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Hitra izdelava prototipov

Rapid Prototyping

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Industrija je zahtevala vedno krajše čase pojavljanja izdelkov na tržišču, večje število različic, nižje cene in druge izboljšave izdelkov; zaradi teh zahtev se je razvilo področje hitre izdelave prototipov (HIP). V današnjem času lahko z uporabo sistemov HIP hitro izdelamo, preskusimo in proučimo prototipne izdelke, kar pripomore k skrajšanju časa razvoja novega izdelka. Izdelki, izdelani na ta način, imajo tako natančnost in kakovost površine kakor deli, izdelani z odrezovanjem (struženje, frezanje itn.).

Članek obravnava primerjavo med konvencionalnimi metodami izdelave prototipov in sodobnim postopkom razvoja novega izdelka, predstavljene so različne tehnologije HIP za razvoj in izdelavo novega izdelka ter njihove prednosti.

(Ključne besede: izdelava prototipov hitra, tehnologije izdelave, rapid prototyping, modeliranje)

Industry requires shorter times to launch products on to the market. It also demands product variety, lower prices and other product improvements. As a consequence of these demands Rapid Prototyping (RP) has been developed. It is now possible to produce, test and investigate prototypes more rapidly than ever, which helps in time shortening for new product development. Products made by RP have accuracy and quality of the surface as good as parts made by cutting (turning, milling, etc.).

This paper describes and compares the benefits and differences between conventional and various RP methods of product development.

(Keywords: rapid prototyping, prototype making, rapid prototyping technologies, modelling)

1 IZZIV DEVETDESETIH LET IN VLOGA HITRE IZDELAVE PROTOTIPOV

Glede na to, da je bila v 70. in 80. letih tekmovalnost predvsem pri ceni, kakovosti in razpoložljivosti izdelka ter ne nazadnje pri upoštevanju želja strank, je izziv 90. predvsem v nadzorovanju stroškov in času prihoda izdelka na trg.

Vse te zahteve v zadnjih letih so narekovale sodobne načine, po katerih je mogoče priti čim hitreje in ceneje do prototipnega izdelka ter s tem tudi skrajšati čas razvoja končnega izdelka. K temu je pripomogel tudi skokovit razvoj računalniške tehnologije, saj je računalniška integracija navzoča v vseh fazah izdelave končnega izdelka.

V današnji porabniški družbi je "doba trajanja izdelka"(sl. 1) merjena v obdobju nekaj let ali celo nekaj mesecev in se bo tudi še skrajševala, zato dragocenega časa ne smemo izgubljati s predolgimi zaporednimi fazami razvoja.

V diagramu (sl. 2) je prikazana potencialna izguba tržnega deleža in s tem dobička v primeru, da

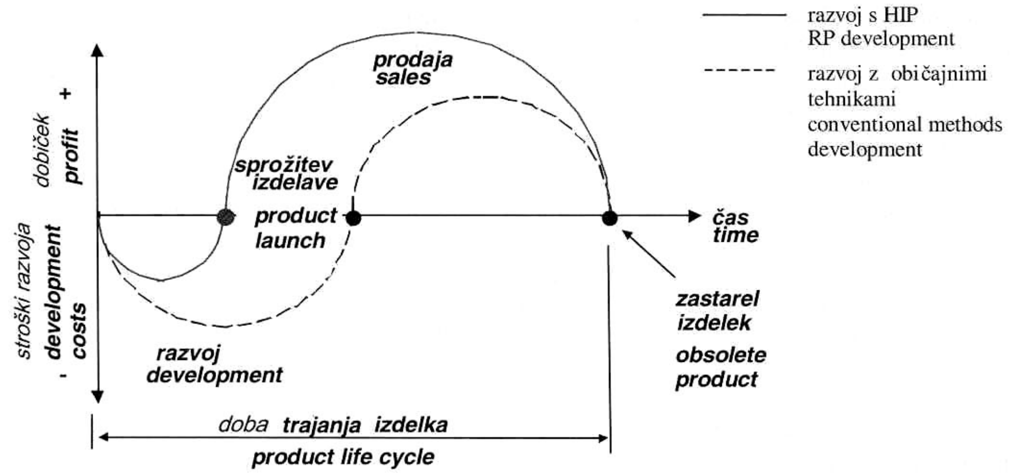
1 THE CHALLENGE OF THE NINETHIES AND THE ROLE OF RAPID PROTOTYPING

Competition in the 70s and 80s was above all about price, quality, product availability and customer choice, but in the 90s the emphasis has shifted in the direction of controlled costs and reducing the time-to-market as much as possible.

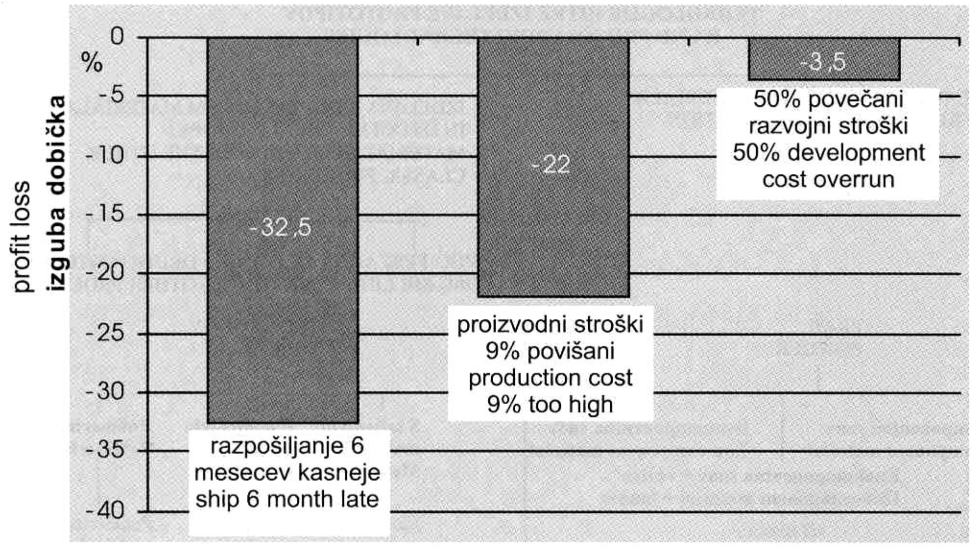
All those requirements in the past forced the appearance of modern technology which makes it possible to get prototypes cheaper, faster and with shorter development time for new products. Making prototypes depends upon the rapid development of computer-aided integration which is having an immediate impact at all stages of the manufacturing cycle.

In todays consumer society, product life cycles (Fig. 1) can be measured in terms of a few years or even a few months, and continue to shorten, therefore the precoius time mustn't be lost by successive phase development.

The diagram (Fig. 2) shows potential loss of profit. The time to market is of vital importance as the profitability of the product can be seriously



Sl. 1. *Doba trajanja izdelka [3]*
Fig. 1. *Product life cycle [3]*



Sl. 2. *Potencialna izguba dobička [3]*
Fig. 2. *Potential loss of profit [3]*

zamudimo z razpošiljanjem izdelka na trg. Če pride izdelek šest mesecev prepozno na trg, se celoten dobiček, ustvarjen v njegovi dobi trajanja zmanjša za tretjino (prvi stolpec). V primeru, da povečamo proizvodne stroške za 9%, še vedno izgubimo 22% dobička (srednji stolpec). Če pa uporabljamo sodobne postopke pri razvoju novega izdelka, kot je HIP, pa izgubimo samo 3,5% dobička, kjub temu da se razvojni stroški povečajo za 50% (tretji stolpec).

Kot rezultat vseh zgoraj naštetih dejstev so si konstrukterji in tehnologi pod velikimi pritiski prizadevali, da bi zadostili vsem zahtevam specifikacije izdelka in terminskih rokov. Sporne omejitve je treba na vsak način odstraniti in izdelati najboljši, funkcionalni in tehnološki izdelek z nadzorovanimi stroški in v čim krajšem času.

Zato se je pojavila želja, čim hitreje izdelati prototip, ki bo vizualno ter v neki meri tudi

impaired by being late. The product will ultimately get lower market share than it would have, had it been delivered on time. If a product is six months late to the market the total profit generated by the product during its life will be reduced by one third (first column). In case that production cost are 9% too high we still lose 22% of potential profit (second column). The third column shows 50% development cost overrun by using RP technology but potential loss of profit is only 3.5%.

As a result of this, designers can be under severe pressure as they strive to satisfy the requirements of the product specification and meeting delivery dates. Conflicting constraints have to be juggled and reconciled to produce a balanced functional and manufacturable product within the cost budget and time frame.

For these reasons, the prototype has to be produced as fast as possible with some visual and funkcionalno čim bolj ustrezal novemu izdelku, to pa omogoča prav tehnologija hitre izdelave prototipov. Razvil se je nov postopek razvoja izdelkov in materiali, ki omogočajo izdelavo orodij za nekaj deset izdelkov. To pa ponavadi zadošča za potrebe testiranj in predstavitve novega izdelka. V to skupino sodijo silikonska orodja, orodja iz umetnih snovi in orodja iz nizko taljivih kovin (Al-zlitine). Vendar za vsa našteta orodja potrebujemo model, ki ga je bilo do nedavnega treba izdelovati ročno, sedaj pa ga dajejo različni postopki hitre izdelave prototipov.

