© Strojniški vestnik 50(2004)4,229-238
ISSN 0039-2480
UDK 621.762.5:621.793
Kratki znanstveni prispevek (1.03)
© Journal of Mechanical Engineering 50(2004)4,229-238
ISSN 0039-2480
UDC 621.762.5:621.793
Short scientific paper (1.03)

Raziskave postopka neposrednega laserskega sintranja

Investigation of Direct Metal Laser Sintering Process

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V prispevku so prikazane značilnosti neposrednega laserskega postopka sintranja (NLPS) in nekatere praktične uporabe v slovenskem orodjarstvu. Raziskave se nanašajo na mikrostrukturne in morfološke analize kovinskih prahov ter ustrezne kemično, mikrostrukturno in mehansko karakterizacijo izdelkov NLPS. Namen raziskave je poiskati ustrezno površinsko obdelavo in prevleke za izboljšanje toplotnih in obrabnih karakteristik lasersko sintranih izdelkov.

(Ključne besede: sintranje lasersko, obdelave površin, prevleke, karakteristike obrabe)

This paper presents some characteristics of the direct metal laser sintering (DMLS) process and applications of this technology in the Slovenian tool-making industry. Research is focused on micro-structural and morphological analyses of the metal powders and subsequent chemical, micro-structural and mechanical characterizations of the DMLS products, with the aim to find the proper surface finishing and coatings to improve the thermal and wear characteristics of the laser sintered products.

(Keywords: laser sintering (DMLS), surface finishing, coatings, wear characteristics)

0 UVOD

Poleg stereolitografije je lasersko sintranje kovinskih prahov drugi postopek tehnologij hitrega prototipiranja, ki je postal tržno uspešen v začetku devetdesetih let. Od začetkov, ko so bili kot velik uspeh predstavljeni lasersko sintrani izdelki z velikimi izmernimi odstopanji, je bil narejen velik razvoj, tako na materialih kakor na sami laserski tehnologiji [1]. Danes je lasersko sintranje vsekakor eden od najnaprednejših postopkov za hitro izdelavo prototipov, hitro izdelavo orodij in hitro proizvodnjo. Uporablja se za sintranje plastičnih in kovinskih materialov ter izdelavo livarskih modelov iz peska. Eden od zadnjih izčrpnih pregledov teh tehnologij skupaj s predstavitvijo bodočega razvoja je bil narejen v okviru CIRP-a [2].

Za sintranje kovinskih prahov sta tržno trenutno na voljo dva sistema. Podjetje DTM (www.3dsystems.com) je razvilo dvostopenjski postopek. Njihov sistem deluje na podlagi pretaljevanja veziva, ki pri nizkih temperaturah združuje kovinski prah v želeno obliko (SLS - Selektivno lasersko sintranje). Z dodatno toplotno obdelavo izžgejo pri visokih temperaturah vezivo in

0 INTRODUCTION

Following on from stereolithography, the laser-sintering rapid-prototyping process became commercially available at the beginning of the 1990s. Initially, some parts with poor dimensional accuracies were presented as being a success; since then, however much has been developed in terms of the material and also in the laser technology [1]. Nowadays, laser sintering is one of the most appropriate processes for RP (rapid prototyping), RT (rapid tooling), and RM (rapid manufacturing) purposes; it is used for the sintering of three types of material: plastic, metal and sand. One of the most comprehensive reviews of these technologies together with the future perspectives has been recently presented by CIRP [2].

For sintering metal powders there are two commercial systems available. 3D systems (www.3dsystems.com) developed a two-stage process, a system based on melting a binder at low temperatures that bound a metallic powder in the desired shape (Selective laser sintering – SLS). During additional post processing the binder is burnt out in a high temperatures and the metal powder is sintered to form a solid metal product, followed by infiltration with bronze povežejo prah v trdni kovinski izdelek, temu sledi še vnos brona ali bakra. Glavna pomanjkljivost tega postopka je v večjih izmernih odstopanjih izdelka zaradi potrebne toplotne dodelave. V podjetju Electrical Optic Systems (EOS - www.eos-gmbh.de) pa so razvili enostopenjski postopek oziroma različne stroje za sintranje plastike, peska in kovinskih prahov. Pri sintranju kovinskih prahov, ki se imenuje neposredno lasersko sintranje kovinskih prahov, laserski žarek velike gostote neposredno tali kovinski prah (oziroma eno od njegovih komponent) in s tem neposredno oblikuje izdelek brez potrebne poznejše toplotne obdelave (sintranje s pomočjo kapljevite faze).

Najnovejši stroj, EOSINT M250 Extended, ki se že uspešno raziskovalno in tržno uporablja za razvojno podporo lokalni in slovenski industriji, je iz zadnje generacije nemškega proizvajalca EOS. V prispevku so prikazane nekatere možnosti za uporabo postopka NLPS, praktične industrijske izkušnje ter raziskave površinskih obdelav in prevlek za izboljšanje obrabnih in toplotnih lastnosti sintranih izdelkov.

1 NLPS – NEKATERE ZNAČILNOSTI POSTOPKA

Postopek neposrednega laserskega sintranja kovinskih prahov se lahko uporablja za dve vrsti uporab: izdelavo lasersko sintranih vložkov orodij za brizganje plastike in litje barvnih kovin ter neposredno proizvodnjo kovinskih komponent kot končnih izdelkov. Zapletene geometrične oblike izdelkov, ki jih je težko ali celo nemogoče izdelati z običajnimi metodami (npr. zahtevne notranje kanale) je za potrebe delujočih testiranj (npr. za avtomobilsko, elektronsko ali industrijo gospodinjskih naprav) že mogoče izdelati s postopki laserskega sintranja. Z izboljšavami mehanskih lastnosti sintrancev in z zadovoljivimi natančnostmi lasersko sintranih delov so se tudi odprle popolnoma nove možnosti za prehod na nove tehnologije hitre proizvodnje [3].

