstavlja razmerje med razliko tlaka na izstopu in vstopu sesalne cevi in kinetično energijo na vstopu. Definiran je z enačbo:

points and around the vanes can be observed. When using the Kato-Launder production term the distribution of turbulent kinetic energy is much more uniform (Fig. 5b and 5d). This results in a reduction of the flow-energy losses in the case of the k-ε model by 2.5% on the coarse grid and 4% on the refined grid, while in the case of the k-ω model the reduction was 4% on the coarse grid and 9.7% on the refined grid. The smallest flow-energy losses were obtained with the SST k-ω model, where the distribution of turbulent kinetic energy was also the most uniform. In the case of the k-ε model some reduction in the flow-energy losses was also obtained by the use of wall functions with a fixed y^+.

As a result of the runner analysis, the torque on the shaft and the runner efficiency were compared. The difference in torque on the shaft is small, less than 0.35%. The runner efficiency is the smallest in the case of the standard k-ε model and the largest in the case of the k-ω SST model. With grid refinement, the runner efficiency increases by approximately 1%.

The flow in the draft tube was calculated with both two-equational models. The flow-energy losses and the coefficient of pressure recovery (C_p) were compared. C_p represents the ratio of the difference in pressure at the draft-tube outlet and inlet and the kinetic energy at draft tube inlet. C_p is defined by the equation:

$$C_p = \frac{\int_{S_2} p v_t dS - \int_{S_1} p v_t dS}{\frac{\rho}{2} \int v^2 v_t \, dS} \quad (5),$$

pri čemer je S_1 vstopni, S_2 pa izstopni prerez sesalne cevi, p je tlak, v_t je transportna komponenta, v pa absolutna hitrost. Z modelom k-ε dobimo manjše izgube in višji C_p kakor z modelom k-ω. S Kato-

where S_1 and S_2 are the inlet and outlet draft-tube cross-sections, respectively, p is the pressure, v_t the transport velocity component, v the absolute velocity. The flow-energy losses obtained with the k-ε model are smaller

Preglednica 1. *Energijske izgube v toku v kaskadi, dobljene z različnimi turbulentnimi modeli na redki in gosti mreži*

Table 1. *Flow-energy losses in the tandem cascade obtained by several turbulence models on coarse and refined grids*

A - standardne log. stenske funkcije / standard log.-law wall functions

B - stenske funkcije s fiksnim y^+ / fixed y^+ wall functions

C - kombinacija stenskih funkcij za nizka in visoka Re števila / combined low and high Re wall functions

Turbulentni model Turbulence model	Model za tok ob steni Near-wall model	$\Delta E/g$ m 113 580 vozlov 113 580 nodes	$\Delta E/g$ m 374 130 vozlov 374 130 nodes
k-ε, standardni model /k-ε, standard model	A	0,4289	0,3728
k-ε, standardni model /k-ε, standard model	B	0,4114	0,3616
k-ε, Kato-Launder	A	0,4184	0,3578
k-ε, Kato-Launder	B	0,4054	0,3450
k-ε, RNG	A	0,4135	0,3590
k-ε, RNG, Kato-Launder	A	0,4023	0,3547
k-ε, RNG, Kato-Launder	B	0,4023	0,3662
k-ω, standardni model /k-ω, standard model	C	0,4338	0,3828
k-ω, Kato-Launder	C	0,4163	0,3455
k-ω, Kato-Launder, SST	C	0,4033	0,3087

Preglednica 2. *Navor na os turbine in izkoristek gonilnika, dobljena z različnimi turbulentnimi modeli na redki in zgoščeni mreži*
Table 2. *Torque on the shaft and runner efficiency obtained by several turbulence models on coarse and refined grids*
A - standardne log. stenske funkcije / standard log.-law wall functions
B - stenske funkcije s fiksnim y^+ / fixed y^+ wall functions
C - kombinacija stenskih funkcij za nizka in visoka Re števila / combined low and high Re wall functions

Turbulentni model Turbulence model	Model za tok ob steni Near-wall model	72 000 vozlov, 72 000 nodes		243 000 vozlov, 243 000 nodes	
		M Nm	η %	M Nm	η %
k-ε, standardni model /k-ε, standard model	A	368,84	90,49	371,87	91,61
k-ε, Kato-Launder	A	368,98	90,72	372,12	91,83
k-ε, RNG, Kato-Launder	A	369,03	90,67	372,26	91,82
k-ε, RNG, Kato-Launder	B	369,10	90,67	372,53	91,85
k-ω, standardni model /k-ω, standard model	C	369,99	90,88	372,75	91,89
k-ω, Kato-Launder	C	370,08	91,03	373,03	92,04
k-ω, Kato-Launder, SST	C	370,15	91,13	373,11	92,14

Preglednica 3. *Energijske izgube v toku in koeficient rekuperacije tlaka v sesalni cevi, dobljene z različnimi turbulentnimi modeli na redki in zgoščeni mreži*
Table 3. *Flow-energy losses and coefficient of pressure recovery in the draft tube obtained by several turbulence models on coarse and refined grids*
A - standardne log. stenske funkcije / standard log.-law wall functions
C - kombinacija stenskih funkcij za nizka in visoka Re števila / combined low and high Re wall functions

Turbulentni model Turbulence model	Model za tok ob steni Near-wall model	170 000 vozlov 170 000 nodes		452 000 vozlov 452 000 nodes	
		$\Delta E/g$ m	C_p %	$\Delta E/g$ m	C_p %
k-ε, standardni model, k-ε, standard model	A	0,257	51,02	0,251	51,9
k-ε, Kato-Launder	A	0,2528	52,02	0,2421	53,43
k-ε, RNG, Kato-Launder	A	0,2667	51,21	0,2689	50,39
k-ω, standardni model /k-ω, standard model	C	0,2616	49,31	0,2535	51,58
k-ω, Kato-Launder	C	0,2665	49,53	0,2588	50,33
k-ω, Kato-Launder, SST	C	0,272	47,52	0,273	48,37

Preglednica 4. *Izkoristek turbine v optimalni točki obratovanja za različne turbulentne modele in za dve gostoti mrež*
Table 4. *Turbine efficiency at the best-efficiency point for different turbulence models and for coarse and refined grids*
A - standardne log. stenske funkcije / standard log.-law wall functions
C - kombinacija stenskih funkcij za nizka in visoka Re števila / combined low and high Re wall functions

Turbulentni model Turbulence model	Model za tok ob steni Near-wall model	η/η_{opt} redke mreže coarse grids	η/η_{opt} goste mreže refined grids
k-ε, standardni model / k-ε, standard model	A	0,9126	0,9292
k-ε, Kato-Launder	A	0,9159	0,9332
k-ε, RNG, Kato-Launder	A	0,9146	0,9313
k-ω	C	0,9158	0,9311
k-ω, Kato-Launder	C	0,9182	0,9349
k-ω, Kato-Launder, SST	C	0,9196	0,9376

Launderjevim popravkom dobimo pri modelu k-ε manjše izgube, pri modelu k-ω pa se izgube celo povečajo. Z modelom k-ω SST dobimo največje izgube in najnižji C_p.

Z upoštevanjem izgub v posameznih delih turbine in navora na os turbine smo za oba dvoenačbna modela na redki in gosti mreži izračunali izkoristek turbine. Izkoristek, deljen z izmerjenim izkoristkom v optimalni točki obratovanja, je prikazan v preglednici 4. Pri vseh modelih se z zgoščanjem mreže izkoristek poveča za od 1,5 do 1,7%. Največji izkoristek dobimo z modelom k-ω SST, najmanjšega pa s standardnim modelom k-ε.

4 IZRAČUN TOKA V TURBINI BREZ PODATKOV IZ MERITEV

Pri vseh do sedaj prikazanih rezultatih je bil pretok pri določenem odprtju vodilnika in vrtljajih podatek, dobljen iz meritev. Kadar pa razvijamo novo turbino, tega podatka nimamo. Poznamo le razpoložljivi padec in vrtljaje, pri katerih bo turbina obratovala. Zato se v tem primeru naloge lotimo drugače. Na vstopu v turbino podamo le smer toka in totalni tlak, na izstopu pa statični tlak. Med izračunom se oblikuje pretok, ki ustreza dani tlačni razliki. Če računamo spiralo posebej, je postopek nekoliko bolj zapleten, saj ne vemo, kolikšen del tlačne razlike pomenijo izgube v spirali in kolikšen del odpade na preostalo turbino. Postopek postane iterativen. Za prvi približek vzamemo, da izgube v spirali pomenijo 1% celotnega razpoložljivega padca. Vstopne in izstopne robne pogoje za preostali del turbine predpišemo tako, da ustrezajo preostalim 99% razpoložljivega padca. Kot rezultat numerične analize toka dobimo neki pretok. Za ta pretok izračunamo tok v spirali in izgube v njej. Seštejemo tlačno razliko v spirali in v preostali turbini. Če se ta seštevek razlikuje od razpoložljivega padca, ustrezno popravimo vstopne in izstopne pogoje za izračun toka od predvodilnika do izstopa iz sesalne cevi. Po nekaj korakih se v okviru predpisane natančnosti približamo razpoložljivemu padcu. Ker se izgube v spirali večajo s kvadratom pretoka, tok v spirali računamo le enkrat, nato pa le še preračunamo izgube, ki ustrezajo novemu pretoku.

Tako smo izračunali tok v petih obratovalnih točkah pri nominalnem padcu. Računali smo z modelom k-ε s Kato-Launderjevim popravkom. Primerjava med izmerjenim in izračunanim pretokom je prikazana na sliki 6. Pri bolj zaprtem vodilniku je izračunani pretok nekoliko manjši od izmerjenega, pri večjih odprtjih vodilnika pa večji od izmerjenega. Največje odstopanje je

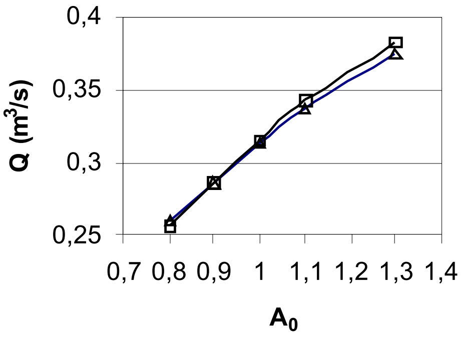
than those obtained by the k-ω model. With the Kato-Launder change of production term the flow-energy losses in the case of the k-ε model are reduced, while in case of the k-ω model they increase. With the k-ω SST model the largest flow-energy losses and the smallest C_p are obtained.

From the flow-energy losses in all the turbine parts and from the torque on the shaft, the turbine efficiency was calculated. The efficiency values, divided by the measured efficiency at the best-efficiency point, are presented in Table 4. For all the turbulence models used the efficiency obtained on the refined grid is from 1.5% to 1.7% higher than those obtained on the coarse grids. The highiest efficiency is obtained with the k-ω SST model and the smallest with the standard k-ε model.

4 ANALYSIS OF THE FLOW IN A TURBINE WITHOUT MEASURED DATA

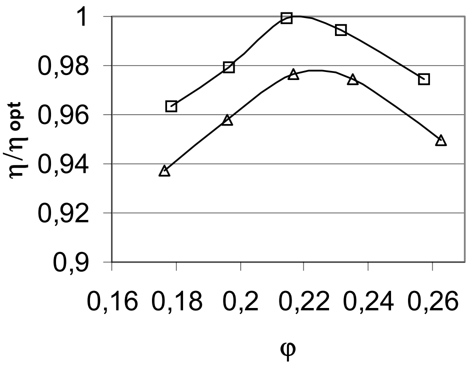
All the results presented so far were obtained from calculations where the discharge coresponding to a certain guide-vane opening and speed was obtained from measurements. When a new turbine is being developed, the discharge for a certain operating point is not known: we know only the avaible head and speed. Therefore, we have to solve the problem in a different way. At the turbine inlet the direction of the flow and the total pressure is prescribed, while at the outlet, the static pressure is prescribed. During the calculation, the discharge, which corresponds to the difference in pressure, is calculated. When the spiral casing is calculated separately, the procedure is a bit more complicated, because we do not know, how much of the head coresponds to the spiral casing and how much to the other turbine parts. The procedure becomes iterative. For the first approximation it can be assumed that the flow-energy losses in the spiral casing are 1% of the avaible head. Then we prescribe the inlet and outlet boundary conditions for the other parts of the turbine in such a way that the difference in the total pressure corresponds to 99% of the avaible head. A discharge is obtained as a result of a numerical analysis. For this discharge flow analysis of the spiral casing is made and we sum up the difference in the pressure in the spiral casing and in the other turbine parts. If the sum is not equal to the avaible head, we change the boundary conditions for the analysis of the flow from the stay-vane inlet to the draft-tube outlet. In a few steps, we obtain the discharge for which the calculated head is equal to the avaible head. The flow-energy losses in the spiral casing increase quadratically with the discharge, therefore, the flow in the spiral casing is calculated only once. For a new discharge only the flow-energy losses are recalculated.

In this way the flow at five operating points for the nominal head was calculated. The calculation was made with the Kato-Launder k-ε model. The calculated and measured discharge are compared in Fig. 6. For small guide-vane openings the calculated discharge is smaller than the measured one, while for large guide-vane openings it is larger. The largest descrepancy is 1.9%. The calculated efficiency is



□ - izračun - calculation
Δ - meritve – measurement

Sl. 6. *Izmerjeni in izračunani pretok pri dani geometrijski obliki, padcu in vrtljajih*
Fig. 6. *Measured and calculated discharge for a given geometry, head and speed*



□ - izračun - calculation
Δ - meritve – measurement

Sl. 7. *Izračunani in izmerjeni izkoristek pri dani geometrijski obliki, padcu in vrtljajih*
Fig. 7. *Calculated and measured efficiency for a given geometry, head and speed*

1,9%. Izračunani izkoristek je za okoli 2,5% manjši od izmerjenega, oblika krivulje se dobro ujema z meritvami (sl. 7).

