K. J. Kerns
HA International, LLC, ZDA / US

Dokument ob srebrni obletnici združenja AFS Četrt stoletja sprememb na področju orodij in jeder za 3D-tiskanje: Razvoj postopka neposredne proizvodnje form za litje

AFS Silver Anniversary Paper A Quarter Century of Change in 3D Printing Molds and Cores: An Evolution from the Direct Shell Production Casting Process

Povzetek

Tehnologije aditivne proizvodnje so se pojavile pred več kot 25 leti s tehnologijo, znano kot neposredna proizvodnja form za litje (Direct Shell Production Casting – DSPC). Ta postopek omogoča izdelavo orodij z jedri in-situ za neposredno vlivanje delov skoraj brez izmeta. Razvoj inovacij je pri 3D-tiskanju jeder in orodij potekal hitro. V tem prispevku bo pregledan generacijski razvoj procesne tehnologije, aplikacij, materialov in hitrega uvajanja 3D-tiskanja v industriji litja kovin.

Ključne besede: aditivno, postopek DSPC, hitro prototipiranje, brizganje, 3D, pesek, tiskanje, litje kovin, ulitki skoraj brez izmeta, livarna

Abstract

Additive manufacturing technologies emerged over 25 years ago with a technology known as Direct Shell Production Casting (DSPC). This viable process produces molds with in-situ cores to pour castings directly into near-net shape parts. The evolution of innovation has taken a fast track in the 3D printing of cores and molds. This paper will review the generational developments in process technology, applications, materials, and rapid adoption of 3D printing in the metalcasting industry.

Keywords: additive, DSPC, rapid prototyping, jetting, 3D, sand, printing, metalcasting, near-net, foundry

1 Uvod

Aditivna proizvodnja (AM), znana tudi kot 3D-tiskanje s peščenih form (3DSP), hitro prototipiranje in neposredna digitalna proizvodnja (DDM), je proizvodni postopek, pri katerem se s 3D-tiskalnikom na kraju samem izdelajo peščena jedra, forme ali

1 Introduction

Additive Manufacturing (AM), also known as 3D Sand Printing (3DSP), Rapid Prototyping, and Direct Digital Manufacturing (DDM), is a manufacturing process that constructs sand

Avtorske pravice 2024 American Foundry Society /
2024 AFS Transactions ©American Foundry Society

forme z jedri. Koncept aditivne proizvodnje je korenito spremenil tradicionalne tehnike litja v pesek. Koncept se hitro razvija zaradi zahtev industrije ter naložb proizvajalcev originalne opreme (OEM) in njihovih partnerjev za povečanje velikosti, dimenzijskih zmogljivosti, hitrosti, procesnih zmogljivosti, naprednih materialov in stroškov uporabe.

Dr. Ely Sachs, pravi vizionar in pionir na področju 3D-tiskanja, je znan kot izumitelj tehnologije tiskanja z brizganjem veziva. Sachs se je leta 1986 pridružil fakulteti Massachusetts Institute of Technology (MIT) in hitro postal vodilni na področju hitrega prototipiranja, revolucionarnega koncepta 3D-tiskanja, in je zaslužen za nastanek izraza »3D-tiskanje«. Medtem ko se je 3D-tiskanje sprva uporabljalo predvsem za izdelavo modelov in vzorcev za izdelavo prototipov in testiranje, si je Sachs zamislil prihodnost, v kateri bodo 3D-tiskalniki lahko neposredno izdelovali funkcionalne dele. Ta vizija se je uresničila in danes se tehnologija 3D-tiskanja uporablja za različne namene, od izdelave medicinskih vsadkov do letalskih in vesoljskih komponent.

Tiskanje z brizganjem veziva, ki ga je izumil Sachs, je edinstvena tehnologija 3D-tiskanja, ki s tekočim vezivom selektivno veže delce prahu plast za plastjo in ustvari 3D-predmet. Ta tehnologija ima v primerjavi z drugimi metodami 3D-tiskanja več prednosti, med drugim:

- Hitro tiskanje z brizganjem veziva je ena od najhitrejših tehnologij 3D-tiskanja, ki so na voljo, zato je idealna za množično proizvodnjo.
- Vsestranskost – tiskanje z brizganjem veziva se lahko uporablja z različnimi materiali, vključno s kovinami, keramiko in polimeri.
- Stroškovna učinkovitost – tiskanje z brizganjem veziva je razmeroma cenovno ugodna tehnologija

cores, molds, or molds with core geome- try in-situ using a 3D printer. The AM concept has revolutionized traditional sand-casting techniques. It continues to evolve quickly due to industry demands and investments by Original Equipment Manufacturers (OEMs) and their partners to expand the size, dimensional capability, speed, process capability, material advancements, and cost of use.

Professor Ely Sachs, Ph.D., a true visionary and pioneer in the field of 3D printing, was known as the inventor of binder jet printing technology. Sachs joined the faculty of Massachusetts Institute of Technology (MIT) in 1986 and quickly became a leader in the field of rapid prototyping, revolutionizing the concept of 3D printing, and is credited with coining the term “3D printing.” While early 3D printing was primarily used for creating models and patterns for prototyping and testing, Sachs envisioned a future where 3D printers could produce functional parts directly. This vision became a reality, and today, 3D printing technology is used in a wide variety of applications, from creating medical implants to manufacturing aerospace components.

Binder jet printing, invented by Sachs, is a unique 3D printing technology that uses a liquid binding agent to selectively bind powder particles together, layer by layer, to create a 3D object. This technology offers several advantages over other 3D printing methods, including:

- High speed—binder jet printing is one of the fastest 3D printing technologies available, making it ideal for mass production.
- Versatility—binder jet printing can be used with a wide variety of materials, including metals, ceramics, and polymers.
- Cost-effectiveness—binder jet printing is a relatively inexpensive 3D printing technology, making it accessible to a wider range of users.

3D-tiskanja, zato je dostopna širšemu krogu uporabnikov.

2 3D-Tiskanje z brizganjem se najprej pojavi kot DSPC

Dr. Ely Sachs je s sodelavci na Tehnološkem inštitutu v Massachusettsu (MIT) v začetku 90. let prejšnjega stoletja razvil metodo brizganja veziva, ki je postala vsestranska proizvodna metoda, združljiva z različnimi materiali, vključno s kovinami, keramiko in peskom. V zgodnjih 90. letih prejšnjega stoletja je družba Soligen Technology, Inc. pridobila licenco za tehnologijo in razvila postopek DSPC (Direct Shell Production Casting) z uporabo ene same brizgalne tiskalne glave v stroju Alpha. Skupina uporabnikov, med katerimi so bili partnerji s področja letalske in vesoljske industrije, biomehanike, livarn, univerz in razvoja materialov, je oblikovala konzorcij, ki je pred zaprtjem podjetja konec devetdesetih let prejšnjega stoletja razvil beta različico postopka DSPC. Poznavalci tehnologije so postopek DSPC cenili kot napreden, vendar ga je trg sprejel počasi, zato je bilo težko vzdrževati njegov razvoj.

DSPC je bil postopek, pri katerem so se uporabljale geometrijske datoteke stereolitografije ali STL za izdelavo form, ki nadomešča livarsko modelarstvo in posredno kovinske izdelke majhnih serij. Staljeno kovino so vlili neposredno v keramično formo za litje, ki je vključevala livne sisteme. V postopku DSPC je bilo mogoče izdelati jedra, forme in forme z in situ jedri, kar pomeni, da so bila jedra del forme. S tem se je prihranil čas in izboljšala natančnost izdelanih delov.

V postopku DSPC se je uporabilo anorgansko koloidno vezivo in fini keramični prah. Vezivo se je z zeleno trdnostjo povezalo s keramičnim prahom, nato pa

2 3D Inkjet Printing First Emerges as DSPC

First developed in the early 1990s by Ely Sachs, Ph.D., and fellow researchers at MIT, binder jetting emerged as a versatile manufacturing method compatible with various materials, including metals, ceramics, and sand. In the early 1990s, Soligen Technology, Inc. licensed the technology and developed the Direct Shell Production Casting (DSPC) process using a single jetting printhead in their Alpha. A group of users, including aerospace, biomechanical, foundry, universities and material development partners created a consortium that developed a Beta version of the DSPC process before the company closed in the late 1990s. Those familiar with the technology revered the DSPC process as being ahead of its time, but it was slow to be adopted by the market, and it became difficult to sustain its development.

Direct Shell Production Casting (DSPC) was a process that used Stereolithography or STL geometric files to generate molds to replace tooling and indirect short-run metal parts. Molten metal was poured directly into a ceramic casting shell, which included the gating systems. DSPC could create cores, molds, and molds with in-situ cores, meaning that the cores were made integral, within the mold. This saved time and improved the accuracy of the produced parts.

