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Lasersko sintranje orodja za tlačno litje aluminija

Laser-Sintered Tools for the Die-casting of Aluminum

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V prispevku so prikazani rezultati uporabe neposrednega laserskega sintranja kovinskih prahov (NLSK) kot postopka hitre izdelave orodij za tlačno litje aluminija. Za izvedbo raziskave smo izbrali za izdelek navijalnik varnostnega pasu (uporaba v avtomobilski industriji). Skladno z zahtevami glede izdelave prototipnih orodij smo sedanjo konstrukcijo običajnega orodja ustrezno prilagodili in naredili nekatere izboljšave materiala za sintranje kakor tudi postopka sintranja. Primerjalna vrednostna analiza med običajno izdelavo orodij in NLSK je pokazala, da je z NLSK čas izdelave dosti krajši. Končne raziskave so bile usmerjene v industrijsko testiranje orodja izdelanega z NLSK in analizo njegove obstojnosti za potrditev postavljenega raziskovalnega cilja, tj. izdelati 5.000 praktičnih izdelkov v industrijskem okolju.

(Ključne besede: izdelava orodij hitra, sintranje lasersko, litje aluminija, litje tlačno)

In this paper some results from using a DMLS (direct metal laser sintering) rapid-tooling solution for aluminum die-casting are presented. The product chosen for the investigation was a car safety-belt strap winder (an application for the automotive industry), and according to the requirements of the prototype tools, we have adapted the construction of the classic tools and made some improvements to the material and the sintering process. The comparative-value analysis with classical tooling has shown that the time of production with the DMLS process is considerably shorter. The final investigation was focused on the industrial testing of the DMLS, followed by the tool analysis after die-casting to confirm the research goal, i.e., 5,000 practical parts produced.

(Keywords: rapid tooling, laser sintering, aluminium castings, pressure die casting)

0 UVOD

Kakor opisuje svoji objavi Gideon [1], so postopki hitre izdelave prototipov v zadnjem desetletju že dosegli široko uporabo, vendar je trg za hitro izdelana orodja (kot ene prvih uporab hitre proizvodnje za neposredno izdelavo orodij za tlačno litje) še vedno zelo omejen. Čeprav so izdelovalci opreme in prahov za sintranje zelo napredovali (na primer EOS ([2] do [4])) in čeprav ni dvoma o tem, da se lahko sintrana orodja brez težav uporablja za brizganje plastičnih izdelkov v serijah preko 100.000 kosov, ni veliko potrditev glede uporabe teh orodij v praksi.

Vendar so potrebe po izdelavi majhnih serij različnih komponent, izdelanih s postopki tlačnega litja, v zadnjem času čedalje večje. Tudi splošne težnje po skrajšanju dobavnih časov in zmanjševanju

0 INTRODUCTION

According to Gideon [1], rapid prototyping has gained very wide acceptance over the past decade, but the market for rapid tooling (as a first application of rapid manufacturing for the direct and fast production of tools for injection molding) remains limited. Even producers of the equipment and the powder materials have made significant progress (e.g., EOS ([2] to [4])), and there is no doubt that tools can be used for series up to 100,000 shots for injection-molding applications, but there are no results to confirm this in practice.

The need for small-series production for die-cast components has arisen during recent years. The general development trend to speed-up tooling times has forced tooling companies to intensify mold stroškov sili orodjarje v večanje učinkovitosti razvoja in izdelave orodij. Zato je zanimanje za nove tehnološke rešitve tudi vse večje. Doslej ni bilo na voljo hitrih in ekonomsko upravičenih postopkov za izdelavo orodij, ki bi jih lahko uporabili za majhne serije tlačno litih izdelkov. Orodja je bilo treba izdelati iz ustrezno trdih orodnih materialov z običajnimi postopki frezanja in elektro erozijsko obdelavo (EDM), saj je tlačno litje veliko bolj zahteven in obremenilen postopek (visoke temperature taline in s tem velike toplotne obremenitve taline na orodja). Kratki časovni krogi in dodatno hitro ohlajanje odlitkov povzroča tudi toplotne razpoke v orodjih, zato je obstojnostne čase teh orodij mogoče napovedovati le približno.

Glede na to orodjarji za izdelavo orodij za tlačno litje aluminija vse bolj zahtevajo hitre in cenovno sprejemljive rešitve, ki jim bodo omogočale hitrejšo povrnitev vlaganj v orodja. Za veliko primerov je že dovolj, da so orodja primerna za litje do 1.000 odlitkov, za tehnične prototipe celo v količini do 100 odlitkov. Vendar je za hitro izdelavo orodij trenutno na voljo le nekaj rešitev, saj se v primeru tlačnega litja aluminija in podobnih barvnih kovin postavljajo skrajne zahteve glede visokih temperatur in tlakov [5]. V povezavi s to problematiko in glede na vpeljavo opreme za NLSK so bile narejene določene temeljne raziskave značilnosti postopka neposrednega laserskega sintranja, pa tudi pregled mogočih uporab te tehnologije v slovenski orodjarski industriji [6].

Preizkusni rezultati so tesno povezani s praktičnimi orodjarskimi uporabami ([7] in [8]); izdelanih je bilo veliko število orodij za potrebe brizganja plastičnih izdelkov, nekaj jih je bilo tudi uporabljenih za izdelavo orodij za tlačno litje zlitin cinka in drugih barvnih kovin. Poleg tega je bilo NLSK uspešno uporabljeno za neposredno izdelavo končnih izdelkov zapletenih oblik (primeri vključujejo zahtevne izdelke za smučarske vezi, plezalno opremo). Raziskave so bile tudi usmerjene v mikro-strukturno in mehansko ovrednotenje izdelkov na osnovi NLSK za določitev ustrezne površinske obdelave in prevlek za izboljšanje toplotnih in obrabnih značilnosti lasersko sintranih izdelkov ([9] in [10]).

V tem prispevku so prikazani nekateri zadnji raziskovalni rezultati in izkušnje, pridobljene z uporabo NLSK za izdelavo orodij za tlačno litje aluminija. V povezavi z dejavnostmi projekta Eureka [11] smo raziskovali: kako oblikovati vložke orodij pri uporabi postopka laserskega sintranja, kakšni so ustrezni prahovi za sintranje, kakšne postopke

manufacturing, and therefore the overall interests for new technological solutions is very high. In the past there were no fast and economical tooling solutions for small-series production in die-casting because the molds had to be made by milling and EDM (Electrical Discharge Machining) in hard steels. Die casting is a much more vigorous process than injection molding, mainly due to the high processing temperatures and the high heat loads of the casting metals. The comparatively short cycle times and the rapid cooling of the cast products induce continuous thermal fatigue in the tooling and so only approximate life times can be predicted for the molds.

For these reasons, the toolmakers for high-pressure die-casting urgently require rapid tooling solutions that will give them a faster return on a tool. For such tools, as few as 1000 castings are required for short-run tooling, and for technical prototypes this figure can be as low as 100 castings. For pressure die-casting applications, only a few rapid-tooling solutions exist due to the high temperatures and pressure loads (see Dolinšek, [5]). Following this problem and in relation to the introduction of DMLS equipment some basic research on the characteristics of the direct metal laser sintering (DMLS) process and the applications of this technology in the Slovenian tool-making industry have been performed [6].

