Materials Today: Proceedings 45 (2021) 277–283

Contents lists available at ScienceDirect

Materials Today: Proceedings

journal homepage: www.elsevier.com/locate/matpr

A review on advances in 3D metal printing

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ARTICLE INFO

Article history:
Received 3 August 2020
Received in revised form 4 October 2020
Accepted 14 October 2020
Available online 16 December 2020

Keywords:
Metal Additive Manufacturing
Metal Printing Advances
Z-Axis Strength
Factors Affected

ABSTRACT

This is review paper on advances in 3D metal printing. There are many 3D printing methods are available for different type materials. The 3D part is manufactured directly from 3D virtual part which is drawn in software like catia, solidworks, UGNX and etc. and the manufacturing is almost same in all type of machine which is built up of material layer by layer approach. But in this paper we will see the advances in 3D metal printing and the melting process used in metal is difficult and different than plastic. Additive manufacturing features freedom to part for part consolidation, part complexity, part design, lightweighting and design for application in 3D printing like automobile application, aerospace, marine, oil and gas applications. The techniques of 3D printing are explained in this report. But 3D manufacturing is not as good as conventional machining since the parts are a week in strength in Z-direction. There are some factors which reduce 3D part strength like a surface finish, porosity, etc. are discussed in this report and also one case study is prepared for factors affecting the part.

Selection and peer-review under responsibility of the scientific committee of the 4th International Conference on Advanced Research in Mechanical, Materials and Manufacturing Engineering-2020.

1. Introduction

Now a days 3D Printing is an emerging field in manufacturing industries since the complex and different types of parts are required according to real life. Additive Manufacturing is also known as 3D printing, and it is the process of joining two similar materials to make a part form 3D CAD model, usually carried out layer by layer manufacturing as opposite to subtractive manufacturing process. The 3D CAD file is needed to be designed in software like Solidworks, Catia and UGNX etc. After the designing the part, the part should be save in .STL (STereoLithography) file format and this is standard file format for additive manufacturing. This STL file is put into a 3D printing system. The 3D printing machine has its own software which is used to maintain some parameters like layer thickness to be made, output temperature of laser by controlling the laser thickness, orientation of part to be printed so that less support structure material will required and output density of 3D printed part. It is different from traditional computer numeric controlled (CNC) processes that selectively remove material from a part to create desired geometric shapes. This tool-less manufacturing approach gives the industry less energy use and new design flexibility and shortens time to market. The main applications of additive manufacturing [1] are rapid tooling, rapid prototyping, composite parts and direct part manufacturing. The two main sources of any 3D printings machines are:

- Energy Source
- Input Raw Material

The input raw material can be plastic or metal powder or wire and in case of an energy source, an electron beam or arc is used (Fig. 1).

This paper aims to tell the advances in 3D metal printing, problems in 3D metal printing, strength in Z-direction of metal printing and the case study in dental prosthetic restorations is also gave to understand the advancement in 3D metal printing. The above introduction tells that there are many different techniques of 3D manufacturing techniques but some of them are similar to each other. In the next chapter, various applications are discussed with different manufacturing methods.

1.1. Method of metal 3D printing

1.1.1. Selective laser sintering / melting (SLS/SLM)

Selective laser sintering [2] is a powder-based technology. A laser as a source of energy is used to bond or sinter the powder

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https://doi.org/10.1016/j.matpr.2020.10.436
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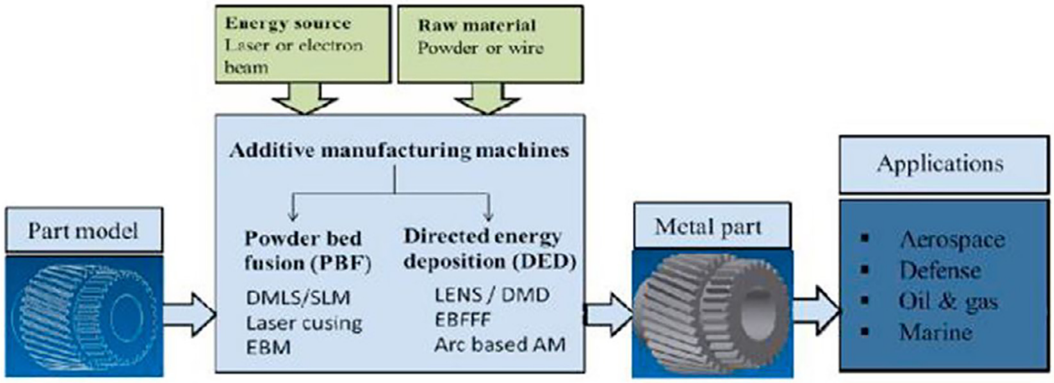

Fig. 1. Common metal additive manufacturing process [1].

layer by layer into a solid part. The powder needs to be fine grains and suitable thermoplastic properties so that the metal can be viscous, flows and solidifies quickly. Layer thickness depends upon the laser power. The laser is travel along with the cross-section of a part according to layer cross-section at that time (Fig. 2).

