



Processes and applications of metal additive manufacturing

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ABSTRACT

Additive Manufacturing (AM) is an appropriate name to describe the technologies that erect 3D objects by enumerating layer-upon-layer of material, hence the name additive, whether the material is thermoplastic, metal, concrete, exclusive materials such as ceramics, carbon fibre or even human tissues. A 3D Slicing programme (to slice the 3D model into successive layers), machine equipment configuration, and material layering are all popular AM technologies. The Slicing programme decodes data from the CAD file, slices it into successive layers, and converts it to G-codes after it is created. When we run this G-code in the AM System, the computer builds a 3D component by layering liquid resin, powder, or solid filaments on top of each other. Rapid prototyping (RP) is one of the quickest-growing automated manufacturing innovations, with the ability to go from CAD models to finished products. Powder Bed Fusion (PBF) and Direct Energy Deposition (DED) are two kinds of metal additive manufacturing techniques. The metal additive manufacturing method can also be classified by material type, energy source, build scale, and so on. This paper discusses the relevance of metal additive manufacturing and provides detailed information on the processes of Selective Laser Melting, Selective Laser Sintering, Direct Metal Deposition, and Laser Metal Deposition.

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1. Introduction

“Additive Manufacturing” is a relatively recent word. The International Committee F42 for Additive Manufacturing Technologies proposed it in 2010 to group all technologies capable of handling and working a wide variety of materials (from thermoplastics to polymers and metals) in a tool-less manufacturing process [1]. Aerospace, naval, automobile, biomedical, design, jewelry, architecture, and electronics are among the industries that have been affected by the introduction of additive manufacturing into the manufacturing world.

The global additive market is growing rapidly and is projected to continue to expand in the future [Fig. 1]. It was valued at \$9.3 billion in 2018, a significant rise from \$5 billion in 2015. Well-known companies such as Optomec, HP, Renishaw, EOS are con-

stantly studying and developing new AM systems. By 2025, the automotive, aerospace, and medical industries will account for 51% of the Additive Manufacturing industry.

The slow and steady rise of AM in the industrial world is based primarily on the following distinguishing features:

- Additive Manufacturing systems are “easy to operate”.
- There are no cutting tools or moulds available.
- Possibility of achieving Functionally Graded Material (FGM).

2. Metal additive manufacturing systems

Parts with intricate features or embedded components, as well as parts that replace a convulsed assembly with a single piece, can be produced using metal additive manufacturing. Three broad categories of metal additive manufacturing include (i) Wire Feed System (ii) Powder Feed System and (iii) Powder Bed System [2].

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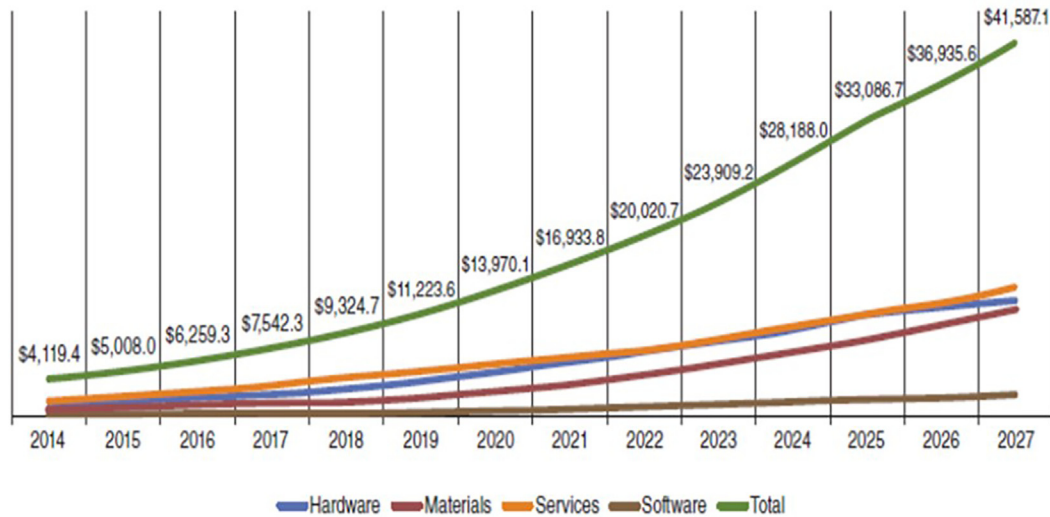


Fig. 1. Projected global AM market size between 2016 and 2027 (billion US\$) [1].