Pri NLPS laserski žarek tali sestavine praškastega materiala, ki se ga dodaja v tankih plasteh (približno 0,02 mm). Po vsakem prehodu po površini nanese plasti, laserski žarek oblikuje dvorazsežno obliko želenega izdelka. S premikanjem dvižne posode in ponovnim dodajanjem plasti materiala pa dosežemo trirazsežno obliko izdelka (sl. 1).

Nekatere značilnosti NLPS:

- izdelava po načelu dodajanja plasti materiala
- lasersko sintranje posameznih prečnih površin
- izdelava blizu končnih izmer, najmanjši skrčki
- popolnoma avtomatizirano, krmiljenje prek osebnega računalnika
- mešanica kovinskih prahov, brez polimernih veziv
- brez visoko temperaturne dodatne obdelave
- hitra in neposredna izdelava komponent in vložkov orodij neposredno iz podatkov RPN
- optično snemanje in laser 240 W CO_2

or copper. The main disadvantage of this process is the poor dimensional accuracies achieved as a result of the thermal post processing; however, an advantage is that only one machine is required used for a variety of powder materials. The second option - a single stage process comes - from Electrical Optic System (EOS - www.eos-gmbh.de), which has developed different machines for sintering plastic, sand and metal powders. In the process of sintering metal powders (Direct Metal Laser Sintering - DMLS), a laser beam of high intensity directly melts a metal powder (or one of its components), thus the parts are produced without any subsequent thermal treatment (liquid phase sintering).

The latest generation of this type of machine, the EOSINT M 250 Extended, is already being successfully employed in commercial and research applications as development support for local and Slovenian industry. This paper presents some of the possibilities of the DMLS process, practical industrial experience and research into proper surface finishing and coatings for improvements to the thermal and wear characteristic of the sintered products.

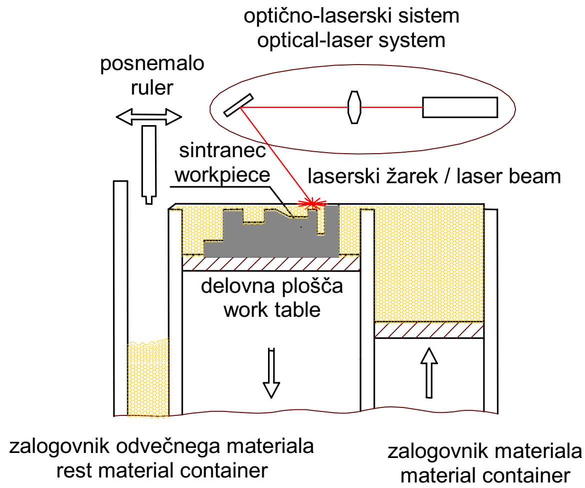
1 DMLS – SOME CHARACTERISTICS OF THE PROCESS

The direct laser sintering of metal powders can be used for two main applications: the direct laser sintering of tool inserts for the injection moulding of plastics and the casting of aluminium, and the direct production of steel component as final products. Geometries that are difficult or even impossible to produce by conventional methods – examples include complicated internal channels - can now be used for functional testing (for example, the automotive, electronics and household-appliance industries). The improved mechanical properties and accuracy of laser-sintered parts have also opened new possibilities for transferring RT technology to rapid manufacturing [3]).

In the DMLS process a laser beam is used to melt the ingredients of metal powder, which is added as a thin layer (approximately 0.02 mm). After each pass over the surface layer the laser beam creates a two-dimensional shape of the desired product. With the movement of the powder container and the addition of the next layer of powder a three-dimensional form of the product can be produced (Fig. 1).

Some of the main characteristics of DMLS:

- layered, material- additive manufacturing
- laser sintering of a cross-sectional area
- net-shape process, minimal shrinkage
- fully automatic, PC-controlled process
- metal powder mix, no polymer binders
- no high-temperature post processing
- rapid and direct manufacturing of metal components and tool inserts from CAD data
- scanning optics and 240 CO_2 laser



Sl. 1. *Načelo laserskega sintranja kovinski prahov*
Fig. 1. *The principle of laser sintering metal powder*

Izdelki, ki jih je mogoče izdelati s tem strojem, so lahko do velikosti 250X250X185 mm, zato je treba večja orodja izdelati po delih in jih kasneje sestaviti. Stroj neposredno uporablja model v obliki ».stl« (narejen v kateremkoli programu RPN), ustrezna programska podpora (Magic proizvajalca Materialise) pa ga spremeni v obliko ».sli«. Model je s tem razrezan na posamezne sloje za dvorazsežno krmiljenje laserskega žarka; s tem ni potrebnega dodatnega programiranja ŠK strojev (znatni prihranki na času izdelave orodja [4]).

