A Critical Review of Material Properties and Defects in Metal Additive Manufacturing

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Abstract

Metal Additive Manufacturing has emerged as an advanced manufacturing technology capable of producing complex geometries with high material utilization, design flexibility, and reduced manufacturing waste. The increasing industrial adoption of Metal Additive Manufacturing in aerospace, automotive, biomedical, and energy sectors has accelerated research on process optimization, material performance, and defect mitigation. In additive manufacturing, the component is prepared layer per layer deposition of the desired material. The layer development method or the material deposition method may vary based on the type of strategy used. This review critically examines major metal additive manufacturing processes, including Directed Energy Deposition, Wire Arc Additive Manufacturing, Powder Bed Fusion & Binder Jetting with emphasis on their process mechanisms, material characteristics, and industrial applications. The technology has gained recognition in various industries but also have a lot of challenges. These key manufacturing challenges including residual stresses, porosity, cracking, anisotropy, distortion, and surface irregularities are systematically discussed along with their formation mechanisms and mitigation strategies. Considering these limitations, there are a lot of areas where this technology needs a looking into. This review also highlights recent developments in process monitoring, post-processing methods, and intelligent manufacturing approaches for improving build quality and reliability. Finally, future research directions involving in-situ monitoring, artificial intelligence-based process control, multi-material fabrication, and sustainable manufacturing are discussed to support the advancement of metallic additive manufacturing technologies.

Keywords:

Residual stress, directed energy deposition, Defect formation, Powder bed fusion, Metal matrix composites etc.

1. Introduction

One of the most cutting-edge manufacturing techniques for creating intricate metallic components with high geometrical accuracy, less material waste, and greater design flexibility is metal additive manufacturing, or MAM. Additive manufacturing produces components through layer-per-layer deposition of material straightly from digital models, allowing the fabrication of the intricate structures that are difficult or impossible to manufacture using outmoded techniques. Owing to these capabilities, metal additive manufacturing has gained considerable attention in aerospace, automotive, biomedical, defence, marine, and energy industries for the production of lightweight structures, customized implants, tooling systems, and high-performance engineering components [1-7]. The growing industrial demand for high-strength, lightweight & geometrically complex metallic components has accelerated the development of several metallic additive manufacturing technologies. MAM processes can be broadly categorized into Directed Energy Deposition (DED), Binder Jetting (BJ), Powder Bed Fusion (PBF) & wire-based additive manufacturing techniques as shown in figure 1. Among these processes, Direct Metal Laser Sintering (DMLS), Laser Powder Bed Fusion (LPBF), Selective Laser Melting (SLM) & Electron Beam Melting (EBM) are widely utilized for manufacturing high-density metallic parts with superior dimensional accuracy and surface finish. Wire Arc Additive Manufacturing (WAAM) & Directed Energy Deposition are increasingly adopted for large-scale structural applications due to their reduced material wastage, high deposition rates and capability to repair or refurbish damaged components. These manufacturing technologies provide significant advantages in terms of material utilization, production flexibility, shortened lead time, and near-net-shape fabrication [8-15].

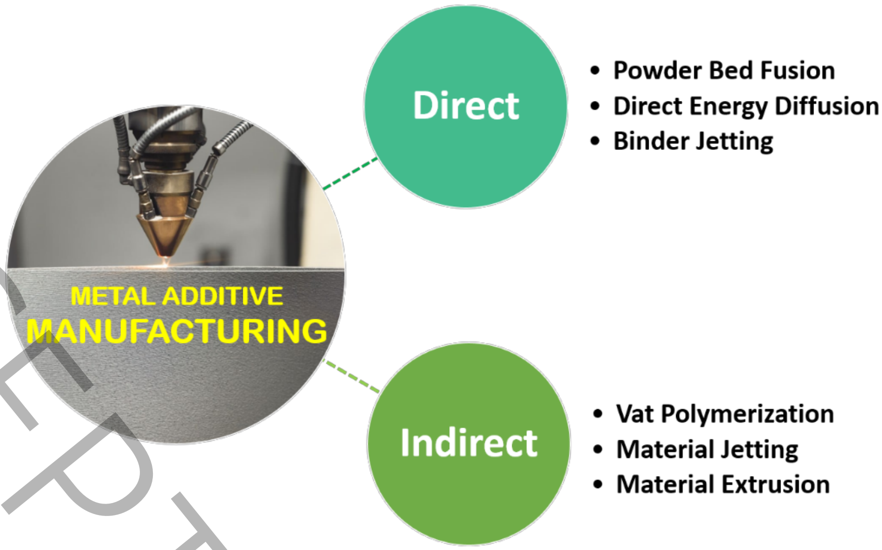

Fig. 1. Classification of Metal Additive Manufacturing [8]

