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Additive Manufacturing of Aerospace Alloys: Material, Process and Applications Review

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Abstract

This review presents an overview of the advancements in Additive Manufacturing (AM), focusing on its applications, processes, materials, and evolving roles across various industries extracting the research from more than hundred research and/or review articles. With manufacturing technology continually spreading in the aerospace industry, this research focuses on exploring the ways in which adoption of AM technologies can bring improved flexibility of designs, optimization of waste, and productivity than conventional approaches to manufacturing. For instance, Laser Powder Bed Fusion (LPBF) and Selective Laser Melting (SLM) processes are reviewed regarding the ability to strandline the mechanical properties of aluminum and titanium alloys that are used in aerospace engineering. It also discusses the difficulties related to the material homogeneity, process control and post processing which are crucial for the quality and reliability of aerospace parts. The findings derived from this body of literature not only help elaborate the literature by extending knowledge regarding the effects of AM in aerospace production but also assist in charting the future direction of investigation in this dynamic domain.

Keywords

Additive Manufacturing, Aerospace, Aluminum Alloys, Titanium Alloys, Selective Laser Melting

1. Introduction

Additive Manufacturing (AM) can be defined as the family of processes that deposit material successively to build an object of desired geometry from a three-dimensional digital model. AM builds parts and structure by depositing layer by layer gradually, it is therefore capable of creating designs that are challenges in other ways. Cutting down costs are minimal thereby helping to control wastage which makes this approach to be useful especially when working on the aerospace, biomedical and electronics products. With the improvement of AM technologies, they are deployed on ever more difficult materials, particularly ceramics and metal matrix composites, thereby increasing the competencies of AM (Mahmood et al. 2021). Using plastics, metals, and ceramics the technologies of additive manufacturing have been adopted in aerospace, automotive, and medical industries. Because of its effectiveness in the minimization of waste, reduction in lead time, and enabling the creation of prototypes within the shortest time, it has become one of the crucial advances in the current manufacturing systems (Yılmaz 2021).

2. Literature Review

The literature brings out increased adoption of Additive Manufacturing (AM) in aerospace industry due to advantages such as intricate designs and minimal material usage. Several case studies point to the impact on performance of techniques like Laser Powder Bed Fusion (LPBF) and Selective Laser Melting (SLM) in improving the mechanical characteristics of the aerospace alloys including titanium grades (Bouzaglou, Golan, and Lachman 2023) and aluminum alloys (Ferro, Varetti, and Maggiore 2023a). Conventional manufacturing technologies are used to manufacture large-sized parts (Maffia et al. 2023) and aircraft manufacturing parts (Shafi et al. 2023). Friction stir welding has also been reported as an alternate to improve structure strength (Barakat et al. 2023). Similarly lattice structures of aerospace applications are discussed in (J. Liu et al. 2022). The studies reveal that such processes enhance tensile strength, ductility, and fatigue characteristics. This review aims at presenting a general picture of existing trends and signs of further work in the area of additive manufacturing.

3. Methods

This review applies a systematic literature review technique to evaluate developments in Additive Manufacturing (AM) of aerospace alloys regarding primary materials, processes, and applications. Several databases are consulted such as taylor and francis, Hindawi, springer, and Google Scholar etc. More than 100 peer-reviewed articles and papers, conference proceedings and industry reports published in the last decade were surveyed. Figure 1 presents a comprehensive research methodology for additive manufacturing of aerospace alloys.