2 PRAHOVI ZA UPORABO NLPS

Trenutno se za NLPS največ uporabljata dva različna materiala: DirectMetal - DM20 (20 mm prah) temelji na bronu in je primeren za vložke orodij za brizganje plastičnih mas do 10.000 kosov in delujoče prototipe), DirectSteel - DS20 (20 mm prah) pa temelji na jeklu in je primeren je za vložke orodij za brizganje plastičnih mas do 100.000 kosov, tlačno litje barvnih kovin in zlitin do 1.000 odlitkov ter delujoče kovinske prototipe). Nekatere najpomembnejše značilnosti sintranih izdelkov iz teh materialov so prikazane v preglednici 1 [5].

Izbira prahov je odvisna od izdelovalnih zahtev za orodja (ali izdelke), saj vrsta prahu značilno vpliva na stroške izdelave sintrancev. Čas sintranja ni odvisen le od velikosti izdelka, definirajo ga tudi hitrost sintranja (med 2 in 15 mm^3/s), velikost in zapletenost oblik izdelka ter zrnatost uporabljenega prahu.

Ugotovili smo, da tudi pri uporabi najnovejših materialov obstajajo določeni problemi, ki posledično omejujejo praktično uporabo sintranih izdelkov (manjša temperaturna obstojnost, slabše mehanske lastnosti orodij, prevelike hrapavosti površin, premajhna obrabna odpornost, pokanje sintrancev na prehodih in zaokrožitvah itn.). Za boljše

Parts can be produced with maximum dimensions of 250mm X 250mm X 185mm; tools with bigger dimensions need to be produced separately and assembled. The machine can use models made in ».stl« format (any commercially available software); the software called Magic, from Materialise, transforms a model into the ».sli« format. In this case a model is cut into layers for the 2-D control of the laser beam; ths means that an additional NC programme for machine tools is not required (significant time and cost savings in the production of the tools [4]).

2 POWDERS FOR DMLS APPLICATIONS

For DMLS applications two different powders are recently used: DirectMetal - DM 20 (grain size 20 µm) is based on bronze (for tooling inserts for injection moulding up to 10,000 pieces and for functional prototypes), and DirecSteel - DS 20 (grain size 20 µm) is based on steel (for tooling inserts injection moulding up to 100,000 pieces, aluminium casting up to 1,000 castings and for functional metal prototypes). Some of the most important characteristics of the sintered parts are presented in Table 1 [5].

The choice of the powder depends on the manufacturing demands of the tools (products), it significantly influences the cost of the laser-sintered part. The sintering time is not defined only by the size of the part but also by the sintering speeds (between 2 and 15 mm^3/s), which vary depending on the complexity of the product's shape and the powder granulation.

However, it has been found that even the use of these advanced materials some difficulties related to the practical applications of sintered products (for example, the lower temperature resistance and hardness of the tools, the higher surface roughness, the low wear resistance, the cracking of the sintered parts at the edges and rounded corners, etc.),

Preglednica 1. *Značilnosti izdelkov DMLS*
Table 1. *Some of the characteristics of the DMLS parts*

Značilnosti / Characteristic	***DM 20***	***DS 20***
dosegljiva izmerna natančnost v µm attainable accuracy of the part (µm)	± 50	± 50
najmanjša debelina stene v mm minimum thickness of the wall (mm)	0,6	0,7
poroznost strukture v min % porosity of the part (min %)	8	2
natezna trdnost v MPa tensile strength (MPa)	400	600
trdota v HB hardness (HB)	110	220
hrapavost površine Ra v µm surface roughness Ra (µm)	9	10
hrapavost po udarjanju (peskanju) Ra v µm roughness after shot peening Ra (µm)	3	4
hrapavost po poliranju Rz v µm roughness after polishing Rz (µm)	< 1 µm	
koeficient toplotne razteznosti v 10^{-6}/K coefficient of thermal extension (10^{-6}/K)	18	9
toplotna prevodnost v W/mK pri 25 ^{0}C thermal conductivity (W/mK at 25 ^{0}C)	25	13
najvišja delovna temperatura v ^{0}C maximum working temperature (^{0}C)	400	800

razumevanje postopka sintranja in za uspešno uvajanje te tehnologije je bilo zato treba narediti določene raziskave in analize, ki so se nanašale na značilnosti uporabljenih prahov ter izdelanih sintranih plasti. Metalurške raziskave so bile narejene v sodelovanju z IMT, NTF Univerze v Ljubljani in podjetjem TCK. Najprej smo opredelili največ uporabljene prahove (DM 20 in DS 20). Vzorci so bili pripravljeni z metodami običajne metalografije, za analizo pa smo uporabili optično in elektronsko mikroskopijo (natančna poročila raziskav so v [6] do [8]).