Despite the rapid advancement of metal additive manufacturing technologies, several technical challenges continue to limit their widespread industrial implementation. The layer-wise deposition process involves repeated cooling & heating cycles, severe variations in temperature and rapid solidification rates, which significantly affect the mechanical performance and microstructural development of manufactured parts. These thermal phenomena frequently result in the formation of residual stresses, porosity, cracking, lack of fusion defects, anisotropy, delamination, balling effects, & geometrical distortion. The Residual stresses generated during fabrication may lead to dimensional instability, reduced fatigue life, crack initiation, and premature component failure. Similarly, porosity and incomplete fusion defects can deteriorate the tensile strength, ductility, corrosion resistance, and structural integrity of metallic components. Therefore, understanding the relationships among processing parameters, thermal behaviour, microstructural evolution, and defect formation is essential for improving the quality, reliability, and performance of additively manufactured metallic structures. The adoption of metal additive manufacturing has expanded significantly across multiple industrial sectors due to its ability to manufacture customized and high-performance components with reduced material consumption and enhanced design freedom [16-22]. In aerospace applications, metal additive manufacturing is utilized for fuel nozzles, lightweight lattice structures, blades of turbine & structural bracket. In biomedical engineering, orthopaedic devices, dental structures, patient-specific implants and porous scaffolds are increasingly manufactured using metal AMT due to their ability to produce difficult geometries with controlled porosity and improved biological compatibility. Similarly, automotive and energy industries employ additive manufacturing for tooling applications, lightweight components, heat exchangers, and rapid prototyping (RT). The capability of MAM to reduce fabrication lead time and optimize material utilization has further strengthened its industrial relevance. Significant contributions in metal additive manufacturing have also been reported by researchers from Iran, particularly in the areas of process modelling, thermal–mechanical simulation, and defect prediction. Iranian research institutions have demonstrated the development of finite element-based thermo-mechanical models for Directed Energy Deposition (DED) and Wire Arc Additive Manufacturing (WAAM), incorporating moving heat source and temperature-dependent properties of material formulations such as Goldak's double ellipsoidal model. These investigations have successfully validated residual stress predictions using experimental techniques such as X-ray diffraction. In addition, Iranian researchers have contributed to parameter optimization frameworks for Laser Powder Bed Fusion (LPBF), focusing on energy density control, scan strategy optimization, and porosity minimization to improve part density and mechanical integrity [23-25].

The present review critically examines major metal additive manufacturing processes with emphasis on defect formation mechanisms, residual stress evolution, material properties, and process–microstructure–performance relationships. The review further discusses commonly used metallic materials, mechanical characteristics, industrial applications, manufacturing challenges, and defect mitigation strategies associated with metal additive manufacturing. In addition, latest developments in in-situ monitoring, process optimization, post-processing techniques & intelligent manufacturing approaches are discussed to deliver a comprehensive understanding of current research trends and future chances in metal additive manufacturing.

The remainder of this paper is organized as follows. Section 2 discusses major metal additive manufacturing processes and their classifications. Section 3 examines residual stress development and defect formation mechanisms in metal additive manufacturing. Section 4 reviews metallic materials and metal matrix composites used in additive manufacturing applications. Section 5 discusses material properties and process-performance relationships. Section 6 presents industrial applications of metal additive manufacturing, while Section 7 discusses its advantages and limitations. Finally, future research directions and concluding remarks are presented in the final sections of the paper.

2. Metal Additive Manufacturing Processes

These processes are categorized based on feedstock material, deposition mechanism, energy source & material consolidation technique employed during fabrication. These processes manufacture metallic components through a layer-per-layer deposition tactic directly from CAD models, enabling the production of difficult geometries with less material wastage & improved design tractability compared with conventional manufacturing methods. Metallic feedstock can be provided as wire or powder and consolidated using laser beams, electron beams, plasma arcs, or other high-energy heat sources, depending on the processing method. The selection of a suitable metal additive manufacturing process depends on several factors including dimensional accuracy, deposition rate, material compatibility, surface quality, production cost, and application requirements [26-28].

2-1- Powder Bed Fusion (PBF)

This Fusion is one of the most extensively adopted MAM technologies due to its capability to produce extremely dense metallic parts with great surface polish and outstanding dimensional precision. In this process, a thin layer of metallic residue is blowout over the construct platform and precisely fused with an electron beam or high-energy laser. The procedure is repeated layer-per-layer till the complete part is fabricated. Selective Laser Melting (SLM), Laser Powder Bed Fusion (LPBF), and Electron Beam Melting (EBM) are among the most common PBF technologies used for manufacturing titanium alloys, stainless steels, aluminum alloys, cobalt-chromium alloys, and nickel-based superalloys [29-31].

2-2- Directed Energy Deposition (DED)

It is also an another important MAM technique in which concentrated thermal energy is used to melt metallic feedstock during deposition. In these systems, feedstock material is delivered as wire or powder directly into the melt pool formed by a laser, plasma arc or electron beam heat source. The process is predominantly appropriate for part repair, modification of surface, cladding & large-scale structural fabrication due to its material utilization efficiency & high deposition rate. Compared with Powder Bed Fusion processes, DED offers greater flexibility for manufacturing large components and repairing damaged structures; however, it generally exhibits lower dimensional accuracy and poorer surface finish [32–35].

2-3- Wire Arc Additive Manufacturing (WAAM)

This is a wire-fed additive manufacturing method that utilizes an electric arc as source of heat for melting metallic wire feedstock. Owing to its elevated rate of deposition, low cost of material & appropriateness for large-scale fabrication, WAAM has enlarged substantial attention in aerospace automotive, marine & heavy engineering companies. The process enables the fabrication of large metallic structures with abridged material waste compared with orthodox subtractive process of manufacturing. Furthermore, WAAM systems are comparatively economical because they employ commercially available welding equipment and wire feedstock materials [36–39].

2-4- Binder Jetting

In order to create the necessary geometry layer by layer, a liquid binder is carefully deposited onto a powder bed using this non-fusion-based AM technique. Unlike fusion-based additive manufacturing technologies, Binder Jetting does not involve direct melting during fabrication, thereby minimizing residual stress development and thermal distortion. The fabricated green parts are subsequently subjected to post-processing operations such as sintering or infiltration to achieve the required density and mechanical strength [40–42].

The assortment of a suitable metal additive manufacturing process hinge on application requirements, material compatibility, production scale, cost considerations, and desired component performance. Continuous advancements in process optimization, thermal management, in-situ monitoring, and post-processing techniques are expected to further enhance the reliability, productivity, and industrial adoption of metal additive manufacturing technologies [43–45].