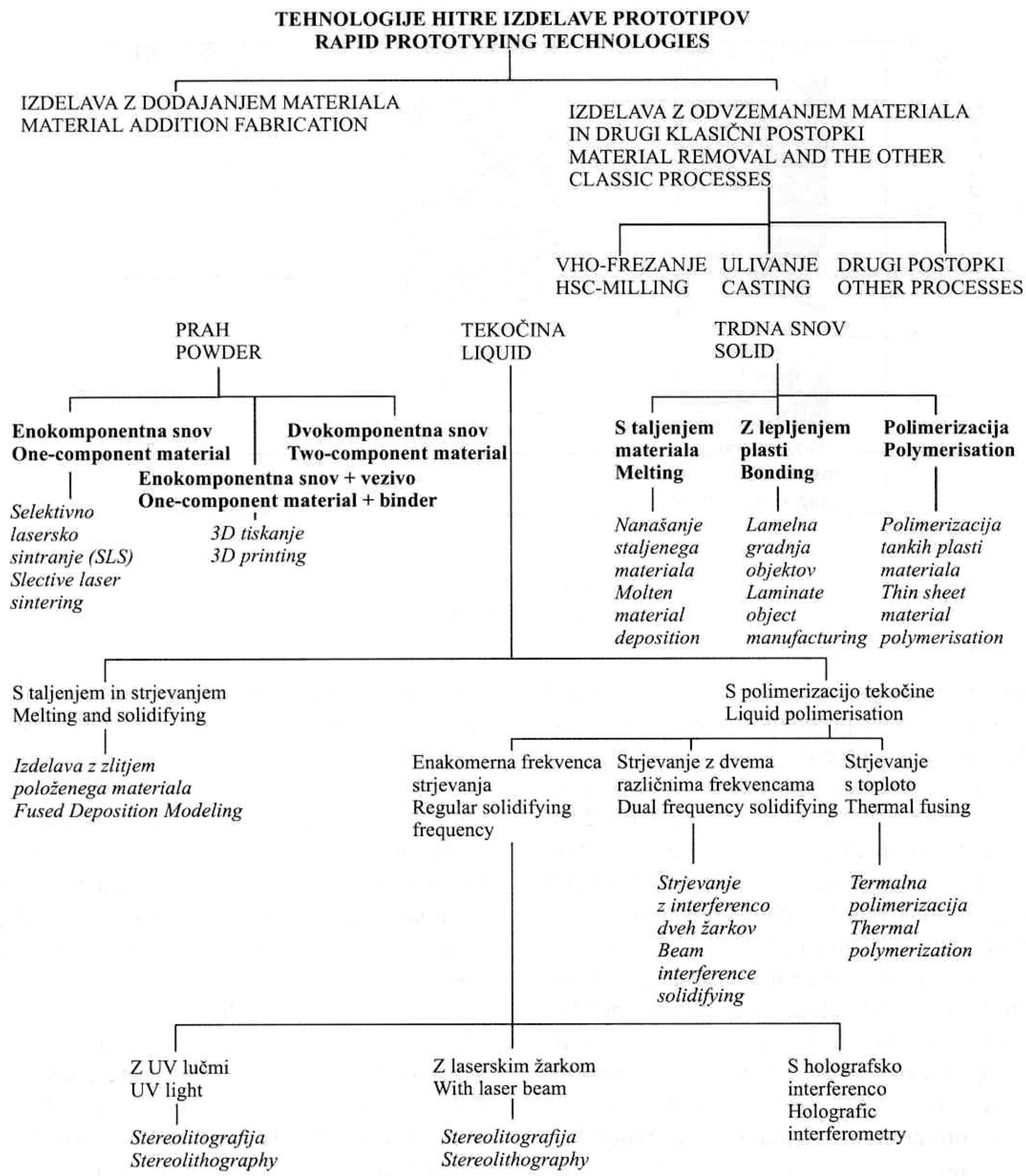
2 DEFINICIJA IN KLASIFIKACIJA TEHNOLOGIJE IZDELAVE PROTOTIPOV

Hitra izdelava prototipov (HIP) je nov strokovni izraz, za skupino tehnologij, ki zgradi

semi-functional properties being the same as in the final product, and this can only be achieved with rapid prototyping technology. A new approach to developing products has appeared and materials have been synthesized which enables producing tools only for several products. Usually they satisfy needs for testing and presentation a new product. To this group belong silicon tools, made of artificial materials and of low fusible metals (Al-alloys). However, for all the listed tools a mould is needed, which has so far been produced manually. Nowadays a mould can be made by several RP technologies.

2 DEFINITION AND CLASSIFICATION OF RAPID PROTOTYPING

Rapid prototyping is a new term for a group of technologies which build solid, physical 3-D, ob-



Sl. 3. *Prikaz različnih tehnologij hitre izdelave prototipov [7]*
Fig. 3. *Classification of Rapid Prototyping Methods [7]*

tridimenzionalni fizični model, neposredno iz datoteke računalniško podprtega načrtovanja (RPN - CAD) brez posredovanja človeka. Za komercialne potrebe se je prvič pojavil leta 1986. Vse do danes pa se je razvila vrsta postopkov HIP, od katerih jih je pet komercialno razširjenih po vsem svetu (sl.3).

1. Tehnologija HIP pomeni most med konstruiranjem in proizvodnim procesom in jo delimo v dve kategoriji:
   - Tehnologije, ki dodajajo material med gradnjo prototipa.
   - Tehnologije, ki odvzemajo material med izdelavo prototipa.
2. Dodajni material, potreben za izdelavo prototipa, pa razdeli metode na:
   - Tehnologije na osnovi tekočine, ki strjujejo smolo z uporabo elektromagnetnega sevanja.
   - Taljenje in spajanje nepovezanih delcev (v obliki prahu) v želen profil.
   - Lepljenje tankih, na določene konture odrezanih plošč.

2.1 Procesna veriga za izdelavo modela

Prav tako kakor pri drugih izdelovalnih procesih ima procesno načrtovanje zelo pomembno vlogo pred začetkom obdelave s HIP.

Vsi sistemi za HIP imajo podobno procesno verigo (sl. 4), v kateri je pet korakov: tridimenzionalno modeliranje, sprememba in prenos podatkov, preverjanje in priprava, gradnja in poznejša obdelava.

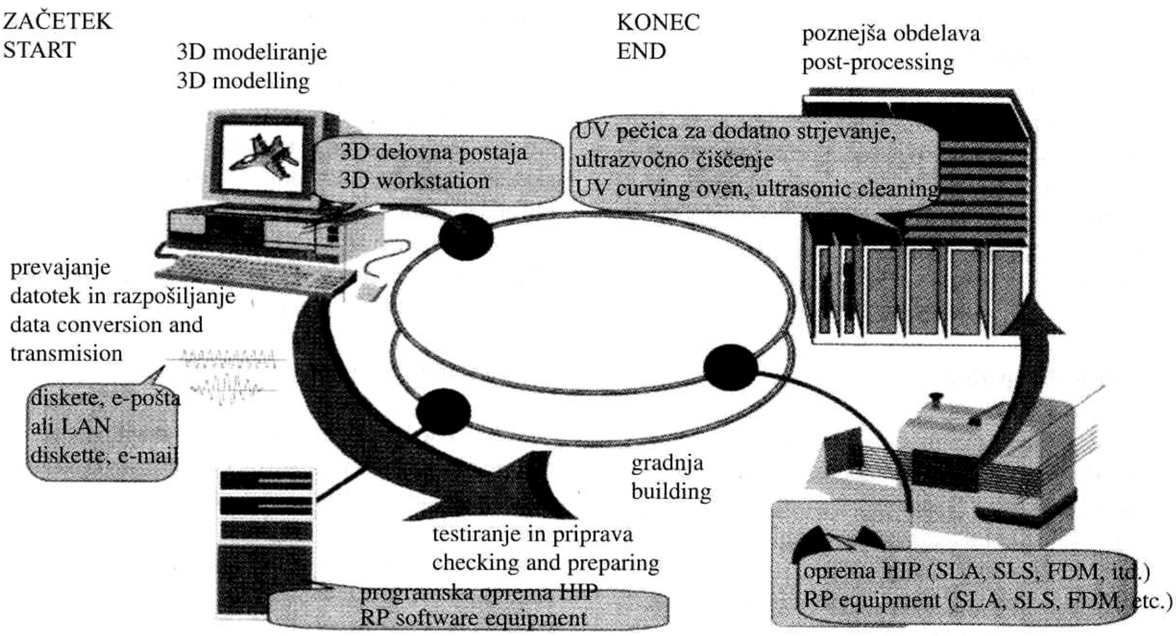
jects, directly from CAD data without human interference. Commercial rapid prototyping appeared 1986. A wide range of rapid prototyping technologies have now been developed, five of which have been successful introduced around the world (Fig. 3).

1. Rapid prototyping is a new technology which bridges the design and manufacturing process, it can be grouped broadly into two categories:
   - Technologies which add material as the prototype is built up.
   - Technologies which remove material as the prototype is machined out of a solid block.
2. Material additive processes may be further divided by the type of material used in the prototype formation:
   - Liquid based technologies that involve the solidification of a resin by the use of electromagnetic radiation.
   - The melting and fusing of the discrete particles into the required profile.
   - The bonding of solid sheets of material cut to a predetermined profile.

2.1. Model production process chain

However, like other fabrication processes, process planning has significant role before the RP commences.

All RP systems generally have a similar type of process chain (Fig. 4). There are a total of five steps in the chain: 3-D modelling, data conversion and transmission, checking and preparing, building and post-processing.



Sl. 4. *Procesna veriga tehnologije hitre izdelave prototipov [1]*
Fig. 4. *Process chain of the Rapid Prototyping Process [1]*

Preglednica 1. *Komercialno dostopni postopki HIP [7]*
Table 1. *Commercially available RP technologies [7]*

Postopki HIP RP technology	Čas prihoda na trg Date Launched	Proizvajalec Manufacturer
stereolitografija stereolithography (SLA)	1988	3D Systems
lamelna gradnja objektov laminated object manufacturing (LGO - LOM)	1991	Helisys
selektivno lasersko sintranje selective laser sintering (SLS)	1992	DTM
modeliranje s talilnim nanašanjem fused deposition modelling (MTN - FDM)	1991	Stratays
strjevanje skozi motno steklo solid ground curing (SMS - SGC)	1991	Cubital

Preglednica 2. *Druge tehnologije HIP v razvoju [7]*
Table 2. *Some of the other RP technologies under development [7]*

Postopki HIP RP technology	Čas prihoda na trg Date Launched	Proizvajalec Manufacturer
fotostrjevanje photosolidification (LS)	V razvoju Under Development	Light Sculpturing Inc.
neposredno lupinasto ulivanje direct shell production casting (DSPC)	1995	Soligen Inc.
izdelovalec modela model maker (MM)	1995	Sanders prototype Inc.
izdelava modela z nanašanjem delcev ballistic particle manufacturing (BPM)	1995	BPM Technology
3D tiskanje 3D printing (3DP)	1995	Massachusetts Institute of Technology

3 DANAŠNJE DOSTOPNE HIP TEHNOLOGIJE IN NJIHOV RAZVOJ

Dandanes je komercialno dostopnih pet osnovnih tehnologij.

