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An overview on Metal printing

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Abstract: This paper reviews the rapidly emerging manufacturing technology that is also called additive manufacturing (AM), direct digital manufacturing, 3D printing, freeform fabrication etc. This paper provides a broad overview on additive manufacturing/ metal printing technologies. AM is capable of producing complex shapes using metals, polymers, ceramics and composites also of reducing waste, lead time and costs.

Keywords: Powder bed fusion (PBF), Binder jetting (BJ), Direct energy deposition (DED)

Introduction:

Additive manufacturing is defined by ASTM as "the process of joining materials to make objects from a 3D model, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms: additive fabrication, additive process, additive technique, additive layer manufacturing, layer manufacturing and freeform fabrication [1][2][10]." This definition refers widely to all materials like metals, ceramics, polymers, composites and biological systems.

Process categories	**Technologies**	**Materials**
Binder Jetting	3D- jetting, Ink-jetting, S-print, M-print	Metal Polymer ceramic
Material Jetting	Polyjet, Ink-jetting, Thermojetting	Photopolymer Wax
Direct Energy Deposition	Direct Metal deposition, Laser Deposition, Laser Consolidation, Electron Beam direct melting	Metal powder and wire
Material Extrusion	Fused Deposition Modelling	Polymer
Sheet Lamination	Ultrasonic Consolidation, Laminated object Manufacture	Hybrids Metallic Ceramics
Powder Bed Fusion	Selective Laser Sintering, Selective Laser Melting, Electron Beam Melting	Metal Polymer Ceramic
Vat Photo-polymerzation	Stereolithography, Digital Light Photography	Photopolymer Ceramic

According to ASTM, the AM technology can be classified into several categories (Table-1) : Binder jetting (BJ), material jetting (MJ), direct energy deposition (DED), sheet laminations (SL), material extrusion (ME), powder bed fusion (PBF), and vat photo-polymerization (VPP) [1] [2]. Due to stacking layers, the parts produced by AM technologies have some anisotropy in specific directions. Selection of appropriate orientation during manufacturing of parts can reduce the anisotropy.

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AM were applied in the area of rapid prototyping first and then tooling.AM can produce 3D structure with high shape complexity. With the development of easy-to-use systems with sufficiently fast build speed and lower system price, AM are facing many challanges such as:- thermo mechanical properties, anisotropy, long term stability, cost, corrosion, creep etc[3].AM has the ability to reduce waste, lead time and costs and also to produce complex shapes.

Additive Manufacturing Techniques:
Currently, most widely used AM techniques in metal printing are:- Powder bed fusion, binder jetting, direct energy deposition.

Powder Bed Fusion (PBF):
PBF is most commonly used for 3D metal printing in dentistry and comes in three types: SLS, SLM, and EBM. In PBF, a selective thermal energy (either by laser or electron beam) fuses the region of a powder bed. This process is used for metals as well as polymers.SLS can be used for a range of polymers, metals and alloy powder while SLM can be only used for certain metals such as steel and aluminium [4]. PBF is more suitable for more accurate complex small size parts [20].
Kruth et.al stated that the binding mechanism highly influenced the build speed and part properties [5]. Fabrizio Fina et. Al worked for suitability of SLS in the medical field using two pharmaceutical grade polymers and found SLS as versatile and practical in this field [6].SLM can effectively produce porous structures that have mechanical and biomedical properties similar to those of human bone [7]. Rafi et.al, found differences in mechanical properties of Ti64 based printed material processed by SLM and EBM [8]. Harish et.al conducted a study to understand the effect of powder characteristics and energy density on 17-4 stainless steel densification and mechanical properties and confirmed that UTS and hardness improved as energy density for atomized water and gas powder improved and atomized gas powder exhibited greater mechanical properties and densification at low energy density [9]. Alberta et.al investigated the effect of post processing heat treatment and of building platform temperature on mechanical properties of LPBF A357 and reported that highest mechanical properties were achieved at 140 ^{0}C and 170 ^{0}C [10]. Fayazafar et.al found is a study that thermal properties are affected by building orientation of steel parts processed through LPB and LPF [12].

Binder Jetting (BJ):
Binder jetting is an additive process that selectively deposits a liquid bonding agent to fuse the powder materials. Since the binder jetting is independent of powder of power source or other temperature related constraint, a wide range of material can be used in the binder jetting process :- metals (titanium alloys, nickel alloys, copper alloys etc.), sand, glass, ceramics, wood etc. [1] [2][11][17].
Sanjay et.al found saturation level and feed-to-powder ratio as critical parameters which influence the mechanical properties [11].Fayazfar et.al stated that the infiltration changes the material character as it improves the mechanical properties [12]. Michael Doyle et.al reported in a study that layer thickness of SS420 and bronze parts affected the mechanical properties than orientation [13].Binder jetting additive manufacturing has applications in the area of medical, biomedical and life science [14]. Yun Bai et.al suggested larger particle size which improves resolution and surface quality [15]. H. Chen et.al reported that for the best surface roughness, the optimal process parameters were :- layer thickness 50µm, printing saturation 90%, heater power ratio 70% and drying time 30s [16]. Succeeding tempering of 420SS parts using BJ additive manufacturing led to reduction in micro hardening due to decomposition of martensite [17]. Huang et.al manufactured thin alumina ceramic cores using BJ additive manufacturing and results showed that increase in ZBC content led to decrease in surface tension of binder [18].