Table 1. Major Metal Additive Manufacturing Processes [26-42]

Process	Feedstock	Heat Source	Advantages	Limitations	Applications
SLM/LPBF	Powder	Laser	High accuracy, dense parts	Residual stress, expensive	Aerospace, biomedical
EBM	Powder	Electron beam	Reduced residual stress	Poor surface finish	Implants, aerospace
DED	Powder/Wire	Laser/plasma	High deposition rate	Low accuracy	Repair, cladding
WAAM	Wire	Electric arc	Low cost, large structures	Distortion, rough surface	Marine, aerospace
Binder Jetting	Powder	Binder agent	Low thermal distortion	Post-processing needed	Tooling, prototyping

3. Residual Stresses and Defect Formation in Metal Additive Manufacturing

Residual stresses and manufacturing defects are among the most significant challenges limiting the reliability, dimensional accuracy, and mechanical performance of metal additive manufacturing components. During the AM process, metallic resources undergo repeated cooling & heating cycles go with by rapid melting & solidification. These thermal cycles generate steep temperature gradients and localized thermal expansion-contraction phenomena within the fabricated layers, resulting in the growth of residual stresses & various microstructural defects. The severity of these faults hinge on several aspects comprising material properties, deposition strategy, process parameters, heat input, cooling rate, and component geometry. Defect formation not only deteriorates the mechanical properties of fabricated structures but also adversely affects fatigue life, corrosion resistance, dimensional stability, and structural integrity of metal additive manufacturing components [46–49].

3-1- Residual Stress Formation Mechanism

Internal stresses caused by heat that persist in a material after the manufacturing process is finished are known as residual stresses. In metal additive manufacturing, residual stresses primarily originate from non-uniform heating and rapid cooling during layer-per-layer deposition of material. Confined melting followed by fast solidification generates severe thermal gradients between the surrounding material & molten pool, resulting in irregular contraction & thermal expansion. As newly deposited layers cool and shrink, the previously solidified material restricts deformation, prominent to the accumulation of tensile and compressive residual stresses within component. Residual stress development is strongly influenced by process parameters such as laser power, scanning speed, layer thickness, hatch spacing, deposition strategy, and interlayer cooling conditions [50–53]. Finite element models incorporating transient heat transfer and elastoplastic constitutive behaviour have been developed to simulate thermal cycles in stainless steel 316L and nickel-based alloys. These studies typically employ Goldak's double-ellipsoidal heat source model combined along with element activation techniques to simulate material deposition. Validation against X-ray diffraction measurements has demonstrated that tensile residual stresses are predominantly concentrated near the topmost layers of the build while compressive stresses are perceived in the substrate region due to thermal constraint effects. Furthermore, parametric studies indicate that laser power and scanning speed significantly influence peak residual stress magnitude by controlling thermal gradients and cooling rates. [54]

3-2- Porosity and Lack-of-Fusion Defects

Porosity is one of the most frequently observed defects in metal additive manufacturing and significantly affects the density, mechanical strength, fatigue resistance, and corrosion performance of fabricated components. Porosity formation generally occurs owing to gas entrapment, incomplete melting, unstable behaviour of melt pool, keyhole instability, or insufficient fusion between adjacent layers.

The defects which is Lack-of-fusion are primarily related with inadequate energy input during fabrication. Inadequate laser power, excessive scanning speed, improper hatch spacing, or non-uniform powder spreading may prevent complete melting of metallic powders, resulting in irregular voids and weak interlayer bonding. In contrast, excessive energy input may produce keyhole porosity due to vaporization-induced instability within the molten pool [55–59]. LPBF defect formation have shown that volumetric energy density shows a critical role in defining porosity morphology & distribution. At low energy input conditions, lack-of-fusion defects dominate owing to deficient melt pool overlap, whereas at excessively high energy densities, keyhole-induced porosity is observed due to vaporization-driven instability. Experimental mapping of process windows has demonstrated that optimized hatch spacing and scanning speed combinations can reduce porosity below 1% in stainless steel and titanium alloy systems. [60]

3-3- Cracking and Delamination

Cracking is another critical defect encountered in metal additive manufacturing processes and is primarily associated with excessive thermal stresses, rapid solidification, metallurgical incompatibility, and microstructural brittleness. Solidification cracking may occur during the final stages of molten pool solidification because of restricted material contraction and insufficient liquid metal feeding between dendritic structures [61–63].

3-4- Defect Mitigation Strategies

To reduce residual stresses and defect generation in MAM, a number of process optimization and post-processing techniques have been developed. Controlling heat input, melt pool stability, and cooling behaviour requires careful consideration of process factors such as laser power, scanning speed, layer thickness, hatch spacing, and deposition technique. Proper powder handling and feedstock quality control are also essential for reducing porosity and contamination-related defects. Thermal management techniques such as substrate preheating, interlayer cooling, and controlled heat input have been widely investigated to decrease thermal gradients & residual stress accretion. In addition, optimized scanning strategies including alternating scan directions and island scanning patterns help distribute thermal stresses more uniformly during fabrication.

Post-processing treatments are extensively utilized to enhance the structural integrity & mechanical performance of additively manufactured parts. Heat treatment and hot isostatic pressing effectively reduce residual stresses, eliminate internal porosity, and improve microstructural uniformity. Mechanical surface treatment methods including shot peening, laser peening, and rolling-assisted processing have also demonstrated significant improvements in fatigue resistance and surface quality [64–68].

