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Review Article

Metal 3D Printing - A Comprehensive Review on Materials, Methods and Properties

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Abstract:
Metal 3D printing, which is also referred to as additive manufacturing (AM), encompasses a manufacturing technique that fabricates parts through the deposition of powder, wire, or sheets in a meticulous layer-by-layer fashion. Throughout the course of time, numerous methodologies have been devised to manufacture metal components by means of AM. The primary objective of this comprehensive review is to explore into the intricacies of metal 3D printing, including an examination of the advancements made in the realm of new materials tailored specifically for AM processes, as well as an exploration of the methods and properties of the materials printed.

Keywords: *Metal 3D Printing, Mechanical properties, Printing methods, Biomedical applications*

1. Introduction

Metal 3D printing, or metal additive manufacturing, has transformed the fabrication of metal items through additive manufacturing methods. This advanced technology facilitates the production of high-quality components with intricate geometries, while also allowing for the customization of designs to fulfill specific requirements. Diverse approaches have developed to improve the possibilities of metal 3D printing, each enhancing various facets of precision, quality and scalability. A notable technique involves the metalization of 3D-printed polymers by a thiol-mediated electroless plating procedure. This method entails the chemical alteration of the surfaces of 3D-printed polymer components to facilitate the deposition of metallic layers, hence improving conductivity and structural integrity [1]. A commonly researched technique employs titanium alloy wire alongside a hollow conical electron beam. This procedure entails the heating and melting of titanium wire to produce homogeneous Ti-6Al-4V material, yielding layered titanium-based structures with enhanced mechanical qualities and corrosion resistance [2]. Moreover, selective metallization can be accomplished through direct plating, wherein acrylate-and methacrylate-based monomers are amalgamated with silver seeds, resulting in the effective production of conductive and functionalized components [3]. Another method, metal droplet-based 3D printing, employs soluble supports to produce components with superior internal surfaces, rendering it suitable for exacting applications such waveguides and antenna horns [4]. Moreover, material extrusion additive manufacturing, similar to metal injection molding, has garnered interest due to its straightforwardness and economic efficiency in fabricating metal components [5].

The applications of metal additive processes are extensive and interdisciplinary. Liquid metal alloys, especially those derived from gallium, exhibit significant potential in flexible electronics and soft robotics. According to Vafadar et al. [15], these alloys are essential for the advancement of flexible electronic circuits and gadgets exhibiting significant deformability, as well as soft robotic actuators necessitating accurate and sensitive movement.

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The incorporation of liquid metal alloys in 3D printing has enabled the development of innovative sensors and adaptive systems with distinctive features, including reconfigurability and self-healing properties. Moreover, metal 3D printing provides exceptional design flexibility, facilitating multimaterial configurations and spatially diverse microstructures. This indicates that components can be fabricated with varying material properties in specific areas, enhancing mechanical performance, thermal regulation and other functional characteristics [12]. The technology's capacity to fulfill the stringent criteria necessary for micro-electromechanical systems (MEMS) and micro-engineering represents another vital application. In the past two decades, micro-additive manufacturing (micro-AM) methods have been advanced to produce intricate 3D microstructures with exceptional resolution and precision. Methods like as MSL and EFAB have demonstrated notable efficacy in the fabrication of functional micro-components featuring complex patterns [28]. Likewise, metal 3D printing has demonstrated its utility in communication systems by enabling the fabrication of metal antennas. Investigations into the fabrication of horn antennas via 3D printing have demonstrated that this method can substantially lower production expenses while preserving structural integrity and functionality [32]. The fabrication of these components illustrates how metal 3D printing is pioneering advancements in fields necessitating exacting engineering and material characteristics.

However, despite these developments, numerous challenges persist that delay the extensive adoption and optimization of metal 3D printing. A significant problem is the regulation and reduction of flaws throughout the production process. Defect formation, especially during solidification and subsequent processing, continues to be a significant concern. Research conducted by Khairallah et al. [13] reveals the meso-nanosecond dynamics that affect defect formation, encompassing heat fluctuations and swift cooling rates, which may result in porosity, fractures, and other structural inadequacies in printed components. Advanced modeling and process control solutions are necessary to enhance the uniformity and quality of metal components. The durability of welded components in metal 3D printing remains a mostly unexamined domain. Wani ZK et al. [34] noted that although welding is frequently employed in post-processing, there is a paucity of studies examining the impact of the welding process on the strength and durability of 3D-printed components, especially under mechanical stress.

Moreover, productivity and dimensional constraints pose obstacles in the realm of polymer-based 3D fabrication techniques. Despite the capability of technologies like FDM, DIW, SLA and BJ to integrate magnetic elements into polymer matrices, these approaches encounter challenges concerning low productivity and the restricted dimensions of printed components [70]. These limitations impede the capacity to expand the technology for more extensive industrial applications. Another problem involves the formulation of binder compositions utilized in metal injection molding and material extrusion methods. Research indicates that meticulous optimization of binder formulations is crucial for producing high-quality sintered components with minimal flaws, including shrinkage and voids. Compositions intended for powder injection molding (PIM) can be modified slightly for additive manufacturing, enhancing control over the sintering process and yielding superior outcomes [71].

In the wider scope of metal layer-by-layer fabrication, Frazier [6] provides an extensive analysis of the underlying science of the technology. The review underscores the significance of comprehending heat transfer, solidification, and solid-state precipitation, as these elements profoundly affect the ultimate properties of 3D-printed metal components. In the absence of precise control over these aspects, ensuring consistent mechanical performance across several batches of components becomes challenging. Wire-feed additive manufacturing, a potential approach, emphasizes the introduction of metal wire into the system to fabricate large-scale components. Ding et al. [10] examined recent developments in this field, emphasizing the necessity for additional research on optimizing wire-feed systems to enhance the efficiency and quality of printed metal structures. Metal 3D printing has experienced significant advancements in techniques and applications; yet, numerous problems must be resolved to fully realize its promise. Challenges associated with defect formation, post-processing methods such as welding and production scalability must be addressed. Ongoing research in these domains will be crucial for the progression of metal additive manufacturing and the expansion of its applications across several industries, including electronics, robotics, aerospace and healthcare.

