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Metal Additive Manufacturing Materials: A State-of-the-Art Review

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Abstract

3D printing, or Metal Additive Manufacturing (MAM), has significantly changed the manufacturing world as it allows the creation and optimization of complex designs previously thought impossible. The body of this article is devoted to analyzing materials and their properties, such as processability, microstructure, and mechanical characteristics, applicable to silicate MAM. It also describes Powder Bed Fusion (PBF), Directed Energy Deposition (DED), Binder Jetting (BJ), and Material Extrusion (MEX) methods of MAM in terms of their material compatibility and fields of use. The paper emphasizes the lack of materials that fulfil the requirements, the formation of defects, and the optimization of the process as the challenges that still need to be addressed. These challenges, alongside the expansion of the field of MAM, will serve as the basis for further research.

Major Findings: *Current work presents a review of metals used in MAM, a lack of material availability and challenges of the process. The work advocates analysis of material properties which are desirable for MAM.*

Keywords: *Mechanical Properties, Metal Additive Manufacturing, Microstructure, Powder Metallurgy, 3D Printing*

1.0 Introduction

Metal Additive Manufacturing (MAM) is a revolutionary technology that enables unprecedented design freedom, rapid prototyping, and the potential for on-demand, customized production[1]. Compared to traditional subtractive manufacturing processes, MAM constructs parts layer-by-layer from digital models, adding material where needed. Layer-wise manufacturing makes it possible for new levels of geometric complexity, lightweight structures, and embedded functions. The aerospace, automotive, biomedical, and tooling industries are increasingly employing MAM to produce complex parts with enhanced performance characteristics[2].

The secret of MAM is the material. While polymers and ceramics have seen widespread use in additive manufacturing, and metals possess enormous potential through high mechanical properties, thermal conductivity, and electrical conductivity, and thus are of utmost significance for high-performance and structural applications, the unique processing conditions of MAM, i.e., rapid heating and cooling, local melting and solidification, and layer-by-layer fabrication, impose certain requirements on material choice and process development[3]. Material properties and process parameters are intertwined and influence each other significantly to establish the ultimate microstructure, defect density,

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and thus the performance of AM-fabricated metal components.

This review seeks to paint a comprehensive picture of the metal additive manufacturing material landscape. It will systematically survey the dominant metallic materials, processability by different MAM approaches, and the resulting material properties. It will also outline the challenges and opportunities in material development and utilization in fast-growing technology, and emphasize the pivotal role of materials science and engineering in developing the future of MAM[4].

2.0 Metal Additive Manufacturing Processes and Material Compatibility

Various MAM processes have been designed, with varied energy sources, material feedstock forms, and processing mechanisms. Knowledge of the basic principles of the processes serves to be beneficial for an understanding of material selection and process-material interactions[5]. The major MAM processes for metals can be categorized broadly into:

2.1 Powder Bed Fusion (PBF)

PBF processes like Selective Laser Melting (SLM) and Electron Beam Melting (EBM) use a powder bed as feedstock. High-energy beam (electron beam or laser beam) selectively melts and fuses the powder particles layer by layer to the CAD shape[6].

- **Selective Laser Melting (SLM):** SLM employs the use of a laser as an energy source under an inert gas or vacuum atmosphere. It is of high resolution and is able to build complex parts with thin features. Typical materials treated by SLM include stainless steels, titanium alloys, Aluminium alloys, nickel-based super alloys, and cobalt-chromium alloys[7].
- **Electron Beam Melting (EBM):** Using a high-energy electron beam in a vacuum. EBM usually works at high temperatures and scanning rates compared to SLM, resulting in increased buildup rates. It is ideal for high melting point and reactive materials such as titanium alloys and nickel-based superalloys[7].
- **Material Compatibility in PBF**: Powder materials possessing specific particle size distribution, flowability, sphericity, and chemical composition are needed for PBF processes. High laser or electron beam absorptivity, good melting characteristics, and low cracking and distortion tendencies are the desired characteristics for materials used in PBF[8].

