BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Volumul 66 (70), Numărul 3, 2020
Secţia
CONSTRUCŢII DE MAŞINI

CRITICAL ANALYSIS OF THE EXISTING SOLUTIONS IN THE FIELD OF METAL 3D PRINTERS

BY

LUCIAN-PETRU PĂVĂLOI*, FLORIN NEGOESCU,
BOGDAN CIOBANU and CĂTĂLIN GABRIEL DUMITRAŞ

“Gheorghe Asachi” Technical University of Iaşi,
Faculty of Machine Manufacturing and Industrial Management

Received: July 14, 2020
Accepted for publication: September 21, 2020

Abstract. The aim of this paper is to critically analyse the existing solutions in 3D printers for metal parts. The paper will present a short introduction in the field of 3D printers with a specific focus on the ones designed to 3D print metal parts, the existing solutions on the market and their analysis, concluding with a clear comparison of the advantages and the disadvantages observed and ending with the forecasted evolution of this domain.

Keywords: analysis; 3D printing; metal parts.

1. Introduction

The history of 3D printing starts in the 19th century when the first attempts of making tridimensional sculptures were made, by the French self-entitled painter, sculptor and photographer François Willème (Education Pro on Genesis Framework, 2019), who remained know in the history for inventing the photo sculpture (Fig. 1).

---

*Corresponding author; *e-mail*: pavaloilucian@gmail.com

Fig. 1 – The projection apparatus and pantograph in the studio of François Willème.

The evolution of 3D printing gained more development later on, after 30 years, when Joseph E. Blanther registered a patent for a new method of producing topographical relief maps using different layers of material, overlapping and trimming them, in order to show the heigh variations (Fig. 2).

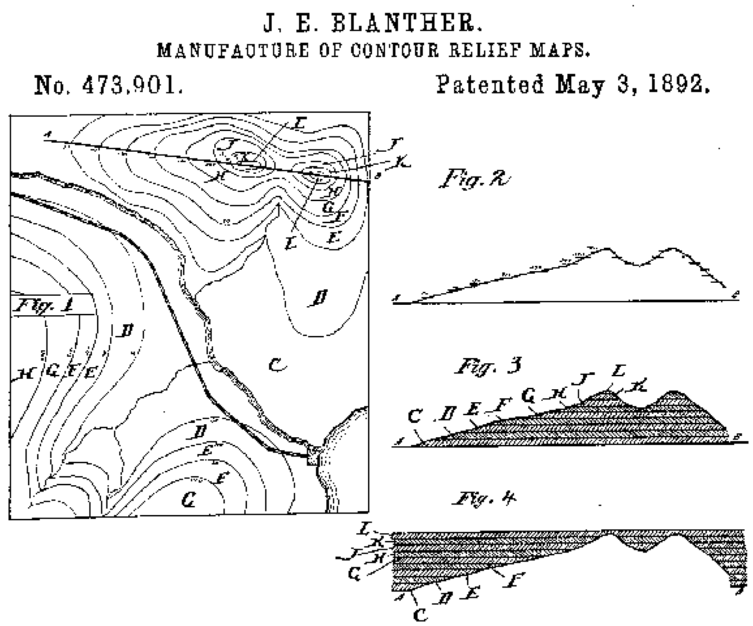


Fig. 2 – J.E. Blanther, Manufacture of contour relief maps patent no. 473.901.

Several similar developments have been made and some other patents were registered over the years, culminating with the announcement of Charles W. Hull in 1992 showing the world the first stereolithographic 3D printer produced by the Stratasys company (Fig. 3).

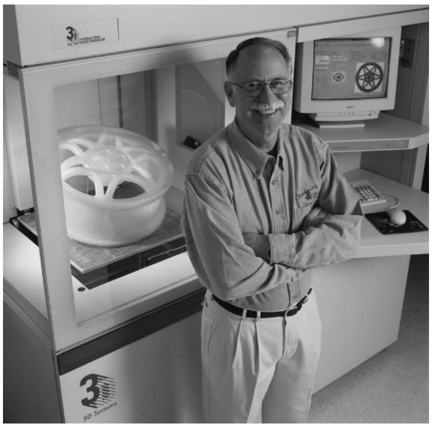


Fig. 3 – Charles W. Hull, the founder of the 3D Systems Company
and the inventor of the first SLA 3D printer.

Fast forward to the present days, we can say that the industry boomed, filling the gaps, from hobby size to 3D printing farms and other industrial size 3d printers, especially in the prototyping area but also by creating new niches and possibilities never thought to be possible thus far (the 3D printing of blood vessels and other body organs, the 3D printing of tools (Fig. 4) to be used in space (Jennifer Harbaugh, 2014) and basically anything one could think of).

Fig. 4 – Commander Barry Wilmore showcasing the 3D printed rachet key,
designed by Noah Paul-Gin,
Made In Space Inc. engineer, in the International Space Station 42.

According to one of the latest studies (Arne Holst, 2018) in the industry, the main 3d printing technologies available in the present and the most commonly used are the following: FDM (Fused deposition modelling), SLS (Selective laser sintering), SLA (Stereolithography) followed by DMLS (Direct metal laser sintering) and SLM (Selective laser meting) (Fig. 5).

