

Additive manufacturing (3D printing) of metals and alloys: current trends and future outlook

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Introduction

3D printing, also referred to as Additive Manufacturing (AM), has become a demanding technology in the world which can fabricate three-dimensional objects in a layer-by-layer fashion using computer-aided design (CAD) models. AM possesses the unique ability to create complex geometries not conducive for conventional manufacturing techniques such as injection moulding, forging, and machining. AM has the ability to process a wide variety of materials including thermoplastics, hydrogels & semi-solids, photo-curable resins, elastomers, ceramics, metals & alloys, paper, and other composites. Consequently, this leading technology finds applications in myriad industrial and commercial sectors including biomedical engineering, medicine, dental, pharmaceutical, food, automotive, aerospace, military, electronics, and construction fields (Appuhamillage *et al.* 2019).

Metal 3D printing, one of the increasingly developing areas of AM, started in 1994 with the invention of the first metal 3D printer; EOSINT M250 by ElectroOptical Systems, Germany. It used basically a low-temperature alloy for the AM process. Ten years later, in 2004, the same company introduced the first laser-based powder bed fusion 3D printer; EOSINT M270 in which a diode pump-based laser of 200 W melted metal feedstock. Since then, many research efforts are being conducted in the metal AM field manifesting its applications in diverse disciplines including medical implants and prosthetics, aerospace, automobile, defense, marine, oil and gas, die and mould designing, and jewelry (Gadagi *et al.* 2021).

There is a variety of metals and alloys currently being utilized in metal AM. Table 1 summarizes some of the common metal types used in metal AM with remarks on their main properties and application(s).

Table 1. Common metal/alloy types used in metal AM along with their main properties and application(s).

Common Metal Types	Remarks
Stainless steel (alloy groups; 304, 316, and 17-4)	High strength if non-porous, corrosion-resistant
Tool steels (D2, A2, and H13)	High strength, wear-resistant, applicable for dies and tools
Titanium and Ti64	High strength, for lightweight parts
Aluminum 7075, 4047, 6061, 2319, and 4043	For lightweight parts
Inconel® 718, 625	Low corrosion, high-temperature resistance, for engine parts
Cobalt Chrome	Superalloy for biomedical and aerospace applications
Gold/Silver	Pure metals for jewelry, biomedical uses
Niobium, Niobium-Zirconium	High-temperature & chemical resistance, for aerospace
Tantalum	Better chemical resistance
Hastelloy® Nickel Chromium	Tough, high temperature and crack resistance- for turbines, nuclear components
Tungsten and Alloys	Super high density, for radiation shields, collimators, engine parts

There are many AM-based techniques that process metals and alloys. These include metal powder bed fusion (PBF), directed energy deposition (DED), jetting techniques, and metal filament extrusion (rarely). Following section elaborates on these techniques with the emphasis on basic processing mechanism, materials involved, pros and cons, and applications.

Metal powder bed fusion

Depending on the energy source used and the basic processing mode, metal PBF is carried out under four methods including selective laser sintering (SLS also referred to as laser PBF), selective laser melting (SLM), electron beam melting (EBM) and direct metal laser sintering (DMLS). Table 2 depicts a detailed classification of metal PBF methods.

Table 2. Classification of metal PBF methods. Adapted from Meng *et al.* 2023.

Technique	Description	Materials	Advantages	Limitations
SLS	Laser selectively scans and melts metal powder layers using a set speed and energy density	Titanium (Ti) alloys; cobalt-chromium (Co-Cr); stainless steel (SS); nickel (Ni)-Ti alloys	<ul style="list-style-type: none"> - Fast print speed, - High material utilization - No significant need for support structures 	<ul style="list-style-type: none"> - Powdery surface finish - Requiring post-printing process - Odor generation
SLM	High power laser completely melts each metal powder layer, resulting a dense strong printed object	Almost all alloy types	<ul style="list-style-type: none"> - Higher accuracy than SLS (0.02 mm); - Variety of materials; - Smooth surface finish - Suitable for complex internal structures 	<ul style="list-style-type: none"> - Low speed - Possible delamination & porosity - Stress and misalignment within the final product
EBM	High energy electron beam completely melts the metal powder. Produces a dense object.	Ti alloys; Co-Cr	<ul style="list-style-type: none"> - High forming efficiency; - High product strength and less impurity - Fabrication of brittle materials due to low cooling rate 	<ul style="list-style-type: none"> - Low accuracy - Poor surface finish - Post-printing requirements - Expensive equipment - Lengthy printing times
DMLS	Electronically driven laser beam melts down thin layers of metal powder aggregated by a nozzle	Almost all alloy types	<ul style="list-style-type: none"> - Low distortion, - Processability of high melting metals - Functional gradient materials and parts fabrication - Surface defect repairing of parts 	<ul style="list-style-type: none"> - Poor surface roughness - Uncontrollable composition & microstructure - Complex residual stress

Figures 1-3 illustrate some of the metal PBF-based 3D printed materials targeting various applications.



