Additive Manufacturing: The Current State of the Art and Future Potential

John A. Slotwinski

ABSTRACT

Additive manufacturing (AM, also known as 3-D printing) technologies offer the potential to revolutionize the creation of parts, disrupt supply chains, and positively affect every major industry in existence today. However, technical challenges are preventing the full vision of AM from being realized. The Johns Hopkins University Applied Physics Laboratory (APL) uses AM extensively to create prototypes and functional parts in support of its missions. This article summarizes the current state of the art, provides poignant examples of current AM capabilities, and offers a glimpse of the future potential.

INTRODUCTION

Additive manufacturing (AM) is defined in international standards as a "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies."[1] Two features distinguish AM processes from other manufacturing processes: they are driven by a digital design, and they make parts one layer at a time. Any manufacturing process that does not meet both of these criteria (such as metal welding) is not an AM process (although, like in the case of welding, the process phenomena might be similar). Figure 1 illustrates the difference between AM and traditional manufacturing processes. The term *3-D printing* is frequently used as a synonym for AM. However, in reality, 3-D printing is only a subset of AM processes, restricted to low-cost polymer-based extrusion processes that produce modest parts.[1]

AM offers several advantages over conventional material removal and forming manufacturing processes. These include the capabilities to (1) make parts with extremely complex geometries (including internal features); (2) streamline mass customization so that specific part modifications, such as those enabling biomedical implants to compensate for each patient's geometry, are simple to make; (3) fabricate parts out of materials that are difficult to machine conventionally because of their hardness (such as tungsten or titanium); (4) combine multiple part assemblies into single monolithic parts; (5) make parts with deliberately induced surface porosity, which results in improved performance for biomedical implants by providing structures for osseointegration; and (6) rapidly accelerate new part development and prototyping, even for those cases where AM is not the final production method.

AM processes are classified into seven categories.[1] Each of these have significant differences in terms of capabilities, materials, system cost, required

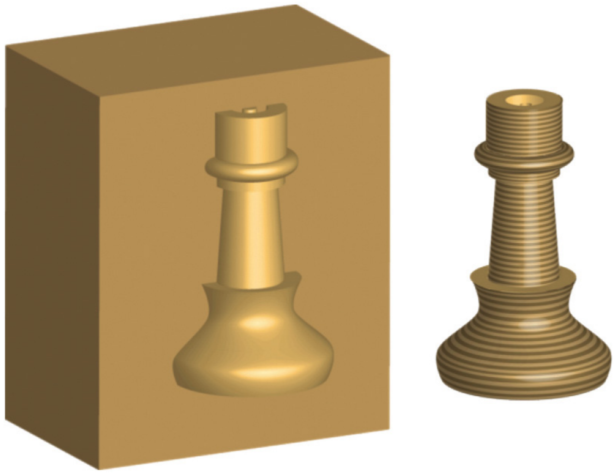

Figure 1. Traditional manufacturing processes vs. AM. Shown are identical parts made from traditional removal processes (left) and AM processes (right). (Originally published in Ref. 2).

infrastructure, and expertise required to realize AM parts. These categories are listed below, along with the primary materials supported:

1. Material extrusion (polymers, metal-embedded polymers), where material is selectively dispensed through a nozzle or orifice
2. Powder bed fusion (polymers, metals, ceramics), where thermal energy selectively fuses regions of a powder bed
3. Directed energy deposition (metals), where focused thermal energy fuses materials by melting them as they are being deposited
4. Material jetting (polymers), where droplets of build material are selectively deposited
5. Binder jetting (polymers, metals, ceramics), where liquid bonding agent is selectively deposited to join powder materials
6. Vat photopolymerization (polymers), where liquid photopolymer in a vat is selectively cured by light-activated polymerization
7. Sheet lamination (paper, polymers, metals), where sheets of material are bonded to form an object

APL uses many of these processes extensively to create prototypes and functional parts in support of its missions. A 2016 *Johns Hopkins APL Technical Digest* article[2] highlights several examples. Two articles in this issue, by Peitsch et al. and Storck et al., highlight current innovative work in advanced AM materials and process understanding.

