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Uporaba numeričnih simuliranj pri razvoju orodij za izdelavo pločevinastih sestavnih delov avtomobilov

The Use of Numerical Simulations in the Development of Tools for the Sheet-Metal Parts of Cars

Gašper Gantar - Marko Ljevar - Karl Kuzman

V Sloveniji obstaja veliko orodjarn, ki izdelujejo orodja za izdelavo avtomobilskih pločevinastih sestavnih delov. Z namenom, da bi skrajšali razvojne čase in zmanjšali število napak na orodjih, se v zadnjem času intenzivno uporabljajo numerična simuliranja na podlagi metode končnih elementov (MKE). Izdelovalne tehnologije so v t.i. navideznem okolju preverjene še pred izdelavo orodij. Napake so odkrite v zgodnji fazi razvojnega kroga, zato je njihovo odpravljanje cenejše. V prispevku je prikazan postopek vključevanja numeričnih simuliranj v krog razvoja orodja za izdelavo novega izdelka.

(Ključne besede: preoblikovanje pločevine, simuliranje numerično, razvoj izdelkov, optimiranje)

Many tool-manufacturing companies in Slovenia are producing the tools required for the sheet-metal parts of cars. Numerical simulations based on the finite-element method (FEM) have recently become widely used in order to reduce the development times and the number of mistakes associated with the manufacture of these tools. Production technologies are tested in the so-called virtual environment before the tools are produced. Mistakes are detected at an early phase of the development cycle, and as a result, their removal is cost effective. In this paper we present the implementation of numerical simulations in the development cycle of a tool for a new product.

(Keywords: sheet metal forming, numerical simulations, product development, optimization)

0 UVOD

Potek postopkov preoblikovanja pločevine je odvisen od številnih parametrov, ki jih je težko nadzorovati. Za določitev optimalne kombinacije teh parametrov so potrebni testi, za katere je treba izdelati testna orodja, zato so ti testi dragi in dolgotrajni. Kadar testi niso uspešni, je treba testna orodja predelati ali izdelati nova in teste ponoviti, kar še podaljša čas do zagona redne proizvodnje. Preoblikovalne postopke je zato smiselno preveriti z uporabo numeričnih simuliranj v t.i. "navideznem okolju" še preden so narejena orodja.

1 UPORABA NUMERIČNIH SIMULIRANJ V KROGU RAZVOJA NOVEGA IZDELKA

Postopek uvedbe novega izdelka je predstavljen na sliki 1. Numerična simuliranja je primerno uporabljati v različnih fazah. Uporaba mora biti čimbolj organizirana. Na začetku je za grobo oceno velikega števila konstrukcijskih rešitev smiselno uporabljati hitrejše toda manj zanesljive tehnike,