DSPC used an inorganic colloidal binder and a fine ceramic powder. The binder used green strength to bond the ceramic powder together, followed by the printed bed of powder being placed in a kiln to calcine and transition the colloidal silica to an irreversible bond to set the printed geometry. DSPC molds were dimensionally stable, meaning that they retained their shape and size after firing and during casting. The unprinted material was removed and recycled to reduce waste. DSPC castings were a near-net shape, meaning that they required little machining se je natisnjena plast prahu postavila v peč, da se koloidni silicijev dioksid kalcinira in spremeni v nepovratno vez, s čimer se vzpostavi natisnjena geometrija. forme DSPC so bile dimenzijsko stabilne, kar pomeni, da so ohranile svojo obliko in velikost po žganju in med litjem. Nenatisnjen material je bil odstranjen in recikliran, s tem pa se je zmanjšala količina odpadkov. Ulitki DSPC so bili skoraj brez izmeta, kar pomeni, da jih je bilo treba po ulivanju le malo mehansko obdelati. Na splošno je postopek DSPC omogočil prvi vsestranski način za posredno izdelavo kovinskih delov majhnih serij brez livarskih modelov.

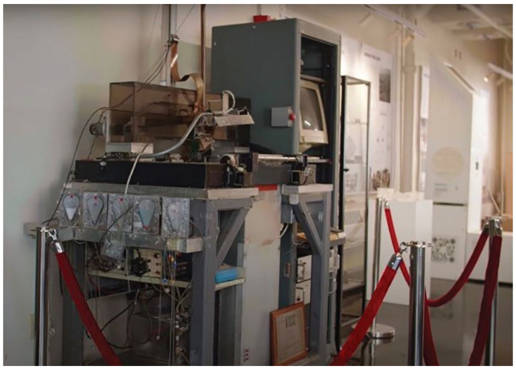
Slika 2. DSPC, stroj generacije beta in Yehoram Uziel, izvršni direktor in kreativni vodja družbe Soligen Technologies Inc.

Figure 2. DSPC, Soligen Technologies Inc.'s Beta generation machine, and CEO and creative Yehoram Uziel.

3 Potreba po 3D-tiskanju peščenih form - Tehnologija v proizvodnji pred četrt stoletja

V eni generaciji so se tehnologije hitrega prototipiranja uveljavile in začele uporabljati. Tri vrste tehnologij hitrega prototipiranja

after casting. Overall, the DSPC process supplied what could be considered the first versatile way to produce short-run metal parts indirectly without tooling.



Slika 1. »Stroj Alpha«, prvi »pravi stroj«, je bil razvit na univerzi MIT za 3D-tiskanje z brizganjem

Figure 1. The "Alpha machine," the first "real machine," was developed at MIT for 3D jet printing

3 Need for 3D Sand Printing - Technology lin Manufacturing a Quarter Century Ago

Within a generation, rapid prototyping technologies have become widely accepted and used. The three types of rapid prototyping technologies are subtractive, additive, and hybrid. These technologies present a valuable resource for making well-informed decisions in the planning, design, testing, and production of castings.

One of the key benefits of rapid prototyping is its use in advanced engineering technologies and concurrent design methodology. This allows for the effective execution of product solutions.

Looking back to the early days of rapid prototyping, managers and engineers had a vision of success but lacked the technology to achieve it. Successfully launching a new so subtraktivna, aditivna in hibridna. Te tehnologije so dragocen vir za sprejemanje premišljenih odločitev pri načrtovanju, oblikovanju, preskušanju in proizvodnji ulitkov.

Ena od ključnih prednosti hitrega prototipiranja je uporaba tega postopka v naprednih inženirskih tehnologijah in metodologiji sočasnega načrtovanja. To omogoča učinkovito izvedbo rešitev izdelkov.

Če se ozremo nazaj na začetke hitrega prototipiranja, so imeli vodje in inženirji vizijo, niso pa imeli tehnologije, s katero bi jo uresničili. Uspešna uvedba novega izdelka je bila odvisna od hitrih in učinkovitih metod razvoja izdelka ter prilagodljivih proizvodnih procesov.

Čas je bil bistvenega pomena, saj bi lahko že relativno kratke zamude povzročile izgubo tržnega deleža. Dr. David Cole s Prometnega inštituta Univerze v Michiganu je leta 1994 ocenil, da so ameriški proizvajalci avtomobilov v povprečju potrebovali 52 tednov za vzpostavitev koncepta avtomobila, medtem ko je konkurenca potrebovala 40 tednov. Dr. Cole je napovedal, da bo do leta 2003 dobavni rok ameriških proizvajalcev avtomobilov predvidoma 38 tednov oziroma 34 tednov pri konkurenci, s čimer se bo razlika zmanjšala. Dejal je še, da mora industrija za ponovno pridobitev konkurenčne prednosti skrajšati dobavne roke, izboljšati prodajo in storitve za stranke ter povečati ozaveščenost o tehnoloških spremembah in njihovem izvajanju v industrijskem okolju.

Paul Mikkola, ki je v času izdelave tega članka že uporabljal hitro izdelavo prototipov za izdelavo eksperimentalnih prototipov v oddelku za pogonske sklope koncerna GM, je dejal: »Da bi bili livarji konkurenčni, morajo postati agresivni in izdelovati ulitke skoraj končne oblike, ki zmanjšujejo ali odpravljajo strojno obdelavo. Hitra izdelava product depended on quick and efficient product development methods and flexible manufacturing processes.

Timing was essential, and even relatively short delays could result in a loss of market share. In 1994, Dr. David Cole, at the University of Michigan’s Transportation Institute, estimated that the average lead time for US automakers to introduce a concept car was 52 weeks, compared with the competition’s 40 weeks. Dr. Cole predicted that, by 2003, the U.S. automaker’s lead time was expected to be 38 weeks and 34 weeks, respectively, narrowing the gap. He further said that to regain the competitive advantage, the industry must reduce lead time, improve sales and service to the customer, and increase the awareness of technological change and its implementation of this technology in the industrial climate.

Paul Mikkola, who at the time of this original paper was already using rapid prototyping to produce experimental prototypes at GM’s Powertrain Division, said, “In order for foundrymen to be competitive, it is necessary to become aggressive and produce near-net shape castings that reduce or eliminate machining. Rapid prototyping has proven that it has the potential for accomplishing this goal for the automotive metalcasting industry.”[1]

Don Sabin, a design engineer for John Deere’s Product Engineering Center, Waterloo, Iowa, noted during this period, “Currently, the time required to introduce a new tractor to the market is almost five years. We would like to see this time reduced to less than three years and find out what rapid prototyping can do to reduce the ‘conceptualization-to-market introduction’ time span. There is a definite need for a fast way to produce functional prototypes that can be used for verification or as a pattern to produce a metal casting.”[2]

prototipov je dokazala, da ima potencial za dosego tega cilja v avtomobilski industriji kovinskih ulitkov.«[1]

Don Sabin, inženir za načrtovanje v John Deerejevem centru za inženiring izdelkov v Waterlooju v Iowi, je v tem obdobju ugotovil: »Trenutno je čas, potreben za uvedbo novega traktorja na trg, skoraj pet let. Želimo si, da bi se ta čas skrajšal na manj kot tri leta, in ugotoviti, kako lahko hitro prototipiranje pripomore k skrajšanju časa od konceptualizacije do uvedbe na trg. Obstaja velika potreba po hitrem načinu izdelave funkcionalnih prototipov, ki se lahko uporabijo za preverjanje ali kot vzorec za izdelavo kovinskega ulitka.«[2]

4 Hitro naprej na 3DSP za Ford Ecoboost

Proizvodnja glav valjev je zahteven postopek, saj je treba pri litju uporabiti od 12 do 20 jeder in komponent forme. Tradicionalni postopek je vključeval izdelavo livarskih modelov z obdelavo iz modelnih plošč in izdelavo peščenih form. Vendar je 3D-tiskanje peščenih form temeljito spremenilo proizvodnjo peščenih form za kovinske ulitke, saj ponuja veliko hitrost, prilagodljivost in stroškovne prednosti.

Paul Susalla, vodja oddelka za hitro proizvodnjo v Fordovi tovarni v Dearbornu v Michiganu, pravi: »Izdelava vseh orodij bi trajala več mesecev in zahtevala veliko denarja. Poleg tega je nekatera jedra zelo težko izdelati. Zdaj, ko uporabljamo 3D-tiskanje, je treba le dobiti datoteko, jo dati v stroj in dobiti enaka jedra,« pravi. »Pri tem nista potrebna opremljanje z orodjem in čas.«[4]

Najpomembnejša prednost 3D-tiskanja peščenih form je hitrost. »Če pogledamo tradicionalni način izdelave ulitka, je treba počakati več mesecev, preden dobimo prvi

4 Fast Forward 3DSP for Ford Ecoboost

Manufacturing cylinder heads is challenging, requiring 12 to 20 cores and mold components to be sand-cast. Traditionally, the process involved making patterns by machining them from tooling boards and packing foundry sand in the mold. However, 3D sand printing has revolutionized the production of sand molds for metal castings, offering significant speed, flexibility, and cost advantages.