2.1. Wire feed systems

In wire feed systems, a laser or an electron beam is used to melt a wire, and the process is carried out in an inert gas setting (Fig. 2). The wire moves in three dimensions, and these systems are widely used in applications where the metal deposition rate is high. Due to the high deposition rate and excessive heat input, wire feed systems are prone to distortions and higher residual stresses.

2.2. Powder feed systems

The laser beam is used in powder feed systems to scan the X-Y plane and build the part in layers. The printed layer often moves in the Z-axis to duplicate the previous layer on top of it. The powder is sprayed onto the surface of the treated component through a nozzle that is melted from a beam.

2.3. Powder bed systems

G-Code knowledge is used by powder bed systems to evenly distribute powder around the bed with a thickness equal to the layer height. According to the details contained in the CAD data sheet, powder is selectively melted by a laser source or an electron

beam. A new powder layer is created once the selectively melted powder layer moves down, and the process continues until the final part is formed.

3. Powder bed fusion systems

To sinter, a metallic powder bed fusion systems utilize a high-energy power source. PBF can further classify into Selective Laser Sintering and Electron Beam Melting depending on power source [4]. Even though the concepts of both systems are identical, the processing steps are somewhat different.

3.1. Selective Laser Melting (SLM)

The laser beam passes through a series of lenses and is projected onto the desired path with the aid of mirrors in the SLM method (Fig. 3). The create platform moves downward after the powder is selectively melted. The metal powder-carrying slider slides over the construct plate, depositing a new layer of powder, and the process continues.

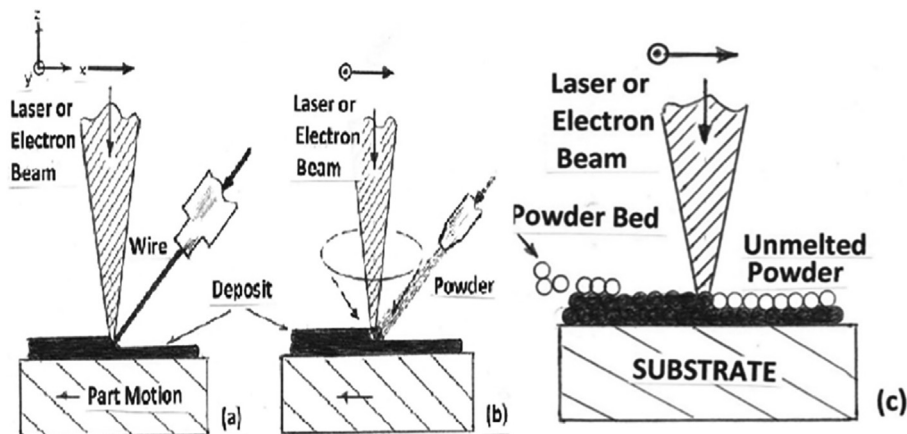


Fig. 2. (a) Wire Feed System; (b) Powder Feed System; (c) Powder Bed System [3].

