Additive Manufacturing of Metals: A Review

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Abstract

Over the past 20 years, additive manufacturing (AM) has evolved from 3D printers used for rapid prototyping to sophisticated rapid manufacturing that can create parts directly without the use of tooling.

AM technologies build near net shape components layer by layer using 3D model data. AM could revolutionize many sectors of manufacturing by reducing component lead time, material waste, energy usage, and carbon footprint. Furthermore, AM has the potential to enable novel product designs that could not be fabricated using conventional processes.

This proceedings is a review that assesses available AM technologies for direct metal fabrication. Included is an outline of the definition of AM, a review of the commercially available and under development technologies for direct metal fabrication, possibilities, and an overall assessment of the state of the art. Perspective on future research opportunities is also be presented.

Introduction

AM technologies build near-net shape components layer by layer using 3D model data. AM technologies are the direct descendents of the work in 3D printing and could revolutionize many sectors of U.S. manufacturing by reducing component lead time, cost, material waste, energy usage, and carbon footprint. Furthermore, AM has the potential to enable novel product designs that could not be fabricated using conventional subtractive processes and extend the life of in-service parts through innovative repair methodologies.

For the aerospace industry this could lead to a reduction of required raw materials used to fabricate an in-service component, which is known as the "buy-to-fly" ratio. AM could also lead to new innovations for lightweight structures that could see application in unmanned aerial vehicles. For the medical industry, AM is already leading to a revolution in customized medicine where dental implants, orthopedics, and hearing aids are manufactured to fit an individual's unique physiology.

Applications where legacy parts are still necessary for operation and fabricators are no longer in business, for instance aging aircraft systems or older power stations, could use AM to create parts direct from a CAD file. For consumer products artistic and aesthetic designs can be directly manufactured without concern for standard manufacturing practice.

Definition of Additive Manufacturing

AM has grown up organically from the early days of rapid prototyping, and as a dynamic field of study has acquired a great deal of related and redundant terminology. The ASTM F-42 committee was recently formed to standardize AM terminology. According to their first standard, ASTM F2792-10, AM is defined as:

> *"The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing technologies."*

There are many related terms used to describe AM and common synonyms include: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication.

Global Landscape in Additive Manufacturing

The overall global market for AM exceeded $1 billion in 2009 with direct revenues for systems and materials sales of over $500 million.(1) There was a decline in market and revenue due to the recession in 2007 and 2008, but the market is projected to have rebounded in 2010. Ninety percent of the AM machines sold are 3D printers for making polymer-based parts and models.

In addition to market growth, the visibility of AM technology and industry is increasing. In early 2010, a group of companies led by Materialise formed a group to do collective marketing for AM.(2) The cover story for a recent issue of the U.K. magazine The Economist addressed the potential of AM as a revolutionary manufacturing technology.(3)

Although a majority of the current global activity in AM is using polymer-based systems, there has been a good deal of activity and interest in metallic part fabrication. Metallic part fabrication has been of interest due to the possibility for direct fabrication of net or near-net shape components without the need for tooling or machining. There has been particular interest in aerospace and biomedical industries owing to the possibility for high performance parts with reduced overall cost for manufacturing.

Researchers and industry leaders in the European Union (EU) have identified AM as a key emerging technology.(4) Teaming relationships have been formed between university, industry, and government entities within and across countries. Generally speaking, the overall level of activity and infrastructure in the EU is superior to that of the U.S. in this key area. Several large cooperative projects have been funded on the order of millions of dollars across Europe, including the Rapid Production of Large Aerospace Parts(5) and the Custom Fit project(6) for mass customized consumer and medical project manufacturing.

In 2009, a workshop was held in the U.S. to form a roadmap for research in AM for the next 10-12 years.(7) That effort focused on identifying possibilities for development in design, process modeling and control, materials, biomedical applications, energy and sustainability, education, and efforts at development in the overall AM community. Their overall assessment is that there are many opportunities for these technologies if investments are made to continue to advance the state-of-the-art. A key recommendation of that report is the establishment of a national test bed center that could leverage equipment and human resources in future research and to demonstrate the concept of cyber-enabled manufacturing research.