At Ford, Paul Susalla, Section Supervisor of Rapid Manufacturing at the Dearborn, Michigan facility, says, “Creating all the tooling would take months and a lot of money. Plus, some of these cores are extremely tough to make. Now, when using 3D printing, it is just a matter of getting a file, putting it through the machine, and coming out with the same cores,” he says. “There is no tooling, no time involved.”[4]

The most significant benefit of 3D sand printing is its speed. “In a nutshell, if you look at the traditional way of making a casting, you are months out before you get your first casting, and with 3D sand printing, you can have a casting in a matter of days to a couple of weeks,” Susalla says. He explains that if you are using tooling, it might be four months before you get your first part and realize that it is not what you want, then the tooling must be changed. “If you look at the product development cycle, Ford, GM, and Chrysler only give you x number of months to years to put it on paper and then get it on the street,” he says. “As an engineer, you only have a certain amount of time to get your part right. The traditional method might give you only three shots at getting the part right, but 3D sand printing allows you to create multiple iterations simultaneously because you are not committed to tooling.”

ulitek, s 3D-tiskanjem peščenih form pa lahko ulitek dobimo v nekaj dneh do nekaj tednih,« pravi Susalla. Pojasnjuje, da lahko z livarskim modelom traja štiri mesece, preden dobite prvi del in ugotovite, da ni ustrezen, nato pa morate model zamenjati. »Če pogledate razvojni cikel izdelka, vam Ford, GM in Chrysler dajo na voljo le x mesecev ali let, da ga pripravite na papirju in nato predstavite na cesti,« pravi. »Kot inženir imaš na voljo le določen čas, da narediš svoj del pravilno. S tradicionalno metodo lahko naredite le tri poskuse, da bi del izdelali pravilno, 3D-tiskanje peščenih form pa vam omogoča hkratno izdelavo več iteracij, saj niste vezani na livarski model.«

Susalla pravi, da je namesto ene zasnove ulitka takoj na voljo pet do šest zasnov. V nekaj tednih je mogoče oceniti teh pet ali šest zasnov, sprejeti nekaj inženirskih odločitev in pripraviti spremembe ali celo novo zasnovo ulitka za oceno. Zato pravi, da imate pri 3D-tiskanju peščenih form veliko možnosti za optimizacijo zasnove z vidika kakovosti, stroškov, časa, varčevanja z gorivom, zmogljivosti in varnosti.

Druga znana prednost 3D-tiskanja peščenih form je, da odpravlja tradicionalne omejitve pri načrtovanju ulitka. »Nekaj lahko naredite tako, kot si želite, da bi bilo zasnovano, in tako, kot je možno izdelati,« pravi Susalla.

Vendar pa ugotavlja, da je pri Fordovi izdelavi glave valja orodje oblikovano enako kot v proizvodnji – z livarskimi nagibi in delilnimi ravninami – tako da testni ulitek predstavlja tisto, kar bo nastalo v proizvodnem procesu.

Izdelava prototipov na podlagi CAD ima v primerjavi z običajnimi prototipi z računalniškim numeričnim krmiljenjem (CNC) številne prednosti. Te prednosti lahko skrajšajo čas inženirskega projektiranja kosa in zmanjšajo stroške zaradi nepotrebnih sprememb proizvodnega

According to Susalla, instead of one design, you are looking at five to six designs right off the bat. Then, within a matter of weeks, you can have already evaluated those five or six designs, made some engineering decisions, and produced alterations or even innovative designs to evaluate. So, with 3D sand printing, he says you have plenty of opportunities to optimize the design for quality, cost, time, fuel economy, performance, and safety.

Another known benefit of 3D sand printing is that it eliminates traditional design limitations. “You can make something the way it wants to be designed versus how it can be manufactured,” Susalla says.

He notes, however, that when Ford makes a cylinder head, the mold is shaped the same as it will be in production—with draft angles and parting lines—so that the test part represents what will be coming out of the production process.

There are many advantages to producing CAD-based prototypes over conventional computer numeric control (CNC) prototypes. These advantages can reduce engineering part design time and minimize costs due to unnecessary changes to the production tooling. Design and manufacturing engineers have always faced tough questions about whether to build a prototype to ensure understanding or go directly to tooling based on a solid model or simulation alone, expecting to save time and cost. Rapid prototyping tools can provide key technical observations and peace of mind. Whether a printed prototype or a casting produced using a 3D printed sand mold with in-situ cores, rapid prototyping intends to obtain greater knowledge to evaluate product form, fit, and functional performance earlier in the development cycle.

orodja oz. livarskega modela. Inženirji, ki se ukvarjajo s projektiranjem in proizvodnjo, so se vedno soočali z zahtevnimi vprašanji, ali naj izdelajo prototip, da bi zagotovili razumevanje, ali pa se neposredno lotijo izdelave livarskega modela samo na podlagi končnega kosa ali samo na podlagi simulacije in s tem prihranijo čas in stroške. Orodja za hitro prototipiranje lahko zagotovijo ključne tehnične ugotovitve in varnost. Ne glede na to, ali gre za natisnjen prototip ali ulitek, izdelan s 3D-tiskanim peščenimi formami z in-situ jedri, je namen hitrega prototipiranja pridobiti več znanja za oceno oblike, prileganja in funkcionalne učinkovitosti izdelka na začetku razvojnega cikla.

5 Vidik livarske modelarne

Številne livarske modelarne še vedno uporabljajo tradicionalne metode izdelave modelov, čeprav te postajajo vse bolj problematične. V članku o spremembah v industriji modeliranja so bile opredeljene naslednje kritične težave:

- Povečana raven ročnega dela in dodelave predstavlja pomembno ozko grlo pri proizvodnji velikih serij natančnih modelov in orodij. Za izvedbo ključnih elementov je potrebnega preveč časa.
- Izginjajoče veščine – povprečna starost livarskih modelarjev v ZDA je 58 let. Zaradi dolgega obdobja vajeništva, ki je potrebno za usposabljanje novih modelarjev, v industriji primanjkuje znanj in izkušenj za izpolnjevanje strogih zahtev današnjih konkurenčnih livarn.
- Manjše tolerance in večja natančnost – livarne se usmerjajo v litje skoraj končne oblike, ki zahteva manjše tolerance od tistih, ki se pričakujejo pri strojni obdelavi. Včasih je bila

5 Pattern Shop Perspective

Many pattern shops are still content with traditional patternmaking methods, but these methods are increasingly problematic. An article on changes in the patternmaking industry identified the following critical problems:

- Elevated levels of handwork—finishing operations constitute a significant bottleneck for high-volume production of precision patterns and molds. Too much time is spent finishing critical features.
- Disappearing skills—the average age of patternmakers in the US is fifty-eight. The long apprenticeship needed to train new patternmakers means that the industry lacks the skills and experience to meet the stringent requirements of today’s competitive foundries.
- Tighter tolerances and greater accuracy—foundries are moving toward near-net shape casting, which requires tighter tolerances than those expected in machining. While 0.060 inches was once good enough, 0.005 inches is now the standard tolerance, and some customers demand 0.002 inches or better.

The identified challenges are all interrelated. For example, the elevated levels of handwork and disappearing skills make it difficult for pattern shops to meet the tighter tolerances and greater accuracy demanded by foundries. Traditional prototyping and subsequent patternmaking methods have become increasingly inadequate to meet the demands of modern manufacturing. Pattern shops and foundries wanting to remain competitive must embrace modern AM technologies and develop new skills to utilize them effectively.

dovolj velika toleranca 1,52 mm, zdaj pa je standardna toleranca 0,13 mm, nekatere stranke pa zahtevajo celo 0,05 mm ali manj.

Vsi izzivi so medsebojno povezani. Na primer, zaradi večjega obsega ročnega dela in izginjajočih spretnosti modelarne težko izpolnjujejo strožje tolerance in večjo natančnost, ki jih zahtevajo livarne. Tradicionalne metode prototipiranja in naknadnega modeliranja so postale vse manj primerne za izpolnjevanje zahtev sodobne proizvodnje. Modelarne in livarne, ki želijo ostati konkurenčne, morajo sprejeti sodobne tehnologije aditivne proizvodnje in razviti nova znanja za njihovo učinkovito uporabo.