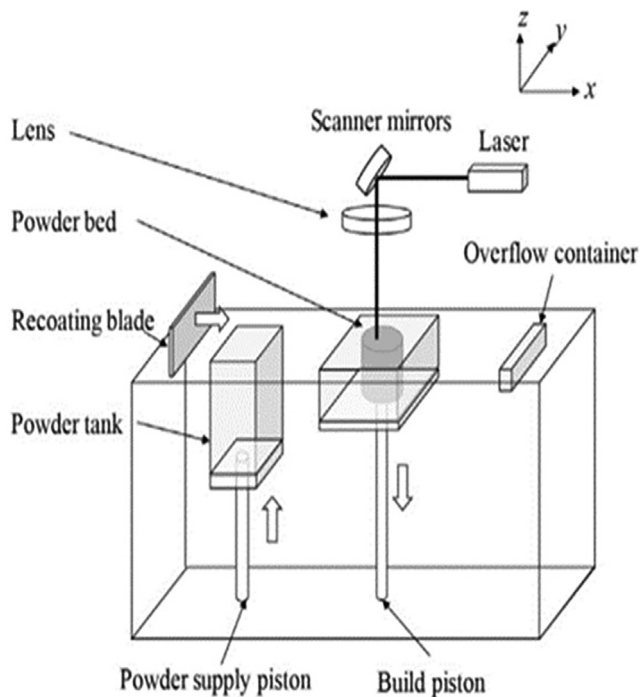


Fig. 3. Selective Laser Melting Process [3].

3.2. Electron beam Melting (EBM)

The electron beam source is held at the top of the powder bed system in the EBM phase. The reflecting system controls the movement of the electron beam (Fig. 4). The fresh powder is poured onto the platform using a powder hopper, and the powder content is applied to the top of the previously melted layer using a rake.

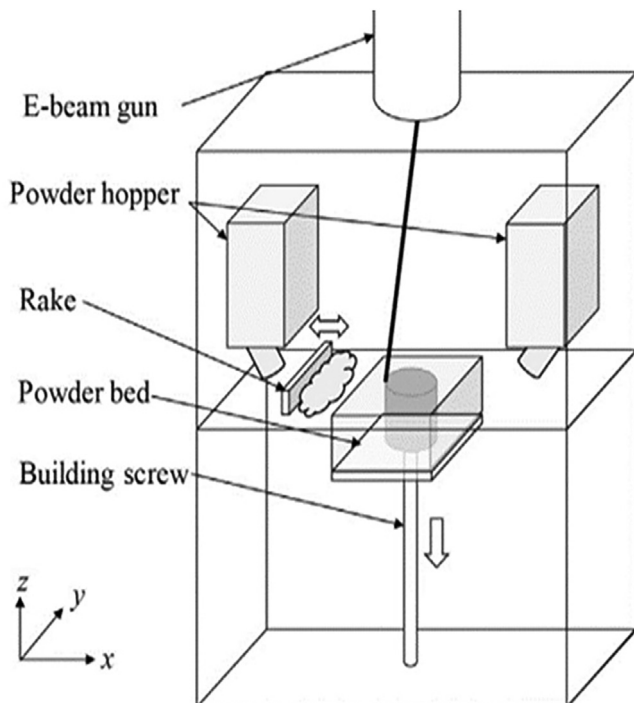


Fig. 4. Electron Beam Melting Process [3].

4. Direct energy Deposition systems

This method uses a laser to deposit metal powder layer by layer, directly from the CAD model, to form three-dimensional components. The technique can be used for various engineering and biomedical applications to fabricate custom shaped, functionally graded material parts [5]. Titanium alloys are widely known to be one of the best materials for biomedical applications.

4.1. Direct metal Deposition (DMD)

The DMD process is depicted schematically in (Fig. 5). The laser feed system, powder distribution system, CNC motion control system, and feedback control system were the main components of the DMD system. The DMD procedure may be carried out at room temperature or in a regulated environment [6]. In the DMD process, a high-powered laser beam melts a solid substrate's surface, creating a melt pool into which a metallic powder is injected. The powder is melted and fused to the substrate by the laser, resulting in a completely thick, metallurgically bonded bead [7]. A continuous layer is created by overlapping the beads by 50% or more. The method can be used to make single-material or multi-material pieces. Components with a near-net form have been created using this technology.