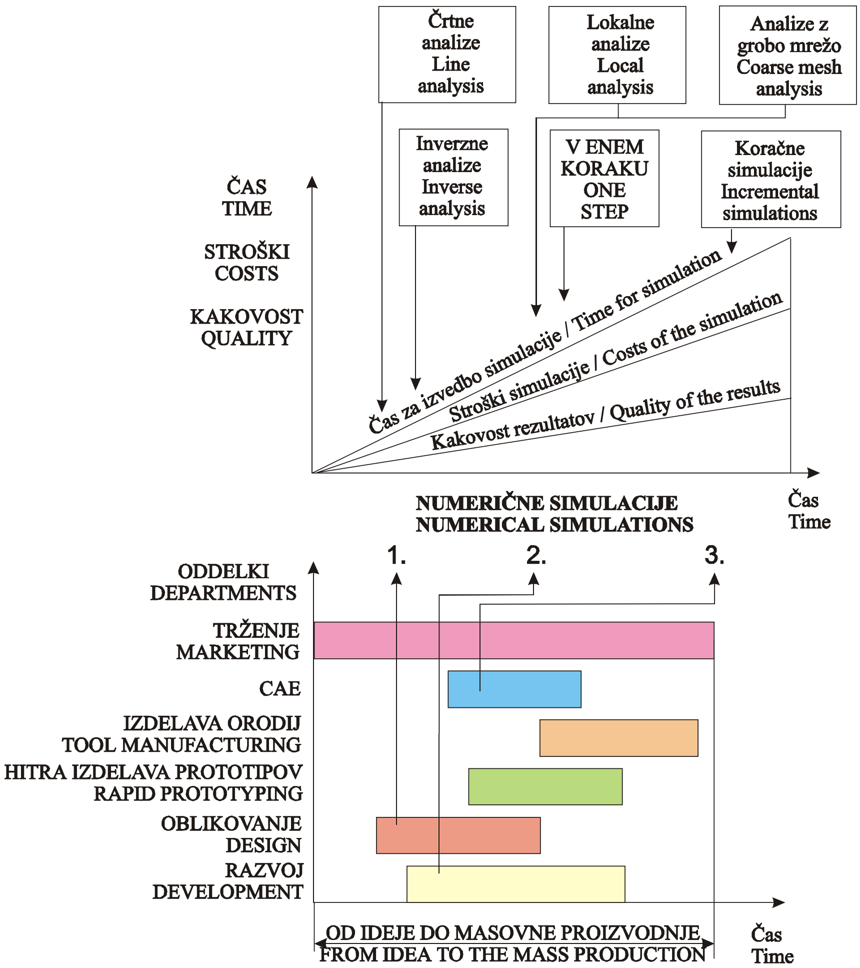
0 INTRODUCTION

Stamping processes depend on numerous parameters that are hard to control, and so tests are needed to determine the best combination of these parameters. As prototype tools have to be produced, such tests are costly and time consuming. If the tests are not successful the tools need to be remade or new prototype tools need to be manufactured, and as a result the start of production is delayed. It is reasonable, therefore, to test the forming processes by means of numerical simulations in the virtual environment before the forming tools are produced.

1 THE USE OF NUMERICAL SIMULATIONS IN THE PRODUCT DEVELOPMENT CYCLE

The product development cycle is presented in Figure 1. It makes sense to perform the numerical simulations at different stages and it is important that the procedure is as organised as possible. At the beginning a lot of design solutions should be roughly evaluated by quick but less reliable kasneje pa je treba uporabiti bolj zanesljive a tudi časovno potratne tehnike za končno optimizacijo izbrane rešitve, kakor je prikazano na sliki 1. V prispevku je prikazan primer, pri katerem so bila numerična simuliranja uporabljena šele v orodjarni, ki je izdelala proizvajalna orodja, zato je bil uporabljen programski paket, ki omogoča izvedbo natančnih koračnih numeričnih simuliranj.

techniques, only later should more reliable but also more time-consuming techniques be used for the final optimisation of the selected solution, as presented in Figure 1. In this paper we present an example where numerical simulations were used in a tool-manufacturing company producing forming tools, therefore, software that performs a reliable incremental numerical simulation was used.



Sl. 1. *Postopek uvedbe novega izdelka [1]*
Fig. 1. *The product development cycle [1]*

Numerična simuliranja predstavljajo zanesljivo orodje za napovedovanje poteka preoblikovalnih postopkov in omogočajo napovedovanje: trganja, gubanja, končne debeline pločevine, zaostalih napetosti, površinskih napak in elastičnega izravnavanja obdelovanca, optimalno začetno geometrijsko obliko platine ter sil in pritiskov na aktivne površine orodja [1]. V tujini z uporabo numeričnih simuliranj preverijo izdelovalne tehnologije za več ko 30% glavnih pločevinskih sestavnih delov. Na ta način vnaprej napovejo in preprečijo več ko 50% napak [2].

Numerična simuliranja predstavljajo tudi eno od orodij za uvajanje in izvajanje sočasnega inženirstva, saj omogočajo vnaprejšnje

Numerical simulations represent a reliable tool for the prediction of forming processes and enable the prediction of the following: tearing, wrinkling, final sheet thickness, residual stresses, surface defects, springback, optimum initial blank shape, forces and pressures on the active surfaces of the tool [1]. The forming technologies for more than 30% of major sheet-metal parts in other countries are tested by means of numerical simulations. In this way more than 50% of errors are predicted and prevented [2].

Numerical simulations also represent one of the fundamental tools for establishing and performing concurrent engineering, as they enable early predictions and simplify the exchange of information between the napovedovanje in poenostavijo dialog med člani razvojne skupine. Konstrukter izdelka, tehnolog in izvajalec numeričnih simuliranj vzpostavijo boljši dialog pri sočasnem razvoju izdelka.

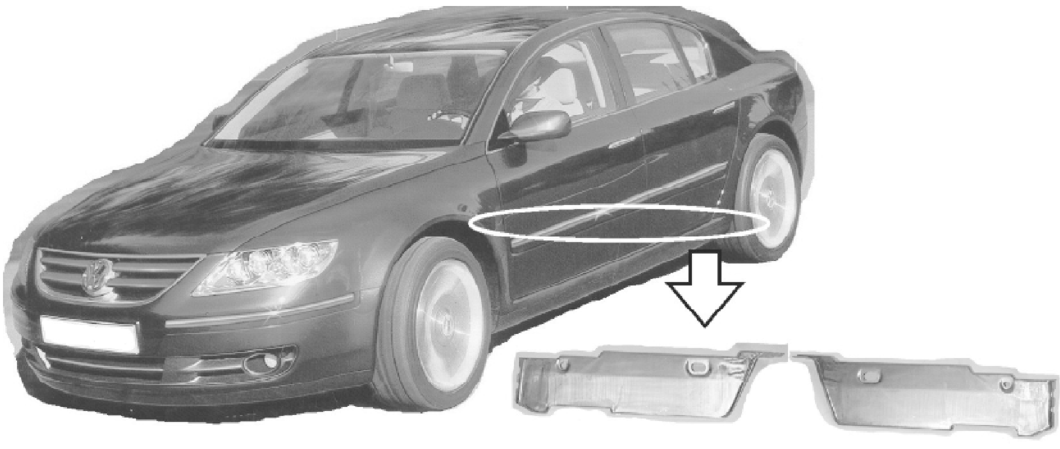
members of the development team. The product designer, the production-process designer and the numerical-simulation expert can establish a much better dialog during the concurrent development of the product.