Our experimental results are closely related to practical tool-making applications ([7] and [8]); a number of tools were produced for injection-molding applications, and some of them were used in the production of tools for zinc alloy and aluminum die casting. Additionally, DMLS has been used for the direct production of parts with complicated shapes (examples include demanding sintered parts for ski bindings and equipment for climbers). Research has also been focused on microstructural and morphological analyses of the metal powders and the subsequent chemical, microstructural and mechanical characterizations of 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 ([9] and [10]).

In this paper some recent research results and experiences using a DMLS tooling solution for aluminum die-casting are presented. According to the activities within a Eureka project [11] we investigated how to design suitable inserts for the direct laser sintering of metal powders, determine a proper poznejše obdelave in prevleke orodij potrebujemo, kakšni so delovni parametri za tlačno litje aluminija in ali je tržno upravičeno uporabljati NLSK za izdelavo orodij za tlačno litje aluminija.

1 POSTOPEK TLAČNEGA LITJA ALUMINIJA IN UPORABA HITRE IZDELAVE ORODIJ

Tlačno litje aluminija je zelo pomemben postopek pri masovni proizvodnji komponent skoraj končnih izmer in je še vedno glavna usmeritev za izdelavo litih lahkih in obremenjenih komponent v avtomobilski industriji. Postopek je stroškovno sprejemljiv le v primeru litja zadostnih količin izdelkov, saj so zaradi zapletenih oblik in vrhunskih zahtev po ustrezni dobi trajanja potrebna velika investicijska vlaganja v orodja.

Pri tlačnem litju aluminija so temperaturne razlike med litim izdelkom in talino tudi čez 500 °C, temperaturni gradient je še posebej velik v bližini različnih votlin in prehodov. Talina, ki z visokim tlakom (tudi čez 800 bar) vstopa v orodje, povzroča velike mehanske obremenitve oziroma napetosti v orodjih. To pa pomeni, da želimo sintrane vložke uporabljati v najbolj kritičnih delih orodij, kjer so toplotne in mehanske obremenitve največje. Za doseganje uspešnih rezultatov je pri uporabi NLSK vložkov za tlačno litje treba upoštevati nekatere omejitve in opozorila. To se nanaša na praškasti material, na oblikovanje izdelkov in orodij, na sam postopek sintranja ter na končno obdelavo vložkov orodij.

Nekateri začetni preizkusi na področju tlačnega litja so že pokazali, da je mogoče NLSK uporabiti kot zelo primerljiv postopek za izdelavo orodij. V nekaterih primerih lahko NLSK primerjamo z izdelovalnimi rešitvami, pri katerih so uporabljene tehnologije odrezovanja (poročilo EOS [12]). Za manjše količine brizganih izdelkov so cilji običajno naslednji: obstojnost vložkov orodij do 1.000 tlačno litih kosov in sprejemljiva kakovost izdelkov brez pojava razpok (za najbolj uporabljane postopke tlačnega litja, npr. aluminij, magnezij, cink). Pri cinku in magneziju so te zahteve že izpolnjene, pri tlačnem litju aluminija pa obstaja še vedno nekaj težav, ki zahtevajo nadaljnji razvoj postopka NLSK.

Glede na vse te postavljene zahteve smo prve raziskave že opravili. Za testiranje NLSK orodij za tlačno litje aluminija v industrijskem okolju smo oblikovali poseben testni izdelek (material AlSi9Cu3, temperatura taline 690 °C, tlak 780 barov, hitrost taline na vstopu v orodje 50 m/s). Različni sintrani vložki iz DirectSteel 20 so bili ustrezno obdelani in površinsko

powder material, define suitable post-processing and coatings, and also some operating conditions for die casting are proposed with a commercial justification for using DMLS for die casting.

1 THE ALUMINUM DIE-CASTING PROCESS AND RAPID-TOOLING APPLICATIONS

Aluminum 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.

In die casting the temperature difference between the molten metal and the mold can be over 500ºC, and the temperature gradient is highest in the mold 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 mold flow. This means that sintered inserts need to be used in the 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.

Some early experiments in die-casting have already indicated that DMLS can also be used as a highly competitive process and in some cases it can be compared to machining technologies (EOS report [12]). The short-term target in die-casting is as follows: durability up to 1000 parts, acceptable crack-free quality for the main die-casting metals (aluminum, magnesium and zinc). For zinc and magnesium the demands have already been met, but in aluminum casting there are still some problems and further development needs to be done.

According to all known preconditions a special testing part was designed and suitable tooling inserts were prepared according to different post-processing methods for pressure die-casting in an industrial environment (material, $AlSi_9Cu_3$; temperature of the molten material, 690ºC; pressure, 780 bar; speed at the entrance to the mold, 50 m/s), using DirectSteel 20 material. Due to a problem caused zaščiteni. Zaradi pojava poroznosti sintranega materiala in s tem povezane slabe oprijemljivosti prevleke pri tej raziskavi prevleka ni pokazala pričakovanih prednosti [13].

S počasnejšim sintranjem na površini izdelka oblikujemo dodatno staljeni zunanji sloj, s tem se zmanjša poroznost sintranca in izboljšajo površinske značilnosti vložka orodja. Rezultati litja (število kosov) so v tem primeru povsem enaki kakor pri uporabi prevleke. V obeh primerih je bilo brez razpok narejenih več ko 210 kosov, prve vidne razpoke so se pojavile šele po 250 kosih. Obstojnostno merilo vložkov je bilo postavljeno glede na pojav prvih razpok na izdelku, razpoke so se pojavile na najbolj obremenjenih delih orodja (na ovirah pri vstopu taline v orodje zaradi posebne konstrukcije testnega izdelka [14]).

Raziskave so torej potrdile, da je mogoče odliti dovolj kosov, če pri sintranju uporabljamo postopek zunanjega zataljenega sloja in ustrezno prevleko. Zaradi visokih tlakov pri litju aluminija je treba sintrane vložke tudi dodatno pripraviti in obdelati (postopek, ki vključuje udarjanje s keramičnimi kroglicami, poliranje orodja za izboljšanje poroznosti in površinske hrapavosti pod 1 μm ter nanos dodatne prevleke za izboljšanje površinske trdote [15]). Zaradi najnovejšega razvoja prašnih materialov, še posebej pa možnosti uporabe trdih prevlek, so rezultati vse boljši, kar podpira nadaljnji razvoj v smeri obrabnih in temperaturnih izboljšav značilnosti sintranih vložkov orodij [16].

by the porosity of the sintered material and the subsequent poor deposition of the coatings, the coatings did not show great potential for die-casting applications [13].

With the application of the up-skin layer the surface porosities can be reduced and the surface characteristics can be improved; inserts have shown almost the same characteristics as when using coating. There were 210 parts produced without cracks, the first visible cracks appeared after 250 shots. The life criteria of the inserts were set in relation to the first visible cracks on the parts; however, due to the special design of the part with the barriers at the entrance to the mold flow, the cracks actually appeared near those barriers [14].

Observations, therefore, confirmed that more parts can be produced using an up-skin approach and subsequent coatings. Due to the high loads during the casting of the aluminum some necessary machining and post processing after the sintering needed to be done (up-skin technology including shot peening and polishing to improve the porosity and surface roughness below 1 μm and an additional hard coating with different layers to improve the surface hardness) [15]. The recent development of powder materials and particularly the application of hard coatings have, therefore, given good prospects for the further improvement of the wear and temperature resistance of tool inserts for die-casting applications [16].