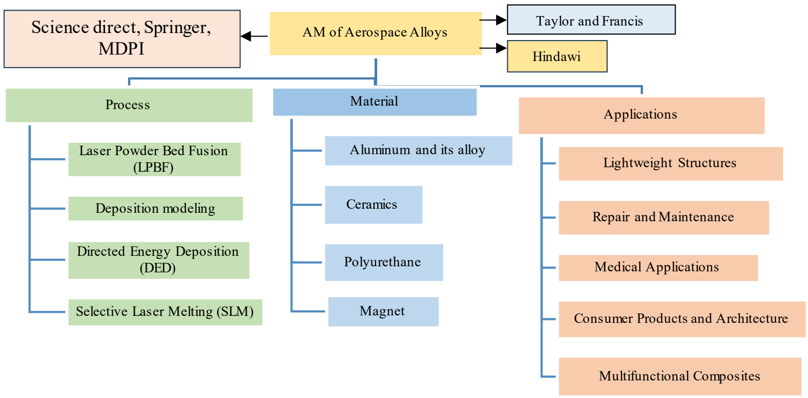

Figure 1: Research Methodology

4. Manufacturing Processes used for AM

4.1 Laser Powder Bed Fusion (LPBF)

Laser powder bed fusion (LPBF) is one of the commonly used AM process where laser energy sources is used to melt the substrate (powder form). The powder is spread as thin layer and melted by focused laser as per the part design. However, the part profile may slightly deviate from the set design. Intra- and inter-repeatability of profile deviations for an AlSi10Mg tooling component manufactured by Laser Powder Bed Fusion has been sown in Figure 2 providing insight into the LPBF (Zongo et al. 2018). The process is well suited for variety of alloys and composites like tungsten, tungsten alloys, and tungsten-based composites (H. Li et al. 2024a). Laser energy and power density (Hatos et al. 2024), scan speed and powder size (Shi et al. 2024) play important role in deciding the mechanical properties and structures of the parts. Addition of nano-powder in LPBF has the ability to improve grain refinement, tensile strength and hardness of the manufactured parts. The LPBF has been found to manufacture parts made up of Al-alloy 2024 (Yao and Xie 2024), K418 superalloy (Chen et al. 2022), refractory metal alloy (WMoTaNbV) (Huber, Bartels, and Schmidt 2021), and many others reflecting the usability of LPBF on wide variety of alloys.

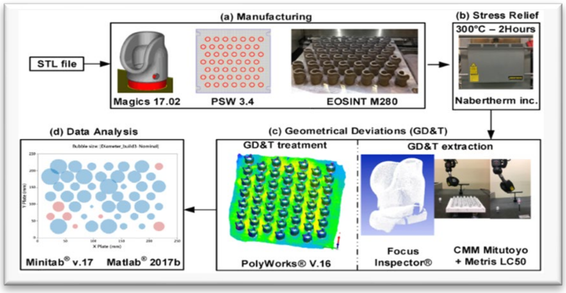

Figure 2. Experimental protocol of LPBF (Zongo et al. 2018).

4.2 Fused Deposition Modeling (FDM)

Fused deposition modeling (FDM) is also commonly known as 3D printing process. It is described using the following schematic shown in figure 3a. Essential sub-systems are shown in the diagram; the filament feed system, the heated nozzle that extrudes the material and the build platform which forms the three-dimensional objects in a step by step manner. FDM is useful in developing complex designs. The critical role is the appropriate selection of the process parameters from which the layer height and raster angle are reported to be the critical ones (Gebisa and Lemu 2018). These parameters affect the flexural properties of the manufactured parts. The paper (Caiazzo and Caggiano 2018a) presents a machine learning-based approach to predict the trace geometry for optimization of AA2024. This paper (Kumar et al. 2022) presents an experimental investigation of machine-induced damage of graphene/carbon incorporated thermoset polymer nanocomposites.