Obstaja še vrsta drugih HIP postopkov, ki so še v razvoju.

Vse naštete tehnologije delujejo na podlagi dodajanja materiala med gradnjo prototipa, podobno kakor stereolitografija. Prav tako je tudi tukaj potrebna poznejša obdelava, to sta peskanje in poliranje za odstranjevanje stopničenja plasti. Modele na koncu tudi pobarvajo in polakirajo za zaščito proti vlagi ter za bolj stvaren videz.

3.1 Stereolitografija

Proces gradnje se začne z nastavitvijo ploščadi na gladino fotopolimerne smole in gradnjo podpor (velikosti 7,5 mm), na katerih začne nastajati izdelek (sl. 5). Laserski snop deluje na površino tekočega fotopolimera in ga pri tem strjuje. Po koncu gradnje določenega sloja se pozicionirna ploščad pomakne (ponavadi za 0,15mm) za eno stopnjo nižje. Sledi preplavitev fotopolimera na prejšnjo strjeno plast. Tako se naredi izdelek plast za plastjo od spodnjega sloja navzgor.

3 CURRENTLY AVAILABLE RP TECHNOLOGIES AND DEVELOPMENT

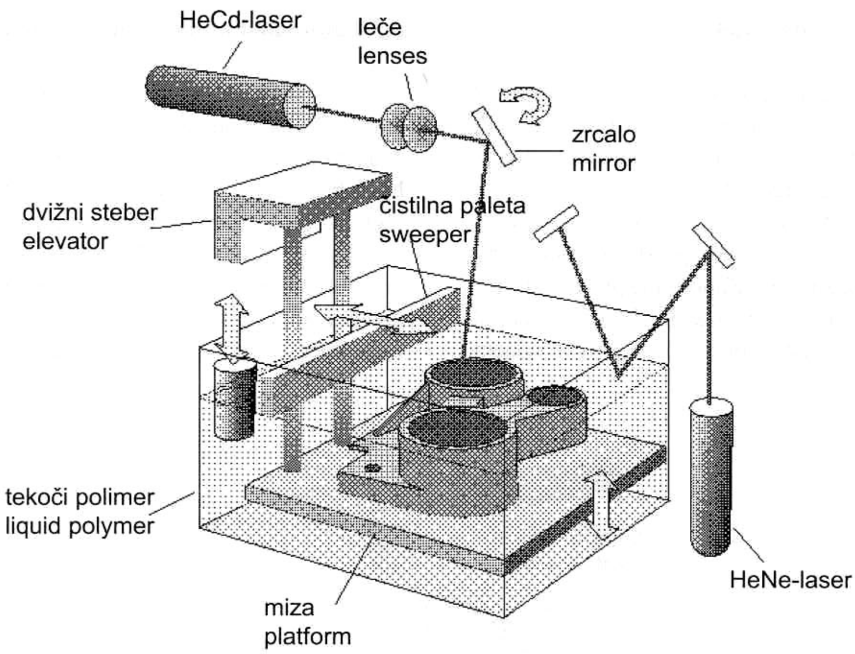
At present there are, commercially available, five basic RP technologies.

There are also a number of other technologies at present under development.

All the RP technologies listed above add material as the prototype is built up, in a similar way to stereolithography. Additional fabricating, such as sanding and polishing, is also required. These processes are used to eliminate the layer stair-stepping effect. Finished prototypes can be painted and varnished to prevent the impact of moisture and improve presentation.

3.1 Stereolithography

The building process begins with positioning the elevator near the surface of the photo-curable liquid and building the support structure (size 7.5 mm) (Fig. 5). The laser beam scans the liquid surface and solidifies the polymer in its path. After the completion of each layer the elevator is lowered by a predefined step (usually 0.15 mm) and the next layer is created in the same way. This is followed by polymer flooding on the previous solidifying layer. The object is thus built in a bottom-to-top fashion.



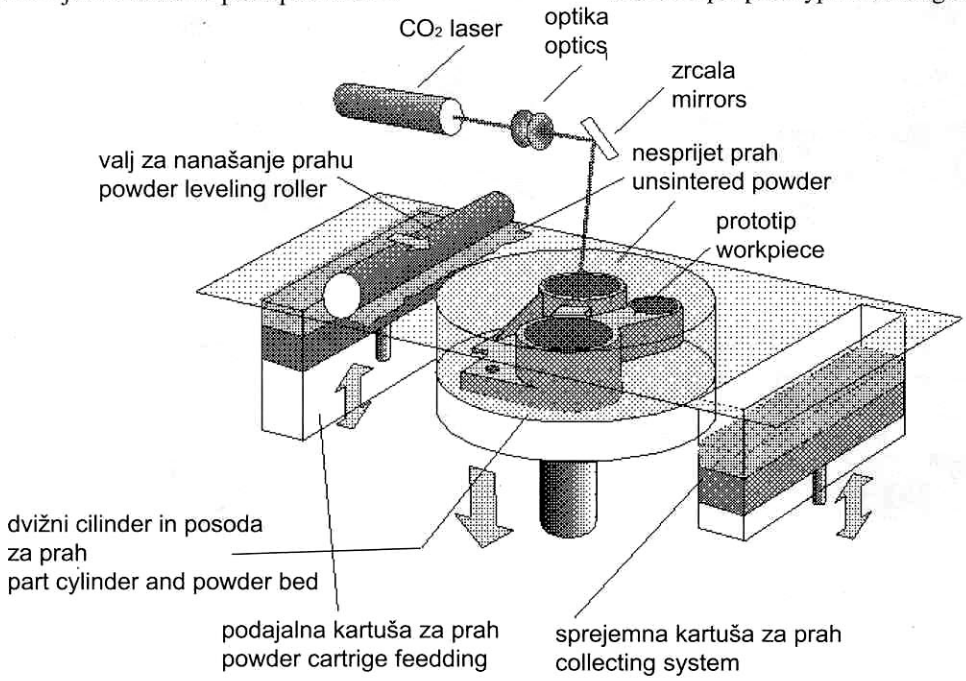
Sl. 5. *Delovanje stereolitografije [16]*
Fig. 5. *A schematic drawing of an stereolithography [16]*

3.2 Selektivno lasersko sintranje (SLS)

Selektivno lasersko sintranje (sl. 6) je ena izmed pionirskih tehnik, razvitih za hitro izdelavo prototipov na praškasti osnovi in jo lahko primerjamo z SLA. Pri postopkih SLS z laserskim žarkom sintramo prašek v dodajani plasti. Kot gradbeni material pa se največ uporablja vosek, najlon in kovina. Največja prednost tega postopka je v veliki hitrosti gradnje prototipa in uporabi različnih materialov v primerjavi z ostalimi postopki za HIP.

3.2 Selective laser sintering (SLS)

SLS is one of the pioneering techniques developed to fabricate the prototype of a part quickly, on a powder-material basis (Fig. 6). The process is similar to SLA, but this time an infrared laser beam is used to fuse the powdered thermoplastic material layer by layer. Building materials such as wax, nylon and metal are used in this process. The main advantage of this process is a higher part-building speed and using various material compared to other rapid prototype technologies.



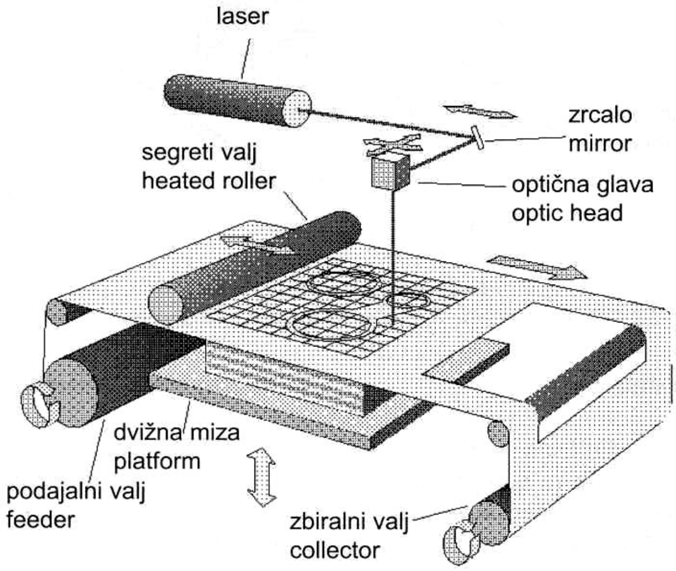
Sl. 6. *Selektivno lasersko sintranje [16]*
Fig. 6. *A schematic drawing of an selective laser sintering [16]*

3.3 Lamelna gradnja objektov (LGO)

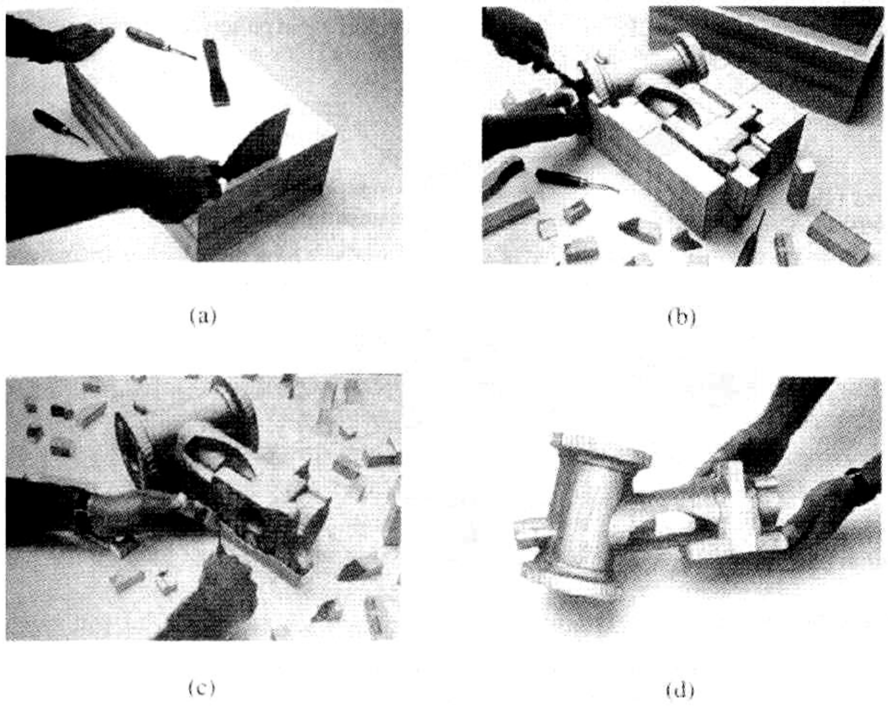
Hitra izdelava prototipov kakor je postopek LGO (sl. 7), se na osnovi gradnje s trdimi materiali, v primerjavi s tekočimi fotomateriali močno razlikuje. Pri tem procesu se gradi objekt v tankih plasteh, le da se tukaj uporabljajo tanke lamele, ki so lahko iz različnega materiala (papir, plastika, pločevina, keramika, kompoziti itn.). Zaporedne plasti materiala se lepijo med seboj s snovjo, ki je občutljiva na tlak in temperaturo, razrežejo pa se z laserjem ali nožem.