6 Razvoj iz procesa DSPC

Brizganje veziva je vsestranska tehnologija aditivne proizvodnje, ki so jo raziskovalci na tehnološkem inštitutu v Massachusettsu razvili v zgodnjih devetdesetih letih prejšnjega stoletja. Družba Extrude Hone je leta 1996 pridobila ekskluzivno licenco za komercialni razvoj postopkov 3D-tiskanja z brizganjem, ki so jih izumili na MIT za uporabo s kovinskimi, keramičnimi in peščenimi materiali. ExOne, vodilni ponudnik 3D-tiskalnikov z brizganjem veziva, je bil ustanovljen leta 1995 kot oddelek »ProMetal« podjetja Extrude Hone z namenom razvoja 3D-tiskalnikov za kovine. Ime ExOne izhaja iz imena podjetja Extrude Hone. Postopek se včasih imenuje »posredno« 3D-tiskanje, tiskanje orodij in tiskanje form, ker se natisnjeni predmeti uporabijo za izdelavo končnega izdelanega predmeta.

6 Evolution from DSPC Process

Binder jetting is a versatile additive manufacturing technology that MIT researchers developed in the early 1990s. In 1996, Extrude Hone obtained an exclusive license to commercially develop inkjet 3D printing processes invented at MIT for use with metal, ceramic, and sand materials. ExOne, a leading provider of binder jet 3D printers, was founded in 1995 as the “ProMetal” division of Extrude Hone with the mission of developing metal 3D printers. The name ExOne was derived from the Extrude Hone Company. The process is sometimes called “indirect” 3D printing, printed tooling, and mold printing because the printed objects are used to create the final manufactured object.

Slika 3. Tiskalnik za peščene forme ExOne S-Max

Figure 3. The ExOne S-Max sand printer

Slika 4. 3D-tiskalnik za peščene forme voxeljet VX 2000

Figure 4. A voxeljet VX 2000 3D sand printer

Tudi na področju 3DSP se je leta 1995 na Tehnični univerzi v Münchnu rodilo zagonsko podjetje »voxeljet«. Leta 1998 so pridobili prve patente in istega leta vstopili na trg 3DSP. Svoj prvi tiskalnik za peščene forme so leta 2002 poslali družbi BMW.

V naslednjih letih sta obe podjetji pomembno prispevali k razvoju trga na področju materialov za tiskalnike, hitrosti, natančnosti in velikosti strojev. Obe podjetji sta sprejeli koncept neprekinjenega delovanja tehnologije 3D-tiskanja, ki omogoča, da se stroškovno učinkoviti procesni koraki izdelave in razpakiranja izvajajo vzporedno, ne da bi se prekinilo delovanje celotnega sistema.

Napredek na področju opreme za brizganje veziva in nadzora procesov je povzročil revolucijo v tehnologiji aditivne proizvodnje, saj omogoča izdelavo kakovostnejših delov, povečuje učinkovitost proizvodnje in širi možnosti uporabe materialov.

Stroji za brizganje veziva so v zadnjih letih doživeli velik napredek, saj so opremljeni s tiskalnimi glavami, ki lahko kapljice veziva nanašajo z natančnim nadzorom in visoko ločljivostjo. Zaradi te prilagodljivosti različnim formulacijam veziv so nastali deli z vrhunsko obdelano površino, ločljivostjo in mehanskimi lastnostmi.

Napredni sistemi za nanašanje plasti peska in brizganje veziva ustvarjajo enakomerne in konsistentne plasti, kar izboljša kakovost in dimenzijsko natančnost natisnjenih delov. Ti sistemi zmanjšujejo aglomeracijo prahu, zamašitve in neenakomerno razpršitev veziva, kar zagotavlja, da je vsaka plast nanesena z želeno debelino in enakomernostjo.

Oprema za brizganje veziva zdaj vključuje napredne senzorje, kamere in programsko opremo, ki zagotavljajo spremljanje in nadzor tiskanja v realnem času. To omogoča odkrivanje in odpravljanje

Also, on the 3DSP front, “voxeljet” was born as a start- up from the Technical University of Munich in 1995. In 1998, they gained their first patents, entering the 3DSP market of the same year. They shipped their first sand printer in 2002 to BMW.

In the following years, both companies pioneered significant contributions to the market in printer materials, speed, accuracy, and build envelope size. Both companies have crossed the threshold to continuously operating 3D printing technology that allows cost-effective building and unpacking process steps to run in parallel without interrupting the entire system’s operation.

Advancements in binder jetting equipment and process control have revolutionized this additive manufacturing technology, enabling the production of higher-quality parts, increasing production efficiency, and expanding material options.

Binder jetting machines have advanced significantly in recent years, with print heads that can deposit binder droplets with precise control and high resolution. This adaptability to various binder formulations has produced parts with superior surface finish, resolution, and mechanical properties.

Advanced powder handling and recoating systems create uniform and consistent powder layers, which improve part quality and dimensional accuracy. These systems minimize powder agglomeration, clogging, and uneven spreading, ensuring each layer is deposited with the desired thickness and uniformity.

Binder jetting equipment now includes advanced sensors, cameras, and software enabling real-time printing monitoring and control. This allows for detecting and correcting potential issues, such as powder bed irregularities, binder saturation levels, and temperature fluctuations. This ensures that the process remains stable and consistent throughout the build, resulting in parts with improved dimensional accuracy, surface finish, and mechanical properties.

morebitnih težav, kot so nepravilnosti plasti peska, stopnje nasičenosti veziva in temperaturna nihanja. Tako je postopek stabilen in dosleden ves čas izdelave, rezultat pa so natisnjeni deli z izboljšano dimenzijsko natančnostjo, kakovostjo površine in mehanskimi lastnostmi.

7 Razvoj tehnologij veziv

Medtem ko je postopek DSPC uporabljal koloidno anorgansko vezivo in fini keramični prah, je k uspehu sodobnih sistemov 3DSP prispevalo tudi več dosežkov na področju materialov.

V raziskavi, ki je potekala na Univerzi Severne Iowe, je bila uporabljena pridobljena tehnologija, vključno s tiskalniki za peščene forme ExOne S-Max, voxeljet VX1000 ter Tinker-Omega alpha in beta, da bi zagotovili dragocene povratne informacije dobaviteljem smol, aktivatorjev, čistil, ognjevarnih premazov, modifikatorjev peska in materiala za tiskalno podlago. V okviru tekočih skupnih raziskav so bili pridobljeni novi materiali za postopek brizganja veziva, ki omogoča izdelavo visokokakovostnih delov z minimalno naknadno obdelavo in hitro odstranitvijo delov iz orodja, ter več kot petindvajset domačih virov kremenčevega in cirkonskega, keramičnega in kromitnega specialnega peska v sodelovanju s tržno dobavno verigo za postopek 3D-tiskanja s peščenimi kalupi. Raziskava je bila del projektnega razpisa partnerstva America Makes, katerega cilj je bil povečati uporabo 3D-tiskanja peščenih form v livarski industriji.

Brizganje veziva je vrsta aditivne proizvodnje, ki se vse pogosteje uporablja za izdelavo peščenih jeder in form. Pri tem se reaktivna smola, običajno vezivo na osnovi furfuril alkohola (FA), nanaša na podlago, kot je kremenčev pesek, predhodno obdelano

7 Evolution of Binder Technologies

While the DSPC process utilized a colloidal inorganic binder and fine powder ceramic, the success of modern 3DSP systems has also benefited from several developments in materials.

Research conducted with the University of Northern Iowa utilized acquired technology, including the ExOne S-Max, voxeljet VX1000, and Tinker-Omega alpha and beta sand printers, to provide valuable feedback to the suppliers for resin, activators, cleaners, refractory coatings, sand modifiers, and print bed material. The ongoing collaborative research has yielded new materials for the binder jetting process that produces high-quality parts with minimal post-processing and fast part extraction and over twenty-five domestic sources of silica and zircon, ceramic, and chromite specialty sand in collaboration with the market supply chain for the 3D sand printing process. The research was part of an America Makes project call to increase the adoption of 3D sand printing in the foundry industry.

Binder jetting is a type of additive manufacturing that is increasingly used to create sand cores and molds. It does this by depositing a reactive resin, typically a furfuryl alcohol-based (FA) binder, onto a substrate, such as silica sand, pretreated with an acid catalyst. Other aggregates used in metal casting, such as zircon, chromite, and synthetic ceramics, can also be used as the substrate.

Binder jetting uses a furfuryl alcohol-based (FA) binder like the more common furan nobake binder. The FA binder cures when it contacts a sulfonic acid catalyst, such as toluene sulfonic acid in water.

The binder jetting process begins with a layer of pre-treated substrate, such as silica sand, spread evenly across a build box.

s kislinskim katalizatorjem. Za litje kovin se lahko uporabljajo tudi drugi ognjevzdržni materiali, kot so cirkonij, kromit in sintetična keramika.