2 RAZISKOVALNI CILJI IN METODOLOGIJA

Z uporabo novega prahu za sintranje DirectSteel H20, ki od vseh razpoložljivih materialov omogoča največjo trdnost, trdoto, obrabno odpornost in površinsko gostoto, je treba po postopku NLSK izdelati prototipno maloserijsko orodje za tlačno litje aluminijeve zlitine. Postavljeni raziskovalni cilji so:

(1) razvoj NLSK orodij in ustrezne površinske obdelave za tlačno litje aluminija v industrijskem okolju,
(2) dokazati, da lahko z NLSK vložki uspešno izdelamo 5.000 tlačno litih zapletenih izdelkov iz aluminija,
(3) izdelek in/ali geometrična oblika orodja morata biti takšna, da bo mogoče izrabiti vse prednosti NLSK (zahtevna geometrijska oblika in notranje hlajenje orodja).

Ustrezen izdelek za raziskavo in testiranje orodja je bil navijalnik avtomobilskih varnostnih

2 RESEARCH GOALS AND METHODOLOGY

Using the new sintering material DirectSteel H20, which offers the highest strength, hardness, wear resistance and surface density of all available materials, it is necessary to produce prototype small-series tools for the pressure casting of aluminum alloy with the DMLS process. The research goals were defined as follows:

(1) Development of the DMLS tools and a suitable surface treatment for the die casting of aluminum applications in a practical industrial environment,
(2) To prove that sintered DMLS inserts can successfully produce at least 5000 complex parts in aluminum die casting,
(3) The product and/or tool geometry must be such that the advantages of the DMLS process can be utilized (complex geometries and internal cooling channels etc.).

A suitable product for the investigation and the tool-testing was a car's safety-belt strap winder, a pasov, tržni izdelek, kjer se velikokrat zahteva prototipe v količini nekaj tisoč kosov. Izdelek ustreza poglavitni zahtevi, je dovolj zahteven, hkrati pa ne presega izmer, ki jih lahko izdelamo s sintranjem (omejitev stroja).

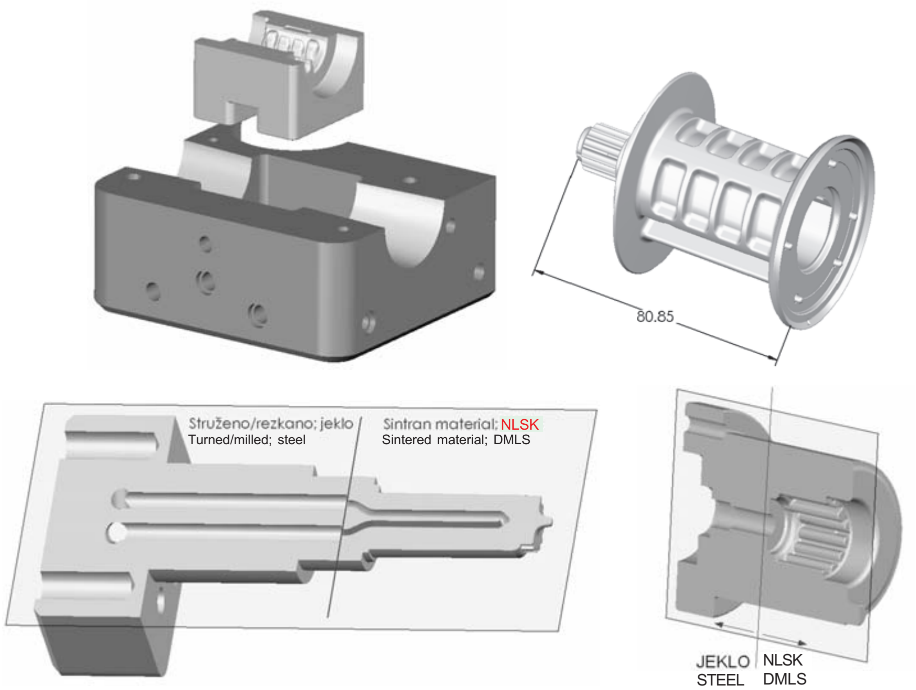
Zaradi specifičnosti NLSK je bilo potrebno konstrukcijo orodja ustrezno prilagoditi. Novo orodje je takšno, da so uporabljeni sintrani vložki orodja tam, kjer so zapletene gravure. S kombinacijo hitrejših in cenejših običajnih postopkov za izdelavo ogrodja orodja smo dosegli optimalno kakovost in ceno (sl. 1). Ogrevni sistem in vsi potrebni priključki so postavljeni na zunanji del orodja. Zaradi modulne zasnove orodja je mogoče oblikovne vložke zamenjavati in z najmanjšim stroškom izdelati orodje, ko se pojavi nov tip izdelka. Dodatno je bilo izdelano tudi notranje hlajenje daljših stranskih jeder (trnov), ta možnost obstaja edino pri uporabi NLSK.

Sestavljeno orodje in njegova notranjost s ogrevnim sistemom je prikazana na sliki 2. Za preprečevanje temperaturnih skokov in posledičnega pokanja gravur vložkov orodja ogrevni kanali niso nameščeni v neposredni bližini gravur. Bistvo ogrevanja je v vzdrževanju ustrezne temperature orodja in ne v lokalnem hlajenju gravur.

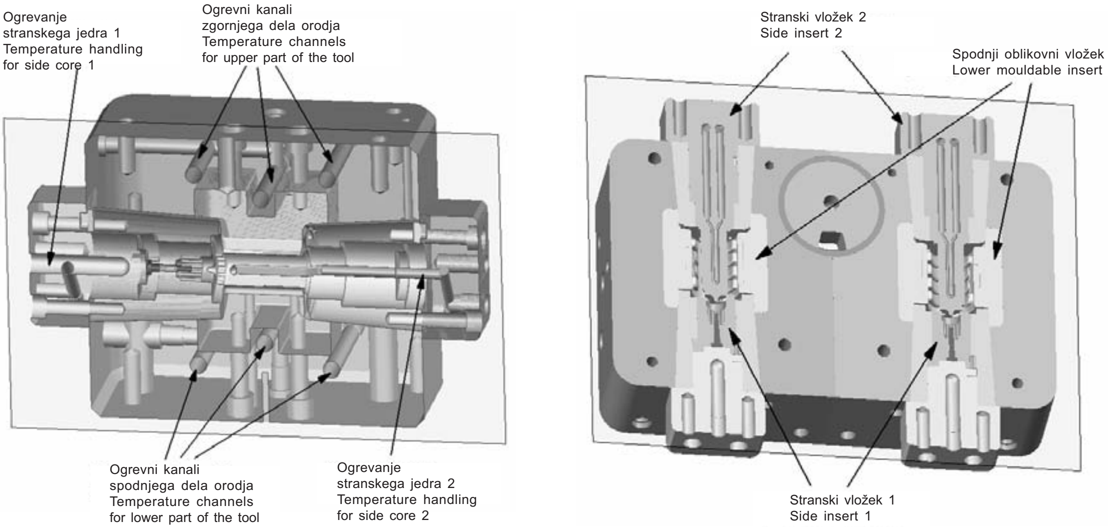
marketable product, where prototypes in a series of up to a few thousand pieces are commonly demanded. The product meets the basic requirement, i.e., it was complex enough, and at the same time its dimensions did not exceed the limits set by the sintering machine.

