IMK-14 – Istraživanje i razvoj u teškoj mašinogradnji 23(2017)2, SR57-62
UDC 621 ISSN 0354-6829

Prednosti i ograničenja aditivne proizvodnje

A. Vranić[1*], N. Bogojević[1], S. Ćirić Kostić[1], D. Croccolo[2], G. Olmi[2]
[1] Fakultet za mašinstvo I građevinarstvo u Kraljevu, Univerzitet u Kragujevcu, Srbija, vranic.a@ mfkv.kg.ac.rs
[2]Department of Industrial Engineering (DIN), University of Bologna, Bologna, Italy

Ovaj rad predstavlja diskusiju mogućih grešaka i problema koji se mogu javiti u toku procesa direktnog selektivnog laserskog sinterovanja (DMLS) kao i njihovog uticaja na kvalitet proizvedenog dela. Direktno selektivno lasersko sinterovanja metala predstavlja jednu od tehnologija aditivne proizvodnje (AM izvedeno od „Additive Manufacturing“) koja omogućava brzu proizvodnju kompleksnih funkcionalnih delova, sa visokom preciznošću, bez korišćenja dodatnih alata za obradu, samo uz pomoć 3D CAD modela. Proces za zasniva na proizvodnji dodavanjem materijala u slojevima. Laserski zrak topi naneti materijal u ravni formirajući površinu koja odgovara preseku dela za dati sloj. U toku DMLS procesa mala zapremina metalnog praha se topi i hladi velikom brzinom što može uzrokovati pojavu zaostalih napona. Moguća je pojava problema u toku proizvodnje, koji zavise od parametara procesa poput tipa materijala, debljine sloja, orijentacije dela, temperature radne ploče i komore. Problemi se manifestuju u vidu promene geometrije, deformacije dela u toku proizvodnje ili odvajanja od radne ploče, sagorelog materijala, strukturnih grešaka poput poroznosti, uključaka i mikro prslina u zapremini dela.

Ključne reći: aditivna proizvodnja, direktno lasersko sinterovanje metala, poroznost, zaostali naponi, uključci, inicijalna prslina, deformacije.

0. UVOD

Za razliku od tradicionalnih metoda proizvodnje, aditivna proizvodnja (u daljem tekstu AM) predstavlja tehnologiju koja omogućava proizvodnju delova iz slojeva. Za proizvodnju je potreban 3D CAD model dela koji se proizvodi i mašina za AM. 3D CAD model se podeli na slojeve koji predstavljaju površine koje će laser topiti. Debljina sloja zavisi od parametara procesa i tipa materijala. Kompletan proces formiranja sloja se odvija u jednoj ravni. Danas su dostupne različite tehnologije za aditivnu proizvodnju delova od metala, koje rade na različitim principima i sa različitim materijalima [1-3]. Može se napraviti podela u smislu nanošenja i topljenja metala koji se odvijaju na dva načina. Jedan način je gde se materijal dodaje preko cele radne površine u određenom sloju a potom laser ili elektronski zrak selektivno topi samo onu površinu nanetog materijala koja odgovara površini sloja. Drugi način se bazira na simultanom dodavanju i topljenu materijala na površini koja odgovara sloju koji se proizvodi. Kao jedna od AM tehnologija Direktno lasersko sinterovanje metala (DMLS) je jedna od AM tehnologija koja omogućava proizvodnju potpuno funkcionalnih delova.

U ovom radu su predstavljene neke mogućnosti i ograničenja na koje korisnici mogu naići korišćenjem AM tehnologija sa akcentom na DMLS, koji predstavlja jednu od najvažnijih AM tehnologiju za proizvodnju delova od metala. Pripada grupi koja se zasniva na nanošenju materijala preko cele radne površine gde se naknadno topi samo ona površina koja odgovara sloju koji se proizvodi. Kako se ne koriste nikakvi dodatni alati u procesu proizvodnje, moguće je proizvesti kompleksne funkcionalne forme prikazane na Sl. 1. Topljenje materijala se odvija kontrolisanim kretanjem laserskog zraka male snage, velikog intenziteta pomoću ogledala, u skladu sa oblikom površine koja se sinteruje. Stapanje slojeva se odvija kako u vertikalnom tako i u horizontalnom pravcu. Rastopljeni materijal se tokom hlađenja vezuje za prethodno očvrsnuti materijal sa strane i za prethodno formirani sloj ispod. U horizontalnoj ravni se stapanje odvija preklapanjem tragova sinterovanja. Pravac gradnje dela je normalan na ravan gradnje.

Sl. 1: Lake ćelijske strukture proizvedene DMLS-om

Proizvodni proces se odvija na radnoj ploči, čija je uloga u pozicioniranju i fiksiranju delova koji se grade posredstvom oslonaca ili direktnom vezom dela sa pločom. Zbog temperaturnog gradijenta koji je rezultat procesa u delovima se javljaju zaostali naponi koji mogu uzrokovati deformacije u procesu proizvodnje.

*Kontakt adresa autora: Fakultet za mašinstvo i građevinarstvo u Kraljevu, 36000 Kraljevo, Dositejeva 19, vranic.a@mfkv.kg.ac.rs

1. PRIMENA AM TEHNOLOGIJE

U radu će biti pomenute neke od oblasti primene AM tehnologije.

U novije vreme je interesantna primena AM tehnologija u proizvodnji delova sa aspekta uštede materijal, preko optimizacije oblika i u proizvodnji laganih ćelijskih struktura od metala. Objavljeni su rezultati nekih istraživanja laganih ćelijskih struktura proizvedenih DMLS tehnologijom na bazi legure aluminijuma [4]. Moguće je proizvesti lagane ćelijske strukture upotrebom tehnologije mikro liva uz određena ograničenja. Proizvedeni su delovi sa odnosom mase i zapremine u iznosu od 7.5% do 15%. Za manje odnose mase i zapremine, ćelije su pokazale tendenciju loma usled male debljine materijala. Postoji ograničenje u vezi debljina zidova i dimenzija rešetkaste strukture, a zasniva se na prečniku fokusa lasera, granulacije materijala i slično. Zaključak autora je da se sa povećanjem masenog odnosa povećava nosivost i čvrstoća ćelijske strukture proizvedene DMLS tehnologijom što povoljno utiče na integritet dela. DMLS tehnologija je korišćenja u razvoju olakšanog egzoskeleta za prst, koristeći leguru aluminijuma [5]. Ranije su ovakvi tipovi delova bili masivni i teški a upotrebom ovih tehnologija situacija se menja. Smanjenjem mase utiče se na uštedu u eksploataciji ovakvih delova kroz smanjenje u potrošnji energije prilikom kretanja, kao na primer kod robotske ruke. Manja masa znači manju inerciju i manje potrebne energije za pokretanje.

EADS je koristio DMLS tehnologiju za optimizaciju mase kopči za vezivanje pojaseva i kod šarki poklopaca motora aviona [6]. Delovi proizvedeni DMLS tehnologijom su se pokazali znatno bolje u eksploataciji od delova proizvedenih mikro livom za isti proizvod. Uštede se prave i na osnovu emisije štetnih gasova i u potrošnji materijala. Renishaw kompanija je koristila AM za proizvodnju rama bicikle sa optimizovanom topologijom [7]. Cilj je bio proizvesti deo sa minimalne mase a maksimalne nosivosti. Na ovaj način je otvorena je ušteda u materijalu u iznosu od 33% (Fig.2).