Based on results from the roadmap developed in 2009, EWI organized an Additive Manufacturing Consortium (AMC) to bring together key partners in the U.S. AM community. The AMC now consists of 20 member and partner organizations, representing industry members, government agencies and other partner organizations, and key universities active in the field of AM research. The main goal of the AMC is to advocate on a national basis for investment in AM technologies to move them into the mainstream of manufacturing technology from their present emerging position. The highest rated technical need is to produce mechanical property data suites for qualification of combinations of the many processes and materials of interest.

Technologies for Direct Metal Parts Fabrication

The scope of this review includes AM technologies that directly form metallic parts or deposit metals. "Indirect" processes, where a casting insert is fabricated for a mold then formed into a part, or a "green" body where extensive post manufacturing thermal processing is required are not included. Additionally, the focus of this review is on the "build" stage of the AM process.

The two main components of any metal AM process are the type of raw material input and the energy source used to consolidate or form the part. In this report three main technology categories of direct metal fabrication are included: powder bed, laser powder injection, and free form fabrication systems that do not use lasers.

Powder Bed AM

In powder bed AM systems, the build envelope is an enclosed chamber that can be operated in vacuum or filled with an inert gas to prevent oxidation of reactive metal powders like titanium and aluminum. In the center of the chamber, a reservoir of metal powder is smoothed using a leveling system. The chamber is then pre-heated to a pre-determined temperature depending on the process, around 100°C for laser based and 700°C for electron beam. The laser or electron beam is then scanned over the surface of the metal powder in the pattern of the part, building up a single layer, usually between 20 and 200 μm thick. The build reservoir is then lowered a single layer thickness, a leveling system provides fresh powder on top of the part, and the process is repeated until the final build is finished.

ARCAM Electron Beam Melting

ARCAM is a Swedish company founded in 1997 with manufacturing electron beam melting (EBM) technology-based machines as their central focus.(8) The technology uses a heated powder bed of metal in a vacuum that is then melted and formed layer by layer using an electron beam energy source similar to that of an electron microscope. This EBM technology is one of the most widely used AM technologies.

The latest machines offered by ARCAM are the A1 and A2. The A1 is built specifically for medical applications, while the A2 is designed for aerospace and other industries. Each is equipped with an electron beam that can provide power up to 3500 W. The A1 has a maximum build volume of 200 × 200 × 180 mm and the A2 has a build volume of 200 × 200 × 350 mm. The build rate is 55 cm3/hr for Ti-6Al-4V optimized for high surface finish and 80 cm3/hr optimized for a fast build rate. Surface finish is approximately 25-35 Ra. The machines operate in a vacuum of 10-4 mbar and with a new "multi-beam" technology the electron beam can scan anywhere from 1-100 spots at a time. Materials available from ARCAM currently include Ti-6Al-4V, ELI Ti, CP Ti, CoCr, γ – TiAl, and many others are under development.

The EBM machines are used for medical applications in industry and ARCAM introduced their A1 machine at the end of 2009 that is specifically geared for the medical market. ARCAM has been working with Adler Ortho in Milan Italy to develop their technology to manufacture the acetubular cup for hip implants. Since 2007, over 10,000 of these hip implants have been produced and more than 1,000 have been implanted in patients with positive doctor feedback.

In addition to hip implants, knee and facial implants can be custom manufactured using the EBM as well. The Walter Reed Army Medical Center in Washington, D.C. has purchased an ARCAM machine to manufacture patient matched implants for wounded warriors on site.

Avio, an Italian aerospace company, has been working with ARCAM to develop capability to manufacture γ –TiAl intermetallic components for applications like turbine blades or other high-temperature areas of engines. This is an important advance because TiAl is a useful high-temperature material. However, due to its intermetallic structure, it is brittle and difficult to machine. These intermetallic components are excellent examples of how near-net shape processing using AM is enabling new engineering advances.