Due to the specifics of the DMLS procedure the construction of the tools was properly modified. The new construction required sintering only the tool parts with complicated engravings. Therefore, with the combination of faster and cheaper classic cutting processes for making a tool base we ensured the optimal quality and the price of the tool (Fig. 1). The temperature handling system and all the necessary connectors were placed on the exterior part of the tool. Due to the modular design, the approach of using changeable tool inserts resulted in a fast switch to the new type of product with minimum expenses. Additionally, conformal cooling was designed within the long side core (kernel); such an approach is only possible when using the DMLS process.

The assembled tool and the internal view with the temperature handling system are shown in Figure 2. To prevent temperature shocks and consequent cracks, the temperature channels are not placed close to the engravings. The essence of handling temperature is to maintain the proper temperature of the tool rather than local cooling of the engraving.



Sl. 1. *Modularna zgradba orodja: vložek, stranska jedra in izdelek (navijalnik avtomobilskih varnostnih pasov)*
Fig. 1. *Modular tool design: insert, side cores and the product (safety-belt strap winder)*



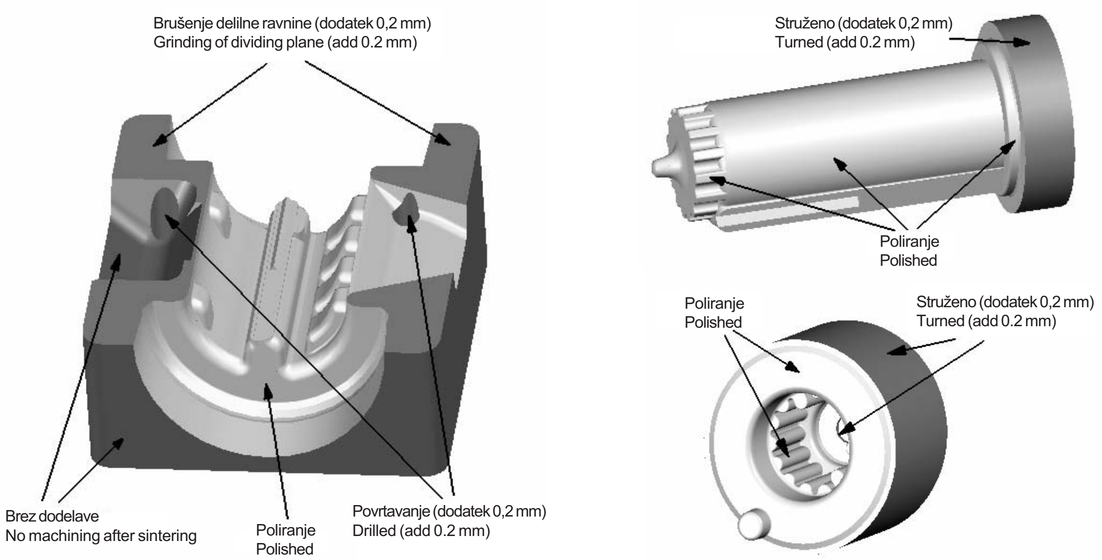
Sl. 2. *Sestavljeno orodje, lega ogrevnih kanalov ter stranskih jeder*
Fig. 2. *Assembled tool with the position of the temperature channels and side cores*

Za izdelavo vložkov orodij iz materiala DSH20 (za brizganje plastičnih izdelkov) se običajno uporablja tako imenovana strategija "dvojnega sloja - jedro": zunanji sloj sintramo z uporabo visoke vstopne toplote in razmeroma majhnimi hitrostmi gibanja laserskega žarka (hitrost gibanja žarka 80 mm/s in podajalni premik 0,25 mm). Zato je zunanji sloj zelo gost in ima najboljše mehanske značilnosti (trdota 380 do 420 HV). Notranji sloj je področje v notranjosti vložka, običajno ga sintramo z velikimi hitrostmi gibanja žarka (hitrost gibanja žarka 200 mm/s in podajalni premik 0,25 mm), zaradi česar se pojavi določena poroznost v materialu (trdota 340 do 380 HV). Poroznost notranjosti je običajno ~ 5%. Parametri "dvojni sloj - jedro" so dali dobre rezultate pri uporabi sintranih orodij v serijski proizvodnji, v načelu bi morala biti enaka strategija ustrezna tudi za sintranje orodij za tlačno litje aluminija. Glavna razlika je v delovni temperaturi litja in visoki krožni temperaturni obremenitvi taline aluminija, ki orodje izrazito toplotno obremenjuje. Za lasersko sintranje vložkov orodij so za to potrebni posebna pozornost in določene spremembe parametrov sintranja, poleg tega so bila za doseganje večje trdnosti dolga stranska jedra izdelana le z uporabo parametrov zunanjega sloja.

Pred končnim sestavljanjem orodja je za zagotavljanje boljše kakovost orodij in izdelkov treba gravure vložkov ustrezno polirati in nekatere površine tudi dodatno mehansko obdelati. Delilne površine vložkov orodij in kanale za vgradnjo stranskih jeder je treba brusiti (zaradi ustreznih

The standard approach to sintering injection-molding tools from DSH20 material has been called the "double-skin–core" strategy: the "outer skin" is built using a high heat input and relatively slow scanning parameters (scanning speed 80 mm/s with hatch distance 0.25 mm). Therefore, this outer skin is very dense and has the highest mechanical properties (hardness 380 to 420 HV). The "inner skin" is the inside area, which is normally sintered at a higher speed (scanning speed 200 mm/s with hatch distance 0.25 mm), so resulting in some porosity inside the material (hardness approximately 340 to 380 HV). The porosity of the inner skin is typically ~ 5%. These "double-skin–core" parameters have given good results for injection molding, even for serial production, and in principle the same strategy should also work for aluminum die casting. The main difference is the operating temperature of the molding process and the higher cyclic heat input that is transferred into the tool by the molten aluminum. Therefore, some extra precaution and changes have been decided on for the laser sintering of tool inserts, and also long side cores were built-up using only the "outer skin" parameters to make them stronger.

Before the final assembly of the tool, the engravings of the inserts need to be polished and some surfaces also machined to ensure the better quality of the tool or products. The parting surfaces of the tool inserts and the hollows for the side cores need to be grinded to ensure suitable fitting and the



Sl. 3. *Potrebna dodatna obdelava sintranih kosov orodja*
Fig. 3. *Required post-machining of the sintered parts*

prilegov in toleranc), stranska jedra pa postružiti (sl. 3).

Primerjalna vrednostna analiza med orodjem, izdelanim z običajnimi metodami in z uporabo NLSK, je pokazala, da je predvsem čas izdelave pri NLSK precej krajši. Razlika je večja, čim večji je delež EDM (potopna erozija). Zato je tudi sintranje stranskih jeder stroškovno bolj ugodno od izdelave oblikovnih vložkov (zgornji in spodnji del orodja), še posebej, če jih lahko skoraj v celoti izdelamo s frezanjem. V primeru, ko je ogrodje orodja narejeno za večje število prototipov in ko menjujemo le vložke orodja, pa je NLSK hitrejše in tudi cenejše od običajnega postopka izdelave orodij.