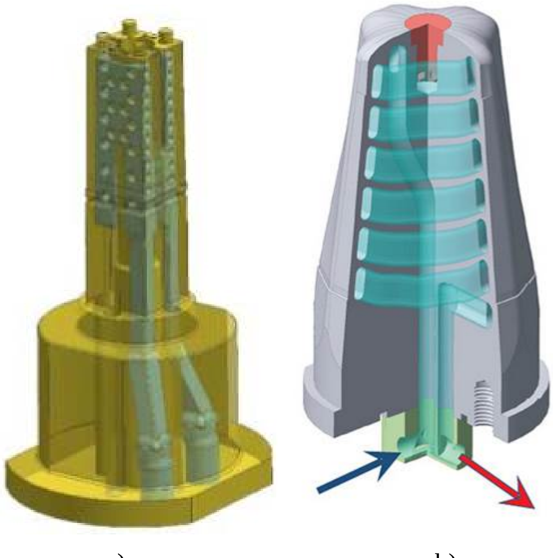
Sl. 2: Delovi rama za bicikl za Empire Cycles proizvedenih od strane Renishaw [7]

Robot Bike Co. je koristeći usluge Renishaw kompanije, proizveo olakšani ram bicikle, kombinujući vezne elemente od titanijuma proizvedenih na mašini za selektivno lasersko topljenje (SLM) AM250 koja poseduje laser snage 200W (Fig. 3) i cevi proizvedene od karbonskih vlakana [8]. Ovo je dobar primer kombinacija dve vrhunske tehnologije u proizvodnji lakih delova velike čvrstoće.

Sl. 3:Optimizovani oblik delova rama Robot Bik Co. [8]

Objavljena je brošura od strane Evropske asocijacije za metalurgiju praškastih materijala, sa primerima primene različitih AM tehnologija u proizvodnji delova od metala sa optimizovanom geometrijom i masom. Neki od sadržanih primera su držači satelitskih antena od legure titanijuma Ti6Al4V proizvedenih topljenjem elektronskim zrakom (EBM), olakšani vijci od nerđajućeg čelika, brizgaljke kompleksnog oblika od legure kobalt hroma, lopatica turbine od inkonela sa unutrašnjim kanalima za hlađenje, i drugi [9]. Brošura može poslužiti kao uputstvo, inženjerima i projektantima, da steknu utisak o mogućnostima primene AM tehnologije. U optimizaciji geometrije sa najboljim odnosom mase i zapremine prema nosivosti, AM pruža najveće mogućnosti koje inženjeri i dizajneri treba da iskoriste. Na ovaj način je inženjerima olakšano projektovanje delova čiji je oblik optimizovan u skladu sa opterećenjem. Neka ograničenja koja postoje kod klasičnih tehnologija proizvodnje ne postoje u AM proizvodnji. U slučaju kada je za neku površinu potrebna mašinska obrada, mora se voditi računa o mogućnosti prilaska alata toj površini. Osim što je moguće optimizovati masu, moguće je optimizovati i broj delova u sklopu. Kako ova tehnologija ne poseduje ograničenja u pogledu prilaza alata, moguće je spojiti i proizvesti, više delova koji su razdvojeni zbog tehnoloških ograničenja proizvodnje klasičnim metodama, kao jedan komad.

AM je pokazao odlične mogućnosti u proizvodnji alata za brizganje plastike. Materijali koji se koriste su dobrih karakteristika a tehnologija pruža veliku slobodu u pogledu geometrije projektovanog dela. Gotova da nema ograničenja, što su proizvođači alata i uočili. Kod kalupa za brizganje plastike su najvažniji kvalitet površine dela koji se brizga i ciklus brizganja. Kvalitet površine zavisi od kvaliteta obrađene površine alata, koliko dobro je moguće ispolirati alat i kakva su adheziona svojstva materijala koji se brizga. Ciklus brizganja je drugi važan faktor iako je rasprostranjeno mišljenje da je najvažniji ,ako se kvalitet odnosno efikasnosti zanemari. Efikasnost bi u ovom slučaju bila proizvodnja delova maksimalnog kvaliteta za minimalno vreme. Mogu se napraviti alati sa kojima se skraćuje ciklus proizvodnje a povećava se kvalitet proizvedenog dela, što se postiže kanalima unutar alata, koji prate konturu dela koji se brizga. Ovakav tip hlađenja se naziva komforno hlađenje. Ovakav tip kanala za hlađenje je teško proizvesti drugim tehnologijama osim AM. Ovim se klasičan oblik hlađenja (fontanom i sl.) menja i potiskuje iz upotrebe. U pogledu geometrije kanala za hlađenje nema ograničenja ukoliko se alat proizvodi AM tehnologijom, jer se kanali prave u toku same izrade dela. Objavljeni su rezultati istraživanja u vezi korišćenja AM u proizvodnji alata za brizganje plastike sa optimizovanim kanalima za hlađenje [10,11]. Autori su koristili ANSYS programski paket za u istraživanju uticaja optimizovanih kanala na hlađenje alata tokom brizganja. Rezultati pokazuju skraćenje ciklusa od 22% do 45% sa optimizovanim kanalima za hlađenje proizvedenih AM tehnologijom, koji prate konturu dela [12]. Neophodno je voditi računa o razlici ulazne i izlazne temperature vode. Rezultati istraživanja nekih oblika kanala za hlađenje su prikazani na Sl. 4 [13].


a) b)

Sl.4:Primer optimizovanih kanala za hlađenje

a) Deo alata za LEGO

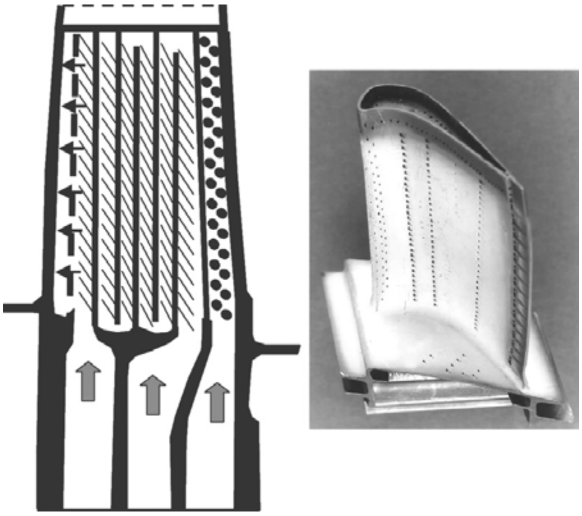
9) Deo alata BKL, Polymold

EOS GmbH (Electro Optical Systems, Germany) proizvođač DMLS mašina je predstavio neke prednosti korišćenja ovih tehnologija u proizvodnji alata [14, 15].

Aditivna proizvodnja nalazi primenu i u medicini, pružanjem mogućnosti izrade personalizovanih implanata sa projektovanom poroznom strukturom prema potrebi čoveka za koga se projektuje [16]. U rekonstruktivnoj plastičnoj hirurgiji se AM koristi za proizvodnju implanata koji prati topologiju ljudske lobanje kako bi se vratio prvobitni oblik lica nakon oporavka [17, 18]. Moguće je brzo proizvesti personalizovane proteze, koje pružaju bolji komfor pacijentu, jer je oblik specijalno prilagođen njegovoj konstituciji i obliku tela za koji se pravi [19]. Jedina prepreka može biti cena izrade, jer su troškovi materijala i amortizacije visoki.

Sl. 5: Personalizovana proteza za nogu [19]

Veliki potencija AM tehnologije ležu u avio industriji. Kao najzahtevnija grana industrije, konstantno se razvija stavljajući pred inženjere sve veće zahteve u pogledu smanjenja mase sa povećanjem nosivosti i efikasnosti. Jednu od grana avio industrije predstavlja proizvodnja turbina i lopatica turbina za mlazne motore. AM može izaći na kraj sa zahtevima i izazovima koje kompleksni oblik turbina zadaje u proizvodnji. U nekom trenutku će AM postati nezamenjiv u razvoju turbina i lopatica turbina, zbog mogućnosti koje nudi.



Sl. 6: Primer kanala za hlađenje lopatica turbine [20]

Lopatice turbina su mašinski delovi kompleksnih oblika, čija proizvodnja nije prosta usled komplikovanih geometrijskih uslova koje moraju ispuniti.

Spoljni oblik turbine je samo jedan deo problema, unutrašnji kanali za hlađenje su podjednako kompleksan problem pogotovu ako se uzme u obzir veličina poprečnog preseka i geometrija kanala. Uloga im je da hlade lopaticu u uslovima kada radna temperatura prevazilazi temperaturu topljenja materijala od koga je lopatica izrađena, čime se efikasnost povećava. Moguće je koristiti nekoliko tipova kanala za hlađenje površine lopatice [20]. Zbog geometrijskih uslova kanala za hlađenje, teško je zamisliti proizvodnju ovakvih turbina nekom drugom tehnologijom osim AM.

