

## Prispevek k hitremu razvoju in izdelavi orodij za globoki vlek pločevine

### Contribution to the Fast Sheet Metal Deep Drawing Tool Development and Production

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V zadnjem desetletju smo pričele velikim spremembam pri svetovnem industrijskem razvoju. Po eni strani so izdelki bolj zapleteni, število njihovih različic narašča, po drugi strani pa se zmanjšujejo tržne dobe trajanja, dobavni časi in cene teh izdelkov. Da bi prenesli vse navedene zahteve, se morajo uvesti nove konstrukcije, materiali in tehnologije, kar pa je skoraj nemogoče brez možne znanstveno – raziskovalne podpore.

Na področju preoblikovanja pločevine, na katerem je avtomobilska industrija njen največji porabnik, je stanje skoraj popolnoma enako, dodatni problem pa je še hiter razvoj izdelkov, hitra izdelava prototipov in njihovo preskušanje. Ker je proizvodnja pločevinastih izdelkov odvisna od posebnih preoblikovalnih orodij, je hitra proizvodnja izdelkov navezana še na izdelavo orodij, glede na to se na široko raziskujejo še tehnologije hitre izdelave orodij.

Članek obravnava splošne probleme in stanje na tem področju s posebnim poudarkom izvirnih slovenskih raziskovalnih prispevkov.

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(Ključne besede: izdelava orodij hitra, orodja slojevita, vlek globoki, sintranje lasersko)

In the last decade we have witnessed significant changes in global industrial development. On the one hand the products are more complex, and the number of their variants is increasing, on the other hand, the product lifetime, the time to delivery and the prices are decreasing because of severe market pressures. In order to sustain these stated demands, new designs, materials, and technologies must be implemented, which requires the strong support of research and development activities.

In the sheet metal processing sector, and for its biggest consumer, the automotive industry, the situation is nearly the same, but with the additional problems associated with fast part development, rapid prototyping and testing. As the production of sheet metal parts depends on special forming tools, the fast production of parts is related to the production of these tools and as a result new technologies for rapid tooling are being widely investigated.

The paper discusses the general problems and the situation in this field with special emphasis on Slovenian original research contributions.

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(Keywords: rapid tooling, laminated tools, deep drawing, laser beam sintering)

#### 0 UVOD

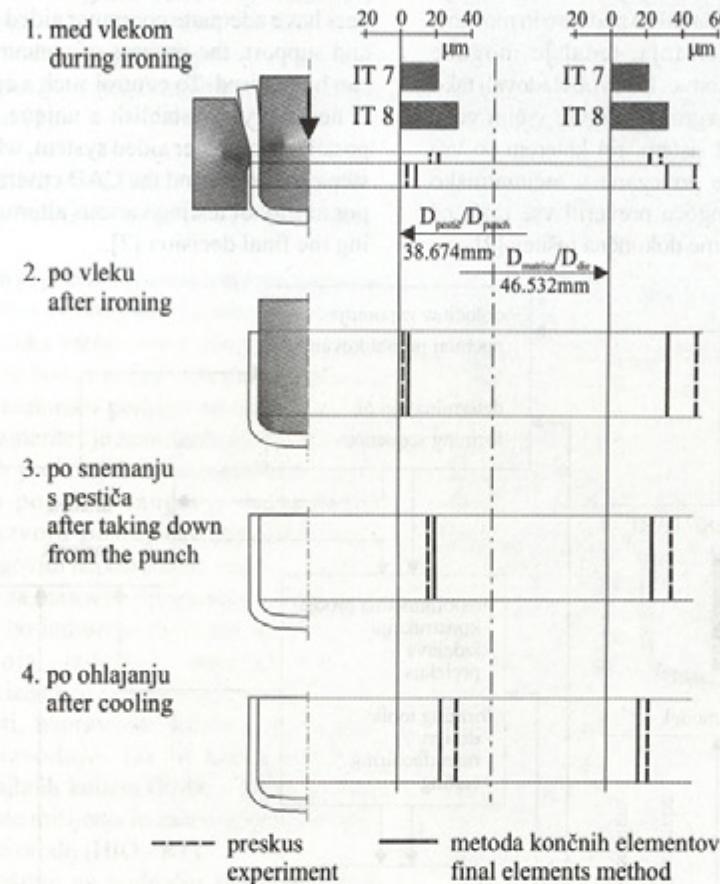
Pločevinasti sestavni del, ki je bil razvit kot del končnega izdelka (na primer avtomobila), ima zelo zapleteno obliko, njegove lastnosti kot trdnost, zmožnost sprejemanja deformacijske energije, odstopanja debeline in oblike, so natančno vnaprej določene. Zato se zelo redko zgodi, da se izdelek napravi z eno samo preoblikovalno operacijo, običajno je celotna tehnološka veriga sestavljena iz izrezovanja surovca, nekaj operacij globokega vleka in/ali izbočevanja, krivljenja, kalibriranja ter končnega izrezovanja izdelka. Da bi določili optimalno zaporedje, je treba upoštevati veliko parametrov in robnih pogojev, kakor so snovne lastnosti pločevine, nastajenje in prenos topote, elastične deformacije

#### 0 INTRODUCTION

A sheet metal component developed to be integrated into a final product (for example, a car) can have a very complex geometry, its various properties such as strength, deformation energy absorption and thickness and shape fluctuation are precisely defined in advance. For this reason it is very seldom that the part can be produced in one single forming operation, normally the whole technological chain consists of blanking the preform, some deep drawing and/or stretching operations, bending, coining and final cutting of the part. To define the optimum sequence, a lot of parameters and boundary conditions should be considered, such as: material properties, heat generation, heat transfer, and elastic deforma-

sistema izdelek/orodje/stroj navezanega na kasnejše elastično vračanje izdelka. Iz tega izhaja, da preoblikovalno orodje ni nikoli natančnen negativ izdelka, oblika orodja mora biti spremenjena ob upoštevanju prej naštetih dejstev (sl. 1).

tion of the part/tooling/machine system connected to the later spring back of the part. From this reason the forming tool is never an exact negative of the part in production, its shape must be designed taking into account all of the above factors (Fig 1).