A primary advantage of using the EBM technology is that the build chamber is kept relatively hot, typically between 700 and 1000°C. This leads to lower induced stresses in the parts because of smaller amounts of cooling during the build cycle. It has been shown that Ti-6Al-4V processed using the EBM process can have comparable ultimate tensile strength and elongation properties as wrought material. Another advantage of the EBM process is that it has a faster build rate compared to laser-based powder bed systems. However, the surface roughness for EBM parts is higher and post machining is necessary for many applications.

EOS Direct Metal Laser Sintering

EOS is a German company founded in 1989 that manufactures equipment for metal AM focused on their Direct Metal Laser Sintering (DMLS) technology.(9) The DMLS process works by melting fine powders of metal in a powder bed, layer by layer. A laser supplies the necessary energy and the system operates in a protective atmosphere of nitrogen or argon. The build volume of the M 280, EOS' most recent machine, is 250 × 250 × 325 mm, and it is equipped with either a 200 or 400 W Yb-fiber laser system.

EOS sells powders that are specifically developed for the DMLS process. The materials currently available include Al-Si-10Mg, a CoCr superalloy, tool steel, stainless steel, Ti-6Al-4V Grade 5, Ti 6Al-4V Grade 23, and CP-Ti. Nickel alloys 625 and 718 are currently under development. EOS continually works with designated centers of excellence to develop new powders for the process. Tailoring of the powder and build processing conditions is essential to the repeated manufacture of parts and structures with low porosity and adequate dimensional accuracy. It has been reported that DMLS has been used to manufacture superalloy turbine components that are already making their way onto test rigs.(1)

An advantage of DMLS is that there has been a substantial amount of work using the system and as a result it is one of the most production robust AM technologies on the market. Additionally, the surface finish produced is superior to the EBM process with a surface finish of around 8.75 Ra. However, the build rate is slower than using EBM. Since the powder bed is held at a relatively low temperature, stresses can be induced in parts so innovative supports are required to prevent distortion of certain types of builds. Anisotropy can also develop in the build section due to heating and/or cooling cycles. Post-fabrication heat treatments can be required to normalize the properties in the x-y and z build directions depending on application requirements.

Concept Laser Laser Cusing

Concept Laser is a subsidiary of the Hoffman Innovation Group based in Lichtenfels, Germany. They have developed a laser powder bed technology called Laser Cusing that integrates laser melting, marking, and machining into one tool.(10) They currently offer three machines for sale, the M1, M2, and M3 with the M3 being the latest and most advanced offering.

The M3 is the largest laser powder bed machine on the market. The build volume for this machine is 300 × 350 × 300 mm. This build volume is enabled by their patented technology for controlling the laser mirrors. With this technology, the laser beam deflection is controlled by a series of direct drive motors and mirrors as opposed to a fixed optical lens. A 200 W fiber laser is used to melt the material in an inert atmosphere of nitrogen. Materials available include stainless steel, tool steels, aluminum alloys, CoCr, Ti-6Al-4V, and Alloy 718.

The Laser Cusing machines are also capable of laser marking and cutting in concert with the laser deposition process. This novel technology enables more accurate small-scale builds than are possible using only standard laser powder bed technology. Furthermore, the surface finish of a part can be improved and micro-scale features produced.

MTT Selective Laser Melting

MTT Technologies Group of Stone, England has developed a powder bed laser-based technique they call Selective Laser Melting (SLM).(11) The energy for melting is provided by a 100 to 400 W Yb-fiber laser. The SLM 250 which is the latest model system and has a build volume of 250 × 250 × 300 mm. As is the case with Concept Laser's Laser Cusing machine, the MTT machines use a combination of linear direct drive motors and mirrors rather than fixed optical lens. The MTT machines conduct the SLM process in a nitrogen or argon atmosphere. In contrast to most of the other powder bed laser machines that operate with positive pressure atmospheres, the SLM machines are fitted with a vacuum chamber that can be fully purged between build cycles. This allows for lower oxygen concentrations and reduced gas leakage.

