Recent Developments in Metal Additive Manufacturing

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Abstract

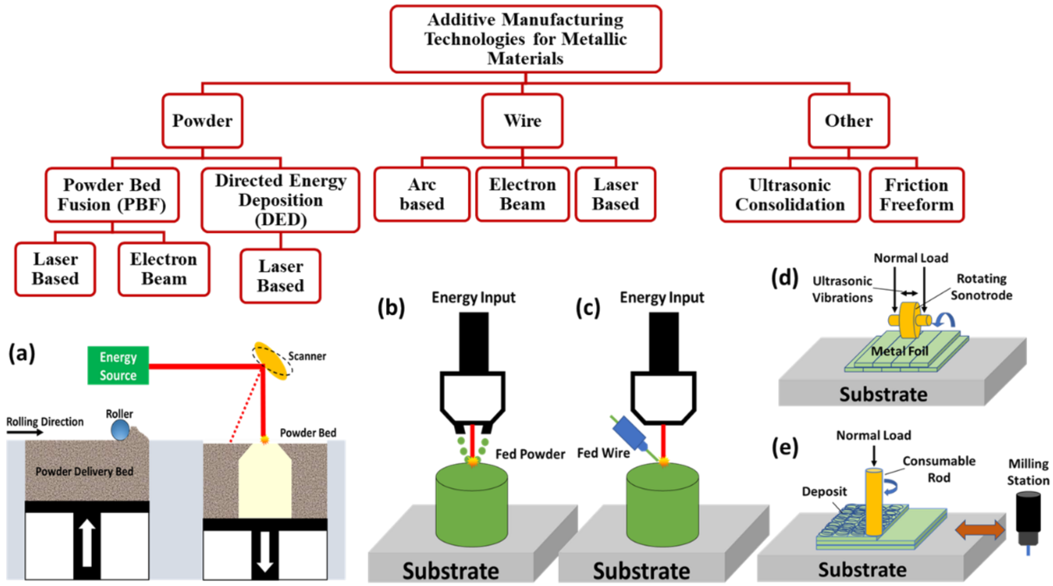
Additive manufacturing (AM) or 3D printing has revolutionized the modern metal manufacturing industry. AM technology allows for fabrication of highly customized 3D objects where both shape and composition can be tailored. Compared to traditional methods, metal AM technology has advantages in saving time and cost. Recent developments in metal AM systems include upgrades in energy source and part resolution, which leads to better part quality and improved reliability. This brief review article summarizes recent developments in metal AM technologies as well as the current challenges and future trends.

1. Introduction

Additive manufacturing (AM) or 3D printing is a familiar term today across all ages in which a computer aided design (CAD) file is processed layer-by-layer to manufacture the 3D shape. This approach can be utilized to fabricate highly customized objects, which otherwise cannot be made using traditional manufacturing methods. Additionally, there are other advantages of AM including high material utilization, minimum fixed cost, not labor intensive, and generally environmentally friendly. Current AM technologies can be used with all types of materials e.g., metals, polymers, ceramics and composites. Among them, perhaps AM of metallic materials has shown the greatest impact in various industries including aerospace, automobile and biomedical [1–8]. The advantages of using AM technologies to fabricate metallic materials are not only to produce complex geometries, but also to design and fabricate structures with customized properties using monolithic, bimetallic or multi-material compositions [9-11].