Tribološke lastnosti lasersko sintranega orodja za tlačno litje aluminija lahko bistveno izboljšamo, če ga zaščitimo z ustrezno trdo prevleko PVD (fizikalno naparjanje v parni fazi). Ta mora biti abrazijsko obstojna in mora imeti veliko trdoto, hkrati pa mora biti kemijsko inertna in oksidacijsko obstojna. Tem merilom najbolj ustrezata prevleki CrN in TiAlN PVD. Glede na to, da je standardno lasersko sintrano jeklo preveč porozno (DirectSteel 20 [13]) in zaradi premajhne nosilnosti (zaradi majhne trdote), smo preizkusili kombinacijo kemijsko nanesenega trdega niklja (Ni-P) in trde PVD prevleke. Ugotovili smo, da breztokovno naneseni trdi nikelj dobro zapolni pore na površini orodja, če je njegova debelina primerljiva z izmerami por (10 do 20 μm). Tako debela plast Ni-P bistveno izboljša nosilnost lasersko sintranega vložka.

required tolerances, and the side cores also need to be machined by turning (Fig. 3).

The cost analysis between the classical production of the tools compared to DMLS showed that the time of production when using DMLS is considerably shorter. The difference in relation to the classical method depends on the extent of the EDM. Therefore, the sintering of the side cores is much more cost-effective than the production of tool inserts (the upper and lower parts of the tool), particularly when they can be made just by milling. However, if the base of the tool is made for several prototypes and only the inserts are changed, the DMLS approach is faster, and can also be cheaper than the classic methods.

The tribological characteristics of a laser-sintered tool for aluminum die-casting can be significantly improved by the deposition of suitable PVD (Physical Vapour Deposition) hard coatings, which have to be abrasive resistant (and with a high hardness), and at the same time as chemically inert and resistant to oxidation as possible. Based on these preconditions CrN and TiAlN PVD coatings can meet the demands. Due to the problem of the porosity of standard laser-sintered steel (DirectSteel 20 [13]), and due to its lower load capacity (low hardness), a combination of hard nickel (Ni-P) and hard PVD coatings has been investigated. It was found that electroless coatings are suitable for filling the pores on the tool surface; however, with the precondition that the thickness of the coatings is higher than the dimensions of the pores (10 to 20 μm). Such a layer of Ni-P can, therefore, improve the load capacity of the laser-sintered tools.

Alternativa temu hibridnemu postopku zaščite je nanos samo prevleke PVD. Vendar je v tem primeru treba izdelati orodje tako, da je hitrost sintranja vrhnje plasti orodja (do globine približno 1 mm) čim manjša, da dobimo majhno poroznost. Površino je treba predhodno tudi utrditi z obstreljevanjem z jeklenimi kroglicami, da zagotovimo ustrezno nosilnost razmeroma krhki trdi prevleki. Kakovost nanosa prevleke je mogoče določiti z uporabo testa razenja. Merilo za oprijemljivost prevleke je nastanek mikrorazpok, ki ga spremlja pojav zvočne emisije in naglo povečanje sile razenja (ko se v razi začne prevleka luščiti). Kakor vidimo iz spodnjega posnetka SEM (sl. 4), se je prevleka CrN pričela luščiti pri sili razenja okrog 65 N, kar pomeni, da je oprijemljivost s tehnološkega vidika dobra.

Primerjava mehanskih lastnosti CrN in TiAlN trdih prevlek PVD je pokazala, da je oprijemljivost obeh prevlek primerljiva, medtem ko je mikrotrdota TiAlN znatno večja. Zato smo se odločili, da bomo za zaščito lasersko sintranega orodja za tlačno litje aluminijevih zlitin uporabili prevleko TiAlN.

3 PREIZKUSNI REZULTATI IN RAZPRAVA

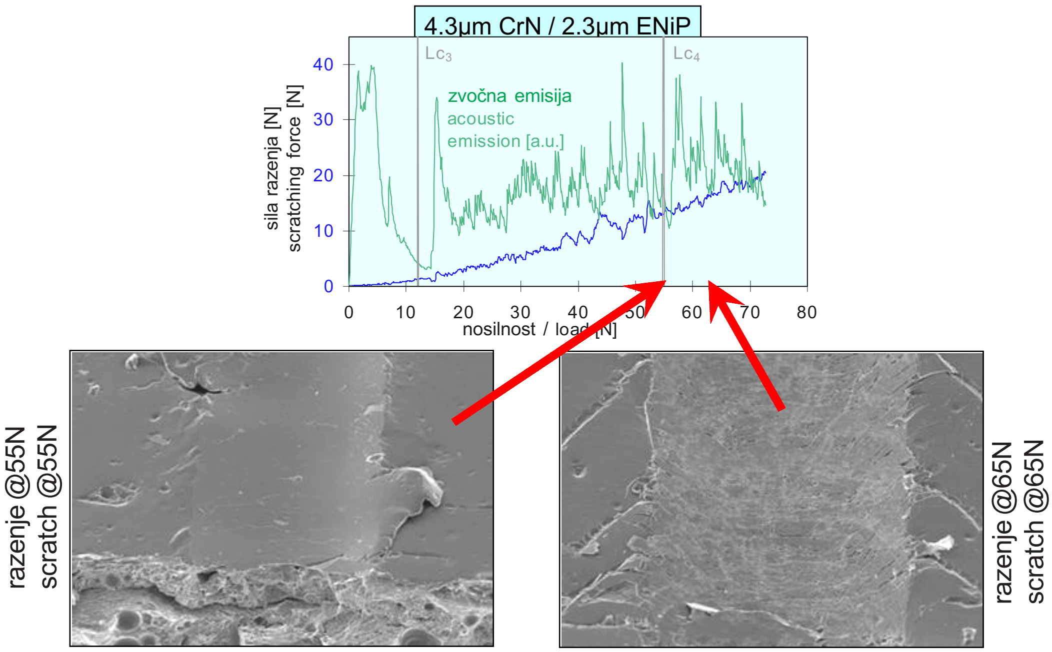
Testiranje NLSK orodij se je pričelo v industrijski livarni avgusta leta 2005. Izbrano je bilo

The alternative to such a hybrid coating process is the deposition of just a PVD coating. A basic precondition for such a deposition is the tool shape, where the speed of sintering of the upper layer of the tool (depth of 1 mm) is as low as possible to obtain minimal porosity. The surface has to be additionally hardened before the deposition, a shot-peening process is used to ensure the proper load capacity demanded for the deposition of brittle and hard coatings. The quality of the deposition can be investigated using a scratch test. The appearance of acoustic emission and the rapid increase in the scratching force when the coating starts to delaminate are a measure of the adhesion of the coating. As we can see from the SEM picture (Fig. 4), the CrN coating starts to delaminate at a scratch force of 65 N, which from the technological point of view indicates that adhesion of the coating is good enough.

A comparison of the characteristics of the CrN and TiAlN hard PVD coatings has shown that the adhesion of both coatings is comparable; however, the microhardness of the TiAlN is much higher. Therefore, the TiAlN prevailed as the best choice for the deposition of hard coatings on the laser-sintered tool.