5 SKUPNI IZRAČUN TOKA V CELOTNI TURBINI

Pri dosedanjih izračunih smo računali spiralo posebej, pri kaskadah predvodilnika, vodilnika in gonilnika pa smo se omejili na en periodični del. S tem smo predpostavili, da je tok med poljubnima lopaticama enak. To zlasti v primeru predvodilnika ne drži. V obravnavanem primeru celo lopatice predvodilnika niso enake, ampak se njihova dolžina manjša od vstopnega dela proti ostrogi spirale. Da bi ugotovili, kolikšen je vpliv ločenega izračuna toka v spirali in vpliv omejitve kaskad na en periodični del, smo izračunali tok v celotni turbini od vstopa v spiralo do izstopa iz sesalne cevi z vsemi predvodilnimi, vodilnimi in gonilnimi lopaticami. Zaradi premajhnih računalniških zmogljivosti je uporabljena računska mreža zelo redka, ima okoli 510 000 vozlov. Za primerjavo rezultatov v optimalni točki obratovanja smo tudi ločen in sklopljen izračun ponovili na enako redkih mrežah. Primerjali smo izračunane izkoristke, deljene z izkoristkom v optimalni točki obratovanja. Z ločenim izračunom vsakega dela turbine smo dobili vrednost 0,851, z ločenim izračunom spirale in skupnim izračunom toka v preostalih delih 0,929, s skupnim izračunom toka v celotni turbini pa 0,9398. Izkoristek pri skupnem izračunu toka v celotni turbini je največji predvsem zaradi manjših izgub v kaskadah predvodilnika in vodilnika. Te izgube so se zmanjšale zaradi skupnega izračuna spirale in kaskade. Pri izračunih, pri katerih smo se omejili na en periodični del, smo vzeli najdaljšo predvodilno lopatico in smo tudi zato dobili prevelike izgube.

about 2.5% less than the measured one (Fig. 7). The shape of the calculated efficiency curve is in good agreement with the measurements.

5 COUPLED CALCULATION OF THE FLOW IN A COMPLETE TURBINE

In all the calculations so far, the flow in the spiral casing was calculated separately and the stay vane, the guide vane and the runner cascades were reduced to one periodical part. It was assumed that the flow between any two blades or vanes is equal. However, this is not true, especially for stay vanes. The stay vanes are not equal, their length decreases from the inlet part to the nose of the spiral casing. To see effect of a separate calculation of the spiral casing and the effect of the reduction of the cascades' domains to one periodical part, the flow in the whole turbine, from the spiral casing inlet to the draft-tube outlet with all the stay and guide vanes and all the runner blades was calculated simultaneously. Due to insufficient computer capacity the grid is very coarse, it consists of about 510 000 nodes. To compare the results at the best-efficiency point, the separate and coupled calculation was also repeated on equally coarse grids. The calculated values of efficiency, divided by the measured efficiency at the BEP were compared. By a separate analysis of each turbine part a value of 0.851 was obtained, by a separate analysis of the spiral casing and coupled analysis of the other turbine parts we got a value of 0.929, and by a simultaneous calculation of the whole turbine a value of 0.9398 was obtained. The efficiency was the highest for a simultaneous calculation of the flow in the whole turbine, mainly due to the smaller flow-energy losses in the stay- and guide-vane cascades. The reason for the smaller losses in the tandem cascade is the coupled calculation of the spiral casing. In the calculation where the domains were reduced to one periodical part the flow between the longest two stay vanes was calculated and that was also the reason for the too high flow-energy losses.

6 SKLEP

Iz prikazanih rezultatov lahko povzamemo, da z ločenim izračunom toka v spirali in s skupnim izračunom toka v dvojni kaskadi, gonilniku in sesalni cevi dovolj natančno napovemo lego optimalne točke obratovanja, tudi oblika diagrama izkoristka se dobro ujema z izmerjeno. Izračunani izkoristek je za okoli 3% manjši od izmerjenega, vendar se z zgostitvijo mrež izmerjenim rezultatom zelo približamo. Pri ločenem izračunu smo z zgostitvijo mrež in vključitvijo Kato-Launderjevega popravka v model k-ε dobili za 2% višji izkoristek. Enako izboljšanje lahko pričakujemo tudi pri sklopljenem izračunu na gosti mreži, ki pa zaradi premajhnih računalniških zmogljivosti ni bil izveden. Sklepamo, da se s sklopljenim izračunom na zgoščeni mreži s Kato Launderjevim modelom k-ε izmerjenemu izkoristku lahko približamo na 1%.

S skupnim izračunom toka v celotni turbini na zelo redki mreži smo dobili za 1% večji izkoristek kakor pri ločenem izračunu spirale in skupnem izračunu toka v preostalih delih. S tem smo pokazali, da je izračunani izkoristek v prejšnjih izračunih premajhen tudi zaradi ločenega izračuna toka v spirali in omejitve kaskad na en periodični del. Zato lahko bolj kakor na 1% natančne vrednosti izkoristka pričakujemo le z izračunom celotne turbine na zelo gosti mreži.

V postopku razvoja novih gonilnikov je pomembno, da tudi v primeru, ko ne poznamo pretoka pri danem odprtju vodilnika, tega lahko dokaj natančno izračunamo. Tudi v tem primeru se lega optimalne točke obratovanja in oblika diagrama izkoristka dobro ujemata z izmerjenimi rezultati.

6 CONCLUSION

From the results presented it can be concluded that by a separate analysis of the flow in a spiral casing and a coupled analysis in a tandem cascade, runner and draft tube, the position of the best-efficiency point and the shape of the efficiency diagram are accurately predicted. The calculated efficiency is about 3% lower than the measured one, but with grid refinement the calculated results approach the measured ones. With grid refinement and by including the Kato-Launder production term in the k-ε model the efficiency of the separate analysis increased by 2%. The same improvement can be expected for a coupled calculation on a refined grid. This calculation was not performed due to computer capacity. We would expect that the efficiency obtained with a coupled calculation on a refined grid would be within 1% of the measured value.

The efficiency obtained from a simultaneous calculation of the flow in a complete turbine with a very coarse grid is 1% higher than that obtained by a separate analysis of the spiral casing and a coupled analysis of the flow in the other turbine parts. This result shows that the calculated efficiency is also too low because of a separate analysis of the spiral casing and the reduction of cascades domains to one periodical part. Therefore, less than a 1% difference between the calculated and measured efficiency can be expected only with a coupled calculation of the whole turbine on a very fine grid.

In the design process it is very important that when the discharge coresponding to a certain guide-vane opening is not known, it can be calculated accurately enough. Also, in this case the position of the best-efficiency point and the shape of efficieny diagram is in good agreement with measured results.

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Analiza raznosa tlaka pri uporabi prilagodljivega pridrževala z možnostjo nadzora pridrževalne sile med globokim vlekom

An Analysis of the Spreading of a Holding Pressure by Means of a Pliable Blank Holder with the Controllable Holding Force during a Deep-Drawing Process

Boris Jerman - Roman Hodnik - Janez Kramar

Eden od pomembnejših parametrov globokega vleka je sila pridrževanja preoblikovanca. Zaradi izboljšanja kvalite zahtevnejših izdelkov je v zadnjem času izražena potreba po možnosti časovnega in krajevnega nadzora sile pridrževanja. Za učinkovit krajevni nadzor je potrebno toga pridrževala nadomestiti s prilagodljivimi ali segmentnimi. V prispevku so prikazane razmere pridrževanja s prilagodljivim pridrževalom debeline 30 mm, ki pritiska na preoblikovanec s 16 hidravličnimi valji med postopkom izdelave testnega izdelka. Rezultati raziskave prikazujejo krajevno porazdelitev tlaka prilagodljivega pridrževala na preoblikovanec za več zaporednih stanj med postopkom ob upoštevanju spremembe oblike in debeline preoblikovanca.

(Ključne besede: globoki vlek, pridržala, sile pridrževanja, analize uporabnosti)

One of the most important parameters in the deep-drawing process is the force holding the blank. In a desire to improve the quality with products of complex geometries, forming technology has focused developments on better time-and-place control of the holding force. For a more efficient location control of the holding force it is necessary to replace highly rigid blank holders with pliable or segmented blank holders. This paper discusses the holding conditions when a pliable blank holder of thickness 30 mm presses against the blank with 16 hydraulic cylinders during the process of forming a test product. The results of the research show the local distributions of pressure acting on the blank for a sequence of states during the process, taking into account the changes in the shape and the thickness of the blank.

(Keywords: deep drawing, holders, holding force, applicability analysis)

0 UVOD

Globoki vlek pločevine je postopek preoblikovanja, ki se v velikoserijski proizvodnji s pridom uporablja že dlje časa. Navkljub široki uporabi v industriji, pa postopek še zdaleč ni optimalen. Poleg razvoja preoblikovalnega postopka samega, se v zadnjem času velik poudarek daje tudi obliki izdelka, ki naj poleg funkcionalnosti zagotavlja tudi optimalen izdelovalni postopek, torej optimalno obliko orodja in minimalno število preoblikovalnih operacij ([1] in [2]).

Kljub omenjenim uspehom, ostaja ena od najpomembnejših nalog načrtovalcev zagotovitev optimalnih parametrov globokega vleka. Med temi parametri je pomembna tudi primerno porazdeljena sila pridrževanja preoblikovanca [4]. Zaradi zakonitosti

0 INTRODUCTION

The deep drawing of sheet metal is a forming procedure that has found widespread use in high-volume production. In spite of this, the deep-drawing process is far from being optimized. Besides development of a metal-forming process, in recent years, great emphasis has been put on the product's shape, which should, in addition to functionality, enable the optimized running of the forming process, i.e. the optimum shape of the forming tool and the minimum number of forming operations ([1] and [2]).

Despite considerable success, choosing the best parameters for the deep-drawing process still remains an important task for process planners. One of the parameters that is especially difficult to optimize is the adequately distributed blank-holding force [4].

toka materiala med preoblikovalnim postopkom se debelina in površina preoblikovanca pod pridrževalom s časom spreminjata, zaradi česar v splošnem ni mogoče shajati niti s časovno, niti s krajevno konstantno silo pridrževanja. Problem je velik predvsem pri zapletenejših izdelkih. Lokalno povečanje sile pridrževanja pri stiskalnici s togim pridrževalom je možno, vendar imajo uporabljene metode kar nekaj pomanjkljivosti.

V zadnjih letih je opazen razvoj sistemov, ki omogočajo krajevni in časovni nadzor sile pridrževanja med postopkom globokega vleka, kar omogoča izboljšanje kakovosti izdelka in večjo stopnjo preoblikovanja med eno operacijo. Naštete prednosti so pomembna vzpodbuda za raziskave in nadaljni razvoj takih pridrževalnih sistemov, katerih osnova je bodisi: pridrževanje s prilagodljivim (podajnim) ali pa s segmentnim pridrževalom. V pričujočem prispevku je analizirana možnost zagotovitve optimalne krajevne porazdelitve pridrževalnega tlaka s prilagodljivim pridrževalom. Tako pridrževalo se pod vplivom pridrževalne sile deformira ter se (delno) prilagodi trenutni obliki površine preoblikovanca. S tem se poveča njuna medsebojna dotikalna površina in doseže ustreznejša lokalna porazdelitev pridrževalnih tlakov. Za uspešno uporabo predstavljenega koncepta je potrebno zagotoviti predvsem ustrezno preoblikovalnost pridrževalne plošče in ustrezno število (hidravličnih) aktuatorjev.

Zadana naloga zahteva izračun tlakov pridrževala na preoblikovanec. V ta namen je bilo treba izdelati analizo prostorskega dotika (kontakta) med preoblikovancem in pridrževalom. Taki kontaktni problemi so malo raziskani že na elementarni ravni [5], raziskave v smeri kontaktnih napetosti v tehnoloških pogojih globokega vleka pa se pojavljajo šele v zadnjih letih ([3], [4] in [6]). Za razliko od raziskav ([3] in [4]), ki se nanašajo na učinkovanje enega hidravličnega valja preko toge plošče in primerno dolgih vmesnih stebričkov na tanko prilagodljivo ploščo, ima pričujoča raziskava namen proučiti interferenco (medsebojno učinkovanje) več hidravličnih valjev neposredno na tanko prilagodljivo ploščo (prilagodljivo pridrževalo). Za analize je izbrana metoda končnih elementov (MKE). Uporabljen je programski paket ANSYS®. Opazovane so razmere pri nekaterih elementarnih primerih dotika in kasneje tudi razmere med realnim globokim vlekom.

1 PORAZDELITEV TLAKOV POD PRIDRŽEVALNO PLOŠČO V ODVISNOSTI OD NJENE DEBELINE

Za uspešno načrtovanje krajevnega nadzora pridrževalne sile je potrebno poznati porazdelitev tlaka pod pridrževalno ploščo. Raziskan je vpliv enega hidravličnega valja na tlak pod pridrževalno ploščo v odvisnosti od njene

Due to the laws of material flow during the forming process, the thickness and area of the blank covered by the holder will vary with time. This is why, in general, it is not possible to do the job with a locally constant or time-constant force, and the problems get bigger for products with complex geometries. On a press with a rigid blank holder it is normally possible to increase the local holding force, but the methods applied to achieve this have a few disadvantages.

In recent years, development trends have been directed towards systems with place and time control of the holding force during the deep-drawing process. This type of control would improve product quality and forming efficiency in a single operation. These advantages have encouraged further research and development to improve blank-holding systems. There are two main principles for this kind of holding systems: a system with an elastic (pliable) blank holder and a system with a segmented holder. In this paper we have looked at ensuring optimal local distribution of the holding pressure with a pliable holder. Under the influence of the holding force applied, a pliable blank holder deforms and (partially) adjusts itself towards momentary blanks shape. So the size of the interacting contact surface increases and a better local distribution of the holding pressure is achieved. In addition to a suitable number of hydraulic actuators, such a system requires the appropriate deformability of the holding plate to give us the desired local pressing effects.