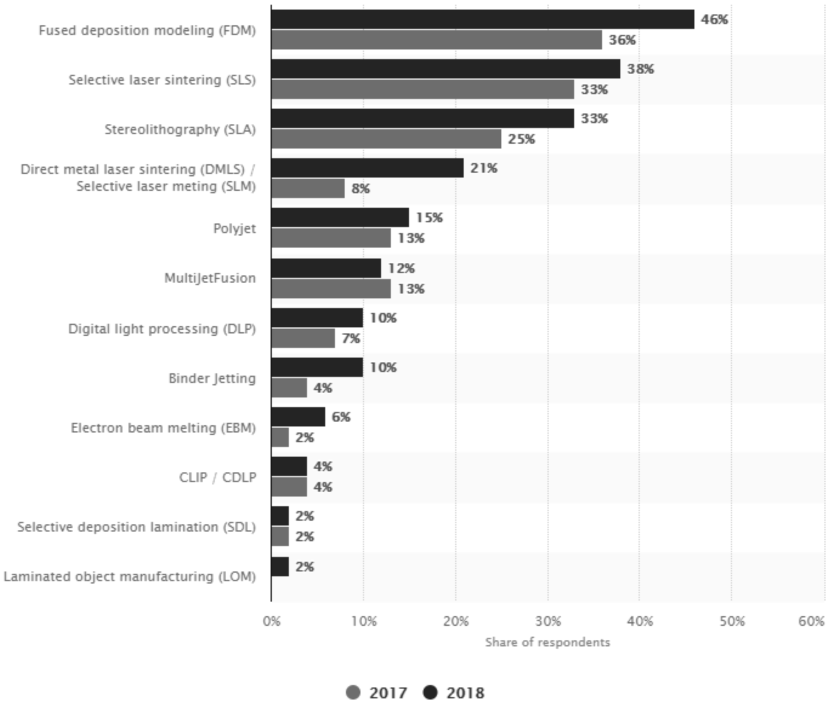


Fig. 5 – The 3D printing technologies from 2017 to 2018.

2. Critical Analysis of the Existing Solutions in the Field of Metal 3D Printers

Following the idea of overcoming the limitations of the parts created using the “conventional” 3d printing technologies available so far (mostly FDM and SLA), there have been made innovations towards the 3d printing of metal parts or parts with similar structure or strength as those from metals. Thus, the metal 3d printing has been gaining more and more ground in the last years, on a fair reason, because of the unique practicality and aesthetic proprieties that certain materials, in this specific case, metals and combination of metals, can offer. Another good reason why the metal 3d printing has become such an interesting subject is because some parts can be 3d printed in batches. Some metal 3d printed parts are as good or even better than their traditionally created equivalents.

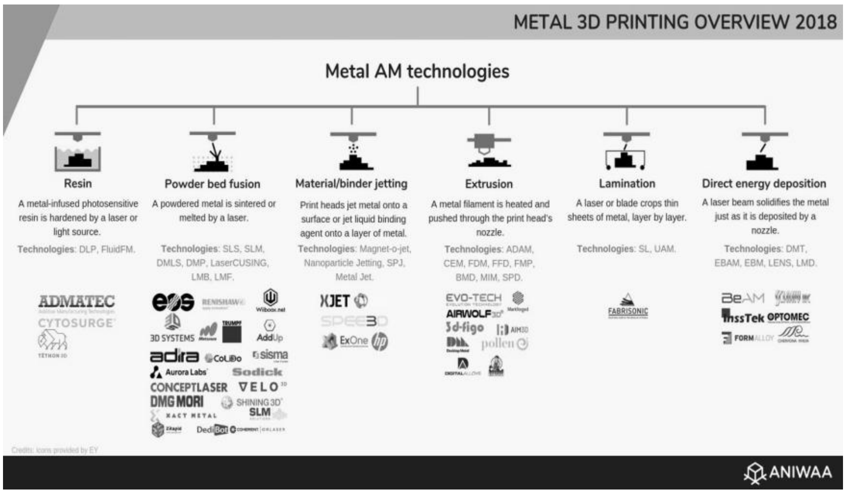
In most of the cases of traditional manufacturing of metal parts, transforming the metal raw material to the finished part is a laborious and long process that in most of the cases requires more than one piece of equipment that usually have high retail prices and are not easily available to the public sector.

A large part of the parts conventionally made before 3D printing result in an excess use of materials, the aircraft manufactures waste up to 90% of the metallic material they use for creating the final component. This is where 3D printing comes into the picture because 3D printing metal parts utilize less energy and reduce the waste close to zero. The finite metal 3D printed parts can also be up to 60% lighter that their conventionally made equivalent. Solely the air space industry saves up millions of dollars every year thanks by reducing the weight of the air crafts thus reducing their fuel consumption.

Many professionals from the industry adopt the metal 3D printing technique to create prototypes or personalized items, even if the price of metal 3D printers is usually high, most of them in the range of 80,000 USD up to 1,000,000 USD. These rather expensive equipment is usually best suited for the air space, automotive, healthcare and engineering industries.