4.3 AM of Multifunctional Composites

The AM used in multifunctional parts include primary processes such as wire arc additive manufacturing (WAAM) (Gierth et al. 2020), laser/arc metal wire additive process (Casalino, Karamimoghadam, and Contuzzi 2023a), and secondary processes such as water jet surface finishing (T. Zhang et al. 2024), heat treatment in general (Teixeira et al. 2020), heat treatment of WAAM (Yang et al. 2023), and surface characterization (Buchenau et al. 2023) etc. These composites/alloys researched via AM include Body-Centered Cubic (Z. Liu et al. 2024), titanium based products (Tebaldo et al. 2024), Ti-6Al-4V parts (Buchenau et al. 2023), TMCP Ti-6Al-4V parts (Teixeira et al. 2020), AlMg5Mn aluminum alloy (Gierth et al. 2020), AlSi10Mg composite (Grozav et al. 2023), and large-scale robot-based polymer and composite (Akbari et al. 2022a). Figure 3b shows the AM of full size chair from printing ABS material. Study of mechanical properties and structure analysis of multifunctional composites is also vital. For instance, infill pattern, mechanical properties (Kiswanto, Kholil, and Istiyanto 2023), buckling properties (Shah et al. 2022), lattice structure (Ferro, Varetti, and Maggiore 2023b) and surface structures (Niu et al. 2022) are evaluated in such studies. AM of copper and silver composites are also studied in (Robinson et al. 2022) to explore how AM affect the properties of these materials. Optimization of AM processes is another area of interest (Kiswanto, Kholil, and Istiyanto 2023) and (Grozav et al. 2023). Optimization of the process is also essential to have better surface quality of the multifunctional composites (So et al. 2022). Other relatively less researched area include the use of artificial intelligence in AM (Ghimire and Raji 2024a), impact of AM in supply chain (Debnath et al. 2022), and the recycling of AM waste materials (Tebaldo et al. 2024) and (Smythe, Thomas, and Jackson 2020).

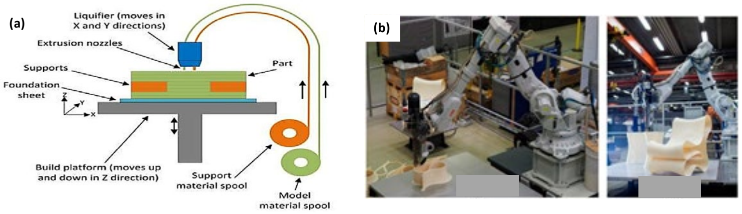

Figure 3. (a) Schematic of FDM and (b) IRBAM system set-up for full size chair of ABS (Akbari et al. 2022b).

4.4 Directed Energy Deposition (DED)

Direct Energy Deposition (DED) is a group of AM technologies. It includes directed light fabrication (DLF), electron beam direct manufacturing (EBDM), direct metal deposition (DMD), and laser engineered net shaping (LENS). Wire

Arc Additive Manufacturing (WAAM) process is one of the methods of DED. Figure 4 (a, b &c) illustrates the WAAM process, showcasing its principles through three different welding techniques. The article (Egan 2023) reviews the state-of-the-art design methodologies, optimization techniques, and emerging trends in the field of design for additive manufacturing, showing a possible further development and application. This paper (Kawalkar, Kumar Dubey, and Lokhande 2022) reviews recent progress and challenges in wire arc additive manufacturing, including process mechanisms, characterization of materials, and industrial applications. In this paper a numerical investigation for particle behavior is discussed with the precision of deposition in the DCS cold spray AM processes. The work (Halder et al. 2024) is based on the effect of interlayer delay on the temperature rise, phase transformation, and mechanical properties of single-wall Ti-6Al-4V part. The study (Marko et al. 2022) presents the approach to quality prediction in DED with the aid of artificial neural networks.

4.5 Selective Laser Melting (SLM)

Selective laser melting is a process where laser beam scans a selective part of the substrate and melt the material layer by layer. Figure 4d shows the schematic of SLM showing the process parameters. Several research articles have shown the use of SLM. The paper (Waqas et al. 2021) focuses on the investigation of the surface and dimensional quality of thin-wall AlSi10Mg parts. The research presents a design and investigation of surface-based lattice structures. An experimental as well as FEA is performed to investigate the buckling characteristics of lattice structures (Shah et al. 2022). This paper (S. Liu and Guo 2020) reviews current research on SLM processing of magnesium alloys. Another review paper (Agius, Kourousis, and Wallbrink 2018) is aimed at giving a review of mechanical properties of Ti-6Al-4V fabricated by SLM. This process also allows the development of smart devices from shape-memory polymers (Díaz Lantada 2017). High temperature in SLM may deform the final part (Davies et al. 2017). Machine learning approach can help predicting the SLM response (Caiazzo and Caggiano 2018b).