Sl. 1. Celovita analiza procesa globokega vleka z redukcijo stene [1]  
Fig. 1. Complex ironing process analysis [1]

Konstrukcija in izdelava preoblikovalnih orodij predstavlja naslednjo skupino problemov. Konstruktor orodij mora najprej dobiti celovito informacijo o preoblikovalnih operacijah, kakor so stične napetosti v povezavi z gibanjem pestičev, povečevanje stičnih površin in uporabljenega maziva, potrebe po dodatnih elementih npr.: pločevinska držala, snemala itn. Konstrukcija orodja mora končno biti še prilagojena za razpoložljiv preoblikovalni stroj, na njegovo kinematiko, dovoljene obremenitve, največje izmere orodja, togost stroja, stregi itn. Ko je vse to določeno, tedaj lahko pričnemo s konstrukcijo in načrtovanjem izdelave orodja.

Tradicionalni postopek na področju preoblikovanja pločevine je bil zaporeden, kar pomeni, da je določitvi števila operacij sledila konstrukcija orodij, temu njihova izdelava, preskušanje, prilaganje in popravila. Takšen način predolgo traja in ni več primeren za hitro odzivanje na zahteve trga.

The design and manufacturing of forming tools presents another set of problems. The tool designers must firstly get all the information about the forming steps with data such as contact stresses related to the movements of the punches, the contact surface expansion and the use of lubricants, needs for additional tool elements such as blank holders, strippers, etc. The tool design must finally be tailored to the chosen forming machine, its kinematics, allowable loads, maximum tool dimensions, stiffness, handling, etc. When all these have been defined, the tool design and manufacturing process planning can start.

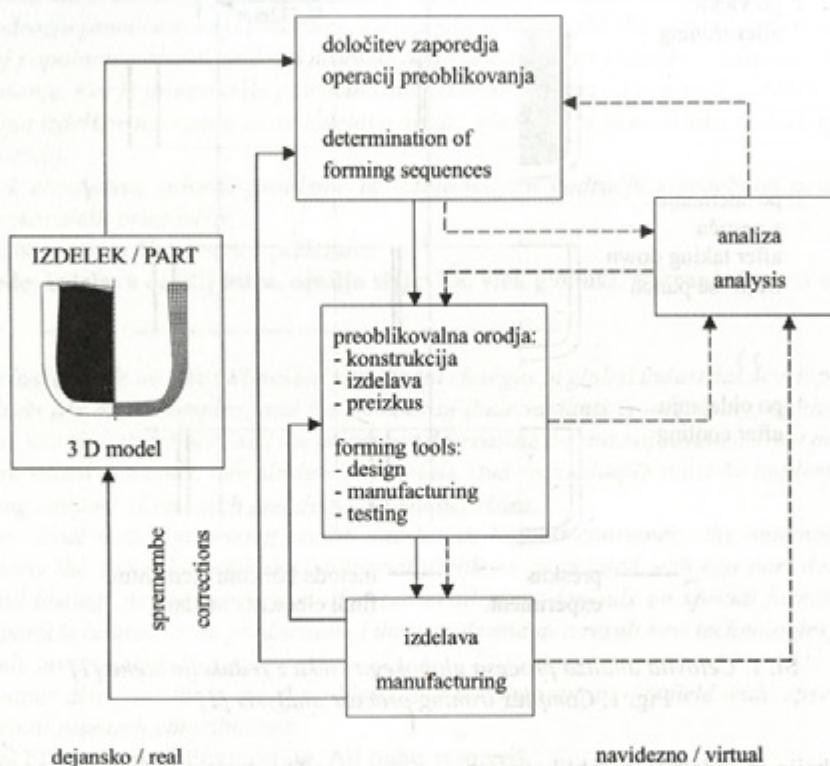
The traditional approach in sheet metal forming was sequential, meaning that a stage like forming sequence design had to be followed by tool design, then by tool manufacture and finally by tool testing, adjusting and corrections. Such an approach is very time consuming and no longer suitable for the fast reactions demanded by the market.

## I RAČUNALNIŠKO PODPRT RAZVOJ POSTOPKOV IN ORODIJ

Razvoj preoblikovalnega postopka, konstrukcija pripadajočih orodij in njihova kasnejša izdelava, vse to je močno med seboj odvisno; če imajo vsi udeleženi partnerji računalniško podporo in možnost medsebojnega komuniciranja, tedaj je mogoče vzpostaviti sočasno inženirstvo. Da bi obvladovali tako zapleten sistem, je treba zgraditi celovit, v čim večji meri računalniško podprt sistem, pri katerem so vse poprej navedene stopnje povezane v računalniško podprt rom okolju, ki omogoča preveriti vse različne možnosti, preden se sprejme dokončna rešitev [2].

## I COMPUTER AIDED PROCESS AND TOOL DEVELOPMENT

The development of the forming process, the associated tool design and the subsequent tool production are very closely related; if all the partners have adequate computer aided communications and support, the process of concurrent engineering can be realised. To control such a complex system it is necessary to establish a unique, and as much as possible, computer aided system, where all the stated steps are linked and the CAD environment offers the possibility of testing various alternatives before taking the final decision [2].



Sl. 2. Načrtovanje postopka preoblikovanja, konstrukcije in izdelave orodja [2]

Fig. 2. Metalforming process planning, tool design and tool manufacturing [2]

Na sliki 2 je zveza med načrtovanjem tehnologije preoblikovanja in konstrukcijo ter izdelavo orodij podprta z analizo preoblikovalnega postopka. Ta analiza lahko temelji na skupinski tehnologiji, zakonih podobnosti, parametrični analizi uspešnih podobnih tehnoloških rešitev in na numeričnih metodah, kakršna je metoda končnih elementov (MKE).

Slika 2 je sestavljena tudi z nekaj povratnimi informacijskimi povezavami. Z vidika varčevanja s časom in denarjem so najbolj zaželeni informacije in popravki postopkov v čim bolj zgodnjih stopnj načrtovanj, posebno še, če se to dogaja v navideznem okolju (desna stran slike 2). Toda, da bi se lahko zanesli na takšne z numeričnimi metodami pridobljene informacije, je treba predhodno izpeljati meritve in preskuse.