2 ANALIZA POKROVNEGA DELA PREČNEGA NOSILCA

Orodja za izdelavo dveh pločevinskih sestavnih delov za podvozje nove VW limuzine, ki sta predstavljena na sliki 2, so bila naročena v slovenski orodjarni. Ker sta dela simetrična, so v orodjarni, predlagali, da bi izdelalovali oba hkrati v enem preoblikovalnem orodju in ju v zadnji operaciji prerezali na dva dela. Predlagana rešitev je omogočila zmanjšanje stroškov za izdelavo orodja in povečanje produktivnosti v proizvodnji (s vsakim gibom pehala bi bila izdelana dva izdelka). Oblika, sestavljena iz obeh delov, ki jo je treba izdelati v prvi operaciji globokega vleka, je zelo zapletena, zato so bila za testiranje in optimizacijo proizvodne tehnologije uporabljena numerična simuliranja.

2 ANALYSIS OF THE COVER OF THE TRANSVERSAL RAIL

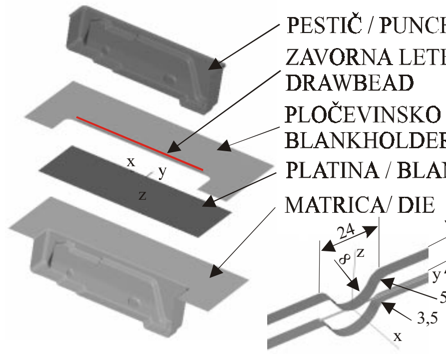
The tools for the production of two sheet-metal chassis parts for a new VW limousine, presented in Figure 2, have been ordered from a Slovenian tool-manufacturing company. Since the parts are symmetrical the tool-manufacturing company had the idea to produce both of them in the same tool-set and cut them into two during the final forming operation. The idea promised a large reduction in tool-manufacturing costs and an increased productivity (two parts are produced by each punch stroke). The geometry combined from both parts, which has to be produced by deep drawing in the first forming stage was very complex. Numerical simulations were used to test and optimise the production technology.



Sl. 2. *Pločevinasta sestavna dela*
Fig. 2. *Sheet-metal chassis parts*

Predstavljeno numerično simuliranje je bilo izvedeno s programskim paketom PAM-STAMP. MKE model za prvo operacijo globokega vleka je predstavljen na sliki 3. Ker je izdelek simetričen, je bil uporabljen polovični model. Preostale preoblikovalne operacije: rezanje, luknjanje in upogibanje niso bile vprašljive in niso bile preučevane. Površine delov orodja so bile diskretizirane s trikotnimi in štirikotnimi elementi kot popolnoma toge, platina je bila diskretizirana s štirikotnimi elementi z elasto-plastičnim reološkim modelom. Za popis utrjevanja je bil uporabljen Krupkowskijev zakon. Celoten model je sestavljen iz 22400 elementov. Trenje med platino in deli orodja je bilo upoštevano s Coulombovim zakonom trenja. V nadaljevnaju so predstavljeni samo tisti rezultati numeričnih simuliranj, ki so bili pomembni za odločanje.

The numerical simulation was performed using PAM-STAMP software. The FEM model for the first deep-drawing operation is presented in Figure 3. Since the product is symmetrical, a half-model was used. Other forming stages: cutting, piercing and bending were not critical and were excluded from the study. The surfaces of the tool parts were discretized with triangular and quadrangular surface elements, which were assumed to be perfectly rigid. The blank sheet was discretized with quadrangular elements, representing the material with an elasto-plastic constitutive law. For the material-hardening determination, the Krupkowski law was used. The model consisted of 22400 elements. The friction between the blank and the tool parts was modelled using Coulomb's law. Only the results of the numerical simulations that were important for the decision-making process are presented.



MATERIAL: VW11-ZSt E220
Zakon utrjevanja $\sigma_f = 547 \cdot \varphi^{0,24}$ (1)
Napetost tečenja $R_p = 240$ MPa
Koef. anizotropije $r_0 = 1{,}72$ $r_{45} = 1{,}72$ $r_{90} = 1{,}72$
Debelina pločevine $s = 1{,}5$ mm

Koeficienti trenja :
$\mu = 0{,}12$ (pestič) / 0,08 (držalo, matrica)

Dolžina delovnega giba = 256 mm

MATERIAL: VW11-ZSt E220
Hardening law $\sigma_f = 547 \cdot \varphi^{0,24}$ (1)
Yield stress $R_p = 240$ MPa
Coef. of anisotropy $r_0 = r_{45} = r_{90} = 1{,}72$
Sheet thickness $s = 1{,}5$ mm

Coefficients of friction :
$\mu = 0{,}12$ (punch) / 0,08 (die, blankholder)