Kada se uzme u obzir sve prethodno, jasno je da će AM biti sve prisutnija i u ostalim granama industrije a i u životu. U razvoju novih proizvoda i personalizovanoj proizvodnji će biti nezamenjiva zbog mogućnosti malo serijske i pojedinačne proizvodnje.

2. OGRANIČENJA AM TEHNOLOGIJA

Kada se uzmu u obzir sve dosada navedene prednosti AM tehnologija, reklo bi se da je „Svemoguća“ i bez ograničenja što je daleko od istinitog. Korišćenje AM tehnologija zahteva promenu u konceptu razmišljanja proizvodnje, „reset“ i svež način razmišljanja u projektovanja delova. Treba imati na umu da prilikom projektovanja dela nema potrebe voditi računa o prilasku alata itd. Ograničenja u pitanju kompleksnosti dela su drugačija i mogu se zanemariti u velikom procentu ali ne i zaboraviti. Odsustvo mašinske obrade je diskutabilno i o tome će biti kasnije reči.

Neka od ograničenja koja su u vezi sa AM tehnologijom su:

- Minimalna debljina zida dela je 0,4mm za DMLS, 0,3 - 0,5mm za SLM, 0,6-1mm za EBM.
- Ograničenja u vidu gabarita, zavisi od mašine.
- Postoje ograničenja u pogledu raspoloživih materijala raspoloživih za proizvodnju
- Cena materijala je veoma visoka, zbog visoke cene proizvodnje. Pogotovu za praškaste materijale.
- Nekada je neophodna upotreba oslonaca u proizvodnji što zahteva naknadnu obradu.
- Kvalitet površine je nizak usled zalepljenog praha za površinu.
- Prisustvo zaostalih napona.

Osim gore navedenih ima još ograničenja, i svi oni mogu izazvati poteškoće u toku procesa proizvodnje ili u eksploataciji.

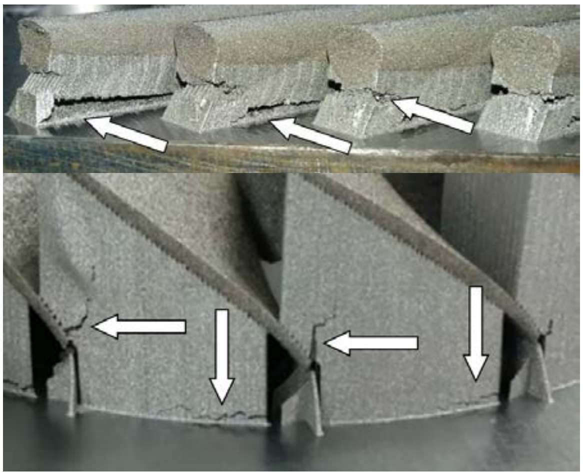
Minimalna debljina zida koji se može proizvesti je u vezi sa prečnikom fokusa lasera i postojanošću i stabilnošću dela u toku proizvodnje. Neophodno je obezbediti dobru vezu prethodnih i narednih slojeva kako bi deo koji se proizvodio bio fiksiran i obezbedila tačnost i preciznost proizvodnje. Zbog loše veze dela za radnom pločom, moguće je odvajanje dela od ploče i prekida dalje proizvodnje. Debljina zida zavisi od prečnika fokusa lasera, elektronskog zraka ili žice. Sa povećanjem prečnika mora se povećati i debljina zida. Nemoguće je proizvesti zid koji je manje debljine od prečnika fokusa lasera, žice itd. Ovo predstavlja tehnološko ograničenje.

Dimenzije dela zavise od dimenzije radne zapremine mašine i od raspoložive količine materijala za proizvodnju u mašini. Proizvodni proces se odvija u inertnoj atmosferi ili vakumu, kako bi se sprečila oksidacija materijala u toku procesa proizvodnje. U nekim slučajevima poput kod proizvodnje delova malih gabarita, je poželjno da radna zapremina bude malih gabarita. Na taj način se prave uštede u potrebnoj količini materijala za proizvodnju i brzini proizvodnje. Primer je proizvodnja nakita od zlata. Zlato je prilično skupa sirovina za AM proizvodnju a nakit od zlata je relativno malih dimenzija. U ovom slučaju mašine velikih radnih zapremina nisu pogodne za upotrebu iz dva razloga. Prvo količina neophodnog materijala za proizvodnju u takvim mašinama je obično velika. Nerealan je odnos radne zapremine i potrebnog materijala prema dimenzijama delova koji se proizvode. Drugo, vreme potrebno za nanošenje materijala ko ovih mašina je nešto duže zbog količine materijala koji se nanosi. Kompromis je napravljen kod tehnologija gde se materijala simultano nanosi i topi samo tamo gde je potrebno vršiti proizvodnju, te potrebna količina materijala zavisi samo od mase dela, ne i od radne zapremine.

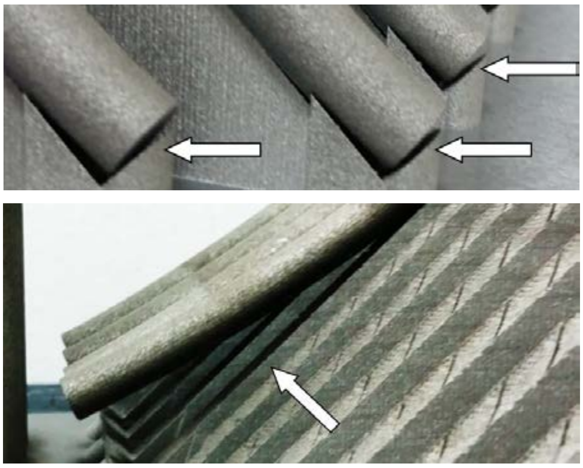
U zavisnosti od tehnologije variraju i vrste raspoloživih materijala za proizvodnju. Raspoloživi materijali se uglavnom baziraju na legurama titanijuma, aluminijuma, nikla i hroma. Nisu sve legure čelika koje se koriste u klasičnoj proizvodnji dostupe i za proizvodnju aditivnim tehnologijama. Za aditivnu proizvodnju su dostupne samo odabrane legure čelika sa specijalnim karakteristikama. Ovo je trenutna situacija koja u stvari zavisi od troškova proizvodnje žice odnosno praha. Praškasti materijali se proizvodne uglavnom gasnom ili vodenom atomizacijom. Troškovi procesa proizvodnje praha su visoki a količina praha koja se može proizvesti je ograničena, što čini ovaj prah skupim.

Proizvodnja započinje na radnoj ploči od metala koji je kompatibilan sa metalom od koga se proizvodi deo. Za proizvodnju delova od legure aluminijuma je potrebna ploča od legure aluminijuma i slično. Razlog je kompatibilnost materijala, kako se delovi ne bi odvajali u toku procesa proizvodnje. Uloga radne ploče je višestruka, od oslanjanja i fiksiranja kako bi se obezbedio konstantan položaj delova i u odvođenju toplote iz zone topljenja materijala.

Prisustvo zaostalih napona je rezultat velike brzine topljenja i hlađenja delova [22,23]. Ukoliko vrednost zaostalih napona prevaziđe vrednost zatezne čvrstoće dela, moguće su pojave mikro prslina. [24,25]. Kako bi se prečile deformacije i savijanje delova koji se proizvode, neophodna je dobra veza delova i radne ploče. U slučaju deformacija i savijanja delova može doći do kontakta noža za nanošenje materijala sa delovima, što bi uzrokovalo zaustavljanjem posla ili još gore oštećenjem mašine. Korišćenjem adekvatne termičke obrade ili izostatičkog sinterovanja moguće je eliminisati zaostale napone i pore u materijalu [23,26]. Zaostali naponi su niži ukoliko se radna ploča zagreva na višim temperaturama [27]. Ovo je karakteristično za EBM tehnologiju [28]. Kako bi se sprečile bilo kakve deformacije koje bi uzrokovale odvajanje dela od ploče, veza preko oslonaca između ploče i dela mora biti dovoljno jaka. Veliki zaostali naponi mogu izazvati prsline i pukotine u delu. Na slici 7. su prikazani primeri pukotina nastalih usled prisustva zaostalih napona.