The system is mainly consists of laser, scanner, roller or powder delivery mechanism and fabrication powder system. This SLS system begins with spreading the powder from powder delivery to fabrication piston. The spreading is done by the roller onto the platform where the part is being to produce [2]. The spreading of powder is forward stroke of roller and same roller is used to level the powder on fabrication piston by using reverse stroke of roller so that the surface of part bed will get homogenize. The powder is usually preheated just below its melting temperature by using a heating mechanism to reduce the porosity, thermal distortion, shrinkage, requirement of laser power and to improve the laser absorption and wettability. The most common heating mechanisms are resistive heaters, feed cartridges and infrared heaters.

After [2] the powder bed is spread the high power laser beam is scan on powder bed, the scanning is corresponds to the cross-section of sliced surface of part of CAD model. The computer system is used to control the laser beam and the scanning of the is laser is integrated to the same, which heats the powders corresponding cross-section of sliced part enough to melt partially the sintered powder and totally melts the fine particle so that the current layer will get to stick previous layer. Once the scanning of current layer will done, the powder delivery piston moves up and the fabrication piston moves down, and new layer of powder is deposited. The movement of piston is depends upon the layer thickness of powder bed and power of laser beam. The power of laser beam depends on the penetration depth of heat on powder bed and part means the higher power of laser beam the higher thickness of penetration depth of heat, but lower the thickness of layer better the surface finish of finished part. This process will continue until the complete three dimensional parts is being made. Afterwards, the unsintered powder is removed by using pump and the part is cleaned by using brushes and the powder can be recycled. The part can take considerable amount cool down time before the part is taken from the chamber. In case of SLS, the overhang part does not require any extra support; the unsintered loose powder itself acts as a support to part. This is major advantage of the SLS process. The part manufactured by SLS is utilised to generate prototypes and models, moulds, tools and patterns required for short-run production.

Material

- Polyamides, Polystyrenes
- Thermoplastic Elastomers
- Stainless Steel, Bronze, Tool Steel, Zinc

Application

- Prototypes: - Investment Casting, automotive Hardware, Wind Tunnel Models.

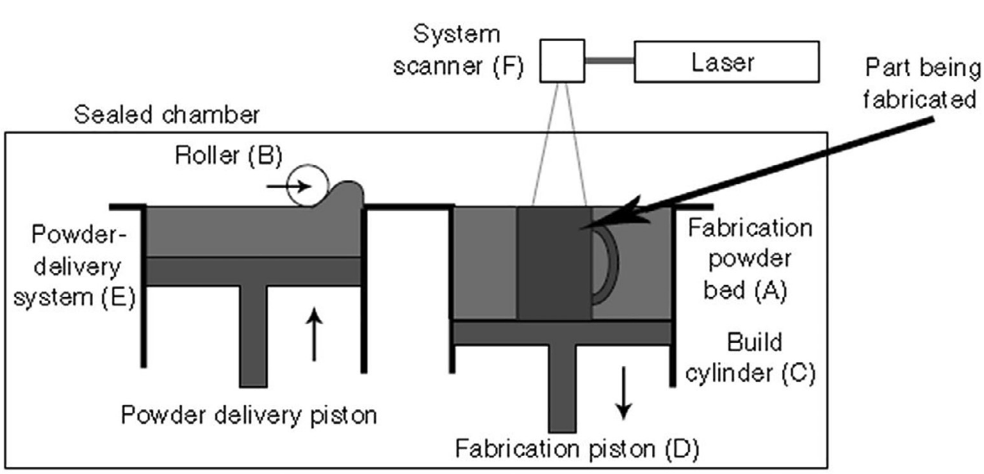

Fig. 2. A laser sintering process.

- End-Use Parts: - Aerospace, military, medical, and electronics hardware.
- Rapid manufacturing of tooling, jigs, and fixtures.

Advantages

- Sintering powder itself use as a support structure for the sintered part, no extra support structure is required.
- Parts possess high strength and stiffness.
- Complex Structure with interior components can be manufactured without trapping the material inside.
- The parts can be print with the fully functional part.