The AM technologies for metallic materials can be categorized based on the type of feedstock materials and energy source, which are shown in **Fig. 1**. Powder and wire feedstock materials are commonly used in metal AM technologies. Among different metal AM technologies, powder bed fusion (PBF) (**Fig. 1a**) and directed energy deposition (DED) (**Fig. 1b**) are the most ones that use powder as feedstock material. Selective laser melting (SLM) and selective laser sintering (SLS) techniques are two types of PBF methods that uses laser as an energy source. Current laser based PBF systems equip optical fiber laser instead of CO_2 or Nd:YAG lasers, which improves the consistency and power of the laser. Another PBF technique is electron beam melting (EBM), which uses a high-power electron beam as the energy input instead of laser. Unlike the laser based PBF processing, which requires an inert gaseous printing environment, for EBM, the parts are fabricated in a vacuum chamber. In EBM processing, the electron beam preheats the entire powder bed before the printing of each layer is done. This could help to avoid the residual stresses in the fabricated object and the formation of martensitic phase due to rapid cooling. The latest PBF systems are able to achieve powder layer thickness as low as 20 μm, and minimum feature size between 100 and 150 μm [12–14]. The fine resolution could greatly improve the density and the quality of the as-fabricated parts along with surface finish. Quad-laser system is another advanced configuration of current SLM machines which substantially increase the print rate [15]. Directed energy deposition (DED) technique is a metal AM technology which directly feeds the powder(s) to the focal point of the laser by carrier gas. When the laser scans across the surface of the melted region, the previous molten pool experiences rapid solidification to form a bulk structure. Modern DED equipment involves optical fiber lasers as energy input to optimize the part's quality and improve reliability. Another important feature of DED system is multiple powder feeders, where the powder feed rate of each powder feeder can be controlled individually. This feature is extremely useful for multi-material structure fabrication. Moreover, the latest DED systems utilize 5-axis or free-axis CNC stage instead of 3-axis. The deposition head modified with current co-axial powder deposition method shows better powder convergence at the focal point that has increased the efficiency of powder usage. Furthermore, current technology also offers various monitoring devices such as melt pool sensors, laser power monitor and layer control monitor adding to the metal AM system, which gives better *in situ* tracking of process and processing parameters control.

Using wire as feedstock materials for metal AM has also been found very promising [16]. The concept of wire-based deposition (**Fig. 1c**) is very similar to powder-based DED but using metal wire. Arc-based, electron beam, and laser-based wire depositions are the three main energy sources. Besides using powder and wire form as feedstock materials, there are some other forms of feedstock materials as well. For example, ultrasonic consolidation (**Fig. 1d**) uses thin metallic foils as feedstock. The metallic foil experiences normal load and high frequency ultrasonic vibrations which creates atomic diffusion across the metal-metal interfaces to achieve strong bonding between the layers. The concept of friction freeform fabrication (**Fig. 1e**) is very similar to conventional friction welding, which uses a consumable rod as feedstock material. By rotating the rod at high speed against the substrate, the frictional heat is generated that consume the rod to achieve deposition. The HP® metal jet technology uses binding agent and a powder-bed to form green metallic structures. The as-fabricated parts need to be binder removed and sintered. Desktop Metal® and Markforged® are similar to conventional extrusion-based printers. The feedstock metal-polymer composite is made by high shear mixing of the metallic powders with polymeric binders. The parts made by this technology also require post processing – both binder removal and sintering. Although many manufacturing problems have been overcome by applying metal AM technologies, however there are still challenges that require further development.



Major Metal AM Technology	Advanced AM System Features	Advantages
PBF	• Laser source: Optic fiber and E-beam • High resolution • Multi-laser scan	• Improve the quality of the printed parts • More types of materials can be processed • Reduce time cost
DED	• Laser source: Optic fiber • Multiple powder feeders • 5-axis CNC stage • Co-axial powder deposition	• Improve the quality of the printed parts • Multi-material AM • Increase the efficiency of powder usage • Non-flat surface deposition

Figure 1. Different additive manufacturing technologies for metallic materials based on feedstock form and fabrication processes - (a) PBF; (b) DED; (c) wire-based deposition; (d) ultrasonic consolidation; and (e) friction freeform. The table summarized various features of current major metal AM systems and their advantages.