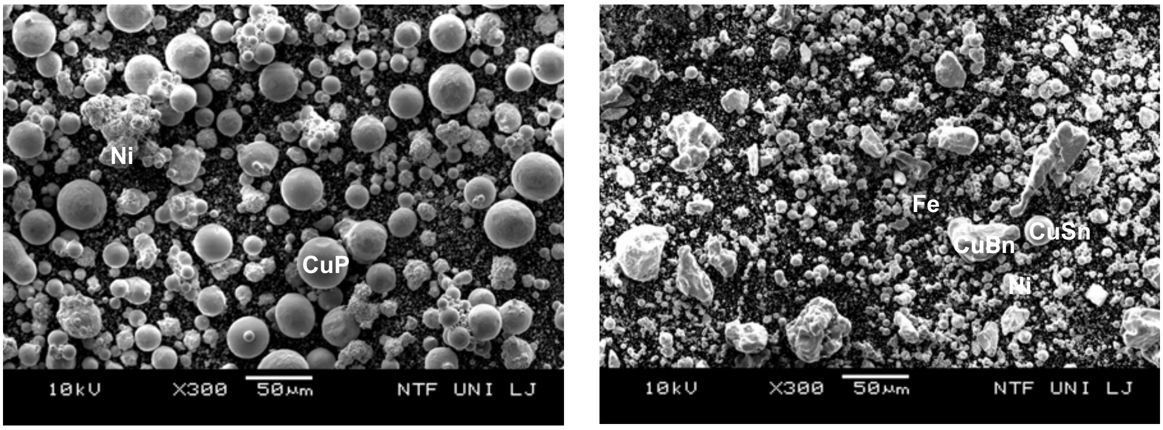
Ugotovili smo, da je prašna mešanica materiala DM 20 sestavljena iz dveh komponent; Cu-P delci prahu so velikosti 10 do 80 mm, delci Ni pa velikosti 20 do 30 mm (sl. 2a). Oblika prahov je bila pregledana z vrstičnim elektronskim mikroskopom VEM, sestava prašnih mešanic pa določena s točkovno analizo EDS (Cu-P delec vsebuje 88,7 mas % Cu in 9,8 mas % P). To pomeni, da je ta material primerljiv s fosforjevim bronom (prah predzlitine CuP10). V primeru materiala DM torej uporabljamo prašno mešanico, sestavljeno iz Cu-P in tehnično čiste kovine Ni.

Prašna mešanica DS 20 je sestavljena iz štirih komponent (sl. 2b): prašnih delcev nepravilnih oblik Fe in Cu-P, krogličnih delcev Cu-Sn ter manjših skupkov delcev Ni. Deležna analiza EDS je pokazala, da Cu-Sn delec vsebuje 85,6 mas % Cu; 13,5 mas % Sn. To pomeni, da je uporabljen standarden kositrov bron CuSn10. V primeru materiala DS torej uporabljamo prašno mešanico Cu-Sn ter CuP z dodatkom prahu čistega Fe in Ni.

still exist. For a comprehensive understanding of the sintering process and for the successful introduction of this technology, a number of investigations related to the characteristics of the powders and the individual sintered layers were performed. IMT Ljubljana, NTF University of Ljubljana and the TCK COMPANY supported the metallurgical research. As a first step the main powders were characterised (DM 20 and DS 20). Samples were prepared using classical metallography and for analysis we used optical and electron microscopy (for details see reports [6] to [8]).

We found that the DM 20 powder mixture consists of two components: Cu-P powder particles with size 10 to 80 µm, and Ni particles with size 20 to 30 µm (Fig. 2a). The shape of the powder particles was examined using SEM analysis and the composition was determined with an EDS analsis. The Cu-P particles consist of 88.7 mass % of Cu and 9.8 mass % of P; this material can be compared with phosphorus bronze (powder of pre-alloy CuP10). In the case of the DM 20 powder we are effectively using a powder mixture of Cu-P and technically pure Ni.

The powder mixture DS 20 consists of four components (Fig. 2b): irregular shapes of Fe and Cu-P powder particles, spherical particles of Cu-Sn, and smaller Ni particles. A quantitative analysis of the EDS spectra revealed that the Cu-Sn particles consist of 85.6 mass % of Cu and 13.5 mass % of Sn; this indicates that a standard tin bronze is used. In the case of DS 20 we are effectively using a powder mixture of Cu-Sn, Cu-P and technically pure Fe and Ni.



a) b)

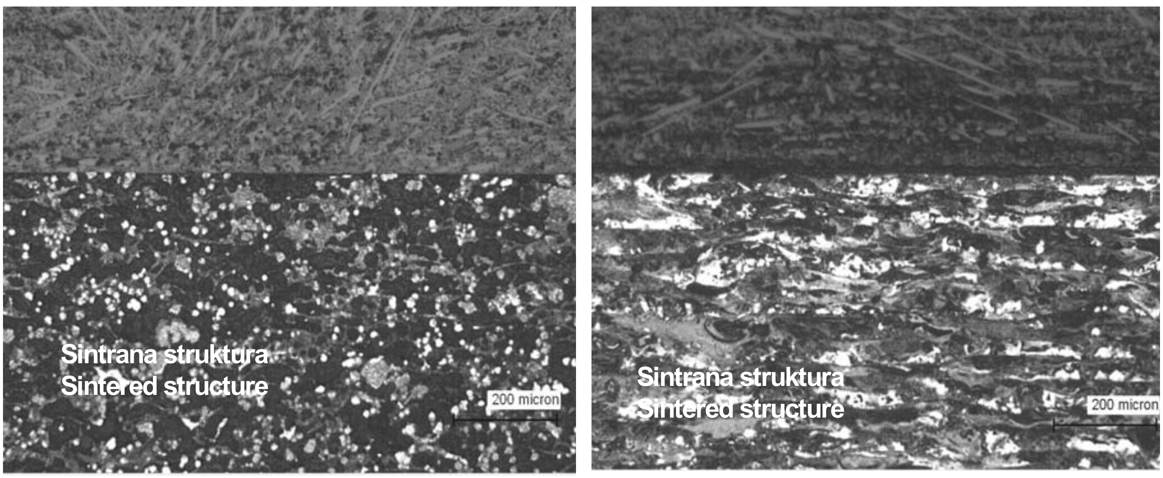
Sl. 2. *Posnetek VEM prašnih mešanic; a) DM 20 in b) DS 20*
Fig. 2. *SEM photograph of powder mixture; a) DM 20, b) DS 20*