Figure 1. Human face implant (Ti- laser PBF).

Source: <https://www.voxelmatters.com/black-fungus-patients-receive-metal-3d-printed-face-implants/>

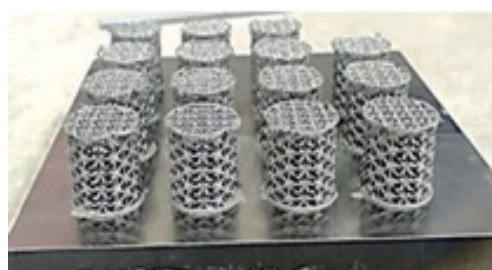


Figure 2. Cellular implant plugs design for Osteoarthritis (Ti- SLM). Adapted from Rehman *et al.* 2023.

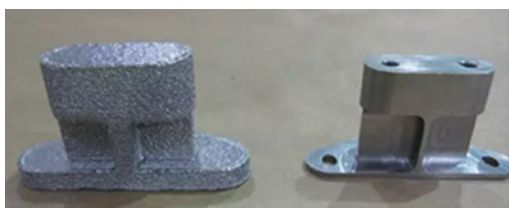


Figure 3. Alloy brackets (Ti-6Al-4V-EBM). Adapted from D'alesio and Christensen, 2019.

Directed energy deposition

DED systems utilize electron beam/laser/plasma arc as the energy source to directly melt and deposit metal/alloy powders on the workpiece layer-by-layer. Figure 4 and 5 depict some of the DED based 3D printed metallic materials used for military and material manufacturing applications respectively.

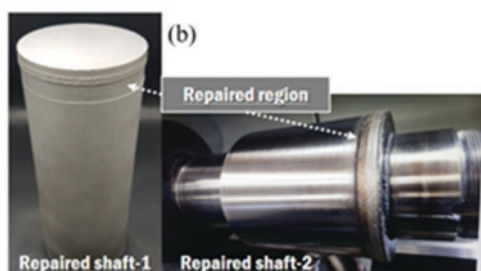


Figure 4. DED based 3D printed metals as weapon components. Adapted from Ahn *et al.* 2021.

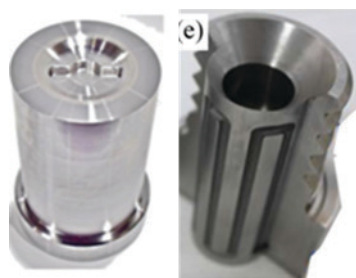


Figure 5. DED based 3D printed metals as moulds and dies. Adapted from Kim *et al.* 2015.

Jetting methods

Jetting-based AM techniques usually present in two- basic types material jetting (MJ) and binder jetting (BJ). In MJ, droplets of liquid resin are selectively deposited via inkjet-style printheads and solidified by UV curing to fabricate the 3D object. In BJ, an industrial printhead selectively deposits a liquid binding agent onto a thin layer of powder particles. Upon inter-layer adhesion due to the binder, the 3D object is formed.

Figure 6 and 7 illustrate some of the inkjet-based 3D printed metallic materials.

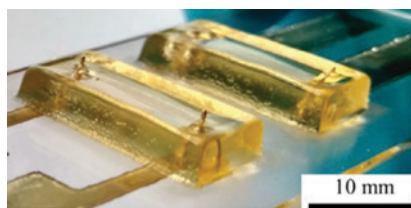


Figure 6. Inkjet 3D printed silver metal electrodes and pillars. Adapted from Sowade *et al.* Adv. Eng. Mater. 2019.



Figure 7. Inkjet 3D printed complex metal part. Source: <https://www.materialsampleshop.com/products/metal-3d-printing-inkjet-route>

Future outlook

Most of the metal AM materials are currently being targeted for medical implants and prosthesis for several parts of human body including knee joints, spinal cord, femoral bones, talus, and trabecular bones. Nevertheless, many orthopedic surgeons are unfamiliar with AM related software, processing, and cost etc. Hence, integrated computer platform should be developed enhancing communication between several professional bodies such as radiologists, orthopedic surgeons, chemists, and engineers. Safety, biocompatibility, degradation properties, and bioactivity studies before and after printing needs to be carried out to meet industrial and clinical standards. Furthermore, appropriate laws and regulations need to be placed regulating the use of customized implants. In addition, continuing research efforts are needed for development of novel metal alloys for improved strength and light-weight properties that would enhance the capabilities and applications of metal AM. Environmental impact and sustainability factors of 3D printable metallic/alloy components also need to be concerned in designing novel formulations.

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