Disadvantages

- Porous and brittle
- Prone to shrinkage and warping
- Produces a lot of waste
- Expensive

1.1.2. Electron beam melting (EBM)

The Electron beam melting process [3] is established in the year of 1990s at the University of Sweden. It is also similar to a SLS method based on powder technology but the laser scanner is replaced with an electron beam of 4 KW to produce fully dense part. Due to nature of laser sintering process the porosity cannot easily be avoided. The melting of powder takes place when electron at the half the speed of light strikes on the powder surface, then that will induces the kinetic energy. For conductive material, in general, the electron beam is more energy-efficient than a laser. Fig. 3 shows powder-based machine and a part is fabricated on an EBM. The part is designed in a 3D CAD program or created from a patient's CT-scan. As explained in introduction the part is saved in STL file format and uploads in machine. The part is built layer-by-layer up by melting metal powder with the EBM process. The outcome is a 3D metal part with a functional part, which can be directly used in operation. The parts are fabricated in a vacuum and to enhance material properties and limit internal stresses the temperature in a vacuum chamber is maintained at about 1000 °C.

A layer of powder metal is spread on the powder bed or platform which is placed in chamber of a vacuum. A metal powder is preheated to reduce the residual stress concentration in finished part which prevents the distortion. The electron beam [4] gun used to selectively sinter the preheated metal powder by decreasing the speed or increasing the beam power. The electrons emitted from electron beam are heated over 2500 °C and with half the speed of light these electrons are accelerated through the anode as shown in Fig. 3. A magnetic lens brings the beam into focus, and another magnetic field controls the deflection of the beam. After this the focused electron beams hits the powder bed, kinetic energy is developed and converted into the heat energy which is used to melts the metal powder. By controlling the number of electrons in beam the power is controlled. To get well defined hardening of fabricated part the cooling should be controlled. As with other processes, the parts require some final machining after fabrication. The processing of part in a vacuum provides a clean environment that improves metal characteristics. After completing the one layer the powder bed platform is lowered and new layer of metal powder is spread by roller mechanism, the same roller is used to level the powder bed. This process will continue until the complete three dimensional parts is being made. The outcome of this process is fabrication of fully dene part. The finished part is used to generate prototypes, models, moulds, tools, patterns and even the part can be directly used in a fully functional operation.

Materials

- Titanium
- Chromium-Cobalt Alloys

Advantage

- Manufacturing speed. In EBM, the beam can be separate to heat the metal powder in different places simultaneously, which significantly speeds up production. A laser must scan the surface point by point.
- Pre-heating the powder before it melts limits the deformations and thus reduces the need for reinforcements and supports during manufacturing.

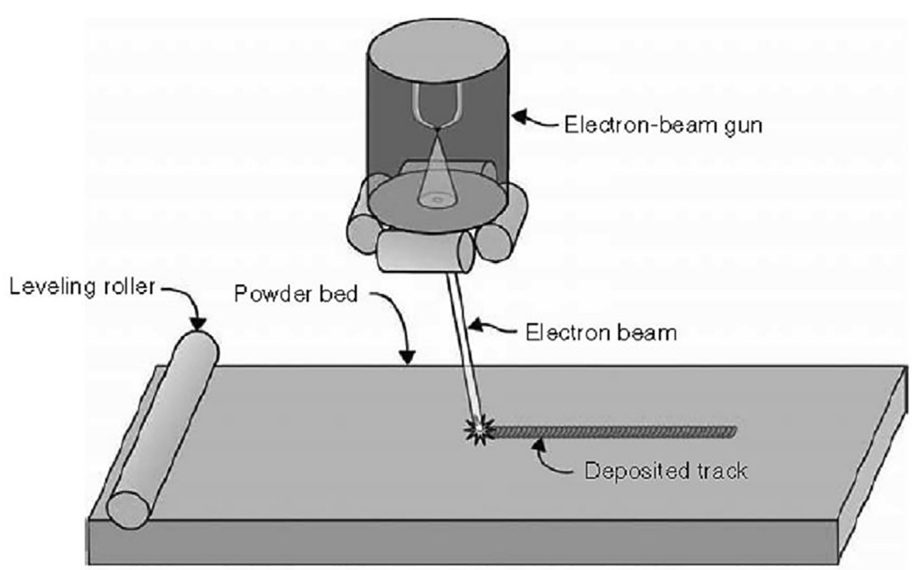

Fig. 3. EBM melting the powder using the speed of the electrons.