In Figure 2 the loop between forming technology and tool design and manufacturing is supported by forming process analysis. This analysis can be based on group technology, similarity laws, parametric analysis of successful similar technological solutions and on numerical methods such as finite elements method (FEM).

Figure 2 consists also of some inverse information loops. In terms of cost and time reduction it is most desirable that information is obtained and process correction instigated at an early stage, and preferably performed in the virtual environment (right side of the Fig 2). In order to rely upon such numerically obtained information, corresponding measurements and tests should be carried out as early as possible.

Ko postavljamo osnove za numerične metode, moramo sprejeti določene matematične modele. Ker je izvedba teh modelov rezultat našega znanja in izkušenj, je skoraj nemogoče pričakovati, da bodo prvi izračuni dali pravilne rezultate. Izboljševanje modelov je torej naša najpomembnejša in stalna naloga, z numeričnimi simuliranjami se matematični model in njegovi procesni parametri natančneje uglasijo s pripadajočimi eksperimentalnimi rezultati [3].

## 2 HITRA IZDELAVA ORODIJ ZA MAJHNE KOLIČINE PLOČEVINASTIH IZDELKOV

Preden se prične masovna izdelava zapletenih izdelkov, na primer avtomobilov, je treba opraviti vrsto preskusov. Z vidika varčevanja z denarjem in časom se pričakuje, da se bodo v bližnji prihodnosti ti preskusi prenesli v računalniško podprtvo navidezno okolje. Potrditev teh usmeritev je že mogoče najti v poročilih zelo naprednih proizvajalcev avtomobilov [4], ki napovedujejo popolno zaupanje računalniško podprtemu razvoju postopkov preoblikovanja pločevine z njegovim neposrednim navezovanjem na izdelavo orodij za masovno proizvodnjo. Toda hkrati s temi gibanji bo industrija še vedno zahtevala (na stopnji razvoja izdelka) manjše količine materializiranih izdelkov z enakimi lastnostmi, kakršne bodo imeli tisti, napravljeni kasneje pri pogojih masovne proizvodnje. Da bi uresničili hitro proizvodnjo majhnih količin (PMK - SQP), je treba spremeniti načine mišljenja in začeti uporabljati hitre metode izdelave orodij (HIO - RT).

Vse rešitve na področju tehnologij hitre izdelave orodij imajo enak začetni pogoj, vse so uspešne, če je bil izdelek popisan z ustreznim tridimenzionalnim RPK modelom, če je preoblikovalni proces nadzorovan z zanesljivimi numeričnimi metodami, če je število preoblikovanih stopenj minimizirano. Zato, da bi zmanjšali razvojne stroške, mora biti nato PMK načrtovana, da se vsak posamičen tehnološki korak lahko samostojno opravi, kar omogoča uporabo manjših strojev, za katere ni nujno, da so vsi na isti lokaciji.

Letos je bila zamisel, ki je predstavljena na sliki 3, preverjena tudi v slovenskem industrijskem projektu, pri katerem so sodelovali Fakulteta za strojništvo Univeze v Ljubljani ter TECOS – razvojni center orodjarstva Slovenije in EMO Orodjarna iz Celja, katerega elementi so temeljili na posebnem raziskovalnem projektu [5].

Slike 3 tako vidimo, da je potreben le en sam dejanski komplet orodij (stopnja številka 4), druge stopnje se lahko opravijo na posebni laserski napravi.

Ker je bil proces globokega vleka razvit ob pomoči zanesljive metode končnih elementov (poprej večkrat natančno uglašen s sedanjimi industrijskimi

When establishing a base for a numerical computation a corresponding mathematical model must be adopted. Since the objectivity of this model is a result of our knowledge and experiences, it is rather unrealistic to expect a perfect solution after a single trial. The improvement of the model is therefore always an important concern, one has to use numerical simulations intensively in order to tune the mathematical model and its parameters with respect to the experimental results [3].

## 2 RAPID TOOLING FOR SMALL QUANTITIES OF SHEET METAL COMPONENTS

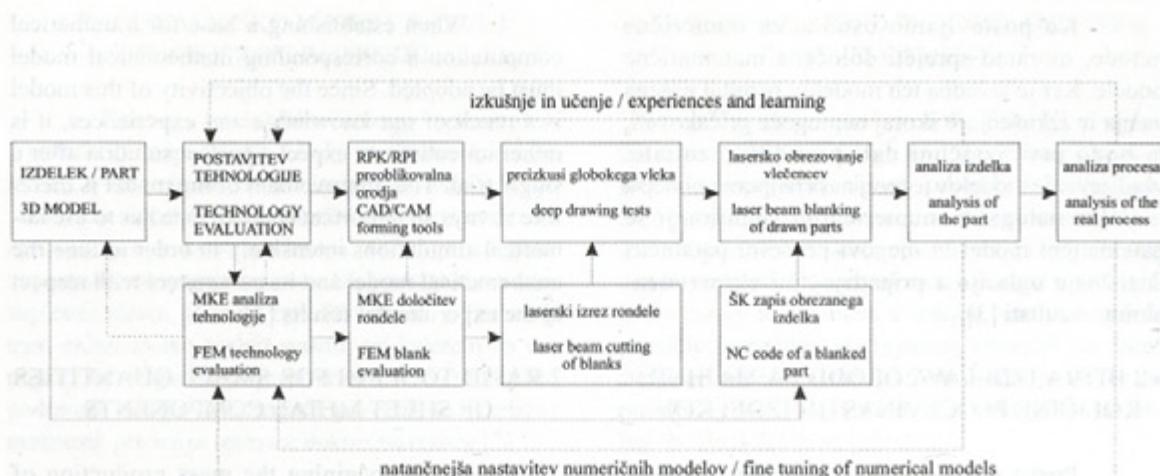
Before beginning the mass production of complex products, for example cars, a variety of tests should be performed. In order to reduce as far as possible time and costs it is expected that in the near future all these tests will be transferred to a computer supported virtual environment. The confirmation of these trends can be found in some recent reports from the most advanced car producers [4] where they predict total confidence in the computer aided sheet metal forming process development, directly linked to the tool manufacturing for mass production. However, in addition to this computer based development industry will still demand (during the product development phase) small quantities of materialised parts with the same performance as those manufactured later under the conditions of mass production. To realise fast and small quantity production (SQP), a new way of thinking, new rapid tool (RT) manufacturing technologies should be used as well.