Pri brizganju veziva se uporablja vezivo na osnovi furfuril alkohola (FA), npr. uveljavljen vezivni sistem nobake. Vezivo FA se strdi, ko pride v stik s katalizatorjem s sulfonsko kislino, kot je toluen sulfonska kislina v vodi.

Postopek brizganja veziva se začne s plastjo predhodno obdelane podlage, kot je kremenčev pesek, ki se enakomerno razporedi po delovni komori. Velikost delovne komore je lahko od 300 × 200 × 150 mm do 4000 × 2000 × 1000 mm. Debelina predhodno obdelane podlage je navadno približno 0,3 mm.

Tiskalna glava nato brizga reaktivno vezivo na plast peska. Tiskalna glava uporablja podobno tehnologijo kot standardni brizgalni tiskalniki, vendar vezivo nanese v posebnem vzorcu, da ustvari želeno geometrijo dela. Ta postopek se ponavlja, dokler ni izdelan celoten del.

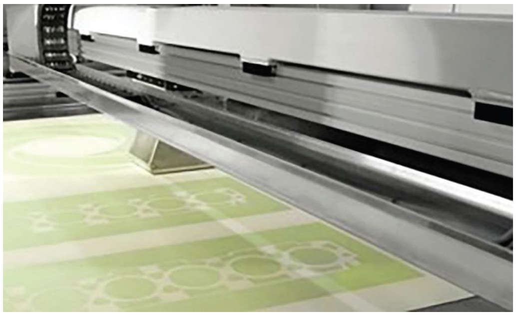
Delovna komora vsebuje vezani in nevezani pesek. Po končanem postopku tiskanja je odstranjevanje oblikovanih jeder iz delovne komore lahko zamudno in težavno. S strjenimi oblikami je treba ravnati previdno, nevezani pesek pa je treba skrbno odstraniti z dela s krtačenjem ali sesanjem. Opozoriti je treba, da se lahko reaktivno vezivo na furanski bazi oddalji od želene geometrije in se strdi, pri čemer nastane »lepljiv« pesek, ki ga je težje odstraniti z dela, zlasti v primerjavi s popolnoma nestrjenim peskom.

Medtem ko so vezivni sistemi na osnovi furfuril alkohola in kislin najpogosteje uporabljena fenolna veziva, so zaradi svoje trdnosti v vročem in možnosti naknadne obdelave z odstranjevanjem peska vse bolj priljubljeni dvokomponentni vezivni sistemi z utrjevanjem v hladnem in enokomponentni

Build boxes can range in size from 300 × 200 × 150 mm to 4000 × 2000 × 1000 mm. The thickness of the pre-treated substrate is typically around 0.3 mm.

Slika 5. Tiskalna glava brizga vezivo na osnovi furfuril alkohola

Figure 5. Printhead jetting furfural alcohol-based binder



Slika 6. Delovna komora z natisnjenimi jedri utrjenimi s furfuril alkoholom in neutrjenim peskom prevlečenim z aktivatorjem

Figure 6. Printed bed with cured furfuryl-alcohol printed cores and activator-coated but unprinted sand.

A print head then jets the reactive binder onto the sand layer. The print head uses technology similar to standard inkjet printers but deposits the binder in a specific pattern to create the desired part geometry. This process is repeated until the entire part is built.

The build box contains both bonded and unbonded sand. After the printing process is complete, removing the core shapes from vezivni sistemi z utrjevanjem v vročem. Tudi anorganski sistemi postajajo izvedljivi.

Glavna veziva so posebna furanska veziva za brizganje. Ta veziva morajo imeti posebne fizikalne in kemične lastnosti, kot sta dinamična viskoznost in površinska napetost, da lahko uspešno delujejo v postopku brizganja. Za brizganje veziva je potrebno vezivo z nizko dinamično viskoznostjo, da ga je možno zlahka brizgati skozi tiskalno glavo. Vezivo mora imeti tudi nizko površinsko napetost, da se enakomerno razporedi po plasti peska. Posebna furanska veziva za brizganje so bila skrbno oblikovana, da izpolnjujejo te zahteve. To zagotavlja natančno brizganje veziv, optimizacijo življenjske dobe tiskalne glave ter izdelavo visokokakovostnih jeder in orodij.

Ekonomska upravičenost 3D-tiskanja peščenih form je odvisna od produktivnosti in hitrosti odstranitve delov. Z drugimi besedami, jedra in orodja je treba natisniti hitro, vendar je pomembno tudi, da se jih hitro odstrani iz delovne komore, da se lahko začne naslednji postopek tiskanja. Raziskovalci in inženirji si prizadevajo izboljšati postopek brizganja veziv na več načinov, kar vključuje:

- Zmanjšanje migracije smole – pomagalo bo izboljšati kakovost natisnjenih delov in zmanjšalo količino potrebne naknadne obdelave.
- Izboljšanje preglednosti delov – tako boste lažje pregledali natisnjene dele in ugotovili morebitne napake.
- Pravilna hitrost (Speeding par)
- Ekstrakcija – povečala bo produktivnost postopka brizganja veziva, ki bo tako postal stroškovno učinkovitejši.
- Manjši vpliv na okolje – okolju prijazna, biološko razgradljiva veziva lahko pomagajo zmanjšati vpliv postopkov brizganja veziva na okolje.
- Močnejši deli z manj napakami –

the build space can be time-consuming and difficult. The cured shapes must be handled carefully, and the unbonded sand must be carefully brushed or vacuumed away from the part. It should be noted that the reactive furan binder can migrate away from the desired geometry and cure, creating “sticky” sand that can be more difficult to remove from the part, especially compared to fully uncured sand.

While the furfuryl alcohol-based binder/acid systems are the most used phenolic type binders, 2-part cold curing and 1-part heat curing systems are gaining popularity due to their hot strength and post-processing desandability. Inorganic systems are also becoming viable.

The primary binders developed are specialized furan binders for binder jetting. These binders must have specific physical and chemical properties, such as dynamic viscosity and surface tension, to work successfully in the jetting process. Binder jetting requires a binder that has a low dynamic viscosity so that it can be easily jetted through the print head. The binder must also have a low surface tension to spread evenly on the sand layer. Specialized furan binders for binder jetting have been carefully formulated to meet these requirements. This ensures that the binders can be jetted accurately, optimize the life of the printhead, and produce high-quality cores and molds.

The economic viability of 3D sand printing depends on both productivity and the speed of part extraction. In other words, it is essential to print cores and molds quickly, but removing them from the build box is also important so that the next print can begin. Researchers and engineers are working to improve the binder jetting process in several ways, including:

- Reducing resin migration—this will help improve the printed parts’ quality and z izboljšanimi vezivi lahko dobite vitalnejše dele z manj napakami, kar je ključnega pomena za številna področja uporabe.

8 Aditivna proizvodnja: Naslednja raven konkurenčne prednosti

Morda je trajalo četrt stoletja, da smo prišli do točke, ko so se livarske modelarne in livarne v celoti vključile v aditivno 3D-tiskanje peščenih form. Vendar pa mnogi menijo, da je aditivna (3D) proizvodnja sodobna tehnološka inovacija in v tem kontekstu neizogibna. Uporablja se predvsem za tiskanje plastike in kovin, vendar se vse bolj uveljavlja v industriji litja kovin za tiskanje peščenih jeder in form.

Prehod na 3D-tiskanje peščenih form in prevzem posrednega 3D-tiskanja peščenih form je potekal hitreje kot na drugih trgih 3D-tiskanja, npr. tiskanja kovin, verjetno zato, ker so končni postopek litja kovin in lastnosti litja že znani in sprejemljivi večini inženirjev ali livarjev.Uporaba tehnologije tiskanja 3DSP za izdelavo končnih ulitkov je vse pogostejša, zlasti za visoko specializirane dele in dele majhnih serij.

Leta 1996 je podjetje Extrude Hone od Tehnološkega inštituta v Massachusetts pridobilo licenco za komercialni razvoj 3D-tiskanja z brizganjem za uporabo s kovino, keramiko in peskom. Leta 2002 je podjetje na trgu predstavilo svoj prvi tiskalnik za izdelavo peščenih form in jeder za litje kovin. V naslednjih letih so se podjetja in postopek 3D-tiskanja peščenih form hitro razvijali, tehnologija pa je pridobivala funkcionalne zmogljivosti in zaupanje uporabnikov.

V letu 2014 se je trg litja kovin okrepil z zgodnjimi uporabniki, ki so bili ključni pri izpopolnjevanju tehnologije in materialov za optimalno delovanje in stroškovno

reduce the amount of post-processing needed.