Sl. 7: Primeri prslina usled prisustva zaostalih napona kod delova proizvedenih DMLS-om na EOS M280



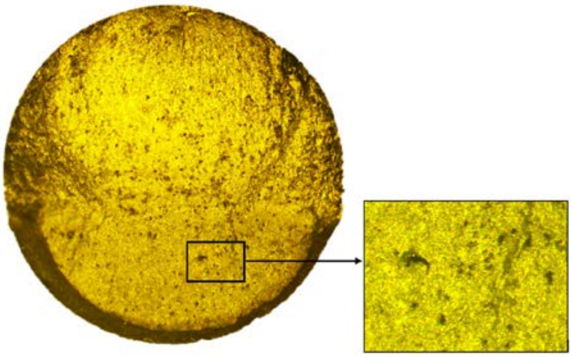
Sl. 8:Primer odvajanja dela od oslonaca

Kako bi se delovi lakše odvajali od oslonaca, generišu se zubi kako veza oslonaca i dela. Zubi moraju biti dovoljno jaki da spreče deformacije dela usled zaostalih napona a omoguće odvajanje dela od oslonaca kada se proizvodnja završi. U suprotnom zaostali naponi mogu izazvati odvajanje dela od oslonaca (primer na Sl.8). U ovom slučaju ne gine odvajanje dela i kontakt sa kretnim elementima, što uzrokuje propast posla i moguće oštećenje mašine.

Sl. 9: Savijanje sinterovanog materijala

Nije moguće proizvesti delove bez čvrste veze sa radnom pločom (samo u prahu) zbog mogućnosti pomeranja dela u odnosu na ploču i odvođenja viška toplote. Ukoliko se prepusti zanemare, i ne isplaniraju se adekvatni oslonci, može doći do savijanja materijala usled prisustva zaostalih napona a usled dejstva visoke temperature koja se ne odvodi, dolazi do oštećenja materijala u vidu pregrevanja. Čak i za male prepuste se moraju postaviti oslonci kako ne bi došlo do deformacija koje bi uzrokovale propast posla i oštećenje mašine. Ovaj slučaj je prikazan na Sl.9 gde se nož za nanošenje praha zaglavio zbog povijenog prepusta. Nije bilo moguće nastaviti proces proizvodnje zbog deformacija koje su prepusti bez oslonaca uzrokovali. Objavljeni su rezultati nekih istraživanja deformacija u toku DMLS proizvodnje delova od legure aluminijuma [29].

Poroznost i uključci u materijalu su rezultat procesa i parametara proizvodnje. Na primer kod DMLS-a i SLM-a snaga lasera, prečnik fokusa lasera, veličina preklapanja traga lasera, debljina sloja i brzina sinterovanja utiču na prisustvo grešaka u strukturi [30,31]. Moguće je da kod različitih mašina i tehnologija a istih materijala prisustvo grešaka nije isto. Na Sl. 10 je prikazano prisustvo poroznosti na površini loma dela proizvedenog DMLS-om.



Sl. 10: Površina loma epruvete proizvedene na M280 od MS1alatnog čelika (EOS Gmbh)

3. ZAKLJUČAK

U radu su razmatrani tehnološki aspekti aditivne proizvodnje delova od metala sa aspekta prednosti i nedostataka.

Prednosti tehnologije su što nudi velike mogućnosti u proizvodnji kompleksnih delova, lakih ćelijskih struktura, delova sa optimizovanim oblikom. Omogućava proizvodnju delova samo uz pomoć mašine za AM i 3D CAD modela. Značajno štedi vreme i novac prilikom razvoja novih proizvoda. Omogućava brzu malo serijsku i pojedinačnu proizvodnju. Gotovo da je nezamenjiva u pogledu proizvodnje delova sa kompleksnim unutrašnjim kanalima, gde za sada nema konkurentnu tehnologiju. Troškovi tehnologije su diskutabilni. Cene mašina se mogu porediti sa cenama nekih vrhunskih obradinih CNC centara, međutim cena materijala je još uvek visoka.

AM pruža velike mogućnosti u pogledu personalizovane proizvodnje. Ova tehnologija nikada neće niti može zameniti klasične vidove proizvodnje. One jednostavno nisu međusobno konkurentne.

Projektanti i inženjeri se moraju upoznati sa AM tehnologijama sa potpuno novim konceptom razmišljanja, kako bi razumeli sve prednosti i ograničenja koja nisu prisutna prilikom projektovanja za proizvodnju klasičnim tehnologijama. Zaostali naponi, uključci, kvalitet površine, ograničenja u gabaritima, dostupni materijali i dodatne obrade su samo neke od stvari koje treba imati u vidu.

ZAHVALNOST

Ovaj rad predstavlja deo istraživanja u okviru projekta "Advanced design rules for optimal dynamic properties of additive manufacturing products - A_MADAM" koje je finansirano od strane Evropske Unije kroz HORIZON 2020 program za istraživanje i inovacije, Marie Skłodowska-Curie grant No 734455.

LITERATURA

[1] Bourell, D. L., et al. "A brief history of additive manufacturing and the 2009 roadmap for additive manufacturing: looking back and looking ahead." Proceedings of RapidTech (2009): 24-25.

[2] Herderick, E. "Additive manufacturing of metals: A review." Materials Science & Technology (2011): 1413-1425.

[3] Aliakbari, Mina. "Additive manufacturing: State-of-the-art, capabilities, and sample applications with cost analysis." (2012).

[4] Yan, Chunze, Liang Hao, Ahmed Hussein, Simon Lawrence Bubb, Philippe Young, and David Raymont. "Evaluation of light-weight AlSi10Mg periodic cellular lattice structures fabricated via direct metal laser sintering." Journal of Materials Processing Technology 214, no. 4 (2014): 856-864.

[5] Manfredi, D., Flaviana Calignano, Elisa Paola Ambrosio, Manickavasagam Krishnan, Riccardo Canali, Sara Biamino, Matteo Pavese et al. "Direct Metal Laser Sintering: an additive manufacturing technology ready to produce lightweight structural parts for robotic applications." Metall. Ital 10 (2013): 15-24.

[6] Light, Cost and Resource Effective – Researching Sustainability of Direct Metal Laser Sintering (DMLS)

[7] http://www.renishaw.com/en/first-metal-3d-printed-bicycle-frame-manufactured-by-renishaw-for-empire-cycles--2415

[8] http://www.renishaw.com/en/blog-post-a-3d-printed-mountain-bike-that-you-can-buy-today--389

[9] European powder metallurgy association, Introduction to additive manufacturing technologies, A Guide for Designers and Engineers, 2015, 1st edition.

[10] Jahan, Suchana A., and Hazim El-Mounayri. "Optimal Conformal Cooling Channels in 3D Printed Dies for Plastic Injection Molding." Procedia Manufacturing 5 (2016): 888-900.

[11] Jahan, Suchana A., Tong Wu, Yi Zhang, Hazim El-Mounayri, Andres Tovar, Jing Zhang, Douglas Acheson, Razi Nalim, Xingye Guo, and Weng Hoh Lee. "Implementation of Conformal Cooling & Topology Optimization in 3D Printed Stainless Steel Porous Structure Injection Molds." Procedia Manufacturing 5 (2016): 901-915.

[12] Scott Young, “Additive Manufacturing Applications for the Tooling Industry: Custom Conformal Cooling for Injection Molding”, Bastech, Inc, 2016.

[13] Augustin Niavas, Shaping the future of die and moulds: EOS tooling applications, EOS, Krailling, (2010)

[14] Shellabear, Mike, and Joseph Weilhammer. "Tooling applications with EOSINT M." EOS Whitepaper, Krailling (2007).