At this moment, several metal 3D printers options (Fig. 6) are available on the market and most of the companies develop their own variations of the existing technologies used in metal 3D printing such as:

- Powder Bed Fusion - PBF: Direct Metal Laser Sintering - DMLS, Direct Metal Printing - DMP, Laser CUSING, Laser Beam Melting - LBM, Laser Metal Fusion - LMF, Selective Laser Sintering – SLS, Selective Laser Toping - SL);
- Directed Energy Deposition - DED: Direct Metal Tooling - DMT, Electron Beam Additive Manufacturing - EBAM, Electron Beam Melting - EBM, Laser Engineered Net Shaping - LENS, Laser Metal Deposition - LMD;
- Metal Material Jetting - MJ or Binder Jetting - BJ: Magnet-o-Jet, Nanoparticle Jetting, Single Pass Jetting - SPJ, Metal Jet;
- Fusible Filament Fabrication - FFF: ADAM - Atomic Diffusion Additive Manufacturing, CEM - Composite Extrusion Modelling, FDM - Fused Deposition Modelling, FFD - Fused Feedstock Deposition, FMP - Filament Metal Printing, BMD - Bound, Metal Injection Moulding – MIM;
- Lamination: Sheet Lamination – SL, Ultrasound additive manufacturing – UAM;
- Resin Metal 3D printing: DLP - Digital Light Processing, Fluid Manufacturing - FM, SLA - Stereolithography.



METAL 3D PRINTING OVERVIEW 2018

Metal AM technologies

Resin

A metal-infused photosensitive resin is hardened by a laser or light source.

Technologies: DLP, FluidFM.

Powder bed fusion

A powdered metal is sintered or melted by a laser.

Technologies: SLS, SLM, DMLS, DMP, LaserCUSING, LMB, LMF.

Material/binder jetting

Print heads jet metal onto a surface or jet liquid binding agent onto a layer of metal.

Technologies: Magnet-o-jet, Nanoparticle Jetting, SPJ, Metal Jet.

Extrusion

A metal filament is heated and pushed through the print head's nozzle.

Technologies: ADAM, CEM, FDM, FFD, FMP, BMD, MIM, SPD.

Lamination

A laser or blade crops thin sheets of metal, layer by layer.

Technologies: SL, UAM.

Direct energy deposition

A laser beam solidifies the metal just as it is deposited by a nozzle.

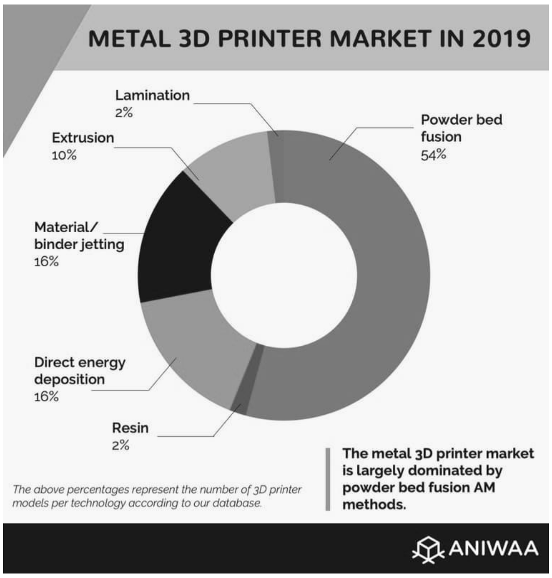
Technologies: DMT, EBAM, EBM, LENS, LMD.

Credits: icons provided by EY

ANIWAA

Fig. 6 – Some of the techniques used in metal 3D printing (Ludvine Cherdo, 2020).

At the present, the most frequently used metal 3D printing technology is Poweder Bed Fusion (Fig. 7) where the equipement creates a tridimensional object using an high power focused laser on a metalic powder. The studies made by the Aniwaa companyu in the year of 2019 clearly show how the metal 3D printer market is shared among available technologies.



METAL 3D PRINTER MARKET IN 2019

The above percentages represent the number of 3D printer models per technology according to our database.

The metal 3D printer market is largely dominated by powder bed fusion AM methods.

ANIWAA

Fig. 7 – A breakdown of the metal 3D printer market by technology types. Source: Aniwaa database (2019).

The materials used in 3D printing can range from very common ones to some very exotic and expensive ones such as: aluminium, steel, brass, cooper, zinc, bronze, titan, Inconel, chromium cobalt, some precious materials such as gold, silver and platinum and other composed metals such as aluminium injected nylon 12.

Most of these materials used in metal 3d printing come in different forms, such as:

- Metallic powder;
- Metallic filament;
- Metallic rod;
- Metallic sheets;
- Metallic filled resin;

Any of the above-mentioned metals and many more can offer unique metal 3D printing mechanical and aesthetical proprieties enlarging the applications area. Analysing the differences among several metals, in special to those with similar proprieties, brings long term advantages when there are specific project requirements.

Each method of materials processing or fabrication (Fig. 8) can impact on structure of the material and thus one can change the characteristics of the fabricated material.

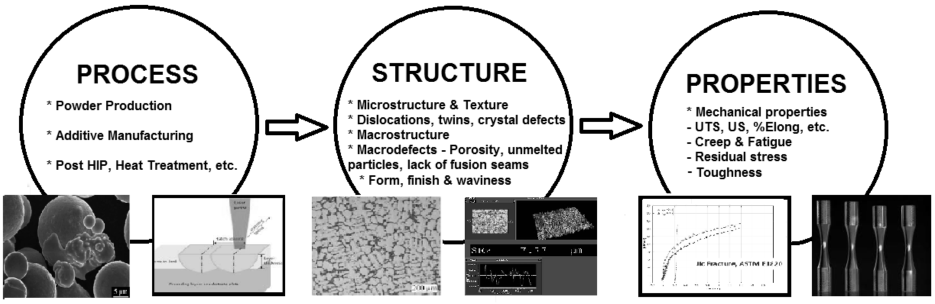


Fig. 8 – Process-structure-property relationships in metal additive manufacturing. Source: NASA, Zygo & Other.

