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Exploring 3-D printing: Additive manufacturing for metallic components, processes, structures, and properties

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ABSTRACT

This study offers a comprehensive analysis of metal additive manufacturing (AM), a production technique that uses digital 3D models to directly construct intricate metallic components layer by layer. It discusses the key procedures in metal AM, such as directed energy deposition (DED), binder jetting (BJ), and powder bed fusion (PBF), emphasizing how they can create parts with complex geometries that are impossible to achieve with conventional manufacturing techniques. In addition to addressing issues like anisotropy and joint flaws related to the process, the focus is on metal additive manufacturing's exceptional ability to produce components with complex geometries and specific microstructures that traditional manufacturing cannot provide. The paper also explores the significance of post-processing approaches for performance enhancement and how process parameters influence the mechanical and structural properties of the produced components. Applications in the industrial, automotive, and medical fields highlight the technology's versatility and growing market potential. By integrating digital design with functional metal components, this synthesis aids in the design, optimization, and selection of suitable metal AM methods for advanced metallic component manufacture.

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1. Introduction

The manufacturing technique known as AM, or 3D printing, allows for creating items by printing one layer at a time under the guidance of a digital 3D model [1-4]. Complex geometries that are nearly impossible to build using traditional technologies may now be manufactured because of this special feature. Because of this, AM is a tool resource that allows designers to produce complicated or bespoke models in a single step without being constrained by traditional manufacturing constraints such as significant material waste, the inability to build complex forms, or the requirement for specialized tooling [5]. AM provides various benefits over conventional production processes, such as increased structural efficiency, geometric flexibility, customization [6], and lower material use [2]. It is coupled with the opportunity for functionally graded materials and prestressing, repair, and strengthening prospects [6]. It also decreases or eliminates assembly time and expense [7, 8]. Metals, ceramics, and polymers are just a few materials that AM technology may work with [8-11]. Researchers and companies are becoming more interested in metallic materials [12]. Along with the aforementioned advantages, metal AM may offer other environmental benefits, including less waste, improved quality, lower emissions of pollutants, and the ability to produce components on demand [9, 10]. Even though metal AM offers significant advantages, only a small number of industries [13], including dentistry [14], construction [6], and aerospace [15], are now using metal AM technologies to their full potential. The biomedical and industries now manufacture metal additives to create highly customized or small-batch high-value end-use products [16, 17]. AM methods encompass a range of procedures that frequently involve an energy source, such as an electron beam or laser. Then, AM methods are divided into directed deposition and powder bed processes according to the kind of substrate employed. AM procedures include, but are not restricted to, EBM, DED, etc. The most common metallic materials used in AM are alloys made of steel, aluminum, titanium, and nickel [2]. The present status of metal additive manufacturing is authoritatively summarized in this overview, which covers basic procedures, materials, structural traits, and properties. It highlights how the technology has the ability to completely transform manufacturing by making sophisticated, high-performance metallic components possible. However, it also points out the problems that still need to be solved and the future lines of inquiry required to fully reap the rewards of 3D printed metal parts in various sectors.

2. Additive manufacturing processes for metals

The most appropriate term for 3D printing or rapid prototyping is AM. This technology is concerned with creating prototypes and finished goods in any form or size that meet specifications [18]. Using liquid or semisolid paste, powder, and solid materials, this new technique creates objects that may either be printed into their final dimensions and shape or, if necessary, postprocessed to take on their final shape [19, 20]. Utilizing traditional machining techniques to manufacture 3D printed objects is known as post-processing. AM can quickly catch market updates because of its many applications, which include prototyping, printing end-user items, and repairing components at a cheaper cost and time. This offers excellent chances to get into the business [8, 21].

2.1. Powder bed fusion (PBF)

PBF techniques are used in most metal AM systems (Fig. 1). Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM), Selective Laser Melting (SLM), and Direct Metal Laser Melting (DMLM) are standard metal PBF techniques [22]. Heat is used in all of these systems to fuse the powdered materials. The variations depend on the powder materials and energy source [7]. For example, EBM employs an electron beam as its energy source, whereas SLS, DMLS, and SLM use lasers [23]. Only metallic components are produced using SLM and DMLS techniques among these technologies [24]. The fundamental idea behind these two technologies is often the same. Laser Metal Fusion (LMF), another name for SLM, is mainly used for single-component metals like aluminum, whereas DMLS is frequently used for metal alloys like titanium and aluminum [25]. With the exception of the fact that laser beams produce fragile metal layers and a uniform melt pool, the DMLM method is pretty similar to the DMLS technique. The main benefits of this method over DMLS are reduced porosity and better surface quality [13]. In EBM technology, a high-energy electron beam is used to fuse metal powder together, instead of a laser in SLM printers. Owing to the components, they may be stacked inside the build volume. EBM technology is more productive than SLM systems. However, owing to the high energy density and quick heat cycles, the AM products still have greater degrees of distortion and residual stresses [26].