[15] Mayer, Siegfried. "Optimised mould temperature control procedure using DMLS." EOS Whitepaper, EOS GmbH Ltd (2005): 1-10.

[16] Parthasarathy, Jayanthi, Binil Starly, and Shivakumar Raman. "A design for the additive manufacture of functionally graded porous structures with tailored mechanical properties for biomedical applications." Journal of Manufacturing Processes 13.2 (2011): 160-170.

[17] Jardini, A. L., M. A. Larosa, M. F. Macedo, L. F. Bernardes, C. S. Lambert, C. A. C. Zavaglia, R. Maciel Filho, D. R. Calderoni, E. Ghizoni, and P. Kharmandayan. "Improvement in Cranioplasty: Advanced Prosthesis Biomanufacturing." Procedia CIRP 49 (2016): 203-208.

[18] Jardini, André Luiz, Maria Aparecida Larosa, Rubens Maciel Filho, Cecília Amélia de Carvalho Zavaglia, Luis Fernando Bernardes, Carlos Salles Lambert, Davi Reis Calderoni, and Paulo Kharmandayan. "Cranial reconstruction: 3D biomodel and custom-built implant created using additive manufacturing." Journal of Cranio-Maxillofacial Surgery 42, no. 8 (2014): 1877-1884.

[19] Roland K. Chen, Yu-an Jin, Jeffrey Wensman, Albert Shih, Additive manufacturing of custom orthoses and prostheses—A review, Additive Manufacturing, Volume 12, Part A, October 2016, Pages 77-89, ISSN 2214-8604, https://doi.org/10.1016/j.addma.2016.04.002.

[20] Bunker, R. S. Innovative gas turbine cooling techniques. WIT Press, Southampton, UK, 2008.

[21] https://github.com/Gongkai-AM/Machine-Guides/blob/master/Arcam%20EBM%20Guide.md

[22] P. Edwards, M. Ramulu, Fatigue performance evaluation of selective laser melted Ti–6Al–4V, Materials Science and Engineering: A, Volume 598, 26 March 2014, Pages 327-337, ISSN 0921-5093, http://dx.doi.org/10.1016/j.msea.2014.01.041.

[23] Kasperovich, Galina, and Joachim Hausmann. "Improvement of fatigue resistance and ductility of TiAl6V4 processed by selective laser melting." Journal of Materials Processing Technology 220 (2015): 202-214.

[24] Sanz, C., and V. García Navas. "Structural integrity of direct metal laser sintered parts subjected to thermal and finishing treatments." Journal of Materials Processing Technology 213.12 (2013): 2126-2136.

[25] Zeng, Kai, Deepankar Pal, and Brent Stucker. "A review of thermal analysis methods in laser sintering and selective laser melting." Proceedings of Solid Freeform Fabrication Symposium Austin, TX. 2

[26] Pal, Snehashis, et al. "The Effect of Post-processing and Machining Process Parameters on Properties of Stainless Steel PH1 Product Produced by Direct Metal Laser Sintering." Procedia Engineering 149 (2016): 359-365.

[27] Campanelli, Sabina Luisa, et al. Capabilities and performances of the selective laser melting process. INTECH Open Access Publisher, 2010.

[28] http://www.arcam.com/technology/products/arcam-a2x-3/

[29] Atzeni, Eleonora, and Alessandro Salmi. "Study on unsupported overhangs of alsi10mg parts processed by direct metal laser sintering (dmls)." Journal of Manufacturing Processes 20 (2015): 500-506

[30] Aboulkhair, Nesma T., et al. "On the formation of AlSi10Mg single tracks and layers in selective laser melting: Microstructure and nano-mechanical properties." Journal of Materials Processing Technology 230 (2016): 88-98.

[31] Gong, Haijun, et al. "Analysis of defect generation in Ti–6Al–4V parts made using powder bed fusion additive manufacturing processes." Additive Manufacturing 1 (2014): 87-98

IMK-14 – Research & Development in Heavy Machinery 23(2017)2, EN57-62
UDC 621 ISSN 0354-6829

Advantages and Drawbacks of Additive Manufacturing

A. Vranić[1*], N. Bogojević[1], S, Ćirić Kostić[1], D. Croccolo[2], G. Olmi[2]

[1] The Faculty of Mechanical and Civil Engineering in Kraljevo, University of Kragujevac, Serbia, vranic.a@ mfkv.kg.ac.rs
[2]Department of Industrial Engineering (DIN), University of Bologna

Abstract - This paper presents some various imperfections that can occur during Direct Metal Laser Sintering (DMLS) and their effects on part quality. Direct Metal Laser Sintering is one of the Additive Manufacturing (AM) technologies that enables fast production of an accurate, functional, complex shape parts and tools, without additional tooling, directly from 3D CAD model. This process is based on layer by layer manufacturing, where the fusion of the metal powder is performed by selective melting with laser beam. The laser beam moves and scans area that correspond to section of the part for the specific layer. In the DMLS the part is built layer by layer, where the process of the melting and solidification occur in small volume in relatively short time. Thanks to this kind of approach, the DMLS has much less limitations than the subtractive methods of part production. However, the production in the layers has some drawbacks, which can have a significantly influence on the part geometry, structural errors and part imperfections. Some of the advantages as well and drawback of the DMLS of metal parts has been presented in this paper.

Keywords: Maraging steel, Stainless steel, Additive manufacturing, Direct Metal Laser Sintering, Porosities, Machining, Fatigue, Initial crack, Tooling, Defects.

0. INTRODUCTION

Unlike traditional methods of manufacturing, where products are made by removing or forming material using different sets of machines or tools, Additive Manufacturing (AM) technologies make product by joining successive layers of a material. Parts are being built using 3D CAD model and AM machine. CAD model is divided in layers of appropriate thickness that correspond to manufacturing process based on the type of machine and the material. Whole process of the melting of the material is performed in the one plane that corresponds to the one layer. There are various technologies for AM of the metal parts, which work on different principles and with different metal materials [1-3]. It is possible to distinguish two ways of material deposition and melting. One is where powder material is deposited on whole building surface where laser or electron beam selectively melts area that correspond to layer of the part. Second is where material is simultaneously deposited and melted on the needed area that correspond to section of the part that is being built. One of the AM technologies that enables manufacturing of functional metal parts is Direct Metal Laser Sintering (DMLS) to which accent is put in this paper. DMLS belongs to first group regarding to the material deposition and melting. This type of the methodology offers quick manufacturing of the complex and functional parts which are shown on Fig. 1. DMLS use the laser beam for melting of the powder, whose movements (scanning) are controlled with a set of mirrors. In this way, mirrors direct laser beam on the powder surface that need to be exposed and melted. In the process of the cooling, the melted powder has been bonded with previous layer, bonding in the vertical direction, as well and with previous laser trace in the current layer, horizontal bonding. In order to achieve a solid part, a good fusion and material bonding need to be performed in both directions. The parts in AM technologies are always built in the direction perpendicular to the layers, in the most cases in the vertical – z direction.

Fig. 1: Lightweight structures manufactured by DMLS

In DLMS, the parts are being manufactured on base plate, which has role to remove heat and prevent motion and deformation of objects that may occur due to the residual stresses caused by thermal gradient. Manufactured parts are thus connected to the platform by supports that are manufactured simultaneously with the object.

*Corresponding author: Faculty of the mechanical and Civil Engineering, 36000 Kraljevo, Dositejeva 19, vranic.a@mfkv.kg.ac.rs

1. APPLICATION OF THE AM

One of the interesting fields of the AM application is in light weight structures, where manufacturing via subtractive machining is impossible. The evaluation the manufacturability and performance of AlSi10Mg aluminium alloy based lattice structures, fabricated by DMLS has been published by Chunze Yan, et all [4]. There are possibilities to manufacture lattice structures using an investment casting or similar technologies, but this approach for single part or small series can be time and cost consuming. In this case AM has significant advantage. With DMLS, the structures were manufactured with volume fraction of 7.5% to 15%. In lower fraction, structures tend to damage due to small dimension of the strut, which are closed to dimension of the laser beam focus diameter. In this case, it is shown that there are the limitations in minimal thickness of the walls and struts of the lattice structures. Authors concluded that compressive modulus and strength of the DMLS manufactured lattice structures increase with increase of the volume fraction. The application of the light weight structures and their advantages are also performed and on finger exoskeleton part built from aluminium alloy AlSiMg using DMLS [5]. In the past, these types of the parts were bulky and heavy. Manufacturing these parts as light weight benefits to lower energy consumption in movement and speed of robotic arm, due to low mass and inertia.