All approaches in rapid tooling technologies have the same precondition that they are successful only: if the part is described with an appropriate 3D CAD model, if the forming process is controlled by reliable numerical methods, and if the number of forming steps are minimised. Also to minimize the development costs, the SQP should be designed in such a way that each technological step can be performed separately, which would allow the use of smaller machines, not necessary at the same location.

Recently the idea presented in Fig. 3 was tested in a Slovenian cooperative industrial project between the Faculty of Mechanical Engineering at the University of Ljubljana, TECOS – Slovenian Tool and Die Development Centre, Celje and EMO – Tool Company Celje, the elements of it are based on a special research project [5].

From Figure 3 it can be seen that only one real deep drawing tool set is needed (stage number 4), the other steps can be performed separately by appropriate laser beam equipment.

As the deep drawing process was evaluated using reliable FEM (previously fine tuned several



Sl. 3. Kombiniran računalniško (RPN) in lasersko podprt proces globokega vleka manjših količin izdelkov (PMK)  
Fig. 3. Combined CAE and laser assisted SQP deep drawing process evaluation

rešitvami), je bila kot rezultat te obravnave pridobljena tudi dvodimenzionalna informacija v obliki potrebne rondele, ta je bila takoj prenesena na dvodimenzionalni stroj za rezanje z laserskim žarkom, ki je rondele nato tudi izrezal. Po opravljeni operaciji globokega vleka je potrebna še ena operacija rezanja, s katero se loči izdelek od odpadnega venca. V želji, da se opravi takša operacija le na nekaj deset kosih, je postal stroj z laserskim žarkom (z več nadzornimi osmi) zopet najustreznejša naprava.

## 2.1 Slojevite matrice za globoki vlek

Postopek, ki je predstavljen na sliki 3, je mogoče še izboljšati, če se namesto matrice, izdelane na običajen način (z veliko odpornostjo proti obrabi, ki pa za prve preskuse ni potrebna) nadomestijo z drugimi, ki so bile izdelane veliko hitreje in ceneje in še imajo zadovoljivo obstojnost proti obrabi.

Na področju izdelave matric le za preskusne izdelke ali za proizvodnjo manjših količin obstaja vrsta različnih tehnologij, ki se začnejo z leseni modeli, do litja nekovinskih materialov ali nizkotaljivih kovin do frezanja posebnih polimerov. Leta 1980 je Nakagawa [6] predstavil zamisel, da bi se orodje za rezanje pločevine sestavilo iz lasersko narezanih pločevin, kasneje leta 1987 pa je isti avtor še poročal, da se v japonski industriji uporablja že več ko 100 takšnih rezalnih orodij [7], leta 1984 je predstavil prve eksperimentalne rezultate uporabe slojevitih matrice za globoki vlek [8].

Orodja za globoki vlek, ki so bila sestavljena iz pravokotno narezanih pločevinastih lamel, kakršno so predstavili japonski avtorji, je bilo treba kasneje frezati, da se je stopničasta oblika spremenila v ustreznejšo. Ker pa se laserski žarek lahko nagne za

times by existing industrial solutions), its output was 2D information of the blank which was transferred to a 2D laser beam cutting machine and the blanks were subsequently manufactured. After performing the deep drawing operation another cutting operation is needed to separate the part from the rest of the sheet. In order to realize this operation on only some tens of parts, the laser (with more control axes) is again the most convenient machine.

## 2.1 Laminated deep drawing dies

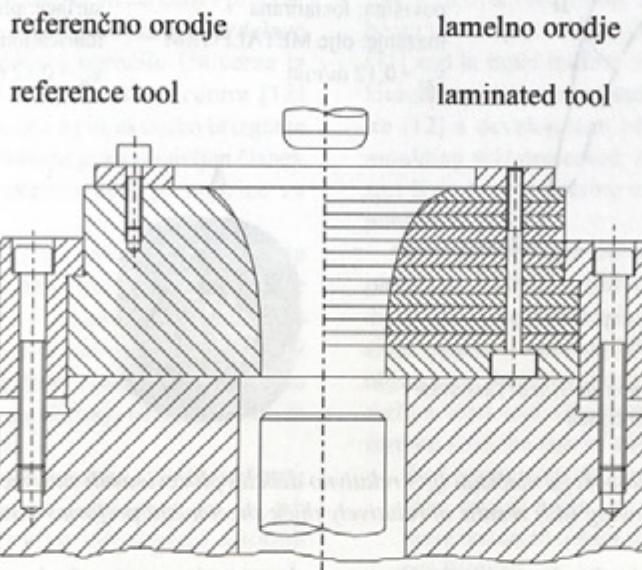
The process presented in Fig. 3 could be improved if instead of a conventionally manufactured (with high wear resistance which is for first tests not needed) die, it was to be replaced with a new one, produced much faster and more cheaply and with sufficient wear resistance.

In the field of deep drawing dies production for test runs and SQP there are a variety of different technologies starting from wooden models, casting of non metal materials or low melting metals, or milling of special polymers. In 1980, Nakagawa [6] presented an idea to build a sheet metal blanking tool with laser cut steel lamellae, later on in 1987 the same author reported that in Japan more than 100 blanking tools were used in industry [7], in 1984 he presented the first experimental results of [8] laminated deep drawing dies.

The deep drawing tools assembled with perpendicular laser cut lamellae, as presented by Japanese authors, had to be subsequently milled to transform the stepped forms into the appropriate shape. As the laser beam could be inclined to a certain degree,

določen kot, je bil proces Nakagawe izboljšan tako, da se tanko pločevinasto slojevito orodje sestavi v obliku poligona, ki je že zelo podoben zahtevani obliki orodja [9]. Takšen poligonski profil vlečne matrice se mora nato le spolirati in je že primeren za preskusne vleke ali proizvodnjo manjših količin.