Punch stroke = 256 mm

Sl. 3. *Model MKE*
Fig. 3. *FEM model*

2.1 Rezultati prvega numeričnega simuliranja

Ker platina na koncu obdelovalnega postopka na nekaterih mestih ni v stiku z držalom pločevine, je bilo pričakovano gubanje in zato je bilo prvo numerično simuliranje izvedeno z zavornimi letvami dolžine 790 mm. Zavorne letve, katerih geometrijska oblika je predstavljena na sliki 3, zavirajo tok materiala v srednjem delu orodja in s tem zmanjšujejo nevarnost gubanja. Pred simuliranjem je bila izvedena kalibracija zavorne letve, ki je pokazala, da zavorna letev zavira tok pločevine s silo F_d=330N/mm in poskuša razpreti matrico in držalo s silo F_u=800N/mm. Glede na izkušnje zaposlenih v orodjarni, je bila izbrana platina velikosti AxB=1000x750mm. Z uporabo Sieblove enačbe smo izračunali primerno silo držala $F_{drž}$ = 1000 kN [4].

Rezultati numeričnega simuliranja so napovedali porušitev obdelovanca na več mestih že precej pred koncem obdelovalne operacije (preglednica 1). Trganje je bilo napovedovano s primerjavo deformacijskih stanj v elementih modela s krivuljo mejne deformljivosti (KMD), ki je bila izračunana teoretično [5]. Deformacijska stanja, ki ležijo nad zgornjo krivuljo, napovedujejo porušitev. Gubanje pločevine ni bilo napovedano.

2.2 Rezultati drugega numeričnega simuliranja

Numerično simuliranje je bilo izvedeno še enkrat brez zavornih letev in z manjšo silo držala

2.1 Results of the first numerical simulation

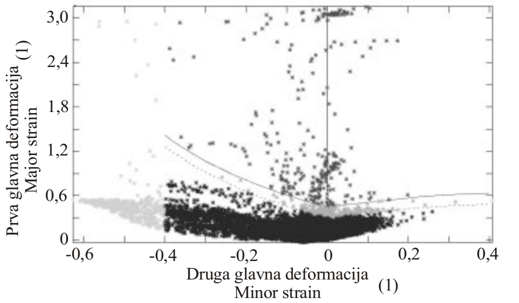
Since the blank is not in contact with the blankholder in some places at the end of the forming process we expected wrinkling, therefore, the first numerical simulation was performed with drawbeads of length 790 mm. Drawbeads, the geometry of which is presented in Figure 3, constrain the material flow in the central part of the tool and reduce the danger of wrinkling. Drawbead calibration, performed before the numerical simulation, showed that the drawbead brakes the sheet metal with the force F_d=330N/mm and lifts the blankholder with the uplift force F_u=800N/mm. The initial blank dimensions AxB=1000x570mm were determined, based on the previous experience of the process designers in the tool-manufacturing company. The appropriate blankholder force $F_{drž}$ = 1000kN was calculated with the Siebel equation [4] .

The results of the numerical simulations predicted the fracture of the work-piece at several places, long before the end of the forming operation (see Table 1). The fracture prediction was made by comparing the strain states in the elements of the model to the forming limit curve (FLC) of the given material, which was calculated theoretically [5]. The strain states above the upper curve predict fracture. No wrinkling was predicted in the first numerical simulation.

2.2 Results of the second numerical simulation

The numerical simulation was repeated without the drawbeads and with a lower blankholder

Preglednica 1. *Rezultati prvega numeričnega simuliranja*
Table 1. *Results of the first numerical simulation*

<table>
<tr><td colspan="2">1. NUMERIČNO SIMULIRANJE (ustavljena 72 mm pred koncem delovnega giba)
$F_{drž}$=1000kN , zavorne letve=DA, velikost platine AxB=1000x750 mm
1st NUMERICAL SIMULATION: (stopped 72 mm before the end of the tool stroke)
$F_{drž}$ = 1000kN , Drawbeads = YES , blank dimensions AxB = 1000 x 750 mm</td></tr>
<tr><td>Diagram mejne preoblikovalnosti
Forming limit diagram</td><td>Mesta, kjer je napovedano trganje
Places of predicted fracture</td></tr>
<tr><td>


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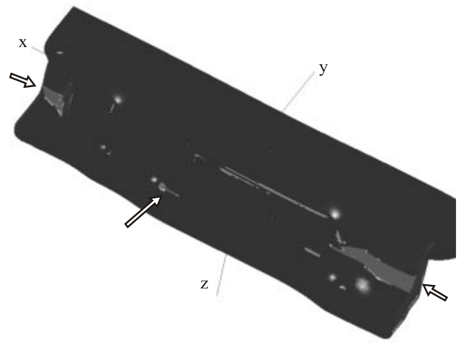
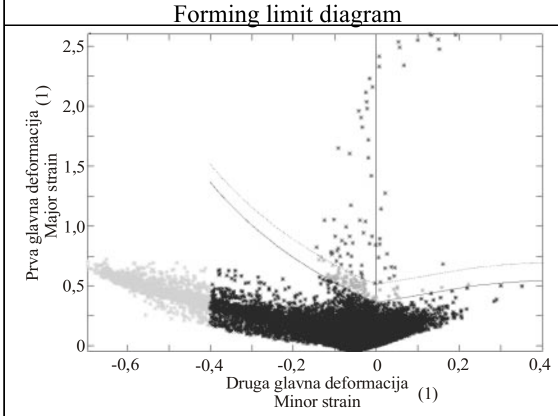