Even if some aspects that involve powder metallurgy and welding characterize additive manufacturing (AM) metallurgy this type of metallurgy has its very own set of relation namely processing-structure-property. The microstructure can be modified by this type processing (crystals, size, orientation and shape of grains), which will lead to change of the physical-mechanical properties of the alloy. These modification also alter the behaviour of the material behave.

Several alloying additions can create an alloy that is brittle if it is used in forging, wrought or rolling processing. Powder metal and additive fabrication could be the new possibility to produce certain highly alloyed materials. The structure of the alloy can be different. For example, titanium based alloys will get more oxygen, which will strengthen titanium. If the level of oxygen is high, the titanium based alloy will crack. Metals obtained by powdered technologies can be contaminated by oxygen and nitrogen, depending on the metal alloy.

Through EBM processes one can obtain residual stress that is less cracking in comparison to processes that use laser melting (LM), direct energy deposition (DED) or wire feeding. This is due to a slowly cooling. DED or wire fed processes could be used to deposit multi-materials, thus obtaining parts that have harder cores and surface resistant to wear. The DED processes can be used in repairing wear or tooling surfaces. The elemental segregation can be reduce by processes that employ melting and solidify the metal deposits. Thus it can be used in developing better microstructure but rapid cooling could lead to delamination and can retain metastable phase thus increasing residual stress. Binder jet deposits are not inclined to delamination, but the “green” parts can be porous and delicate until sintered or fired (Table 1).

Table 1

Comparison Between Primary Metal Additive and 3D Printing Processes. Source ORNL

Defect or feature	LM	EBM	DED - powder fed	DED – wire fed	Binder Jetting	Sheet lamination
Feedstock	Powder	Powder	Powder	Wire	Powder	Sheets
Heath source	Laser	E-beam	Laser	Laser / E-beam	N/A / Kiln	N/A / Ultrasound
Atmosphere	Inert	Vacuum	Inert	Inert / Vacuum	Open air	Open air
Part repair	No	No	Yes	Yes	No	No
New parts	Yes	Yes	Yes	Yes	Yes	Yes
Multi-material	No	No	Possible	Possible	Infiltration	Yes
Porosity	Low	Low	Low	Low	High	At sheet interfaces
Residual stress	Yes	Material dependant	Yes	Yes	Unknown	Unknown
Substrate adherence	Yes	Not typical	Yes	Yes	N/A	Yes
Cracking	Yes	Yes	Yes	Yes	Fragile green bodies	No
Delamination	Yes	Yes	Yes	Yes	No	Yes

Table 1
Continuation

Defect or feature	LM	EBM	DED - powder fed	DED – wire fed	Binder Jetting	Sheet lamination
Rapid solidification	Yes	Yes	Yes	Yes	No	No
In situ aging	No	Yes	No	No	No	No
Overhangs	Yes	Yes	Limited	Limited	Yes	Limited
Mesh structures	Yes	Yes	No	No	Limited	No
Surface finish	Medium – rough	Rough	Medium – poor	Poor but smooth	Medium – rough	Machined
Build clean-up from process	Loose powder	Sintered powder	Some loose powder	N/A	Loose powder	Metal shavings

If considering cracking or residual stress, these represents major problems in the 3D printed metal part manufacturing (Fig. 9). Casting, welding, cold forming can influence the residual stresses level that could determine cracks in components. Residual tensile stresses can decrease fatigue strength. In order to solve the problem it can be done heat treatments to parts in order to decrease the residual stress level, but even so part deformation and cracking can be obtained during this process.

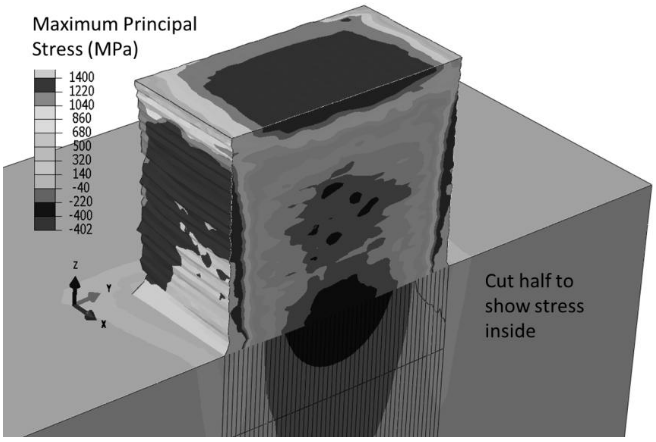


Fig. 9 – Residual stress profile analysis in an additive manufactured part. Source: EWI.

Residual tensile stresses can determine the occurrence of the cracks in components. Shrinkage and segregation can be seen during AM that contains melting and then solidification steps. Liquation can be seen because of the constituents from the alloy that solidify first. After reheating, one can obtain cracks in these liquated regions, usually in PMZ.