Nakagawa's process was improved in such a way that the thin sheet laminated tool was assembled with a polygonal shape being very similar to the required tool contour [9]. Such polygonal drawing die profiles were later on only polished and were then ready for tests and SQP.



Sl. 4. Referenčna in slojevita matrica za globoki vlek

Fig. 4. Reference and laminated deep drawing die

Prvi preskusi s slojevitimi in referenčno matrico, ki je bila izdelana na običajen način (sl. 4), so pokazali, da je proces globokega vleka stabilen, uporaba poligonsko lasersko narezanih jeklenih pločevin pa je dobra in zanesljiva metoda za hitro proizvodnjo orodij.

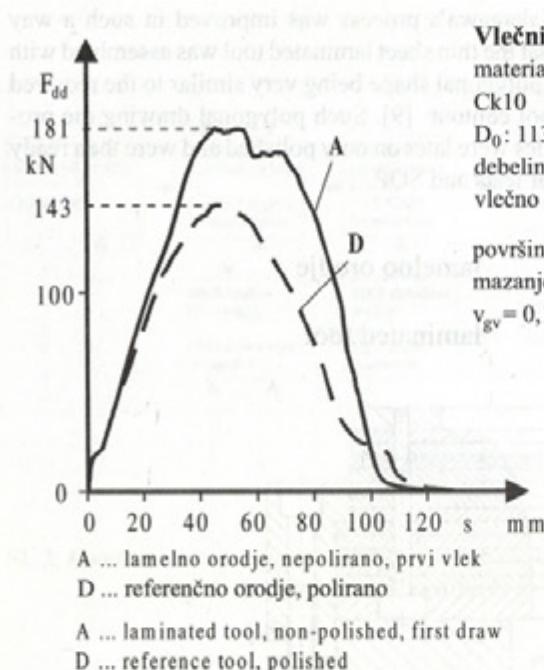
V nadaljevanju so se raziskave na tem področju prenesle na proizvodnjo nerotacijskih izdelkov, kar pomeni, da nagibni kot posamezne lamele ni bil več konstanten, da notranja površina matrice ni več rotacijsko simetrična, temveč jo predstavlja zapletena tridimenzionalna ploskev. Da je bilo mogoče izpeljati to zamisel, je bilo treba rešiti vrsto problemov pri vodenju laserskega žarka, potreben je bil petosni računalniško numerično krmiljen laserski sistem. V okviru skupnega slovensko – nemškega projekta je bila takšna matrica izdelana in preskušena, rezultati so bili predstavljeni z vabljenim predavanjem na mednarodni laserski konferenci [10].

V nadaljevanju raziskovanega dela smo nato ugotovili veliko prilagodljivost industrijske uporabe slojevitih hitro izdelanih orodij, če sta preoblikovalni proces ter konstrukcija in izdelava orodij tako tesno povezana, kakor je prikazano na sliki 3. Če je namreč metoda končnih elementov ocenila, da bo prišlo do porušitve izdelka, se lahko oblika orodja spremeni, vlečenje ponovi (seveda vse v navideznem okolju) v toliko približevalnih zankah, dokler proces ne postane stabilen, dokler ne zagotovi dobrih

The first tests with laminated and conventionally produced reference dies (Fig. 4) have shown that the drawing processes are stable, the use of polygonary laser cut steel sheets is a good and reliable method for the fast production of rapid tooling.

In the continuation of research in this field we moved into the production of non rotational parts which means that the inclination angle of the individual lamella is not constant, the inner die surface is therefore no longer a rotational symmetric plane but has a complex 3D contour. To realise the idea a lot of problems in the field of laser beam control have to be solved, a five axes CNC laser system was needed. In a common Slovenian – German project the dies were produced and tested, and the results were presented in an invited paper at an international laser conference [10].

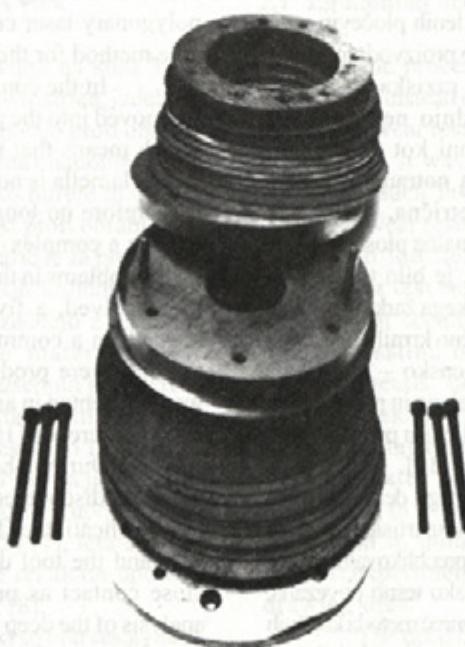
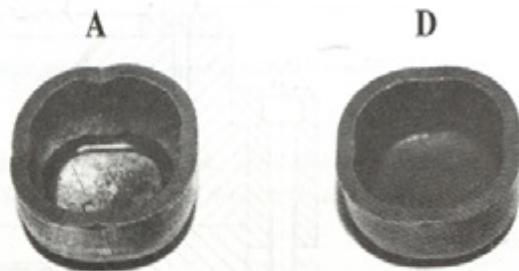
During the continuation of our research work we discovered a great flexibility in the industrial application of laminated RT if the forming process and the tool design and manufacturing are in close contact as presented in Fig. 3. When FEM analysis of the deep drawing process predicts the failure of the part, the tool shape can be changed and the drawing repeated (all in the virtual environment) using sufficient iteration loops so that the process is stable ensuring good products[10]. According to the



Sl. 5. Nekaj rezultatov globokega vlečenja (gv) relativno debelih pločevinastih surovcev v nerotacijske lončke  
Fig. 5. Some deep drawing (dd) results of relatively thick sheet metal preforms into non rotational cups

izdelkov [10]. Na podlagi te končne oblike orodja se lamele lasersko izrežejo, orodje sestavi in realni preskusi lahko stečejo. V primeru, ko želimo izdelati družino geometrijsko podobnih izdelkov, se lahko orodje sestavi iz različnih lamel, ki so lahko izdelane tudi z različnimi tehnologijami (sl. 6).