In order to achieve our objective we had to calculate the pressures acting on the blank. This meant we had to analyse the space contact between the blank and the holder. This kind of contact problem has been given little attention, even on an elementary level [5], and research reports that focused on the technology of deep drawing can be traced only in recent years ([3], [4] and [6]). In contrast to reports ([3] and [4]), where an action of one hydraulic cylinder is transferred to a thin pliable plate by means of rigid plate and intermediate bars, this paper shows the combined effects of multiple cylinders, acting directly on the thin plate (pliable blank holder). In the performed analysis the finite-element method (FEM) and ANSYS® software package were used. Initial observations were of the conditions present in some elementary cases of contact, after which conditions during a real deep-drawing process were also studied.

1 THE PRESSURE DISTRIBUTION UNDER THE HOLDING PLATE AS A FUNCTION OF ITS THICKNESS

For the successful planning of the local control of the holding force it is necessary to know the pressure distribution under the holding plate. An analysis was made of the influence of one hydraulic cylinder and a series of cylinders on the pressure under the holding debeline ter vpliv več zaporedno nameščenih valjev. Proučevana so pridrževala debelin 60, 80 in 100 mm. Modelirana so s prostorskimi končnimi elementi. Analiza temelji na predpostavki, da je površina, na katero pritiska pridrževalo, ravna in toga ter je zato nadomeščena s podporami v ustrezni smeri. Med pridrževalom in podlago so nameščeni kontaktni elementi. Trenje med pridrževalom in podlago ni upoštevano. Sila posameznega valja znaša 684 kN. Predstavljena je kot tlak v krogu s premerom 60 mm.

plate as a function of its thickness: holders with a thickness of 60, 80 and 100 mm were studied. The holders were modeled by volume finite elements, with the analysis based on the assumption that the surface pressed down by the holder is flat and rigid and can be replaced by supports acting in the required direction. The contact elements were placed between the blank holder and the support. The friction between the plate and the support was not considered. Each of the applied cylinders acted with a force of 684 kN. This force is represented as a pressure acting on a circle with a diameter of 60 mm.

1.1 Model z enim hidravličnim valjem

Pridrževalo je predstavljeno kot kvadratna plošča s stranicama 500 mm. Celotna spodnja površina se opira na togo oporo. Na gornjo stran pridrževala (v središču) deluje en hidravlični valj. Porazdelitve napetosti, glede na debelino pridrževala so v tem primeru skoraj simetrične okoli simetrijske osi hidravličnega valja (diagram 1).

1.1The model with one hydraulic cylinder

The blank holder is represented as a square plate with sides of 500 mm. Its complete lower surface is supported by a rigid support. One hydraulic cylinder acts on the upper side of the blank holder (in the centre). The distributions of stresses as a function of the blank-holder thickness are, in this case, nearly symmetrical, spreading around the symmetry axis of the hydraulic cylinder (Graph 1).

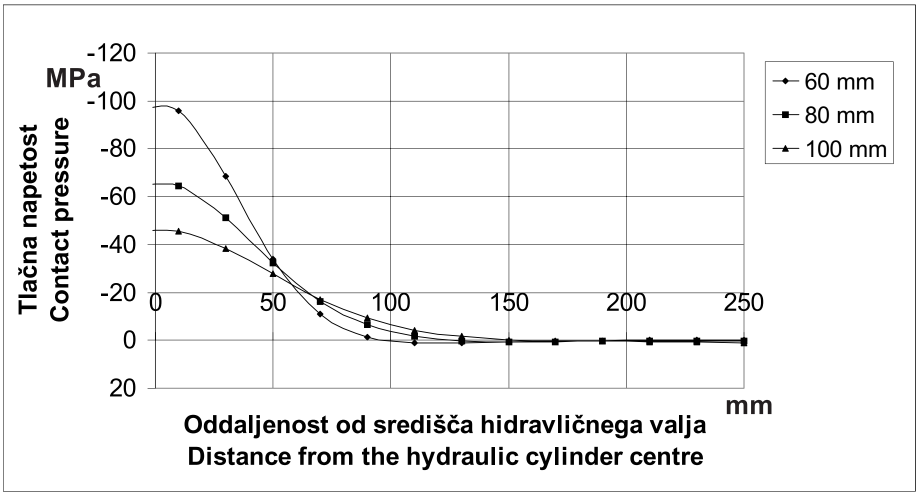


Diagram 1. *Porazdelitev tlakov pod pridrževalom v odvisnosti od oddaljenosti od središča hidravličnega valja za debeline pridrževala 60, 80 in 100 mm*

Graph 1. *The pressure distribution under the blank holder versus the distance from the hydraulic cylinder centre for the blank holder thicknesses 60, 80 and 100 mm*

Iz diagrama 1 je razvidno, da debelejše pridrževalo (kot je bilo pričakovati) delujočo silo hidravličnega cilindra »razmaže« po večji površini, torej se pojavi pritisk pridrževala na platino na večjem območju in z manjšim povprečnim in manjšim največjim tlakom.

From graph 1 we can see that the thicker blank holder — as expected — spreads the applied force of the hydraulic cylinder over a larger area. The pressure of the blank holder occurs over a wider area of the blank having a lower average and lower a maximum pressure.

1.2 Model s šestimi hidravličnimi valji

Pri dejanski izvedbi pridrževanja s prilagodljivim pridrževalom je običajno uporabljenih več hidravličnih valjev, nameščenih tako, da največkrat pritiskajo na površino pridrževala v bližini kakšnega od robov. Tak rob predstavlja npr. rob platine, ki med procesom globokega vleka potuje in

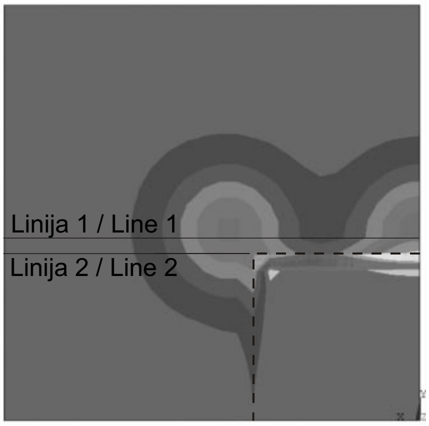
1.2 The model with six hydraulic cylinders

In the actual process of holding a blank with a pliable blank holder, usually more than one hydraulic cylinder is used. In most cases the cylinders are positioned in such a way that the pressure produced is acting near an edge. Such an edge can be a blank's edge (changing position and shape during the protudi rob matrice, na katerem se platina začne preoblikovati. Od teh robov dalje preoblikovanec pridrževala ne podpira več.

V modelu je pridrževalo predstavljeno kot kvadratna plošča s stranico 1000 mm. Vpliv robov matrice je popisan s pomočjo izreza na platini v velikosti 400 x 400 mm. Na zgornjo stran pridrževala, ob robovih matrice, je nameščenih 6 hidravličnih valjev. Njihova lega je razvidna is slike 1. Iz diagrama 2 je razviden skupen vpliv sosednjih valjev.

cess of deep drawing) or a draw ring's edge. From these edges onwards the blank holder is no longer supported by the sheet metal.

The blank holder is represented as a square plate with sides of 1000 mm. The draw ring's edges are represented as a square-shaped cutting with sides of 400 mm. To the upper side of the blank holder beside the draw ring's edges six hydraulic cylinders are acting. Their positions are shown in figure 1. Graph 2 shows the combined effects of the adjacent cylinders along two lines.



Sl. 1. *Prikaz četrtinke modela s šestimi hidravličnimi valji in izrezom*
Fig. 1. *One quarter of a model with six hydraulic cylinders and square-shaped cutting*

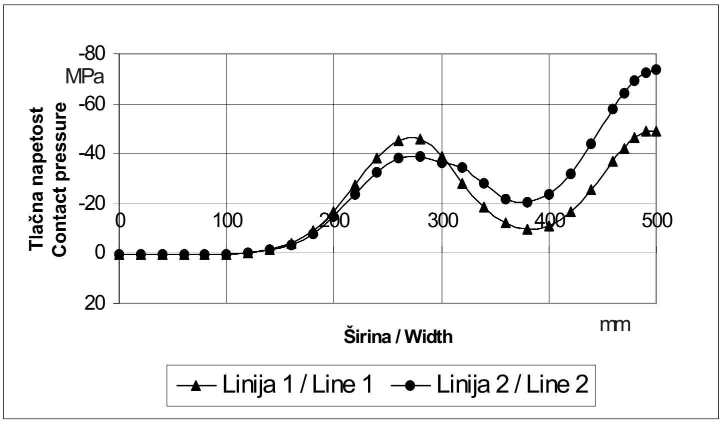


Diagram 2. *Porazdelitev tlakov pod pridrževalom na linijah 1 in 2*
Graph 2. *The pressure distribution under the blank holder along lines 1 and 2*

2 RAZISKAVA VPLIVA RAZLIK V DEBELINI LAMELE NA POGOJE PRIDRŽEVANJA

Analize v prejšnjem poglavju temeljijo na predpostavki, da je pločevina, na katero pritiska pridrževalo, ravna in toga. To zadosti dobro velja za začetek in začetno fazo globokega vleka. Kasneje se, zaradi zakonitosti tečenja materiala med globokim vlekom, pojavijo opazne razlike v debelini pločevine ([4], [1] in [2]). Zaradi tega je potrebna analiza, ki upošteva dejansko debelino in obliko preoblikovanca, na katerega nalega pridrževalo.

2.1 Vhodni podatki za analizo

2.1.1 Oblika in izmere testnega izdelka

Ker je izbrani tip analize (MKE) numeričnega značaja, je za opazovanje potrebno izbrati izdelek določenih dimenzij. Izbran je pomivalnemu koritu podoben izdelek z izmerami 400 x 400 mm s polmeri zaokrožitve 80 mm na vogalih med stranicami in 45 mm na dnu korita. Na sliki 2 je vidno nastajajoče korito ter deformirani robovi platine (pred deformacijo pravilni osemkotnik). Odtenki sivine predstavljajo razliko v debelini

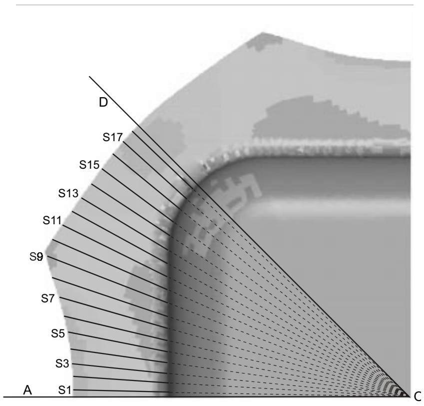
2 THE STUDY OF THE EFFECTS OF VARYING THE THICKNESS OF THE SHEET-METAL PLATE ON THE HOLDING CONDITIONS

The analysis in previous section is based on the assumption that the sheet metal subjected to the blank-holder pressure is perfectly flat and rigid. This is true for the initial conditions and the first phase of deep drawing. In subsequent phases, however, due to the laws of material creep in the deep-drawing process, large differences occur in the thickness of the sheet metal ([4], [1] and [2]). This fact requires to make a further analysis that considers the real thickness and shape of the blank which is in contact with the blank holder.

2.1 Entry data for analysis

2.1.1 Shape and dimensions of the test product

Because the selected form of analysis (FEM) is of the numerical kind, the studied object has to have concrete dimensions. Our object was a semi-finished product resembling a kitchen sink with dimensions of 400 x 400 mm and a radius of rounding of 80 mm in the corners between the sides, and 45 mm at the bottom of the sink. The formation of the sink and the deformed blank's edges are shown in figure 2. Beams S1 till S18 are also shown (the meaning of these beams is ex-



Sl. 2. *Prikaz četrtinke preoblikovanca med globokim vlekom (pogled od zgoraj)*
Fig. 2. *A fourth of the blank during the deep-drawing process (viewed from top)*

preoblikovane pločevine [2]. Prikazani so tudi žarki S1 do S18, katerih pomen je pojasnjen v poglavju 2.1.2. Črki A in D označujeta robova 1/8 modela preoblikovanca in pojasnjujeta položaj teh robov na slikah 3 in 8.

plained in section 2.1.2). The intensity of the grey colour shows changes in the thickness of a blank [2]. Using letters A and D the edges of 1/8 of the model of the product are signed. This designation explains the position of this edges in figures 3 and 8.

2.1.1 Oblika in izmere preoblikovanca med globokim vlekom in optimalna sila pridrževanja

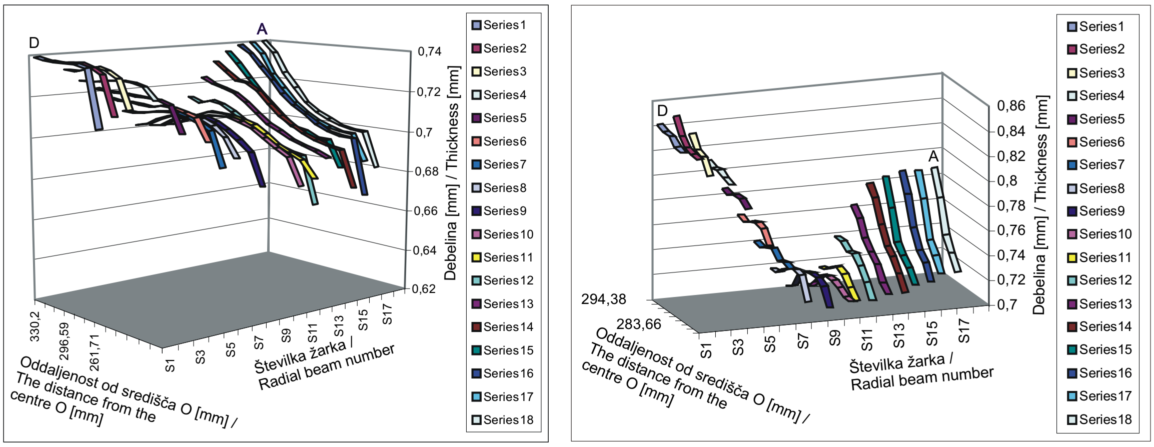
Za izdelavo testnega izdelka je bila izbrana platina debeline 0,7 mm v obliki pravilnega osemkotnika (slika 4-b), katerega velikost je določena z oddaljenostjo 700 mm med njegovimi vzporednimi robovi.