2.2 Directed Energy Deposition (DED)

In DED, the material is melted using a focused energy beam (laser or electron beam) and is simultaneously deposited, typically in the form of wire or powder. DED is suitable for building large parts and repairing existing components, but it generally results in lower resolution and surface finish compared to PBF[9].

- **Laser Engineered Net Shaping (LENS)/Direct Metal Deposition (DMD):** These utilize a focused laser beam to melt the feedstock powder fed into the melt pool simultaneously. The DED-powder processes have increased deposition rates and are suited best to large components and repairs. Common materials are stainless steels, titanium alloys, nickel-based superalloys, and tool steels[10].
- **Wire Arc Additive Manufacturing (WAAM):** It uses an electric arc to provide heat and a metal wire as the feed material. WAAM is capable of very high deposition rates, making it suitable for manufacturing large structural components. Steel, Aluminium alloys, and titanium alloys are common feedstocks for WAAM[11].

2.3 Binder Jetting (BJ)

BJ processing utilizes a liquid binder to bind powder particles selectively in a layer-by-layer fashion. The sintered and debound printed parts are then used to achieve final densification and mechanical properties[12].

- **Metal Binder Jetting (MBJ):** A liquid binder is selectively jetted onto a powder bed to bind particles together. MBJ is highly scalable and high-throughput, and potentially lower-cost than PBF and DED. An extremely broad range of materials, including stainless steels, tool steels, titanium alloys, and nickel-based alloys, can be processed.
- **Material Compatibility in BJ:** MBJ requires powders with high flow ability and sinter ability. Binder system and sintering process are the most

Table 1. Summary of metal AM processes and process and representative example materials[14]

Process Category	Process Example	Feedstock Form	Common Materials	Advantages	Limitations
Powder Bed Fusion (PBF)	SLM, EBM	Powder	Stainless Steels, Ti Alloys, Ni Superalloys, Al Alloys, Co-Cr Alloys	High resolution, Complex geometries, good surface finish (SLM)	Slow build rate, Powder handling, Size limitations
Directed Energy Deposition (DED)	LENS/DMD, WAAM	Powder, Wire	Stainless Steels, Ti Alloys, Ni Superalloys, Tool Steels, Al Alloys	High deposition rate, Large parts, Repair capability (DED), Scalability (WAAM)	Lower resolution, Rougher surface finish, Heat-affected zone
Binder Jetting (BJ)	Metal Binder Jetting (MBJ)	Powder	Stainless Steels, Tool Steels, Ti Alloys, Ni-based Alloys	High throughput, Scalability, potentially lower cost, Complex geometries	Post-processing (debinding and sintering), Lower density compared to PBF/DED

important factors that decide the final density and characteristics of BJ-fabricated parts. BJ is a relatively fast and cost-effective process, but it often requires post-processing steps to achieve desired mechanical properties[12,13]. Table 1 offers a summary of MAM processed and process categories and representative example materials.

3.0 Materials and Special Alloys Employed in Metal AM

An expansive range of metallic materials is researched and employed in MAM, driven by the specific requirements of different applications. Some significant groups of materials and some common examples of alloys are discussed below:

3.1 Stainless Steels

The most utilised MAM materials are the austenitic stainless steels 316L and 304L, owing to their superior corrosion resistance, good mechanical properties, and fairly good weldability. 17-4PH precipitation hardening stainless steel is increasingly finding use for applications needing enhanced strength[8,9].

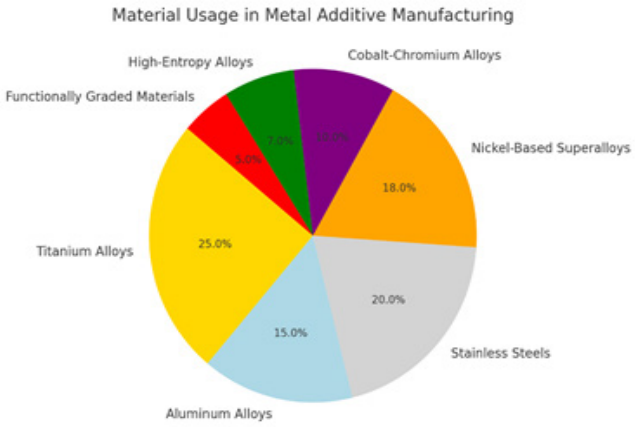


Figure 1. Material usage in MAM8.