</td></tr>
</table>

Preglednica 2. *Rezultati drugega numeričnega simuliranja*
Table 2. *Results of the second numerical simulation*

<table>
<tr><td colspan="2">2. NUMERIČNO SIMULIRANJE
$F_{drž}$=540kN , zavorne letve=NE, velikost platine AxB=1000x750 mm
2nd NUMERICAL SIMULATION
$F_{drž}$ = 540 kN , Drawbeads = NO , blank dimensions AxB = 1000 x 750 mm</td></tr>
<tr><td>Diagram mejne preoblikovalnosti
Forming limit diagram</td><td>Oblika obdelovanca
Shape of the work-piece</td></tr>
<tr><td>


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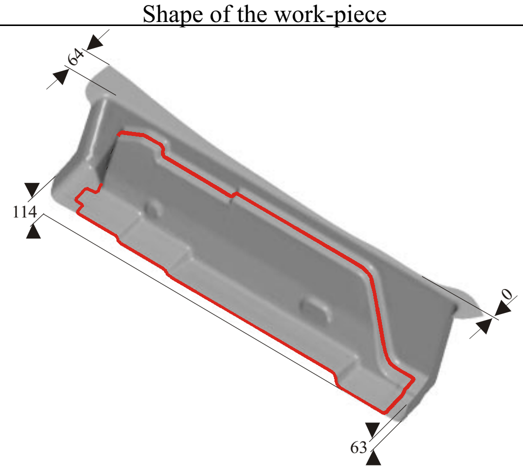

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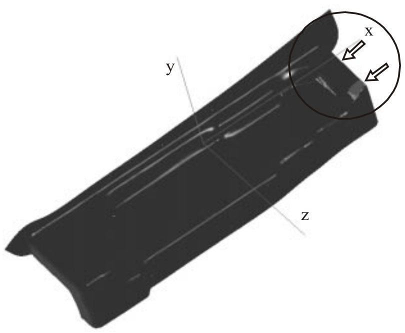
<tr><td colspan="2">Mesta, kjer je napovedano trganje
Places of predicted fracture</td></tr>
<tr><td>


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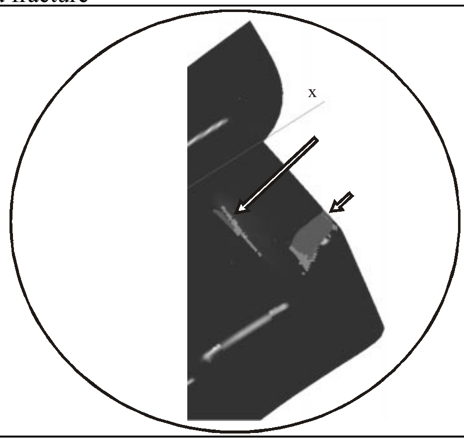

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</table>

$F_{drž}$=540kN z namenom, da se izboljša tok materiala v orodje in na ta način bistveno zmanjša nevarnost trganja. Nevarnost gubanja je večja, toda ker preučevana izdelka nista na vidnem mestu, so manjše gube sprejemljive.

Numerično simuliranje je tudi tokrat napovedalo trganje pločevine, a samo na enem kritičnem mestu obdelovanca.

2.3 Rezultati tretjega numeričnega simuliranja

Če primerjamo obliko obdelovanca po izvedbi operacije globokega vleka in končnih sestavnih delov (preglednica 2), ugotovimo, da na kritičnem mestu obdelovanca ostane po operaciji globokega vleka precej odvečnega materiala. Sile držala ni bilo več mogoče zmanjšati, zato je bila edina možnost za izdelavo sestavnega dela z eno operacijo globokega vleka nadaljnje zmanjšanje začetne velikosti platine.

Tretje numerično simuliranje je bilo izvedeno z manjšo platino. Stik med platino in držalom je bil bistveno zmanjšan in pričakovano je bilo gubanje platine. Kako bi potekal globki vlek manjše platine, smo poskušali napovedati s tretjim numeričnim simuliranjem.

force $F_{drž}$=540kN in order to improve the flow of the material into the die and therefore to considerably reduce the danger of fracture. The danger of wrinkling is increased but since the studied parts are not visible the minor wrinkles are acceptable.