3.3 Laminated object manufacturing (LOM)

Solid-based rapid prototyping systems are very different from liquid-based foto-curing systems. This process (Fig. 7) glues together layers of foils that have been cut to the desired shape. Paper, plastics, metal sheets, ceramics and composites are used for building up prototypes. In this building phase, thin layers of adhesive-coated material, which are pressure and temperature sensitive, are sequentially bonded to each other and individually cut by a laser beam or knife.



Sl. 7. *Lamelna gradnja objektov [16]*
Fig. 7. *A schematic drawing of an laminar object manufacturing [16]*



Sl. 8. *Ločevanje izdelka z lamelno gradnjo [16]*
Fig. 8. *Separation of the laminated object manufacturing [16]*

Zadnja faza vključuje ločevanje podpornega, veznega materiala iz izdelka (sl. 8).

(a) Iz aparata LGO odstranimo delovno mizo, na kateri je pravkar nastajal izdelek.
(b) Potrebujemo kladivce, nož oz. žlico za kitanje za odstranjevanje kosa z delovne mize.
(c) Odvečni vezni material se brez težav odstrani s površine izdelka.
(d) Površino izdelka peskamo, poliramo in barvamo.

The last phase in this process includes separating the part from its support material and finishing it. The separation sequence is as follows (Fig. 8).

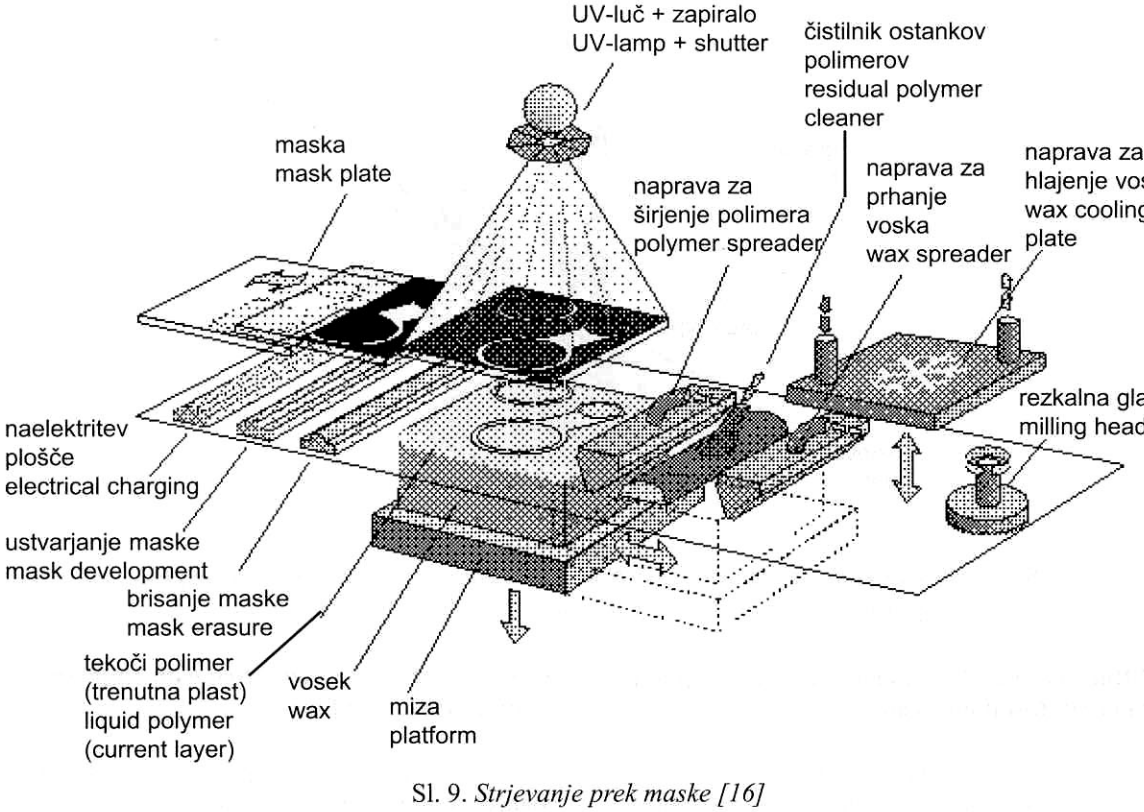
(a) The metal platform, home to the newly created part is removed from the LOM machine.
(b) Normally, a hammer and a putty knife are all that are required to separate the LOM block from the platform.
(c) Cubes are easily separated from the object's surface.
(d) The object's surface can then be sanded, polished or painted as desired.

3.4 Strjevanje prek steklene maske (SMS)

Ta postopek je bil razvit v Izraelu. V primerjavi s SLA, se tudi tukaj uporablja fotopolimerna smola in v vodi topljiv vosek za gradnjo podpor, vendar ta postopek ne uporablja laserja za strjevanje. Sistem SMS naelektri stekleno ploščo, glede na podatke o določenem prerezu modela. Nato pa se na ploščo razprši črn prah, ki se prilepi na tiste dele površine, ki so bili naelektreni, odvečni prah pa odstranimo. Prah ustvari optično masko, ki preprečuje prehod ultravijoličnim žarkom. Tanko plast smole nato nanesemo na površino, jo postavimo v napravo in prekrijemo z masko ter jo izpostavimo ultravijolični svetlobi. Tam, kjer je maska prozorna, se pod njo smola vulkanizira (sl. 9).

3.4 Solid ground curing (SGC)

The SGC process was originally developed in Israel. This technique involves the use of photo-polymer resins but, unlike SLA, SGC does not utilise lasers. In the SGC system ionography is used to create a charge distribution on a glass plate, corresponding to the cross-section for a given layer. Black toner powder is then spread over the image, with the toner powder selectively adhering at charged locations. Excess toner is then removed. At this point, the black toner powder has formed an optical mask. A thin layer of resin is than prepared on a support carriage/substrate which is moved to the exposure station. The glass plate, bearing the mask for that cross-section, is positioned above the substrate and then exposed to a flood of UV radiation from a high-power UV emitting lamp. The liquid photopolymer resin is then selectively cured wherever the mask is transparent (Fig. 9).



Sl. 9. *Strjevanje prek maske [16]*
Fig. 9. *A shematic drawing of the solid ground curing process [16]*

3.5 Tridimenzionalno tiskanje

Metoda tridimenzionalnega tiskanja gradi plast podobno kakor tiskalnik (pljuvalnik), vendar na osnovi odlaganja praška iz šob. Praškasti material se odlaga po plasteh z napravo za širjenje, ki potuje po delovni površini in je zelo podobna delovanju tiskalnika. Razlika med običajnim tiskalnikom in 3D je ta, da se uporablja prašek kot gradnik za vsak narejen sloj. Po končani gradnji objekta plast za plastjo, ga dodatno segrevamo v peči ter s tem strdimo vezivo in okrepimo objekt. Material, ki se uporablja, je kovinski ali keramični prah ali metalno keramični kompozit s kaloidnim kremenom ali polimerom kot vezivom.

3.6 Modeliranje s talilnim nanašanjem (MTN)

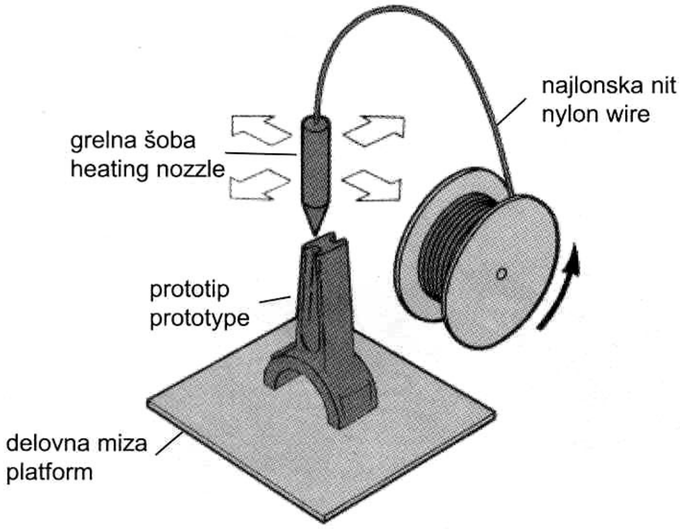
Proces MTN (sl. 10) je v splošnem bolj navdihnjen od zgoraj opisanih tehnik. Ta komercialno razširjen postopek MTN, deluje na osnovi gradnje izdelka plast za plastjo z vbrizgavanjem stopljenega polimera iz šobe. Glava stroja za MTN je sestavljena iz šobe za gradnjo izdelka in iz dodatne šobe za gradnjo podpor. Material, ki je v obliki najlonske nitke, se v tej glavi stali in nanaša na plast, z uporabo prostorninske črpalke. Po končanju gradnje vseh plasti na izdelku, sledi še odstranjevanje podpor.