Vlečni parametri:	Drawing parameters:
material roncole:	blank material:
Ck10	Ck10
$D_0: 113 \text{ mm}$	$D_0: 113 \text{ mm}$
debelina: $s_0 = 5,0 \text{ mm}$	blank thickness: $s_0 = 5.0 \text{ mm}$
vlečno razmerje: 2,16	drawing ratio: 2.16
površina: fosfatirana	surface: phosphated
mazanje: olje METALFORM	lubrication: oil METALFORM
$v_{gv} = 0,12 \text{ m/min}$	$v_{dd} = 0.12 \text{ m/min}$



Sl. 6. Elementi orodja za globoki vlek, ki so bili napravljeni z različnimi tehnologijami [10]  
Fig. 6. Elements of a deep drawing die produced by different technologies[10]

latest tool geometry, the lamellae should be laser cut, tools assembled and tests performed. In the case, where a family of geometrically similar parts are to be produced, the tools could be assembled of different lamellas also produced by different technologies (Fig.6).

## 2.2 Neposredno lasersko sintranje aktivnih delov orodij

Proizvodnja majhnih količin pločevinastih izdelkov potrebuje ustrezeno orodje za globoki vlek, ki mora biti čim hitrejš izdelano. Ker lasersko podprtne tehnologije vstopajo v različna izdelovalna področja, je v zadnjih desetih letih opazna integracija neposrednega sintranja z laserskim žarkom v procese hitre izdelave prototipov (HIP) [11] in hitre izdelave orodij (HIO). Tako lahko v poročilu Univerze iz Erlangena in Bavarskega laserskega centra [12] zasledimo razvoj RT orodja za injekcijsko brizganje plastične mase, v letu 1996 pa je bil objavljen članek o neposrednem laserskem sintraju matrice za globoki vlek [13].

Leta 1997 je Evropska zveza podprla mednarodni raziskovalni projekt za nadaljnje raziskave stabilnosti procesa globokega vleka, če se pri tem uporabljajo neposredno lasersko sintrani aktivni deli orodij [14]. Med mnogimi projektnimi cilji preskusov globokega vlečenja nizkoogljičnih in aluminijevih pločevin so:

- primerjava sil pri vlečenju v referenčnem (jeklenem) orodju in sintranem ter iz teh rezultatov pridobiti prvo informacijo o tornih razmerah,
- eksperimentalno preverjanje analize MKE globokega vleka,
- raziskava obrabne odpornosti oziroma razvoja obrabe sintranih orodij,
- in končno določiti optimalne: kemično sestavo kovinskega prahu, proces sintranja z laserskim žarkom ter zaključnih procesov.

Ko smo v okviru projekta definirali testni izdelek, je bila s pomočjo programov MKE oziroma PAM-STAMP programa opravljena analiza postopka vlečenja. Da bi dobili zanesljive rezultate, smo poprej s kontinuirnim nateznim preskusom dobili potrebne preoblikovalne (krivulja plastičnosti, faktorji anizotropije) značilnice uporabljenih pločevin. MKE je bila najprej uporabljena zato, da bi vnaprej ugotovili največjo mogočo višino končnega izdelka, pri čemer je bil omejitveni pogoj ta, da morajo lokalne deformacije na izdelku ležati pod krivuljo analitično ugotovljene krivulje mejnih deformacij. V drugem koraku je bila nato določena oblika rondevle, podatki o njeni geometrijski obliki so bili posredovani enoti NC za rezanje z laserskim žarkom in rondevla je bila izrezana.

Za ovrednotenje postavljenega programa je bilo sestavljeno in izdelano posebno orodje, hkrati s tem pa so bili neposredno lasersko sintrani aktivni deli tega orodja (sl. 7). Za eksperimente je bila uporabljena dvojno delujoča hidravlična stiskalnica, ki je v Laboratoriju za preoblikovanje na Fakulteti za strojništvo Univerze v Ljubljani.

## 2.2 Direct laser sintered active tool parts

The SQP of sheet metal parts needs an appropriate deep drawing tool set which has to be manufactured as fast as possible. As laser supported technologies have entered into different fields of manufacturing, over the last ten years a rapid development has been observed in the integration of direct laser beam sintering processes into rapid prototyping (RP) [11] and in rapid tooling (RT). In a report from the University of Erlangen and the Bavarian Laser Centre [12] a development of RT for plastic injection moulding was presented, in 1996 a paper on the direct laser beam sintering of a deep drawing die was published [13].

In 1997 the EU supported a multinational project on further investigation of the stability of the deep drawing process when using direct laser beam sintered active tool parts [14]. Among several project objectives the deep drawing experiments with low carbon steel and aluminium sheets should be performed with the aim of determining:

- the comparison of forces when drawing in reference (steel) tools and sintered tools, and from these results to obtain initial information concerning friction;
- an experimental evaluation of deep drawing FEM analysis;
- the wear resistance and the wear propagation of the sintered tools;
- and to define the optimum chemical composition of powders, the laser beam sintering processes and post processes.

After the experimental part was defined, the FEM analysis of the deep drawing process was performed using the PAM-STAMP software. To generate reliable results, the necessary sheet metal formability data (flow curve, anisotropy values) were obtained using continuous tension tests. The FEM analysis was used primarily to discover the maximum height of the part where the limiting factor was the need for the computed strain pattern to lie below the analytically determined forming limit curve. In the next step the shape of the blank was obtained, its geometrical data were transferred to the NC unit of the laser beam cutting machine and the blanks were produced.

To evaluate the defined research programme, a tool set was designed and manufactured, parallel with this, the active tool parts (Fig. 7) were direct laser sintered. For the experimental work, the double stroke hydraulic press, installed in the Forming Laboratory at the Faculty for Mechanical Engineering - University of Ljubljana, was used.

vrtenje bojta na hitrih brzostih med 1000-1200 rpm.