V splošnem je sintranje definirano kot postopek, pri katerem pride do zmanjšanja velikosti in števila por med osnovnimi delci ob hkratnem krčenju komponent (delcev kovinskega ali keramičnega prahu), le to pa je združeno z rastjo kristalnih zrn in močno vezavo med sosednjimi delci (povzročeno z visokimi tlaki in temperaturami). Lasersko sintranje (NLPS) je postopek posebnega zgoščevanja, pri katerem z laserskim žarkom pretalimo določene sestavine prašne mešanice v skoraj kompaktno zlitino. Zaradi delovanja energije laserja najprej začnejo prašni delci med sabo delati vezi, s tem začnejo rasti, hkrati pa se povečuje tudi kompaktnost medsebojnih povezav. To se dogaja med delci v posamezni plasti prahu, pa tudi med različnimi plastmi. Debelina prve plasti in tudi naslednjih je enaka zrnatosti uporabljene prašne mešanice (v našem primeru je povprečna velikost približno 20 mm, sl. 3).

Osnova sintranega materiala DM 20 je torej Cu-Ni zlitina, zlitinski dodatek je P, ki med postopkom

Generally speaking, sintering is defined as a process involving a reduction in the size and the number of pores between particles, and the simultaneous contraction of the components (metal powder particles or ceramic powder), together with the growth of the crystal grains and strong binding between neighbouring particles (usually caused by high pressures and temperatures). Laser sintering (DMLS) can be described as a special process of condensation where a laser beam melts ingredients of powder mixture into a compact alloy (liquid phase sintering). Because of the laser's energy the powder particles start to interact with the formation of mutual bindings, the powder particles then start to grow and the compactness of the linkages is intensified. This process occurs between particles in a particular layer and also between the layers. The thickness of the first and the next layer is equal to the grain size of the powder (in our case the average grain size is 20 μm, see Fig. 3)

The basis of the DM 20 sintered material is a Cu-Ni alloy, during the melting process P - as the

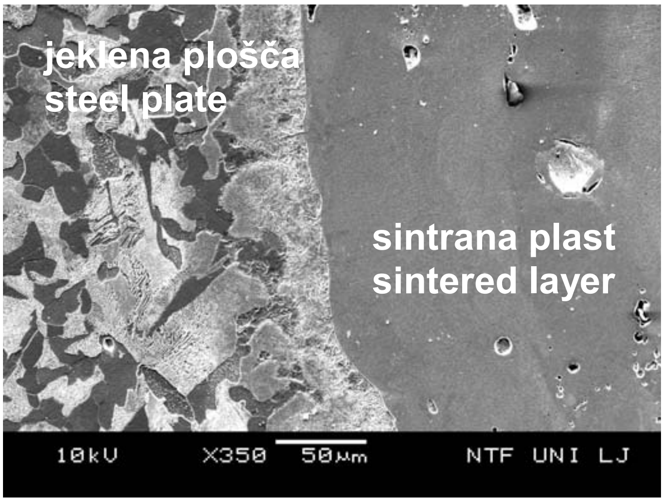


a) b)

Sl. 3. *Plastna mikrostruktura sintranih materialov; a) DM 20 in b) DS 20*
Fig 3. *Layered structure of laser-sintered material; a) DM 20, b) DS 20*

taljenja deluje kot dezoksidant, sočasno tvori tudi lahko taljive evtektike. S tem je omogočeno sintranje v prisotnosti tekoče faze. Hkrati P kot zlitinski element močno utrjuje osnovno Cu-Ni zlitino, kar daje razmeroma velike trdote strukturi dobljeni z NLPS. Osnova sintranega materiala DS 20 je sistem Fe-Ni-Cu, zlitinska dodatka P in Sn omogočata nastanek nizkotaljivih faz, P pa nadomešča C in daje strukturi ustrezno trdoto. Izdelava orodij DMLS se začne na osnovni plošči (material C45 z 0,45 m% C, mikrostruktura je iz lamelarnega perlita in ferita), na katero laser natopi prvo plast prašnega materiala. Raziskave so pokazale, da sta prva plast in podložna plošča spojeni brez napak (sl. 4).

alloying element - acts as an de-oxidant and also forms easily-melting eutectics. This means that sintering occurs in the presence of a liquid phase, and simultaneously, P also strengthens the basic Cu-Ni alloy in such a way that a relatively high hardness of the sintered material is produced. The basis of the DS 20 sintered material is Fe-Ni-Cu, P and Sn - as alloying elements - form easily-melting phases, P is a substitute for C and also gives the structure an appropriate hardness. The sintering of DMLS tools starts from a basic plate (material C45 with 0.45 mass % C, the microstructure is lamellar perlite and ferrite), on which the laser melts a first layer of powder material. Our investigations showed that the first layer and the basic plate are joined without defects (Fig. 4).