Disadvantages

- Precision. At the powder level, the electron beam is a little wide than the laser beam, which reduces the accuracy.
- The size of the parts that can be manufactured. On the other hand, laser machines offer manufacturing volumes at least twice as high.

1.1.3. Direct metal deposition (DMD)

The basic system [5] is similar to SLS and EMB only melting process of metal powder is different and in this process the computer-controlled laser is used which will assist direct metal manufacture. The powder metal together with the high power laser is utilized in DMD system to build highly dense metal structure. The part is built layer-by-layer under the control of software to validate parameters like mechanical and geometric integrity.

The whole system in enclosed in chamber that is clear with argon so that the oxygen level will be below 10 ppm [6]. Due to low level of oxygen there is no impurity pick up at time of deposition. The laser beam usually travels through the centre of the head and is focused to a small spot by one or more lenses. To fabricate each layer of object the X-Y plane table is moves in raster fashion. After completing one layer the head moves vertically upwards. The metal powder is feed through the feeding system; this feeding system has the ability to flow small quantities of metal powder very precisely. By using inert pressurized carrier gas and by gravity the metal powder is delivered and which is circulated across the circumference of head. Whenever the feeding is not required an inert gas is used to shield the metal pool from atmospheric oxygen for better control of properties and by providing better surface wetting to get layer to layer adhesion (Fig. 4).

Materials

- Ti-6Al-4V
- Inconel 625
- Stainless Steel

Applications

- Production of direct functional parts
- Moulds
- Dies: - Aluminium, Tool Steel.

Advantages

- At reasonable speed, this process has the ability to build a part with good mechanical properties and have fully dense part.
- For high value components, DMD process is efficient method that reduces time to market, speed and cost.

Disadvantages

* There are other issues to be improved, such as surface finish, dimensional accuracy, microstructure control and residual stress built into components.
* The traditional DMD or RP processes are using three-axis tables, and thus support structures are very often needed in building overhang parts.

2. Factors affecting the performance of metal 3D printing

- Quality of Raw Material
- Environmental Controlled Machine Lab

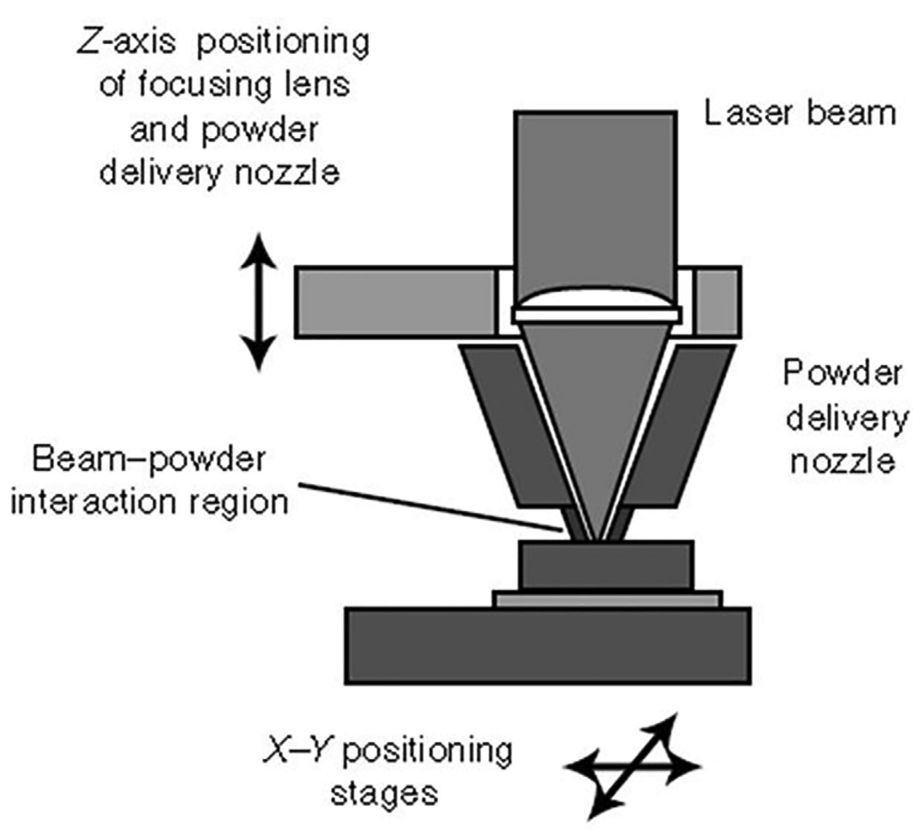

Fig. 4. The schematics of the DMD process.

