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RECENT ADVANCES IN METAL 3D PRINTING FOR INDUSTRIAL APPLICATIONS: A REVIEW

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ABSTRACT

Metal additive manufacturing (AM), commonly referred to as metal 3D printing, has emerged as a transformative manufacturing technology enabling the fabrication of complex metallic components directly from digital models. In the last decade, advancements in laser systems, powder metallurgy, and process monitoring technologies have significantly improved the reliability and industrial adoption of metal additive manufacturing. This review paper discusses recent developments in major metal 3D printing processes including powder bed fusion, directed energy deposition, binder jetting, and sheet lamination techniques. The study also highlights commonly used metallic materials such as titanium alloys, stainless steel, aluminium alloys, and nickel-based super alloys. Furthermore, industrial applications in aerospace, automotive, biomedical, and tooling industries are examined. The review also addresses technical challenges such as residual stresses, surface finish limitations, and high production costs. Finally, future research directions and technological developments are discussed. The study indicates that metal additive manufacturing has strong potential to revolutionize modern manufacturing systems through design flexibility, material efficiency, and rapid product development.

KEYWORDS: Metal Additive Manufacturing, Metal 3D Printing, Powder Bed Fusion, Directed Energy Deposition, Industrial Applications, Additive Manufacturing.

1. INTRODUCTION

Additive manufacturing is a manufacturing technique that builds components layer by layer directly from digital models. Unlike traditional manufacturing processes such as machining, casting, and forging, additive manufacturing allows the fabrication of complex geometries and internal structures that are difficult to produce using conventional methods.

Metal additive manufacturing has gained significant attention due to its ability to produce high-strength components with reduced material waste and shorter manufacturing lead times. The technology enables engineers to design lightweight structures and optimize mechanical performance.

In recent years, industries such as aerospace, automotive, biomedical engineering and energy production have increasingly adopted metal additive manufacturing technologies. The ability to manufacture customized components with complex shapes makes this technology highly attractive for modern engineering applications.

Recent advancements in laser technology, powder material development, and digital manufacturing systems have further accelerated the growth of metal additive manufacturing. These developments have improved process stability, part quality, and overall production efficiency.

2. MATERIALS AND METHODS

2.1 Additive Manufacturing Processes Analysed

The main metal additive manufacturing processes analysed in this study include:

The present study examines four major metal additive manufacturing (AM) processes that are widely reported in contemporary research and industrial practice. These processes differ in terms of material delivery mechanism, energy source, bonding principle, and application domain.

2.1.1 Powder Bed Fusion (PBF)

Powder Bed Fusion is a **fusion-based additive manufacturing process** in which a thin layer of metal powder is selectively melted using a high-energy heat source such as a laser or electron beam. The process is repeated layer-by-layer to fabricate fully dense metallic components.

PBF is characterized by:

- High dimensional accuracy and fine feature resolution
- Ability to produce complex geometries and internal structures
- High cooling rates leading to refined microstructures

However, research identifies challenges such as residual stress development, porosity formation, and relatively low builds rates. Due to its precision and material properties, PBF is extensively used in aerospace and biomedical applications.

2.1.2. Directed Energy Deposition (DED)

Directed Energy Deposition is a process in which metal powder or wire feedstock is delivered directly into a melt pool generated by a focused energy source such as a laser, electron beam, or plasma arc.

Key characteristics include:

- High deposition rate compared to powder bed systems
- Capability to manufacture large components
- Suitability for repair and remanufacturing applications

Unlike PBF, DED offers greater flexibility in material deposition, including multi-material fabrication. However, it typically exhibits lower dimensional accuracy and surface finish, requiring post-processing.

2.1.3. Binder Jetting

Binder jetting is a powder-based additive manufacturing process where a liquid binder is selectively deposited to join powder particles. The printed “green part” is subsequently sintered in a furnace to achieve final strength.

Key features:

- No high-energy heat source during printing
- Reduced thermal distortion compared to fusion processes
- High production speed and scalability

Limitations include:

- Lower mechanical strength before sintering
- Shrinkage and dimensional variation during post-processing

Binder jetting is widely explored for mass production of complex metal components and tooling applications.