The full vision for what AM might accomplish is imaginative and inspiring. If realized, the capability to fabricate any part out of any material at any location could be positively disruptive across all industries. Examples of this vision include:

- The production of parts with extreme geometrical complexity, including features that cannot be made with other manufacturing processes, such as internal features, and parts with atypical material properties such as gradient structures, designed porosity, lattice structures, and topologically optimized structures that are lighter weight and structurally superior to conventionally produced parts
- Support for distributed logistics, including part production in remote or austere environments, and part replacement at the point of need, especially when replacing parts for legacy systems that do not have existing manufacturing sources
- The democratization of manufacturing and the ability for anyone to produce parts, including unique parts, in their homes
- Bioprinting of functional replacement organs and for therapeutic medicine, such as printing new skin for burn victims
- On-demand fabrication of customized electronics and fully functional robotics
- Rapid and customized construction of houses, bridges, and other large-scale infrastructure, including potentially in disaster relief or extraterrestrial environments

Although the full vision for AM has not yet been realized because of a number of significant technical challenges, these challenges have not diminished the potential or the progress being made to make the vision a reality. The next section presents a snapshot of the current state of the art, along with representative examples, as well as examples of the future capabilities of AM, especially as those capabilities support the realization of the future vision for AM. And while predicting the future is hard, we can elucidate what is reasonably possible within the next 25 years, using the vision as a guide.

CURRENT STATE OF THE ART AND FUTURE CAPABILITIES

Polymer

Polymer AM processes are widespread, with material extrusion machines representing the largest percentage of AM machines in use today. While new applications for polymer AM are announced regularly, most of the polymer AM production technologies are technically mature and stable. Polymer extrusion systems suffer from a lack of fine feature resolution, while polymer vat photopolymerization and material jetting systems can produce some of the smallest features among all of the AM processes. However, polymer materials are generally limited by mechanical properties that are inferior to those of metals. Some AM capabilities with composite material have been demonstrated, but these systems are not pervasive.

Going forward, the AM application space will continue to grow unfettered, and new AM materials will be developed in a consistent manner. Although the machines themselves are not likely to change significantly, improvements are being made to make them more repeatable and robust.

Metal

Metal AM processes such as powder bed fusion and directed energy deposition produce parts with good dimensional resolution and superior mechanical properties relative to polymer processes. However, the physics of these processes is extremely complex, is not completely understood, and can result in materials that have complicated microstructures and properties. The complexity stems from the extremely fast melting and solidification of the material, the remelting and resolidification of previously deposited material, and the complex interactions between the thermal processing source (either a laser or electron beam) and the metal powder. These facets result in materials that have complex and nonuniform microstructures.

Additionally, these processes usually run "open loop," with no real-time sensor feedback that allows the system to make the minute process adjustments needed to maximize the quality of the part. Challenges to implementing in situ sensors include limited space and attachment points inside the build chamber and the obvious requirements to avoid physical interference with the machine's processing functions (such as powder spreading or laser scanning) and safety systems (for example, systems maintaining the inert atmosphere). Some nascent work in process modeling and in situ sensing has increased understanding and potential optimization of these processes, but actual progress has been neither rapid nor widely applicable. Because of this complexity and because of the high costs of these metal systems, they are not as pervasive as polymer AM systems. Additionally, the number of metal materials that can be built "out of the box" is limited (roughly 10 different alloys) and does not include materials that have high industrial interest, such as copper, tungsten, and high-strength aluminums. Some recent advances are now making these materials possible. Modestly sized build volumes for powder bed fusion systems have also been characteristic, although machines with much larger build volumes are now becoming commercially available.