2. 3D printing materials

Advancements in additive manufacturing (AM) have transformed the manufacturing sector, especially with the emergence of metal additive manufacturing techniques such as Metal Fused Deposition Modeling (FDMm). FDMm provides an economical, customizable and intuitive method for fabricating solid metal components, specifically utilizing materials like 316L Stainless Steel, 17-4PH Stainless Steel and high-melt Iron alloy filaments. This paper examines the methodologies and parameters utilized by different researchers in the printing, debinding, and sintering processes for metal FDM filaments, highlighting the necessity for uniform and optimum parameters within the industry [30]. Sames et al. [7] examine the metallurgy and processing science of metal additive manufacturing. It examines the various methodologies employed in metal additive manufacturing, including powder bed fusion and directed energy deposition. They offer summary tables detailing the mechanical properties of diverse metallic alloy systems, including Ti-6Al-4V, TiAl, stainless steel, Inconel 625/718 and Al-Si-10Mg. A novel production method using the casting of Field's metal into dielectric molds produced via fused deposition modeling (FDM). FDM is a prevalent rapid prototyping method; yet, it has constraints in generating high-quality 3D electrically conductive objects. Utilizing Field's metal allows for the transformation of dielectric molds into conductive structures, facilitating the fabrication of complex 3D designs. An examination of various thermoplastic materials utilized in FDM was conducted to identify the most appropriate candidates based on processing temperature, relative permittivity and loss tangent. The technology demonstrates the capability to incorporate functional metamaterial devices with elevated Q-factors into conventional FDM systems, thus enabling the production of curved and three-dimensional geometries. The utilization of aqueous metal salt electrolyte solutions as metal cation precursors for Electrohydrodynamic Reductive Precipitation Additive Manufacturing (EHD-RP AM) by Porenta et al. [36]. The shift from sacrificial sources to aqueous electrolytes is anticipated to expand the variety of materials available for this approach. Optimal results were achieved at a metal ion concentration of 1 mM, facilitating the deposition of high-purity structures for copper (Cu), silver (Ag) and zinc (Zn). The methodology was further developed to produce alloys like Cu-Ag, Cu-Zn and Cu-Ag-Zn, with meticulous control over the composition. This method facilitates alloy modification and the production of materials with tailored characteristics for diverse applications. Numerous methodologies for 3D printing Metal-Organic Frameworks (MOFs) are presently in the nascent phases of advancement. Direct-ink technique entails the amalgamation of metal-organic frameworks (MOFs) with chemicals to create a paste appropriate for direct printing; yet, it encounters difficulties in attaining a balance between MOF accessibility and the rigidity of the item. Indirect printing involves the application of MOFs onto preprinted objects, constituting a two-step procedure. The development of a composite filament using MOFs demonstrates potential for traditional 3D printers, although it encounters obstacles with MOF accessibility. Notwithstanding these challenges, the 3D printing of MOFs possesses significant potential for surmounting these impediments [47]. The obstacles related to the 3D printing of polymers and metals through the development of functional composites utilizing thermoplastic elastomers, Field's metal, and graphene are being surmounted. The application of fused filament fabrication facilitates the 3D printing of recyclable composites with adjustable internal structures and varied characteristics. The correlation between structure and properties is elucidated via the utilization of multi-physics modeling. The transformation of the 3D structures from insulative to conductive is accomplished via the melting and coalescence of Field's metal nanoparticles. The integration of graphene significantly improves the conductivity of the composites. This platform, integrating polymers and metals, has significant potential for progress in soft electronics, robotics and energy storage [48].

Another element is to examine the efficacy of gas metal arc welding (GMAW)-based 3D printing within the framework of affordable open-source metal 3D printers. The study investigates diverse applications employing a modified Computer Numerical Control router and an economical open-source metal 3D printer, encompassing the repair of existing components, the fabrication of products utilizing the substrate as a component, high-resolution 3D printing, near-net shape objects, and the production of integrated items through a combination of steel and polymer 3D printing. The findings illustrate the potential of GMAW-based 3D printing for the decentralized production of valuable products across several applications [64]. The production of alumina/AlSi12 composites utilizing the fused deposition modeling (FDM) technique and gas-pressure infiltration, as described by Kremzer et al. [67]. This procedure entails the 3D printing of porous ceramic frameworks utilizing filaments infused with alumina powder, succeeded by debinding and sintering. Thermogravimetric analysis and differential thermal analysis were conducted to refine the degradation and sintering protocol. The sintering procedure produced porous alumina ceramic samples devoid of residual carbon, while liquid metal infiltration successfully occupied open pores, creating a three-dimensional aluminum phase network. The engineered materials demonstrated reduced porosity, a uniform distribution of the reinforcing phase and enhanced mechanical characteristics relative to the matrix, with a hardness exceeding twice that of the matrix. This technology is regarded as both novel and practical for the production of these composite materials. Huang et al. [68] demonstrate that TiC-reinforced 17-4PH stainless steel composites, produced via fused filament fabrication 3D printing, exhibit improved wear resistance. The microstructure exhibits refined grains and the incorporation of 10 wt% TiC attains peak hardness (434 HV) and a 3.3-fold decrease in wear rate. This enhancement is chiefly ascribed to the fine grain and secondary phase strengthening.

This study examines the accuracy of dimensions and porosity of copper-filled components produced via fused filament fabrication (FFF) in 3D printing. The cuboid components were produced in a vertical alignment, and the study established that factors like the layer height, printing temperature, and printing speed significantly influence dimensional correctness and porosity. Multi-objective optimization recommended specific parameter settings: a layer height of 0.1 mm, a print speed of 40 mm/s, an extrusion multiplier of 0.94 and a temperature of 200°C, to minimize dimensional errors and attain a target porosity of 20%. These findings facilitate the selection of the most optimal 3D printing parameters for metal-infused filaments in FFF procedures. The evolution of industrial applications is observing increased use of 3D-printed goods made from specialized metal alloys. A crucial feature in this context is the dilation behavior, particularly under temperature variations, which holds particular importance in industries such as aerospace. The present study focuses on samples of AlSi10Mg alloy produced via laser powder bed fusion (PBF-LB/M). To investigate the properties of dilation in additively made components, taking into account the effects of the production technique and the orientation utilized throughout the 3D printing process. This research underscores the importance of considering dilation behavior to achieve accurate functional dimensions, especially in components subjected to minimum mechanical stress and requiring high precision [76].