The contraction from the liquid phase to solid volume can lead to solidification cracks (Fig. 10), usually these cracks are in the centre of a weld or casting, arc-based additive processes where there is a hotter melt pool heating forms.

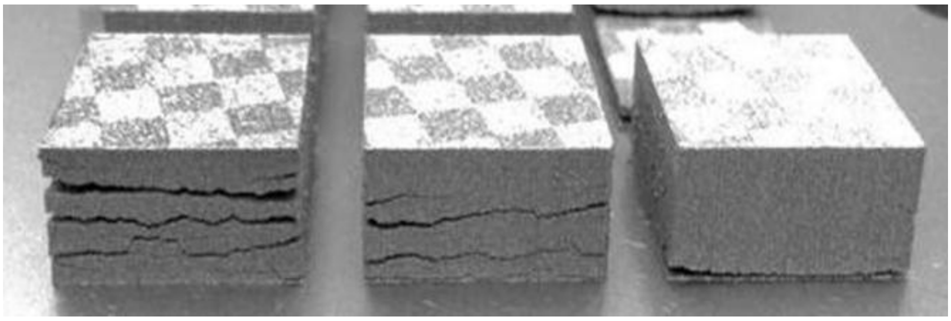


Fig. 10 – Layer delamination and cracking is a common a problem in selective laser melting (SLM). Source: ORNL.

In the "Effect of Si on the SLM processability of IN738LC", (Switzerland Brevet nr. IN738LC, 2016) researchers R. Engeli, et al. reported the appearance of solidification or liquation cracks during selective laser melting AM of Inconel, which was attributed to the lower melting silicon constituent. One would expect liquation and solidification cracking to be less of a problem in electron beam additive processes, which use highly focused, high energy density sources. Layer delamination and cracking is another problem, which can occur in selective laser melting.

Because multiple layers are obtained, heat increase and in that part the o grain or microstructure become coarse. The duration of an EBM process can take between 5 and 80 hours in order to obtain temperature under 100°C after layer melting is finished, depending on the size and form of the parts, so AM part could experience a significant amount of recrystallization and annealing within the chamber.

By heating powders in the air atmosphere one can determine oxidation, so the processes like LM, EBD or DED use inert atmospheres or vacuum. If one cannot controlled the atmosphere in the metal deposition chamber, then it can be seen oxidation and contamination of the deposited material, which can embrittlement the part. Aircraft alloys are usually vacuumed arc re-melted (VAR) in order to produce a cleaner and uniform product with increased properties required for critical applications. Some of AM equipment have a difficult fabrication of the parts from oxidation-prone materials. Mostly the powder is loaded in open air and do not have a specific chamber of loading. Additive systems from SLM Solutions Group AG use inert gas to protect virgin and recovered metal powder from oxidation such as SLM 280 and 500 (Fig. 11) selective laser melting (SLM) machines as well as their PSM sieving stations.

Fig. 11 – SLM machine with powder transport, sieving and storage occurring in a closed system with inert gas atmosphere. Source: SLM Solutions.

When it comes to the Surface finish in the additive manufacturing technology, the surfaces become rougher with respect to conventional processes. Additive parts can be machined in order to obtain a better surface roughness. Superfinishing processes could determine surface improvements without modification of the geometry of the AM parts. Abrasive or honing can be used to improve the surfaces of internal channels. In the NASA technical report “Additive Manufacturing Overview: Propulsion Applications, Design for and Lessons Learned” by Kristin Morgan (United States Brevet nr. MSFC-E-DAA-TN44554, 2017), engineering project manager from the NASA Marshall Space Flight Center, the fatigue performance of selective laser melted 718 nickel-based alloy (UNS N07718) was calculated after various post-build surface finish enhancement processes. Samples with low level of stress were the closest to approach the mechanical properties of the MMPDS design values for NO7718, as shown in Fig. 12.

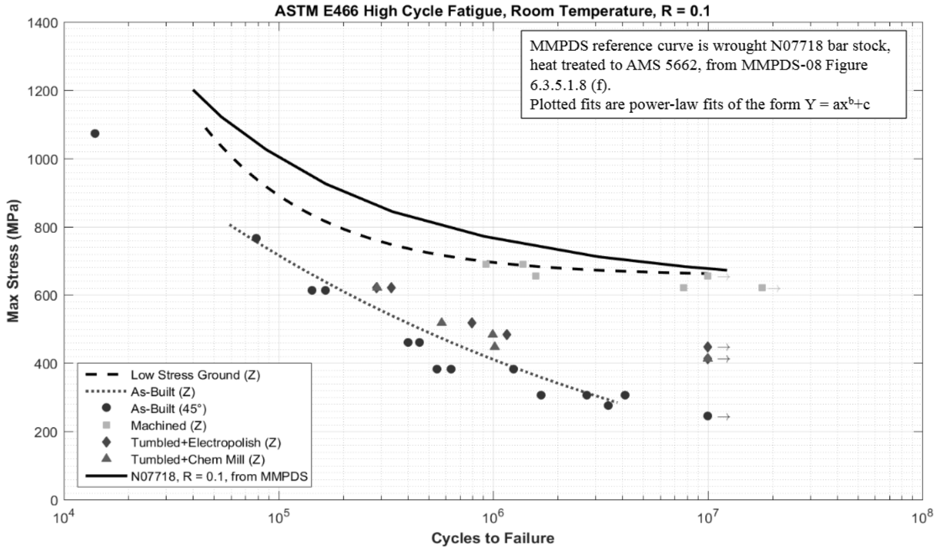


Fig. 12 - High cycle fatigue (HCF) of additive manufactured Inconel 718, demonstrating impact of surface roughness on fatigue life. Source: NASA.