2. Common Metals and Alloys Used in Metallic AM

Titanium alloys: Titanium (Ti) alloys are one of the most extensively studied metallic materials using AM. Ti alloys are widely used in many aerospace and biomedical applications due to high specific strength and fracture resistance, good formability, excellent corrosion and fatigue resistance as well as good biocompatibility [17]. Many studies have reported that Ti alloys can be processed by applying different AM methods such as PBF and DED [18–22]. The microstructure of Ti alloys show columnar grains due to rapid solidification during AM processing. Such microstructure is normally found in AM processed parts, and tend to grow through multiple layers along the build direction. Studies have shown that the morphology of columnar grains results in anisotropic properties in AM processed parts [18,23,24]. Researchers have reported that acicular martensitic α' phase was obtained in AM processed Ti6Al4V specimens [22,25], which tends to increase the strength and decrease the ductility of the Ti6Al4V samples. Post heat treatments are often applied to Ti6Al4V parts to increase ductility by decomposing α' phase to α and β phases [20,21,25]. Recent studies also demonstrate that complex structures such as porous and lattice structures can be manufactured using AM of Ti alloys (**Fig. 2i**). Mechanical properties of AM fabricated porous and lattice structures of Ti alloys have shown outstanding energy absorption capacities and impact resistance compared to bulk Ti [26,27]. Since 3D printed titanium implants have already been approved by the US Food and Drug Administration (FDA), further design modification with the help of AM of Ti alloys could bring significant benefits to medical implants.

Steels: Various steels such as austenitic, duplex, martensitic, maraging and precipitation-hardened steels, have been processed via AM. Compared to conventionally produced steels, AM fabricated steels show different microstructures and precipitation phases, which may lead to variability of mechanical properties [28]. Microstructures of AM processed steels show fine and crystallographically textured features due to rapid solidification along with non-equilibrium conditions (**Fig. 2ii**) [28]. Heat treatment is normally applied to AM fabricated steels to acquire desired properties. Studies have shown that SS 316L processed by laser based PBF technique has fully austenitic and columnar grains with grain size about 1 μm [29,30], which is significantly finer compared to the conventionally fabricated SS 316L. In addition, studies have illustrated that both austenitic and ferritic phases were obtained from DED processed SS 316L. In DED processing, the micro-segregation during solidification results in enrichment of Cr and Mo, which are both ferrite phase stabilizers [31,32]. Although an enrichment of Cr and Mo was also found in the intercellular region of PBF made SS 316L, the amount of ferritic phase stabilizer was not enough to stabilize a ferritic phase region. Furthermore, researchers have reported that the PBF made austenitic SS materials enhances strength without compromising ductility [28]. With new AM machines, it is possible to monitor and control the cooling rate via adjusting processing parameters to obtain customized mechanical properties of different steels.

Aluminum alloys: Current aluminum alloys that can easily be additively manufactured are still limited due to poor laser absorption and low weldability of Al alloys. The most common Al alloys for AM are eutectic Al-Si and Al-Si-Mg alloys (e.g., Al12Si and AlSi10Mg). These alloys contain Si, which improves the laser absorptivity [9]. Research has shown that DED fabricated Al12Si material had a fine microstructure with eutectic Si embedded in the Al matrix which enhanced thermal properties [33]. Another study showed that AlSi10Mg processed via laser based PBF had exceptional cavitation erosion resistance compared to same material prepared by casting due to fine grain microstructure developed by the AM processing [34].

Other alloys: Nickel-based alloys and high entropy alloys (HEAs) have attracted significant attention for their unique properties. These types of alloys are primarily used in applications with extreme environment such as high temperature, corrosive and complex loading conditions. Nickel-based alloys are typically difficult to process due to poor machinability. Although nickel-based alloys can be processed by conventional methods such as casting and powder metallurgy, these methods cannot fabricate parts with complex geometries on a part-by-part basis. Similar issues occur when processing HEAs. Additionally, conventionally fabricated HEAs have considerable limitations on refined microstructure and mechanical properties [28,35,36]. Recent results show the possibility of using metal AM technologies to process nickel-based alloys and HEAs to overcome the issues caused by conventional methods. Studies have shown that Inconel 625 lattice structures (**Fig. 2iii**) fabricated via SLM demonstrate exceptional ductility which can be a candidate material for energy absorption applications [37]. In addition, the SLM fabricated TiN particle reinforced CoCrFeNiMn HEA materials had refined and nearly equiaxial grains, while the strength of this material can reach above 1.0 GPa [38].