Prvi naložen cilj bolja rezanja je uspel, saj so dosegli veliko skladnost med rezljivo in rezljivim materialom. Sledila pa je izkušnja s dobljenimi rezljivimi deli. Tudi v tem primeru je bilo potreben pravilno izvedeni proces. Vredno je pomeniti, da je rezljivo delo zelo težko rezati. Tako je rezljivo delo včasih potreben rezljivo delo, ki je običajno podobno ali manjšo. Še posebej je težko rezati delo, ki ima različne geometrije. Prav tako je težko rezati delo, ki ima različne geometrije.

Sl. 7. Prvi komplet neposredno lasersko sintranega pestiča in matrice

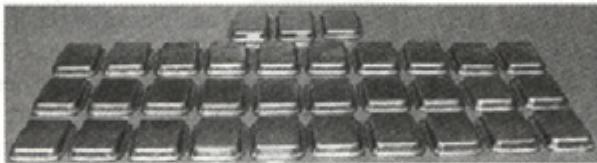
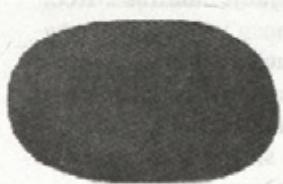
Fig.7. The first of direct laser sintered punch and die set

Izdelki / part

izdelek / part



laserski izrez rondel  
laser cut blank



Sl. 8. Vzorec globoko vlečenih izdelkov iz 0,3 mm debele nizko ogljične pločevine

Fig.8. Sample of deep drawn parts from 0,3 mm thick low carbon steel sheet

Pri analizi prvih rezultatov smo nadalje tudi ugotovili, da ni bistvene razlike med silami, če se vlečene opravi v konvencionalnih ali lasersko sintranih orodjih. Do podobnih sklepov smo prišli tudi pri analizi različnih pogojev mazanja (sl. 9).

Najpomembnejši problem pri uporabi hitro izdelanih orodij je njihova geometrijska stabilnost in obrabna odpornost. Med prvimi preiskami z dvema skupinama s po 30 preskušanci smo ugotovili:

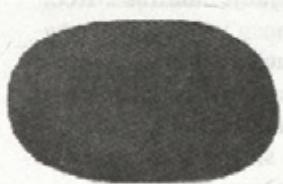
- pri vlečenju aluminija ni bilo nobene obrabe orodja,
- majhna obraba (0,1 mm) in to le v najmanjšem polmeru orodja je povzročila tudi manjše povečanje sile vlečenja.

Prvi rezultati kažejo, da je vlečenje s hitro izdelanimi orodji možno diktirati (sl. 10).

Analiza rezultatov kaže, da je rezljivo delo zelo težko rezati. Vredno je pomeniti, da je rezljivo delo zelo težko rezati. Tako je rezljivo delo včasih potreben rezljivo delo, ki je običajno podobno ali manjšo. Še posebej je težko rezati delo, ki ima različne geometrije. Prav tako je težko rezati delo, ki ima različne geometrije.

The tests confirmed that the FEM is a reliable tool for virtual deep drawing process evaluation because the computer aided and experimentally obtained results were in good agreement. The drawing process was stable, and we managed to produce some tens of good parts (Fig.8).

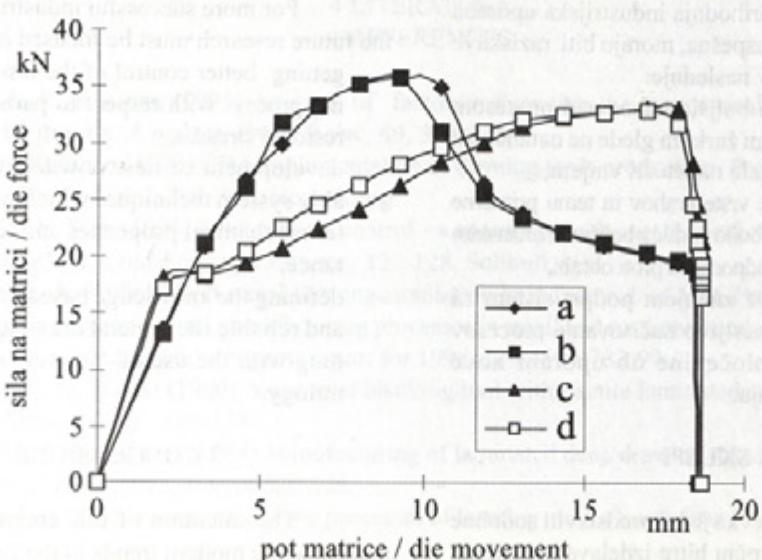
laserski izrez rondel  
laser cut blank



Analysing the initial results, we established that there was no significant difference between forces when either conventional or laser sintered tools were used. A similar conclusion was drawn concerning the influence of different lubrication conditions (Fig.9).

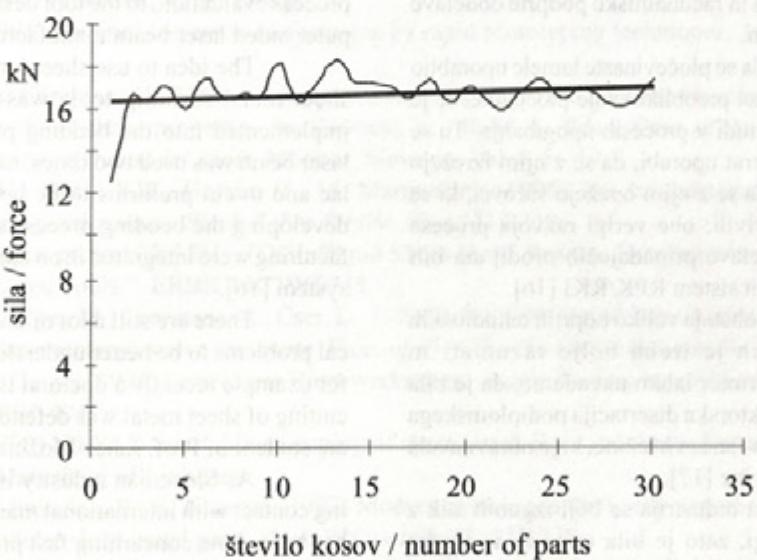
The most important problem with the use of rapid tools is their geometrical stability and wear resistance. During the initial tests we performed two series of experiments, each of them using 30 parts. The results were:

- no tool wear with the drawing of aluminium,
- a small amount of wear (0.1 mm) only on the smallest die corner which was also reflected in a slight increase in the drawing force (Fig.10).