EADS has shown an application of DMLS technology for manufacturing of brackets with optimised topology [6]. Their examinations have shown a better result in manufacturing off the brackets with DMLS than with investment casting. Savings are being made through carbon footprint and material waist. Renishaw used AM machine to manufacture bicycle frame for Empire Cycles with optimised topology [7]. Aim was to design parts with maximum strength and minimum part weight. The weight saving of the 33% was achieved through topology optimisation (shown on Fig.2).

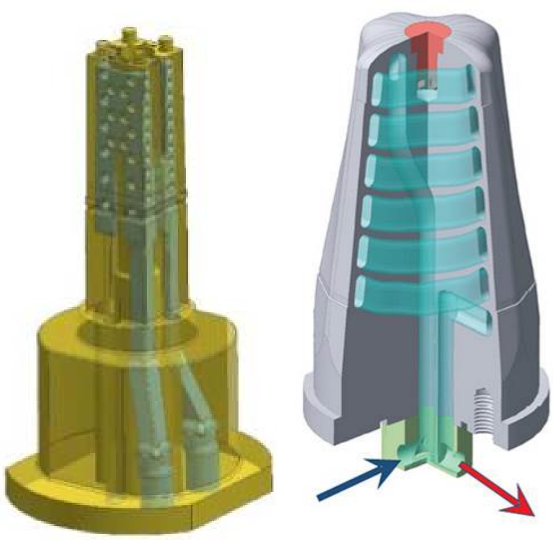
Fig. 2: Lightweight bycicle frame for Empire Cycles manufactured by Renishaw

Robot Bike Co. has also used Renishaw service and produced light weight montane bike frame, combining additively manufactured titanium lugs and carbon fibre tubing [8]. Parts had been produced on an AM250 laser melting machine with 200W laser (Fig. 3). This is good example of manufacturing light weight product using a different cutting edge technologies.

Fig. 3: Lightweight bycicle frame for Robot Bik Co.

European Powder Metallurgy Association had issued a brochure, with application of various AM technologies for manufacturing of metal parts and components with topology and mass optimization. Some examples, which they showed in brochure, are Ti6Al4V support for satellite antenna made by EBM with a lightweight design made by topology optimization, lightweight stainless screws, complex CoCr Fuel Injector made by DMLS, hollow Ni 718 turbine blades made by SLM, etc. [9]. This Brochure can be used as guideline for engineers to get a wider picture about AM possibilities. In topology optimisation, AM technologies provide great opportunity for engineers and designers to manufacture parts with best mass-load ratio. Engineers now can design parts which are optimised for loads in particular sections, with greater freedom in the part design and shape. Some restrictions that exist in classical manufacturing are not present in AM manufacturing. In the case where it is necessary achieve higher surface quality, the machining is mandatory and an attention in part design is needed. The AM has shown significant advantages in the manufacturing of the products with optimised mass.

Another application of AM has found in the tooling process for injection moulding. Since the AM technologies offers great design and manufacturing freedom, manufacturers of injection mould tools saw their opportunity to widely use this technology. Most important factor in injection moulding is quality of the part and cycle time. Quality of the part is depended up on surface quality of the mould, polishing capabilities and adhesion of the tool material. Cycle time is the second important factor even though it is a widespread opinion that it is first and most important factor. This is the true only if efficiency is not taken in consideration. Efficiency in injection moulding could be interpreted as production of the good parts for shortest cycle time. Two previously mentioned factors are interdependent. Using AM technology, it is possible to achieve lower cycle time with better part quality. This is achievable by using a cooling channels designed near by the surface of the tool. This kind of cooling channels are called “conformal cooling” channels. This type of cooling channels is hard to achieve using other manufacturing technologies than AM, and in this way, traditional straight cooling channels can be replaced with channels that follows geometry of the part. There are no limitations regarding channel tooling accessibility since they are being made during additive manufacturing process. Some research of optimisation, die conformal cooling channels had been performed by Suchana A, J. et all [10,11]. Authors used ANSYS workbench to analyse different channels cross section geometry, length and pitch number. The application of this type of the cooling have been results in cycle time reduction from 22% to 45% [12]. Authors underlined importance of temperature at the end of the channels, which depends upon channels length and cross section dimension. Research of AM conformal cooling for LEGO, gave lowest temperatures at the channels ends (inlet 20C°, outlet 51°C) Fig. 4 a). Cycle reduction of up to 42% was done for child goblet by Polymold Fig. 4 b) [13].



a) b)

Fig. 4: Example of conformal cooling chanels in tools

Tool insert with conformal cooling for LEGO

Conformal cooling for BKL, Polymold

More advantages and application of the additive manufacturing in the tooling production using DMLS are presented by EOS GmbH, manufacturer of DMLS machines [14, 15].

Additive manufacturing also making its path in medical application. Nowadays, AM gives the possibility to produce custom medical implants with porous structure and tailored mechanical properties toward patients’ needs such as custom hip implants [16]. Cranioplasty surgery use AM technology to make implants shapes that perfectly fit a patient anatomical structure with good aesthetical results after recovery [17, 18].

Fig. 5: Example of custom made Foot orthoses [19]

Research about use of AM for manufacturing custom foot orthoses was also done [19]. Benefit of technology is fast and custom gained Foot orthoses and prosthetic sockets with good fit and adequate strength, which brings better comfort to a person. Only thing that could be drawback is based on financial aspect, dealing with the high manufacturing cost.

Maybe biggest potential of AM application is in Aerospace industry. This is one of most demanding industry area, constantly developing, where more and more demanding tasks are being posted to the engineers, regarding mass reduction and efficiency of machinery. A typical demand is a turbine development and manufacturing. The AM can meet demands in manufacturing complex and challenging structures. During turbine blade development and manufacturing, AM started to be irreplaceable due to reduction of the time and cost.

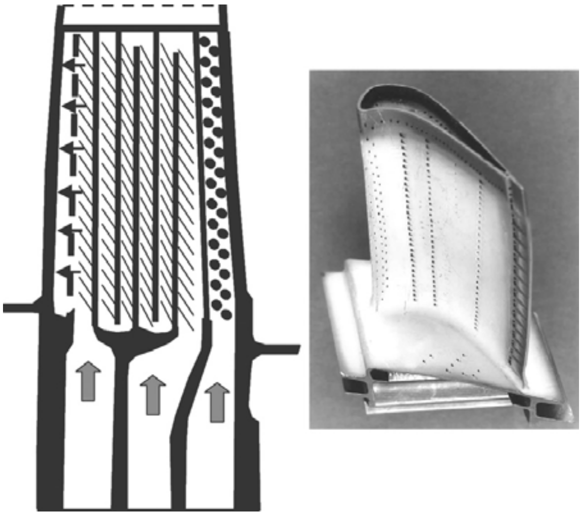


Fig. 6: Example of cooling circut inside blade [20]

Turbine blades are very complex machine parts, whose manufacturing is not so simple due to complex geometrical conditions. Outer surface shape complexity is one part of the problem, another problem is inner cooling channels, being built inside blade. Efficiency of turbine blade is depended from operational temperature. This temperature can sometimes exceed melting temperature of the blade material. Channels should cool the turbine blade and keep the temperature under melting point. Couple of the cooling methods can be used, such as: micro cooling passages that goes close to the blade surface, latticework (vortex) cooling, turbulated channel cooling etc. [20]. Due to small dimension and complex topography, inside blade, it is hard to imagine any other technology for manufacturing these types of cooling channels, other than AM.