Platina se med postopkom globokega vleka plastično deformira, zaradi česar se pojavi pomikanje ter deformiranje njenih robov ter lokalno spreminjanje

2.1.2 The shape and dimensions of the blank during the deep-drawing process and the optimum holding force

To manufacture the test product we chose a blank with a thickness of 0.7 mm in the form of a regular octagon (Fig. 4b), with the distance 700 mm between the parallel edges.

During the deep-forming process the blank deforms plastically, while its edges move and deform resulting in a varying local thickness. The thickness



a) Stanje 5: Razlika med najmanjšo in največjo debelino plošče je ~ 0,07 mm
a) Phase 5: The difference between the minimum and maximum thickness of the sheet bar is ~ 0.07 mm

b) Stanje 8: Razlika med najmanjšo in največjo debelino plošče je ~ 0,15 mm
b) Phase 8: The difference between the minimum and maximum thickness of the sheet bar is ~ 0.15 mm

Sl. 3. *Prikaz debeline preoblikovanca med globokim vlekom za stanji 5 in 8. Serije S1 do S18 predstavljajo radialne žarke S1 do S18 iz središča modela (točka O na sl. 2) proti njegovim robovom. Žarki so enakomerno porazdeljeni na 1/8 modela (45^{O}). Za lažjo orientacijo sta označeni tudi mesti A in D (glej tudi sl. 2 in 8)*
Fig. 3. *Thickness of the blank during deep drawing in phase 5 and 8. The series from S1 to S18 represent the radial beams S1 to S18 from the centre of the model O /Fig. 2) towards its edges. The beams are evenly distributed over 1/8 of the model (45^{O}). For better orientation, spots A and D are marked, too (see also Fig. 2 and 8)*

njene debeline. Debelina se poveča na mestih, kjer se pojavijo večji presežki materiala [2]. Postopek globokega vleka testnega izdelka je bil simuliran z uporabo programskega paketa PAM-STAMP®, od koder izhajajo podatki o obliki in izmerah preoblikovanca za 10 zaporednih stanj in tehnološka optimalna sila pridrževanja F_o = 848 kN [2]. Končna globino vleka je bila 180 mm.

Analiza obnašanja prilagodljivega pridrževala je bila izvršena za začetno fazo (0), kjer je platina še popolnoma nedeformirana (sl. 4b), ter za stanji 5 in 8, kjer se pokaže najprej zmerna in nato velika sprememba debeline preoblikovanca (sl. 3a in 3b).

2.2 Model preoblikovanca s pritisnjenim pridrževalom

Osnova za izgradnjo modela z MKE so podatki o debelini pločevine preoblikovanca na posameznem mestu, v skladu s poglavjem 3.1. Rezultati iz PAM-STAMP®-a so bili za posamezno opazovano stanje preneseni v ANSYS® s pomočjo vmesnika, napisanega v programskem jeziku Fortran. V prostorskem modelu sta z elementi modelirana pridrževalo in preoblikovanec v ustreznem stanju. Dotik med njima je ustvarjen z ustreznimi kontaktnimi elementi. S spodnje strani je preoblikovanec podprt v smeri svoje debeline, s čimer je za začetek vpeljana predpostavka ravne in nedeformljive podlage (matrice). Vpliv hidravličnih valjev je vnesen kot tlak na površino naleganja pestiča valja na pridrževalo. Površina naleganja je krog s premerom 50 mm (sl. 5). Zaradi večkratne simetričnosti je modelirana le 1/8 modela, kar omogoča znatne prihranke pri računskem času. Na slikah je včasih zaradi lažje predstave prikazana bodisi četrtina ali pa polovica modela.

2.2.1 Preoblikovanec v modelu

Matrica orodja za prvo stopnjo globokega vleka ima robove, obdelane v obliki krivulje, ki omogoča čim boljši pretok materiala. Ta krivulja zasede v tlorisu pas 12 mm okoli osnovne oblike korita, tako da znese površina, kjer platina (sl. 4-b) ne nalega na matrico (in torej tudi pritisk pridrževala na platino ni smiselen) 424 x 424 mm s polmerom zaokrožitve 92 mm (400+2x12=424, 80+12=92). Na tej površini platina ni modelirana. Debelina in oblika zunanjega roba platine oz. preoblikovanca je modelirana v skladu s poglavjem 2.1.2 za vsako izmed opazovanih stanj.

2.2.2 Pridrževalo v modelu

Pridrževalo je modelirano kot kvadratna plošča s stranico 720 mm (sl. 4a). V sredini ima luknjo za pestič orodja za globoki vlek. Analizirana so bila

increases at spots with bigger surpluses of material [2]. The deep-drawing process that we used for the test product was simulated with the PAM-STAMP® software package. The simulation gave us data on the shape and dimensions of the blank during the process for ten sequential states and the optimum technological holding force F_o = 848 kN [2]. The drawing depth was 180 mm.

The analysis of the behaviour of the pliable blank holder was made for the initial phase (0), where the blank is still completely undeformed (Figure 4-b) and the phases 5 and 8 where first a moderate and then a large change in the thickness of the blank can be observed (Fig. 3a and b).

2.2 Model of the blanks with a pressed-down holder

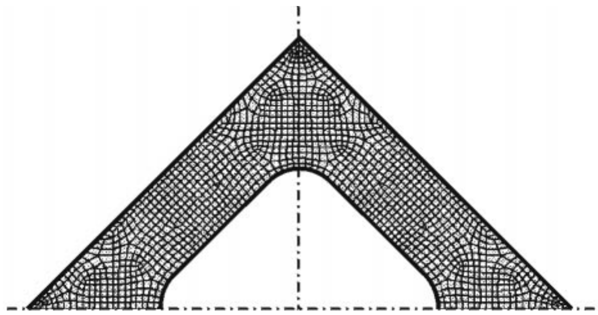
The FEM model was built on the basis of the thickness data at individual points on the blank, defined in 2.1. For each phase of the study the results obtained with PAM-STAMP® were transferred into ANSYS® using an interface written in FORTRAN. In the space model, the volume elements are used to model the holder and the blank in the appropriate phase. The contact between them is created by adjustable contact elements. From the bottom up the blank is supported in the direction of its thickness, and an initial assumption of a flat and undeformable support (die) is introduced. The influence of the hydraulic cylinders is entered as the pressure acting on the bearing area of the cylinder punch on the holder. The bearing area is a circle with a diameter of 50 mm (fig. 5). Because of the multiple symmetry only 1/8 of the model is modeled, which enables considerable savings in computation time. To give a clearer picture the figures are sometimes shown as either a quarter or a half of the model.

2.2.1 The blank in the model

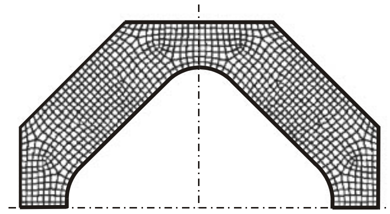
The die of the tool for the first degree of deep drawing has its edges machined in the form of a curve to ease the flow of material. In the ground plan this curve takes a 12-mm wide band around the basic shape of the trough so that the area where the blank (Fig. 4-b) is not carried by the die (so the pressure of the holder on the blank is ineffective) is 424 x424 mm with a radius of curvature of 92 mm (400+2x12 = 424, 80+12=92). The blank is not modelled on this area. The thickness and shape of the outer edge of the blank or blank are modelled as described in section 2.1.2 for each of the observation phases.

2.2.2 Blank holder in the model

The blank holder is modelled as a square plate with sides of 720 mm (Fig. 4a). In the middle it has a hole for the punch of the deep-drawing tool.



a) Pridrževalo z luknjo za pestič
a) Blank holder with a hole for the punch



b) Plošča brez dela, ki nima opore na matrici (stanje 0 tik pred začetkom vleka)
b) Sheet bar without the area not carried by the die (Phase 0 right before the start)

Sl. 4. *Pridrževalo in plošča v modelu po MKE (prikazana ena polovica)*
Fig. 4. *FEM models of blank holder and sheet bar (only half of each model is shown)*

pridrževala različnih debelin, prikazani pa so rezultati za t = 30 mm.

2.2.3 Obremenitve modela

Proučevanih je bilo več primerov namestitve hidravličnih valjev. Prikazani so rezultati za primer pridrževanja s 16 valji (2 valja na 1/8 pridrževala - sl. 5). Sila na en valj je bila (v skladi s poglavjem 2.1) F_{o1} = 848/16 = 53 kN.

Sili F_{o1} valjev 1 in 2 (sl. 5) bi bili lahko različni, za kar pa v konkretnem primeru ni bilo potrebe, saj sta bili, zaradi pojava neenakomernih debelin preoblikovanca, že enaki sili dovolj za dokaj dobro ujemanje dobljenega stanja z želenim, dokler je pridrževalo s svojo prilagodljivostjo lahko sledilo obliki neravnin (sl. 8 in 9).

Analiza je bila opravljena za več vrednosti pritisne sile hidravličnih valjev F_{v1}. Vpeljan je faktor k, kot večkratnik optimalne obremenitve: $F_{v1} = k \cdot F_{o1}$. Rezultati so prikazani za k = 1 in 1,5.

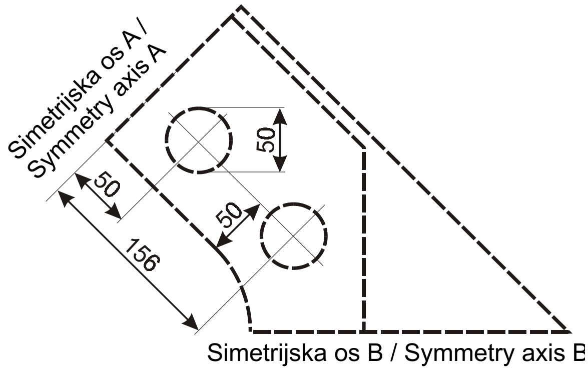
Several thicknesses of blank holder were analyzed. The results are shown for t = 30 mm.

2.2.3 Loads in the model

Several arrangements of hydraulic cylinders were studied. The results are shown for the case of holding with 16 cylinders (2 cylinders per 1/8 of the holder, see fig. 5). The force per one cylinder was (according to 2.1) F_{o1} = 848/16 = 53 kN.

The forces F_{o1} of cylinders 1 and 2 (Fig. 5) could be different, but there was no requirement in the studied example because the occurrence of a non-uniform thickness of the blank meant that equal forces were enough to make the resulting state match relatively well to the required state as long as the blank holder could, thanks to its pliability, follow the uneven shapes (Figs. 8 and 9).

The analysis was carried out for several values of the compression force of the hydraulic cylinders F_{v1}. Factor k is introduced as a multiple of the optimum load: $F_{v1} = k \cdot F_{o1}$. The results are shown for k = 1 and 1.5.



Sl. 5. *Lega pestičev (premera 50 mm) hidravličnih valjev na 1/8 pridrževala*
Fig. 5. *The position of punches (diameter 50 mm) of the hydraulic cylinders on 1/8 of the holder*

2.3 Rezultati

Rezultati so prikazani kot tlaki na površini preoblikovanca na strani, ki je v dotiku s pridrževalom. Opazovana je napetost v smeri z, torej v smeri debeline preoblikovanca.

2.3.1 Rezultati stanja 0

Po pričakovanju so razmere zelo podobne razmeram pri dotiku na togo in ravno podlago. Ujemanje je logično, ker je platina na začetku konstantne debeline.

Iz slik 6 in 7 je razvidno, da navkljub povečevanju pridrževalne sile preko njene optimalne vrednosti (k = 1,5), ne dobimo tlaka pridrževanja na celotno območje platine. To se ne zgodi niti pri dvojni (k = 2) optimalni sili (analiza je izvršena, vendar rezultati zaradi pomanjkanja prostora niso prikazani). Iz tega bi lahko sklepali, da je pridrževalo pretanko, ker ne omogoča dovolj širokega raznosa tlačnih napetosti, da bi se sosednja napetostna stožca prekrila in bi bila razporeditev pridrževalnega tlaka enakomernejša. Kot bo razvidno iz nadaljnih rezultatov pa to ne drži povsem, saj povečanje debeline pridrževala zmanjšuje preoblikovalnost in s tem prilagodljivost.

2.3.2 Rezultati stanja 5

Razmere nasproti stanju 0, ko je bila platina še konstantne debeline, so se pri stanju 5 močno spremenile. Iz slik 8 in 9 je razvidno, da se je slika pridrževalnih tlakov močno spremenila. Slika 8 prikazuje razmere pri optimalni sili (k=1). Največji tlaki se ne pojavljajo več pod pestičema hidravličnih valjev, temveč na mestih A in D, kjer je pločevina trenutno najdebelejša (glej tudi sliko 3).

Ker je pridrževalo dovolj tanko in s tem podajno, se toliko upogne, da dobimo dotik med pridrževalom in platino tudi na mestih pod valjema (mesti B in C) in s tem bistveno enakomernejšo porazdelitev pridrževalnih tlakov. Pri analizi enakega modela z debelejšim pridržalom (t=60 mm), tega dotika ni bilo (analiza je izvršena, vendar rezultati zaradi pomanjkanja prostora niso prikazani), zaradi česar sta bili izrazitejši konici na mestih A in D, podobno kot se to dogaja pri neprilagodljivih pridrževalih.