- **316L Stainless Steel:** Excellent corrosion resistance, good ductility, widely used in biomedical, chemical, and food processing industries.
- **304L Stainless Steel:** Corrosion-resistant, less expensive than 316L, used for general engineering application.
- **17-4PH Stainless Steel:** High strength and hardness after heat treatment, used in the aerospace, tooling, and medical fields.

- **Duplex Stainless Steels:** Austenitic and ferritic phases blended, with increased strength and corrosion resistance. Found in AM for specific applications[11].

3.2 Titanium Alloys

Titanium alloys, particularly Ti-6Al-4V (Grade 5) and commercially pure titanium (CP-Ti), are in great demand in the aerospace, biomedical, and automotive industries due to their extremely high strength-to-weight ratio, excellent corrosion resistance, and biocompatibility[12].

- **Ti-6Al-4V (Grade 5):** General-purpose titanium alloy, high strength, superior fatigue life, used extensively in aerospace and implants[14].
- **CP-Ti (Grade 2, 4):** Excellent biocompatibility and corrosion resistance, used in medical implants and chemical process equipment.
- **Ti-6Al-4V ELI (Extra Low Interstitial):** High fatigue and fracture resistance compared with standard Ti-6Al-4V, used in ultra-severe aerospace applications[15].
- **Ti-13Nb-13Zr:** Designed specifically for biomedical applications, this alloy exhibits improved biocompatibility and lowers Young's modulus compared to Ti-6Al-4V, reducing stress shielding effects in bone implants[16].
- **New Titanium Alloys:** Research is underway to develop new beta and near-beta titanium alloys for AM with improved properties or novel functions.

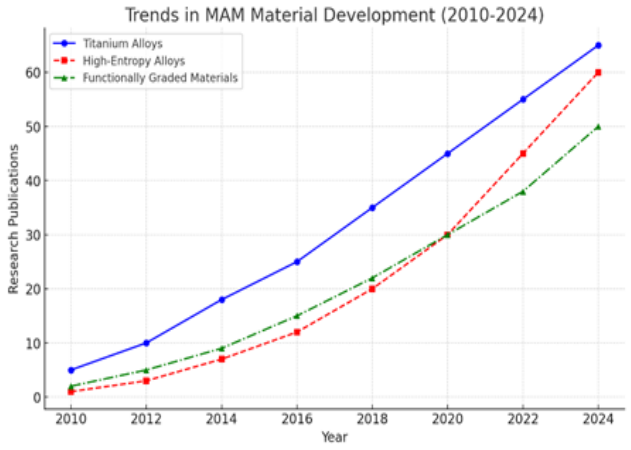


Figure 2. Recent trends in MAM material development[16].

3.3 Aluminium Alloys

Aluminium alloys offer low density, good strength-to-weight ratio, and good thermal conductivity, making them attractive for aerospace, automotive, and heat exchanger applications. However, Aluminium alloys are generally more challenging to process via MAM due to their high reflectivity to laser energy and susceptibility to hot cracking[12].

- **AlSi10Mg:** Commonly used aluminium alloy in AM, good castability and strength, suitable for structural components and heat sinks.
- **AlSi7Mg:** Similar to AlSi10Mg, slightly lower silicon content, also used for structural applications.
- **AlCu4 (2024):** This high-strength aluminium alloy is used in aerospace applications. However, it presents challenges during AM due to its susceptibility to hot cracking. Research is focused on optimizing processing parameters and compositional modifications to overcome these challenges[13].
- **High-Strength Aluminium Alloys (e.g., Al 7075, Scalm alloy®):** More challenging to process in AM due to hot cracking susceptibility, significant research efforts are focused on overcoming these challenges and tailoring processing parameters.

3.4 Nickel-Based Superalloys

Nickel-based superalloys, including Inconel 718, Inconel 625, and Hastelloy X, possess notable high-temperature strength, exceptional creep resistance, and powerful corrosion resistance. These properties are instrumental in their use in aerospace, gas turbines, and chemical processing industries.