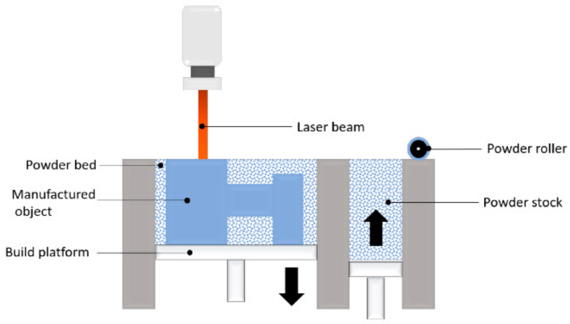

Fig. 1. Schematic representation of PBF techniques [27].

2.2. Directed energy deposition (DED)

Methods often used to repair or add extra material to existing components, DED is a more sophisticated additive printing technique [28]. A nozzle on a multi-axis arm of a standard DED machine drops molten material onto a designated surface, where it hardens. A laser, electron beam, or plasma arc heat and melt the material. The thickness of the layer is the distance at which the item is lowered. Until every layer has been deposited, these procedures are repeated [14]. From an energy standpoint, DED may be divided into two primary groups: thermal energy and cold spray [29]. Kinetic energy, another name for cold spray, is the process of adding material in the form of small particles to a substrate that has enough kinetic energy to form a dense layer or coating [30]. Using a laser beam, electron beam, plasma, or arc, the other class of DED devices concentrates on thermal energy. This team adds the wire or powder feedstock material to the construction platform one at a time after selectively melting it [29]. Metal component fabrication is the main application for DED technology [31]. In order to print at greater deposition rates with lesser resolution, this AM group uses robotic welding methods [32]. Standard DED procedures include Lase Clading (LC), Laser-Engineered Net Shaping (LENS), Wire-based Joule printing, Electron Beam Additive Manufacturing (EBEAM), Wire and Arc Additive Manufacturing (WAAM), and Hybrid Systems (HS) [33]. Table 1 summarizes typical DED procedures in this comparison table.

Table 1
Common DED processes.

Process	Energy source	Key characteristics	Advantages	Disadvantages	Ref.
EBEAM	Electron beam	Uses focused electron beam in vacuum, high deposition rates, and low residual stress	High deposition rate; suitable for reactive materials, low residual stress	Requires vacuum, high equipment cost, and limited material diversity	[33]
WAAM	Electric arc (GMAW)	Wire-based DED using arc welding, high material utilization, and large build volume	High production rate (up to 5 kg/h); large build volume; low wire cost; mechanical properties comparable to forged parts	Lower precision; requires post-machining; limited to wire feedstock	[34]
LENS	High-power laser	Powder-based laser DED, high precision; hermetically sealed argon environment to prevent oxidation	High precision, versatile material options; suitable for repairs and adding features.	High powder cost; powder handling challenges	[35]
LC	Laser	Laser melts feedstock to build or repair surface layers; often used for coating or repair	High precision, good metallurgical bonding, suitable for surface enhancement	Limited build size; slower than wire arc methods	[36]
HS	Combination (laser + machining or arc)+	Combines different heat sources and feedstock types to optimize deposition	Improved control over microstructure and properties; flexible feedstock	Complex equipment, higher cost	[37]

2.3. Binder jetting (BJ)

In comparison to metal PBF, BJ technology requires no support structures. It produces far more accurate objects by printing the desired metal parts in layers using metal powder and a liquid-state binder [38], as shown in Fig. 2. The binder droplets consolidate the powdered materials within and between sliced layers [13].

In addition to being an inert method, BJ offers many benefits, including the flexibility to employ a variety of materials like metal, polymer, and ceramics, and a considerable number of powder/binder combinations [14].

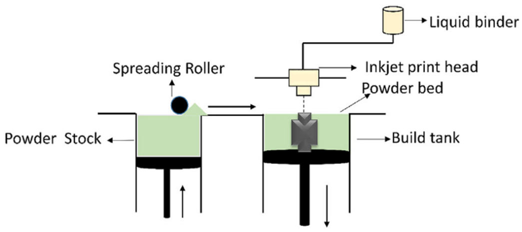

Fig. 2. Schematic representation of BJ process [39].

3. Structural characteristics of 3D-printed metals

The AM technique, which constructs components layer by layer, significantly impacts the unique structural properties of 3D-printed metals. These traits impact their overall performance, microstructure, and mechanical qualities.

3.1. Microstructure properties

Anisotropic microstructures are produced when directional heat removal causes grains in techniques like as SLM and electron beam powder bed fusion (E-PBF) to elongate along the build direction. For instance, SLM 316L stainless steel has elongated austenitic grains around 10 µm wide to improve mechanical strength. These grains are far finer than their traditional wrought or cast counterparts [40, 41].

Another critical factor is powder particle size; coarse powders encourage equiaxed fine grains, which enhance isotropy and mechanical qualities like strength and ductility, whereas fine powders often result in coarse-columnar grains [42].

3.2. Mechanical properties

Defects affect mechanical qualities, with porosity and surface quality being essential variables. Various approaches of lowering porosity have been put forth [43]. For instance, penetrating the sintered body with vitreous materials, applying cold/hot isostatic pressure on the green body, introducing dopants or a viscous liquid-forming phase, and selecting ceramic powders with an appropriate granulometric distribution [44, 45].