Pri povečani pridrževalni sili (k=1,5) se poveča tudi površina pridrževala, ki se dotika preoblikovanca, kar zmanjšuje intenzivnost konic napetosti v točkah A in D.

2.3.3 Rezultati stanja 8

Iz slik 10 in 11 je razvidno, da kljub povečevanju pridrževalne sile preko njene tehnološke

2.3 Results

The results are shown as pressures on the blank surface on the side that is in contact with the blank holder. The stress in the direction of z-axis is observed, i.e. in the direction of the thickness of the blank.

2.3.1 Results of phase 0

As expected the conditions are very similar to those present in the contact with the rigid and flat support. This resemblance is logical since at the beginning the blank has a constant thickness.

From Fig. 6 and 7 we can see that in spite of an increase in the holding force beyond its optimum value (k = 1.5), the holding pressure is not obtained over the entire area of the blank. This does not happen even when the optimum force is doubled (k =2 – results are available but not shown because of the space limitation). From this it is possible to conclude that the blank holder is too thin, as it does not provide a wide enough distribution of compressive stresses for covering the influence of adjacent cylinders and providing a more uniform distribution of stresses. As will be seen from the results below, this is not true since an increase in the thickness of the blank holder reduces the deformability and consequently the pliability.

2.3.2 Results for Phase 5

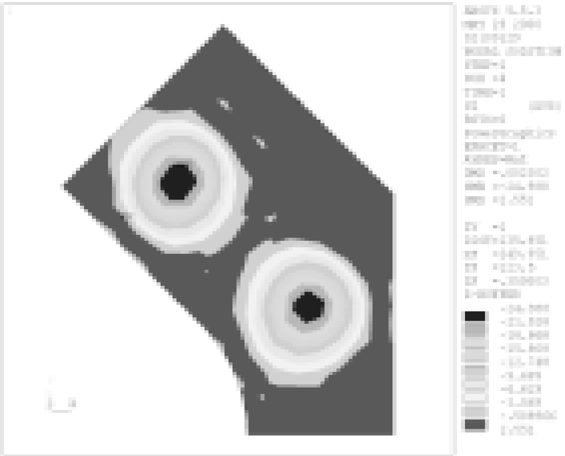
Compared to phase 0, when the blank still had a constant thickness, the conditions in phase 5 are very different. From Fig. 8 and 9 we can see a considerable change in the pressing effect. Fig. 8 denotes the conditions at the optimum force (k = 1). The highest pressing effect no longer occurs under the punches of the hydraulic cylinders but on the points A and D where the sheet metal is momentary the thickest (see also Fig. 3).

Since the blank holder is thin enough, and therefore pliable, it bends sufficiently to also create a contact between the blank holder and the blank on the places under the cylinders (spots B and C), providing a substantially more uniform distribution of pressure. In the analysis of the same model but with a thicker blank holder (t = 60 mm) this contact was not created (results are available but not shown because of the space limitation) and peaks on spots A and D were more explicit, similar to the case of the non-pliable holder.

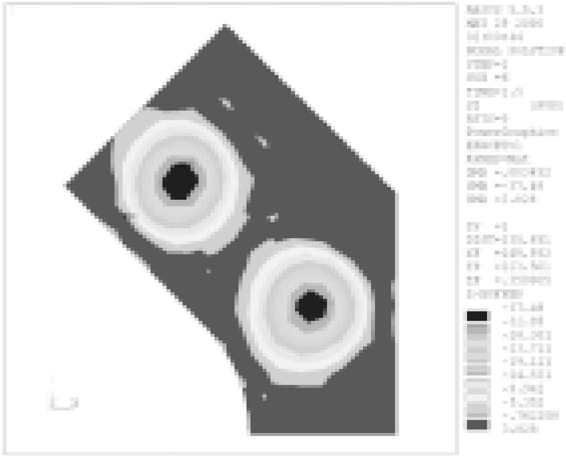
For the increased holding force (k = 1.5) the area on the holder touching the blank increases, too, resulting in a lowering of peak pressures on spots A and D.

2.3.3 Results for Phase 8

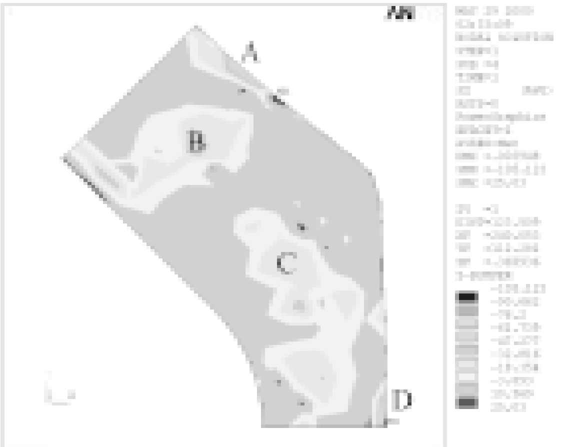
From figs. 10 and 11 we can see that in spite of an increase in the holding force beyond its



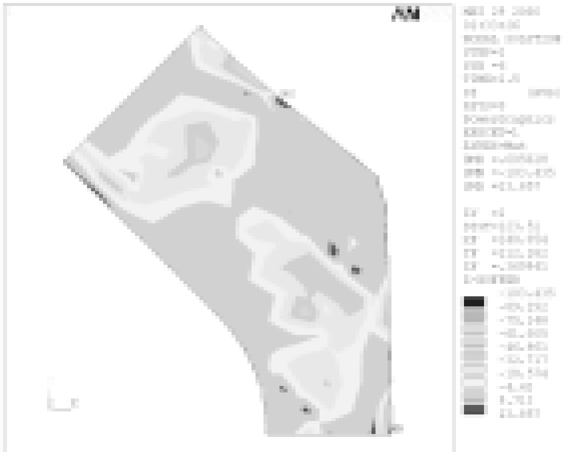
Sl. 6. *Stanje 0: tlak pridrževala v MPa na preoblikovanec pri k= 1*
Fig. 6. *Phase 0: Pressure [MPa] on the blank at k = 1*



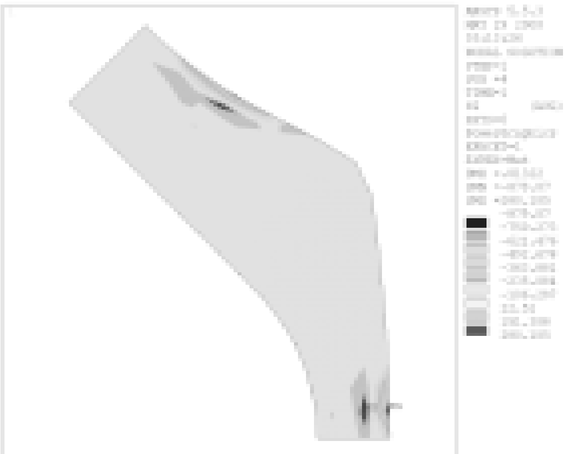
Sl. 7. *Stanje 0: tlak pridrževala v MPa na preoblikovanec pri k= 1,5*
Fig. 7. *Pressure [MPa] on the blank at k = 1.5*



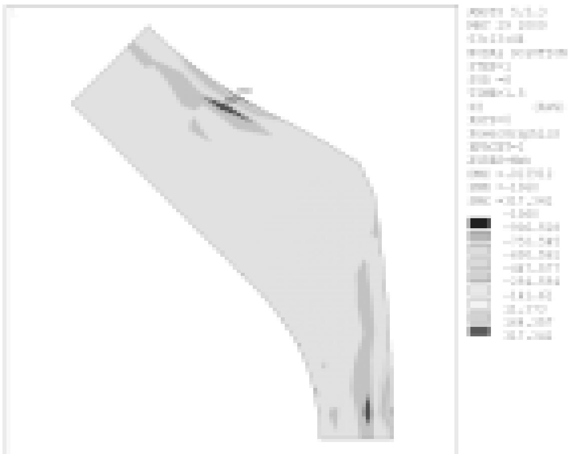
Sl. 8. *Stanje 5: tlak pridrževala v MPa na preoblikovanec pri k= 1*
Fig. 8. *Phase 5: Pressure [MPa] on the blank at k = 1*



Sl. 9. *Stanje 5: tlak pridrževala v MPa na preoblikovanec pri k= 1,5*
Fig. 9: *Phase 5: Pressure [MPa] on the blank at k = 1.5*



Sl. 10. *Stanje 8: tlak pridrževala v MPa na preoblikovanec pri k= 1*
Fig. 10: *Phase 8: Pressure [MPa] on the blank at k = 1*



Sl. 11. *Stanje 8: tlak pridrževala v MPa na preoblikovanec pri k= 1,5*
Fig. 11: *Pressure [MPa] on the blank at k = 1.5*

optimalne vrednosti (k = 1,5), neposredno pod valjema ne dobimo več dotika med pridrževalom in preoblikovancem, kar kaže na premajhno prilagodljivost pridrževala glede na velikost neravnin (sl. 3b). Seveda pa je treba opozoriti na dejstvo, da napetosti v pločevini v konicah bistveno presegajo mejo plastičnosti (primerjalna napetost je še večja). Zaradi tega se vrhovi neravnin v naravi plastificirajo in zmanjšajo, s čimer se spremeni porazdelitev tlakov. V sedanjem modelu plastifikacija pločevine še ni upoštevana.

3 ZAKLJUČEK

Analiza prilagodljivega pridrževala in kontaktnih razmer med njim in platino je pokazala, da se da z ustrezno postavitvijo pritisnih hidravličnih valjev, velikostjo pritisne sile v posameznem valju in debelino pridrževala, ustvariti približno željen pritisk pridrževala na platino, vendar le med prvo fazo vleka, ko ima platina še konstantno debelino. Zaradi sprememb debeline preoblikovane pločevine med vlečenjem (deformacija platine), se razmere v dotiku spreminjajo in slika dotika med pridrževalom ter preoblikovancem se spremeni – dotik se ohrani le na območjih, kjer je pločevina preoblikovanca odebeljena. Če želimo dotik in s tem pridrževalni tlak na tem mestu ohranjati, je potrebno uporabiti še tanjše pridrževalo in mesta pritiska hidravličnih valjev izbrati ustrezno, glede na pričakovano deformacijo preoblikovane pločevine. Zaradi pojava deformacije pločevine, se ne da ustvariti povsem poljubnega stanja pritiskanja pridrževala, mogoč pa je vpliv v tolikšni meri, da se na določenem področju zagotovi v povprečju potreben pridrževalni učinek.

Navedene ugotovitve kažejo na naslednje potrebne korake ob nadaljevanju raziskav: analiza ter proučitev možnosti uporabe prilagodljivega pridrževala posebne oblike (izvedba z ustreznimi zarezami za dosego neenakih togosti vzdolž površine pridrževala in s tem povečanja njegove deformljivosti ob možnosti hkratnega povečevanja njegove imenske debeline) ter proučitev možnosti uporabe segmentnega pridrževala (sestavljeno pridrževalo).

Poleg tega bi bilo potrebno uvesti tudi nekaj izboljšav modela. Ker se lokalno pojavljajo napetosti preko meje plastičnosti, bi bilo treba upoštevati plastičnost platine (izvedba nelinearne, elasto-plastične analize). Upoštevati bi bilo treba tudi vpliv dodatnih normalnih napetosti (ki nastajajo zaradi postopka globokega vleka) na postopek plastifikacije. Izboljšanje modela bi dosegli tudi z upoštevanjem elastičnosti (podajnosti) matrice.

technologically optimum value (k = 1.5) directly under the cylinders no greater contact is obtained between the holder and the blank. This points to a lack of pliability of the blank holder with respect to the size of the uneven planes (fig. 3b). Here it should be mentioned that the stresses in the sheet metal in the peaks significantly exceed the yield point (the equivalent stress being even higher). Therefore the peaks of the uneven planes undergo plastification and are flattened out and this changes the pressure distribution. In the existing model the plastification of the sheet metal was not considered.

3 CONCLUSION

The analysis of a pliable blank holder and the contact conditions between the holder and the blank has shown that through a suitable arrangement of the hydraulic cylinders, magnitude of the pressing force and thickness of the blank holder it is possible to achieve a more-or-less desirable pressing effect of the holder on the blank, but only during the first phase of deep drawing when the blank still maintains a constant thickness. Due to the changes in the thickness of the formed sheet metal during the drawing process (deformation of the blank) the conditions in the contact change and the contact intensity between the holder and the blank changes, too. The contact remains only on the points where the sheet metal is thickened. If we want to maintain the contact and the pressing effect on this point it is necessary to use an even thinner blank holder, and select the locations of the contact pressure of the hydraulic cylinders considering the expected deformation of the formed sheet metal. Because of the deformation of the sheet metal it is impossible to achieve the exact pressing effect required, however, it is possible to influence the conditions to such an extent to obtain the pressing effect that is usually required.

These findings point to the following necessary steps in future research: analysis and study of the possibility of using a pliable blank holder with a special shape (a design with cut outs to achieve non-uniform rigidity along the surface of the blank holder which would increase its deformability while at the same time providing the possibility of increasing its nominal thickness), and the study of the possibility of using a segmented holder (segment-built holder).

In addition, it would be necessary to introduce a few improvements to the model. Since locally stresses exceed the yield point, it would be necessary to consider the plasticity of the blank (a non-linear, elasto-plastic analysis). It would also be necessary to consider the effects of additional normal stresses (occurring due to the deep-drawing process) affecting the plastification process. The model could also be improved by considering the elasticity (pliability) of the die.

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Analize kakovosti pridrževanja pločevine pri globokem vleku

Analysing the Quality of Sheet-Metal Holding during Deep Drawing

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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]:

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

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

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]:

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].