Sl. 9. Sile (na pestiču in držalu pločevine) pri vlečenju jeklene pločevine (a-referenčno orodje/brez maziva, b-sintranano orodje/brez maziva, c-sintranano orodje/mazano z oljem, d-referenčno orodje/mazano z oljem)

Fig. 9. Forces (punch and blank holder) when drawing steel sheet metal (a-reference die/no lubricant, b-sintered die/no lubricant, c-sintered die/oil, d-reference die/oil)



Sl. 10. Največje sile pri vlečenju jeklene pločevine skozi sintranano matrico ob mazanju z oljem

Fig. 10. Maximum forces when drawing steel sheets in a sintered tool set with oil as a lubricant

Potem ko smo opravili prve prekuse z neposredno lasersko sintranimi HIO, smo prišli do naslednjih sklepov [15]:

- neposredno sintranje z uporabo laserskega žarka je postopek z enim samim korakom od RPK modela do uporabnega prototipnega orodja,
- zapletenost orodja je praktično neomejena,
- mogoče je obdelovati velik izbor materialov,
- proces globokega vleka je mogoče izvesti, izdelki imajo stabilno geometrijsko obliko,
- pogoji trenja so skoraj enaki tistim v običajnih jeklenih orodjih.

After performing the first experiments with direct laser beam sintering the following facts can be stated [15]:

- direct laser beam sintering is a single step process from CAD model to functional prototype tools,
- the tool geometrical complexity is nearly unlimited,
- it is possible to process a wide variety of materials,
- the deep drawing process is reliable, the produced components have a stable geometry,
- the friction conditions were nearly equal to the situation of drawing in a conventional steel tool set.

Zato, da bo prihodnja industrijska uporaba teh postopkov še bolj uspešna, morajo biti raziskave usmerjene predvsem v naslednje:

- zagotoviti je treba boljši nadzor nad procesom sintranja z laserskim žarkom glede na natančnost izdelka in na zaostale napetosti v njem,
- razviti je treba nove vrste prahov in temu primerno sistemski tehnike, ki bodo vodile k boljšim mehanskim lastnostim in boljši odpornosti proti obrabi,
- postaviti je treba z znanjem podprt sistem za hitre in bolj zanesljivo načrtovanje procesov preoblikovanja pločevine ob uporabi nove tehnologije sintranja.

### 3 SKLEPI

Namen prispevka je bil predstaviti sodobne smeri razvoja na področju hitre izdelave zapletenih pločevinastih izdelkov. Še enkrat je treba poudariti, da je industrijska uporaba navedenih tehnologij uspešna le tedaj, če je v celoti računalniško podprta, in to od tridimenzionalnega popisovanja izdelka, do MKE ovrednotenja procesa preoblikovanja in do konstrukcije orodja in računalniško podprte obdelave z laserskim žarkom.

Zamisel, da se pločevinaste lamele uporabijo za izdelavo orodij za preoblikovanje pločevine, se je uspešno uporabila tudi v procesih upogibanja. Tu se laserski žarek dvakrat uporabi, da se z njim izrežejo orodne lamele in da se z njim izrežejo surovci, ki se bodo kasneje zakrivili; obe verigi razvoja procesa upogibanja in izdelave pripadajočih orodij sta bili priključeni v celovit sistem RPK/RKI [16].

Se vedno obstaja veliko odprtih tehnoloških problemov, ki jih je treba bolje razumeti in obvladovati, kot primer lahko navedemo, da je bila letos obranjena doktorska disertacija podiplomskega študenta profesorja Janeza Možine, ki je obravnavala poševni rez pločevine [17].

Slovenska industrija se boji izgubiti stik z mednarodnimi trgi, zato je bila opravljena široka raziskava o hitri izdelavi modularnih pločevinastih izdelkov, ki bi lahko zadovoljili posebne zahteve kupcev [18]. Končno je bilo ugotovljeno, da je strateška usmeritev slovenskega orodjarstva uvedba novih tehnologij, podprtih z domaćim razvojem in raziskavami [19].

### Zahvale

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For more successful industrial applications the future research must be focused on:

- getting better control of the laser beam sintering process with respect to parts accuracy and residual stresses,
- development of new powder types and suitable system techniques which will lead to better mechanical properties and tool wear resistance,
- defining the knowledge based system for faster and reliable sheet metal drawing process planning with the use of the new sintering technology.

### 3 CONCLUSIONS

The intention of this contribution was to present some modern trends in the field of fast production of complex sheet metal components. It is necessary to stress again that industrial implementation of these technologies could be of the greatest benefit only if it is completely computer supported from the 3D part modelling, to the FEM forming process evaluation, to the tool design and to the computer aided laser beam manufacturing.

The idea to use sheet lamellas for building sheet metal forming tools was also successfully implemented into the bending processes. Here the laser beam was used two times, to cut the tool lamellae and to cut preforms to be bent, both routes for developing the bending process and the tool manufacturing were integrated in an appropriate CAD/CAP system [16].

There are still a lot of unsolved technological problems to be better understood and controlled, for example recently a doctoral thesis about oblique cutting of sheet metal was defended by a postgraduate student of Prof. Janez Možina [17].

As Slovenian industry is also aware of losing contact with international markets, a broad study has been done concerning fast production of modular sheet metal parts to fulfil specific customers demands [18]. Finally, it has been established that the strategic orientation of the Slovenian toolmaking sector should be the implementation of new technologies supported by their own research and development [19].

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