Table 2. Defects and Mitigation Strategies [50-68]

Defect	**Cause**	**Effect**	**Mitigation**
Porosity	Incomplete melting	Reduced strength	Parameter optimization
Cracking	Thermal stress	Structural failure	Preheating
Residual stress	Rapid cooling	Distortion	Heat treatment
Delamination	Poor bonding	Weak layers	Scan optimization
Anisotropy	Directional solidification	Non-uniform properties	Post-processing

4. Metallic Materials and Material Properties in Metal Additive Manufacturing

AM technology can create and fabricate complicated geometry composites without additional apparatuses and execute multi-material production that traditional assembling techniques can't offer. A typical AM process is revealed in fig. 3. As shown, 3-D model is converted into STL format. The machine setup is done by preparing the base and once the sample is made, it is post processed and finished [69–72].

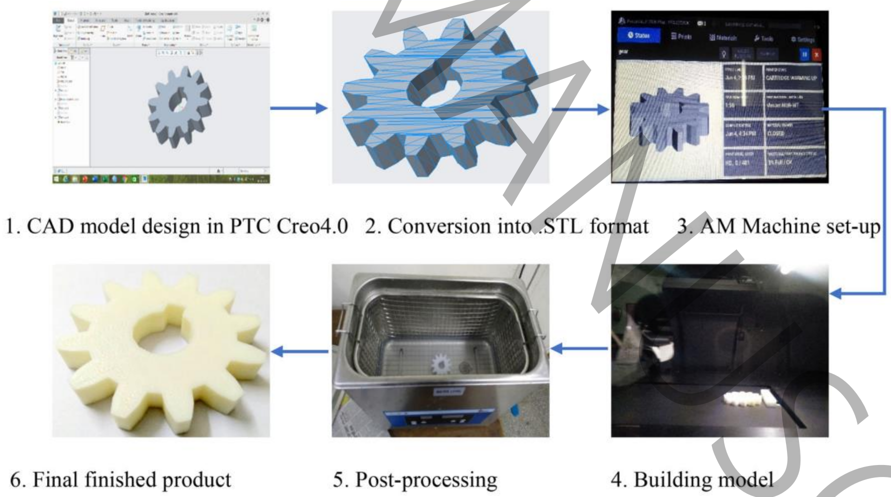

Fig. 2. Steps Involved in AM [69]

Metal matrix composites are a class of materials wherein at least one material is added to a metal to target explicit property upgrades. The Powder metallurgy technology is the most noticeable method to deal with accomplishing metal framework composite parts, but with limitations in the item shapes accomplished, aside from process restrictions. The classification based on preparation method is shown in figure 4.

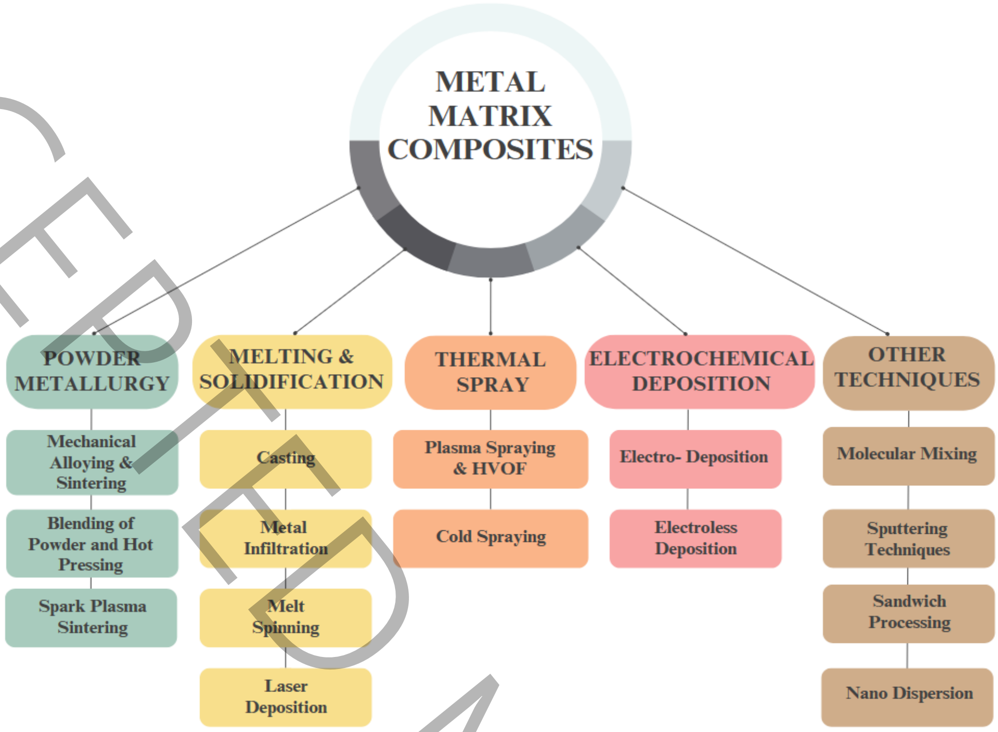

Fig. 3. Metal Matrix Composites Manufacturing Processes [74]

Titanium alloys, particularly Ti-6Al-4V, are among the most extensively utilized materials in metal additive manufacturing because of their high strength-to-weight ratio, excellent corrosion resistance, superior fatigue performance, and biocompatibility. These properties make titanium alloys highly suitable for biomedical, aerospace & high-performance applications. Powder Bed Fusion technologies such as Electron Beam Melting & Selective Laser Melting are extensively employed for processing titanium alloys due to their ability to attain near-full density & excellent dimensional correctness. However, titanium alloys are highly sensitive to thermal gradients and rapid cooling during fabrication, which frequently results in residual stress accumulation, anisotropic microstructures, and microstructural heterogeneity [73–75]. It has been observed that rapid solidification leads to a dominant α′ martensitic phase with acicular morphology, while post-processing heat treatments promote transformation into a bimodal α + β structure, significantly refining ductility & fatigue resistance.