Sl. 4. *Staljeni spoj med osnovno jekleno ploščo in lasersko sintranim prahom*
Fig. 4. *Melted connection between the basic steel plate and the laser-sintered powder*

3 POVRŠINSKA OBDELAVA ZA IZBOLJŠANJE OBRABNE ODPORNOSTI SINTRANIH DELOV

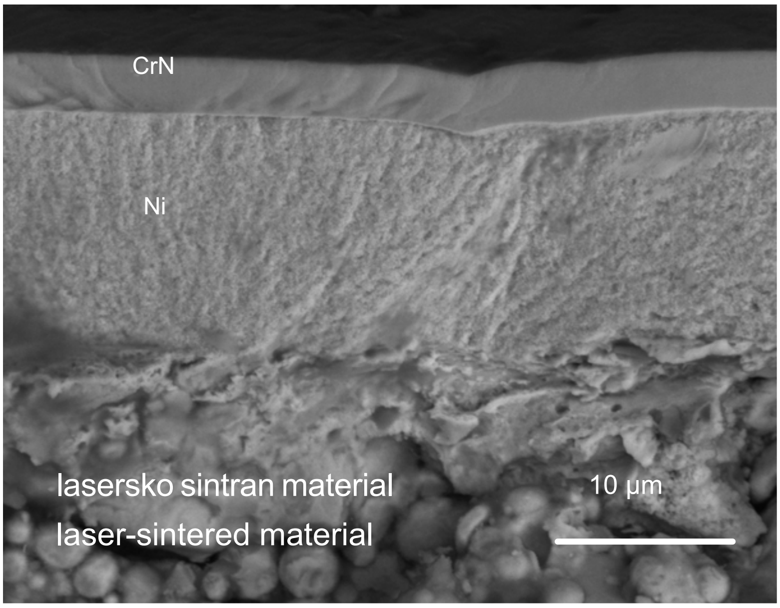
Za doseganje ustrezne hrapavosti površin in izboljšave mehanskih lastnosti je potrebno po sintranju sintrance še dodatno obdelati. Dodatna obdelava vložkov orodij vključuje udarjanje (peskanje) z jeklenimi kroglicami za povečanje površinske trdote in udarjanje s keramičnimi kroglicami znotraj ostrih prehodov zaradi sproščanja notranjih napetosti. Ročno brušenje in poliranje je potrebno zaradi izboljšanja kakovosti površine, posebna pozornost pa je namenjena navpičnim stenam in kanalom. Sledi še drugo udarjanje s keramičnimi materiali za sproščanje površinskih tlačnih napetosti in za izboljšanje učinkovitosti hladilnih plasti.

Značilnosti laserskih sintrancev pa je mogoče izrazito izboljšati prek nanosa trdih površinskih prevlek. Trde prevleke v splošnem izboljšajo obrabne in toplotne značilnosti, vendar doslej ni bilo na voljo ustreznih priporočil, ki bi se nanašala na izbiro ustreznih prevlek. Zadnje

3 SURFACE TREATMENTS FOR IMPROVING THE WEAR AND THERMAL RESISTANCE OF SINTERED PARTS

After the sintering process some additional post processing needs to be performed on the sintered parts in order to achieve an adequate surface roughness and improvements to the hardness. Post processing of the inserts includes shot peening with steel shot to increasing the surface hardness and peening inside sharp corners with fine ceramic media for stress relieving. Manual grinding and polishing is performed to improve the surface quality with special attention to vertical walls and slots; and consequently a second shot peening with fine ceramic media to induce compressive stress to the surface and to improve the behaviour of the lubricant film.

The characteristics of the laser-sintered tool inserts can be significantly improved with the deposition of hard surface coatings. Hard surface coatings tend to improve the wear and thermal characteristics of the sintered inserts. However, so far there are no recommendations related to the choice of appropriate



Sl. 5. *Nanos plasti trdega Ni in prevleke CrN na lasersko sintrano orodje*
Fig. 5. *Deposited layers of Ni and CrN on the laser-sintered tool*

raziskave prevlek so zato usmerjene na izboljšave obstojnosti pri uporabah sintranih vložkov orodij za brizganje abrazivnih materialov in materialov, pri katerih so prisotne velike obremenitve [9]. V sodelovanju z Inštitutom Jožef Stefan, centrom za trde prevleke so že doseženi nekateri uspešni rezultati. Prevleka iz trdega kemičnega niklja zelo dobro zapolni različne razpoke in pore, ki nastanejo pri sintranju, hkrati pa tudi izboljša hrapavost površine orodja. Z nanosom dodatne plasti CrN (za tlačno litje aluminija) ali TiN (za brizganje plastičnih izdelkov) pa se poleg toplotne odpornosti izrazito poveča tudi površinska trdota vložkov orodij (sl. 5).

4 PRAKTIČNI PRIMER – SINTRANO ORODJE ZA TLAČNO LITJE ALUMINIJA

Tlačno litje aluminija je zelo pomemben postopek pri masovni proizvodnji komponent skoraj končnih izmer, še vedno je eden od najpomembnejših postopkov za izdelavo avtomobilskih delov v primerih, pri katerih so večje obremenitve. Postopek je stroškovno sprejemljiv le za litje zadostnih količin izdelkov, zaradi zapletenih oblik in zahtev po ustrezni dobi trajanja so zato potrebna velika investicijska vlaganja v orodja. Pri teh tehnologijah se zato od orodjarjev vse bolj zahtevajo hitre in cenovno sprejemljive rešitve. Za veliko uporab je že dovolj, da so orodja primerna za litje do 1000 odlitkov, za tehnične prototipe celo 100 odlitkov. Vendar je za podporo hitri izdelavi orodij za tlačno litje aluminija in podobnih barvnih kovin trenutno na voljo le nekaj rešitev, saj se v tem primeru postavljajo izredne zahteve glede prenašanja visokih temperatur in tlakov.

coatings. Some recent investigations on the deposition of different coatings have focused on improvements to the tool life and the application of sintered parts for moulding abrasive materials and materials with high loads [9]. Some promising results have already been achieved together with the IJS, Center for Hard Coatings. It was found out that with the deposition of hard nickel it is possible to fill the cavities and cracks of the sintered material and also to improve the surface roughness of the tool. With the additional deposition of a CrN layer (for aluminium casting purposes) or TiN (for the injection moulding of abrasive plastics) in addition to improvements in the thermal resistance, a high surface hardness can also be achieved (Fig. 5).