Taking into account all advantages, the AM will be widely spread in the industry as well and on consumer market, in the near future. It has a great potential to be irreplaceable in development of new products, custom production and single product manufacturing, where small number of pieces is needed.

2. LIMITATIONS

Taking in consideration all presented by now it sounds like AM is almost “almighty” technology with almost no limitations. This is far from truth. This technology demand changes in approach of part manufacturing. In AM the material is not being taken off, but added where is needed. Production in the layers gives opportunity to take off restrains regarding shape complexity in large percent, but complete absence of machining process is questionable.

Some of AM technology limitations are:

- Minimal wall thickness is 0,4mm for DMLS; 0,3-0,5mm for SLM; 0,6-1mm for EBM;
- Building volume is limited according machine,
- Limited amount of material powder types is available,
- The price of the material is high due to powder manufacturing process cost,
- Supports are needed in manufacturing process,
- Surface quality,
- Residual stresses.

In addition to the above, there are more limitations, and they can all cause the difficulties during the production process or in exploitation.

Minimal wall thickness is in correlation with integrity of previously sintered layers. Integrity of previously sintered material must not be endangered and must enable sintering and good bond of successive layers. In this way, separation of the sintered material from the built part and crash of work is prevented. This all depends from laser, electro beam or wire diameter. The bigger diameter demands the grater wall thickness of the part. For example, it is not possible to manufacture wall of 0.3mm thickness with laser or wire diameter of 0.5mm. This is technological restrain.

Part dimensions are conditioned by building volume dimension and amount of material at disposal for manufacturing. Manufacturing is usually performed in vacuum or inert atmosphere, in order to prevent oxidation during the process of sintering. Building volume dimension is sometimes better to be small, in production of small scale parts due to lower cost and higher speed of production. The example is production of jewellery from gold. Gold as a material is very expensive and pieces of jewellery are rather small parts. In this case machines with large building volume are not suitable for production from two reasons. The first reason is the amount of material required for the production of the part which has a small volume. Second reason is the time for application of material is bit higher and raises production time in certain percent. Compromise could be powder and wire feed technology, where material is applied only where needed and material stock is depended just from the part volume.

The materials which can be used for AM will play a significant role where the process will be used. Materials are mostly based on Titanium alloys, Aluminium alloys, Nickel alloys, Chrome alloys. Metal alloys, available for classical manufacturing technologies are not suitable for Additive manufacturing. Most interesting metal alloys for AM technologies are being selected and prepared on the specific way. In the AM machines, the metal alloys are mainly used as powder or wire. Powder materials are usually made by gas or water atomisation. This type of the process production of powder is expensive and gives a limited amount of material which can be used.

Regarding AM process of metal parts, the beginning of manufacturing process must start from base plate. The base plate is a metal plate from material that corresponds to material of the part that needs to be built. For instance, base plate for building parts from aluminium alloys, need to be made from aluminium alloy, etc. The reason for this is compatibility of two materials in the contact, which will lead to the better bonding between parts and building plate. The base plate has double role. One is, to position part on it, keep the part in fixed position and enable precise building one layer over the other. Second role is to transfer heat from the built part away.

As a part of process, melting and solidification of material is done in small volume in short period of time. Result of this are residual stresses in built parts [22,23]. If residual stresses overcome limit of tensile stress, micro cracks can occur [24,25]. To keep part not to curl or deviate, a good connection between part and base plate is mandatory. In the case of the part deformation or curling, the job crash or more serious, damage of the machine due to collision of the moving elements with built part, can happened. The residual stress can be lowered down or even eliminated, using heat treatment or hot isotactic pressuring [23,26]. It is noticed that residual stresses are lower in parts where base plate is heated on higher temperatures [27]. This is the characteristic for EBM process [28]. To prevent curling and detaching parts from base plate, support connection between part and plate must be strong enough. Strong residual stresses can induce cracks on the support structure, as it is shown on Fig. 7.

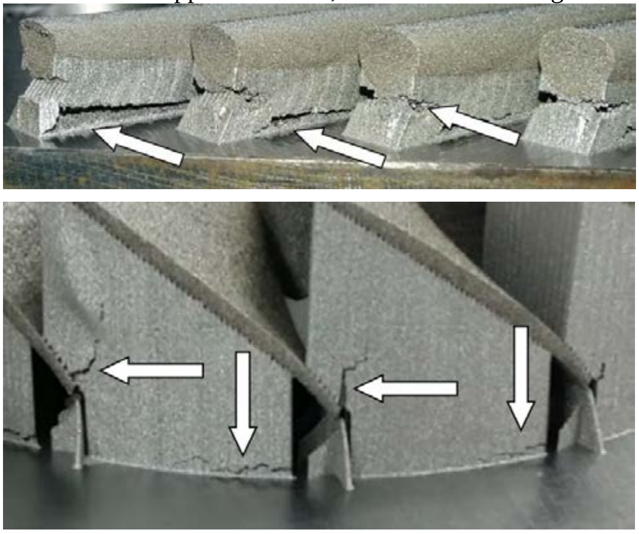


Fig. 7: Example support structure cracks, caused by residual stress on DMLS build part

On the picture (Fig. 7.) cracks are marked on the support structure, between building plate and the part.

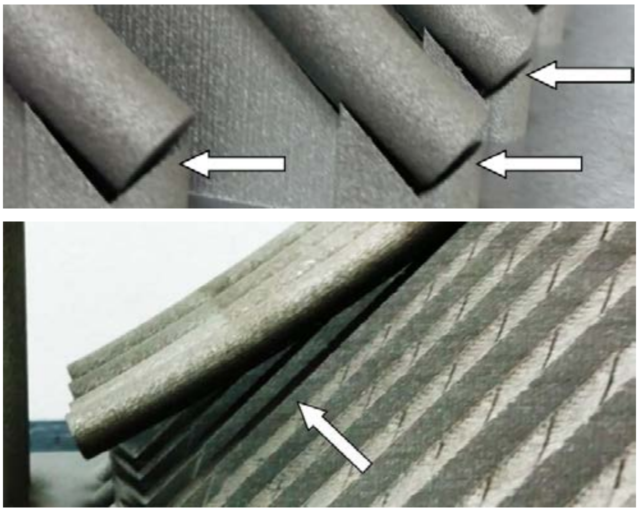


Fig. 8: Example of support structure deatach, caused by residual stress on DMLS build part

For easier detach of parts from support structure, a teeth are generated as bond of support and parts. Teeth need to be strong enough to hold part fixed and enable easy detach of the parts from the supports. If teeth structure is not strong enough, residual stress can cause detachment of the part from support (example of detachment Fig.8). In this case, the collision of mobile elements and parts is certain and job crash is imminent.

Fig. 9: Curling of overhang

The metal powder is not self-supporting so it is not possible to produce the parts without support structure due to weight, forces during powder application and heat generated in melted area. This can be problem if overhangs are neglected in process of support generation. Small overhangs can cause curling, over burn and jam of the machine. This happened during DMLS process where recoater jammed with curled material of small overhanging structure without support (Fig.9). In this case, it was not possible to continue with the production process because the overhanging surface was damaged. The influence of the supports on the overhanging surfaces on the AlSi10Mg parts has been presented in the research of Atzeni. E et all [29].

As a part of the process, porosities in parts are present in certain amount. This phenomenon is present as a consequence of process the laser sintering. For example, in DMLS or SLM process, laser power, laser diameter, speed, offset, layer thickness and scanning speed, has influence in presence of porosities and voids in material [30,31]. It is possible that for different machines and same material, porosities and inclusions presence are completely different.