Additionally, scan strategy modifications such as rotating hatch patterns have been reported to reduce grain texture intensity and mitigate anisotropic mechanical behaviour [76].

Stainless steels are another widely utilized class of materials in metal additive manufacturing due to their outstanding weldability, mechanical strength, corrosion resistance & comparatively lower processing complexity. Austenitic stainless steels such as SS316L are commonly processed using Directed Energy Deposition & Powder Bed Fusion techniques for applications involving tooling, biomedical devices, heat exchangers, and structural components. Stainless steels generally exhibit good processability and reduced crack susceptibility during additive manufacturing compared with several other metallic systems [77–79].

The alloys of Aluminum have also fascinated considerable consideration in MAM due to their high specific strength, thermal conductivity, low density & suitability for trivial structural applications in automotive & aerospace industries. Alloys such as AlSi10Mg are extensively utilized in Powder Bed Fusion processes for producing lightweight components with complex geometries. However, processing aluminum alloys remains challenging because of their high reflectivity, rapid oxidation tendency, and high thermal conductivity, which often lead to unstable melt pool behaviour, porosity formation, and cracking defects [80–82].

The superalloys like Nickel-based including Inconel 625 & Inconel 718 are extensively utilized in metal additive manufacturing for extreme-temperature applications because of their excellent mechanical strength, creep resistance, oxidation resistance & thermal stability. These alloys are particularly suitable for aerospace engines, gas turbines, and energy structures working under severe mechanical & thermal loading conditions. Powder Bed Fusion and Directed Energy Deposition processes are widely employed for fabricating nickel-based alloy components with complex internal geometries and improved material utilization [83–85].

Cobalt-chromium alloys are also important resources used in MAM owing to their excellent wear resistance, hardness, corrosion resistance & biocompatibility. These materials are widely employed in biomedical implants, dental structures, and high-wear engineering applications. Additive manufacturing enables the fabrication of customized cobalt-chromium components with complex geometries and controlled porosity [86–87].

The development of functionally graded materials and metal matrix composites for additive manufacturing applications has received a lot of interest in recent years. It consists of metallic matrices buttressed with ceramic particles, carbides, oxides, or other strengthening phases to improve hardness, thermal stability, wear resistance & mechanical performance.

Although considerable growth has been achieved in the advancement of metallic materials for additive manufacturing, several challenges still remain regarding process ability, defect control, microstructural consistency, and long-term reliability. Future research efforts are increasingly focused on advanced alloy development, high-entropy alloys, multi-material additive manufacturing, intelligent process control, and data-driven optimization techniques for improving the performance and industrial applicability of additively manufactured metallic materials [88–90].

Table 3. Material Properties Comparison [73-90]

Material	**Key Properties**	**Common Applications**
Ti-6Al-4V	High ratio of strength-to-weight	Implants & Aerospace
SS316L	Corrosion resistance	Biomedical, tooling
AlSi10Mg	Lightweight	Automotive
Inconel 718	High-temperature resistance	Turbines
Co-Cr alloys	Wear resistance	Dental implants

5. Materials Properties used for Additive Manufacturing

The mechanical performance and service reliability of metal additive manufacturing (MAM) components are strongly influenced by process parameters, thermal history, material characteristics, and post-processing conditions. Unlike unadventurous manufacturing methods, metal additive manufacturing comprises rapid melting and solidification accompanied by repeated thermal cycling, which significantly affects microstructural evolution, grain morphology, residual stress distribution, and mechanical behavior. Consequently, the final properties of additively manufactured metallic components often exhibit considerable variation depending on the manufacturing process, build orientation, cooling rate, and energy input conditions [91]. Columnar shaped grain development along the building direction is closely associated with mechanical anisotropic in additively produced components. Tensile testing results indicate higher yield strength in vertical direction equated to horizontal direction owing to epitaxial grain growth. However, elongation-to-failure is often reduced in the build direction owing to micro-porosity accumulation & interlayer bonding weaknesses. Post-processing via hot isostatic pressing (HIP) has been demonstrated to significantly reduce these anisotropic effects and improve fatigue life [92].

5.1 Mechanical Properties

The MAM processes are proficient of generating metallic parts with high tensile strength, hardness, and acceptable ductility suitable for structural and engineering applications. Titanium alloys such as Ti-6Al-4V made-up by Powder Bed Fusion technologies frequently exhibition high specific strength & outstanding fatigue resistance because of their refined microstructures and rapid solidification behavior. Similarly, stainless steels and nickel-based superalloys manufactured using additive manufacturing demonstrate favorable mechanical properties comparable to conventionally manufactured components under optimized processing conditions [93, 94].

5.2 Microstructural Characteristics

Microstructural evolution played a crucial role in defining the mechanical & thermal performance of MAM materials. Rapid solidification during additive manufacturing often results in fine cellular or dendritic microstructures with larger cooling rates & non-equilibrium phase formation. In Powder Bed Fusion processes, directional heat flow commonly produces elongated columnar grains aligned along the build direction, leading to anisotropic mechanical behavior [95–98].

5.3 Surface and Wear Properties

Surface quality is a vital factor distressing the functional performance & service life of metal additive manufacturing components. Additively manufactured parts frequently exhibit relatively high roughness of surface owing to partly melted elements, layer stair-stepping special effects, balling phenomena, and unstable melt pool behavior. Poor surface finish may adversely affect fatigue resistance, tribological performance, dimensional accuracy, and corrosion behavior [99–101].