4 PRACTICAL EXAMPLE – SINTERED TOOL FOR PRESSURE DIE- CASTING OF ALUMINIUM

Aluminium die-casting is an important technique for the mass production of near-net-shape components and is still the major automotive casting route for lightweight components used in stressed areas. The high-pressure die-casting process produces the lowest cost-per-part for the castings but requires the highest level of capital investment due to the complexity and longevity of the tooling. Therefore, high-pressure die-casting toolmakers urgently require rapid tooling solutions that will give them a faster return on a tool. For such a tools as few as 1000 castings are required for short-run tooling and as few as 100 castings for technical prototypes. For pressure die-casting applications only a few rapid tooling solutions exist due to the high temperatures and pressures that are involved.

Značilen vzrok za poškodbe orodij pri tlačnem litju aluminija so toplotne obremenitve. Razlike temperatur med litim izdelkom in talino znašajo tudi čez 500°C, temperaturni gradient je še posebej velik v bližini različnih kavitacij in prehodov. Talina, ki z visokim pritiskom (tudi čez 800 bar), vstopa v orodje, povzroča tudi velike mehanske obremenitve oziroma napetosti v orodjih. To pomeni, da želimo sintrane vložke uporabljati v najbolj kritičnih območjih orodij, kjer so termične in mehanske obremenitve največje. Za doseganje uspešnih rezultatov je pri uporabi NLPS vložkov za tlačno litje treba zato upoštevati nekatere omejitve in opozorila. Te se nanašajo na praškasti material, obliko izdelkov in orodij, sam postopek sintranja ter poznejšo obdelavo vložkov orodij [10].

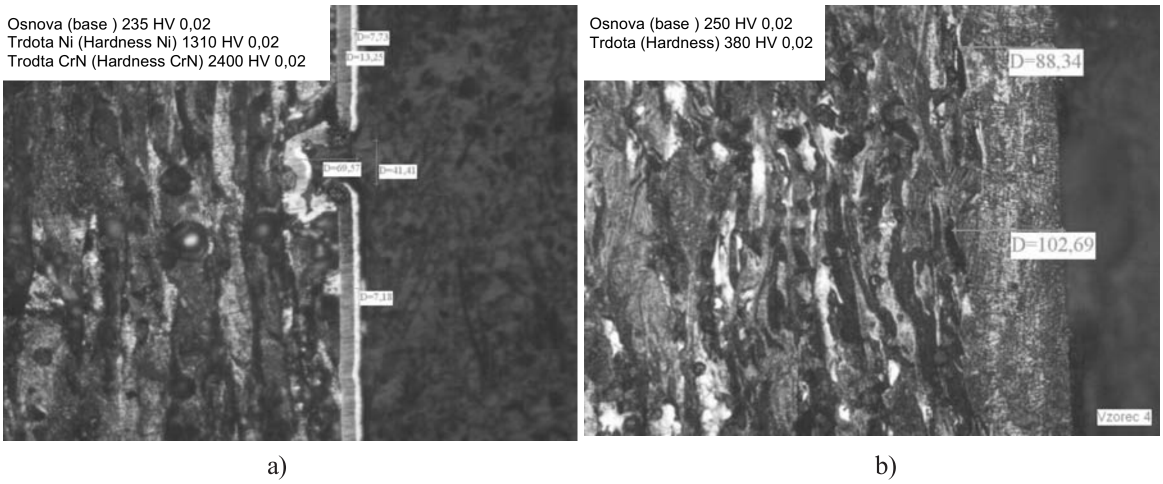
Glede na vse te znane začetne pogoje so bili za testiranje tlačnega litja aluminija v industrijskem okolju oblikovani in izdelani štirje namenski vložki, ki so bili tudi ustrezno obdelani in površinsko zaščiteni (material AlSi9Cu3, temperatura taline 690^{o}C, tlak 780 bar, hitrost taline na vstopu v orodje 50 m/s).

Na sliki 6 sta prikazani dve mikrofotografiji strukture vložkov. Leva slika kaže problem, ki se pojavi zaradi poroznosti strukture sintranega materiala in posledično slabo oprijemljivost prevlek. S tem ne moremo zagotoviti vložkom vseh prednosti, ki bi jih lahko dajale prevleke. Desna fotografija kaže dodatno staljeno zunanjo plast vložkov (v zadnji sintrani plasti debeline 0,94 mm je zataljena še plast debeline 0,006 mm, hitrost sintranja laserja je tu 50 mm/s). S tem se zmanjša poroznost površine sintranca in izboljšajo površinske značilnosti vložka; rezultati litja (število kosov) so v tem primeru povsem enaki kakor pri uporabi prevleke (v obeh primerih narejenih več ko 250 sprejemljivih kosov). Raziskave so torej potrdile, da je mogoče odliti dovolj kosov, če je izdelek ustrezno oblikovan in če se pri sintranju uporablja postopek zunanje zataljenega sloja in ustrezne prevleke.