A significant development that will result in much greater proliferation of metal AM will be robust and validated physics-based models of the processes.[3] As mentioned earlier, these metal processes are very complex. Tractable models that can fully and efficiently predict the process–material relationships, including the final part microstructures, will be transformative. With these models, it will be possible to move much of the currently empirical development into the virtual environment. In addition to making process optimization a reality, these advances will significantly reduce the time it takes to develop new metal materials (since much of the development could be done on a computer) and greatly reduce the brute-force fabrication and testing burden that current qualification methods require, resulting in more instances of metal AM parts for critical applications.

In situ sensors could be used for feedback control of AM processes. In this scenario, the signals from the sensors could be correlated with undesirable process deviations, and an intelligent monitoring and control scheme could send real-time corrections into the machine's process controller.[3]

Validated models used simultaneously with in situ sensors could revolutionize the fabrication of critical metal parts. The predictions from the models could be compared layer by layer with the actual part features (such as dimension, microstructure, or the presence of cracks or porosity) measured by the sensor systems. A discrepancy between the prediction and measurements could indicate that the process has changed. Real-time process adjustments based on these predictions could improve the quality of the part while it is being fabricated.

Qualification and Certification

Critical AM biomedical and aviation parts require regulatory oversight and approval for usage from the cognizant regulatory agencies, such as the Food and Drug Administration (FDA) and the Federal Aviation Administration (FAA). However, qualification for these new AM designs is costly and takes a long time, often years. This is primarily why usage of metal AM parts has not been more widespread in the biomedical and aviation areas. Challenges for qualifying AM parts include the lack of a standardized qualification process; the lack of robust, design-allowable data for AM materials; brute-force approaches that require a large number of test samples; and a potential lack of part consistency.

AM is demonstrably capable of making these kinds of critical, high-quality parts, but there are concerns about the technology being able to do so consistently and reproducibly from build to build or among different machines. Consensus-based industry AM standards, such as those currently being developed by ASTM International and its partners, are essential for making qualification methods more tractable and practical because they provide the underlying test and measurement methods.[4] (Currently ASTM International and ISO have published more than 20 standards.) AM standards are being developed efficiently and with the coordination of standards development organizations, the government, users, and AM machine and material vendors.

Despite the metal process and qualification challenges, many complex metal parts have been built with AM processes, including parts used in demanding applications. A good example is GE Aviation's revolutionary fuel nozzle for the next-generation commercial LEAP jet engine, which is being mass-produced via AM.[5] This nozzle, which received FAA approval, is a redesign of the original multicomponent part. It was redesigned as a single monolithic part with superior performance and lighter weight compared with the original, and it is currently being mass-produced via metal AM.

Given the current pace of and support for standardization efforts, it is likely that there will soon be an even more robust portfolio of salient standards that ease the future development and application of AM. Coupled with the development of validated models and in situ sensors, the number of qualified critical AM parts will grow significantly.

Tooling

Often AM is thought of as being used only to directly produce end-use parts. However, both polymer and metal AM processes have been used extensively, and to good effect, for tooling, fixtures, and molds, which are in turn used in the mass production of parts. Extremely precise molds, complex sand castings, and forms for composite layup have all been successfully used. As an example, APL has demonstrated the use of dissolvable polymer AM forms for producing composite parts with complex geometries.[6]

In the future, the use of AM tooling will grow as the benefits and best practices are communicated more broadly across the manufacturing industry.

Electronics

AM electronics printing—distinct from traditional electronics fabrication that is also sometimes referred to as electronics printing—currently has a low technology readiness level. AM has been demonstrated successfully for the deposition of conformal electrical structures and integrated antennas. Commercial systems can fabricate electronics components such as resistors and capacitors, electrical interconnects, and conductive traces with minimum line widths of 20 μm.[7] However, today the printing of on-demand, complex microelectronics boards is not possible. This type of functionality, which will greatly alter traditional supply chains, will require more mature AM processes that can fabricate smaller features out of both conductors and dielectrics, as well as appropriate tools that can translate electronic designs into the AM processing code required to make the parts.