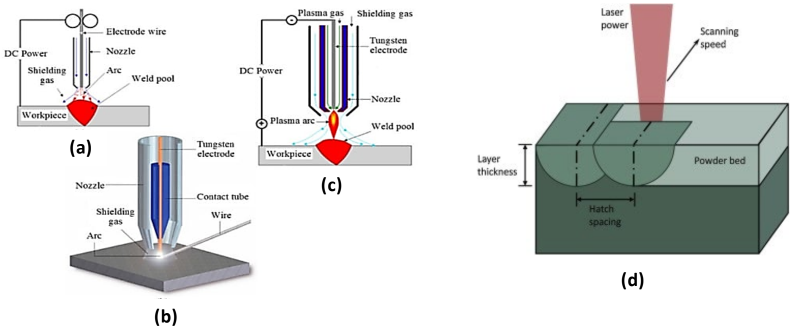

Figure 4. Principle of WAAM: (a) MIG; (b) TIG; (c) Plasma Arc (Huang et al. 2023) and (d) Schematic of SLM (Aramian et al. 2020).

4.6 3D Printing

3D printing is another widely used AM process. Numerous studies including review articles are available addressing different applications, competencies and difficulties in 3D printing. The paper (Salmi 2022) gives an overview of design and applications of 3D printing technologies. A brief analysis of 3D printing of ceramics (Abdelkader et al. 2024) is done on the strength and weakness of using ceramic in 3D printing. Fiber orientation also affect the 3D printed parts performance (Ghimire and Liou 2022a). Creep and recovery behavior of continuous fiber-reinforced composites are studied by (Al Rashid and Koç 2021). The paper (Chowdhury, Ullah, and Teti 2021) is focused on optimizing post-processing of 3D printed TiAl alloy. The paper (Musso, Murmura, and Bravi 2022) considered organizational and supply chain implications for 3D printing technologies within the medical sector.

4.7 Laser Cladding and Pressing

Laser cladding (LC) is one of the surface engineering processes that uses laser to melting and bonding an extra material which is normally a functional or wear/ corrosion resistant alloy. Laser cladding of Al102 powder onto Al4047 substrates has been performed in (Kim et al. 2023) where the influence of processing parameters on cladding quality and microstructure has been investigated. It categorizes the microstructure of the cladding while power setting at 800W and feed rate of 1.5 g/minute as shown in Figure 5a. Pressing is a production technique run on a press machine where materials especially metals and plastics are bent or altered through use of an impact force. The research optimizes surface roughness and the tribological behavior of hot-pressed, recycled cast iron-reinforced bronze metal matrix composites (Güneş et al. 2021). Figure 5b shows the general outline hot pressing.

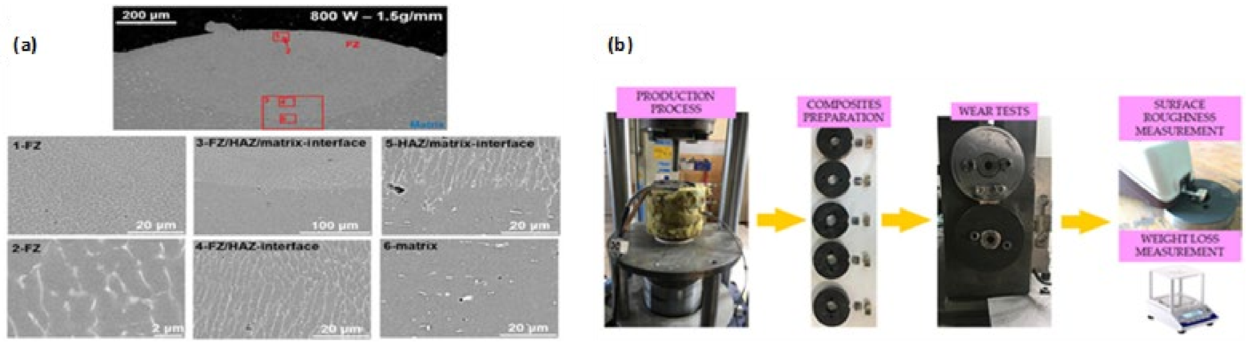

Figure 5. (a) Analysis of microstructure of the cladding (Kim et al. 2023) and (b) outline of hot pressing (Güneş et al. 2021).

