

Recent Advances in Additive Manufacturing for Mechanical Components

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ABSTRACT
Additive Manufacturing (AM), commonly referred to as 3D printing, has significantly transformed the manufacturing sector by enabling the creation of complex geometries, reducing material waste, and offering enhanced customization. This paper reviews the latest developments in AM technologies, focusing on liquid-based, powder-based, solid-based, and laminated fabrication processes. A comparative analysis with traditional manufacturing techniques is presented, highlighting mechanical properties, economic feasibility, and environmental impact. The paper also discusses recent trends including artificial intelligence (AI)-driven monitoring, Physics-Informed Machine Learning (PIML), Robotic Additive Manufacturing (RAM), and Digital Twin (DT) integration. Challenges such as cost, material limitations, and quality control are critically examined. The study concludes by proposing future research directions including sustainable materials and AI-augmented design optimization.
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AM	Additive manufacturing
DL	Deep learning
TO	Topology optimization
PIML	Physics-Informed Machine Learning
RAM	Robotic additive manufacturing
DoF	Degree of freedom
DTs	Digital Twins
SMAs	Shape memory alloys

1. INTRODUCTION

The technologywhich involvesbuilding a part of one layer at a time is quite varied as well as includes different stages of development. Numerous technologies have emerged to accommodate different materials along with improving build times. Newer technologies are continuously being developed while some technologies are commercially available methods of fabricating prototypes. These different methods of additive fabrication can be classified by the type of material that is employed[1].

2. CLASSIFICATION OF AM TECHNOLOGIES

2.1 *Liquid-based processes*

In this process a liquid resin known as photopolymer is hardens when exposed to laser or other light source and thus object layersare formed in selective manner[2].

2.2. Powder-based processes

Successive layers of very fine powder are stacked together.By jetting an adhesive onto each powder layer or by the fusion of powder granules together, the adhesion of powder or granular materials can be obtained. Nylon, ceramics, bio-plastics, wax, stainless steel and titanium are some of the powder adhesion which is commonly used in 3D printing[3].

2.3. Solid-based processes

There are 3D printersthat can create objects by extruding molten or semiliquid material and some can even extrude concrete material also[4].

2.4. Paper based processes

This process is based on lamination.Successive layers of cut paper, plastic or metal are stuck together to build asolid object.When paper is used, it is cut with a blade or laser and then bonded. Spray of multiple inks during the process in order to create full colored 3D printed objects can be carried out[5].

3. TYPES OF 3D PRINTING TECHNOLOGIES

3.1 Stereo-lithography (SLA)

The plastic parts or objects can be built by SLA technique with one single layer at a time which is done be tracing a laser beam on the surface of vat of a liquid photopolymer, inside of which is a movable stage to support the part which is to be built[6]. Laser beam first strikes the surface which creates heat at the surface due to which the object part is melted. The photopolymer solidifies quickly as far as the laser beam strikes the surface. The platform lowers by the thickness of one layer (0.003-0.002 in), and a new layer is created on top. Each layer has to bond with the other one and hence, material having high adhesive property is preferable in such methodology[7].