The study effectively produced OCM nanoparticles (0.05–0.1 μm) that enhanced wettability and stability by utilizing cyclodextrin metal-organic framework particles with 5% wt. ODSA. Stable oil-in-water HIPPEs (volume fraction 0.8, droplet size 7–9 μm) were generated in 60 seconds utilizing 5% wt. OCM. These HIPPEs demonstrated long-term stability, resistance to flocculation, and beneficial gel-like structures at pH levels of 10 to 12. OCMs functioned as stabilizers by forming 2D and 3D cross-linked structures, hence enhancing flocculation and coalescence stability. Regarding edible HIPPEs in extrusion 3D printing, the OCMs-emulsions exhibited little coalescence during freeze-thaw cycles, along with superior 3D printing quality and form retention as printing ink [17].

Zhang et al. [19] examined the metal compositions in raw filaments and the particles released. Crustal metals, especially silicon, demonstrate elevated transfer rates, but certain metals such as bronze and stainless steel display diminished transfer rates. Detected elements in particles, such as boron, arsenic, manganese and lead, indicate external sources, potentially including printers. Notwithstanding the presence of health-related heavy metals in particulate matter, predicted exposure levels often adhere to air quality guidelines; nonetheless, overall particulate exposure in indoor settings may exceed ambient air limits. The unique strategy found for enhancing crosslinking in photopolymers utilized in 3D printing involves the application of silver (Ag) ions for near-infrared (NIR) to ultraviolet (UV)/visible light upconversion (UC). Voxel crosslinking transcends traditional layer-by-layer methods by the utilization of an economical NIR laser, which facilitates curing at certain depths by integrating a ytterbium-thulium co-doped phosphor into the resin. The addition of Ag(I) ions accelerates photo curing tenfold, even with 10 mm of resin. Post-printing, implanted Ag(I) ions function as nucleation sites for electroless copper (Cu) deposition, facilitating the incorporation of metallized components onto various substrates. Selective copper plating enables the fabrication of products with surfaces composed of both plastic (acrylic) and metal (copper) [21]. Flores et al. [23] examine the impact of infusing PLA 3D-printed structures with an iron metal salt and subsequently annealing them in a controlled atmosphere on the final fabrication of titanium alloy components. This eco-friendly manufacturing technology, utilizing polylactic acid (PLA) as a bio-based binder, has the potential to mitigate the environmental impact of titanium processing. The debinding and sintering processes were enhanced to produce metallic components with superior mechanical properties and reduced residual porosity [43].

Binder Jetting (BJ) was established as an innovative powder-based additive manufacturing technique for the production of supported nickel catalysts. The nickel precursor was included into the printing process, eliminating the need for a subsequent impregnation phase. This facilitates more study, particularly for multi-metal catalysts and long-term stability assessments [38].

3. Mechanical properties of metal 3D printed materials

Metal additive processes allows for the production of objects with complex geometries and customized designs, offering advantages over traditional manufacturing methods. Various parameters and processes can affect the mechanical properties of 3D-printed metal objects. The mechanical properties of 3D-printed metallic specimens of aluminum bronze were analyzed and it was found that the tensile strength, relative strain, and hardness increased with increasing laser scanning speed [48]. Martin et al. [8] specifically concentrate on the 3D printing of high-strength aluminum alloys. The authors place emphasis on the mechanical characteristics derived from hardness, tension/compression, fracture toughness, fatigue crack growth, and high cycle fatigue experiments. This discovery of

research provides valuable insights into the mechanical behavior of additively manufactured metallic materials. However, further investigation is necessary to comprehend the effects of test conditions on these properties.
Lewandowski and Seifi [9] present an analysis of the mechanical properties of additively manufactured metallic materials. The different AM techniques utilized and summarize the mechanical characteristics obtained from diverse experiments for the material Ti-6Al-4V. Kok et al. [11] deliver a critical analysis of the anisotropy and heterogeneity of microstructure and mechanical properties in 3D fabrication techniques. The difficulties associated with achieving consistent and uniform properties in printed metal components is reported. This discovery of research emphasizes the necessity for enhanced understanding and control of microstructure and mechanical properties in metal AM. The development of high-entropy alloys (HEAs) for 3D printing is another area of interest in metal 3D printing. Han et al. [14] reviewed recent advances in HEAs for 3D printing and highlighted their potential in achieving superior mechanical properties and enhanced functionality. Further research can explore the optimization of HEA compositions and printing parameters to unlock the full potential of these alloys in various applications.

Riaz et al. studied [22], Composite Extrusion Modeling (CEM) employs Metal Injection Moulding feedstock for 3D printing AISI 8740 steel. Through optimized parameters are extrusion multiplier 107.6%, 180°C extrusion temperature, 20 mm/s nozzle velocity, and 0.050 mm layer thickness. It achieves a dense green part with 98% relative density and minimal surface roughness (Ra = 2.3 µm, Rz = 16.1 µm). Yuqing Lu et al. [16] studied the effects of surface polishing and printing layer orientation on the fatigue behavior of 3 mol% yttria-stabilized zirconia (3Y-TZP) made using stereolithography (SLA). Thirty milled and sixty SLA-printed zirconia specimens were assessed. While 3D-printed specimens showed enhanced fatigue strength after polishing, melled, unpolished samples showed a much higher fatigue strength than 3D-printed, unpolished samples. The parallel printing-layer orientation in 3D-printed specimens produced considerably higher fatigue strength, independent of surface finishing. The study showed that 3Y-TZP fatigue strength is greatly influenced by manufacturing procedures and that polishing has a unique impact on both phase transition and fatigue strength. Milled, unpolished specimens and SLA-printed specimens with parallel printing-layer orientation had the highest fatigue strength after polishing.

The use of thermoplastic 3D printing (3DTP) to create metal-ceramic composites is covered in this research. The technology involves the use of high-filled ceramic and metal feedstocks based on thermoplastic binder systems to generate metal-ceramic composites through AM. The difficulties of modifying the shrinkage behavior of various materials during co-sintering are discussed in the study. The results suggest that the technology offers new potential for the manufacturing of multi-material components and can be applicable to diverse material combinations [52].