• Enough Power Supply

If the above factors are not controlled then some of the defects will appear.

2.1. Surface finish

The surface finish [Fig. 5(a)] is the main factor of any manufactured part, which usually requires machining [7] after printing the part. Due to poor surface finish, the part will have less fatigue strength and part will not meet the design specification. To meet the design specification post-processing of the part is necessary which add-in cost in the part economy. A bad surface quality results due to the layer manufacturing part looks like steps are created on the surface of a part. To prevent this type of defects finer particles of powder should use therefore finer layer thickness can be print.

2.2. Porosity

When a part is being printed in 3D [8], small cavities are form within the part is called porosity. It can cause due to powder used in the process or 3D printing process itself. The density is reduced due to these microscopic porous holes which are formed in a part and can lead to fatigue and cracks. Porosity in a part may also be increased if the powder is too loosely packed or the increase in particle size than the layer thickness.

2.3. Density

The porosity of a part is inversely related to its density. As shown in Fig. 5(b) the porosity [9] increases the the density of a part decreases and the more likely it is to crack or to experience fatigue under pressure. For critical applications, a density of above 99 per cent is required.

2.4. Residual stress

Residual stress is a result of contraction and expansion, cooling and heating that occurs during the metal 3D printing process. When residual stress exceeds the tensile strength of the substrate or printing material, defects, such as warpage of the substrate or cracking in the part, can occur [Fig. 6(a)].

2.5. Cracking

The springing from pores within a part, when the melted metal solidifies cracking may occur or during heating of further an area [Fig. 6(b)]. Stress may occur when the energy source is too strong, during the process of solidification. Delamination may also occur, leading to cracks between layers. If the powder is not melted sufficiently, this may happen as a result.

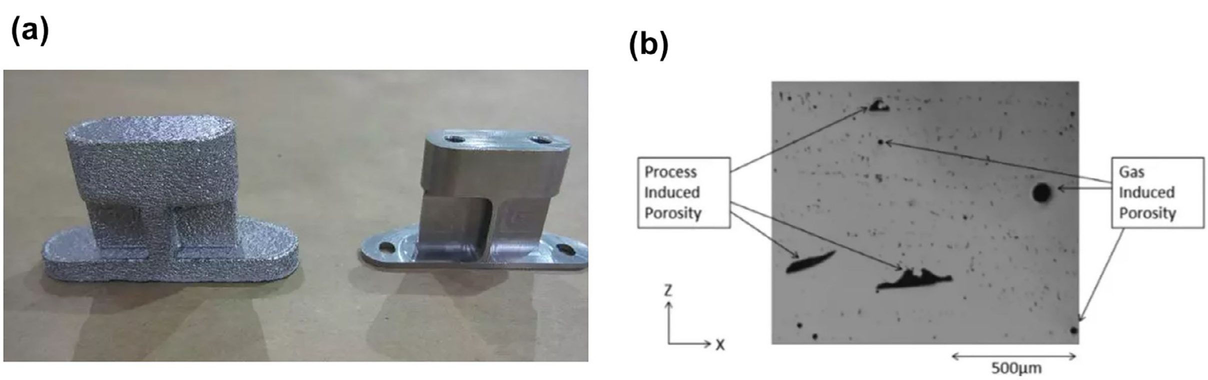

Fig. 5. (a) Two Ti-6Al-4V titanium alloy brackets 3D printed via EBM, before and after machining. (Image courtesy of NASA) [10]. (b) Light optical microscopy showing the comparison of process-induced [10].