Direct Energy Deposition (DED):
Directed energy deposition is defined as "a process of additive manufacturing in which focused thermal energy is used to fuse materials as they are deposited by melting. In DED powder or wire materials are injected into melt-pool instead of scanning on a powder bed.DED can produce single crystal structure and directionally solidified and also can be utilized in maintenance of high tech components such as turbine blades [19]. DED is preferred for larger parts at high processing rate but rough surface finish [20].
Zavidani et.al printed AlSi10Mg alloy using DED process and reported higher hardness of AlSi10Mg

than conventional cast specimen [21] and also for titanium alloy [23]. Carroll et.al found that additional oxygen in the Ti-6Al-4V component increases yield strength and UTS but slightly reduces ductility [22]. Titanium alloys have an ultrafine basket-weaving microstructure and columnar grains that are much more uniform compared to equiaxed grains [23]. Farayibi et.al manufactured TiB2/ Ti-6AL-4V composites and found hardness of 440-480 HV due to Tib2 reinforcement [24]. Lu et.al concluded that heat input affects stress and distortion strongly but poorly by powder feed rate and suggested controlling heat input as an optimal strategy to diminish both [25]. Lu et.al also suggested the variable layer thickness for optimizing model accuracy in the DED process [25]. Another significant point is that surface finish in PBF is better than DED [20].

Discussions:

This section will discuss the various metals used in different additive techniques. Also process parameters affecting mechanical properties will be discussed.

Rebecca et.al stated that LPBF alloy showed a lower passivity range and strong corrosion as compared to conventional wrought equivalent [26]. Chou et.al fabricated Al10SiMg specimen using LPBF and found yield strength of 380MPa and true ultimate compressive strength of 485 MPa [27]. Michael Doyle et.al stated that layer thickness has a significant effect on mechanical properties as elastic modulus increases with decrease in layer thickness [13]. Sufiiarov et.al fabricated 420 Stainless steel using BJ process and achieved 6.8±0.2 g/cm^3 highest density and HV(0.2) 545±6 microhardness [28]. Pavan Kumar et. al noted that post-processing heat treatment enhanced the part properties like wear, tensile strength and hardness of DMLS 420 stainless steel specimen [29].Gong et.al stated that over-melting of Ti-6Al-4V parts using PBF powder bed caused by high energy density leads to defects that cause the vaporization within the melt pool [30]. Johannes et.al stated that laser power can improve the effective absorptivity [31]. Mower et.al tested the mechanical behavior of metallic alloys (AlSi10Mg & Ti6Al4V) and found high ductility with higher strain hardness and yield strength [32].

Table 2 shows the metals, different additive techniques, parameters and affected mechanical properties:

Author	**Technique**	**Metal**	**Parameter**	**Mechanical properties**
Kruth [5]	PBF	Stainless steel	Build speed	Part properties
Rafi [8]	SLM, EBM	Ti64	Cooling rate	Microstructure & tensile strength
Harish [9]	PBF	17-4 stainless steel	Energy density	UTS, Hardness
Alberta [10]	LPBF	A357	Building platform temperature	Yield strength, UTS, elongation break
Fayazafar [12]	LPB & LF BJ,	Ferrous alloy	orientation	Thermal property
Sanjay[11]	BJ	SS316L	Saturation level, feed to power ratio	Mechanical properties
Micheal [13]	BJ	SS420 and bronze parts	Layer thickness, orientation	Elastic modulus, UTS
Yun Bai [15]	BJ	Copper	Particle size	Resolution, surface quality
H. Chen [16]	BJ	L16OA	Layer thickness,	Surface roughness

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			printing saturation, heater power ratio	
Carroll [22]	DED	Ti6Al4V	oxygen	Yield strength,UTS
Lu [25]	DED	Ti-6Al-4V	Heat input, powder feed rate, layer thickness	Stress, distortion
Pavankumar[29]	DMLS	420SS	Post processing heat treatment	UTS,Wear, hardness
Johannes[31]	LPBF	SS	Laser power	Absorptivity

Conclusion:

AM is a process of making 3D objects by deposition of materials usually layer by layer. ASTM classified AM technologies in several categories such as: BJ, MJ, PBF, DED, SL, ME VPP. The most frequently used techniques for metal printing is PBF, BJ, DED. PBF can be used for small complex shapes parts where DED is preferred for larger parts. It can be seen that layer thickness, particle size , powder characteristics, energy density, post processing heat treatment, saturation level, feed to power ratio are some parameters that affect the mechanical properties and biomedical properties.

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