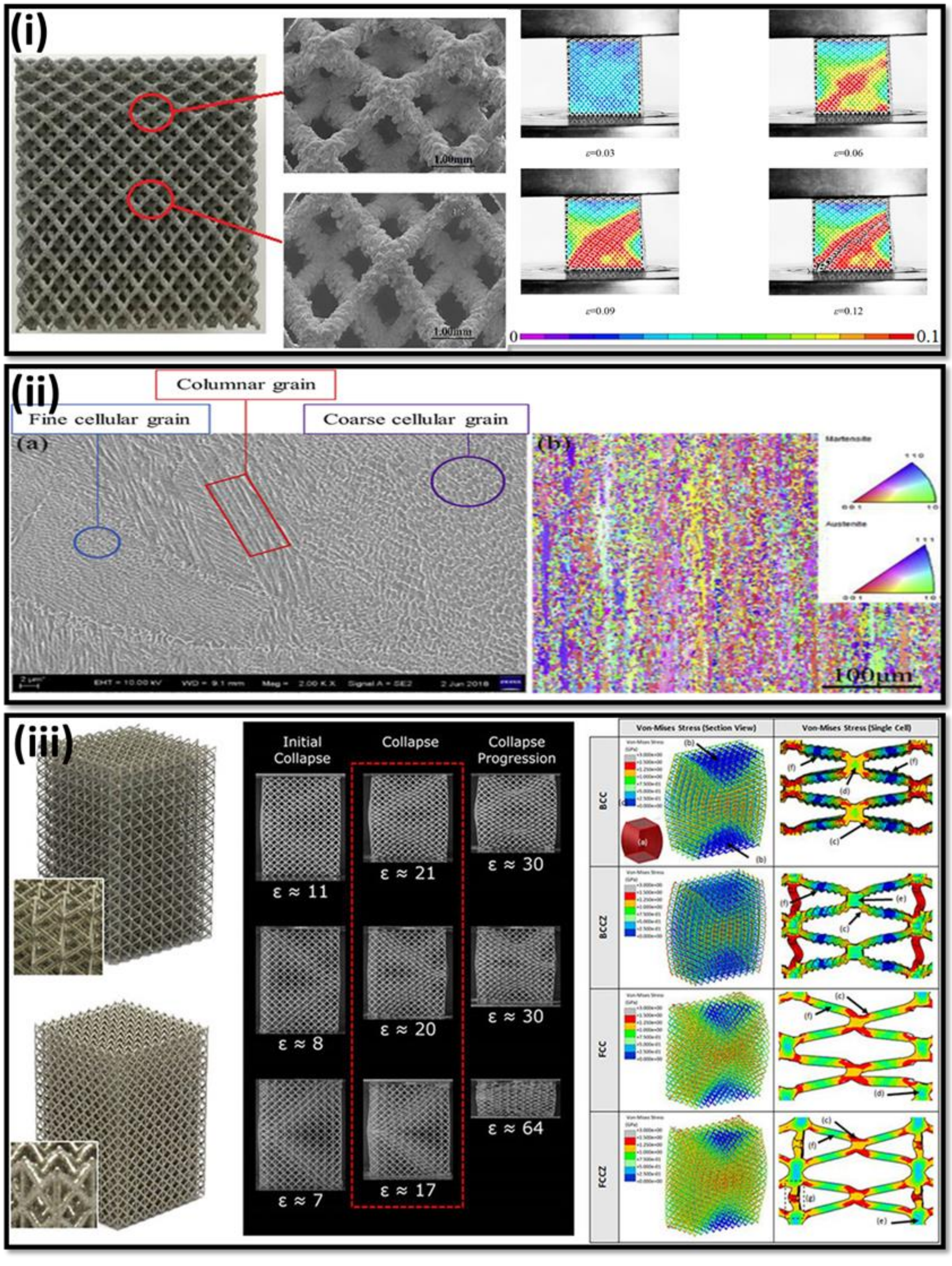


Figure 2. (i) SEM characterization and digital imaging of compression tests of SLM made Ti6Al4V lattice structure [27]. (ii) Microstructure and EBSD characterization of SLM fabricated H13 steels [28]. (iii) Isometric view, graphical and numerical simulation summaries of compression test of SLM fabricated Inconel 625 lattice structure [37].