Available materials for use with the MTT SLM machines are 316L and 17-4PH stainless steels, H13 tool steel, Al-Si-12Mg and Al-Si-10Mg aluminum alloys, CP-Titanium, Ti-6Al-4V, Ti-6Al-7Nb, CoCr, and nickel-based alloys 625 and 718. MTT provides an "open system" where customers can develop their own alloy powder compositions for specific applications.

Phenix Systems Selective Laser Sintering

Phenix Systems is a Riom, France based company that manufactures machines for SLS.(12) This technology is unique in that it can process both metals and ceramics at temperatures up to 900°C. SLS is a powder bed laser technique that uses a 200 W Yb-fiber laser in a nitrogen atmosphere or in a vacuum. The build volume is cylindrical with a maximum 250-mm diameter and a 300-mm height.

The materials that can be used with the Phenix machines are metallic and ceramic powders that are commercially available. Metal components can be made from several materials including stainless steels, tool steels, CoCr, superalloys, and precious metals. For metal components, dimensional accuracy in each direction is ~10 µm, and post processing consists of either sand blasting or polishing. Alumina parts can also be made using these machines.

Laser Powder Injection AM

Another approach to metals AM uses powder injection to provide the material to be deposited. Instead of a bed of powder that is reacted with an energy beam, powder is injected through a nozzle that is then melted to deposit material. The powder may be injected through an inert carrier gas or by gravity feed. With either powder injection methods, a separate supply of shielding gas is used to protect the molten weld pool from oxidation. The part is typically attached to a table that is restored in the x and y directions. The table is fixed and the laser head is raised or repositioned for each layer to be deposited.

The laser powder injection approach is valuable because it can be used to add material to existing high-value parts for repair and the powder material injected can be varied to fabricate compositionally graded parts. The powder injection approach is not constrained to a confined volume as the powder bed systems are. Therefore, these systems can be used to deposit features on large parts such as forgings. In general, this technology is not able to deposit the same volume of material as the powder bed techniques but it is more useful for repair and cladding.

Optomec Laser Engineered Net Shaping

Laser Engineering Net Shaping (LENS) is a powder injected technology that was originally developed at Sandia National Laboratory and has been licensed to Optomec in Albuquerque, NM for manufacturing and development.(13) The system operates by injecting metal powder into a molten pool of metal using a laser as the energy source. These machines can be operated with most commercially available powders, including those used for thermal spray applications. There are currently three LENS systems on the market: the MR-7, LENS 750, and LENS 850-R.

The MR-7 is intended for research related purposes such as rapid alloy screening, fundamental solidification research, and rapid solidification research. Two powder feeders allow gradient materials to be made (where each layer has a different chemistry). The system has a 3-axis motion, a 500-W IPG fiber laser, operates in an inert gas atmosphere, and has a 300 × 300 × 300 mm process window.

The LENS 750 and LENS 850-R machines are intended for applications such as rapid manufacturing, advanced product development, and fabrication and repair of components for aerospace and defense applications. The LENS 750 is the smaller machine and has 3-axis capability (optional additional axis), a 300 × 300 × 300-mm process work envelope, and can be equipped with a 500 W, a 1 kW, or a 2 kW IPG fiber laser. The LENS 850-R has 5-axis capability, a 900 × 1500 × 900 mm process work envelope, and can be outfitted with either a 1 kW or 2 kW IPG fiber laser.

The 850-R machine has been installed at Anniston Army Depot in Alabama where it is used to repair the blisks in the turbine engines of Abrams M1 tanks. Analysis of the economic return from repairing the blisk using the LENS process versus replacing with a new part showed a positive return on investment in the LENS machine.

POM Direct Metal Deposition

Precision Optical Manufacturing (POM) is an Auburn Hills, MI based company that has developed a technology called Direct Metal Deposition (DMD).(14) It is based on a powder injection system that is coupled with a fiber laser on a robotic arm. DMD is well-suited for repair of existing tooling, adding features to large parts, or for the manufacture of new parts. This process has been used to deposit tool steels, Stellite, Inconel, and titanium alloys.