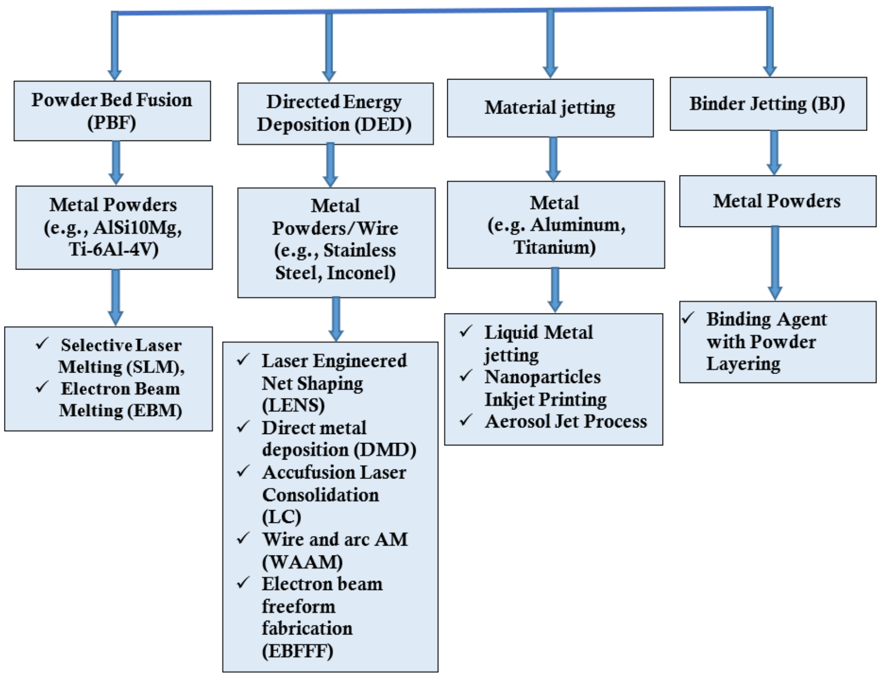

Fig. 1. Different metal 3D printing methods and printing materials

Table 1: Materials, Methods and outcomes of metal 3D printing

Ref. No	Material	Method	Results
[23]	PLA + silver nanoparticles +iron metal salt.	FDM based printing	The impregnated nanoparticles showed strong attachment and interaction with the flow.
[30]	-		Review Paper discussed FDM printed 316L Stainless Steel, 17-4PH Stainless Steel and high melt Iron alloy filaments.
[65]	PLA, Magnetic Iron, and Bronzefill		Hybrid materials with bronze had significantly reduced mechanical properties.
[33]	High impact polystyrene (HIPS), polypropylene (PP) and cyclic olefin copolymer (COC)		HIPS, COC, and PP are the best materials for RF applications.
[66]	Alumnium, carbon fiber		Low and high velocity impact performance of FMLs is superior to plain aluminum and composite material.
[67]	Alumina/$AlSi1_2$		porosity of 0.07 in the sintered ceramic skeletons.
[73]	Polymer molds with an aluminum, ABS		FDM printed polymer molds could be used for the metal injection molding
[74]	Copper-Filled PLA		Dimensional accuracy and porosity - layer height, printing temperature, and print speed
[38]	Ni/Al_2O_3, nickel nitrate-containing ink	Binder jetting printing technique	Ni/Al2O3 catalysts with enhanced activity by NI.
[44]	316L stainless steel		Sintered samples with #C80F20 had optimal mechanical properties.
[42]	Acrylate resin loaded with nickel (Ni) particles acrylate resin loaded with nickel (Ni) particles	Stereolithography (SLA)	Ni particles effectively present in the composite enable homogeneous nickel dispersion.
[47]	MOFs (Metal-Organic Frameworks)		3D-printed MOF monoliths show reduced specific surface area compared to powders.
[46]	316L Stainless Steel	Selective Laser Melting	SLM samples have better average micro hardness than wrought produced samples because to fine microstructures from localised melting and fast solidification.
[48]	18Ni300		Dynamic mechanical characteristics were significantly affected by construction direction, whereas static properties were not.
[58]	-	Wire arc additive manufacturing (WAAM)	FE model accurately replicated structural response of the 3D printed bridge.
[59]	Hot-rolled - S355 steel		Increased axial capacity of 17% to 54% with mass increase of 2% to 26%
[60]	-		The fatigue life of the WAAM-repaired plates was 2.3 times longer than the reference plate.
[54]	Inks with Liquid Metal fillers		Potential applications in actuators, sensors, circuits for soft robotics and electroni
[57]	Hydrophobic silica (HS) nanoparticles	Laser based printing	superhydrophobic coating maintained great water repellency in seawater swashing, preventing dynamic corrosion
[63]	Ti-6Al-4V ELI alloy powder		Loading the Ti cage with G-H filled the holes and created a network of small pores.
[76]	AlSi10Mg alloy		AlSi10Mg alloy is recommended for mechanically low-stress components that require precise functional dimensions.

Table 1: Materials, Methods and outcomes of metal 3D printing (Continuous)

Ref. No	Material	Method	Results
[75]	Cobalt – Chromium – molybdenum based powder, stainless steel 316L-A, stainless steel 17-4PH-A		Differences in printing parameters affect surface and mechanical characteristics of the parts.
[72]	316L medical steel powder	Electron beam melting (EBM) method	Presence of internal threads and holes in the implant increases the stress concentration factor by more than 10 times.
[18]	AISI 316L stainless steel	Bound Metal Deposition (BMD)	The elongation at break was significantly influenced by the build direction for 45° and 90° printing orientations.
[39]	Stainless steel		Heat-treated components have high mechanical properties but high environmental impacts.
[40]			The printing orientation greatly affects the mechanical performances of 3D printed components.
[43]	Polylactic acid (PLA), production of Ti6Al4V feedstock s		Successfully sintered Ti6Al4V components with high densification (93-94%).
[31]	CIM binder flled with NaCl	Extrusion 3D printing	Metal casting in 3D printed NaCl molds was demonstrated with tin and Aluminum.
[41]	Low carbon steel		The optimal slurry formulation for printability, exhibiting appropriate rheological characteristics.
[68]	17-4PH Stainless Steel, TiC	Indirect Metal 3D Printing	Grain size decreases from 65.58 µm to 19.41 µm with increasing TiC content. Wear rate reduced by 3.3-fold with TiC addition.
[62]	-	Direct metal 3D printing	Proposed slot antenna has high radiation efficiency, high gain, and wide bandwidth.
[71]	Iron micro-powders and an organic binder mixtur	Powder Injection Molding based process	Shrinkage in the range of 10-15% for both injection-molded and 3D printed parts.
[45]	Stainless steel metal powder		Presence of residual carbon and oxidation of iron and chromium elements affected sintering.
[22]	Low-alloy steel AISI 8740		Minimized printing voids and smooth surface morphology achieved with optimized parameters.
[53]	Low-melting alloy	Metal additive manufacturing - Field's alloy 3D printing - High aspect ratio printing	High-resolution printing improves printing time efficiency for small features.
[25]	Al2O3/AlSi10Mg	Ultrasonic-assisted metal infiltration	Specific compressive strength and specific energy absorption of the as-fabricated Al2O3/Al IPCs outperformed
[29]	316L stainless steel	Metal-based fabrication techniques and Metal CNC machining	Metal 3D-printed impellers have similar fatigue life compared to CNC-machined impellers.