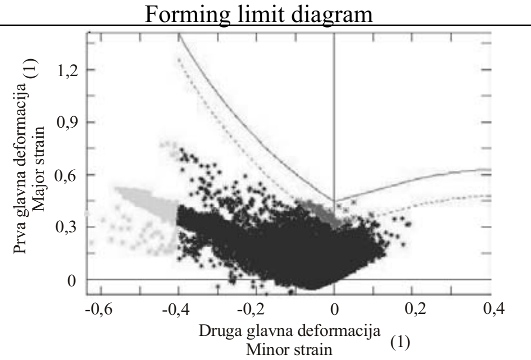
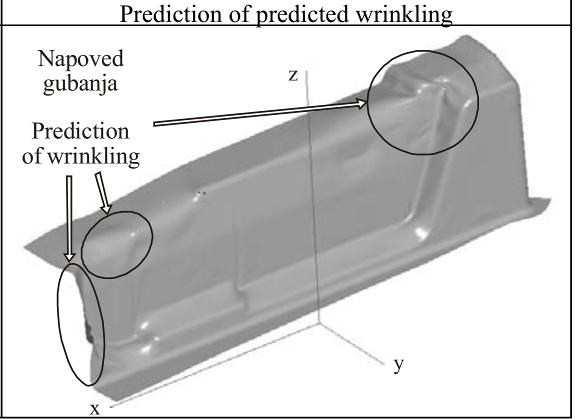
The numerical simulation once again predicted the fracture but this time only in one critical area of the work-piece.

2.3 Results of the third numerical simulation

If we compare the shape of the work-piece after the first deep-drawing operation and the shape of the final product (Table 2) we can see that there is a lot of residual material around the critical area of the work-piece. The blankholder force could not be reduced any more, therefore, the only way to produce the part in a single deep-drawing operation was to further reduce the initial blank size.

The third numerical simulation was performed with a smaller blank. The contact between the blank and the blankholder was reduced considerably and therefore wrinkling was expected. The deep-drawing process with the smaller initial blank size was predicted with the third numerical simulation.

Preglednica 3. *Rezultati tretjega numeričnega simuliranja*
Table 3. *Results of the third numerical simulation*

3. SIMULIRANJE (gubanje 14 mm pred koncem delovnega giba) $F_{drž}$=540kN , zavorne letve=NE, velikost platine *A*x*B*=890x750 mm 3rd **NUMERICAL SIMULATION** (wrinkling 14mm before the end of the tool stroke) $F_{drž}$ = 540 kN , Drawbeads = NO , blank dimensuions *A*x*B* = 890 x 750 mm	
Diagram mejne preoblikovalnosti Forming limit diagram	Mesta, kjer je napovedano gubanje Prediction of predicted wrinkling
	

Rezultati numeričnega simuliranja so napovedali, da je operacija globokega vleka izvedljiva brez porušitve (deformacijska stanja v vseh elementih ležijo pod KMD). Napovedano je bilo intenzivno gubanje. Gube se ob koncu preoblikovalnega giba v orodju izravnajo. Na obdelovancu se kjub temu še vedno poznajo odtiski in manjše gube. Ker predstavljeni izdelki niso na vidnem mestu, so bile manjše gube in odtiski za kupca sprejemljivi. Orodje je bilo izdelano in preskušeno.

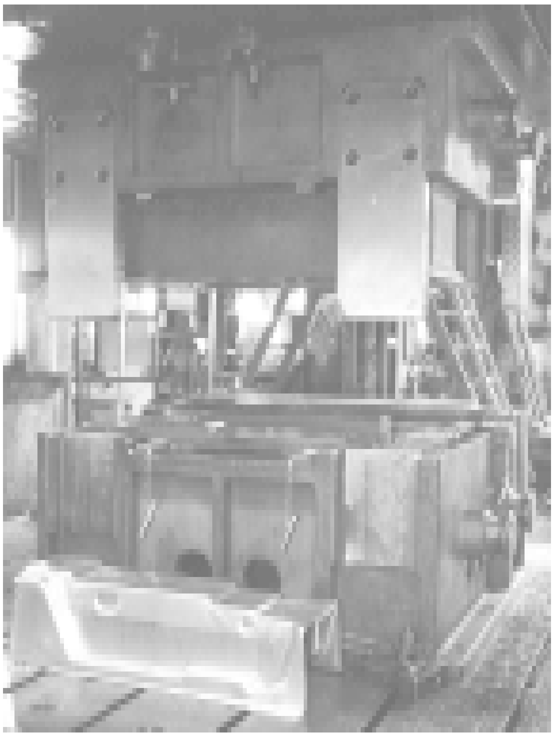
The results of the numerical simulation predicted that the deep-drawing operation was feasible without the danger of fracture (strain states in all elements are below the FLC), however, heavy wrinkling was predicted. At the end of the punch stroke the wrinkles were ironed in the die, but some minor wrinkles and marks on the product surface still remained. Since the parts are not visible, minor wrinkles and marks on the surface were acceptable for the customer. The tool was produced and tested.