5.4 Effect of Post-Processing Treatments

Post-processing treatments play a significant role in improving the dimensional stability, mechanical properties & microstructural consistency of MAM components. The heat treatment processes are generally engaged to relieve stresses, improve ductility & enhance phase stability in additively manufactured materials. Hot Iso-static Pressing is widely utilized for decreasing internal porosity, improving density & enhancing fatigue resistance through simultaneous application of high temperature and pressure.

Although noteworthy progress has been attained in improving the properties and performance of MAM materials, challenges associated with microstructural heterogeneity, anisotropy, surface quality, and defect control still remain. Future research efforts are increasingly focused on intelligent process optimization, real-time monitoring systems, advanced alloy development, and integrated post-processing strategies to improve the reliability and industrial applicability of metal additive manufacturing technologies [102–104].

Industrial Applications of Metal Additive Manufacturing

AM has advanced into numerous industries and has tracked down expanded applications in aviation, automotive, dental and clinical enterprises, toys, design and accessories, craftsmanship, engineering. Mazak fostered an application model for the oil and energy industries, as depicted in figure 5. The material of chamber shaft substrate is a famous material for packaging is treated steel combination (316S31).

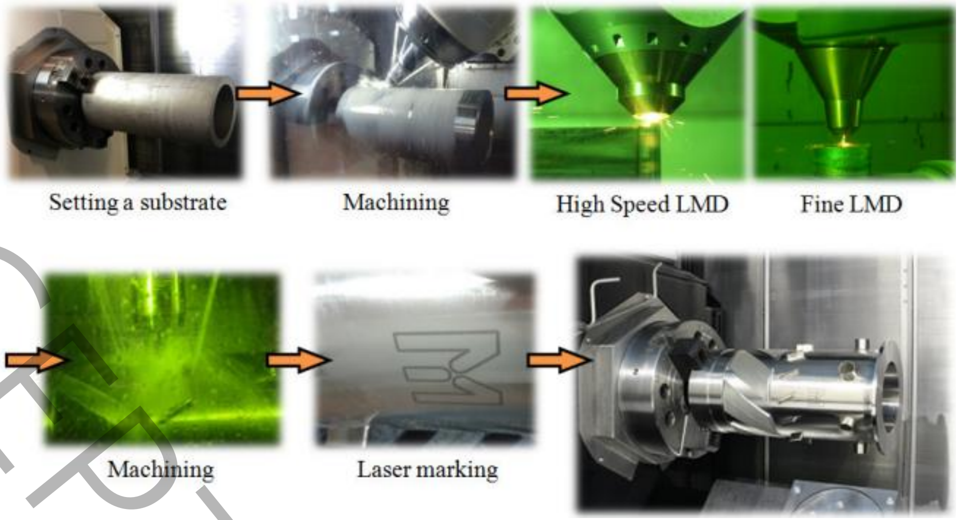

Fig. 4. Application of Metal Additive Manufacturing Process [105]

The aerospace industry represents one of the largest application sectors for metal additive manufacturing due to the growing demand for lightweight structures, fuel-efficient systems, and high-performance materials. Additive manufacturing allows the production of geometrically difficult aerospace parts such as blades of turbine, fuel nozzles, combustion chambers, heat exchangers, brackets, and lattice structures with significantly reduced material wastage. A nickel-based superalloys & Titanium alloys are extensively employed in aerospace applications owing to their high ratio of strength-to-weight, thermal stability & corrosion resistance. Powder Bed Fusion and Directed Energy Deposition processes are particularly suitable for manufacturing aerospace components with intricate internal channels and optimized structural configurations. Furthermore, metal additive manufacturing supports rapid prototyping, part consolidation, and reduced assembly requirements, thereby improving manufacturing efficiency and lowering overall production cost [105–108]. However, stringent aerospace standards require extensive quality control, defect minimization, and mechanical reliability validation before large-scale industrial implementation. Biomedical engineering is another major application area of metal additive manufacturing because of its capability to fabricate patient-specific implants, customized prosthetics, orthopaedic devices, dental structures, and porous scaffolds with excellent geometrical precision and biocompatibility. Additive manufacturing allows the fabrication of complex porous structures that promote Osseo integration and enhance biological compatibility in orthopaedic and dental implants [109–110]. The automotive industry has also increasingly adopted MAM for rapid prototyping, lightweight structures, tooling applications & performance optimization of automotive components. The creation of lightweight, geometrically optimized components that enhance fuel economy and lower emissions is made possible by additive manufacturing. Additive manufacturing methods are being used more and more in the production of parts including engine brackets, exhaust systems, heat exchangers, moulds, dies, and structural supports. Aluminum alloys and stainless steels are commonly employed in automotive applications because of their favourable mechanical properties and lightweight characteristics [111–112].

AM has progressed from quick prototyping to utilitarian prototyping. Now a days AM is utilized in all extents of industry from aviation to food and address an extravagant industry. Less expensive machines make AM more open today than ever previously. Applications of AM in various fields like automotive are Production of spare parts, standardization. Aerospace includes Lightweight, high-density components whereas Sportswear like Protective gear and customized equipment can be made. BMW used the HP Multi Stream Combination metal 3D printer to create a window guide rail for the i8 Roadster. This invention of AM is being utilized underway to generate 100 rails in 24 hours. The i8 Roadster incorporates alternative 3D printed part; an installation for delicate topmost connection, that is produced using an aluminum composite. This part is 44% less heavy than infusion formed plastic connection that was initially applied, however it is multiple times stiffer. The future vehicle models i.e. Bugatti's 2.9 kg Ti6Al4V brake calliper, that was delivered in 2018. This calliper is quite possibly of the biggest calliper on the planet and is made utilizing a SLM Arrangements SLM 500 multi-laser printer, requiring 45 hours to print with 2213 layers, as seen in figure 6 [113–114].