Bioprinting

The term *bioprinting* broadly refers to the use of AM to fabricate both biomechanical devices and living tissue. Biomechanical devices fabricated via AM include implants (such as cranial caps and hip joints[8]) and surgical tools (including customized cutting guides and surgical fixtures). Life-saving trachea implants have been demonstrated on infants born with constrained airways.[9] Several advantages of the AM process make AM parts particularly suitable for biomechanical devices, including the ability to mass customize a general design for each patient's size and geometry, the intentional fabrication of surface porosity for osseointegration, and the use of bioabsorbable materials such as polylactic acid (PLA). PLA is particularly appealing for trachea implants, since the implant will dissolve after it is no longer needed, eliminating the need for a follow-up surgery to remove it. The main limitation of AM implants is the previously mentioned required regulatory oversight. This burden will be eased with the development and adoption of appropriate industrial standards and FDA guidance.

The full vision of fabricating living, on-demand replacement organs is hampered by significant technical challenges. These include being able to fabricate the fine-featured vascularization required for cell functioning, being able to accumulate a sufficient number of cells to form full-scale organs, and controlling the cells' differentiation so that the desired type of tissue is realized. While some small tissues have been achieved, mainly for drug toxicity testing, full-scale implantable organs such as livers and hearts will not be a reality for many years.

Deployability

Deployed AM systems are potentially beneficial for use in austere environments or by deployed military forces, where on-site manufacturing of single components might increase resiliency or military readiness, especially when logistical supply lines are contested or unavailable. For these kinds of scenarios, the types of AM processes mentioned earlier have different considerations, ranging from relatively simple implementations of 3-D printers to metal powder bed systems that have significant infrastructure requirements, like secondary machining operations and high-purity argon gas.

For AM systems that require an inert gas building environment, the amount of gas necessary to support production can be enormous, and gas must be supplied via normal supply lines. Considerations for shipboard deployment also include the impacts of the maritime environment (such as temperature and humidity) and the ship's motion on the quality of the produced AM parts. In addition, certain safety issues must be mitigated, such as the combustion and inhalation hazards associated with the metal powders used for powder bed fusion systems. Recently, the US Navy installed and demonstrated the effectiveness of modest polymer 3-D printers aboard ships and submarines, but the US services have not yet demonstrated industrial-grade metal systems aboard ships.[10]

In the future, more systems will be deployed as the technology advances to mitigate certain challenges. These advances include the possibility of inert gas reclamation and cleaning, the use of native or recycled materials (such as empty plastic water bottles) as input material, and the use of industrial-grade gyrostabilizers to maintain stable AM machine orientations. In extremely remote locations, small battery-powered systems that are portable in a backpack would also increase applicability.

SUMMARY

The impressive and often inspirational vision for AM has not yet been fully realized because of technical and engineering challenges that must be overcome. Despite these challenges, AM has had impressive successes in a variety of applications, including aerospace and biomedical engineering, and these successes offer a glimpse of what may be possible in the future. As the technology improves, the next 25 years will likely bring additional successes that will result in increased impact and pervasiveness for AM—not only at APL but across many organizations.

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John A. Slotwinski, National Security Analysis Department, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

John A. Slotwinski is a senior national security analyst in APL's National Security Analysis Department. He holds a BS in physics from Loyola College (now Loyola University) Maryland and an MS and a PhD in physics from Catholic University of America. John's experience at APL includes leading and conducting additive manufacturing (AM) development activities; researching and implementing advanced additive materials, technologies, and applications; and leading technical teams for advanced AM-related projects. Before joining APL, he spent nearly 25 years at NIST, where his work included managing a large research effort on material standards for AM and contributing expertise in sensor systems to work on additive processes. John is a Fellow of ASTM International and chair of the executive committee of ASTM F42 on AM technologies, a frequently invited speaker on various AM topics, an instructor for Hopkins Whiting School of Engineering's Engineering for Professionals graduate programs, and a visiting research professor at Hopkins. His email address is john.slotwinski@jhuapl.edu.