3.5 3-D Printing

The 3-D Printing technique produces each layer in a manner similar to an ink jet printer but uses a powder deposition process. The powdered material is deposited in layers using a feeder that traverses the work surface along one axis like an ink jet printer. In ink jet printing, each pass of the feeder deposits the ink on a paper layer. This process uses binder with the powder instead of ink, and not only makes one pass, but prints each layer until the part is finished. Once the complete part is built, the part is heated in a furnace to cure the binder and strengthen the part. The unbound powder is then removed using ultrasonic cleaning methods.

3.6 Fused-deposition modelling (FDM)

FDM (Fig. 10) is generally more intuitive than the previous techniques. In short, the process builds a part, layer by layer, using a nozzle that extrudes a soft plastic that hardens quickly after it is put in place. The FDM machine has a head that contains two nozzles for extruding the material. One nozzle is for the actual model or part, and the other is for any necessary support structures. After the FDM head melts the solid material, the nozzles expel very fine layers of the plastic, and the semi-liquid material is extruded through the head using a precision volumetric pump. The molten material heats and fuses with the previous layer, and quickly solidifies. Once the head traces the path of each layer, the support material is peeled off to reveal the completed part.



Sl. 10. *Shematski prikaz delovanja sistema modeliranja s talilnim nanašanjem [16]*
Fig. 10. *A schematic drawing of a fused deposition modelling [16]*

3.7 Računalniško krmiljena (RK) tehnologija na zelo hitrih frezalnih strojih

Med hitro izdelavo prototipov spada tudi RK tehnologija, povezana s hitrim frezanjem, saj zmanjša ceno in čas izdelave ne samo orodij, ampak tudi

3.7 CNC technology connected with High Speed Cutting (HSC) - milling

Another RP technique is CNC technology connected with HSC-milling, which reduces costs and time of tools and models by at least of factor of 2 modelov za 2 do 3-krat. V preteklosti bi zelo težko uporabili RK tehnologijo za hitro izdelavo prototipov; z razvojem programske opreme, sočasnega inženirstva in sistemov za RPN-RP, pa je postalo vse že tako avtomatizirano, da je omogočena hitra in preprosta izdelava modelov. Oba postopka, tako izdelava prototipov v plasteh kakor tudi z odvzemanjem materiala, imata svoje dobre in slabe strani.

Nizozemsko podjetje Delft Spline Systems je razvilo programski paket DeskProto, ki je namenjen za obdelavo številsko krmiljenih (ŠK) prototipov. Sistemi za hitro izdelavo prototipov so predragi, da bi si ga lahko privoščilo vsako podjetje. RK frezanje pa si lahko privošči že skoraj vsako podjetje. RK proces hitre izdelave prototipov se razlikuje od običajne obdelave le po materialu. Pri RK frezanju prototipov se uporabljajo dobro obdelovalni materiali, to so les, umetne snovi in zlitine, ki imajo dobro obdelovalnost. Ti modeli se lahko uporabljajo za vse nadaljnje postopke kot modeli, narejeni z običajnim hitrim prototipiranjem.

Prednosti RK izdelave prototipov pred običajnimi sistemi:

- največja prednost je prav gotovo cena. Običajni RK sistem se dobi že od deset tisoč ameriških dolarjev naprej, za napravo, ki gradi objekt po plasteh, pa je cena od sto tisoč ameriških dolarjev naprej. Seveda so cene močno odvisne od obsega delovnega območja;
- nižji stroški investiranja zmanjšajo tudi ceno prototipov;
- uporaba izdelave prototipov v lastnem podjetju proces izdelave prototipov še pospeši in prihrani nepotrebno izmenjavo podatkov;
- manjša možnost napak, saj tukaj nimamo vplivov vlage, krčenja in temperature. Napake v modelu (reže, sekanje površin in drugo) ne vplivajo na obdelavo;
- mogoča je uporaba široke palete materialov, ki so lahko namenjeni za natančno določene naloge;
- velika natančnost v primerjavi s procesi izdelave modelov po plasteh;
- prehod od modela do orodja je preprost.

Prednosti izdelave modela po plasteh pred numerično krmiljenim frezanjem:

- omogoča izdelavo poljubnih oblik (luknje, spodrezane modele). Tudi ostre notranje robove je mogoče preprosto izdelati;
- zapletenost ne vpliva bistveno na ceno izdelave.

Prednost programskih paketov za RK, namenjenih za hitro izdelavo prototipov, pred običajnimi paketi za RPI:

- preprosta uporaba in nastavitev parametrov tudi neizkušenim delavcem;
- je cenejši;
- uporablja se format modela STL, ki je mnogo bolj stabilen od drugih paketov.

3.8 Vakuumsko litje

Zmožnosti, ki jih ponuja hitro izdelani prototip, so dandanes tako napredovale, da omogočajo

to 3. In the past, CNC technology would rarely be used for Rapid Prototyping, but with software development, concurrent engineering and CAD-CAM systems, automation levels became so high that the rapid and simple production of models became possible. Both RP and CNC processes have positive and negative aspects.

The Dutch company Delf Spline Systems has developed a software package called Deskproto™, which is designed for NC prototype fabricating. In comparison to CNC milling, RP systems could not be afforded by every company. This software package enables simple and automated usage. Comparing with traditional processes, the CNC process for rapid prototyping differs only in use of material. In this process only materials with good fabricating properties, such as wood, plastic materials and alloys can be used.

The key benefits of CNC prototyping comparing with classical systems:

- the main advantage is the relatively low price. Classical CNC systems are much cheaper compared to RP machines, which build a part layer by layer,
- low investment costs consequently reduce the price of the prototype,
- use of prototyping in a company may accelerate and save unnecessary data exchange,
- lower error possibilities, because there is no impact of moisture and temperature. Structural mistakes in the model (slots, holes and other mistakes) have no fabricating influence,
- it is possible to use a wide range of materials, which are used for specific tasks,
- higher accuracy compared with layer-by-layer RP machines,
- it is simple to get tools when the model is made.

Key benefits of layer-by-layer RP equipment compared with NC milling:

- enables the building of parts with any shape (holes, undercuts). It is also possible to build inner edges,
- the complexity of the part has no influence on the price.

The advantages of CNC software packages, used for rapid prototyping compared with classical CAM software packages:

- simple use and parameter adjusting,
- the price is lower,
- STL format is used, which is more stable than other packages.

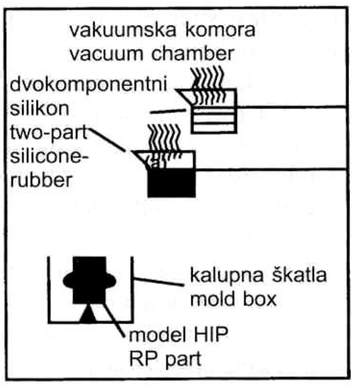
3.8 Vacuum casting

The properties offered by Rapid Prototyping Technology (RPT) parts are sufficiently good nowaizdelavo prototipnih orodij z uporabo procesne verige. Najbolj razširjena metoda je vakuumsko litje. Z uporabo vakuumskega litja lahko iz modela za HIP izdelamo silikonski kalup, ki omogoča izdelavo dodatnih 20 prototipov, obstaja pa še litje iz gnetljive snovi. Število ulitkov je odvisno od zapletenosti geometrijske oblike prototipa, natančnosti in materiala končnega prototipa. Prototipi, uporabljeni za poznejšo obdelavo (vakuumsko litje, litje iz gnetljive snovi), pa so že poprej izdelani s posebnimi tehnikami gradnje prototipa.

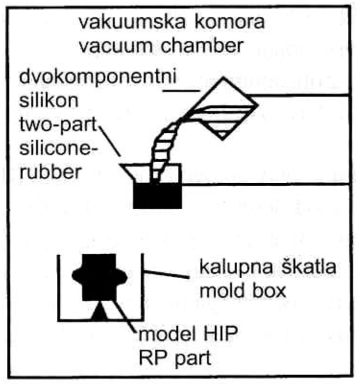
Proces izdelave funkcionalnih prototipov z uporabo vakuumskega litja je opisan na sliki 11. Najprej izdelamo okvir kalupa in vanj položimo prototip, izdelan z metodo HIP ali običajnimi metodami, v katerega ulijemo silikonsko snov.

days to enable the production of prototype toolings by using a process chain. A well-established method is vacuum casting. From the RPT model, one obtains a silicon mould from which approximately 20 parts can be made in Epoxy or investment casting wax. Each one has limitations concerning the geometry of the part, precision, number of parts that can be manufactured, and materials that can be obtained in the final part. In addition, some process chains, such as QuickCast™, are restricted to a certain RP process.

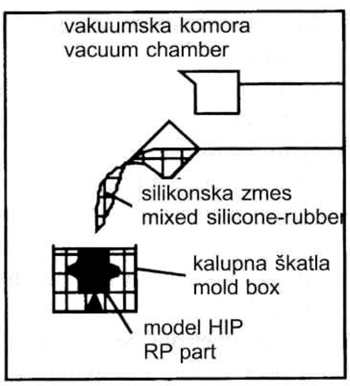
Vacuum casting, the process of making physical prototypes, is depicted in Figure 11. Make a casting frame and set up the master model, made by RP or conventional methods.



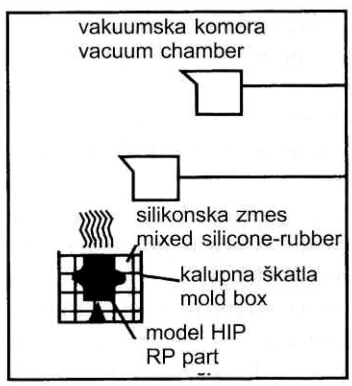
(a)
Najprej se dvokomponentni silikon razplini v vakuumski komori.
The first step in vacuum casting is to degas the two-part silicone-rubber in the vacuum chamber.