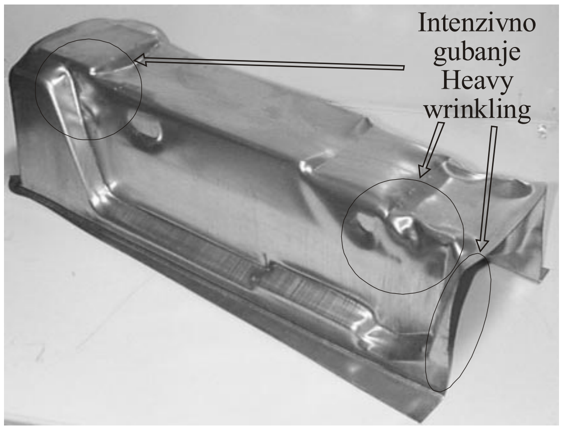
3 PRIMERJAVA REZULTATOV TRETJEGA NUMERIČNEGA SIMULIRANJA IN REZULTATOV PRESKUSOV

Na podlagi rezultatov numeričnih simuliranj je bilo izdelano in preskušeno preoblikovalno orodje. Na sliki 5 desno je prikazan preskušanec, pri katerem je bil gib pestiča ustavljen 14 mm pred koncem preoblikovalne operacije z namenom, da laže opazujemo gubanje.

3 COMPARISON OF THE RESULTS OF THE THIRD NUMERICAL SIMULATION AND THE RESULTS OF TESTING

Based on the results of the numerical simulations the forming tool was produced and tested. In Figure 5 the test-piece is presented, with the punch stroke stopped 14 mm before the end of the forming operation in order to see the wrinkles clearly.

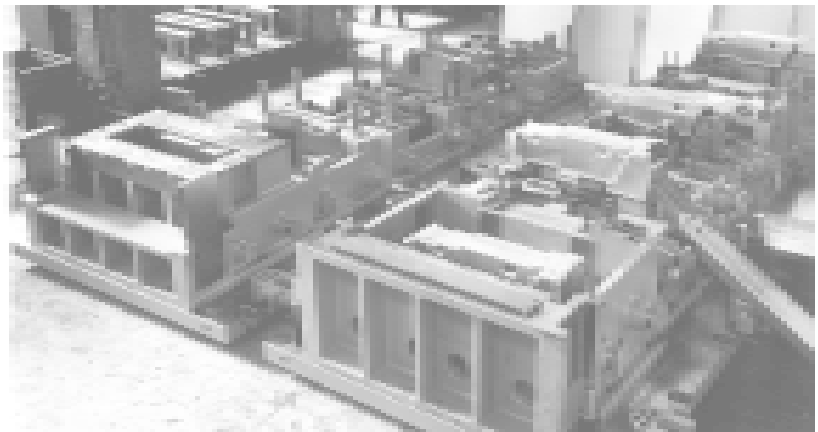




Sl. 5. *Testiranje orodja in testni izdelek*
Fig. 5. *Testing of the tool and test-piece*

Ugotovimo lahko, da je obdelovanec res brez razpok in naguban na napovedanih mestih. Na sliki 6 je prikazano še celotno transferno orodje za izdelavo pokrovnih delov prečnih nosilcev.

It can be concluded that no fracture occurred on the test-piece and the wrinkles are visible at the predicted places. In Figure 6 the whole transfer tool for the production of the covers of the transversal rails is presented.



Sl. 6. *Končno transferno orodje*
Fig. 6. *Final transfer tool*

4 ZANESLJIVOST REZULTATOV, STROŠKI, PREDNOSTI IN ČASI, POTREBNI ZA IZVEDBO NUMERIČNIH SIMULIRANJ

Na podlagi izkušenj, predstavljenih v prispevku in pridobljenih na drugih industrijskih primerih, pri katerih smo primerjali rezultate numeričnih simuliranj z rezultati preskusov, je bila narejena naslednja preglednica, ki opisuje zanesljivost numeričnih simuliranj. Zavedati pa se moramo, da je za doseganje velike zanesljivosti rezultatov treba poprej kalibrirati uporabljani programski paket ter vanj vnesti pravilne in natančne materialne podatke, ki jih je moč dobiti z enoosnim nateznih preskusom. V nasprotnem primeru so lahko rezultati numeričnih simuliranj zavajajoči.

4 RELIABILITY OF THE RESULTS, COSTS, BENEFITS AND TIMES REQUIRED FOR PERFORMING THE NUMERICAL SIMULATIONS

Based on the experience presented in this paper and gained from other industrial examples where numerical simulation results were compared to the results of the testing, the following table presenting the reliability of numerical simulations has been made. Previous calibration of the software is required in order to achieve high reliability of the results. Exact material data, which can be obtained by a uni-axial tensile test, must be inserted into the software or the results of the numerical simulation can be misleading.