- **Inconel 718:** Inconel 718 is a widely used nickel-based superalloy in metal AM due to its excellent high-temperature strength, creep resistance, and corrosion resistance. It is processed by LPBF and DED and is used in aerospace gas turbine components, rocket engine parts, and nuclear reactors[17].
- **Inconel 625:** Similar to Inconel 718, Inconel 625 offers excellent corrosion resistance and weldability. It's frequently used in marine and chemical processing environments.

- **Hastelloy X:** Superior capabilities in resistance to high-temperature oxidation and corrosion; these are found in components of high-temperature furnaces and the hot sections of gas turbines[18].

3.5 Cobalt-Chromium Alloys

Cobalt-chromium alloys, such as CoCrMo and CoCrW alloys, are primarily used in biomedical implants and dental restorations due to their biocompatibility, corrosion resistance, and high strength.

- **CoCrMo (ASTM F75):** Excellent biocompatibility and wear resistance, widely used for orthopaedic implants like hip and knee replacements.
- **CoCrW (Dental Alloys):** High strength and corrosion resistance, used for dental crowns and bridges[19].

3.6 Tool Steels

Tool steels, including H13, M2, and D2, are increasingly used in MAM for tooling and mould inserts due to their high hardness, wear resistance, and ability to create conformal cooling channels for improved thermal management.

- **H13 Tool Steel:** Hot work tool steel, good toughness and thermal fatigue resistance, used for mould inserts and die casting tools.
- **M2 Tool Steel:** High-speed tool steel, excellent wear resistance, used for cutting tools and dies.
- **D2 Tool Steel:** Cold-worked tool steel is characterized by its high hardness and exceptional wear resistance, making it suitable for applications such as blanking dies and punches[20].

3.7 Emerging Materials in Metal Additive Manufacturing

Beyond the established material categories, metal AM is continuously expanding to encompass emerging and novel material systems:

- **Copper and Copper Alloys:** Pure copper and copper alloys are gaining interest in AM due to their excellent electrical and thermal conductivity, making them appropriate for heat exchangers, electrical connectors, and induction coils. However, processing copper in PBF can be challenging due to its high reflectivity to laser radiation and high thermal conductivity, requiring high laser power and specialized process parameters[21].
- **Precious Metals (Gold, Silver, and Platinum):** AM is being explored for processing precious metals for jewellery, dental restorations, and specialized electronic components. PBF and binder jetting are being investigated for creating intricate and customized designs in gold, silver, and platinum alloys[19].
- **Refractory Metals (Tantalum, Niobium, Tungsten, Molybdenum):** Refractory metals exhibit extremely high melting points, high-temperature strength, and corrosion resistance. AM processes like EBM and DED are being explored for niche applications requiring these extreme properties, such as high-temperature tooling, aerospace components, and nuclear reactors.
- **High Entropy Alloys (HEAs):** HEAs are multi-principal element alloys with unique properties, often exhibiting high strength, hardness, and corrosion resistance. AM is being investigated as a promising manufacturing route for HEAs, permitting the formation of complex geometries and exploration of compositional space for tailored properties.
- **Metal Matrix Composites (MMCs):** MMCs combine a metallic matrix with reinforcing particles (ceramics, carbides, etc.) to enhance specific properties like strength, stiffness, or wear resistance. AM, particularly DED, is being explored for fabricating MMCs, allowing for tailored material compositions and microstructures for specific applications.

4.0 Material Properties and Performance of AM-Fabricated Metals

The layer-by-layer production process in MAM greatly affects its microstructure and the overall properties of the metallic components. Metals fabricated using AM often exhibit distinct characteristics compared with their conventionally manufactured counterparts.

4.1 Microstructure

- **Anisotropic Microstructure:** AM products frequently display anisotropic microstructures as a result of the layer-wise build direction and directional heat flow. Depending on the build orientation, this may result in different mechanical properties.
- **Fine Grain Structure:** Compared to conventional casting or forging, MAM methods typically produce finer grain structures because of their rapid solidification speeds. Strength and toughness may be improved in this way.
- **Textured Microstructure:** Material characteristics can be affected by textured microstructures, which are caused by directional heat flow and epitaxial grain development.
- **Solidification Microstructures:** Different solidification microstructures, including cellular, columnar, or equiaxed grains, can form depending on the alloy composition and cooling speeds.