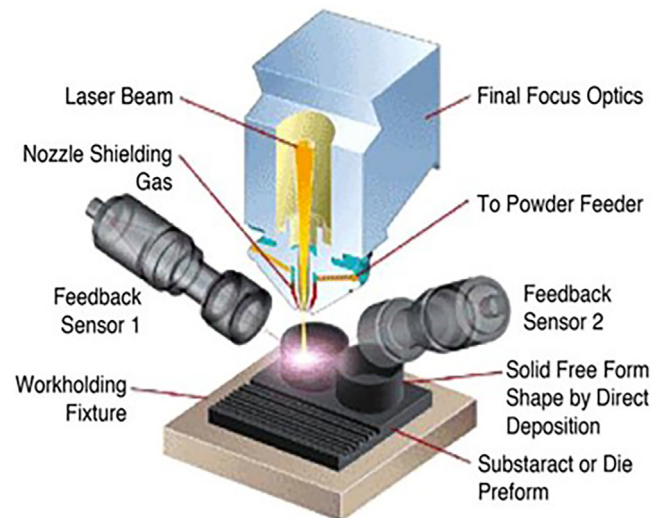


Fig. 5. Direct Metal Deposition Process [6].

4.2. Laser metal Deposition (LMD)

To make a part, laser metal deposition uses wire or powder material and a laser beam that travels along a predetermined path to solidify the object. The feedstock is deposited layer by layer in this process (Fig. 6). A nozzle mechanism feeds a wire into the melt tub, and the powder is deposited with the aid of a coaxial nozzle.

Laser metal deposition improves the surface integrity of metallic components while also helping to improve their oxidation, wear, corrosion, and fatigue resistance. This method maintains a stable bond between the deposited material and subsequent layers, resulting in crack-free surfaces. In terms of precision, laser metal deposition has an advantage.

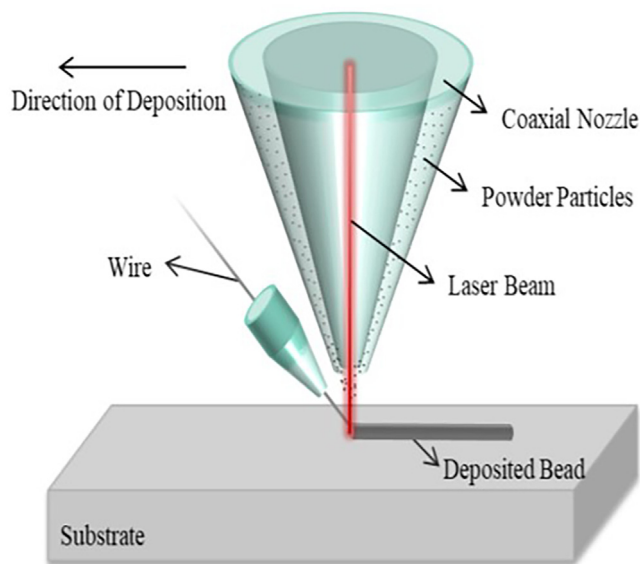


Fig. 6. Laser Metal Deposition Process [8].

5. Alloys and metals used in additive manufacturing processes

5.1. Titanium alloys

In the aerospace, pharmaceutical, and medical sectors, titanium alloys are commonly used. Many attempts have been made in recent decades to produce titanium-based alloys with excellent mechanical properties and biocompatibility. The most widely used titanium alloy in additive manufacturing was $\alpha + \beta$ type Ti-6Al-4 V, which was mostly used in the aerospace industry. It has excellent corrosion resistance and high strength, making it an ideal option for biomaterials, according to subsequent studies. According to

some experts, β type titanium alloys made up of non-toxic elements and having a low modulus are suitable materials for implant applications. Ti alloys have columnar grains in their microstructure. This type of microstructure is common in AM-processed parts and grows in multiple layers along the construct path [9–11].

5.2. Steels

Steels contain a wide range of microstructure ingredients and phases, including austenite, ferrite, and martensite, as well as a wide range of precipitate phases, including intermetallics and carbides. Steels have a wide range of microstructure and mechanical properties due to many of these microstructure constituents [11].