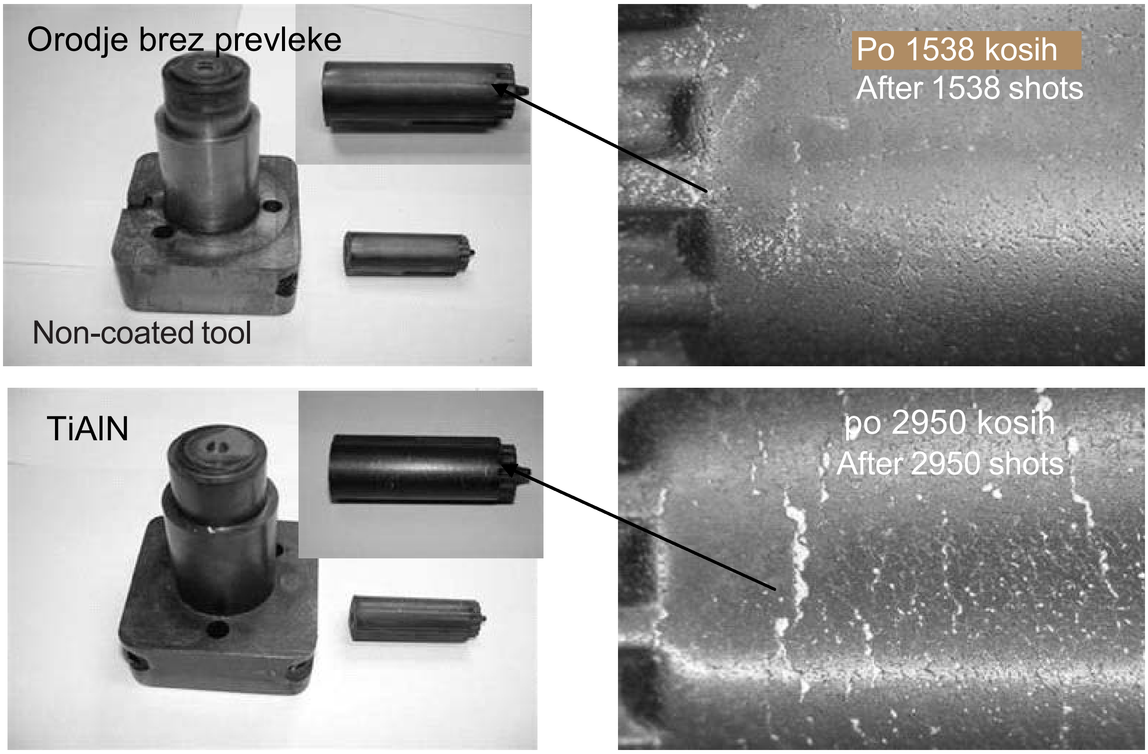
3 EXPERIMENTAL RESULTS AND DISCUSSION

The DMLS tool testing began at the industrial die-casting company in August 2005. A double-



Sl. 4. *Test razenja po nanosu prevleke iz kemijsko nanesenega niklja in trde prevleke PVD*

Fig. 4. *Scratch test after deposition of chemical nickel and the hard CrN coating*



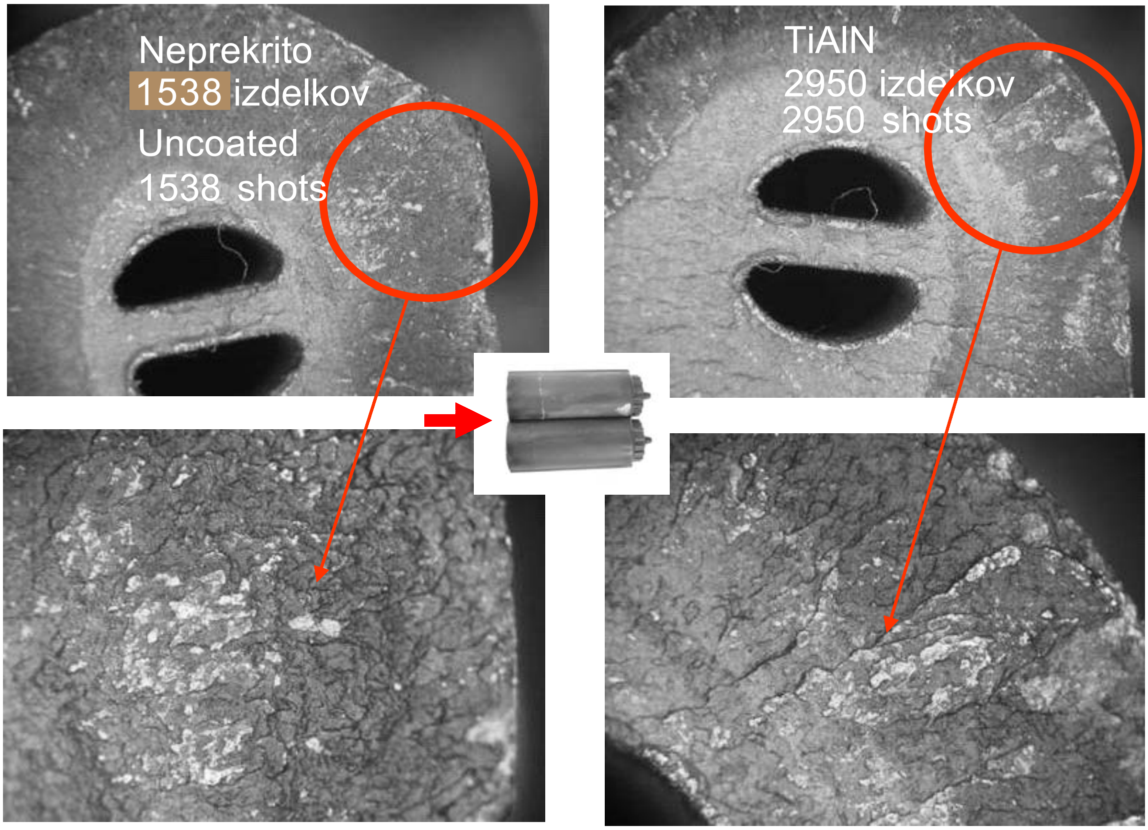
Sl. 5. *Stransko jedro – lom neprevlečenega in prevlečenega orodja*
Fig. 5. *Side cores – brakeage of the uncoated and coated tool*

dvognezdno orodje, vsako gnezdo je vsebovalo štiri sintrane vložke. Uporabili smo stroj za tlačno litje BÜHLER H-160B in standardni aluminij $AlSi_9Cu_3$. Prametri testiranja so bili naslednji: predgrevanje 130 do 215 °C, temperature litja 690 °C, tlak na vstopu taline 600 bar, čas trajanja litja 35 sekund, vsa predhodna opravila in predgrevanje orodja je bilo izvedeno glede na bogate izkušnje strokovnjakov s področja tlačnega litja. Obstojnostni kriterij je bil izbran v obliki loma orodja ali kot pojav prvih vidnih razpok na orodju. Preverjanje je bilo narejeno na podlagi optičnega opazovanja postopka litja in odlitih izdelkov. Ugotovljeno je bilo, da se je neprevlečeno daljše jedro orodja zlomilo pri 1538. brizgu, medtem ko je daljše, s TiAlN prevlečeno jedro zdržalo 2950 brizgov (sl. 5).

Glavni vzrok za lom stranskega jedra je bila upogibna sila na jedro, ki nastane med postopkom polnjenja orodja in ob sprostitvi pri odpiranju orodja. Mogoč vzrok za večjo obstojnost prevlečenega orodja je lahko v tem, da je bilo to orodje med vakuumskim postopkom nanašanja prevleke popuščeno na 450 °C. Primerjava optično-mikroskopskih posnetkov površine neprekritega in

cavity tool was chosen; each cavity was composed of four sintered inserts. A BÜHLER H-160B die-casting machine was used and standard $AlSi_9Cu_3$ aluminum material. The testing parameters were: preheating 130–215ºC, casting temperature 690ºC, melt pressure 600 bars cycle time 35 seconds, and all the preliminary tasks and the machine pre-heating and settings were carried in accordance with the experiences of die-casting specialists. A tool-life criterion has been chosen as a tool breakage or first significant signs of cracks. Therefore an optical observation of the casting process and the parts produced was made during the testing. It was found that the uncoated long side core of the tool broke during the 1538th injection; however, the TiAlN coated long side core withstood die-casting until the 2950th injection (Fig. 5).