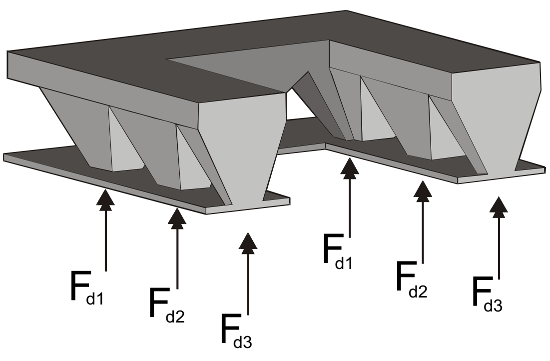
Vsi našteti sistemi optimiranega pridrževanja temeljijo na osnutku elastičnega prilagajanja pridrževala površini pločevine, ki je večje od elastičnih deformacij običajnih pridrževalnih plošč (sl.1). Konstrukcijsko se problematika povečevanja elastičnosti pridrževala rešuje s posebnimi oblikami pridrževalnih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

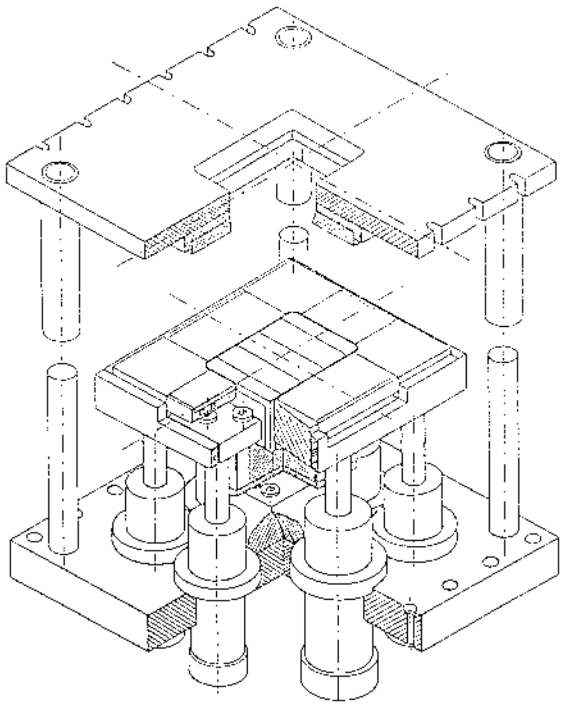
V primeru preoblikovanja krojenih prirezov različnih debelin žal tudi s povečano elastičnostjo pridrževala ne moremo kakovostno pridrževati geometrijsko zapletenih preoblikovancev. Za optimizacijo pridrževanja krojenih prirezov so se zaradi tega razvila posebna segmentirana pridrževala, pri katerih različne 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.

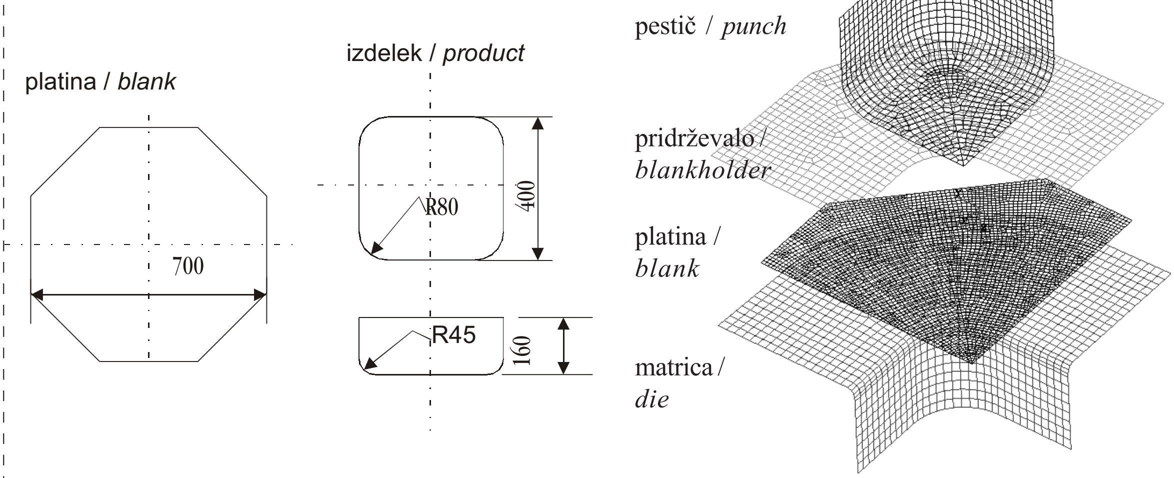
Three different holding concepts used for deep drawing a metal sink were analysed:
- conventional holding with constant blankholder force,
- conventional holding with varying blankholder force,
- holding with segmented blankholder.

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).

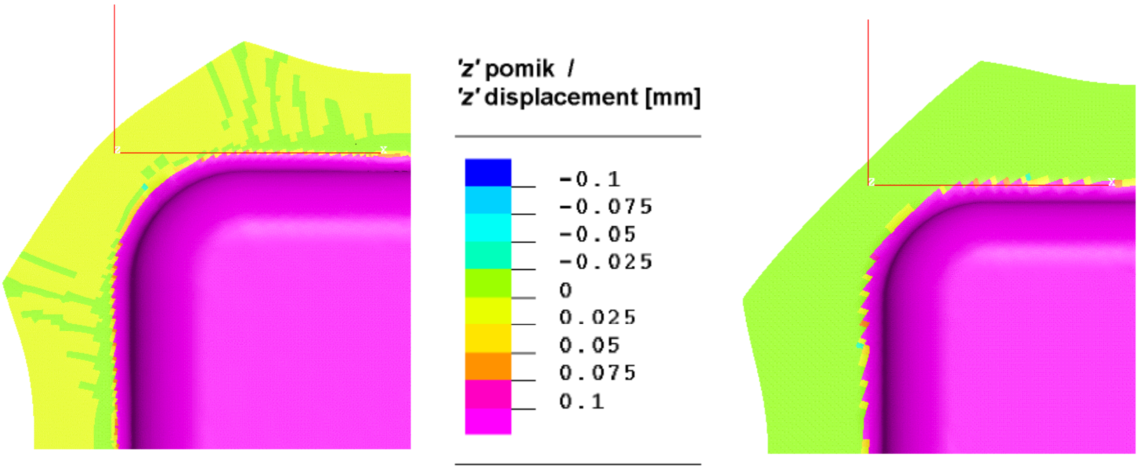
Za najuspešnejše vrednotenje gubanja prirobnice preoblikovanca se je izkazalo določevanje pomikov pridrževane prirobnice v smeri *'z'*. Za kriterij smo vzeli Δz=0,05 mm, znotraj katerega smo lahko zelo dobro določili mejo velikosti sile pridrževanja,

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.

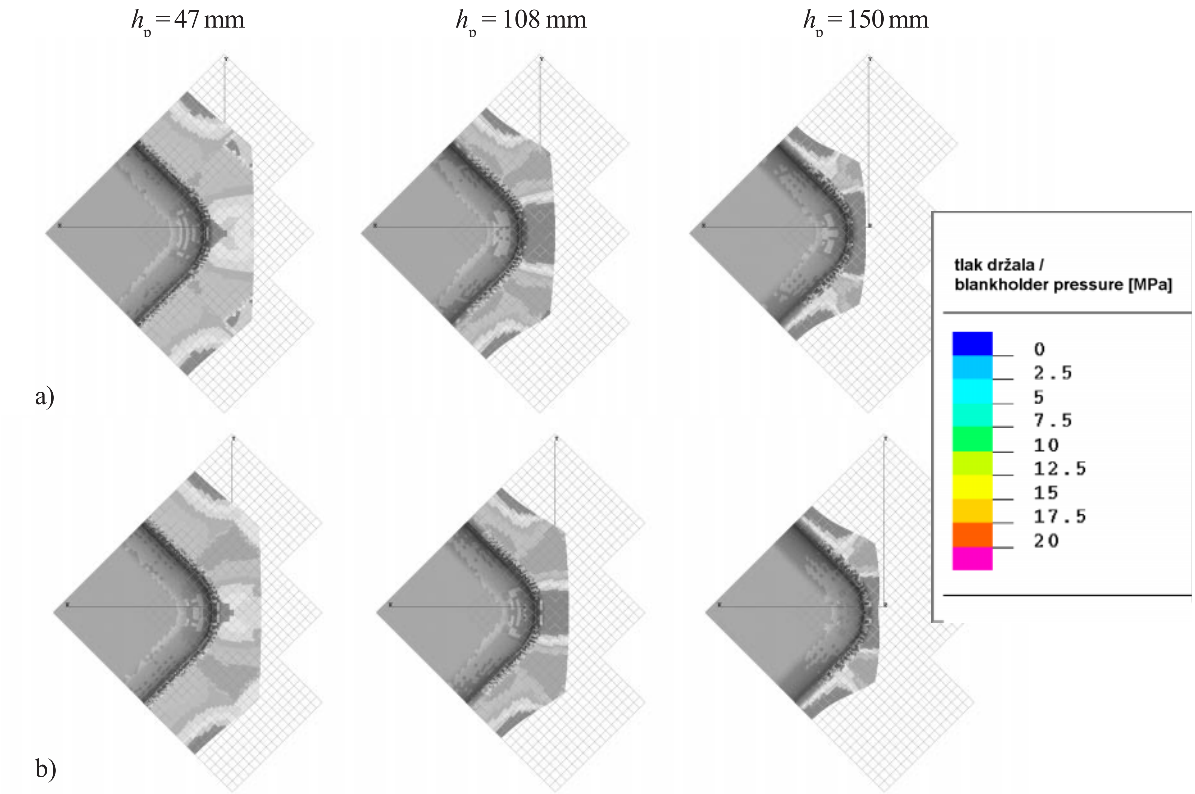
to accurately determine the upper blankholder force limit at which the material began to wrinkle. Figure 3 shows the analysis of the flange wrinkling for two different blankholder forces.

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*

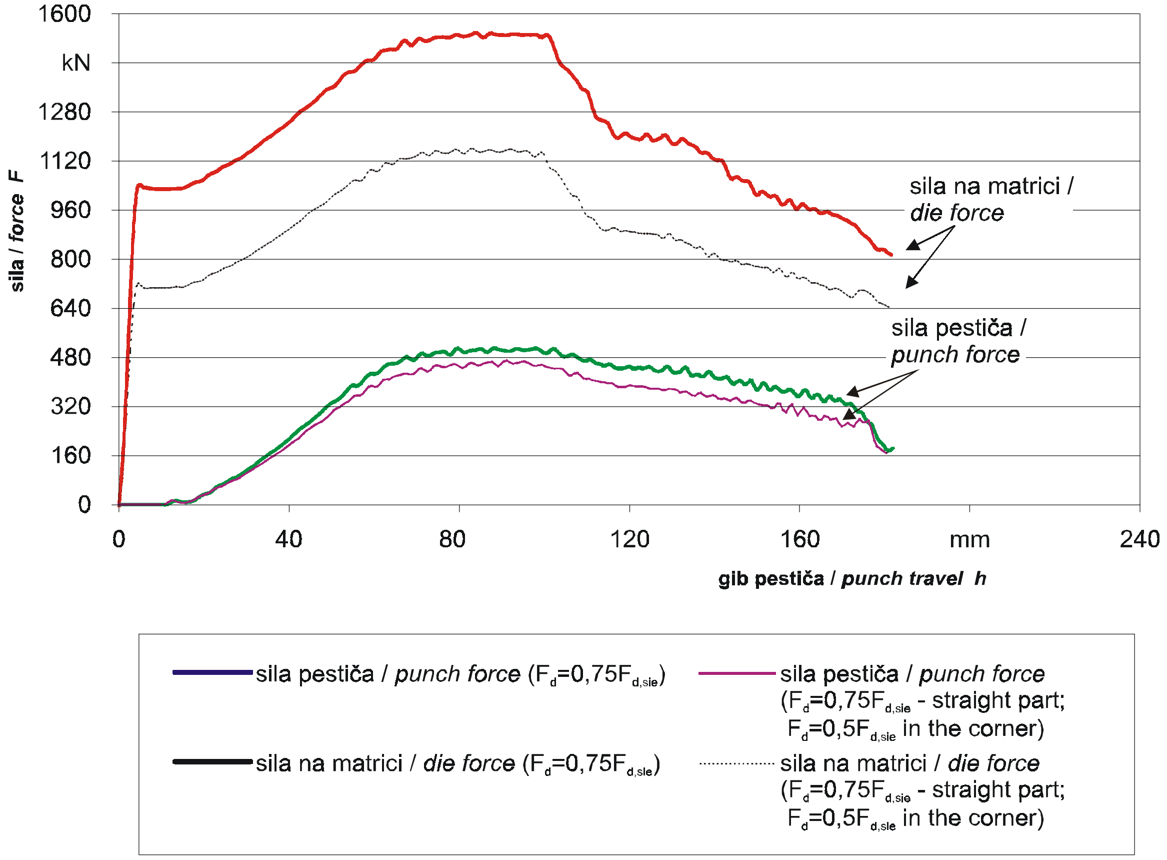
Fig. 4. *Distribution of pressures on the flange for different initial holding pressures: a) p_d =3.6 MPa on all segments and b) p_d = 3.6 MPa on the straight parts and p_d = 2.4 MPa on the edges*

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.