Fig. 5. MAM Brake Calliper [113]

6. Advantages of Metal Additive Process

Metal Additive Manufacturing (MAM) has gained considerable industrial importance because of its capability to fabricate difficult metallic parts with great design flexibility and reduced wastage of material. In contrast to traditional subtractive manufacturing techniques, additive manufacturing produces components layer-per-layer directly from digitized models, allowing the manufacturing of intricate geometries, lattice structures & internal cooling channels that are tough to fabricate using outmoded techniques. These advantages have increased the adoption of metal additive manufacturing in aerospace, biomedical, automotive, tooling, and energy industries [115].

6-1- Design Flexibility: Various dissolving agents diminish the pore content by raising the gases from the dissolved Be that as it may, a uniform outcome couldn't be accomplished. Accomplished along these lines. Thus, a vacuum-cast substrate was utilized for the LPD welding of calculations on cast parts as seen in figure 6. Improvement in which a couple of pores with a low inner strain is available. The welding boundaries were additionally improved and adjusted for the added substance of more modest practical designs as well as huge volume calculations. This study meets the necessities of the auto industry.

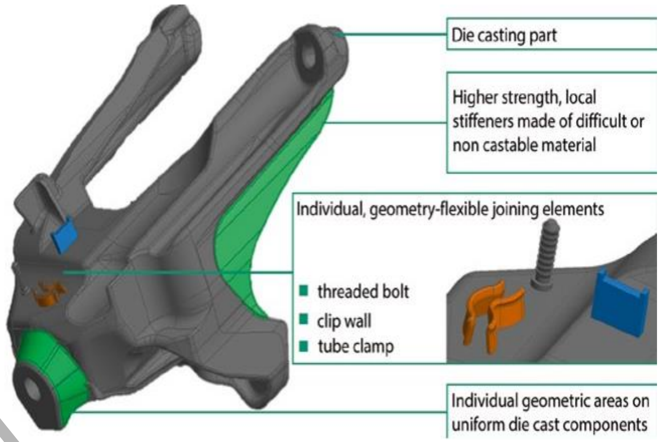

Fig. 6. Die Casted LPD Part with reduced porosity [116]

The boundaries that influence the metal AM methodology and have an immediate effect on the nature of the item like surface unpleasantness and layered exactness furthermore, mechanical way of behaving. The impact of the feedstock material on dimensional accuracy is the essential worry in all metal AM processes [116].

6-2- Optimized Material Utilization: One of the main benefits of MAM is improved material utilization. Conventional machining processes remove large amounts of material from bulk stock, resulting in high wastage and increased production cost. On the other hand, additive manufacturing only deposits material where it is needed, which is especially advantageous for costly materials like titanium alloys and superalloys based on nickel. These process also reduces tooling requirements and shortens production lead time, which is highly advantageous for rapid prototyping, customized manufacturing & low-volume production. AM is perhaps, fastest-developing modern strategy, carrying numerous creative answers for various assembling issues.

6-3- Cost Efficiency: Manufacturing is changing the manner in which specialists plan and assemble parts from new, utilitarian reviewed materials to get done, including those that were once difficult to machine and some other way. Wire-arc AM is arising as standard assembling procedure for creation tremendous metallic quantities with large volume of statements, the current creators have, as of late, announced the possibilities of wire-arc AM handling for manufacture of aluminum nickel bronze (Seize) components for the applications in marine. The aluminium nickel bronze composites (Cu-Al-

Ni-Fe-Mn) are reasonably microstructurally multifaceted materials with an extraordinary blend property like low thickness (10% less heavy than steel), high consumption opposition, high strength, high protection from biofouling & brilliant wear & irking opposition. To summarize, the strengths of AM processes are, fast and precise, no melting, cost-effective, great for prototypes & better accuracy [117].

7. Limitations of Metal AM Processes

Metal additive manufacturing still has a number of technical drawbacks despite these benefits. Steep temperature gradients created by rapid heating and cooling during fabrication sometimes lead to dimensional instability, distortion, cracking, and residual stresses. Defects like porosity, lack of fusion, and anisotropic microstructures can also have a big impact on the mechanical characteristics and long-term dependability of manufactured parts.

Surface finishing and dimensional accurateness also remain major encounters in metal additive manufacturing. Components often require post-processing operations such as machining, polishing, and heat treatment to achieve the desired surface quality and dimensional tolerances [118]. These additional operations increase manufacturing time and production cost. Another key limitation is the larger equipment and operational cost related with metal additive manufacturing structures. In spite of endless positive elements, the WAAM cycle uncovers a few limitations also, challenges for industry that need further examination before the organization of innovations [119]. Limitations like limited availability of feedstock wires, deposition Accuracy inside feed orientation, residual stress and distortion, high porosity, coarse microstructure, heat accumulation, surface cracking, low mechanical performance due to numerous factors such as alloy composition, dimensional inaccuracy, process instability, high wire feed speed can also be observed. For the most part, AM procedures are planned and created to handle specific classifications of materials and then some which one requires either to adjust the equipment of the framework or to foster a viable workhorse material [120]. These challenges are depicted in figure 7.