Concerning the porosity and the microstructure of AM metal 3D printing, the rolled, extruded or forged alloys are 100 percent dense and the recrystallization and mechanical deformation in these processes refine the microstructure or grain structure. A better microstructure or grain structure in an alloy provides a greater number of boundaries that can stop dislocations or cracks when the metal is bent. AM parts and certain components do not have a 100% dense material. Printed stainless steels are mainly highly porous on a microscopic scale, which makes them weak and could not be used in some cases. Pores in a material provide initiation points for crack formation (Fig. 13).

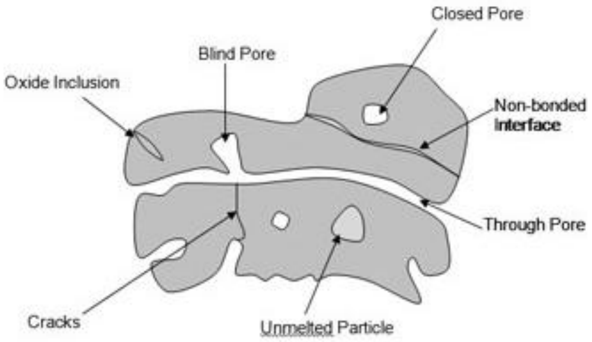


Fig. 13 – Forms of pores, cracks, inclusions, unfused particles and other defects in deposited materials. Source: Plasma Powders & Systems Inc.

Yinmin “Morris” Wang, from California, indicate that “The performance has been awful” (Aerospace Engineering, 2017). The static tensile properties for PM or AM parts are equivalent to manufactured parts, but fatigue and creep properties are sensitive to porosity levels.

According to “The metallurgy and processing science of metal AM” (Fig. 14) in International Materials Reviews, AM parts could contain columnar (especially for the powder bed processes), oriented microstructures. Equiaxed growth in EBM processes can be seen at low gradients of temperature with high liquid-solid interface velocities. In-situ ageing and growth of the grain can be seen in EBM processes as the part cools. The acicular structures have better fatigue characteristics.

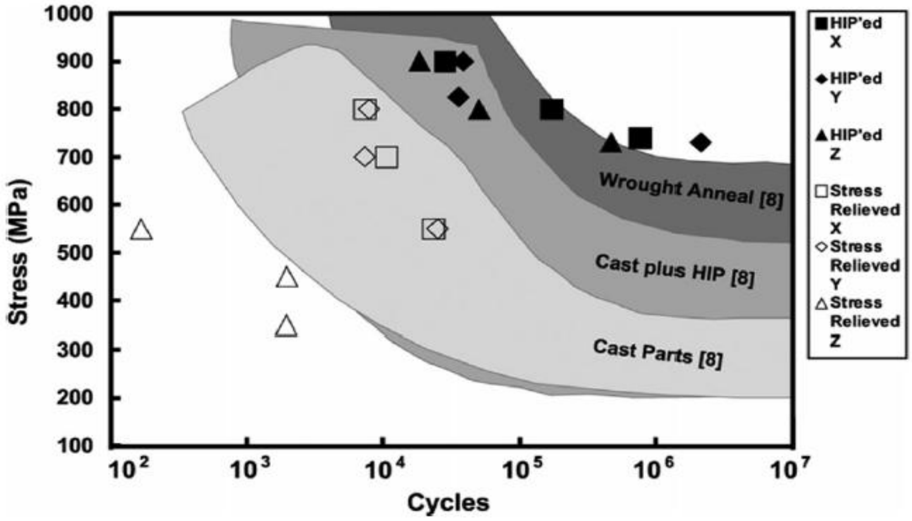


Fig. 14 - Fatigue test results comparing DED, cast and wrought Ti6Al-4V titanium. Source: International Material Reviews.

The properties for additive manufactured parts are influenced by the orientation grain because residual stress and cracks depend on this. Every powder process is characterized by a fibre texture or orientation of the grains. Properties tend to be different based on the directional solidification, so some properties could be enhanced or reduced. Cracks obtained due to fatigue crack in nickel alloys are sensitive to the direction of the crystals relative to the loading axis, so developing the ability to control microstructure and grain orientation is important for critical aerospace components.

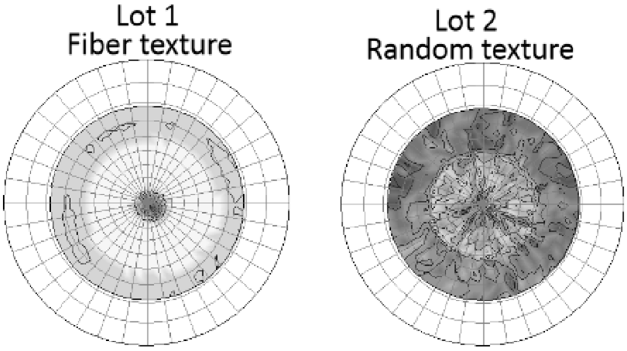


Fig. 15 – Pole figure showing fiber texture in (002) crystallographic direction resulting in higher tensile and fatigue strength of lot 1 samples of EBM additive manufactured Ti6Al4V titanium alloy samples. Source: NASA.