Heat loads often cause failures in die-casting tooling. In die casting the temperature difference between the molten metal and the mould can be over 500°C, and the temperature gradient is highest in the mould cavity areas. Molten material with a high pressure of up to 800 bars also induces high mechanical stresses in the tool inserts, particularly at the entrance of the mould flow. This means that sintered inserts need to be used in the most critical areas where the most demanding thermal and pressure conditions exist. Therefore, when using DMLS inserts in die-casting tooling applications some precautions related to the powder material, the product and tool design, and the sintering and post-processing methods should be taken to ensure successful results (see also [10]).

Based on all known preconditions a special testing part was designed and prepared according to a variety of post-processing methods for pressure die-casting in an industrial environment (material, AlSi9Cu3; temperature of the molten material, 690^{o}C; pressure, 780 bar; speed at the entrance of the mould, 50 m/s).

As an example Fig. 6 shows two micrographs of the used inserts. The left-hand micrograph (Fig. 6a) shows a problem caused by the porosity of the sintered material and the subsequent poor deposition of the coatings. As a consequence the coatings cannot show all their potential for die-casting applications. With the application of a melted up-skin layer (into the last layer thickness of 0.94 mm an additional layer thickness of 0.006 mm with a laser speed of 50 mm/s is melted), the surface porosity can be reduced and the surface characteristics improved (Fig. 6b). Inserts have shown almost the same characteristics as coated version (more than 250 parts produced with both inserts). Observations therefore confirmed that more parts can be produced with an optimum design of the part and using an up-skin approach and subsequent coatings.



a) b)

Sl. 6. *Mikrofotografije prevlečenega vložka orodja; a) prevleka Ni in CrN, b) pretaljena vrhnja plast*

Fig. 6. *Micrographs of the inserts; a) coatings with Ni in CrN, b) melted up-skin.*

5 SKLEP

V okviru sodelovanja med slovenskimi univerzami in industrijo je eden od najpomembnejših postavljenih ciljev tudi oblikovanje tehnoloških inovacij in prenos novih tehnologij v krajevno industrijo. Oprema za NLPS, ki je bila septembra leta 2002 vgrajena v okviru »Regionalnega tehnološkega centra Zasavje«, je slovenski industriji odprla dobre možnosti za uvajanje te tehnologije, še posebej se to nanaša na orodjarje (nekatere uspešne uporabe so že bile predstavljene v npr. [11]).

Obstojnost lasersko sintranih vložkov je že do 100.000 brizganih delov iz plastičnih mas, vendar je uspešnost uporabe odvisna od različnih vplivnih dejavnikov (npr. abrazivni vključki v brizganem materialu, to so polnila s steklenimi vlakni, ki povečujejo obrabo vložkov orodij na vogalih in površinah, kjer je močan pretok taline). Za tlačno litje aluminija ali podobnih neželeznih kovin pa so sintrana orodja trenutno primerna le za namene testiranj (pod 1.000 litih kosov). Vendar najnovejši razvoj prašnih materialov, še posebej pa uporaba trdih prevlek, daje vse boljše rezultate, kar omogoča nadaljnji razvoj v smeri obrabnih in temperaturnih izboljšav značilnosti sintranih vložkov orodij.

Po letu dni od vgraditve opreme za NLPS v Sloveniji lahko trdimo, da smo tehnologijo v glavnem uspešno vpeljali, da smo izvedli že nekaj uspešnih industrijskih uporab, da smo se dejavno vključili v področje raziskav povečanja obrabne odpornosti NLPS orodij, da nas na tem področju vključuje v svoj razvoj izdelovalec opreme za NLPS in da smo udeleženi kot partnerji v predlaganih projektih 6. okvirnega programa EU. Vendar moramo za uspešno uporabo in trženje te tehnologije v slovensko industrijo narediti veliko več kot le kupiti tehnologijo. Investirati je treba veliko več napora v dejavnosti prenosa tehnologije v smislu sprememb inženirskih navad pri konstruiranju izdelkov in načrtovanju tehnologij izdelave pa tudi dosedanje prakse razvoja orodij v Sloveniji.

5 CONCLUSION

Within the scope of the cooperation between the Slovenian universities and industry, one of the most important goals is the creation of technological innovation and the transfer of the newest technologies to the local industry. DMLS equipment, installed in September 2002, gave Slovenian industry the possibility to apply this technology. This is particularly the case for toolmakers. Some successful applications have already been presented, e.g. [11].

The life of laser-sintered tool inserts can be up to 100,000 moulded plastic parts, however, the success is related to the abrasive ingredients of the moulded material (e.g. in the case of glass-fibre ingredients, the wear of the inserts is increased at the corners and surfaces by the intensive flow of the melt). For the casting of aluminium or similar metals the sintered tools are applicable only for testing purposes (less than 1,000 parts). The recent development of powder materials, and particularly the application of hard coatings, have given good results and suggest prospects of further improvements to the wear and temperature resistance of tool inserts.

One year after the installation of the equipment we can say that this new technology has been generally introduced and that several successful industrial applications have resulted. We are also active in the area of wear-resistance research of DMLS tools, we actively participate as a partner in the proposed EU 6 Framework programs, and we collaborate with the producer of the equipment (EOS) in its development activities. However, for the successful application of this technology in the Slovenian toolmaking industry much more needs to be done besides the simple introduction. We need to invest much more into activities of technology transfer in the sense of changing engineering habits and tool-development practice in Slovenia.

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Prejeto:
Received: 2.2.2004

Sprejeto:
Accepted: 8.4.2004

Odprto za diskusijo: 1 leto
Open for discussion: 1 year