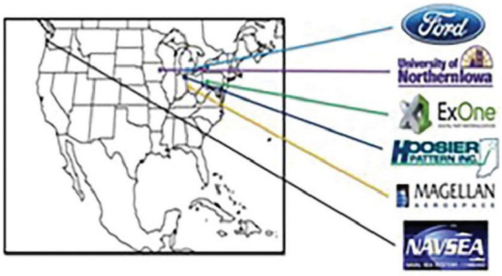
- Improving part clarity—this will make it easier to inspect the printed parts and identify any defects.
- Speeding par
- Extraction—this will increase the productivity of the binder jetting process and make it more cost-effective.
- Reduced environmental impact—environmentally friendly, biodegradable binders can help to reduce the environmental impact of binder jetting processes.
- Stronger parts with fewer defects—improved binders can lead to more vital parts with fewer defects, which is critical for many applications.

8 Additive Manufacturing: The Next Frontier of Competitive Advantage

It may have taken a quarter century to reach the point that pattern shops and foundries fully engage in additive 3D printing of sand. However, many people think of additive (3D) manufacturing as a modern innovation of technology, and in this context, it is inevitable. It has been used primarily for printing plastics and metals but has become more prevalent in the metalcasting industry for printing sand cores and molds.

The move into sand 3D printing and the adoption of indirect sand 3D printing has moved faster than other 3D printing markets, i.e., metal printing, likely because the final metal casting process and casting properties are already familiar and acceptable to most engineers or metal casters. Utilizing 3DSP printing to produce finished castings is growing, especially for highly specialized and low-volume parts.

In 1996, Extrude Hone obtained a license from MIT to commercially develop učinkovitost. Z uvedbo teh naprednih platform lahko livarne zdaj uporabljajo tehnologijo iz prve roke, bodisi z naložbami v svojo opremo bodisi z naročanjem peščenih form in jeder pri specializiranih ponudnikih storitev.



Slika 7. Prvi uporabniki 3D-tiskalnikov za peščene forme, nameščenih leta 2014. (Z dovoljenjem podjetja America Makes, Lamoncha.)

Figure 7. Early adopters of 3D sand printers installed in 2014. (Courtesy of America Makes, Lamoncha.)

Severnoameriška livarska industrija doživlja revolucijo, ki jo poganja hitro uvajanje tehnologije 3D-tiskanja peščenih form. V zadnjih osmih letih se je baza uporabnikov razširila in v Severni Ameriki je nameščenih že več kot 100 strojev. Ta porast je posledica več dejavnikov:

- Nove tehnologije – napredek na področju strojne opreme in materialov za 3D-tiskanje peščenih form je omogočil hitrejši, učinkovitejši in stroškovno učinkovitejši postopek, kar odpira vrata za širšo uporabo.
- Večja ozaveščenost – ker so prednosti 3D-tiskanja peščenih form vse bolj očitne, livarne, livarske modelarne in jedrarne prepoznavajo njegov potencial za racionalizacijo delovnih postopkov, zmanjšanje odpadkov in večjo prilagodljivost načrtovanja.

3D inkjet printing for use with metal, ceramic, and sand. In 2002, the company introduced its first printer to the market, producing sand molds and metal casting cores. In the several years that followed, companies and the 3D sand printing process evolved rapidly, with the technology gaining functional capability and user confidence.

In 2014, the metalcasting market matured through early adopters who were crucial in refining the technology and materials for optimal performance and cost-effectiveness. With the introduction of these advanced platforms, foundries could now leverage the technology firsthand, either by investing in their equipment or by sourcing sand molds and cores from specialized service providers.

Slika 8. Znatna rast števila namestitev 3D-tiskalnikov za peščene forme v letu 2022. (Z dovoljenjem podjetja America Makes, Lamoncha.)

Figure 8. Significant growth of 3D sand printer installations in 2022. (Courtesy of America Makes, Lamoncha.)

The North American metalcasting industry is experiencing a revolution driven by the rapid adoption of 3D sand printing technology. In the past 8 years, the user base has exploded, with over 100 machines

- Prvaki na domačem trgu – nekaj podjetij s sedežem v ZDA je vodilnih pri zagotavljanju inovativnih rešitev za 3D-tiskanje peščenih form in celovito podporo ter tako krepijo zaupanje v tehnologijo na domačem trgu.

Aditivna proizvodnja je hitro razvijajoča se tehnologija s širokim naborom možnosti uporabe. Posebej primerna je za industrijo kovinskih ulitkov, kjer se lahko uporablja za tiskanje peščenih jeder, form in končnih ulitkov.

Prednosti aditivnega 3D-tiskanja peščenih form (3DSP) v proizvodnji ulitkov v primerjavi s konvencionalnimi metodami vključujejo:

- Občutni prihranki v razvojnih fazah – 3DSP bo zmanjšal stroške razvoja, saj ne bo potreboval tradicionalnih orodij in prototipov.
- Izdelava kompleksnih jeder – 3DSP lahko izdela kompleksna jedra hitro in natančno, po konkurenčnih cenah in z visoko stopnjo doslednosti.
- Ničelni ali negativni livarski nagib – 3DSP lahko izdela jedra z ničelnim ali negativnim livarskim nagibom, kar je s tradicionalnimi metodami težko ali nemogoče. To lahko privede do znatnih prihrankov pri stroških, izboljša kakovost in omogoči preučitev zasnove za izboljšanje zmogljivosti ulitkov.
- Hitre spremembe zasnove – 3DSP omogoča hitre spremembe zasnove orodij, jeder ali orodij z in situ jedri, kar lahko skrajša čas izdelave ali omogoči več zasnov z nižjimi stroški.
- Brez naložb v opremljanje z orodji – 3DSP ne zahteva nobenih dodatnih orodij, kar hitro skrajša čas izdelave in stroške, saj lahko neposredno preidete na proizvodnjo delov in omogoča spremembe zasnove brez dodatnih stroškov.
- Združljivost s programsko opremo za

installed across North America. This surge is fueled by a combination of factors:

- Emerging Technologies—advancements in 3D sand printing hardware and materials have made the process faster, more efficient, and more cost-effective, opening doors for broader adoption.
- Increased Awareness—as the benefits of 3D sand printing become more apparent, foundries, pattern shops, and core shops recognize its potential to streamline workflows, reduce waste, and enhance design flexibility.
- Domestic Market Champions—several US-based companies are leading the charge, providing innovative 3D sand printing solutions and comprehensive support, fostering confidence in the technology within the domestic market.

Additive manufacturing is a rapidly growing technology with a wide range of applications. It is particularly well-suited for the metal castings industry, where it can be used to print sand cores, molds, and finished castings.

Pros of Additive 3D Sand Printing (3DSP) Manufacturing in casting production versus Conventional Methods include:

- Significant savings in development stages—3DSP will reduce development costs by cutting the need for traditional tooling and prototyping.
- Complex core making—3DSP can produce complex cores quickly and accurately, at competitive costs, and with a high degree of consistency.
- Zero or negative draft—3DSP can produce cores with zero or negative draft, which can be difficult or impossible to produce using traditional methods.
- This can lead to significant cost savings, improve the quality, and open the design consideration to improve the performance of the castings.

modeliranje – 3DSP je združljiv z večino programske opreme za modeliranje na trgu, zato ga je preprosto vključiti v obstoječe delovne postopke.

9 Možnosti uporabe 3D-tiskanja peščenih form

Družba Ford Motor Company za izdelavo prototipov ulitkov pogosto uporablja 3D-tiskanje peščenih form. Pravzaprav je bil s to tehnologijo izdelan prototip vsakega ulitka v novejšem Fordovem vozilu.

S 3D-tiskanjem peščenih form hitro ustvarite orodja in jedra za prototipne kose, ne da bi prej morali izdelati livarski model. To omogoča več ponovitev zasnove, kar lahko privede do izboljšanja vozil.

Družba Ford Motor Company na primer uporablja 3D-tiskanje peščenih form za izdelavo prototipa vsakega ulitka pri novejših vozilih Ford. To Fordovim inženirjem omogoča hitro in učinkovito izdelavo visokokakovostnih prototipov, kar lahko privede do boljših vozil.

Paul Susalla, Fordov vodja oddelka za hitro proizvodnjo v obratu v Dearbornu v Michiganu, se ukvarja z izdelavo prototipov s 3D-tiskanjem s tiskalnikom za peščene forme ExOne S-15. Poudarja, da »čeprav govorimo o prototipih, bi lahko Fordova količina prototipov presegla količino, ki jo številni proizvajalci štejejo za polno proizvodnjo. Sistem 3DSP uporabljamo za vse svoje prototipne ulitke za pogonski sklop, vzmetenje in druge sestavne dele – glave valjev, bloke valjev, ročične gredi, sprednje pokrove, oljne posode,« pravi Susalla. »V bistvu vse ulitke, ki jih vidite v motorju ali menjalniku, tukaj izdelujemo s 3D-tiskanjem peščenih form.«[4]

Pravi, da so bili prototipi delov za Fordove motorje EcoBoost izdelani na ta način, vključno z »vsemi originalnimi

- Rapid design changes—3DSP allows for rapid design changes to molds, cores, or molds with in-situ cores, which can reduce lead times or allow for multiple designs at reduced costs.
- No tooling investment—3DSP does not require any tooling, which quickly cuts lead time and cost going directly to part production and allows for design changes with no additional costs.
- Compatibility with modeling software—3DSP is compatible with most modeling software on the market, making it easy to integrate into existing workflows.