4.2 Mechanical Properties

- **Tensile Strength and Yield Strength:** Typically, AMs exhibit comparable or even better tensile and yield strength than wrought materials, especially when specific build orientations are considered.
- **Ductility and Elongation:** A variety of factors impart a significant effect on ductility and elongation, from porosity and microstructure to build orientation. Variable processing and post-processing constraints must be optimized to get to the desired ductility levels.
- **Fatigue Performance:** Fatigue behavior is of paramount concern in structural applications. The structural integrity of AM parts is adversely affected because of the presence of porosity and external roughness, hence lowering the anticipated performance under fatigue. HIP and surface finishing are often adopted to improve the fatigue performance[20].
- **Fracture Toughness:** The fracture toughness might be affected by microstructure and defect density. Process parameters and post-processing needed to be optimized as applicable to attain adequate fracture toughness.
- **Creep Resistance:** Creep resistance is of paramount importance for high-temperature applications. AM-fabricated nickel-based superalloys were widely studied for their creep performance, requiring process optimization to minimize the creep deformation[14].

4.3 Defects and Material Quality

- **Porosity:** A typical defect in AM parts that occurs due to incomplete melting, gas entrapment, or lack of fusion. Controlling porosity is very important in achieving the required density and mechanical properties. Usually, porosity is controlled by process optimization, powder quality, and postprocessing (HIP).
- **Lack of Fusion:** Weak interfaces, resulting from the incomplete fusion between either neighbouring layers or powder particles, may hinder mechanical performance. Critical to optimization are the characteristics of process parameters and powder.
- **Residual Stress:** The rapid heating and cooling cycles in MAM may introduce very significant residual stress, which causes distortion, cracking, and dimensional inaccuracies. Stress relief annealing is, therefore, commonly required.
- **Surface Roughness:** AM parts have a higher surface roughness due to the lack of a machining process. As such, machining, polishing, or some chemical etching is often required in postprocessing to get the desired surface finish[16].

4.4 Influence of Processing Constraints and Post-Processing

The photoelastic properties of AM metals were, in fact, very sensitive to processing parameters concerning geometrical, laser power, scan speed, layer thickness, powder bed temperature, and atmosphere control. The careful optimization of these parameters is therefore extremely important to control the microstructure, minimize defects, and accomplish the desired properties of the material itself. In most instances, there will be some necessary post-processing treatments applied to AM parts, from heat treatments such as stress relief annealing, solution annealing, aged, then Hot Isostatic Pressing, machining, polishing, coating, and surface treatment, in

order to satisfy the conditions for desired properties and performance. For example, Hot Isostatic Pressing is well regarded technically among engineers for its ability to reduce porosity and increase the fatigue performance of critical applications[15].

5.0 Challenges and Future Directions in Materials for MAM

Despite significant progress in material development and application for MAM, several challenges and opportunities remain that need to be addressed to further advance the field. Figure 3 represents the material challenges in MAM considering cost, processability, strength, sustainability and standardization.

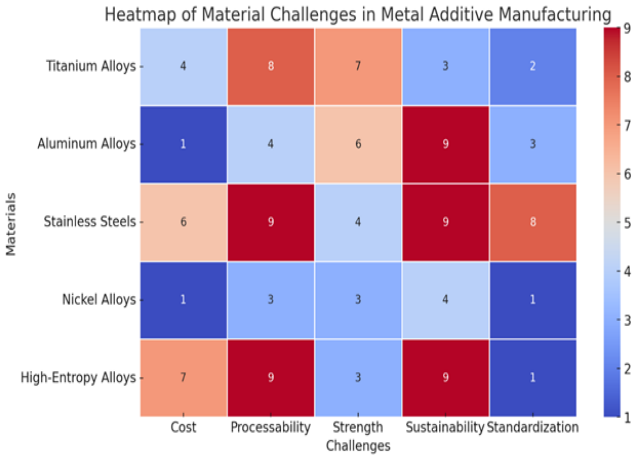


Figure 3. Heat map of Material challenges in MAM[20].