There are two different types of machines developed using this technology. The DMD 105D is contained within an enclosure similar to the powder bed machines. The process work envelope is approximately 12 × 12 × 12 in. This machine can be equipped with a hermetically sealed chamber. The laser is a 1 kW fiber delivered disc laser or diode laser.

The second type is a DMD system has attached to a robotic arm with 6-axis capability and is equipped with a 1 to 5 kW fiber coupled diode or disc laser. Two robotic systems are available: the Model 44R and 66R. The Model 44R has a payload of 60-kg and a work envelope of 1.96 × 2.14 m × 330 degrees. The Model 66R has a payload of 125 kg and a work envelope of 3.2 × 3.67 m × 360 degrees. Robotic DMD systems have successfully been applied to the restoration of precision components such as stub shafts, diaphragms, trim dies and punches, and turbine blades made out of materials such as tool steels, Stellites, Inconel, and titanium.

Accufusion Laser Consolidation

The Integrated Manufacturing Technologies Institute of the National Research Council of Canada in conjunction with GE Global Research has developed a powder injected approach for metals AM called laser consolidation.(15) The process has been licensed to Accufusion to further develop this technology.

The process is very similar to the LENS method, whereby powder is deposited into a molten metal pool using a laser to provide the necessary energy for deposition. Similar to LENS, the Laser Consolidation process is operated in a hermetically sealed container. This process has been used for nickel-based alloys 625 and 718, Ti-6Al-4V, Stellite 6, and iron-based CPM-9V tool steel.

This process is known to produce a better as-built surface finish than the LENS systems; however, it has a lower deposition rate. This is important for the aerospace industry, which is particularly interested in systems that require no post-deposition surface finish. As-deposited surface finishes of 1 to 2 μm can be obtained on Alloy 625 samples.

Free Form Fabrication AM

In addition to the powder injection techniques, there are a range of other approaches that use other types of energy inputs or materials. The energy inputs are electron beam welders, arc welding equipment, or ultrasonic energy. These techniques are generally suited to larger parts than the two powder-based approaches, but dimensional accuracy can be lower.

Sciaky Electron Beam Free Form Fabrication

Chicago based Sciaky, a world leader in electron beam welding equipment development, has developed a technology called Electron Beam Direct Manufacturing (EBDM) (16). The process is similar to laser additive manufacturing (LAM), which has been in development for several years by commercial and academic organizations. However, EBDM uses a specially developed electron beam welding gun to melt the metal to be deposited. The process is operated in a vacuum, which makes it well-suited for a range of materials including reactive and refractory metals.

The EBDM process consists of metal wire that is directed to a molten metal pool and melted by a focused electron beam. Parts are built up layer by layer by moving the welding head along the substrate using a gantry-based robot system that is controlled by a CAD model. A substrate is generally employed and free-standing shapes or preforms are generated without molds or dies. Commercially available welding wires are used as the deposition material. The standard electron beam system is a Sciaky 60 kW / 60 kV welder. The electron beam is electronically focusable and the output power is scalable over a very wide range. This enables a very wide range of deposition rates to be achieved using the same system. The EBDM has been demonstrated for Ti-6Al-4V at deposition rates of 40 lb/hr and surface roughness of 35 Ra.

The EBDM approach has attracted a great deal of interest from the aerospace community and has been shown to be feasible for reducing material usage. The Metals Affordability Initiative, a consortium of U.S. defense manufacturers and the U.S. Air Force have provided funding to reduce the cost and lead time of Ti-6Al-4V aerospace components. Conventional techniques for many components involve starting with a large block of material and machining away significant amounts of material as opposed to EBDM (and AM generally) where net shape parts are fabricated directly reducing titanium usage. This process is particularly suited for mid size forgings of several hundred pounds that contain many features. NASA has also investigated a scaled down version of the EBDM process for use in direct manufacturing platforms in space vehicles.