5. Materials used in Additive Manufacturing

5.1 Aluminum and its Alloys

Since aluminum and its alloys are widely used multipurpose materials especially in aerospace sector (Yao and Xie 2024) and (Xiang et al. 2024), and in tools and industrial equipment (Zongo et al. 2018). Thus, the most widely used materials used in additive manufacturing technologies are found to be aluminum and its alloys. Other forms of materials is reported as aluminum alloys laminates (Díez-Pascual and Naffakh 2013). The commonly used alloys include aluminum-silicon alloys (AlSi10Mg and AlSi12), Aluminum 2024 and (Caiazzo and Caggiano 2018a), 2319 aluminum alloy (Han et al. 2024), and Al-Cu alloys (AlCu4Mg1) (Kenevisi, Yu, and Lin 2021), aluminum-magnesium alloy (Al6061 and Al7075) (R. Li et al. 2023). Aluminum 2319 processed by WAAM followed by laser shock peening has been reported in (Xiao et al. 2024). The WAAM produced parts are used in structural sections, heat exchangers, engine parts and other light weighting uses (Omiyale et al. 2022) and (Ojo and Taban 2023). (D. Liu et al. 2020) applied laser-TIG hybrid additive manufacturing on Al-Cu alloy.

5.2 Ceramics

Ceramics is used as a medium-range material for additive manufacturing (Lee et al. 2024). Frequently used ceramics include oxides (Alumina, Zirconia, Silica), carbides (Silicon, Tungsten), and nitrides (Silicon and Aluminum nitrides), and silicates. A review (Sun et al. 2024) presented the progress in multi material AM of advanced ceramics technology. Industrial potential of AM of transparent ceramics are discussed. Porous ceramic parts can be produced through LDED technique (Yu et al. 2024)**.** Vat photopolymerization AM is another method to produce ceramic parts. Multi-material ceramic components can also be produced through AM (Scheithauer et al. 2024). Microstructural evaluation of AM produced alumina ceramic has been carried out in (Hussain et al. 2024). Support structures and strategies are important elements in deciding the final geometry and precision of ceramic parts produced by 3D printing (R. Ma, Liu, and Lu 2024).

5.3 Polymeric Materials

Thermoplastics are the most widely polymers used in AM. PLA and ABS are the most commonly used materials in thermoplastics. However, limited AM processes deal with thermosets such as SLA. FDM and SLS are suitable to deal with elastomers. Polymeric composites are relatively less used, however carbon fiber and glass fiber composites are reported in some researches (Ghimire and Liou 2022b). Selection of process parameters play important role in final geometry of polymeric 3D printed parts such as PLA (Hasan et al. 2023). The appropriate orientation of built part is also important in reaching out the precise AM parts (Abdulhameed et al. 2022). IRBAM is a method used to produce large scale polymeric parts. 3D printed structured fabric analysis is conducted in (Fajardo, Farez, and Paltán Zhingre 2022). Polymers are also welded with metal to get hybrid structures (Barakat et al. 2023). Binder jetting printing is the method used for geopolymer components (Elsayed et al. 2022). Fuel tank of ABS has been produced through IRBAM (Akbari et al. 2022a).

5.4 Magnetic Materials

Magnetic materials are increasingly but less frequently used in AM. These are ferromagnetic and ferromagnetic classified in three groups. Iron and iron-based alloys, silicon steel, and nickel-iron alloys are considered as soft magnetics in 3D printing. Neodymium-Iron-Boron and cobalt-iron alloys fall under hard magnetic class of 3D printing. Third class is composite magnetics such as polymer bonded magnets. Magnetic mateials are processed through two main types of AM methods, i.e. powder-based (binder jetting, SLM, SLM, & EBM), and Extrusion and resin-based (FDM & SLA).

6. Applications of Additive Manufacturing

The application of additive manufactured parts or end-use products is wide spread depending on the properties and compositions of materials. The use of different AM technologies can be found on variety of materials and the output of the AM processes covers the application areas of several manufacturing sectors such as aerospace, automotive, marine and offshore, energy and power generations, biomedical, and industrial tooling. A brief summary of additive manufactured parts of different materials and their specific applications are provided in the following Table 1.