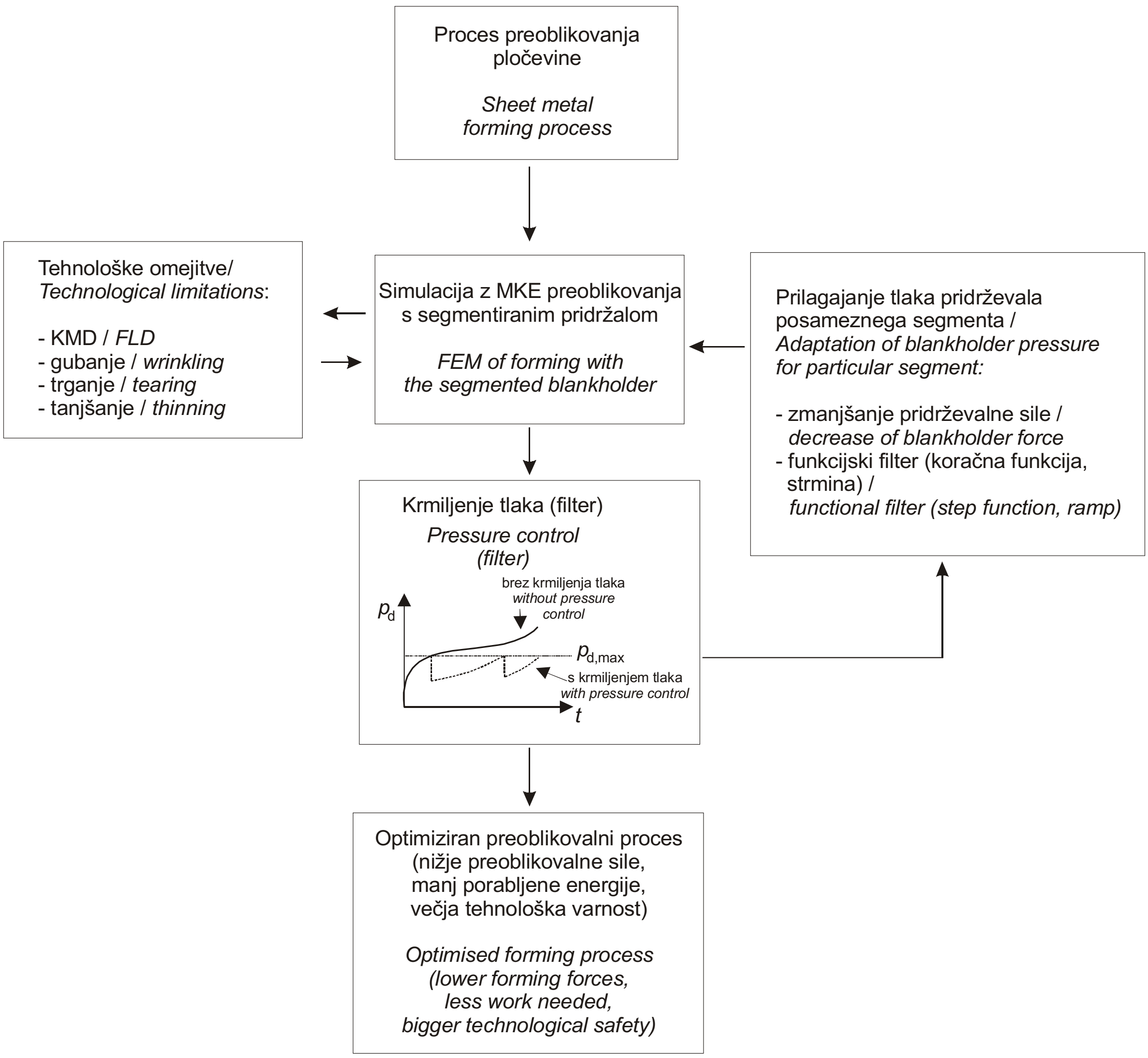
V zadnji fazi analiz smo pridrževalne sile posameznih segmentov časovno spreminjali glede na večanje tlaka na posameznem segmentu. Takšna optimizacija predstavlja nov koncept prilagajanja pridrževalne sile zahtevam preoblikovalnega postopka, ki do sedaj še ni bila izvedena. Zasnova časovne optimizacije 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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Wolf, H.: Stacionarne prisilne vibracije sustava sa zračnostima
Lacko, V., Lacko, P.: Continuously driven resonance
Predin, A., Kastrevc, M., Biluš, I.: Radial pump operating noise and casing vibration analyses

Tehnički vjesnik, Slavonski Brod
2000, 1-2
Čičak, M.: Osiguranje kvalitete programske opreme

Aerospace America, Reston
2000, 1
Flinn, E.D.: Laser inspeciton for composite parts

HLH
Heizung Lüftung/Klima Haustechnik, Düsseldorf
2000, 1
Kähler, A.: Regelungstechnisches Raumlufttemperaturmodell – Teil 1
Francke, D.: Verteilungsmaβstab bestimmt Heizkostenabrechnung- Teil 1
Kunst, B.: Kostenorientiertes Optimieren von Brennwertkesseln – Teil 2
Stiglbrunner, R., Golja, F., Spitzer, J.: Emissionsfaktoren für feste Brennstoffe

2000, 2
Francke, D.: Verteilungsmaβstab bestimmt Heizkostenabrechnung- Teil 2
Kähler, A.: Regelungstechnisches Raumlufttemperaturmodell – Teil 2

2000, 3
Remmers, K.-H.: Thermische Solarkollektoren
Kathöfer, V.: Wärmediagnose von Gebäuden

Renewable Energy World, London
Real, M., Bader, H.-P., Scheidegger, R.: Minimizing the environmental impact of large-scale rural PV
Bridgwater, T.: Towards the "bio-rafinery" – fast pyrolysis of biomass

Vytápení Vetrání Instalace, Praha, Bratislava
2001, 1
Bašta, J.: Boiler burner switching rate and switching difference size
Hagendijk, A.E., Machielsen, C.H.M.: Application of a solar absorption refrigeration system for air-conditioning of buildings

2001,2
Putta, L.: Optimization of air distribution with regards to noise
Hurych, M.: Indispensability of heating systems hydraulic balancing from right regulation point of view
Jokl, V.: European standard for ventilation

Ocene knjig

A. Gardziella u. 7 Mitaut.: Duroplastische Harze, Formmassen und Werkstoffe

Zal.: Expert Verlag, GmbH, Renningen - Malmsheim 2000.
Obseg: format 15 x 21 cm, 280 strani, 213 slik, 412 preglednic, 206 lit. podat.
Cena je 88 DEM.

Duroplasti sodijo med najstarejše polimerne materiale, ki jih uporabljamo v konstrukcijske namene. Prvi postopek fenol-formaldehidne kondenzacije je izvedel Adolf von Baeyer že leta 1872, prvi uporabni material pa je bil patentiran trideset let kasneje, leta 1902. Mehanske lastnosti duroplastov se zaradi zamrežene strukture počasi spreminjajo, zato so zelo zanimivi za uporabo v konstrukcijah. Trenutno so duroplasti še zmeraj najbolj razširjeni polimerni konstrukcijski materiali.

Knjiga pred nami celovito predstavi skupino duroplastičnih materialov v devetih poglavjih.

Prvo poglavje, ki je relativno kratko, je neke vrste uvod v problematiko. Predstavljena je zgodovina razvoja duroplastov, njihove osnovne značilnosti in primeri uporabe v konstrukcijske namene.

Drugo poglavje podaja pregled vseh polimernih materialov s poudarkom na zamreženih polimerih (duroplastih). Predstavljena je kemijska zgradba najpomembnejših materialov in kemijski postopek zamreževanja.

Tretje poglavje je v celoti namenjeno fenolnim smolam, ki so v praksi najbolj razširjene (veliko jih uporabljamo tudi v Sloveniji). Predstavitev je celovita, vse od kemijske zgradbe do primerov uporabe in ekonomskih kazalcev porabe te skupine duroplastov. Zanimivi so primeri uporabe v kombinaciji z lesom, kot lepilo ali celo kot njegov nadomestek.

V četrtem poglavju so obravnavane amidne smole, med katerimi so najbolj znani (poli) uretani. Razložena je kemijska zgradba amidnih smol, postopek zamreževanja in osnove tehnološkega postopka njihove predelave. Posebna pozornost je posvečena njihovi uporabi v izdelavi lakov.

Peto poglavje obravnava poliestrske smole. Podobno kakor v prejšnjih poglavjih je tudi v tem najprej predstavljena kemijska zgradba in tehnologija predelovanja. Na koncu so predstavljeni tudi konkretni primeri uporabe s fotografijami. Predstavljeni so tudi nekateri ekonomski statistični podatki. Zanimiv je podatek, da se poliestrske smole največ uporablja za ročno laminiranje različnih izdelkov.

V šestem poglavju so predstavljene epoksidne smole. Najprej je predstavljena kemijska zgradba in nato tehnologija s primeri uprabe.

Pomembno je poudariti, a sta poliestrska in epoksidna smola še zmeraj najpomembejša konstrukcijska polimerna materiala.

V sedmem poglavju je predstavljena uporaba duroplastov v tehnologiji brizganja. Površno so predstavljene njihove mehanske lastnosti in nato stvarni primeri uporabe.

Posebno poglavje, osmo, je namenjeno predstavitvi kompozitov tipa SMC in BMC. V prvem primeru (SMC) so ojačitvena vlakna nanesena v sloju, v drugem (BMC) pa so enostavno pomešana s polimerno matriko. Prva skupina materialov se zato predeluje s tehnologijo stiskanja, druga pa s tehnologijo iztiskovanja in brizganja. Predstavljena je cela skupina primerov uporabe teh materialov, največ v avtomobilski in elektro industriji.

Zadnje, deveto poglavje govori o uporabi duroplastov v gradbeništvu, kot dodatek h običajnemu betonu, ali kot samostojni gradbeni materiali. Podobno kakor v prejšnjih poglavjih je tudi tukaj predstavljena cela vrsta primerov uporabe.

Knjigo priporočam predvsem konstrukterjem, ki jim je uporaba polimerov v tehniki tuja.

I. Emri

Paul Kenneth Wright: 21st Century Manufacturing

Zal.: Prentice Hall, New Yersey, USA 2001.
Obseg: format 18 x 24 cm, 460 strani, 259 slik, 38 preglednic.
Cena je 13.830 SIT.

Vsebina knjige temelji na zamisli, da novo ustanovljeno podjetje preučuje novo tehnično inovacijo, analizira tržišče, sestavlja poslovni načrt, oblikuje nov izdelek, izdeluje prototip in končne oblike izdelka, išče različne možnosti za izdelavo elektronskih in mehanskih komponent ter pošilja izdelek na tržišče. Vsa glavna poglavja se tudi nanašajo na to tematiko, poseben poudarek je na proizvodnih tehnologijah, zaradi bodočih razvojnih možnosti pa je dodano področje biotehnologije. Glavni namen knjige je tudi prikazati uravnotežen pogled na upravljanje s tehnologijo.

Prvi dve poglavji opisujeta zgodovinski pregled proizvodnje in današnje tehnologije, potrebo po povezovanju različnih proizvodnih aktivnosti, podan pa je tudi kratek povzetek nekaterih osnovnih proizvodnih principov. V nasprotju od teh dveh poglavij - podobno vsebino je mogoče najti tudi drugje - pa se tretje poglavje izrazito razlikuje od besedil, ki običajno opisujejo pregled lastnosti materialov, osnove mehanike ali elektronike ali dajejo poglobljen pregled izdelovalnih procesov. Poudarjeno je, da večina današnjih študentov proizvodnega strojništva morda svoje delo začne na področju izdelovalnih tehnologij, a kmalu postanejo upravljalci tehnologije. Proizvodnja je za njih več ko gola izdelava v proizvodnem obratu, njihove aktivnosti vsebuje tako analizo trga, oblikovanje in načrtovanje proizvodnje, končno izdelavo in iskanje zunanjih virov, prodajo, servis, poleg tega pa morajo biti tudi zmožni preoblikovati proizvodni obrat za potrebe novega izdelka. V uspešni proizvodnji to znajo že od nekdaj, a je dandanes hitrost sprememb takšna, da je treba že študente med študijem pripraviti na takšno okolje. Tretje poglavje knjige zato predstavlja celoten razvojni cikel izdelka z namenom postaviti vsak izdelovalni proces na ustrezno mesto v proizvodnji kot celoti. Ta poglavja so tudi pisana preprosto in pregledno, vključeni so tudi ekonomski dejavniki.

V nadaljevanju imajo poglavja bolj tehnično vsebino, dajejo pregled postopkov hitre izdelave prototipov, CAD/CAM tehnologij, proizvodnje tiskanih vezij, izdelave računalniških komponent, izdelave kovinskih in plastičnih izdelkov ter načinov sestavljanja. Zadnje poglavje pa se nanaša na proizvodna vprašanja prihodnosti. Knjiga je predvsem zanimiva zato, ker daje širok pogled na proizvodne aktivnosti in hkrati vključuje tudi poslovne vidike.

S. Dolinšek

M. Wisniewski: Elastohydrodynamische Schmierung

Zal.: Expert Verlag, GmbH, Renningen- Malmsheim 2000.
Obseg: format 145x21 cm, 214 strani, 144 slik, 12 preglednic, 195 literaturnih virov.
Cena je 76 DEM.

Elastohidrodinamično mazanje (EHD) je opisano v velikem številu knjig in je predmet obravnave širokega kroga raziskovalcev in uporabnikov. Pričujoča knjiga je eden od dodatnih poskusov avtorja, da bi osvetlil tematiko EHD iz zornega kota uporabnika. Avtor v prvih štirih poglavjih opiše zgodovinski razvoj razumevanja hidrodinamičnega mazanja, mehanike dotika in EHD mazanja, nato pa poda lastnosti suhega in mazanega kontakta ter teoretične osnove EHD mazanja. V petem poglavju je avtor opisal metode, ki se uporabljajo za merjenje debeline oljnega filma ter tlaka in temperature v oljnem filmu.

Šesto poglavje obravnava obrabne probleme na zobnih bokih v odvisnosti od EHD mazanja, kar je po moji oceni izredno pomembno za inženirje in vzdrževalce v industriji in razvoju. Za razvojne inženirje in konstrukterje pa je avtor v poglavju sedem nanizal metode za preračun EHD mazanja pri valjčnih ležajih, zobniških dvojicah, odmičnih gredeh in polžastih dvojicah. To poglavje je po mojem mnenju pomemben prispevek avtorja v primerjavi z drugimi knjigami s tega področja.