Steels are the best material for additive manufacturing and 3D printing applications that require the following characteristics:

- Corrosion tolerance and general long-term durability in harsh environments.
- From ultra-hard martensite to compliant multiphase compounds, there is an unrivalled range of microstructure features that can be achieved.
- Better hardness, strength, ductility, wear resistance and toughness.

5.3. Aluminium alloys

Aluminium alloys can use in a variety of industries. They provide a good balance of strength and density and be relatively inexpensive, allowing them to use in applications that require both efficiency and light-weighting [11]. In their paper, Adarsh Patil et al. discussed how AA 7076 alloy reinforced with graphene nano particles would be a popular option for structural applications [12]. Selective Laser Melting (SLM) is widely employed to process Al alloys. Since aluminium is a lightweight metal with decent deformability, it is a good candidate for crumple zones in automobiles.

Table 1
Applications of various AM Processes.

Author	Year	Work Material	Processing Method	Applications
M.N. Ahsan et al. [21]	2010	Ti-6Al-4 V and 316L stainless steel	Laser Metal Deposition	Hip and knee endoprotheses and Dental implants.
Andres Gasser et al. [22]	2010	Inconel 718	Selective Laser Melting	Steam turbine and Gas turbine blades.
Mari Koike et al. [23]	2011	Ti-6Al-4 V	Electron Beam Melting	Dental and Orthopaedic implants.
Atsushi Takaichi et al. [24]	2013	Co-29Cr-6Mo	Selective Laser Melting	Complex geometry dental devices.
Donghong Ding et al. [25]	2015	Ti-6Al-4 V	Wire Feed AM	Automotive and Aerospace components.
C. Y. Yap et al. [26]	2015	316L Stainless Steel	Selective Laser Melting	Dental prostheses and body implants like mandibular canal segment and cortical bone.
Vivek Tiwary et al. [27]	2015	Acrylonitrile-Butadiene-Styrene (ABS)	Fused Deposition Modelling	Patterns for investment casting process.
A.J.Dunbar et al. [28]	2016	Inconel 718	Powder Bed Fusion	Submarines, Petrochemical Plants and Rocket applications
Lai-Chang Zhang et al. [29]	2016	Ti-6Al-4 V and Ti-6Al-7Nb	Selective Laser Melting	Acetabular Cup used in hip joint replacement.
Y. Zhong et al. [30]	2017	SS316L	Electron Beam Melting	Nuclear Fusion applications.
L.Jyothish Kumar et al. [31]	2017	Inconel 718	Laser Metal Deposition	Aerospace Engine components.
T. A. Kalashnikova et al. [32]	2018	321 Stainless Steel	Wire Feed AM	Aviation and Rocket components.
A. Ataee et al. [33]	2018	Ti-6Al-4 V (Ti64)	Electron Beam Melting	Fabrication of metallic scaffolds (bone implants)
Vivek Tiwary et al. [34]	2019	Acrylonitrile-Butadiene-Styrene (ABS)	Fused Deposition Modelling	Medical Implants
Yanhu Wang et al. [35]	2019	CuSi3 + AlSi5-ER4043	In-situ Wire Feed AM	Aero Engine Parts.
P. Wanjara et al. [36]	2019	Ti6Al4V	Wire Feed Electron Beam AM	Aero Engine Turbine manufacturing.
Maria Touri et al. [37]	2019	Alumina Powder	Powder Feed AM	Orthopaedic Implants.
Vivek Tiwary et al. [38]	2020	Acrylonitrile-Butadiene-Styrene (ABS) + Polyethylene terephthalate glycol (PET-G)	Fused Deposition Modelling	Fabrication of a UAV wing
Sen Liu et al.[39]	2021	Ti6Al4V	Laser Wire Feed AM	Aerospace, healthcare, and customized manufacturing.

Table 2
Metal Powder Processing Techniques.