In “AM Research and Development at the NASA Glenn Research Center” report ((United States Brevet nr. WBS 585777.08.20.20.63.03, 2017), it is stipulated that mechanical properties of EBM Ti6Al4V titanium equivalent or superior to MMPDS handbook data values. He notice that processing parameters can modify the texture and impact properties. Lot 1 and lot 2 indicate different mechanical strengths in correlation with texture variation observed by X-ray diffraction (Fig 15). Fig. 16 below indicate the fatigue strength gradient for AM samples taken from the X, Y and Z directions. Z is perpendicular to the deposit surface, X is parallel with the traversing beam and Y is in-plane and perpendicular to Y.

AM properties can match or be enhanced beyond conventional manufactured and cast properties as the structural control of AM evolves. The AM process was underline for break up reinforcing carbide or oxide agglomerates, which should enhance material properties. Also, AM process post-processing parameters need a good control in order to eliminate defects namely porosity (gas or process-induced), high surface roughness, particle contamination from previous material runs (*e.g.*, Nb particles in Ti6Al4V), lack of fusion defects, porosity, residual stress, cracks, warping and undesirable texture. An appropriate thermal processing, namely hot isostatic pressing (HIP) and heat treatments, are necessary to gain superior properties compared to the MMPDS database. Castings and jet engine blades are frequently HIP processed in order to close internal pores and provide dense parts with a better fatigue, toughness and creep properties. HIP increases fatigue strength of AM parts (Fig. 16). On some alloys, the microstructure in powder metal parts can be improved through ageing heat treatments. Surface finish refinement and surface enhancement (shot or laser peening) could be used after HIP in order to further enhance fatigue properties.

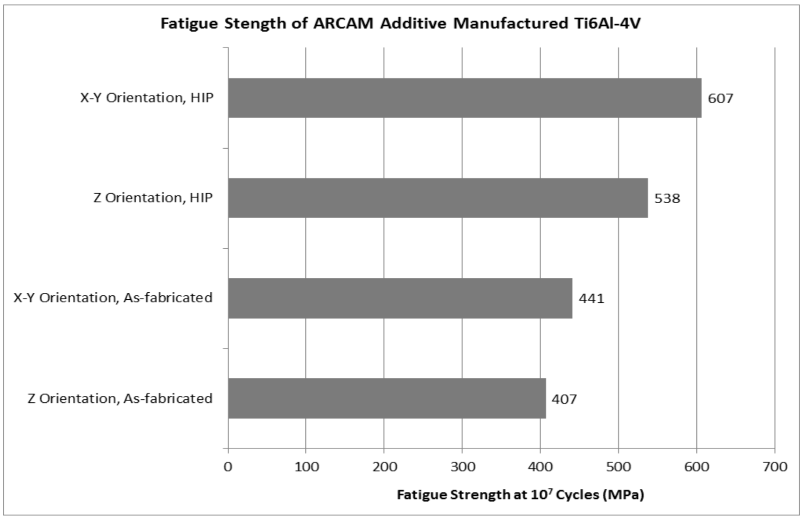


Fig. 16 – Fatigue strength of ARCAM additive manufactured Ti6Al4V.
Source: ASM International.

AM obtain alloys with complex microstructures for applications that implies high-performance materials. Recent research in metal AM lead to new materials with have reduced porosity and enhanced properties obtained by a better microstructures (Fig. 17). In future, the improvement of metal additive part integrity will be obtained by working on the development of improved machine reliability, process quality control, NDE methods for quality assurance, and process control.

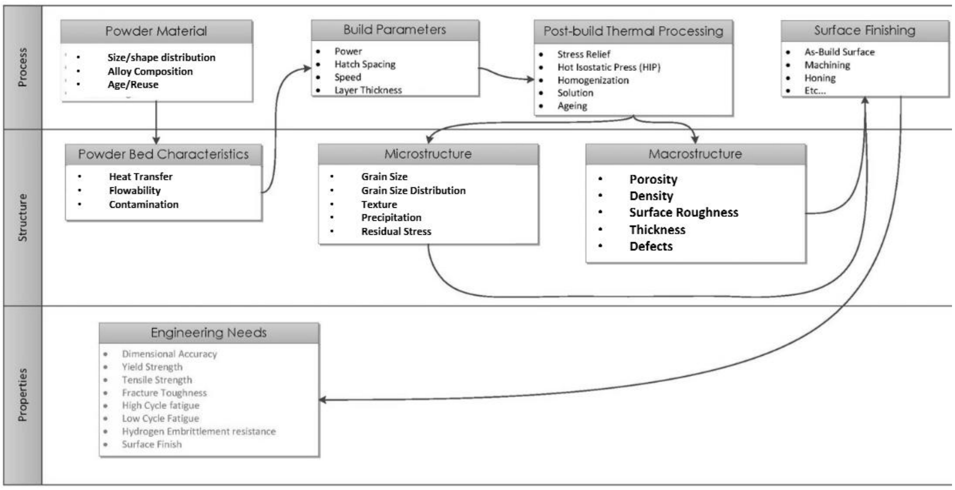


Fig. 17 – Controlling process-structure-property relationships in metal additive manufacturing. Source: NASA Marshall Space Flight Center (Brown).