Zaradi postopkov za izračun EHD mazanja na različnih strojnih elementih, ki jih je avtor nanizal v poglavju sedem, priporočam knjigo vsem tistim inženirjem, ki se srečujejo s tem problemom v praksi pa tudi tistim strokovnjakom, ki si želijo razširiti znanje s področja EHD mazanja.

J. Vižintin

W. J. Bartz in 9 soavtorjev: Schaden an geschmierten Maschinenelementen (Gleitlager, Walzlager, Zahnräder)

Zal.: Expert Verlag, GmbH, Renningen-Malmsheim, 3 pred. izd. 1999.
Obseg: format 15x21 cm, 429 strani, 402 slik, 45 preglednic, 172 literaturnih virov.

Poškodbe na strojnih elementih so vzrok in posledica izrednih zastojev na delovnih, pogonskih in transportnih sistemih. Izredni zastoji na sistemih povzročijo izpad proizvodnje in s tem sekundarne stroške proizvodnje, ki so običajno za nekaj desetkrat večji od primarnih stroškov vzdrževanja sistemov. Zato je razumljivo, da se veliko avtorjev loteva vzrokov za nastanek inicialnih poškodb med obratovanjem, saj je rešitev ali pa vsaj dobro poznavanje teh problemov v praksi ključ za zmanjšanje zastojev in s tem cene izdelka.

Zanimivo je, da je avtor prvo poglavje v knjigi namenil uporabi triboloških znanj za zmanjšanje poškodb na strojnih elementih. V tem poglavju avtor analiziral tribološke probleme med delovanjem sistemov in daje predloge, kako jih zmanjšati, da bi obenem zmanjšali tudi število poškodb na strojnih elementih.

V drugem poglavju je avtor opisal, za različne strojne elemente, oblike in vzroke za nastanek poškodb. Pomebno je poudariti avtorjevo sistematično analizo vzrokov poškodb.

V naslednjih poglavjih so opisane, zelo podrobno, poškodbe in vzroki za nastanek le teh pri obrabnem procesu na stacionarnih zobniških pogonih, zobniških pogonih za vozila, kotalnih ležajih, drsnih ležajih, drsnih ležajih v motorjih z notranjim zgorevanjem ter pri freting utrujanju. Zadnje poglavje je avtor namenil sistemski analizi poškod na strojnih elementih. Pri tem je kritično izpostavil predvsem pomen analize in sistematičnost dela za zanesljivo odkrivanje vzrokov in mehanizmov nastanka ter širjenja poškod na strojnih elementih.

J. Vižintin

Osebne vesti
Personal Events

Doktorati, magisteriji, diplome

DOKTORATI

Na Fakulteti za strojništvo Univerze v Mariboru sta z uspehom zagovarjala svoji doktorski disertaciji, in sicer:

dne 7. februarja 2001: mag. **Gorazd Fajdiga**, disertacijo z naslovom: "Prispevek k širjenju utrujenostne razpoke na bokih zob zobnikov pri upoštevanju EHD obremenitve" in

dne 21. februarja 2001: mag. **Boštjan Harl,** disertacijo z naslovom: "Minimizacija sklepnih sil kinematičnih verig".

S tem sta navedena kandidata dosegla akademsko stopnjo doktorja tehničnih znanosti.

MAGISTERIJI

Na Fakulteti za strojništvo Univerze v Ljubljani je *dne 5. februarja 2001* **Igor Kern** z uspehom zagovarjal svoje magistrsko delo z naslovom: "Eksperimentalna raziskava dinamičnih parametrov na modelu kaplanove turbine".

S tem je navedeni kandidat dosegel akademsko stopnjo magistra tehničnih znanosti.

DIPLOMIRALI SO

Na Fakulteti za strojništvo Univerze v Ljubljani so pridobili naziv univerzitetni diplomirani inženir strojništva:

dne 23. februarja 2001: Simon JENKO, Luka LEBAR, Andraž LIPOLT.

Na Fakulteti za strojništvo Univerze v Mariboru je *dne 22. februarja 2001* Jan VAUPOT pridobil naziv univerzitetni diplomirani inženir strojništva.

*

Na Fakulteti za strojništvo Univerze v Ljubljani so pridobili naziv diplomirani inženir strojništva:

dne 9. februarja 2001: Željko AGNIČ, Tomaž HUMAR, Henrik KOCJANČIČ, Zlatko SCHWEIGER, Boštjan VRHOVNIK;

dne 12. februarja 2001: Boštjan GRIŽONIČ, Franc PAPEŽ, David ROMIH.

Na Fakulteti za strojništvo Univerze v Mariboru so pridobili naziv diplomirani inženir strojništva:

dne 22. februarja 2001: Željko HABULIN, Borut HAŽIČ, Zoran VIDOVIČ.

*

Na Fakulteti za strojništvo Univerze v Mariboru so pridobili naziv inženir strojništva:

dne 22. februarja 2001: Milan HANC, Matjaž MEMON, Karolina NOVAK, Tomaž PERMANŠEK.

Navodila avtorjem
Instructions for Authors

Članki morajo vsebovati:
- naslov, povzetek, besedilo članka in podnaslove slik v slovenskem in angleškem jeziku,
- dvojezične preglednice in slike (diagrami, risbe ali fotografije),
- seznam literature in
- podatke o avtorjih.

Strojniški vestnik izhaja od leta 1992 v dveh jezikih, tj. v slovenščini in angleščini, zato je obvezen prevod v angleščino. Obe besedili morata biti strokovno in jezikovno med seboj usklajeni. Članki naj bodo kratki in naj obsegajo približno 8 tipkanih strani. Izjemoma so strokovni članki, na željo avtorja, lahko tudi samo v slovenščini, vsebovati pa morajo angleški povzetek.

Vsebina članka

Članek naj bo napisan v naslednji obliki:
- Naslov, ki primerno opisuje vsebino članka.
- Povzetek, ki naj bo skrajšana oblika članka in naj ne presega 250 besed. Povzetek mora vsebovati osnove, jedro in cilje raziskave, uporabljeno metodologijo dela,povzetek rezulatov in osnovne sklepe.
- Uvod, v katerem naj bo pregled novejšega stanja in zadostne informacije za razumevanje ter pregled rezultatov dela, predstavljenih v članku.
- Teorija.
- Eksperimentalni del, ki naj vsebuje podatke o postavitvi preskusa in metode, uporabljene pri pridobitvi rezultatov.
- Rezultati, ki naj bodo jasno prikazani, po potrebi v obliki slik in preglednic.
- Razprava, v kateri naj bodo prikazane povezave in posplošitve, uporabljene za pridobitev rezultatov. Prikazana naj bo tudi pomembnost rezultatov in primerjava s poprej objavljenimi deli. (Zaradi narave posameznih raziskav so lahko rezultati in razprava, za jasnost in preprostejše bralčevo razumevanje, združeni v eno poglavje.)
- Sklepi, v katerih naj bo prikazan en ali več sklepov, ki izhajajo iz rezultatov in razprave.
- Literatura, ki mora biti v besedilu oštevilčena zaporedno in označena z oglatimi oklepaji [1] ter na koncu članka zbrana v seznamu literature. Vse opombe naj bodo označene z uporabo dvignjene številke[1].

Oblika članka

Besedilo naj bo pisano na listih formata A4, z dvojnim presledkom med vrstami in s 3 cm širokim robom, da je dovolj prostora za popravke lektorjev. Najbolje je, da pripravite besedilo v urejevalnilku Microsoft Word. Če uporabljate kakšen drug urejevalnik besedil, prosimo, da besedilo konvertirate v navadno ASCII (tekstovno) obliko. Hkrati dostavite odtis članka na papirju, vključno z vsemi slikami in preglednicami ter identično kopijo v elektronski obliki.

Prosimo, da ne uporabljate urejevalnika LaTeX, saj program, s katerim pripravljamo Strojniški vestnik, ne uporablja njegovega formata. V urejevalniku LaTeX oblikujte grafe, preglednice in enačbe in jih stiskajte na kakovostnem laserskem tiskalniku, da jih bomo lahko presneli.

Enačbe naj bodo v besedilu postavljene v ločene vrstice in na desnem robu označene s tekočo številko v okroglih oklepajih

Enote in okrajšave

V besedilu, preglednicah in slikah uporabljajte le standardne označbe in okrajšave SI. Simbole fizikalnih veličin v besedilu pišite poševno (kurzivno), (npr. *v, T, n* itn.). Simbole enot, ki sestojijo iz črk, pa pokončno (npr. ms^{-1}, K, min, mm itn.).

Papers submitted for publication should comprise:
- Title, Abstract, Main Body of Text and Figure Captions in Slovene and English,
- Bilingual Tables and Figures (graphs, drawings or photographs),
- List of references and
- Information about the authors.

Since 1992, the Journal of Mechanical Engineering has been published bilingually, in Slovenian and English. The two texts must be compatible both in terms of technical content and language. Papers should be as short as possible and should on average comprise 8 typed pages. In exceptional cases, at the request of the authors, speciality papers may be written only in Slovene, but must include an English abstract.

The format of the paper

The paper should be written in the following format:
- A Title, which adequately describes the content of the paper.
- An Abstract, which should be viewed as a miniversion of the paper and should not exceed 250 words. The Abstract should state the principal objectives and the scope of the investigation, the methodology employed, summarize the results and state the principal conclusions.
- An Introduction, which should provide a review of recent literature and sufficient background information to allow the results of the paper to be understood and evaluated.
- A Theory
- An Experimental section, which should provide details of the experimental set-up and the methods used for obtaining the results.
- A Results section, which should clearly and concisely present the data using figures and tables where appropriate.
- A Discussion section, which should describe the relationships and generalisations shown by the results and discuss the significance of the results making comparisons with previously published work. (Because of the nature of some studies it may be appropriate to combine the Results and Discussion sections into a single section to improve the clarity and make it easier for the reader.)
- Conclusions, which should present one or more conclusions that have been drawn from the results and subsequent discussion.
- References, which must be numbered consecutively in the text using square brackets [1] and collected together in a reference list at the end of the paper. Any footnotes should be indicated by the use of a superscript[1].

The layout of the text

Texts should be written in A4 format, with double spacing and margins of 3 cm to provide editors with space to write in their corrections. Microsoft Word for Windows is the preferred format for submission. If you use another word processor, please convert to normal ASCII (text) format. One hard copy, including all figures, tables and illustrations and an identical electronic version of the manuscript must be submitted simultaneously.

Please do not use a LaTeX text editor, since this is not compatible with the publishing procedure of the Journal of Mechanical Engineering. Graphs, tables and equations in LaTeX may be supplied in good quality hard-copy format, so that they can be copied for inclusion in the Journal.

Equations should be on a separate line in the main body of the text and marked on the right-hand side of the page with numbers in round brackets.

Units and abbreviations

Only standard SI symbols and abbreviations should be used in the text, tables and figures. Symbols for physical quantities in the text should be written in Italics (e.g. *v, T, n,* etc.). Symbols for units that consist of letters should be in plain text (e.g. ms^{-1}, K, min, mm, etc.).

Vse okrajšave naj bodo, ko se prvič pojavijo, napisane v celoti v slovenskem jeziku, npr. časovno spremenljiva geometrija (ČSG).

Slike

Slike morajo biti zaporedno oštevilčene in označene, v besedilu in podnaslovu, kot sl. 1, sl. 2 itn. Posnete naj bodo v kateremkoli od razširjenih formatov, npr. BMP, JPG, GIF. Za pripravo diagramov in risb priporočamo CDR format (CorelDraw), saj so slike v njem vektorske in jih lahko pri končni obdelavi preprosto povečujemo ali pomanjšujemo.

Pri označevanju osi v diagramih, kadar je le mogoče, uporabite označbe veličin (npr. *t, v, m* itn.), da ni potrebno dvojezično označevanje. V diagramih z več krivuljami, mora biti vsaka krivulja označena. Pomen oznake mora biti pojasnjen v podnapisu slike.

Vse označbe na slikah morajo biti dvojezične.

Za vse slike po fotografskih posnetkih je treba priložiti izvirne fotografije ali kakovostno narejen posnetek. V izjemnih primerih so lahko slike tudi barvne.

Preglednice

Preglednice morajo biti zaporedno oštevilčene in označene, v besedilu in podnaslovu, kot preglednica 1, preglednica 2 itn. V preglednicah ne uporabljajte izpisanih imen veličin, ampak samo ustrezne simbole, da se izognemo dvojezični podvojitvi imen. K fizikalnim veličinam, npr. *t* (pisano poševno), pripišite enote (pisano pokončno) v novo vrsto brez oklepajev.

Vsi podnaslovi preglednic morajo biti dvojezični.

Seznam literature

Vsa literatura mora biti navedena v seznamu na koncu članka v prikazani obliki po vrsti za revije, zbornike in knjige:

[1] Tarng, Y.S., Y.S. Wang (1994) A new adaptive controler for constant turning force. *Int J Adv Manuf Technol* 9(1994) London, pp. 211-216.
[2] Čuš, F., J. Balič (1996) Rationale Gestaltung der organisatorischen Abläufe im Werkzeugwesen. *Proceedings of International Conference on Computer Integration Manufacturing,* Zakopane, 14.-17. maj 1996.
[3] Oertli, P.C. (1977) Praktische Wirtschaftskybernetik. *Carl Hanser Verlag,* München.

Podatki o avtorjih

Članku priložite tudi podatke o avtorjih: imena, nazive, popolne poštne naslove, številke telefona in faksa ter naslove elektronske pošte.

Sprejem člankov in avtorske pravice

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[2] Čuš, F., J. Balič (1996) Rationale Gestaltung der organisatorischen Abläufe im Werkzeugwesen. *Proceedings of International Conference on Computer Integration Manufacturing,* Zakopane, 14.-17. maj 1996.
[3] Oertli, P.C. (1977) Praktische Wirtschaftskybernetik. *Carl Hanser Verlag,* München.

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