3.0 AM of Bimetallic Structures

Although AM of single metallic materials is widely implemented by many current industrial applications, the limited performance abilities of a single composition still requires many systems designed with multiple parts with different compositions. The question can be posed – wouldn't it be nice if we could make a part with different compositions but using one manufacturing operation? Such manufacturing challenge encourages the study of design and fabrication of multi-material structures using AM. The traditional multi-material manufacturing methods such as welding, brazing and soldering are available for joining two types of materials together after those parts are shaped separately. In addition, critical issues of using joining methods such as welding can result in large heat affected zone, non-uniform microstructures, distortion due to residual stress, as well as cracking due to brittle intermetallic phase formation. With the advancement of metal AM technologies, now it is possible to directly fabricate multi-material structures successfully in one operation to achieve desired shape and functionalities.

AM of Bimetallic structures is attractive due to the potential to manufacture innovative products having different compositions. Recent results have shown that various bimetallic structures were successfully made by directly depositing one metallic material on top of another using different metal AM technologies. Joining dissimilar materials is chanlleging due to significant difference in thermal properties between the two materials along with possibilities of the formation of the brittle intermetallic phases. During the joining process, the interfacial region could experience thermal mismatch that is caused by residual stress due to the difference in coeffient of thermal expansions [9]. To overcome this issue, researches developed a method of using compositionally graded transition zone as interfacial region instead of direct deposition to fabricate bimetallic structures composed by dissimilar materials. Bimetallic structures such as Al/Ti6Al4V (**Fig. 3i**), SS 410/Stellite^{TM}, CuSn/18Ni300 and SS 316L/CuSn10 were fabricated by using laser based AM technologies [39–42]. Results show that each metallic material maintained its own properties while having a good bonding strength between the two metallic materials due to a diffused interface. Recent research has also shown that bimetallic structures such as Ti6Al4V/Al12Si, Inconel 718/Cu alloy (**Fig. 3ii**), Ti6Al4V/Invar and Ti6Al4V/Mo alloy were processed by DED methods [9,43–45]. To achieve better performace of the bimetallic structure, a third material can also be introduced to enhance the bonding strength of the interfacial layer. Additionally, the introduced third material can serve as bonding layer to help join the dissimilar materials. Recent studies have demostrated that the bimetallic structures such as SS 410/Ti6Al4V (**Fig. 3iii**) and Ti6Al4V/Inconel 718 (**Fig. 3iv**) were fabricated via DED methods with bonding materials of Nb and vanadium carbide (VC), respectively [46,47].