Author	Year	Powder Material	Processing Method	Applications
R. Shashanka et al. [40]	2015	Fe–18Cr–13Ni Duplex Stainless Steel	Mechanical Alloying (Ball Milling)	Pressure vessels and Heat exchanger tubing
K. Saeidi et al. [41]	2016	SAF 2507 Duplex Stainless Steel	Nitrogen gas atomization	Marine constructions
Fabrizia Caiazza et al. [42]	2017	Inconel 718	Argon gas atomization	Turbine blades
Yueling Guo et al. [43]	2017	Nb–37Ti–13Cr–2Al–1Si	Plasma Rotating Electrode Processing (PREP) in Argon atmosphere	Advanced turbine engines
Wangwang Ding et al. [44]	2019	hydride-dehydride Ti powder	Argon gas atomization (Treated with fluidized-bed reactor)	Aerospace components and biomedical implants
Moustafa Ahmed et al. [45]	2020	316L Stainless Steel	Argon gas atomization	Aerospace and Medical devices
Jie Zhuang et al. [46]	2020	Ti6Al4V (TC4)	Argon gas atomization	Biocompatible materials
Nima Haghdadi et al. [47]	2020	2507 Duplex Stainless Steel	Nitrogen gas atomization	Petrochemical and desalination plants
Parnian Kiani et al. [48]	2020	AlSi10Mg	Water atomization	Industrial lightweight components
D. Jiang et al. [49]	2020	22Cr DSS and 25Cr SDSS	Nitrogen gas atomization	Oil refineries and gas pipelines
Suraj Dinakar Jadhav et al. [50]	2020	CuCr1	Argon gas atomization	Processing of highly reflective copper alloys

Microstructural enhancement is another benefit of SLM processing Al (cast alloys in particular). Cast alloys have historically improved by adding chemical modifiers to refine their microstructures during casting. SLM's high cooling rates result in microstructural refinement during manufacturing without changing the chemical composition.

6. AM research issues

1. To assess the impact of process parameters such as material properties, surface features, and mechanical behavior of AM manufactured components, modelling or experimental work should be used [13].
2. To address component quality problems, in-process monitoring and real-time control in AM systems are being implemented [14].
3. Based on the component complexity, a new material is developed using an AM method [14,15].
4. Assigning certification protocols for the AM processed parts [16,17].
5. Selection of AM process to produce defect free components [18–20].

7. Studies related to various applications of metal additive manufacturing processes

Table 1

8. Studies related to metal powder processing techniques used in additive manufacturing

Table 2

9. Conclusions

By reducing energy use and carbon emissions, additive manufacturing technologies have a positive impact on both the global economy and the environment, according to this report. Powder bed fusion devices, when used in combination with laser or electron beam systems, have proven to be a promising technology for producing biomedical implants. Sheet Lamination Ultrasonic Additive Manufacturing (SL-UAM), Electron Beam Melting Powder Bed Fusion (EBM-PBF), Laser Powder Bed Fusion (LPBF), Binder Jetting (BJ), and Direct Energy Deposition Laser Engineered Net Shaping (DED-LENS) are examples of metallic AM systems. Titanium

alloys are used in biomedical applications because of their superior biocompatibility, low elastic modulus, and corrosion resistance. Direct Metal Deposition can fabricate near net form components and can create complex geometries with greater accuracy. Steels, Titanium alloys, and Ni-base superalloys are among the alloys and metals that can be produced using additive manufacturing.

CRediT authorship contribution statement

Rayappa Shrinivas Mahale: Writing – original draft, Supervision. **V. Shamanth:** Conceptualization, Visualization, Supervision. **K. Hemanth:** Conceptualization, Visualization, Supervision. **S.K. Nithin:** Writing – review & editing. **P.C. Sharath:** Resources, Methodology. **R. Shashanka:** Resources, Methodology. **Adarsh Patil:** Writing – review & editing. **Darshan Shetty:** Writing – review & editing.

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.

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