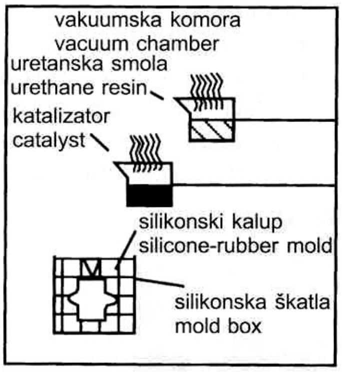
(b)
Razplinjen silikon se zmeša v vakuumski komori.
Once degassed, the two-part silicone-rubber is mixed in the vacuum chamber.



(c)
Po razplinjenju in mešanju se silikon zlije v kalupno škatlo, v kateri je model RP.
After degassing and mixing, the silicone-rubber is poured into the mould-box around the rapid prototyping pattern.



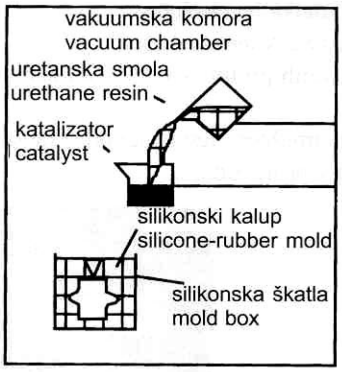
(d)
Po litju silikona v kalup se le ta razplinja v vakuumski komori, nato pa sledi še strjevanje v peči.
After the silicone-rubber is poured, the uncured mould is degassed in the vacuum chamber once again, before being placed in the oven for curing.



(e)

Ko je model za HIP odstranjen iz strjenega kalupa, se kalup ponovno postavi v vakuumsko komoro, v katerem je dvokomponentna uretanska smola, ki je že razplinjena.

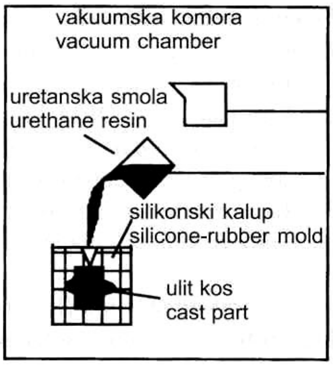
After the mould is cured and the RP master removed, the mould is reassembled and placed back in the vacuum chamber along with the two-part urethane, which is degassed.



(f)

Uretanska smola je zmešana s katalizatorjem v vakuumski komori.

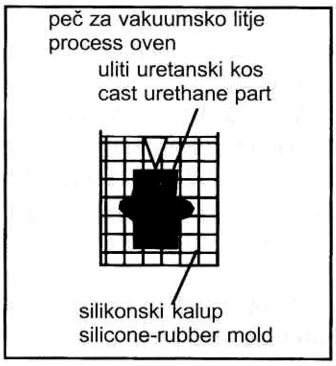
The urethane resin is mixed inside the vacuum chamber.



(g)

Po končanem mešanju in razplinjanju se uretansko smolo ulije v kalup. Ker proces litja poteka v vakuumu, je bojazen za nastanek zračnih mehurčkov in praznih prostorov izključena.

After mixing and degassing, the urethane resin is poured into the mould. Because this takes place in a vacuum, the mould will fill completely with no chance of airpockets or voids.



(h)

Po končanem litju se silikonski kalup, v katerem je ulit uretanski kos, strjuje dve do štiri ure v peči pri temp. 45°C do 65°C.

After the urethane is poured into the mould it is removed from the vacuum chamber and placed in a process oven at 45°C to 65°C for 2 to 4 hours to cure the urethane part.

Sl. 11. *Postopek vakuumskega ulivanja [1]*

Fig. 11. *Vacuum casting [1]*

4 PRIKAZ PRAKTIČNIH PRIMEROV

4.1 Radiatorski ventil

Načrtovanje radiatorskega ventila (sl. 12) s tehnologijo HIP uporablja naslednje korake.

1. Načrtovanje ventila s programskim orodjem Pro/Engineer.
2. Izdelavo začetnega osnutka ventila s SLA. Model damo na vpogled vodilnim v podjetju, kjer se odločijo za določene spremembe.
3. Izboljšanje ventila.

4 CASE STUDIES

4.1 Radiator valve

The design process for a radiator valve (Fig. 12) uses the following steps.

1. Design valve using the Pro/Engineer software package
2. Produce initial valve by SLA. The model can be on approval to the managers and the other responsible people in the company, who can decide on changes.

4. Končna oblika izdelka je narejena.
5. Izdelavo ventila s SLA ter montažo.
6. Izdelavo 20 dodatnih prototipov z vakuumskim ulivanjem.
7. Testiranje izdelka – trpežnost / testiranje vodotesnosti.
8. Model spustimo v proizvodnjo.

3. Design review
4. Final design created
5. Produce working RP valve assembly (SLA)
6. Produce 20 prototypes using vacuum casting
7. Product tested – durability/water-leak tests
8. Design released for production

Sl. 12. *Prikaz razvojnega osnutka ventila z desne proti levi*
Fig. 12. *Radiator valve design concept from right to left*

Kaj s tem dosežemo?

1. Zmanjšan čas od začetnega osnutka do redne proizvodnje za 18 tednov.
2. Varčevanje stroškov za 3,9 DEM/ventil v primerjavi s tradicionalnim konstruiranjem. Torej, 686.000DEM prihranka pri seriji 200.000 ventilov.
3. Zmanjšani stroški izdelave orodij, ker je atestiranih 20 prototipov, in sicer za 187.000 DEM.

What did this achieve?

1. Reduced the time from initial concept to production by 18 weeks
2. A cost saving of DEM 3.9 per valve when compared to the old design. This resulted in a further saving of DEM 686,000 with 200,000 valves.
3. Reduced the tooling cost to produce 20 prototype assemblies by DEM 187,000.

4.2 Primer uporabe tehnologije VHO za izdelavo okrova prototipa mobilnega telefona

Odrezovanje z veliko hitrostjo (VHO) se razlikuje od konvencionalnega RK frezanja, ker sloni na izjemnih zmogljivostih velikih hitrosti. Za izdelavo prototipov postaja hitro frezanje pomembno orodje, ki omogoča hitrejša podajanja, boljšo kakovost površin z manj ročnega dela, večjo natančnost ter široko izbiro materialov. Hitro frezanje zmanjša ročno delo (poliranje, peskanje in dodatna obdelava), namreč vsaka končna obdelava na prototipu zmanjša njegovo natančnost nasproti informacijam, ki so bile oblikovane pri RPN.

Seveda hitro frezanje ne nadomesti v popolnosti postopkov za HIP, kakršna je stereolitografija, predvsem zaradi prezaple-tenosti geometrijske oblike izdelka, prav tako pa je problematična obdelava lupin. Zato je v našem primeru okrov mobilnega telefona namenjen predvsem za vizualno in ne toliko funkcijsko predstavitev.

Obstaja namreč veliko primerov, pri katerih SLA izvrstno zadosti določenim potrebam. Frezanje VHO pa je samo eden od postopkov, pri katerih hitro izdelamo prototipe s čimmanj stroški.

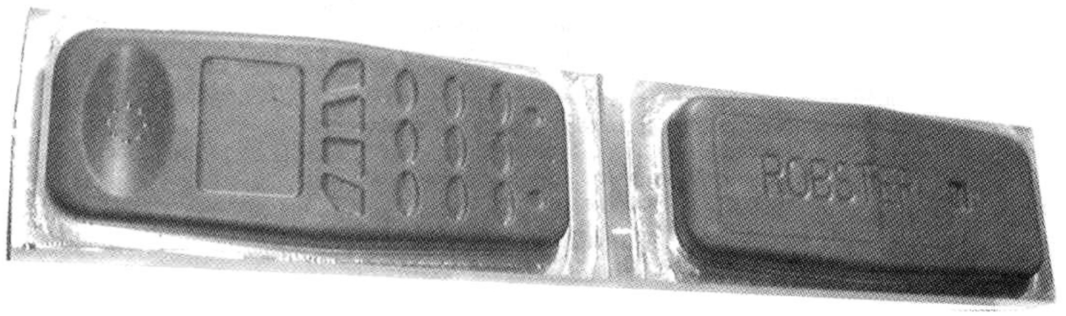
4.2 Case study of using HSC-technology for making prototypes of mobile telephone

High speed cutting (HSC) technology is different from conventional CNC milling in that it relies on high-speed capability and techniques to the extreme. For prototyping, rapid milling becomes a powerful tool that provides faster feed rates, better finishes with less handwork, higher accuracies, and allows a very wide choice of materials. Rapid milling reduces handwork, providing several benefits. It's hard finding good help today for the monotonous work of filing, sanding and polishing parts. Further, no matter how good they are, each finishing stroke on a part reduces its accuracy from the CAD information the part was designed to be.

Rapid milling doesn't replace RP processes completely, as stereolithography. It is hard to make complex geometry part or shell machining. For this reason the mobile telephone prototype is only for visual and not for functional presentation.

There are many cases where stereolithography parts meet the need just fine, and the lower cost can be an advantage hard to overcome with any accuracy or materials. This serves only to emphasize how rapid milling, as with all our current prototyping methods, is just one more tool in the box, another way to approach the job."

Material: termoplast Novilon *Material of the part:* thermoplast Novilon *Obdelovalni stroj:* Mori Seiki, Frontier-m_I *Machine:* *Tehnološki proces:* hitro frezanje za izdelavo prototipov *Manufacturing process*: rapid milling for prototyping *Operacije in orodja:* *Operations and tools*: 	*Grobo frezanje:* steblasto frezalo ϕ 10R0 mm krogelno frezalo ϕ 6R3 mm *Rough milling:* cylindrical cutter ϕ 10R0 mm ball cutter ϕ 6R3 mm *Fino frezanje:* krogelno frezalo ϕ 3R1,5 mm *Finishing milling:* ball cutter ϕ 3R1,5 mm *Odrezovalni parametri:* *Cutting parameters*: n = 8000 - 20000 min^{-1} (multiplikator/multiplicator) v_f = 1000 - 2000 mm/min



Sl. 13. *Prototip izdelan na osnovi tehnologije VHO [29]*
Fig. 13. *HSC technology prototyping part [29]*

Prototip je lahko izdelan iz plastike (sl.13) podobne kakršno ima končni izdelek, izdelan z injekcijskim brizganjem. Izdelan je na osnovi detajlov in dimenzijskih podatkov vsebovanih v modelu izdelka. V zelo hitri prototipni RK stroj pošljemo podatke iz sistema za RPN/RPI, v katerem izdelek zmodeliramo. Prototip pozneje še pobarvamo in olepšamo, tako da je po videzu enak pravim injekcijsko brizganim izdelkom.