5.1 Material Development Gaps

- **Limited Material Portfolio:** While a range of materials are currently used in MAM, the material portfolio is still relatively limited compared to traditional manufacturing. There is a need for developing new alloys specifically designed for AM processes, considering their unique processing conditions and property requirements[22].
- **Tailored Alloys for AM:** Developing alloys with improved processability, reduced hot cracking susceptibility, enhanced flowability (for powders), and tailored microstructures for specific applications is crucial.
- **High-Performance Alloys:** Expanding the range of high-performance alloys, including advanced nickel-based superalloys, high-temperature titanium alloys, and refractory metals, for demanding applications in aerospace and energy sectors is essential.

5.2 Process Optimisation and Control

- **Process-Material Interdependence:** A deeper understanding of the complex interactions among process factors and material behaviour is needed to optimize processes and achieve consistent and reliable part quality[21].
- **In-situ Monitoring and Control:** Monitoring techniques used in parallel with the building process are not only able to inform when defects occur, but also able to correct them will contribute greatly toward improving process control and waste reduction.
- **Multi-Material AM:** Expanding the capabilities of MAM to fabricate multi-material components with tailored functionalities and properties is a significant challenge and opportunity.

5.3 Standardisation and Qualification

- **Material Standards for AM:** It is critical to develop standard material specifications, testing protocols, and quality control procedures for AM materials in order for industrial acceptance and extensive adoption[23].
- **Qualification and Certification:** Establishing robust qualification and certification procedures for AM parts, particularly for safety-critical applications, is crucial for ensuring reliability and performance.

5.4 Cost and Scalability

- **Reducing Material Costs:** It is critical to lessen the expense of custom AM powders and wire feedstocks, and therefore to make MAM more economically competitive; the exploitation of other feedstock sources and the recycling processes therefore really deserves promoting.
- **Improving Process Efficiency and Throughput:** Speeding up the build rate, optimizing processing

parameters for higher efficiency, and developing greater build platforms are needed for scaling and cost-effectiveness of MAM[14].

5.5 Data Availability and Computational Modelling

- **Material Property Databases:** Creating comprehensive material property databases for AM-fabricated metals, considering process-dependent properties and build orientation, is essential for design and simulation.
- **Computational Modelling and Simulation:** Development of these advanced computational models and simulations is expected to allow process optimize and material design through predictions of microstructure evolution, defect formation, and material properties[16].

5.6 Sustainability Considerations

- **Energy Efficiency of AM Processes:** Improving the energy efficiency of MAM processes is crucial for reducing environmental impact.
- **Powder Recycling and Material Utilization:** Developing efficient powder recycling strategies and minimizing material waste in MAM processes is important for promoting sustainability[17].

6.0 Conclusion

Materials are at the heart of metal additive manufacturing. This review has highlighted the diverse range of metallic materials currently employed in MAM, spanning stainless steels, titanium alloys, aluminium alloys, nickel-based superalloys, cobalt-chromium alloys, and tool steels. The unique microstructural characteristics and properties of AM-fabricated metals, influenced by process parameters and post-processing, necessitate a deep understanding of material behaviour in these processes. Though we've made a lot of progress, there are still bumps in finding better stuff, making processes work better, making sure that everyone follows the same rules and making everything bigger and better at the same time. Future research and development efforts should focus on:

- Developing novel alloys specifically tailored for AM processes.
- We're supercharging process control and doing more ongoing monitoring to really improve part quality and reliability.
- Setting up standards and qualification procedures for parts made using additive manufacturing.
- Addressing the sorts of cost problems and scalability hurdles that keep wide adoption at bay in the industrial world.
- Harnessing computational modelling and data science to design better materials and optimize processes using data.

By handling these obstacles and capitalizing on the big opportunities, materials science and engineering will definitely carry on and top things off as the decisive force driving forward machining with metals and fully unlocking its power as a really important new kind of manufacturing process. The future of MAM lies in the synergistic development of advanced materials, robust processes, and innovative applications, paving the way for a new era of customized, high-performance metallic components.

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