Table 1: Materials, Methods and outcomes of metal 3D printing (Continuous)

Ref. No	Material	Method	Results
[32]	Polylactic acid (PLA), one copper tape, conductive paint, and conductive filament.	Two techniques used to metallize a structure printed with polylactic acid (PLA)	Antenna printed with conductive filament achieved better gain and larger bandwidth.
[36]	-	Electrohydrodynamic redox 3D printing from mixed metal salt solutions	Binary and ternary alloys of Ag, Cu, and Zn were successfully deposited.
[51]	-	Tungsten inert gas-based metal open source 3D printer	Acquired parameters suitable for printing at a resolution of 0.36 mm in the Z-axis
[52]	Stainless steel + Zirconia	Thermoplastic 3D printing (New method)	Method allows for the production of metal-ceramic composites.
[64]	-	Low-cost open-source metal 3-D printers	Gas metal arc welding (GMAW) based metal 3-D printing successfully demonstrated applications for SMEs and individual makers.
[21]	$NaYF_4$: (20%)Yb^{3+}, (3%)Tm^{3+}	-	Silver ions enhance the crosslinking of 3D printing photopolymers.
[24]	Titanium reinforced membranes	-	3D-printing technique not fully predictable at this time.

A study [29] analyzes the techno-eco-efficiency of 316L stainless steel pump impellers manufactured by bonded metal deposition 3D printing and CNC machining. Compared to CNC-machined impellers, 3D-printed impellers have greater impact on the environment and life cycle costs despite having better mechanical and hydraulic performance. The 3D printing process's sintering procedure greatly increases the total energy consumption. The eco-efficiency of 3D-printed impellers could be increased by technological advancements including integrating machine elements, decreasing idle time and optimizing the sintering profile. The material extrusion as a possible 3D printing technique for sacrificial metal casting molds, which can be used to create molds with complex geometries such as undercuts. The feedstock, constituted of a commercial CIM binder packed with NaCl, allows for the fabrication of molds that dissolve swiftly in water following metal casting. With the aid of these molds, demonstration parts such as turbine wheels, gyroid structures and gear wheels have been successfully cast in tin and aluminum. By submerging the sintered mold in a saturated NaCl solution, the surface of NaCl molds can be made smoother. The same feedstock was used for both 3D printing and injection molding of bending test bars, which showed excellent strength (12–13 MPa) in three-point bending tests for both printed and sintered NaCl samples [31].

Son H-J et al. [35] investigated how the activator and binder contents affected the microstructure, flexural strength, dependability, and erosion resistance of 3D-printed sand molds during casting. Significant findings include the direct relationship between flexural strength and activator and binder levels, with optimum parameters resulting in increased erosion resistance and dependability. The research found that an ideal value of 0.25A2B produced 3D-printed sand molds with a Weibull modulus (implies distribution of strength and reliability of molds) of 7.8 and a flexural strength of 4.2 MPa. When these molds were used to cast exhaust manifold pieces, the results showed good performance and a 1% increase in turbocharger power output over original parts.

This work examines the mechanical and environmental properties of metal specimens made via Bound Metal Deposition 3D printing. The as-sintered and heat-treated (H900 aging procedure) scenarios are taken into consideration. The specimens that have been heat-treated display enhanced mechanical characteristics, including increased yield and ultimate tensile strengths. As-sintered specimens perform better environmentally, with the printing and sintering processes accounting for a large portion of the environmental impact [39].

The mechanical performance of 17-4 PH stainless steel made by bonded metal deposition additive production methods is assessed in this work. Three-dimensional printed specimens with varying growth orientation angles (0°, 45° and 90°) underwent tensile tests. The main conclusions show that specimens with 0° and 90° orientations had comparable ultimate tensile strengths and Young's moduli, however specimens with a 45° orientation had a decline in mechanical characteristics. Higher strain levels indicated that specimens with a 0° growth orientation performed better. The mechanical behavior of configurations with 0° and 90° growth angles was in line with MPIF Standard 35 [40].

Printing air holes in the fiber preforms is the primary challenge. Nevertheless, additional alterations to the two-head 3D printing configuration would enable the production of airhole-free, all-glass structured preforms using two different kinds of glass. Furthermore, the hand production of this novel class of fibers using the stack-and-draw technique is impractical as it needs the assembling of several thousand pieces. Developing 3D printing further provides a direct path to producing and learning more about the characteristics of this novel family of optical fibers. Two printing heads added to a 3D printing setup could allow for the creation of airhole-free all-glass structured preforms that are appropriate for uses such as nanostructured free-form fibers [41].

A revolutionary 3D printing technique for self-activating metal-polymer composites that can be electrolessly metallized to a desired degree. In order to create the composites, Ni particles that can initiate the electroless deposition process are doped into acrylate-based resin. This eliminates the need for costly and time-consuming intermediary steps. The values of penetration depth and critical energies (amount of energy required to form a solid layer) obtained attest to the composites' SLA high-resolution process ability. The printed material's elastic modulus is significantly increased by the inclusion of Ni nanoparticles. By using multimaterial SLA printing to metallize a Ni-loaded design that was 3D printed on a Ni-free foundation, selective metallization is shown to be feasible. This technique could be used to create multilayered electrical circuits printed in three dimensions or sensors that combine conductive and magnetic materials [42].