Prednosti izdelave prototipa mobilnega telefona z VHO-RK tehnologijo v primerjavi s SLA so naslednje:

1. Neomejena izbira materialov.
2. Večja je natančnost.
3. Kakovost površine je boljša.
4. Nekoliko krajši je čas izdelave.
5. Zmernejša je cena izdelave prototipa.

Optimiranje izbire orodij in tehnoloških parametrov od grobe do zelo fine obdelave pa na osnovi razdelitve rezov omogoča 30 do 50% skrajšanje izdelavnih časov. Za izdelavo funkcijskih prototipov z nadzorovanimi stroški in kratkim časom izdelave je najbolj primerna kombinacija VHO in preostalih postopkov HIP.

Prototypes are machined from plastic (Fig. 13) similar to the products made on the base of injection molded material. They are built using detail and dimensional information contained in the part drawings that will later be used in the construction of production injection mold tooling. The CAD/CAM system data files on the product will be directly downloaded to the custom, high speed prototype CNC machine for automated machining. The prototype is further painted and finished cosmetically to be indistinguishable from a serial injection molded part.

Here are the advantages of the HSC-CNC technology for prototyping mobile phone compared with the SLA:

1. Unlimited choice of materials
2. Higher accuracy
3. Quality surfacing
4. Shorter finishing time
5. Moderate prototyping equipment cost

Optimisation of the tool choosing and technology parameters for rough to finish milling enables reducing the manufacturing time for 30 to 50%. For making functional prototypes with control of costs and in short time the combination of both technologies the HSC and other RP processes is the most suitable.

5 PREDNOSTI TEHNOLOGIJE HITRE IZDELAVE PROTOTIPOV

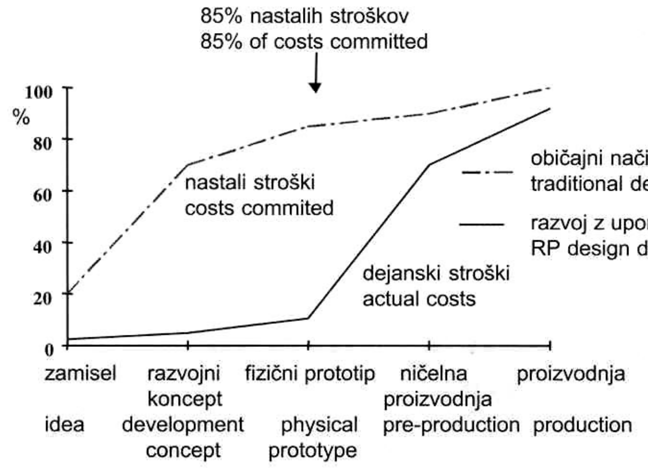
1. Stroški razvoja orodij (sl. 14), še posebno za masovno proizvodnjo, kakor so orodja za tlačno litje, inducirano litje, injekcijsko brizganje, litje

5 THE KEY BENEFITS OF RAPID PROTOTYPING

1. The cost of tooling, especially for mass production processes such as injection moulding, die casting, investment casting, sand casting and

v pesek, kovanje, se dvignejo v sto tisoče dolarjev in traja mnogo mesecev, preden jih končamo, zato je tehnologija HIP v veliko pomoč pri zmanjševanju časa in stroškov (sl. 14).

forming can run into $100,000 and take many months to complete, it is in this area that RP can be a major benefit in cost savings and significant time reduction (Fig. 14).



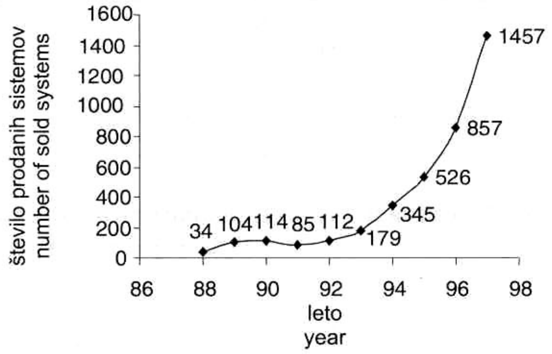
Sl. 14. *Stroški razvoja orodij [3]*
Fig. 14. *Tool development costs [3]*

2. Glede na to, da je veliko dražje delati spremembe na izdelku, ko je proizvodnja v polnem teku, tehnologija HIP pomaga premostiti vrzel med konstruriranjem izdelka, izdelavo prototipov, verifikacijo, testiranjem in zmanjševanjem časa za trg.
3. Konstrukterji niso več omejeni pri uresničevanju svojih zamisli, ker je prototip izdelan v nekaj dneh z zelo majhnimi stroški, poleg tega pa se s tehnologijo HIP izognemo dragim usodnim napakam. Konstrukcijske napake so namreč odkrite veliko prej, preden naročimo izdelavo orodja.
4. Kot informacijsko orodje ima HIP neposreden vpliv na vsa področja izdelovalnega kroga, še posebej v začetnem stanju načrtovanja, ko se konstrukterji, oblikovalci, tehnologi, trgovci in orodjarji posvetujejo z modelom v rokah, glede najboljše poti za izdelavo.
5. Na primer pri tlačno litem ali injekcijsko brizganem izdelku, je položaj delilne ravnine, dolivnih kanalov, odzračevalnih kanalov, hladilnih kanalov, debeline stene in livarskih nagibov ključnega pomena za izdelovalni proces. Prav ti pa imajo neposreden vpliv na kakovost končnega izdelka, nepravilna lega namreč povzroči popačenje, zvitje, delno zapolnitev kalupa, slab pretok materiala ali pa se izdelek uniči pri nepravilno konstruiranem izmetalu.
6. Tudi na področju napetostne analize ima HIP veliko prednost, saj poenostavi izvajanje porušnih in neporušnih testov. Analiza končnih elementov je namreč velikokrat zapletena in včasih celo nemogoča. Poleg tega pa lahko za obremenitvene preskuse uporabljamo prototipe iz enakih materialov, kakršne ima končni izdelek.
7. Hitra izdelava prototipov izdelkov se je začelo širiti na hitro izdelavo orodij za prototipne serije

2. Since it is more expensive to engineer in changes when a product is in full production, RP has gone a long way to bridge the gap between product design, prototyping, product verification, testing and reducing the time to market.
3. Designers are no longer restricted to design concepts and expensive prototypes, which can take weeks to build. New iterations of the design can now be performed and tested in weeks rather than months thus avoiding expensive mistakes.
4. As a communications tool, RP is having an immediate impact at all stages of the manufacturing cycle, particularly at the initial planning stage where designers, manufacturing engineers, process and production planers, and tooling engineers can sit down together with a physical model to discuss the best route for manufacturing.
5. For example in a die cast or injection-moulded product, the position of the mould parting lines, ejectors, air vents, cooling channels as well as web thicknesses and draw angles etc. are of critical importance to the manufacturing process. These have a direct bearing on the finished product quality, as incorrect positioning, or errors in the design of the mould, can result in product distortion, partial mould filling, poor material flow or the product being damaged by failing to eject satisfactorily at the end of the mould cycle.
6. Various mould-filling and flow-analysis programmes are available to assist in determining the gating and risers position, metal flow, heat transfer and cooling rates. However these are complex and empirical information may be available for the proposed new shape to be cast.
7. Rapid prototyping was expanded for the rapid tooling of soft tools (tools for limited pre-pro-

(mehko orodje) in kasneje tudi na izdelavo orodja za proizvodnjo (trdo orodje). Tako so prototipe, ki so jih sprva le vizualno ocenjevali, sedaj začeli uporabljati tudi v proizvodnji. Zaradi prednosti, ki jih ima hitro izdelovanje prototipov, se vsako leto poveča število naprav za 35% (sl. 15).

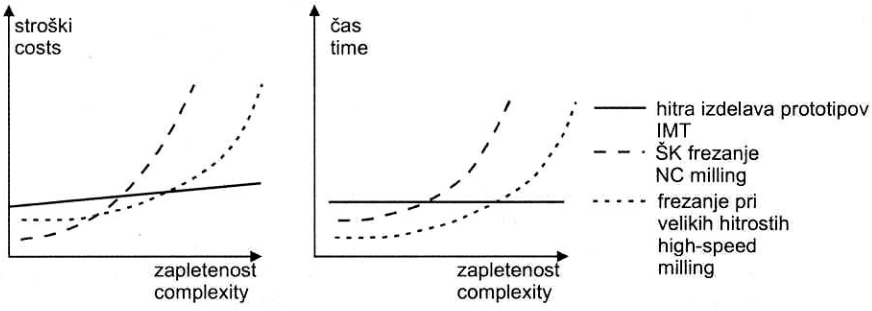
duction) and hard tools (tools for production). Until recently those prototypes were only for visual examination, but now they are also for stress analyses and use in production. These advantages have helped increase the sales of RP technology by 35% (Fig. 15).



Sl. 15. *Naraščanje števila uporabnikov tehnologije RP [16]*
Fig. 15. *Increasing number of RP technology users [16]*

8. Hitra izdelava prototipov verjetno ne bo nikoli nadomestila standardnih metod razvoja izdelka, je pa to eden od načinov, po katerem je mogoče hitreje priti do izdelkov in orodij. Vse bolj se uveljavlja tudi v medicini. Sodobna tehnologija (magnetna resonanca in drugi postopki) je omogočila tridimenzionalno opazovanje človekovih notranjih organov. Tridimenzionalno sliko je treba le še računalniško obdelati in že imamo model, iz katerega lahko naredimo fizični objekt (kosti, sklepe in druge organe).