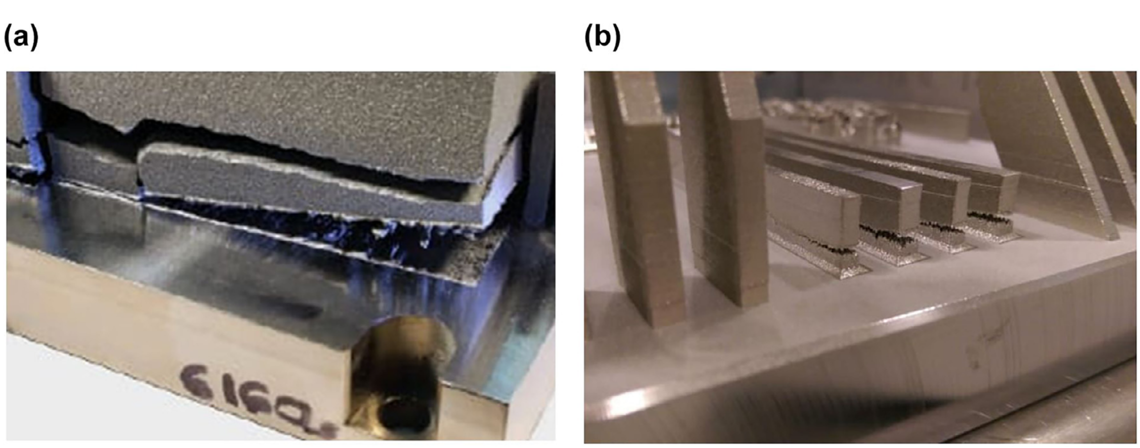

Fig. 6. (a) A titanium parts is ripped from the build plate during a powder bed process due to residual stress buildup [10]. (b) Crack during the powder bed process [10].

Fig. 7. Warpage (Image courtesy of the Center for Additive Manufacturing and Logistics at North Carolina State University) [10].

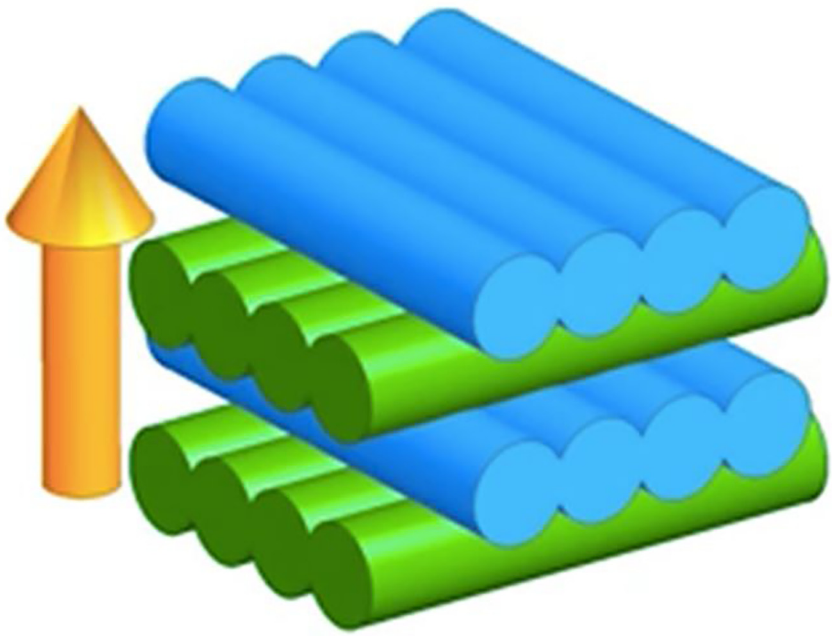

Fig. 8. The strength of the internal bond between the layers of a 3D printed part, which is built up layer by layer, impacts Z-strength [10].

2.6. Warpage

The warp on beings on substrate when substrate material strength decreases the substrate of the thermal stress, eventually causing the part themselves to warp and they collide with part when the powder is recoated. The support structure of ideal number should be placed in a right location the warpage can be stopped (Fig. 7).

2.7. Strength in Z-direction

The 3D printed parts are basically strong in X-axes and Y-axes because there is continuous deposition of metal but in Z-axes direction after completing the one layer the next layer is deposited therefore the bonds in vertically upward direction is weak. The bonds between these layers are anisotropic. As the properties of anisotropic material these 3D printed part is also have different value of physical properties in different direction when measured (Fig. 8).

To understand the critical on the overall part strength impact, the users of 3D metal printer like commercial and industrial should be imperative and user should also think about the end-use and functional application. The user should learn the Z- direction strength of every material. This chapter gives detail information about the different methods of metal 3D printing and factors affecting and strength in Z-direction which always problem in metal 3D printing.

3. Conclusion

From the above study, the conclusions are made as:

- The strength of the 3D printed part is not exactly as conventionally machined parts and it depends on many factors like quality of raw material, an environment in which the machine is working and power supply used for machine.
- The series of presently available materials is even now very large, ranging from nickel alloys and titanium alloys to high-grade stainless steels and is increasing rapidly.
- Additive Manufacturing technologies proposing product difficulty for free but demanding a new product design custom-made for AM.
- Metal 3D printing will reduce the number of trial and error tests, reduce the time between the design and production, mitigate defects and make the printing of more metallic products cost-effective.

CRediT authorship contribution statement

Basavraj Gadagi: Conceptualization, Methodology, Validation, Investigation, Resources, Writing - original draft, Writing - review & editing, Visualization. **Ramesh Lekurwale:** Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] T. Duda, L.V. Raghavan, 3D metal printing technology, IFAC-PapersOnLine 49 (29) (2016) 103–110, https://doi.org/10.1016/j.ifacol.2016.11.111.