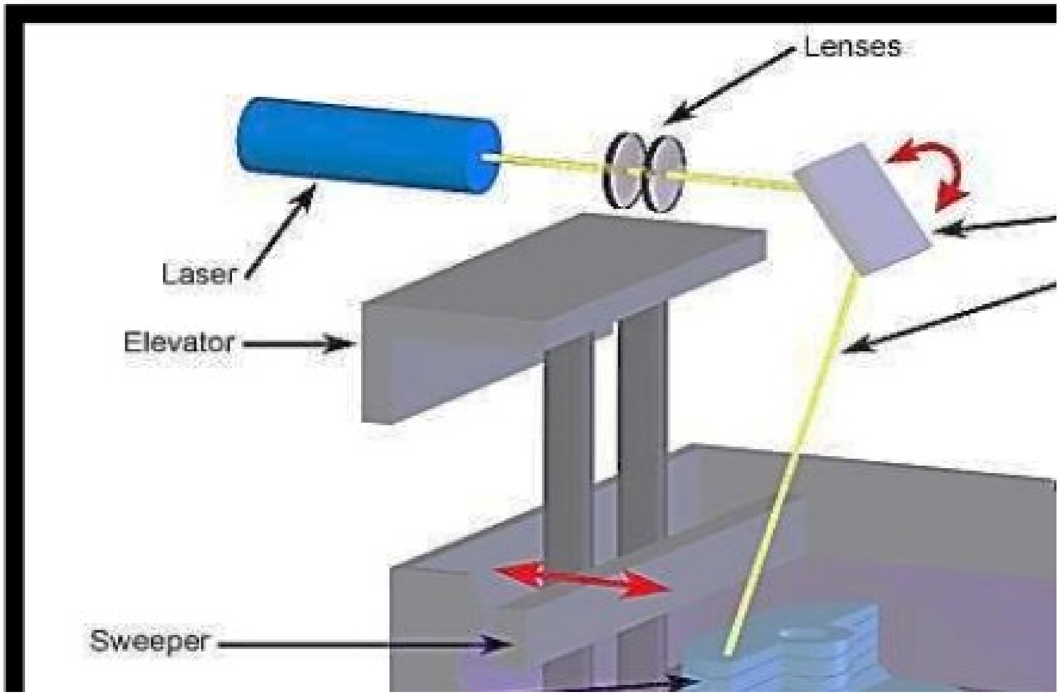

Fig 1: Stereo Technologies [8]

3.2 Fused deposition modeling

Plastic or wax is extruded through nozzle that traces the cross-section of the part layer by layer. Through a coil a plastic filament is unwounded and supplies material to an extrusion nozzle.The nozzle is attached to a X-Y plotter that traces the shape of the part. A separate nozzle is used for support material. The object is built on a stage which moves layer by layer in downward direction. Support structures for overhanging geometries are automatically generated and removed later by breaking them away from object [9].

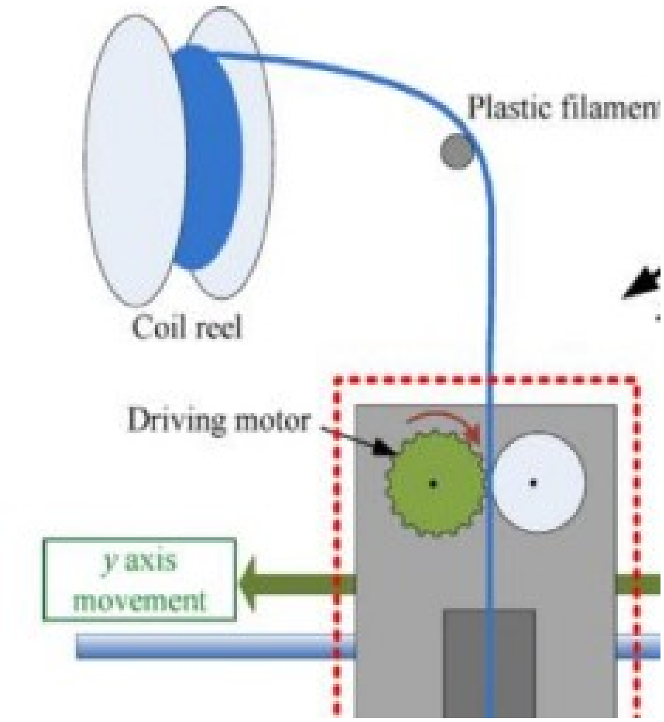

Fig2 :Fused deposition modelling [10]

3.3 Laminated object Manufacturing (LOM)

The main aspects in this method is feed mechanism that advances a sheet over a build platform, a heated roller to apply pressure to bond the sheet layer by layer below, and a laser to cut the outline of the part in each sheet layer. The cutting of outline of the part is done by laser into each layer. After the completion of each cut, the platform lowers by a depth which is equal to the thickness of a sheet (0.002-0.020 in), and a new sheet is placed on top.The platform then rises slightly and the heated roller the presses the new layer onto the existing one. The laser again cuts the shape and the process is repeated until the part is completed. After a layer is cut, the extra material remains in place to support the part during build [11].

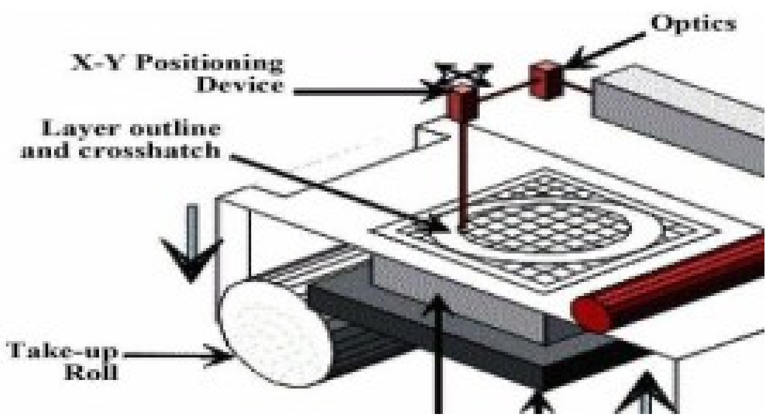

Fig 3 :Laminated object Manufacturing [12]

4. COMPARISION WITH TRADITIONAL METHOD

4.1 Strength to ductility

Since there is more refined microstructure in case of additive manufacturing, it improves the tensile strength and yield strength but reduces its ductility.Conventional methods on the other hand providematerial that is having lower strength but higher ductility. Hence, when it comes for a specific use of a material additive manufacturing is preferable while if there is a requirement of balance of strength and flexibility traditional production methods could prove more suitable [13].