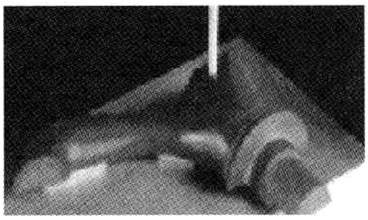
8. RPT does not - and will not - replace completely conventional technologies such NC and high-speed milling, or even hand-made parts. Rather, one should regard RPT as one more option in the toolkit for manufacturing parts. Figure 15 depicts a rough comparison between RPT and milling with respect to the costs and time of manufacturing one part as a function of part complexity.



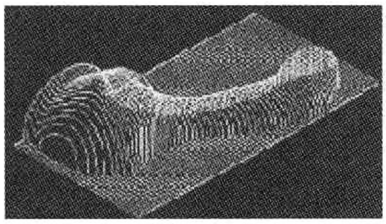
Sl. 16. *Primerjava HIP z drugimi tehnologijami [16]*
Fig. 16. *RP Technologies as conventional technologies [16]*

9. Danes si projektanti, konstrukterji in tehnologi pošiljajo informacije v obliki načrtov ali vse bolj pogosto s pomočjo datotek. Ampak kaj, če ima nov izdelek ali orodje izhodišče v prototipu ali modelu, ki ga je ustvaril rokodelec, mogoče tudi umetnik? V tem primeru podatki za RPN sploh ne obstajajo, verjetno pa tudi načrtov ni na voljo. Zaradi tega se tehnologija za HIP velikokrat pojavlja v povezavi z obrnjenim inženirstvom (sl. 17), ki je zmožno prebrati (mehansko, optično ali lasersko) in spremeniti "oblake" točk v krivulje, površine in mreže, nato pa te digitalizirane geometrijske podatke fizičnega modela vnese v okolje za RPN.

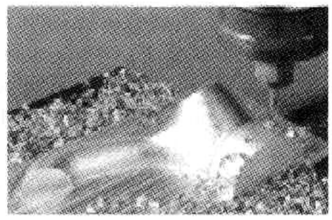
9. Nowadays engineers, designers and manufacturers send information in the form of drawings or more often of files. But what happens, when the new product or tool has the origin in a prototype or model, which was created by a craftsman or an artist? In this case CAD data don't exist and also the drawings are not at disposal. For that reason RP technology has strong connection with Reverse Engineering, which has the ability to read (mechanically, optically or by laser) and transform "clouds" of points in curved lines, surfaces and grids and afterwards all these digital geometry data of physical model to enter in CAD environment (Fig. 17).



ročno narejen izdelek
handmade part



RP model
CAD model



izdelek v obdelavi
machined part

Sl. 17. *Uporaba obrnjenega inženirstva [28]*
Fig. 17. *Using reverse engineering [28]*

5.1 Primerjava prednosti in pomanjkljivosti za tri hitre prototipne metode [26]

5.1 Comparison of advantages and disadvantages for three rapid prototyping methods [26]

metode methods	prednosti advantages	pomanjkljivosti disadvantages
ročno izdelani modeli	• nižji skupni stroški v opremi	• 3 do 4-krat višji stroški • manjša natančnost • ročno delo • dosti daljša doba izdelave
handmade models	• lower overhead in tools	• higher cost by 3 to 4 times • less accurate • all handwork • much longer manufacturing time
stereolitografija	• nižji stroški • hitrejša izdelava	• zelo draga oprema za HIP • omejena izbira materialov • potrebna dodatna končna obdelava • toksične, drage kemikalije • 2D gradnja po plasteh • slab "občutek" za predstavitve
stereolithography	• lower costs • faster manufacturing	• very expensive equipment • limited choice of materials • more hand finishing • irritating, expensive chemicals • 2D layering buildup of part • poor imagination feeling
hitro frezanje	• neomejena izbira materialov • občutek "pravega" izdelka • večja natančnost • krajši čas končne izdelave • globlji vtis na stranke in lažja prodaja izdelka • realna 3D površina izdelka • zmerna cena opreme	• stroški za 10% višji kakor pri stereolitografiji • izdelava lahko 10 do 15% daljša kakor pri SLA • daljši čas gradnje za večjo natančnost • votli deli potrebujejo dodatni čas za frezanje notranjosti
rapid milling	• unlimited choice of materials • true part feeling • higher accuracy • shorter finishing time • deeper impression on customer and easier selling of the part • true 3D surfacing of the part • moderate equipment costs	• costs about 10% higher than with stereolithography • manufacturing 10 to 15% longer than stereolithography • longer building time for fixturing • hollow parts need extra time for milling the inside

6 SKLEP

Uporaba tehnologije za HIP v vseh fazah razvoja izdelka lahko močno pospeši in izboljša proces konstrukcijskih rešitev. Glavna prednost

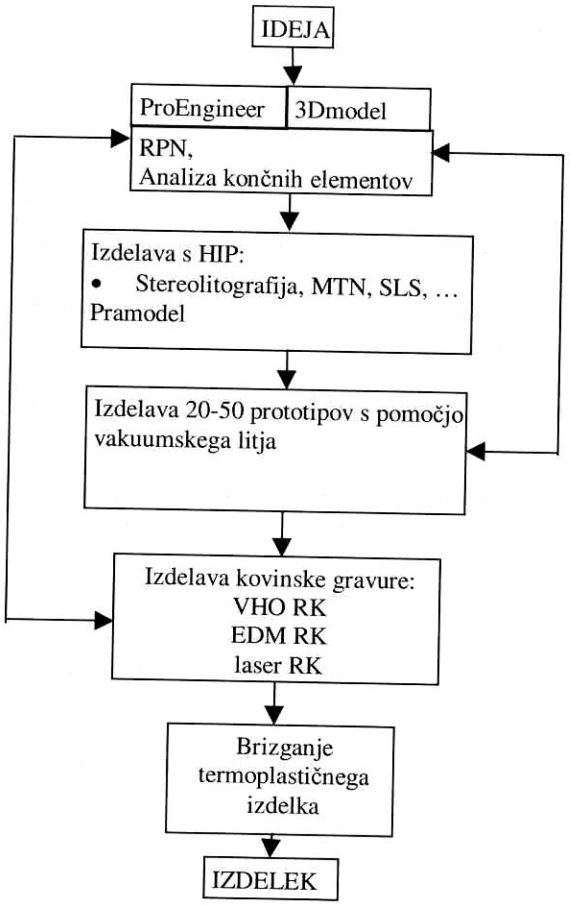
6 CONCLUSION

Implementation of RP technologies in different stages of the development process can accelerate the process of realising design solutions. The main adtehnologije za HIP je prav v hitrosti izdelave prototipa s pomočjo neposrednih posebno avtomatiziranih in integriranih operacij ter priprave podatkov.

Današnji postopki HIP so zelo primerni za uporabo, kakor so izdelava modelov in mehkih orodij (za izdelavo omejenega števila prototipov). Za izdelavo trdih orodij (prava orodja za proizvodnjo) in prototipov iz enakega materiala kakor pravi izdelki, pa je treba dobro preučiti zmožnosti, ki jih ponuja sedanja tehnologija za HIP. Kombinacija obdelave HIP in RK je ponavadi še vedno najboljša rešitev v večini primerov.

Prav gotovo pa bo nadaljnji razvoj postopkov za HIP, opreme in materialov še močneje razširil uporabo na področju proizvodnje prototipov.

Tehnologija HIP je eden od pomembnih gradnikov v sistemu sodobne in hitre proizvodnje v smislu od "ideje do izdelka", kakor kratko na splošno prikazuje slika 18.



Sl. 18. *Uporaba modernih tehnologij od "ideje do izdelka"*

vantage of RP technologies is the speed of part fabrication due to highly automated and integrated data preparation and operation without tooling and fixturing.

Current RP technologies are very suitable for less demanding applications in product development, such as fabrication of models and patterns for indirect tooling. In more demanding cases, such as prototyping and direct tooling one should carefully consider the possibilities of current RP technologies. A combination of RP and CNC machining could be an appropriate solution in many engineering situations.

Nevertheless, further developments in RP processes and equipment, implementation of new materials, etc. will in the future, broaden the application field from prototyping towards manufacturing.

RP technology is a milestone in the system of modern and rapid product development in the sense from "idea to product", which is shown in the scheme below (Fig. 18).

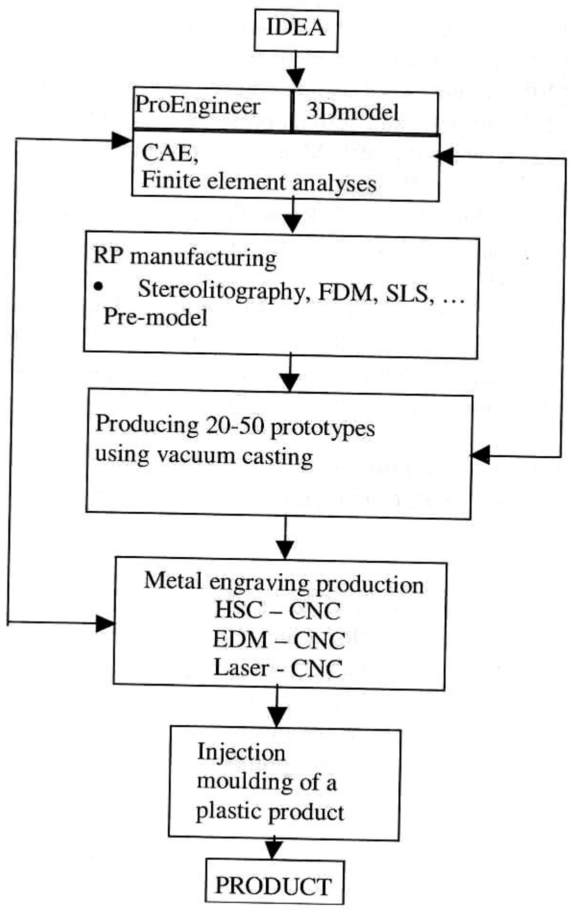


Fig. 18. *Using modern technology from "idea to product"*

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