In Binder Jetting 3D Printing [34], bimodal 316L stainless steel powders—especially those with higher fine fractions—significantly improve the mechanical, surface, and green and sintered sample densities. The present study highlights the significant benefits of bimodal powders and highlights their influence on the effectiveness of metal procedures. The findings have implications for enhanced material properties and their use in various industrial settings.

Akhoundi et al. [45] investigated the use of a screw-based material extrusion 3D printer for the extrusion of metal/polymer composite materials. The ideal debinding procedures, printing settings, and temperature profiles were found. After sintering, specimens kept shape but were brittle, and metal components oxidized, creating compounds. Subsequent research endeavors to enhance the sintering procedure for better mechanical characteristics.

This study presents an economical approach to 3D printing using the E3D "Tool Changer" platform with granular feedstock. The software control, adaption sections, and system components are all described in depth. The quality of the setup is confirmed by mechanical characterizations of sintered 316L steel pieces. Issues such as granule obstruction and temperature gradient management were tackled. With the use of filled pellets, the technique' versatility to a range of materials, such as metal alloys and ceramics, was established. Because of its versatility, the E3D Tool Changer makes it possible to combine various materials and manufacturing tools, which could improve dimensional accuracy and bring additive manufacturing into compliance with industry standards [46]. In order to regulate the liquid metal (LM) microstructure in elastomer composites and create soft, flexible materials with programmable features, this work provides a direct ink writing technique. Emulsion inks with LM fillers enable microstructure control in situ, resulting in 3D structures, films and filaments with distinctive LM patterns. The resulting materials can be either locally conductive or insulating, and they are soft and extremely malleable. Soft electronics, robotics and reconfigurable structures—such as an LED heat sink—are among the applications. These programmable microstructures offer new opportunities for developing technologies demanding compatible materials with multifunctional responses [54].

An arc plasma heat source is used to create a high-throughput metal 3D printing pen (M3DPen) by Kim CK et al. [55]. The M3DPen technique, in contrast to conventional arc-based metal additive manufacturing, uses the surface tension of molten metal to provide continuous material deposition devoid of gravity-induced flow. Freestanding and overhanging structures can be produced in a single process, increasing the possibility for large-scale, high-throughput metallic additive production for a variety of industrial uses. The study analyzes ensuing mechanical properties and novel microstructures achieved through continuous metal deposition, exhibiting its adaptability across diverse alloy systems. There is a method for improving the durability of superhydrophobic products through the use of surface imperfections present in metal 3D printing by laser powder bed fusion additive manufacturing (LPBF-AM). Robust superhydrophobic materials with three-dimensional structures are produced when hydrophobic silica nanoparticles are stored in the flaws, such as ridges and grooves. The hydrophobic coating prevents surface flaws from causing corrosion. Applications requiring corrosion resistance can benefit from LPBF-AM-printed items containing hydrophobic silica nanoparticles since they maintain their hydrophobicity even after being subjected to seawater exposure and abrasion cycles [57].

The flexural buckling response of thirteen hot-rolled I-section columns reinforced at the flange tips by Wire Arc Additive Manufacturing (WAAM) stiffeners was the subject of an experimental examination. Tests of complementary materials were carried out on standard and WAAM steels. Geometry and global defects were determined by 3D laser scanning, and strain and deformation fields were monitored throughout testing by digital image correlation. The findings indicated that while the existing EC3 approach is able to forecast safe-sided capacity for the specimens under examination, more research is required to provide precise design guidelines. WAAM-strengthened columns, notably those with sinusoidal-shaped stiffeners, displayed considerable structural efficiency increases, indicating the potential for material savings [59].

The fatigue strengthening of the damaged steel with wire arc additive manufacturing (WAAM) is another application of the 3D printing. Three steel plates, a reference plate, a plate repaired by WAAM with an as-deposited profile, and a plate repaired by WAAM and then machined with a central crack were tested under high-cycle fatigue loading. A finite element simulation was run to improve comprehension. The fatigue resistance of the WAAM-repaired plates was better; the machined profile plate performed the best, lasting more than 9 million cycles without displaying any signs of wear and tear. This demonstrates how WAAM can be used to mitigate fatigue-related problems in steel structures [60].

The use of PLA filaments packed with bronze powder for 3D printing bronze filaments is done by Oyedotun [61]. The main goals of the research are to characterize the mechanical characteristics and microstructure of the 3D printed bronze specimens, as well as to identify the best processing settings and sintering parameters. The study illustrates the viability of printing bronze filaments on a standard FDM machine with optimal settings by employing a design of experiment (DOE) methodology. The mechanical strengths are considerably impacted by the sintering circumstances, according to the results, which offers important information for prospective engineering applications. A 3D printing technique that generally employs molten polymers. Comparing hybrid materials to typical poly (lactide acid) (PLA) printed products, metal-polymer blends containing metal particles were examined with items manufactured by the use of fused deposition modeling (FDM), The mechanical characteristics of hybrid materials, especially those incorporating bronze, were found to be considerably lower than those of PLA in tensile and bending tests. The quality of the printing process was shown by the 3D-printed objects' tensile strengths, which were comparable to those of the original filaments. The results point to drawbacks in the quick production of mechanically strong products utilizing metal-polymer blends [65].

The mechanical performance of a novel kind of continuously 3D printed carbon fiber-reinforced composite fiber metal laminate (FML) subjected to tensile, impact at low velocities, and impact at high velocities tests were performed on the laminates and the components that made them up. The findings showed that the examined FMLs' tensile strength was noticeably higher than that of standard composite materials. In low-velocity impact testing, the FMLs demonstrated improved performance relative to their constituent materials, with plastic deformation and interlaminar delamination identified as main energy absorption mechanisms. The FMLs outperformed the ordinary composite materials in impact tests conducted at high velocities. The study implies that 3D printing can be utilized to generate hybrid laminates with unique and customizable architectures, laminates [66].

An approach to assess and forecast the fatigue life of metal implants with complicated shapes. A calculated failure cycle exceeding 42,858, deemed sufficient for osseointegration, recommendations for improving fatigue life through manufacturing modes and post-processing, acceptable surface roughness influence, stress concentration factors influenced by design and material, and adequate safety margins for osseointegration are among the key findings [72]. Metal injection molding (MIM) molds are often made from metallic materials using traditional machining techniques. Because of their durability, MIM molds are perfect for mass manufacturing. Nevertheless, 3D printed molds, most especially Fused Deposition Modelling (FDM), provide an affordable substitute for low-volume and bespoke applications when part demand is constrained throughout design iterations. In order to assess the feasibility of using

FDM 3D printed polymer molds in MIM processes, this study compares their performance to aluminum molds and shows that they can be successfully used for a limited number of cycles [73].