When considering the challenges of metal 3D printing, there are some specific factors to take into consideration, such as the ones mentioned in the table below:

Table 2

Comparison of the Factors in Favour for Metal 3D Printing versus the Factors in Favour for the Conventional Methods

Factors in favour for metal 3D printing	Factors in favour for conventional methods
Prototyping of small batches / small volumes	Large production volumes
High material costs (*e.g.* waste is low)	Low material cost
Cases where distributed or remote manufacturing is required (space station, military base, research site)	Centralized manufacturing
Materials difficult or impossible to manufacture	Materials easily manufactured by forming, casting, processing, stamping or other processes
High transportation and logistics costs	Low transport and logistics costs
High processing or manufacturing costs	Low processing or manufacturing costs
Unique materials, geometries and complex assemblies (*e.g.* gradients or composition changes, internal flow cavities, printed foam core or honeycomb structure)	Simple shapes or geometries (*e.g.* 2D or flat parts)
It is possible to consolidate complex assemblies into a single complex part	Consolidation of parts is not feasible
The hard surface finish is acceptable	It is necessary to finish the processed or ground surface
Non-critical parts open to new methods	Mission-critical parts that require established processes, material specifications, test standards, and codes

3. Conclusions

Considering how many different interferences can appear in the additive manufacturing process and the assurance of the fact that some materials might adhere to others or not and that some parts can withstand a higher stress or temperature than others, all these are challenges we need to keep in mind.

The long-term objective may be in fact the additive manufacturing production, but this should be a skillset every engineer should develop so that unique components could be designed and integrated in a given system, to take advantage of the opportunities offered. This technology is something that has to be considered from the design phase of the product to be able to best design the structure, to choose the right materials and to work more efficiently from the beginning.

In conclusion, the scientists and engineers within the field, are all in agreement that only the continuous research and time will help to better implementing the complex process of additive manufacturing for metal parts for the systems on nowadays and for the future. Innovative technologies are blooming new capabilities and the additive manufacturing technology is definitely one of the unlimited exploration possibilities.

REFERENCES

Aerospace Engineering, *New 3D Printing Technique Doubles the Strength of Stainless Steel*, 1.11.2017, available at: http://www.aerospacengineering.net/new-3D-printing-technique-doubles-the-strength-of-stainless-steel/, accessed at 02.06.2020.

Arne Holst, *Most Used 3D Printing Technologies in 2017 and 2018*, Aug 1 2018, available at https://www.statista.com/statistics/560304/worldwide-survey-3D-printing-top-technologies/, accessed at 4.12.2019.

Blanther J.E., *Manufacture of Contour Relief Maps Patent*, American Patent No.473.901/1892.

Carter R.W., *United States Patent No. WBS 585777.08.20.20.63.03* (2017, July 17) Retrieved from https://ntrs.nasa.gov/citations/20170008812.

Education Pro on Genesis Framework, 2019, *François Willème and the Photosculpture (Complete History)*, available at https://history-computer.com/francois-willeme-and-the-photosculpture-complete-history/, accessed at 05.12.2019.

Embracing Opportunity: *Additive Technology for Manufacturing*, Marisa Alia-Novobilski, Air Force Research Laboratory, published at 06.01.2017, available at: https://www.wpafb.af.mil/News/Article-Display/Article/1043404/embracing-opportunity-additive-technology-for-manufacturing/, accessed at 03.06.2020.

Jennifer Harbaugh, 22nd of Dec. 2014, *Space Station 3-D Printer Builds Ratchet Wrench to Complete First Phase of Operations*, available at https://www.nasa.gov/mission_pages/station/research/news/3Dratchet_wrench, accessed at 05.12.2019.

Ludivine Cherdo, *The Best Metal 3d Printers in 2020*, 06.02.2020, available at https://www.aniwaa.com/best-of/3D-printers/best-metal-3D-printer/, accessed at 17.02.2020.

Engeli R., Etter T., *Switzerland Patent No. IN738LC* (2016), Retrieved from http://utw10945.utweb.utexas.edu/sites/default/files/2015/2015-67-Engeli.pdf.

Morgan K., *United States Patent No. MSFC-E-DAA-TN44554* (2017), Retrieved from https://ntrs.nasa.gov/citations/20170006561.

ANALIZA CRITICĂ A SOLUŢIILOR EXISTENTE ÎN DOMENIUL IMPRIMANTELOR 3D PENTRU PIESE METALICE

(Rezumat)

Scopul acestei lucrări este de a oferi o analiză critică a soluțiilor existente în domeniul imprimantelor 3D pentru piesele metalice. În această lucrare se va prezenta o scurtă introducere în domeniul imprimării 3D cu un focus specific pe imprimantele 3D capabile de a realiza piese metalice, o analiză a soluțiilor existente în prezent pe piață, urmată de o comparație a avantajelor și dezavantajelor utilizării acestei tehnologii versus tehnologiile convenționale, fiind urmată de o concluzie privind aceste soluții şi o posibilă evoluție a acestui domeniu.