Table 1. Additive manufacturing applications in different areas of manufacturing.

AM application	Materials and their specific applications	References
Aerospace	*Aluminum and titanium alloys:* Lightweight brackets, panels, and load-bearing parts, heat exchangers**,** combustion chambers, fuel injectors, and air craft seats, *Ceramics:* Thermal protection systems and engine components, *Polymeric:* cabin interiors and structural parts *Magnetics:* Magnetic actuators and shields	(Ahsan n.d.), (Yao and Xie 2024), (Ghimire and Raji 2024b), (Lakhdar et al. 2021a), (Park et al. 2022), (T. Ma et al. 2024), (Selema et al. 2023), (Tan et al. 2022), (Hernandez et al. 2017)
Automotive and Marine	*Aluminum and titanium alloys:* Cylinder heads, pistons, heat sinks, brackets and mounts, Corrosion-resistant parts for naval and commercial vessels, *Ceramics:* Heat-resistant parts, brake discs, *Polymeric:* Prototypes, dashboards, consoles, air ducts, housings, and brackets, *Magnetics:* parts for electric drivetrains, magnetic sensors	(H. Li et al. 2024b), (Tebaldo et al. 2024), (Lakhdar et al. 2021b), (Park et al. 2022), (T. Ma et al. 2024), (Périgo et al. 2019), (pérez et al. 2023)
Biomedical	*Aluminum and titanium alloys:* Implants, **s**urgical tools, *Ceramics:* Dental crowns, bridges, and implants, bone scaffolds*,* *Polymeric:* Prosthetic limbs, single-use surgical tools, tissue scaffolds, customized soles*,* *Magnetics:* Complex-shaped parts of MRI machines	(Guo et al. 2022), (Singh, Saxena, and Singhal 2022), (Galante, Figueiredo-Pina, and Serro 2019), (Arefin et al. 2021), (Saparová and Kovalakova 2024), (T. Ma et al. 2024), (C. Zhang et al. 2021a), (Casalino, Karamimoghadam, and Contuzzi 2023b)
Energy/Power Generation	*Aluminum and titanium alloys:* Turbine, generator parts, heat exchangers, *Ceramics:* Solid oxide fuel cells*,* *Magnetics:* Magnetic components of wind turbine generator, parts of refrigeration	(Shi et al. 2024), (Wang, Dommati, and Hsieh 2019), (Pham, Kwon, and Foster 2021a)
Electronics and Tooling	*Aluminum and titanium alloys:* Jigs, fixtures, molds, lightweight robotic arms, armor tools, *Ceramics:* Cutting tools, molds and dies, Insulators, ceramic boards for electronic circuits*,* *Polymeric:* casings for electronic devices, helmet inserts, *Magnetics:* Motors, generators, transformers, miniature components of headphone and speakers	(Halder et al. 2024), (Dadkhah et al. 2023a), (Shinde et al. 2022), (Dadkhah et al. 2023b), (Rodriguez-Vargas et al. 2023), (Pham, Kwon, and Foster 2021b), (C. Zhang et al. 2021b), (Marko et al. 2022)

7. Conclusion

A comprehensive review is conducted in the field of additive manufacturing. The focus of this research is to find manufacturing processes, materials and applications of additive manufacturing. The following are the conclusions derived from the review:

- The most commonly used material in additive manufacturing is aluminum and titanium alloys. Polymers and ceramics are found to be the second most commonly used materials. The use of magnetic materials is also found to be growing in the field of additive manufacturing.
- The most frequently used manufacturing processes for AM are Selective Laser Melting (SLM),3D Printing, Directed Energy Deposition (DED), Laser Powder Bed Fusion (LPBF).
- AM presents considerable applications in several areas of industrial applications due to the potentials of AM technologies to produce complex geometry and tailor solutions. The highlighted areas of application include aerospace, automotive, electrical and electronics, energy and power generation, biomedical and industrial tooling.

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