The main reason for the breakage of the core was the bending forces during the filling cycle and the relaxation during the opening cycle of the tool. A possible reason for the longer tool life for the coated core could be the fact that during the vacuum-coating process at 450ºC a yielding process occurred. A comparison of the optical microscope photographs



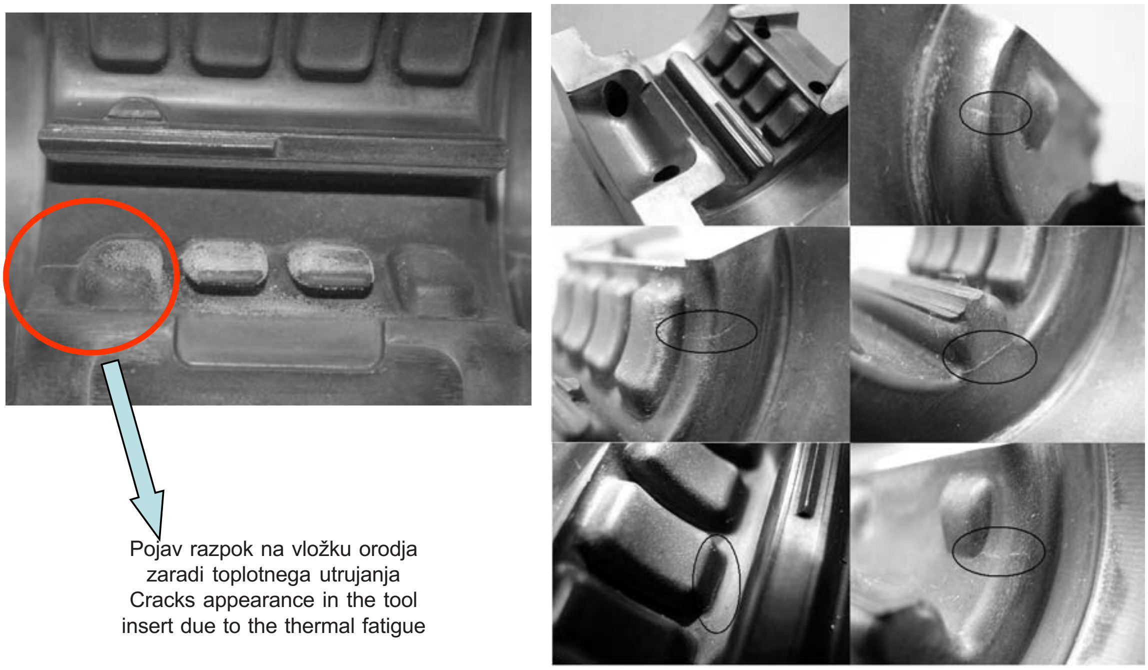
Sl. 6. *Stranska jedra – mehanska utrujenost*
Fig. 6. *Side cores – mechanical fatigue*

prekritega orodja kaže, da je poškodb na prekritem orodju bistveno manj (sl. 6). To pa pomeni, da prevleka izboljša toplotne in tribološke značilnosti vložkov orodij. Vendar pa je večji problem obstojnosti orodja v neustreznem razmerju med trdoto in žilavostjo materiala za izdelavo stranskih jeder (zaradi upogibne sile in posledične mehanske utrujenosti materiala).

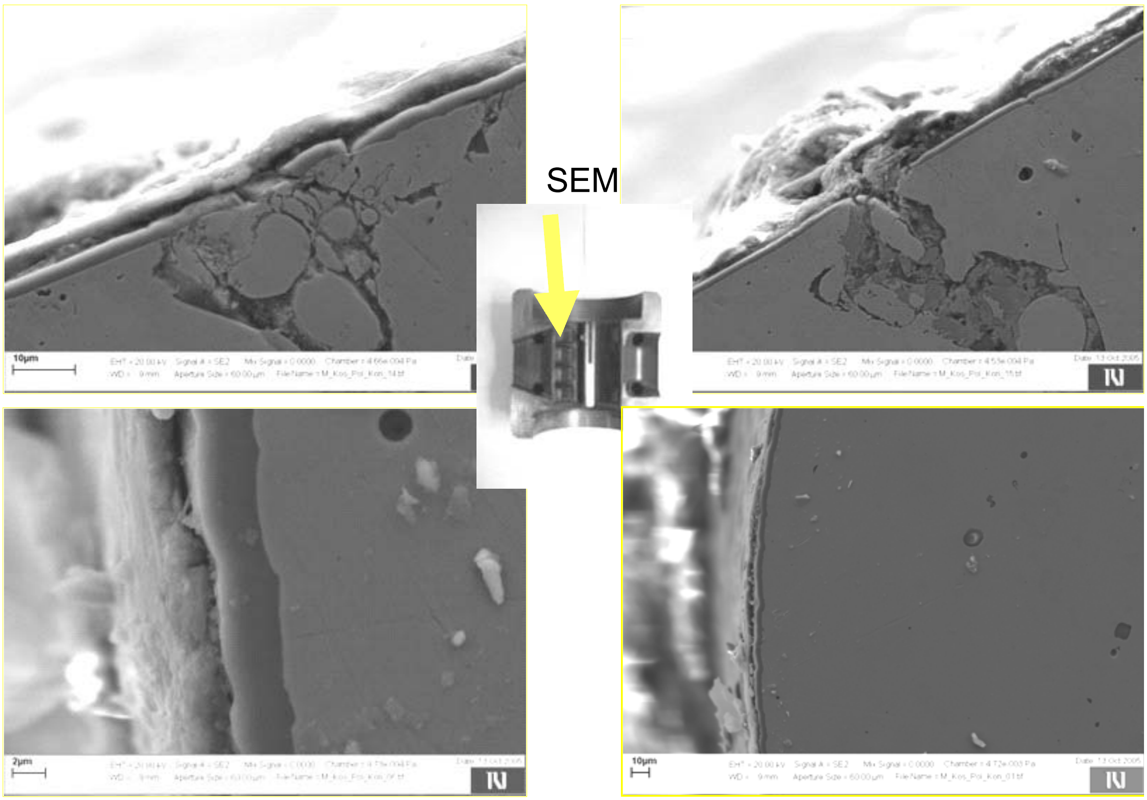
Po pregledovanju izdelkov so bile ugotovljene tudi nekatere vidne razpoke, nastajale so hkrati na obeh vložkih orodja in stranskih jedrih. Vzrok za nastanek razpok je v toplotni obremenitvi orodja (pojav je podoben kakor pri uporabi klasičnih orodij); makroskopske poškodbe in razpoke so vidne na sliki 7. Analiza z vrstično elektronsko mikroskopijo (SEM) toplotno najbolj obremenjenih delov orodja je tudi pokazala, da je prevleka še vedno nepoškodovana na celotni površini vložkov orodij, razen v področjih, kjer so določene poškodbe ali pore (sl. 8). Nekatere od teh so lahko že bile v orodju pred nanosom prevleke, nekatere pa so lahko posledica toplotnih

of the surfaces of un-coated and coated tools shows that there is less damage to the coated tool (Fig. 6). Coatings therefore improved the thermal and the tribological characteristics of the tool inserts; however, the main problem is a proper ratio for the hardness/toughness of the material for side cores (due to the bending forces and the consequent mechanical fatigue).