2.1.4. Ultrasonic Additive Manufacturing (UAM)

Ultrasonic Additive Manufacturing is a solid-state process in which thin metal foils are bonded using ultrasonic vibrations and pressure, without melting the material.

Distinct advantages:

- No melting → minimal residual stresses
- Ability to join dissimilar metals
- Capability to embed sensors and electronics within structures

However, UAM is limited by:

- Restricted geometric complexity
- Lower mechanical strength compared to fusion-based processes

This process is particularly useful in electronics, aerospace and smart structure applications.

2.1.5. Comparison of Major Metal Additive Manufacturing Processes

Process	**Material Form**	**Energy Source**	**Accuracy**	**Typical Applications**
Powder Bed Fusion	Metal Powder	Laser / Electron Beam	Very High	Aerospace, Medical
Directed Energy Deposition	Powder / Wire	Laser / Plasma	Medium	Repair, Large Parts
Binder Jetting	Metal Powder	Binder + Furnace	Medium	Automotive, Tooling
Sheet Lamination	Metal Sheets	Ultrasonic Vibration	Medium	Electronics, Heat Exchangers

3. RESULTS AND DISCUSSION

3.1 Metal Additive Manufacturing Technologies

Powder Bed Fusion (PBF)

Powder Bed Fusion is one of the most widely used metal additive manufacturing technologies. In this process, a thin layer of metal powder is spread across a build platform and selectively melted using a laser or electron beam.

Two common types include:

- Selective Laser Melting (SLM)
- Electron Beam Melting (EBM)

These technologies produce high-precision components with excellent mechanical properties.

3.2 Directed Energy Deposition (DED)

Directed Energy Deposition is another metal additive manufacturing process where metal powder or wire is deposited into a melt pool created by a focused energy source such as a laser or plasma arc.

DED technology is commonly used for:

- Repair of turbine blades
- Manufacturing large metal components
- Surface coating applications

3.4 Binder Jetting

Binder jetting is a powder-based additive manufacturing technique in which a liquid binder selectively joins metal powder particles. After printing, the part is sintered in a furnace to achieve the required mechanical strength.

Advantages include high production speed and reduced thermal distortion.

3.5 Ultrasonic Additive Manufacturing

Ultrasonic additive manufacturing is a solid-state metal 3D printing technique where thin metal foils are bonded using ultrasonic vibrations and pressure.

This method enables the joining of dissimilar metals and embedding sensors within metallic structures.

4. Materials Used in Metal 3D Printing

Common metallic materials used in additive manufacturing include:

- Titanium alloys (Ti-6Al-4V)
- Stainless steel (316L)
- Aluminium alloys (AlSi10Mg)
- Nickel-based super alloys (Inconel 718)

These materials offer high strength, corrosion resistance, and thermal stability.

5. Industrial Applications

Aerospace Industry

Metal additive manufacturing is widely used in aerospace industries to produce lightweight components such as turbine blades, fuel nozzles, and structural brackets.

Automotive Industry

Automotive companies use metal 3D printing for rapid prototyping and manufacturing of lightweight engine components.

Biomedical Industry

Metal additive manufacturing enables the production of customized medical implants such as hip implants, dental implants, and orthopaedic devices.

Tooling Industry

Applications include:

- Injection mould inserts
- Conformal cooling channels
- Cutting tools

6. Challenges in Metal Additive Manufacturing

Despite its advantages, several challenges remain:

- Residual stress formation
- Surface roughness
- High equipment cost
- Limited production speed
- Requirement for post-processing operations

Addressing these challenges is essential for wider industrial adoption.

7. CONCLUSION

Metal additive manufacturing has emerged as a powerful manufacturing technology capable of producing complex and high-performance metal components. Recent advancements in manufacturing processes, materials development, and digital technologies have expanded its industrial applications.

Although several technical challenges still exist, on-going research and technological innovations are expected to overcome these limitations. Future research should focus on improving process efficiency, developing new printable alloys, and reducing manufacturing costs.

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