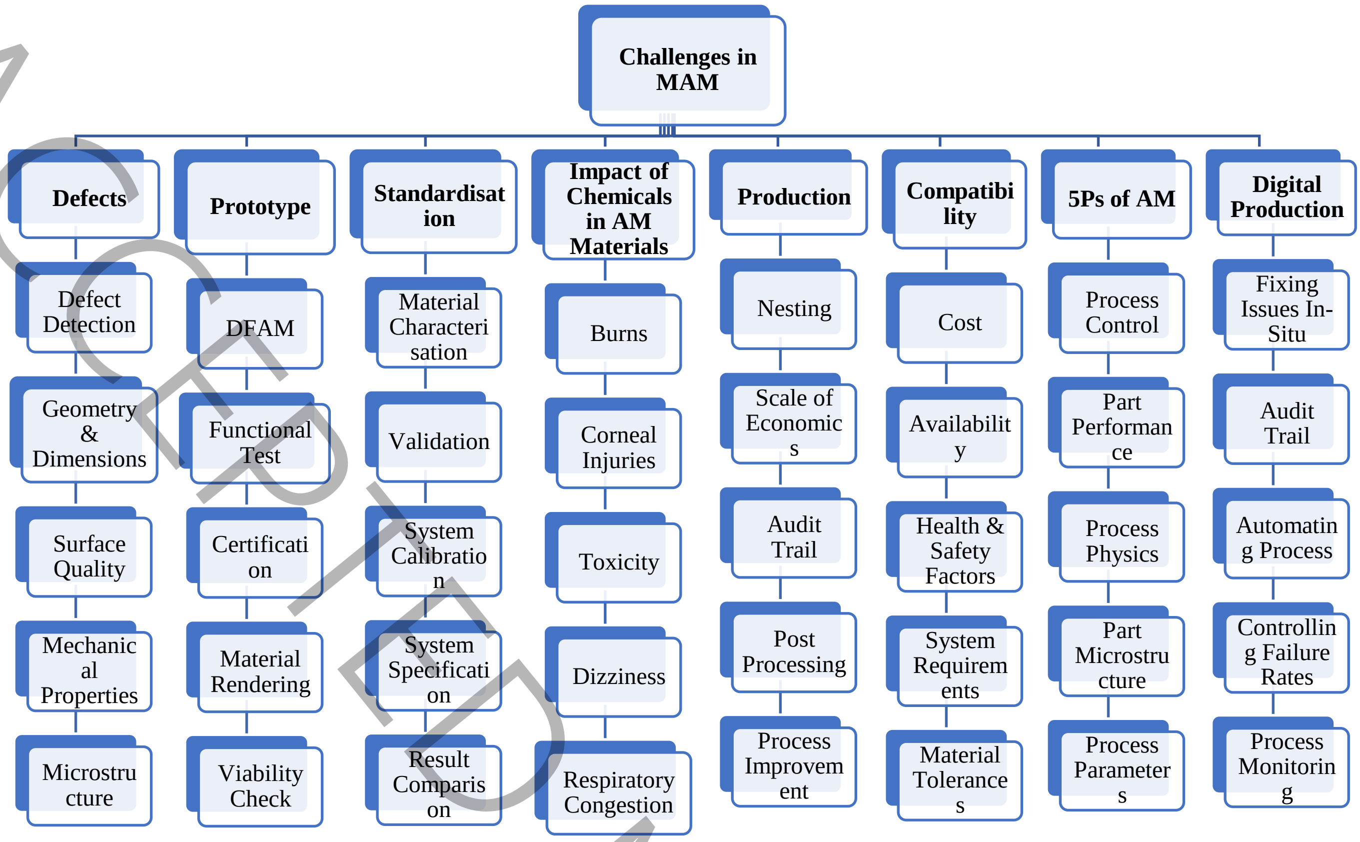

Fig. 7. Classification of Challenges in Metal Additive Manufacturing [119-121]

Despite extensive progress in process modelling and experimental characterization, Iranian studies have highlighted persistent challenges in controlling thermal distortion and achieving consistent microstructural homogeneity in large-scale builds, particularly in WAAM processes. Heat accretion during multi-layer deposition centrals to progressive coarsening of grains and deviation from designed geometry. Furthermore, the lack of real-time closed-loop control systems remains a major limitation in achieving industrial-scale repeatability [121].

8. Future Research Directions and Conclusions

Metal Additive Manufacturing (MAM) has demonstrated significant potential for transforming modern manufacturing by allowing the manufacturing of difficult metallic structures with improved design flexibility, reduced wastage of material, and improved customization capability. The technology has already achieved considerable industrial adoption in aerospace, biomedical, automotive, tooling, and energy sectors owing to its capability to fabricate trivial and high-performance parts with intricate geometries. Nevertheless, a number of technological and financial obstacles continue to prevent metal additive manufacturing technologies from being widely used in industry. Future research in metal additive manufacturing should focus on improving process reliability, dimensional accuracy, and mechanical consistency of fabricated components. Residual stresses, porosity, cracking, anisotropic microstructures, and thermal distortions remain major challenges that significantly affect structural integrity and long-term component performance. Therefore, advanced thermal management approaches, optimized scanning strategies, and improved process parameter control are necessary for minimizing defect formation and enhancing manufacturing quality. The development of intelligent manufacturing systems is predictable to play crucial role in advancement of MAM technologies. Machine learning, Artificial intelligence & data-driven optimization techniques are progressively being investigated for monitoring of real-time process, defect prediction & adaptive process control. In-situ monitoring systems incorporating thermal imaging, melt pool analysis, and sensor-based feedback mechanisms can improve process stability and reduce manufacturing inconsistencies [122–123].

To sum up, metal additive manufacturing has become a very promising manufacturing technique with a lot of promise for use in industry in the future. Although significant advancement has been attained in process development, material optimization & industrial implementation, challenges associated with defect formation, process stability, production cost, and material reliability still require considerable research attention. Continuous advancements in intelligent manufacturing, process optimization, material development, and quality control are expected to further improve the efficiency, reliability, and large-scale industrial adoption of metal additive manufacturing technologies in the coming years [124].

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Authors' contributions

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