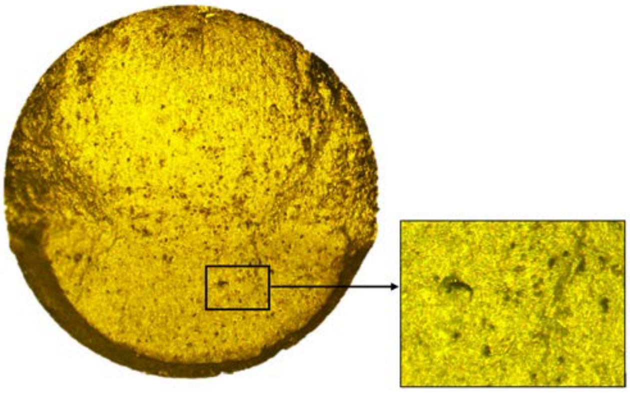


Fig. 10: Break surface of MS1 (EOS Gmbh) DMLS built sample

3. CONCLUSION

Advantages of technology offers great freedom in manufacturing complex shape, light weight parts with topology optimisation, tools for mould industry, prosthetics, and medical implants. AM enables fast production of metal parts without additional tools just with use of 3D CAD model. Considerably saves in the time of development a new product, in production of prototypes or small series can be achieved by using AM. This technology is almost irreplaceable for manufacturing of complex internal structures like conformal cooling channels and lattice structures.

Cost efficiency of AM is disputable. Machines themselves have comparable prices with modern CNC machines, but the material price is still high compared to stock material.

AM offers wide possibilities in custom product manufacturing but it will not completely replace classical production technologies in the near future.

Designers and engineers must be introduced with AM and properly educated, in order to understand all advantages and limitations of the new technology. AM offers great freedom in part shape, but residual stress, porosities, surface roughness, part dimensions, available materials and additional post processing, are just some of the main restrains which needs to be considered.

ACKNOWLEDGEMENT

This research is part of a project that has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 734455.

REFERENCE

[1] Bourell, D. L., et al. "A brief history of additive manufacturing and the 2009 roadmap for additive manufacturing: looking back and looking ahead." Proceedings of RapidTech (2009): 24-25.

[2] Herderick, E. "Additive manufacturing of metals: A review." Materials Science & Technology (2011): 1413-1425.

[3] Aliakbari, Mina. "Additive manufacturing: State-of-the-art, capabilities, and sample applications with cost analysis." (2012).

[4] Yan, Chunze, Liang Hao, Ahmed Hussein, Simon Lawrence Bubb, Philippe Young, and David Raymont. "Evaluation of light-weight AlSi10Mg periodic cellular lattice structures fabricated via direct metal laser sintering." Journal of Materials Processing Technology 214, no. 4 (2014): 856-864.

[5] Manfredi, D., Flaviana Calignano, Elisa Paola Ambrosio, Manickavasagam Krishnan, Riccardo Canali, Sara Biamino, Matteo Pavese et al. "Direct Metal Laser Sintering: an additive manufacturing technology ready to produce lightweight structural parts for robotic applications." Metall. Ital 10 (2013): 15-24.

[6] Light, Cost and Resource Effective – Researching Sustainability of Direct Metal Laser Sintering (DMLS)

[7] http://www.renishaw.com/en/first-metal-3d-printed-bicycle-frame-manufactured-by-renishaw-for-empire-cycles--2415

[8] http://www.renishaw.com/en/blog-post-a-3d-printed-mountain-bike-that-you-can-buy-today--389

[9] European powder metallurgy association, Introduction to additive manufacturing technologies, A Guide for Designers and Engineers, 2015, 1st edition.

[10] Jahan, Suchana A., and Hazim El-Mounayri. "Optimal Conformal Cooling Channels in 3D Printed Dies for Plastic Injection Molding." Procedia Manufacturing 5 (2016): 888-900.

[11] Jahan, Suchana A., Tong Wu, Yi Zhang, Hazim El-Mounayri, Andres Tovar, Jing Zhang, Douglas Acheson, Razi Nalim, Xingye Guo, and Weng Hoh Lee. "Implementation of Conformal Cooling & Topology Optimization in 3D Printed Stainless Steel Porous Structure Injection Molds." Procedia Manufacturing 5 (2016): 901-915.

[12] Scott Young, “Additive Manufacturing Applications for the Tooling Industry: Custom Conformal Cooling for Injection Molding”, Bastech, Inc, 2016.

[13] Augustin Niavas, Shaping the future of die and moulds: EOS tooling applications, EOS, Krailling, (2010)

[14] Shellabear, Mike, and Joseph Weilhammer. "Tooling applications with EOSINT M." EOS Whitepaper, Krailling (2007).

[15] Mayer, Siegfried. "Optimised mould temperature control procedure using DMLS." EOS Whitepaper, EOS GmbH Ltd (2005): 1-10.

[16] Parthasarathy, Jayanthi, Binil Starly, and Shivakumar Raman. "A design for the additive manufacture of functionally graded porous structures with tailored mechanical properties for biomedical applications." Journal of Manufacturing Processes 13.2 (2011): 160-170.

[17] Jardini, A. L., M. A. Larosa, M. F. Macedo, L. F. Bernardes, C. S. Lambert, C. A. C. Zavaglia, R. Maciel Filho, D. R. Calderoni, E. Ghizoni, and P. Kharmandayan. "Improvement in Cranioplasty: Advanced Prosthesis Biomanufacturing." Procedia CIRP 49 (2016): 203-208.

[18] Jardini, André Luiz, Maria Aparecida Larosa, Rubens Maciel Filho, Cecília Amélia de Carvalho Zavaglia, Luis Fernando Bernardes, Carlos Salles Lambert, Davi Reis Calderoni, and Paulo Kharmandayan. "Cranial reconstruction: 3D biomodel and custom-built implant created using additive manufacturing." Journal of Cranio-Maxillofacial Surgery 42, no. 8 (2014): 1877-1884.

[19] Roland K. Chen, Yu-an Jin, Jeffrey Wensman, Albert Shih, Additive manufacturing of custom orthoses and prostheses—A review, Additive Manufacturing, Volume 12, Part A, October 2016, Pages 77-89, ISSN 2214-8604, https://doi.org/10.1016/j.addma.2016.04.002.

[20] Bunker, R. S. Innovative gas turbine cooling techniques. WIT Press, Southampton, UK, 2008.

[21] https://github.com/Gongkai-AM/Machine-Guides/blob/master/Arcam%20EBM%20Guide.md

[22] P. Edwards, M. Ramulu, Fatigue performance evaluation of selective laser melted Ti–6Al–4V, Materials Science and Engineering: A, Volume 598, 26 March 2014, Pages 327-337, ISSN 0921-5093, http://dx.doi.org/10.1016/j.msea.2014.01.041.

[23] Kasperovich, Galina, and Joachim Hausmann. "Improvement of fatigue resistance and ductility of TiAl6V4 processed by selective laser melting." Journal of Materials Processing Technology 220 (2015): 202-214.

[24] Sanz, C., and V. García Navas. "Structural integrity of direct metal laser sintered parts subjected to thermal and finishing treatments." Journal of Materials Processing Technology 213.12 (2013): 2126-2136.

[25] Zeng, Kai, Deepankar Pal, and Brent Stucker. "A review of thermal analysis methods in laser sintering and selective laser melting." Proceedings of Solid Freeform Fabrication Symposium Austin, TX. 2

[26] Pal, Snehashis, et al. "The Effect of Post-processing and Machining Process Parameters on Properties of Stainless Steel PH1 Product Produced by Direct Metal Laser Sintering." Procedia Engineering 149 (2016): 359-365.

[27] Campanelli, Sabina Luisa, et al. Capabilities and performances of the selective laser melting process. INTECH Open Access Publisher, 2010.

[28] http://www.arcam.com/technology/products/arcam-a2x-3/

[29] Atzeni, Eleonora, and Alessandro Salmi. "Study on unsupported overhangs of alsi10mg parts processed by direct metal laser sintering (dmls)." Journal of Manufacturing Processes 20 (2015): 500-506

[30] Aboulkhair, Nesma T., et al. "On the formation of AlSi10Mg single tracks and layers in selective laser melting: Microstructure and nano-mechanical properties." Journal of Materials Processing Technology 230 (2016): 88-98.

Gong, Haijun, et al. "Analysis of defect generation in Ti–6Al–4V parts made using powder bed fusion additive manufacturing processes." Additive Manufacturing 1 (2014): 87-9