9 Applications of 3D Sand Printing

Ford Motor Company uses 3D sand printing extensively for prototyping castings. In fact, every casting in a newer Ford vehicle was prototyped utilizing this technology.

3D sand printing quickly generates molds and cores for prototype parts without making a pattern first. This allows for more design iterations, which can lead to improved vehicles.

For example, Ford Motor Company uses 3D sand printing to prototype every casting in a newer Ford vehicle. This allows Ford engineers to produce high-quality prototypes quickly and efficiently, which can lead to better vehicles.

Paul Susalla, Ford’s section supervisor of rapid manufacturing at the Dearborn, Michigan facility, engages in much of this prototyping, using 3D printing with the ExOne S-15 sand printer. He emphasizes that “though we are speaking of prototypes, Ford’s prototype volumes could surpass what many manufacturers consider full production. We use 3DSP for all our prototype castings in powertrain, suspension, and other components—cylinder heads, cylinder blocks, crankshafts, front covers, oil pans,” glavami valjev za 2-litrski motor EcoBoost, ki jih danes dobimo v številnih vozilih.« Pravzaprav je bilo »prvih 100 motorjev in njihovih glav valjev ulitih s to tehnologijo«.

Slika 9. Kompleksno jedro, natisnjeno s 3D-tehnologijo z anorganskim vezivom in kremenčevim peskom. (Umetniško delo je delo podjetja ExOne.)

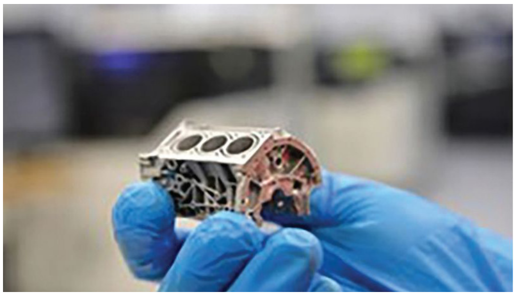
Figure 9. A complex core 3D printed with inorganic binder and silica sand. (Artwork courtesy of ExOne.)

Harold Sears, direktor aditivne proizvodnje pri Fordu, ugotavlja, da je pri Fordovi izdelavi glave valja orodje oblikovano enako kot v proizvodnji – z livarskimi nagibi in delilnimi ravninami – tako da testni kos predstavlja tisto, kar bo nastalo v proizvodnem procesu.

V Fordovem primeru se lahko brizganje veziva uporablja za izdelavo kompleksnih komponent motorja, ki vključujejo več delov, kot so hladilni kanali, strukturni in montažni elementi, v enotno, celovito zasnovo. Pri tem se izkorišča prednost postopka 3DSP in njegova zmožnost izdelave delov, ki vključujejo več komponent v eno samo monolitno strukturo. To lahko poenostavi postopke sestavljanja, zmanjša število potrebnih posameznih sestavnih delov ter izboljša splošno zmogljivost in zanesljivost končnega izdelka.

Ena od ključnih prednosti brizganja veziv za industrijo litja kovin je sposobnost izdelave delov z zapleteno notranjo geometrijo. To vključuje mrežaste strukture,

Susalla says. “Basically, any castings you see in an engine or transmission, we are prototyping here using 3D sand printing.”4



Slika 10. Brizganje veziva se uporablja za avtomobilsko industrijo. (Umetniško delo je delo podjetja ExOne/Ford.)

Figure 10. Binder jetting is used for automotive applications. (Artwork courtesy of ExOne/Ford.)

He says the prototypes for parts on Ford’s EcoBoost engines were made this way, including “all of the original cylinder heads for the 2-liter EcoBoost that you can get on so many vehicles today.” In fact, “the first 100 engines and their cylinder heads were cast using this technology.”

Harold Sears, Direct of Additive Manufacturing at Ford, notes, however, that when Ford makes a cylinder head, the mold is shaped the same as it will be in production— with draft angles and parting lines—so that the test part is representative of what will be coming out of the production process.

In the example at Ford, binder jetting can be used to manufacture complex engine components that integrate multiple parts, such as cooling channels, structural elements, and mounting features, into a single, cohesive design. This capitalizes on the advantage of 3DSP and its capability to produce parts that integrate multiple components into a single, monolithic structure. This can simplify assembly vzorce satovja in konformne hladilne kanale. Ti elementi lahko izboljšajo zmogljivost sestavnih delov z zmanjšanjem teže, izboljšanjem odvajanja toplote ali povečanjem razmerja med trdnostjo in težo. Z brizganjem veziv lahko na primer izdelamo lahke komponente z mrežasto strukturo za letalsko in vesoljsko industrijo, ki pomagajo zmanjšati porabo goriva in emisije. Izdelujemo lahko tudi orodja za tlačno litje s konformnimi hladilnimi kanali, ki izboljšajo čas cikla in kakovost ulitih delov.

10 Pogled v prihodnost

Podjetja po vsem svetu se vse bolj zanimajo za možnosti 3D-tiskanja peščenih form v livarski industriji. Tri kitajska podjetja proučujejo možnost prodaje svojih tiskalnikov v Severni Ameriki, saj ponujajo nižje stroške in hitrejše tiskanje kot nemški tiskalniki, ki so trenutno na voljo. Severnoameriške proizvajalce je upočasnila stroga patentna zaščita nemških podjetij. Vendar pa je ameriški proizvajalec razvil nov 3D-tiskalnik za peščene forme, ki temelji na enokomponentnem vezivnem sistemu na osnovi škroba, prvič razvitem v osemdesetih letih prejšnjega stoletja.

Podjetje VoxelJet, ki trenutno izdeluje 3D-tiskalnik za peščene forem z delovno komoro dva krat štiri metre, je nedavno prejelo 14 milijonov dolarjev za razvoj in izdelavo novega tiskalnika, ki bo dovolj velik za izdelavo orodij za trg vetrne energije pri družbi General Electric.

Nov tiskalnik bo predvidoma velik več kot šest kvadratnih metrov in bo omogočal hitro izdelavo izjemno velikih ulitkov z možnostjo spreminjanja načrtov po potrebi. Poleg tega je bil na področju potrošnega materiala dosežen pomemben napredek pri vezivih, aktivatorjih, čistilih, ognjevarnih premazih, modifikatorjih peska in uporabi

processes, reduce the number of individual components required, and improve the overall performance and reliability of the final product.

For the benefit of the metalcasting industry, one of the key advantages of binder jetting is its ability to produce parts with complex internal geometries. This includes lattice structures, honeycomb patterns, and conformal cooling channels. These features can enhance the performance of components by reducing weight, improving heat dissipation, or increasing strength-to-weight ratios. For example, binder jetting can produce lightweight aerospace components with lattice structures that help reduce fuel consumption and emissions. It can also produce tooling for die-casting tools with conformal cooling channels that improve cycle times and part quality.

10 The Look Ahead

Globally, companies are increasingly interested in the potential of 3D sand printing for the foundry industry. Three Chinese companies are exploring sales of their printers in North America, offering lower costs and faster printing speeds than the German printers currently available. North American manufacturers have been slowed by aggressive patent protection from German companies. However, one US manufacturer has developed a new 3D sand printer based on a single-part starch-based binder first developed in the 1980s.

VoxelJet, which currently produces a 3D sand printer with a working space of two meters by four meters, was recently awarded $14 million to develop and manufacture a new printer large enough to produce molds for the wind energy market with General Electric. The new printer is expected to be over six square meters and will allow for posebnih formarskih materialov. Na trgu se vse bolj uveljavljajo anorganska veziva. Nadaljujejo se prizadevanja za izdelavo obdelave pod 100 RMS s pomočjo veziva, premazov in obdelave tiskarskih datotek.

11 Zaključek

Na splošno je brizganje veziv zanesljiv postopek aditivne proizvodnje, ki ima v primerjavi s tradicionalnimi proizvodnimi metodami več prednosti pri izdelavi kompleksnih delov. Gre namreč za vsestransko tehnologijo, s katero je mogoče izdelati različne komponente za različne industrije.