[2] L. Lü, J.Y.H. Fuh, Y.S. Wong, L. Lü, J.Y.H. Fuh, Y.S. Wong, Selective laser sintering, laser-induced mater, Process. Rapid Prototyp. (2001) 89–142, https://doi.org/10.1007/978-1-4615-1469-5_5.

[3] A.H. Chern, P. Nandwana, R. McDaniels, R.R. Dehoff, P.K. Liaw, R. Tryon, C.E. Duty, Build orientation, surface roughness, and scan path influence on the microstructure, mechanical properties, and flexural fatigue behavior of Ti–6Al–4V fabricated by electron beam melting, Mater. Sci. Eng., A 772 (2020) 138740, https://doi.org/10.1016/j.msea.2019.138740.

[4] V. Lunetto, M. Galati, L. Settineri, L. Iuliano, Unit process energy consumption analysis and models for Electron Beam Melting (EBM): effects of process and part designs, Addit. Manuf. 33 (2020) 101115, https://doi.org/10.1016/j.addma.2020.101115.

[5] A. Ramakrishnan, G.P. Dinda, Direct laser metal deposition of Inconel 738, Mater. Sci. Eng., A 740-741 (2019) 1–13, https://doi.org/10.1016/j.msea.2018.10.020.

[6] H.K.J., M. Arora Advances in Additive Manufacturing, Modeling Systems and 3D Prototyping 2020 Springer International Publishing 10.1007/978-3-030-20216-3

[7] B.A.T. Polonsky, T.M. Pollock, Absorb Energy and Can Create Defects, (n.d.) 8–10.

[8] Davoud Jafari, Wessel W. Wits, Bernard J. Geurts, Metal 3D-printed wick structures for heat pipe application: Capillary performance analysis, Appl. Therm. Eng. 143 (2018) 403–414, https://doi.org/10.1016/j.applthermaleng.2018.07.111.

[9] Shahir M. Yusuf, Nong Gao, Influence of energy density on metallurgy and properties in metal additive manufacturing, Mater. Sci. Technol. 33 (11) (2017) 1269–1289, https://doi.org/10.1080/02670836.2017.1289444.

[10] D. Shamvedi, C. Danilenkoff, S. Karam, P. O'Leary, R. Raghavendra, 3D Printed Periodic Structures in a Horn Antenna for Side-lobe Reduction using Direct Metal Laser Sintering, in: Loughbrgh. Antennas Propag. Conf. (LAPC 2017), Institution of Engineering and Technology, 2017. https://doi.org/10.1049/cp.2017.0244.

Further Reading

[1] Hongfei Wang, Joong Yeon Lim, Metal-ceramic bond strength of a cobalt chromium alloy for dental prosthetic restorations with a porous structure using metal 3D printing, Comput. Biol. Med. 112 (2019) 103364, https://doi.org/10.1016/j.compbiomed.2019.103364.

[2] J.-P.P. Kruth, P. Mercelis, L. Froyen, M. Rombouts, X. Wang, T. Laoui, L. Froyen, Binding mechanisms in selective laser sintering and selective laser melting reference: solid free, Fabr. Proc. 2315 (2004) 357–371, https://doi.org/10.1108/01445150310698652.

[3] Pan Wang, Jie Song, Mui Ling Sharon Nai, Jun Wei, Experimental analysis of additively manufactured component and design guidelines for lightweight structures: a case study using electron beam melting, Addit. Manuf. 33 (2020) 101088, https://doi.org/10.1016/j.addma.2020.101088.

[4] Lawrence E. Murr, Sara M. Gaytan, Diana A. Ramirez, Edwin Martinez, Jennifer Hernandez, Krista N. Amato, Patrick W. Shindo, Francisco R. Medina, Ryan B. Wicker, Metal fabrication by additive manufacturing using laser and electron beam melting technologies, J. Mater. Sci. Technol. 28 (1) (2012) 1–14, https://doi.org/10.1016/S1005-0302(12)60016-4.

[5] Christoph R. Pobel, Fuad Osmanlic, Matthias A. Lodes, Sebastian Wachter, Carolin Körner, Processing windows for Ti-6Al-4V fabricated by selective electron beam melting with improved beam focus and different scan line spacings, RPJ 25 (4) (2019) 665–671, https://doi.org/10.1108/RPJ-04-2018-0084.