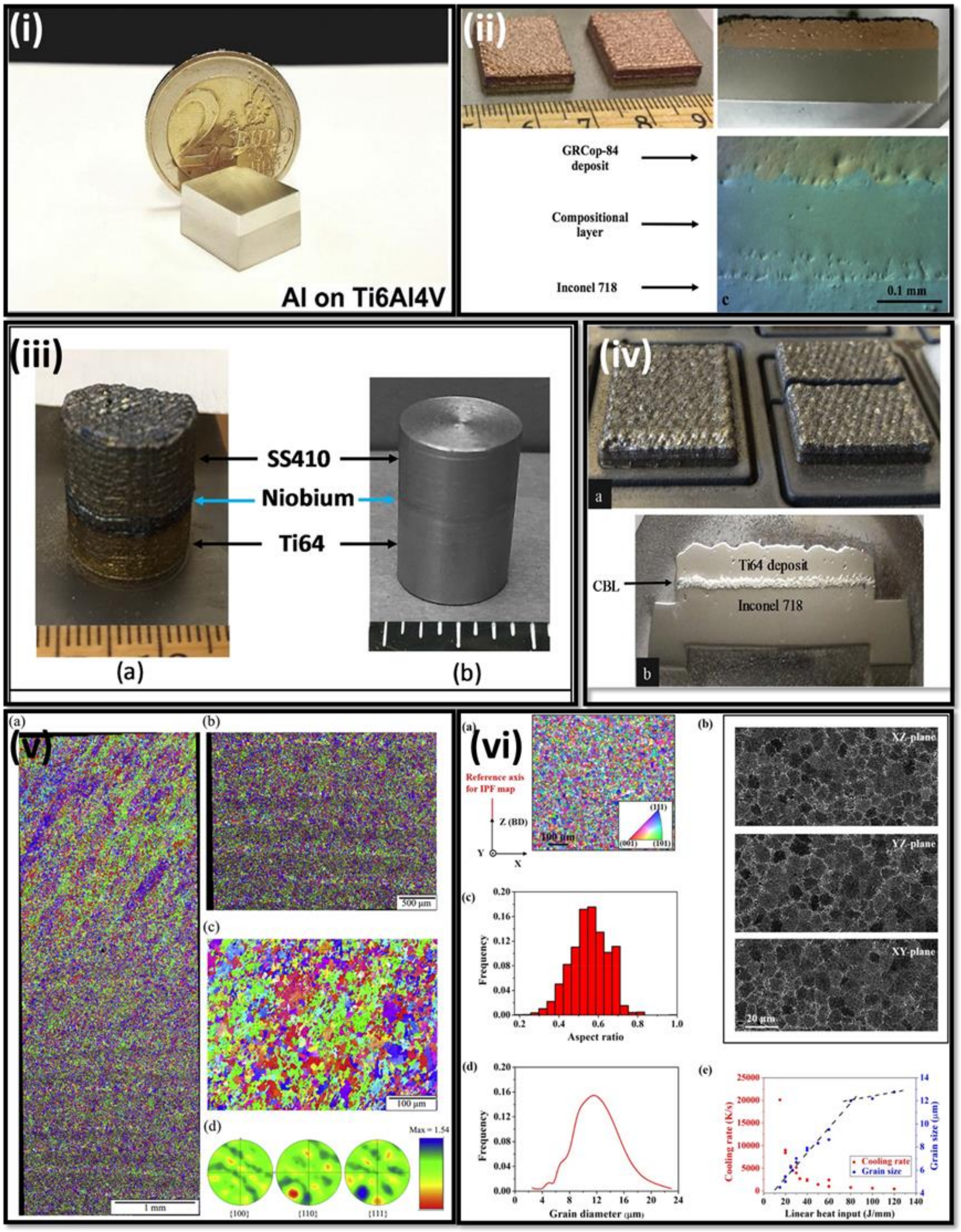


Figure 3. (i) Al/Ti6Al4V bimetallic structure [39]. (ii) Inconel 718/GRCop-84 bimetallic structure [45]. (iii) SS410/Ti6Al4V bimetallic structure [46]. (iv) Ti6Al4V/Inconel 718 bimetallic structure [47]. (v) EBSD maps of LENS™ processed Fe-Co at cross-section [48]. (vi) Microstructure and EBSD map of $AlCoCrFeNiTi_{0.5}$ processed by LENS™ [36].