On basis of a visual inspection of the products it was also found that some cracks are already visible, and they appeared simultaneously in both inserts and side cores. The main problem of cracks is related to the thermal loads (a similar situation can also be found in classical steel materials); macroscopic defects and cracks in the structure are evident in Figure 7. An SEM (Scanning Electron Microscopy) analysis of the main thermally loaded parts of the tool has also shown that the coating still remains un-damaged over the whole surface of the tool, with the exception of the locations where some damage has occurred or pores are present (Fig. 8). Some of them may exist in the tool before the deposition; some of them can be the consequence of



Sl. 7. *Neprikrit vložek po končanem testiranju (po 2950 litih izdelkih)*
Fig. 7. *Uncoated insert at the end of the testing (2950 injections)*



Sl. 8. *Analiza SEM s TiAlN prekritega orodja po 2950 izdelanih kosih*
Fig. 8. *SEM analysis of the TiAlN coated tool after 2950 shots*

obremenitev. Meritve hrapavosti so prav tako pokazale, da površina orodja ni bila optimalno polirana, še posebej v področju kavitacij, ki jih je težko doseči.

Čeprav raziskovalni cilj – tlačno odliti 5.000 kosov v vsakem gnezdu orodja – ni bil dosežen, pa so rezultati vseeno zelo spodbudni. Glede na to, da je bilo testiranje končano, ko se je stransko jedro zlomilo, ne moremo vedeti, koliko dodatnih izdelkov bi bilo mogoče odliti. Po strokovnem pregledu orodja mnenje industrijskih strokovnjakov potrjuje, da je to vsekakor dosegljiva tehnološka meja, če bi izboljšali značilnosti materiala za izdelavo stranskih jeder. Kakorkoli, doslej ni bilo potrditve, da je mogoče NLSK ali druge metode za hitro izdelavo orodij tako uporabiti za uporabo tlačnega litja aluminija v majhnih serijah izdelkov.

5 SKLEP

Predstavljene raziskave in praktične rešitve so del rezultatov projekta Eureka, kjer je bil eden od najpomembnejših ciljev v prenosu temeljnega raziskovalnega znanja v industrijo, ki bodo ustrezale industrijskim zahtevam za prototipno orodje (za izdelavo tržnega izdelka) za tlačno litje aluminija. Na temelju eksperimentalne analize so bili predstavljeni obrabni pojavi in strukturne spremembe na orodju DMLS, pa tudi pričakovanja glede prihodnosti hitre izdelave orodij za potrebe industrije tlačnega litja aluminija.

Dokazano je bilo, da NLSK orodja lahko uporabimo za izdelavo najmanj 2950 tlačno litih kosov v industrijskem okolju, vendar obstaja problem žilavosti in trdote materiala ter posledičnega loma daljšega stranskega jedra. Pomembne so predvsem lastnosti sintranega prahu, zato mora biti razvoj usmerjen bolj na metalurške vidike, saj bomo lahko le tako zadostili zahtevam po izdelavi serijskih orodij za tlačna litja aluminija.

Začetni načrt je bil izdelati sintrano orodje za tlačno litje s strojem EOSINT M250 Xtended in uporabiti najnovejši material DirectSteel H20. Sedaj, dve leti po začetku projekta, ko je le ta v končni fazi, pa začetna izbira materiala in stroja ne predstavlja več najnovejših dosežkov na tem področju. To zato, ker je bil v tem obdobju narejen od EOS tako razvoj NLSK opreme in materiala. Nova zasnova stroja EOS M270 dandanes predstavlja najnovejše dosežke strojne opreme, prav tako so bili razviti novi materiali. Intenzivni razvoj materiala bo omogočal

the thermal loads. The roughness measurement also indicates that the surface of the tool has not been optimally polished, particularly for the cavities that are more difficult to reach.

Although the goal of 5,000 casting parts from each cavity was not achieved, the results are still very promising. As the tests of the tool ended when the coated side core was broken, we cannot say how many additional products could be produced. On the basis of after-tests professional tool examination, the opinion from the industrial experiences confirmed that this will be a reachable technological limit if some material characteristics for the side cores can be improved. However there is also no evidence that the DMLS or a similar rapid-tooling solution has been successfully until now applied for a small series of aluminum die-casting applications in such a way.

5 CONCLUSION

The presented research and the practical solution is part of a Eureka project, where the main goal is to transform basic scientific knowledge to applications that will meet industrial demands for building a prototype tool (on the basis of a practical marketable product) for the die-casting of aluminum. With an experimental analysis the wear and structural changes to the DMLS tool were presented, and the prospects of a rapid-tooling solution for the aluminum die-casting industry have been discussed.

It has been shown that we can use DMLS tools for producing 2950 die-casting parts in an industrial environment; however, there is a problem related to the toughness and the hardness of the material, and consequently the breakage of the movable core parts. Therefore the material properties play a more important role for die casting, and the development focus has to be even more on metallurgy to fulfill the serial tool requirements in aluminum die casting.

The initial plan was to produce the die casting tools with the EOSINT M250 Xtended machine using the current state-of-the-art material DirectSteel H20. Now, two years later, the project is in the final stage and the original selection of the material and machine does not quite represent the state-of-the-art status anymore. This is due to the development work done both in the DMLS hardware and the DMLS materials at EOS. Today, the new machine platform EOS M270 represents the state-of-the-art on the hardware side and new materials izdelavo novih izdelkov tudi na področju orodjarstva, ti bodo spremenili tako tehnične značilnosti orodij kakor tudi samo učinkovitost izdelave orodij.

Dodatni raziskovalni in razvojni rezultati projekta so: zasnova oblikovanja orodij za potrebe NLSK, znanje o postopku sintranja, izkušnje glede dodatne obdelave in ocena ekonomske upravičenosti. Najbolj zanimiv del orodja je stransko jedro, kjer so bili oblikovani notranji hladilni kanali. Tovrstne rešitve dajejo nove zanimive značilnosti, ki jih je mogoče doseči z uporabo laserskega sintranja. S takšnim načinom oblikovanja orodij in z uporabo svobode, ki jo omogoča tehnologija z dodajanjem materiala, bo mogoče najti mnogo boljše izdelovalne rešitve. Dolga jedra bo mogoče učinkoviteje hladiti, kar je zelo zanimivo za uporabo tlačnega litja. Na podlagi bogatih pridobljenih izkušenj opisanega industrijskega testiranja orodij obstajajo velike možnosti za nadaljevanje raziskav (kar je potrjeno od izdelovalca opreme in uporabnika rezultatov).

have also been released for this platform. Intensive material development work will result in the new product(s) also in the tooling areas, which will change not only the technical performance of the tools but also the cost efficiency of the tooling.

Additional research-and-development results are as follows: the tool design for the DMLS, the sintering know-how, the post-machining experiences, the economic justification. The most interesting part in the tool design was the core pin where an internal cooling channel was designed. These kinds of solutions are the most interesting features that can be used in laser sintered tool parts. By designing die casting tools in a modern way and by utilizing the freedom of additive manufacturing technology better solutions will become possible. Long cores and pins can be cooled more efficiently and this should be very interesting for die casting application. Therefore there is great potential for further research according to the rich experiences obtained on the basis of industrial testing (this was also confirmed by EOS-Finland and TCG Unitech).

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