In contrast to traditional dental zirconia milled from a commercial block of comparable composition, Yuqing Lu et al. examined the effects of printing layer orientation and polishing on the fatigue behavior of 3 mol% yttriastabilized tetragonal zirconia polycrystals (3Y-TZP) produced using 3D printing. It was determined that the fatigue strength of the 3D-printed and milled 3Y-TZP was significantly impacted by the production processes [18].

A groundbreaking 3D-printed and electroless metallized z-axis accelerometer has been successfully designed, fabricated, and tested. Leveraging the tri-dimensionality of 3D printing in the mechanical structure design, electroless metallization enables electrostatic testing. The device exhibits promising sensitivity and linear range. Ongoing work focuses on reducing footprint, minimizing capacitive parasitic, and enhancing linearity through innovative mechanical and electrical design approaches [26].

Selective Laser Melting (SLM) is a particular technique of 3D printing utilized in metal Additive Manufacturing (AM). This investigation examines the influence of Volumetric Energy Density (VED) on metal specimens printed through SLM. The characteristics of the surface and the properties of tensile strength, establishing linear correlations between VED and both the roughness of the surface as well as the yield stress and toughness of the material. Models that can predict roughness, yield stress and toughness based on VED are proposed, offering valuable insights into the optimization of 3D printing parameters for the production of metal components with desired surface quality and strength [75].

Metal-based fabrication techniques enable intricate designs with superior customization compared to traditional methods. Studies on aluminum bronze and high-strength aluminum alloys reveal improved mechanical properties with higher laser scanning speeds. Researchers emphasize the importance of understanding test conditions' effects on properties. Analysis of Ti-6Al-4V and microstructure heterogeneity highlights challenges in achieving uniform properties. High-entropy alloys show promise for enhanced mechanical properties. Composite Extrusion Modeling achieves dense steel parts with minimal roughness. Surface polishing and layer orientation significantly affect the fatigue behavior of zirconia. Thermoplastic 3D printing presents potential for metal-ceramic composites despite challenges in shrinkage modification. This research underscores the need for further exploration in metal additive manufacturing. Techno-eco-efficiency of 316L stainless steel pump impellers produced by bonded metal deposition 3D printing versus CNC machining. Although 3D-printed impellers exhibit better performance, they impact the environment and incur higher life cycle costs due to increased energy consumption during sintering. Techniques like integrating machine elements and optimizing sintering profiles could enhance eco-efficiency. Additionally, sacrificial metal casting molds made through material extrusion enable casting of complex geometries, showing promise in applications like turbine wheels. Various studies explore mechanical properties, microstructure, and applications of metal additive manufacturing, emphasizing the need for optimization and further research to unlock its full potential across industries.

4. Applications of metal 3D printing in biomedical

Metal 3D printing has significant potential in the field of biomedical applications**.** In order to create patient-matched constructions, using 3D-printed implantable devices for bone regeneration has advantages. However, regulatory channels hinder the translation to fully resorbable implants, and difficulties with titanium meshes in large-volume alveolar bone lesions pose a hurdle. Although promising, more research and development are needed before 3D-printed tools for craniofacial regeneration may be widely used, as there is currently insufficient data to definitively confirm its predictability in oro-dental and craniofacial bone regeneration [24].

Heart valves made of polymeric materials, such as the 3D-printable TIPI valve, are designed to combine the robustness of mechanical valves with the hemodynamics of biological valves. The latest prototype, TIPI 3.4, displays enhanced performance in regurgitation percentage, systolic pressure gradient, and effective orifice area, resolving concerns concerning thrombogenicity. By removing the core restrictor structure, the valve can move its leaflets in a single direction more easily and has simpler designs that may be produced in large quantities using biocompatible polymers or by 3D printing [25]. The use of titanium 3D-printed metaphyseal cones in revision total knee arthroplasty has revolutionised the surgical management of bone abnormalities, especially with regard to stability. These 3D-printed cones improve surgical procedures, increase adaptability, and lower complications as compared to first-generation cones. Positive results have been shown in short- and mid-term studies, however large patient cohorts and long-term data are missing. Even though well-fixed cone repairs show promise, there are still issues that need to be carefully considered when performing total knee arthroplasty revisions. These issues include bone loss, prosthesis selection, augmentation needs, and patient considerations [27].

Biomedical implants, tissue engineering, and regenerative medicine are just a few of the areas that 3D printing has profoundly changed. The biomaterials—ceramics, polymers, metals, and composites that are utilized in the 3D printing of porous scaffolds for bone tissue engineering are the main topic of this review. It goes over important 3D printing specifications, methods, and difficulties. Biomedical implant production has a bright future because to the developing technology, which also provides researchers and physicians with useful information. The advancement of biomaterial-based 3D printing represents a promising future for the creation of biomedical implants [50].

Using finite element analysis (FEA) studied the tooth-supported surgical guides for dental implant implantation without metal sleeves. The FEA simulation in CATIA v5 software considers guide mesh material and bone characteristics. Findings show that the guide had a maximum stress of 6.92 MPa and little movement during drilling. The developed tooth-supported surgical guide displays the potential to sustain surgery stresses, even in denser bone, without the risk of fracture, presenting a promising alternative in guided implant surgery [56]. In order to optimize their regenerating potential for orthopaedic applications, investigated the loading of gelatin and hyaluronic acid (G-H) into 3D-printed titanium (Ti) cages. G-H and the 3D-printed Ti cage combine to form a micropore-sized porous network that promotes cell adhesion and migration. Osteoconduction and biocompatibility are improved by the gradual release of G-H, which causes the expression of genes associated to bone to increase. The G-H-coated Ti cage exhibits faster bone healing in an in vivo implantation model of a rabbit femur as compared to the pristine version, indicating its potential orthopaedic application [63].