4. Applications of metallic 3D-printing

The capacity of metallic 3D printing to create intricate geometries, bespoke parts, and robust yet lightweight components make it useful in a variety of industries, including automotive and medical and etc.

4.1. Automotive parts

Because it may lower the research, production, and product costs of automotive components, AM technology is a valuable tool in this sector [46, 47]. It is especially intriguing for racing vehicles, where lightweight metals such titanium and aluminum and composites are utilized to create extremely complex structures, because it enables the production of tiny amounts of structural and functional pieces [46].

4.2. Medical devices

Recent advances in the fields of biomaterials, biological sciences, and biomedicine have increased the use of AM techniques. Customization is important in this field, and AM enables the production of a wide range of products with specific properties and shapes that meet the needs of the patient, such as drug delivery systems, medical devices, tissue scaffolds, diagnostic platforms, orthopedic and dental implants, and artificial organs [48]. In recent years, biofabrication through AM has emerged as a new alternative to fabricate tissues [49, 50]. A metal AM orthopedic device that is sold commercially is seen in Fig. 3a.

(a) (b)

Fig. 3. Parts made with additive manufacturing in dentistry and medicine: (a) an orthopedic device made of titanium alloy, and (b) a porous titanium spinal implant [13].

Another illustration is the Titanium AM spinal cage manufactured by the US-based Next Spine (Fig. 3b). This firm claims that when people age, have spinal malignancies, or experience trauma, spine surgery is becoming increasingly prevalent [51]. Custom orthopedic implants that are based on precise bone structure capture are another example. Based on a CT scan, Harrysson et al. [52] created integrated implants. They then used EBM or DMLS technologies to construct the unique implants, which were made of Ti6Al4V.

5. Challenges in metal additive manufacturing

Even while AM was developed to create prototypes quickly, it may also be used to create new items with complicated geometric designs by removing design and production limitations [53]. In order to revolutionize product lifecycle performance, AM is currently expanding quickly into a variety of industrial applications, from flexible design optimization to functional improvement [54].

This inevitably brings with it more cross-disciplinary and case-dependent research challenges, such as function-specific product design and simulation tools, high-quality cross-scale part fabrication, in-process monitoring and effective control, and dependable product lifecycle management. Resolving these challenges will increase fundamental research and provide tangible benefits to industries [1].

5.1. Material limitations

Although the list of metals and alloys that are now acceptable for AM is small, the number of materials for metal AM technologies is growing. Stainless steel, gold, silver, Inconel, copper, titanium alloys, nickel-based superalloys, tool steels, aluminum alloys, platinum, palladium, and tantalum are just a few of the metal materials available to designers today [55, 56]. Since there aren't many metal materials available for AM systems, research and development are working to increase the number of materials and broaden the use of existing metal AM processes. High-entropy alloys, magnetic alloys, bulk metallic glasses (BMG), functionally graded materials (FGM), new metal composite structures, and nano-architected metals are a few examples of the cutting-edge research being done in these areas [13].

5.2. Process optimization

The thickness of each printed layer is determined by the AM technique, processing conditions, and raw material characteristics [57-59]. The thickness of each printed layer is affected by the following factors: material jetting techniques produce the finest layer thickness ($\approx$ 0.02 mm) due to the small jetted droplets; powder bed fusion and vat polymerization origin lower layer thicknesses ($\approx$ 0.1 mm) because of their ability to precisely focus the energy beam radius; and powder bed AM produces lower surface quality than the other AM techniques because of the presence of large and partially melted powder particles on the printed pieces' surfaces [14].

5.3. Design constraints

Because of residual stresses, microstructural features, and relatively high surface roughness, AM processes have an impact on fatigue and fracture strength even though they provide previously unheard-of geometrical design freedom that can lead to significant weight reductions in components [60]. This is caused by flaws, distortions, anisotropy, and stress concentration effects, the impacts of which require further research [1].

6. Conclusion

Investigating 3-D printing for metallic components reveals a revolutionary approach to manufacturing that enables the production of intricate geometries, unique structures, and material properties that are unattainable with conventional techniques. Technologies for metal additive manufacturing, such as PBF, DED, and BJ, offer several advantages, including high accuracy, material efficiency, and design flexibility, which are driving innovation in the automotive, aerospace, and healthcare industries. Continuous advancements in process control and defect detection are enhancing part quality and reliability despite challenges, including high costs, size limitations, and the need for post-processing. Metal 3D printing is emerging as a complementary and increasingly vital technology in modern manufacturing due to its ability to produce near-net-shape products with superior mechanical and thermal properties, as well as environmental benefits like reduced waste and energy consumption. The potential of metal additive manufacturing to transform production and unlock new opportunities in the engineering and biomedical fields will be further harnessed by future research focused on material discovery, process optimization, and application-specific solutions.

Author contributions

Mojdeh Rezaei-khamseh: Conceptualization, Writing – original draft, Writing – review & editing; **Soroush Etebarian:** Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare no conflict of interest.

Data availability

No data is available.

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