4.0 Challenges and Future Trends

During the past three decades, AM of metallic materials have transformed the manufacturing industries. Due to AM's unique ability to customize each product, AM is very popular in concept model and low volume manufacturing. Such ability is needed for example in patient matched medical implants, or space travel related parts, but may not be suitable for high volume manufacturing of functional parts. Moreover, AM of low volume large metal parts are also of significant demand in recent years, and some of the PBF systems are designed specifically to meet such needs. Among the key challenges, starting materials is probably the first one to consider. Due to non-equilibrium solidification in AM, chances are new compositions need to be designed specifically for AM operations instead of borrowing metal powder compositions from the powder metallurgy industry. Online monitoring for defect detection is another important area for AM to minimize manufacturing poor quality parts. Developing post processing treatments to minimize residual stresses and improve surface quality are always in demand for AM processed parts. Methods for non-destructive testing of metallic AM parts are becoming important for the manufacturing of critical components. Finally, dimensional tolerances and isotropic properties are always challenge in AM processed parts that will remain an active research topic for the years to come. In terms of future directions, multi-material AM of different structures will be an exciting topic for the next decade. Addition of machine learning ability with AM operations will also evolve in the coming days to improve reliability of parts. In situ online monitoring of AM operations will become more sophisticated to minimize operator interventions. The processing parameters of metal AM could highly affect the microstructures and mechanical properties of printed parts. Therefore, understanding the effects of processing parameters is critical for metal AM. For example, researchers investigated the microstructure variation of Fe-Co alloys (**Fig. 3v**) and $AlCoCrFeNiTi_{0.5}$ HEA (**Fig. 3vi**) caused by processing parameters variation via a DED AM technology [36,48]. According to the results of characterizations, different micro-morphology was observed by utilizing various processing parameters. Additionally, microstructure and phase formation were directly related to the mechanical properties of fabricated materials. Moreover, if a database about the correlation of temperature/cooling rate versus microstructure formation could be established, it will help to predict or even manipulate the mechanical properties of AM-fabricated metallic materials. Since the processing parameters of AM fabrication of the same material vary from machine-to-machine, establishing such database could also standardize AM processing of metallic materials to increase the reproducibility [49]. Furthermore, finite element analysis (FEA) with optimized algorithms could be used for topology optimization [50]. Using advanced numerical modeling will greatly benefit the design and understand the potential issues beforehand, which could greatly reduce the time spent on experimenting, and then, fabricate the parts with optimized performance.

Metal AM Technology	Processing Steps	Advantages and Disadvantages
SLS/SLM	• Preheat the powder bed • Fill the chamber with inert gas to avoid oxidation • Apply laser scan • Cool down the system for part removal	Advantages: • Excellent for complex geometry • No support material is needed • Good surface finish compared to other techniques Disadvantages: • Cannot fabricate multi-material structure • Post heat-treatment may be required
EBM	• Vacuum the chamber to avoid oxidation and e-beam interaction • Preheat powder bed before each layer • Apply electron beam to fuse the powder • Apply optional heat treatment under vacuum. • Cool down the system for part removal	Advantages: • Product has low residual stress • Vacuum processing environment avoid oxidation Disadvantages: • Size limitations • High power required • Expensive machine.
DED	• Load powders into powder feeders • Fill the chamber with inert gas to avoid oxidation • Laser-powder deposition on substrate • Cooling the structure by moving the laser away from the part	Advantages: • Processing fully dense structure with control on microstructural features. • Control over the composition • Multi-materials and gradient deposition of materials Disadvantages: • Poor resolution and surface finish
Wire-based	• Load wire feedstock into feeders • Using shield gas to avoid oxidation	Advantage: • Using metallic wire as feedstock which is easier to handle compared to metal powder

• Laser/arc scan with wire deposition on substrate • Cooling the structure by moving the laser/arc away from the part	Disadvantages: • Less accurate in dimension • Need for post-processing

Table 1. Advantages and disadvantages of common metal AM technologies.

5.0 Summary

Additive manufacturing or 3D printing of metallic materials are transforming the industry with phenomenal growth for the past two decades. Complex shaped topology optimized functional parts to simple concept models are all manufactured today using AM for biomedical to aerospace to automotive to variety of other industries for saving time as well as cost. AM is also versatile in manufacturing a large variety of metals and alloys that are otherwise difficult to work with such as Ti alloys, steels, Ni-base superalloys and so on. Among different commercial AM technologies, PBF and DED are the two main AM technology platforms that are being used for the majority of applications while friction freeform and ultrasonic consolidation are used in some unique application areas. Although AM technology matured over the years to manufacture parts that are, for example, now FAA and FDA approved, challenges still remain for further process-property optimization towards improving part quality and reliability. It is envisioned that the future of metallic AM will see more applications in the areas of bimetallic and multi-materials structures processed in one operation.

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7.0 Conflict of Interest

None.

8.0 References

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