Preglednica 4. *Zanesljivost numeričnih simuliranj ([6] do [9])*
Table 4. *Reliability of the results of numerical simulations ([6] to [9])*

Namen Aim	Zanesljivot Reliability
določitev optimalne začetne oblike platine determination of optimum initial blank geometry	ZZ
napoved trganja prediction of tearing	ZZ
napoved končne debeline pločevine prediction of final sheet thickness	ZZ
napoved gubanja prediction of wrinkling	Z
napoved elastičnega izravnavanja prediction of springback	DZ
ocena sil in pritiskov na orodje evaluation of forces and pressures acting on the tool	ZZ
napoved površinskih poškodb prediction of surface defects	NZ

ZZ = zelo zanesljivo , Z = zanesljivo , DZ = delno zanesljivo , NZ = nezanesljivo
ZZ = very reliable , Z = reliable , DZ = partly reliable , NZ = unreliable

Napoved elastičnega izravnavanja in površinskih poškodb še ni na zadovoljivi ravni. Drugi avtorji, ki se ukvarjajo z numeričnimi simuliranji, poročajo o istih težavah, ne glede na to, kateri programski paket uporabljajo ([6] in [7]). Čas za izračun predstavljenega primera je znašal 70 ur na delovni postaji Silicon Graphics Indigo2. Če upoštevamo še čas, potreben za pripravo modela in analizo rezultatov, lahko želene napovedi dobimo v nekaj dneh. Kljub dejstvu, da so numerična simuliranja draga in rezultati niso povsem zanesljivi, je uporaba numeričnih simuliranj smiselna. Večino težav je mogoče vnaprej napovedati. Konstrukcijo orodja je v zgodnji fazi razvoja treba preprosto spremeniti z minimalnimi stroški. Minimizirane so tudi zamude pri dobavi.

The prediction of springback and surface defects is still not at a satisfactory level. Other authors dealing with numerical simulations report the same problems, regardless of the software used ([6] and [7]). The calculation time of the presented examples was 70 hours on a Silicon Graphics Indigo2 machine. When taking into account the time required for the preparation of the model and the analysis of the results, the necessary prediction can be obtained within a few days. The use of numerical simulations is reasonable, despite the fact that the use of a numerical simulation is expensive and the results are not completely reliable. The majority of the problems can be predicted in advance. Tool design is easily changed at an early design stage with minimum costs. Delivery delays are also minimised.

5 SKLEP

Podjetja, ki delujejo kot poddobavitelji avtomobilskih proizvajalcev, se soočajo z izrednimi zahtevami za zvečanje kakovosti proizvodov ob

5 CONCLUSION

Suppliers to the automotive industry are facing extraordinary demands for increasing the quality of products, while at the same time lowering hkratnem zmanjševanju razvojnih časov in proizvajalnih stroškov. Kljub temu, da so sestavni deli avtomobilov čedalje bolj zapleteni in so zaradi tega bolj zapletena tudi orodja za njihovo izdelavo, so zamude in dodatni stroški zaradi dodatnih popravil orodij za kupce nesprejemljivi.

Osnovni razvoj numeričnih simuliranj, ki temeljijo na metodi MKE, se je začel pred desetletji. Danes so paketi za izvedbo simuliranj in računalniki razviti do take stopnje, da pomenijo zanesljivo in tudi dovolj hitro orodje za industrijsko uporabo. Na industrijskem primeru je prikazano, kako je mogoče z uporabo numeričnih simuliranj vnaprej napovedati napake pri konstrukciji orodja in načrtovanju tehnološkega procesa. Optimirano orodje je delovalo pravilno in ga po izdelavi ni bilo treba popravljati.

V primerih, ko orodjarna uporablja numerična simuliranja, lahko vzpostavi boljši dialog z naročnikom orodja. Laže se je dogovoriti za spremembe na izdelku, ki ne spremenijo njegove uporabnosti, a izboljšajo njegovo preoblikovalnost. Naročniki orodij se zavedajo prednosti, ki jih prinaša uporaba numeričnih simuliranj, zato raje sodelujejo z orodjarnami, ki so numerična simuliranja že uvedle v svoje razvojne cikle.

development times and costs. The delays and additional costs for repairs to the tools are unacceptable for customers, even though the complexity of the car components and the tools for their production is increasing constantly.

Fundamental research and development of numerical simulations based on a FEM approach began several decades ago. Nowadays, the software for performing numerical simulations and hardware are developed to the level where they represent a reliable and fast tool for industrial use. We have shown, using an industrial example, that numerical simulations can predict mistakes in tool design and production-process planning in advance. The optimised tool was working properly and no repairs were necessary after the production of the tool.

When numerical simulations are used by a tool-manufacturing company a much better dialog can be established with the customer. It is easier to discuss changes to the design of the product that do not change its functionality but achieve better formability. The customers are aware of the benefits of the use of numerical simulations, therefore, they prefer the tool-manufacturing companies that have already implemented numerical simulations into their development cycles.

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6 SIMBOLI
6 SYMBOLS

meja tečenja	σ_f	MPa	flow stress
napetost tečenja	R_p	MPa	yield stress
koeficinet anizotropije	r	-	coefficient of anisotropy
koeficient trenja	μ	-	coefficient of friction
zaviralna sila zavorne letve	F_d	N/mm	constraining force of the drawbead
razpiralna sila zavorne letve	F_u	N/mm	uplifting force of the drawbead
velikost platine	AxB	mm	blank dimensions
sila držala	$F_{drž}$	N	blankholder force
debelina pločevine	s	mm	sheet thickness

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7 REFERENCE

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