Current activities for this technology are focused on improving the post deposition material properties and developing closed loop feedback control systems that will lead to improved repeatability and consistency in the EBDM process.

MER Plasma Transferred Arc Selective Free Form Fabrication

The MER Corporation in Tucson, AZ has developed a technology called Plasma Transferred Arc – Selective Free Form Fabrication (PTA-SFFF) that uses wire and powder filler materials to deposit metals.(17) A PTA torch and positioning stage are manipulated by a robot or multi-axis controller and the path is preprogrammed. Powder is introduced both through the shielding gas and the orifice gas, and the plasma arc welding system provides the energy for melting.

The build volume for the MER PTA-SFFF machine is 2 × 2 ft in the x-y plane, and up to 17 ft in height. This build geometry is the largest build volume capability of any of the approaches reviewed here. Referring to the base of the machine, expandable bellows enable inert gas shielding of the component, but the system does not operate in a hermetically sealed enclosure. The machine uses two constant current DC power supplies that can provide up to 350 A each, and four powder feeders are available that can be used to produce composite structures. This approach has been used to make Ti 6Al-4V and the refractory alloys Mo-Re and Ta-W.

MER has undertaken a number of military SBIR projects focused on leveraging the advantages of the PTA-SFFF process. They include a refractory metal composite gun barrel, advanced munitions, and exploring the use of new $10 per pound titanium sponge-based powder that could significantly reduce the cost associated with forming titanium parts. They have also completed work on an Army SBIR for a composite W-C gun barrel that could withstand wear more effectively than current designs. MER has also fabricated turbine blisks for aerospace companies.

Honeywell Ion Fusion Formation

Honeywell Aerospace has developed a non-powder-based approach they call ion fusion formation (IFF). IFF uses a plasma arc-based welding torch to deposit metal from wire feedstock with an inert gas acting as the plasma forming gas (18). The part is constructed from the direct metal deposition onto a positioning table that can be controlled using an electronic interface.

IFF has been used to deposit Ti-6Al-4V, 347 stainless steel, and aluminum. One advantage of this approach is the faster build up speed and that the parts do not require hot isostatic pressing post treatment as they are fully dense as-deposited. However, the resolution is not as precise as slower deposition rate approaches and the surface must be machined in all cases. For some materials a furnace heat treatment can improve the mechanical properties of the deposit. This approach may potentially be used to repair aerospace components and it appears well-suited to net shape fabrication of circular components such as valve bodies or nozzles.

Rolls Royce Shaped Metal Deposition

Rolls Royce has patented a technology called Shaped Metal Deposition (SMD). The current SMD setup uses a computer controlled synergic gas tungsten arc welding (GTAW) power source that is integrated with a robot.(19) Initially, the SMD setup required a skilled, trained operator to run the machine. With subsequent developments the process has become largely automated.

The SMD technology has been licensed to the University of Sheffield Advance Manufacturing Research Center for further development. Subsequently, the EU funded a program, the Rapid Production of Large Aerospace Components (RAPOLAC), which was conducted from 2007 to 2010. The objective of this program was to improve the technology readiness level of the SMD process. At the culmination of the program a test cell was constructed that encompasses the SMD process.

Nickel alloys, titanium alloys, and steels have all been deposited using SMD technology. However, the main focus for development has been on Ti-6Al-4V deposition. To this point, the SMD process has been used to manufacture simple shapes like boxes and tubes and for adding features to forged pieces. Future development work is focused on extending the manufacturing readiness for materials beyond Ti-6Al-4V.

EWI Hot Wire – GTAW

EWI in Columbus, OH has developed a free form fabrication approach called hot wire gas tungsten arc welding (HW-GTAW). Along with plasma arc welding (PAW) and cold wire GTAW (SMD), HW-GTAW is used to produce free form fabrication parts in a range of alloys from steels, to stainless steels, nickel alloys, and titanium alloys. By using HW-GTAW in contrast to the other arc-based free form fabrication approaches the deposition rate can be increased by roughly an order of magnitude. This improved deposition rate opens up many opportunities including in aerospace and oil and gas manufacturing.