4.2 Economic Analysis

CNC cost will increase as the complexity in the part to be manufactured is increased, however in case of additive manufacturing the cost may decrease or remains the same. The most important advantage of using additive manufacturing is that to produce complex part the design complexity is independent of the cost which allows altering the way products are designed and manufactured. However, high acquisition of 3D printers and high cost associated with the raw materials leads to high costing in case of additive manufacturing [14]. The cost of entry level printers begins around US$150 which is small bed FDM prototyping personal use printers [15]. But the production grade printers can cost anywhere from US$5000 to US$1000000 [16]. Additionally, gas used for additive manufacturing machines requires an inert environment which leads to high costing [17].

4.3 Environmental Impact

Additive manufacturing process is more suitable for workers health as no direct exposure to toxins are there while in case of CNC there is aerosolized cutting fluid due to which HMIS and NFPA health ratings of 1 occurred [18].For Life cycle assessment (LCA) and Life cycle costing (LCC) analysis, the evaluation of entire production should be carried out. For example, when comparing Stereo-lithography machining (SLM) with that of CNC machining (CM) without topology optimization it was found that CNC machining (CM) exhibit around 15% lower environmental impact while by applying optimization Stereo-lithography machining (SLM) outperformed CNC machining (CM), achieving around 21% lower environmental impact [19]

5. RECENT ADVANCES

5.1 Deep Learning

Using deep learning in additive manufacturing helps detect problems, monitor process stability, and ensure quality. The 3D coordinates of a printed part's surface can be captured through point cloud data. Deep learning techniques process this data to find shape issues, surface problems, and process changes. Also, deep learning helps reduce the workload by finding hidden patterns from multiple design iterations [20].

5.2 Physics-Informed Machine Learning

PIML offers a mesh free approach through automatic differentiation which has the potential to navigate the complexities associated with the curse of dimensionality. However, certain assumptions were made for the implementation of PIML which are as follows:

- The deposited metal layer is thin compared to the substrate thickness.
- The latent heat of fusion is neglected.
- Melt pool fluid flow and evaporation are ignored.
- The substrate and deposited material are assumed to beuniform materials with constant properties.
- The laser heat source is modeled as having a Gaussian heat distribution.

- Only half of the domain is analyzed to save the computation time due tosymmetry along the x-z plane [21].

5.3 Robotic Additive Manufacturing

Recent studies use robotic armsin additive manufacturing,called RAM,to improve the process. The multiplane and non-planar slicing method lead to strongerparts,which is possible due to the higherDoFin RAM systems. For RAM systems, the most basic platform utilized in literature is 4-DoF robotic arm such as SCARA arms [22].

5.4 Digital Twin and Industry 5.0

The implementation of DTs in AM leads to identify defects, optimizing the processes as well as improving the overall printing quality [23].Papacharalampopoulos et al. (2023) presented a framework which integrates process selection with DT capabilities and Industry 5.0 (I5.0) criteria, with a focus on sustainability and human inclusion. It evaluates AM and laser welding and demonstrated that I5.0 criteria improved worker well-being and production efficiency. Additionally, the integration of I5.0 Key Performance Indicators (KPIs) improved productivity, material usage, and energy efficiency across all scenarios [24].

5.5 4D Printing

4D printing allows the 3D printed materials to change its function or configuration with respect to time in reference of external conditions such as temperature, light, water, magnetic fields etc. This dynamic technology leverages the smart material to fabricate objects with pre-programmed transformations [25].

6. FUTURE TRENDS

- AI-driven generative design
- Sustainable and biodegradable feedstocks
- Hybrid AM and subtractive techniques
- Real-time quality assurance systems
- Self-healing materials and embedded sensors

CONCLUSION

This paper reviewed foundational technologies, advanced developments, and future trajectories of additive manufacturing. By addressing current limitations and leveraging AI and robotics, AM is poised to redefine mechanical component production. Continued research in material science and intelligent systems will further accelerate its adoption in mainstream industries.

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