Ker je tehnologija brizganja veziv vse bolj razvita, lahko igra ključno vlogo v prihodnosti proizvodnje, saj omogoča proizvodnjo inovativnih, prilagojenih in zapletenih delov, ki jih prej ni bilo mogoče izdelati. Z možnostjo izdelave kompleksnih delov z zapleteno geometrijo in notranjimi značilnostmi ima postopek 3DSP v primerjavi s tradicionalnimi proizvodnimi metodami več prednosti pri izdelavi delov z zahtevnimi zasnovami.

Čeprav še vedno obstajajo izzivi, kot so površinska obdelava, ločljivost in mehanske lastnosti, so raziskave in razvoj precej napredni. Napredek na področju materialov, veziv in večmaterialnega tiskanja bo po pričakovanjih spodbudil rast in uporabo brizganja veziv v številnih panogah, vključno z vesoljsko in letalsko, avtomobilsko, medicinsko in potrošniško industrijo.

Koncept je v četrt stoletja prehodil dolgo pot od tehnologije, ki so jo prvič zasnovali na tehnološkem inštitutu MIT in v družbi Soligen Technologies s postopkom neposredne proizvodnje form za litje (Direct Shell Production Casting). Ta razvoj 3D-brizganja veziva na pesek za izdelavo jeder, form in form z in-situ jedri je

the rapid production of exceptionally large castings, with the ability to revise designs as needed. Additionally, on the consumables front, noteworthy progress has been made in binders, activators, cleaners, refractory coatings, sand modifiers, and use for specialty mold materials. The beginning emergence of inorganic binders in the market and their adoption is building. Efforts to produce sub-100 RMS finish through binder, coatings, and print file processing continue.

11 Closing Remarks

Overall, binder jetting is a robust additive manufacturing process that offers several advantages over traditional manufacturing methods to produce complex parts. It is a versatile technology that can create various components for various industries.

As binder jetting technology matures, it is poised to play a vital role in the future of manufacturing, enabling the production of innovative, customized, and complex parts that were previously unattainable. With the ability to build complex parts with intricate geometries and internal features, 3DSP offers several advantages over traditional manufacturing methods when producing parts with challenging designs.

While challenges such as surface finish, resolution, and mechanical properties remain to be addressed, ongoing research and development are progressing considerably. Advancements in materials, binders, and multi-material printing are expected to drive the growth and adoption of binder jetting in a wide range of industries, including aerospace, automotive, medical, and consumer products.

The concept has come a long way in a quarter century from the technology first conceived at MIT and Soligen Technologies with the Direct Shell Production Casting vsestranski postopek aditivne proizvodnje, ki je še posebej primeren za izdelavo današnjih zapletenih prototipov ali ulitkov malih serij.

Naslednjih 25 let na področju 3D-tiskanja peščenih form bo prineslo temeljite spremembe. Z izpopolnjevanjem in razvojem tehnologije pričakujemo, da se bo pojavilo še več inovativnih in prebojnih vrst uporabe. Možnosti 3D-tiskanja peščenih form so neomejene, od hitrejše in učinkovitejše proizvodnje zapletenih delov do razvoja novih materialov in proizvodnih postopkov.

Zahvala

Avtor bi se rad zahvalil vizionarskemu vodstvu inštituta MIT, razvijalcem 3D-tiskanja in več konzorcijem uporabnikov iz sredine 90. let prejšnjega stoletja do danes za njihovo prizadevanje pri razvoju te tehnologije za naslednje generacije, čeprav industrija litja kovin še ni bila pripravljena, da bi jo v celoti sprejela. Njihova daljnovidnost in pripravljenost na tveganje sta postavila temelje za uspešen razvoj in komercializacijo te tehnologije, ki se zdaj široko uporablja in na številne načine koristi družbi.

Avtor bi se rad zahvalil tudi univerzi University of Northern Iowa in centru Industry 4.0 za njun neprecenljiv prispevek k sodelovanju z inovatorji na področju opreme in potrošnega materiala za nenehno izboljševanje. Njuno sodelovanje je pripomoglo k boljšemu razumevanju zapletenih izzivov in priložnosti dobavne verige.

Zahvala gre tudi članom odbora AFS, ker so bili pripravljeni deliti svoje znanje in izkušnje ter prispevati k točnosti tega članka in napredku 3D-tiskanja peščenih form in jeder.

process. This evolution in 3D binder jetting on the sand to make cores, molds, and molds with in-situ cores is a versatile additive manufacturing process particularly well-suited to produce today’s complex prototype or low- production castings.

The next 25 years in 3D sand printing are poised to be transformative. As technology matures and evolves, we expect to see even more innovative and groundbreaking applications emerge. From faster and more efficient production of complex parts to developing new materials and manufacturing processes, the potential of 3D sand printing is limitless.

Acknowledgments

The author would like to acknowledge the visionary leadership of MIT, 3D Printing Developers, and several consortia of users from the mid-1990s through today for their commitment to advancing this technology to the next generations, even when the metal casting industry was not yet ready to fully embrace it. Their foresight and willingness to take risks laid the foundation for this technology’s successful development and commercialization, which is now widely used and benefiting society in many ways.

The author would also like to acknowledge the University of Northern Iowa’s Industry and the Industry 4.0 Center for their invaluable contributions to working with equipment and consumable innovators to keep improving. Their interactions have helped better understand the supply chain’s complex challenges and opportunities.

The author is also grateful to the AFS Additive Committee members for their willingness to share their knowledge and experience and to help ensure that this paper was accurate and furthered the advancement of 3D inkjet sand printing for molds and cores.

Reference / References

1. Mikkola, P., eksperimentalni inženir, GM Powertrain Division, Saginaw, Michigan, osebni intervju (12. november 1993).
2. Sabin, D., vodja procesnega inženiringa, John Deere Product Engineering Center, Cedar Falls, Iowa, osebni intervju (25. september 1993).
3. Wohlers, T., tehnološki svetovalec, Wohlers Associates, raziskava, predstavljena na temo stroškov, trendov in razpoložljivih tehnologij pri izdelavi prototipov na *konferenci John Deere Rapid Prototyping Conference,* Davenport, Iowa (20. in 21. september 1993).
4. Fuges, Christina, »The New Pattern for Prototyping,« *Modern Machine Shop* (10-22-2013) https://www. mmsonline.com/articles/the-new-pattern-for-proto- typing (zadnji dostop 8. 4. 2024.)

Bibliografija / Bibliography

- Bryant, N., Cygal, D., »Preliminary Investigation on the Influence of Refractory Coatings Formulation on the Surface Roughness of A356 Aluminum Castings Produced by 3D Printed Sand,« *AFS Transactions* (2023).
- Bryant, N., Cygal, D., »Preliminary Investigation on the Influence of Refractory Coatings Formulation on the Surface Roughness of A356 Aluminum Castings Produced by 3D Printed Sand,« Bryant, N., Thiel, J., »Critical Characteristics Affecting the Surface Finish of Castings,« *AFS Transactions* (2018).
- Gibson I., Rosen D., Stucker B., Khorasani M., »Binder Jetting,« Additive Manufacturing Technologies, 2021:237–52. (2021).
- Kerns K., Elliott, W., »Direct Shell Production Process for Near-Net Shape Casting and Tooling,« *AFS Transactions* (1995).
- Kerns, K., »Development of Functional Rapid Prototyping for the Production of Near Net Shape Castings and Its Applications for Concurrent Engineering in the Metal Casting Industry« Raziskava, predstavljena fakulteti za dodiplomske študije, Univerza Severne Iowe (pomlad 1994).
- Mostafaei, A., Elliott, A.M., Barnes, J.E., Li, F., Tan, W., Cramer, C.L., Nandwana, P., Chmielus, M., »Binder Jet 3D Printing-Process Parameters, Materials, Properties, Modeling, and Challenges,« *Progress in Materials Science,* 119:100707 (1. jun. 2021).
- Polygenis, Tasos, »Binder Jetting: A Comprehensive Guide to the Additive Manufacturing Process,« *Wev- olver* (7. jul. 2023). https://www.wevolver.com/arti- cle/binder-jetting-a-comprehensive-guide-to-the-ad- ditive-manufacturing-process (zadnji dostop 8. 4. 2024.)
- Ravi, S., Woods, K., »Design Considerations for Three Dimensional Printed Cores and Molds,« *AFS Transactions* (2015).
- Rittmeyer, Dave, »3D Sand Printing 101«, tehnični članek, predložen za predstavitev na *kongresu AFS Metalcasting Congress 2024, Milwaukee, Wisconsin* (23.–25. april 2024).
- Trinowski, Doug, »Understanding 3D Sand Printers and Binder Technologies« (1. jan. 2019). https://www. foundrymag.com/molds-cores/article/21931923/un- derstanding-3d-sand-printers-and-binder-technologies (zadnji dostop 8. 4. 2024.)
- *AFS Transactions* (2023)