Ultrasonic Additive Manufacturing

Ann Arbor, MI based Solidica developed a metals AM technology called ultrasonic consolidation (UC) in 2001 and sold a small number of "Formation" machines that leverage UC technology.(20) UC uses solid-state ultrasonic metal welding to bond together layers of material with integrated CNC machining used to form net shape parts. The technology was not an immediate success due to the limited power available. It was mainly used for lower strength aluminums and coppers, with a build volume 12 × 18 × 8 in.

Recently, EWI and Solidica have formed a collaboration that has developed a step change extension of this technology called Very High-Power Ultrasonic Additive Manufacturing (VHP-UAM). This technology uses 10× more power to significantly expand the materials that can be joined including high-strength aluminum, steels, and titanium alloys. Furthermore, it increases the build rate by an order of magnitude to approximately 14 lb/hr for aluminum and 20 lb/hr for stainless steel. The first system built has the ability to produce parts of size 6 × 6 × 3 ft. Additionally, the weld head can rotate in roll and pitch allowing for repair of curved surfaces.

Central to these capabilities is that UAM is a solid-state process with bonding occurring without melting and resolidification of metals, thus avoiding the significant property degradation due to melting and resolidification of the other metal AM technologies reviewed. This also enables the technology to bond dissimilar metals to create metal matrix composites. A range of emerging applications are currently under investigation including rapid prototyping, IM tooling, direct parts manufacture, tailored materials, MMC, embedded fibers, smart materials, sensors, cladding, armor, thermal management, and cladding.

Summary and Future of Additive Manufacturing

There is a rich landscape of available technologies and materials for metals AM. Titanium alloys, nickel alloys, high-grade stainless steels, and many others are being manufactured using lasers, electron beam, and arc techniques using a variety of feedstocks.

The most exciting possibilities for AM are for unique applications that could not be fabricated using standard machining practices. Examples include tailored medical implants that can be built with the exact bodily geometry output using an MRI or advanced turbine blades with application specific cooling channel designs. As a fundamentally enabling technology, novel applications that are just beginning to be imagined could be built. Novel functionally gradient materials could be generated using these techniques that could enable entirely new applications.

However, there are a limited number of technologies commercially available and there is a great deal of work to be done on ruggedizing these processes for commercial scale manufacturing. In particular, the larger-scale free form fabrication technologies, though their fundamental technologies are commercially deployed in many industries, are at a lower stage of manufacturing readiness as compared to the powder bed or powder injected laser approaches when it comes to AM part production. Closed loop feedback control sensing systems and intelligent feed forward schemes will need to be developed and integrated into systems to better control the manufacturing cycle. Currently, part properties and quality can vary from machine to machine for a given material and technology. In addition, new methodologies for nondestructive evaluation will need to be developed as many of the microstructures formed have lots of “noise” that inhibits inspection depth using current approaches.

There is a need to understand the material microstructure resulting from a particular thermal processing cycle. Many studies on individual processes and resulting properties have been done, but there is still a need for a comprehensive material property database and testing methodology to be developed. Studies of the effect of processing parameters on dynamic loading in high and low cycle fatigue and impact toughness, creep, and other situations will be important to fully understand the performance of AM parts in service like conditions. The newly formed ASTM F-42 committee is working to write standards that address a wide array of these needs and there is much work still to be done.

To date, there has been a relatively large body of work and focus on Ti-6Al-4V, but not as much on other alloys and metals. This is understandable given its high cost and utility in high-value aerospace and medical applications. There is a rich landscape of other high-value applications requiring metal alloys that include nickel, aluminum, and refractory metals that could be manufactured using AM that heretofore have not been extensively investigated.

AM of metals is opening up new possibilities for low-cost manufacturing and novel assemblies that cannot be made using current technology. To meet the full potential of these processes, continued development to ruggedize the machines for full manufacturing readiness and further understanding of the underlying materials processes is essential. With the pace of advancement already underway, this key emerging field is poised to grow rapidly over the coming years.

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