Another effort to establish sustainable manufacturing practices, this research investigates the promising synergy between 3D printing and recycling. It compares the printability of recycled materials to that of their traditional counterparts and uses sustainability and life cycle analyses to reveal benefits like increased resource efficiency, reduced waste, and customization options. The research places a strong emphasis on innovation, cooperation, and regulations to overcome obstacles and increase the use of recycled materials in 3D printing. With applications across industries, this integration promises a future characterized by resource conservation, circularity, and customized production, fostering a more sustainable manufacturing landscape [20]. Another study looks at how production scheduling based on additive manufacturing is developing. It presents the IP3DMSP mathematical problem, which allows for several build platforms with limited dimensions, improving the scheduling feasibility for 3D printing operations. By extending the IG algorithm, introducing the TIG metaheuristic, and putting forth innovative local search mechanisms, the study greatly enhances the quality of the solutions. Future research on distant production sites, taking into account conflicting tasks, heterogeneous 3D printing machines, learning-based metaheuristics, and incorporating uncertainties into production planning based on additive manufacturing are all suggested by the study. Future studies in this field are positioned to use the TIG metaheuristic as a standard [37] . The democratisation of metal additive manufacturing with low-cost open-source 3D printers. The best printing parameters for a metal 3D printer based on tungsten inert gas are obtained by using particle swarm optimisation (PSO) with open-source software that is free of cost. To optimise the settings for single lines, single-layer planes, cubes, and updated line configurations, four trials are carried out. With a focus on distributed digital manufacturing, the project attempts to extend wire arc additive manufacturing to a variety of systems and material classes [51].

An additional work evaluates Field's metal's printability with electric field-assisted direct-write technology for three-dimensional printing. Line thickness (Z-axis) is highly dependent on parameters such as temperature, nozzle plotting speed, and number of layers, but not 2D resolution (X- and Y-axis). The technique is shown for infill, bridging, and overhanging patterns. Successful prototypes of two applications—body markers for patient location in CT scanning and capacitance measurement devices—showcase the potential of devices at the micrometre level and a variety of metallic alloys for use in future applications [53]. The describes the world's first metal 3D-printed bridge's numerical simulation and safety assessment. A complex finite element (FE) model was created that takes into consideration geometric variability and material anisotropy related to the Wire Arc Additive Manufacturing (WAAM) process. In order to evaluate the performance of the as-built structure, improve design components, take load scenarios into account, and support decision-making outside of physical testing, the FE model was an essential tool. The work emphasises the value of sophisticated numerical modelling for continuous evaluation and safety confirmation of buildings made with novel techniques [58].

Metal 3D printing holds potential in biomedical applications, particularly for patient-matched constructions and implantable devices aiding bone regeneration. Challenges in regulatory approval hinder fully resorbable implants, while issues persist with titanium meshes in large-volume bone lesions. Innovations like the TIPI valve enhance heart valve performance, while 3D-printed metaphyseal cones improve stability in knee arthroplasty revisions. Biomedical implants benefit from porous scaffolds made with ceramics, polymers, metals, and composites via 3D printing. Sustainable practices integrate recycling into 3D printing, promising increased resource efficiency and customization. Production scheduling advancements optimize additive production methods, while low-cost open-source printers democratize metal 3D printing. Electric field-assisted direct-write technology showcases potential for micrometric metallic devices, while sophisticated numerical modeling ensures safety in novel structures like metal 3D-printed bridges.

4.1 3D metal printing for electronic medical devices

3D metal printing has arisen as a revolutionary method for manufacturing electronic medical devices, facilitating the incorporation of sophisticated features into biomedical applications. This novel method integrates the accuracy of 3D printing with the adaptability of electronic materials, enabling the creation of tailored, patient-specific gadgets that improve healthcare provision. 3D printing enables the fabrication of personalised implants and devices that fit patients' unique anatomical structures, hence increasing functionality and outcomes [77]. The integration of conductive materials, such as low-temperature melting alloys, allows for the direct fabrication of electronic circuits onto medical devices, thereby augmenting their capabilities [78].

Stretchable circuits and a strain sensor are developed using an aerosol jet printing technique in additive manufacturing. Aerosol jet printers can achieve high-quality and conformal printing owing to the high resolution of the printers. According to the strain research, the printed stretchable circuit operates fine up to 15 % of strain. A meander line circuit wherein the LED operates when the circuit is stretched in the middle [79]. Silver and gold nanoparticle inks are commonly used in 3D printing of electronics. These metallic nanoparticle inks can be used to 3D print thin-film transistors, capacitors, and other electronic components [81]. Functional inks on textiles can integrate passive electronics and sensors utilising inkjet printing [80]. The gold nanoparticles were used to print in inkjet printing by Rudolf et al. [82]. By using nano gold ink on the paper it opened an avenue for preparing the paper based electrochemical immunosensors, colorimetric sensors and nano-metallic biomedical sensors. And it is found the Intense pulsed light sintering process for fast fabrication of multi-layered electronics such as electrochemical electrodes [83]. That integrating Additive manufacturing with metallic nanoparticles is helpful in the fabrication of 3D-Printed Electronics including Flex and Wearable Electronics. Other conductive materials like copper and aluminium may also be used in 3D-printed electronics The 3D printing or additive manufacturing is versatile technique for developing electronics using metallic nanoparticle ink, namely- silver and gold to build different electronics components and gadgets [84].

5. Conclusion

Metal 3D printing has revolutionized manufacturing by producing complex geometries and customized designs. Higher laser scanning speeds can improve mechanical properties, while high-entropy alloys offer superior functionality. Composite Extrusion Modeling (CEM) can produce dense steel parts with minimal roughness, while thermoplastic 3D printing shows promise for creating metal-ceramic composites. Thermoplastic 3D printing is eco-efficient, but challenges remain in modifying shrinkage behavior. Metal 3D printing has potential in biomedical applications, but faces challenges in regulatory approval and implant performance validation. Advances in production scheduling and low-cost open-source printers are democratizing additive manufacturing operations.

Future investigations in 3D printing materials should concentrate on enhancing metal additive manufacturing techniques, including refining sintering and printing parameters to facilitate wider material applicability and improved reproducibility. Hybrid approaches that integrate processes such as FDM with powder bed fusion have opportunities for improved mechanical characteristics. The incorporation of conductive materials such as Field's metal into fast prototyping has the potential to transform electronics manufacturing. Furthermore, investigating 3D-printed Metal-Organic Frameworks (MOFs) for industrial applications and creating functional composites for soft electronics, robotics, and energy storage are critical domains. Future developments in these technologies will be propelled by scalability, material innovation and sustainability.

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