[6] I.D. Jung, J. Choe, J. Yun, S. Yang, D.Y. Yang, Y.J. Kim, J.H. Yu, Dual speed laser re-melting for high densification in H13 tool steel metal 3D printing, Arch. Metall. Mater. 64 (2019) 571–578, https://doi.org/10.24425/amm.2019.127580.

[7] O. Fogel, S.S. Cohen, Z. Kotler, Z. Zalevsky, Mechanical properties of 3D metallic microstructures printed by laser induced forward transfer, Procedia CIRP 74 (2018) 285–289, https://doi.org/10.1016/j.procir.2018.08.112.

[8] Christoph R. Pobel, Christopher Arnold, Fuad Osmanlic, Zongwen Fu, Carolin Körner, Immediate development of processing windows for selective electron beam melting using layerwise monitoring via backscattered electron detection, Mater. Lett. 249 (2019) 70–72, https://doi.org/10.1016/j.matlet.2019.03.048.

[9] C.J. Todaro, M.A. Easton, D. Qiu, D. Zhang, M.J. Bermingham, E.W. Lui, M. Brandt, D.H. StJohn, M. Qian, Grain structure control during metal 3D printing by high-intensity ultrasound, Nat. Commun. 11 (2020) 1–9, https://doi.org/10.1038/s41467-019-13874-z.

[10] J. D'alessio, A. Christensen, 3D Printing for Commercial Orthopedic Applications: Advances and Challenges history of 3D printing in medicine and orthopedic applications, (2019). https://doi.org/10.1016/B978-0-323-58118-9.00007-5.

[11] Daxian Cao, Yingjie Xing, Karnpiwat Tantratian, Xiao Wang, Yi Ma, Alolika Mukhopadhyay, Zheng Cheng, Qing Zhang, Yucong Jiao, Lei Chen, Hongli Zhu, 3D printed high-performance lithium metal microbatteries enabled by nanocellulose, Adv. Mater. 31 (14) (2019) 1807313, https://doi.org/10.1002/adma.201807313.

[12] T. Mukherjee, T. DebRoy, A digital twin for rapid qualification of 3D printed metallic components, Appl. Mater. Today 14 (2019) 59–65, https://doi.org/10.1016/j.apmt.2018.11.003.

[13] Seung Chan Kim, Woo Lam Jo, Yong Sik Kim, Soon Yong Kwon, Yong Soo Cho, Young Wook Lim, Titanium powder coating using metal 3D printing: a novel coating technology for cobalt–chromium alloy implants, Tissue Eng. Regen. Med. 16 (1) (2019) 11–18, https://doi.org/10.1007/s13770-018-0168-0.

[14] D.D. Hernandez, Factors affecting dimensional precision of consumer 3D printing, Int. J. Aviat. Aeronaut. Aerosp. 2 (2015), https://doi.org/10.15394/ijaaa.2015.1085.

[15] Nader Asnafi, Tawfiq Shams, David Aspenberg, Christina Öberg, 3D metal printing from an industrial perspective—product design, production, and business models 3D-metalldruck aus industrieller sicht—produktdesign produktion und geschäftsmodelle, Berg Huettenmaenn Monatsh 164 (3) (2019) 91–100, https://doi.org/10.1007/s00501-019-0827-z.

[16] R. Rumman, D.A. Lewis, J.Y. Hascoet, J.S. Quinton, Laser metal deposition and wire arc additive manufacturing of materials: an overview, Arch. Metall. Mater. 64 (2019) 467–473, https://doi.org/10.24425/amm.2019.127561.

[17] Tuan D. Ngo, Alireza Kashani, Gabriele Imbalzano, Kate T.Q. Nguyen, David Hui, Additive manufacturing (3D printing): a review of materials, methods, applications and challenges, Compos. B Eng. 143 (2018) 172–196, https://doi.org/10.1016/j.compositesb:2018.02.012.

[18] Yonghan Lee, Sangki Park, Changho Byun, Sun-Kyu Lee, Liquid cooling of laser-driven head light employing heat spreader manufactured by 3D metal printing, Int. J. Precis. Eng. Manuf.-Green Tech. 5 (2) (2018) 295–301, https://doi.org/10.1007/s40684-018-0031-8.

[19] C. Buchanan, L. Gardner, Metal 3D printing in construction: a review of methods, research, applications, opportunities and challenges, n.d.

[20] https://insights.globalspec.com/article/7458/how-strong-are-3d-printed-metal-parts-metallurgical-integrity-in-metal-additive manufacturing [18th Oct 2019, 9.54 AM]