

Development and Implementation of Metals Additive Manufacturing

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Additive Manufacturing (AM) technologies build near-net shape components one layer at a time using data from 3D CAD models. AM technologies are the result of evolution of work in 3D printing and stereolithography (the STL files used to convert 3D CAD to layers for building parts come from stereolithography terminology) and could revolutionize many sectors of U.S. manufacturing by reducing component lead time, cost, material waste, energy usage, and carbon footprint. In addition, 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.

The opportunities for the offshore oil and gas industry largely remain to be identified, but are considered to involve combined functionality, functionally gradient materials, and embedded sensors for structural health or other monitoring functions.

Definition of Additive Manufacturing

AM has grown from the early days of rapid prototyping, and as a dynamic field of study has acquired a great deal of related terminology. The ASTM F-42 committee was recently formed to standardize AM terminology and develop industry standards. 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.”

A key point in this definition is that in order to qualify as AM under the ASTM definition, the 3D model data controlled by a computer must be used as a design precursor. Simply adding or building up material is not included in this process definition. The notion of automation and control using software is an essential distinction in assessing what does and does not fall under the technology of AM. There are many related terms used to describe AM and common synonyms include: additive fabrication, additive layer manufacturing, direct digital manufacturing, and freeform fabrication.

Within the last 20 years, additive manufacturing (AM) has evolved from simple 3D printers used for rapid prototyping in non-structural resins to sophisticated rapid manufacturing that can be used to create parts directly without the use of tooling. Most work to date has been conducted using plastics, but significant effort is now focused on metals.

In principle, a designer can engineer a part using 3D model data in a CAD program and simply email the file to a local manufacturer who can then return the part in a few days. This vision of a new paradigm of mass customized manufacturing is driving much of the excitement in this growing field.

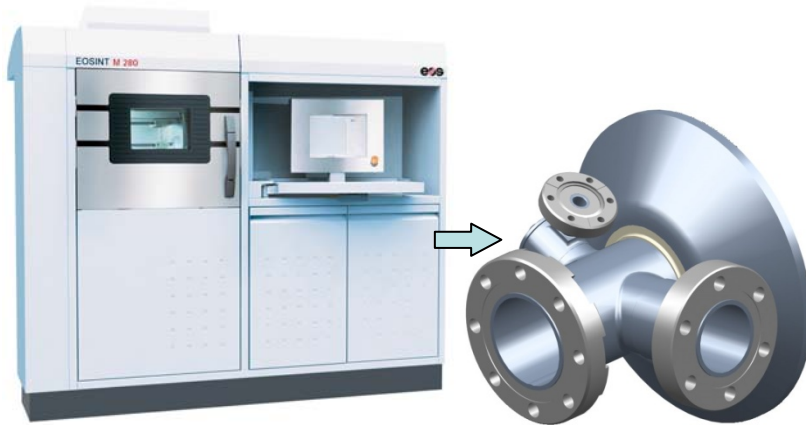


Figure 1. The promise of AM
Current Landscape in Additive Manufacturing

The global market for AM exceeded \$1 billion in 2009 with direct revenues for systems and materials sales of over \$500 million.⁽¹⁾ 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 conduct 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 significant activity and interest in fabrication of metallic parts. This is of interest because of the possibility for direct fabrication of net or near-net shape components without the need for tooling and with minimal or no machining. There has been particular interest in aerospace and biomedical industries owing to the possibility for high performance parts with reduced overall cost. The opportunity for such in the oil and gas industry is only just now being explored.

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. The overall level of activity and infrastructure in the EU is greater to that of the U.S. in this key area. Several large cooperative projects have been funded, worth of millions of dollars across Europe, including the Rapid Production of Large Aerospace Components (Rapolac) and the Custom Fit project⁽⁵⁾ for mass customized consumer and medical project manufacturing. Though much of the original research developing these technologies was done in the U.S., much of the subsequent development has been done elsewhere, particularly in Europe.

In 2009, a workshop was held in the U.S. to form a roadmap for research in AM for the next 10-12 years.⁽⁶⁾ The workshop 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. The overall assessment was 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 the report was the establishment of a National Test Bed Center (NTBC) 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 22 industrial member and partner organizations, representing both large and small 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 advance the manufacturing readiness of AM technologies, and to advocate on a national basis for investment in AM to move these technologies 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 Additive Manufacturing

The two main components of any metal AM process are the type of raw material input and the energy source used to form the part. Three main technology categories of AM are considered: powder bed, laser powder injection, and free form fabrication (FFF) systems that do not use lasers.

The powder bed systems are used in enclosed chambers and energy is supplied by either a laser or an electron beam to melt the powder in a powder bed to form the desired shape, Figure 2. In laser powder injection, a powder nozzle adds material and a laser beam melts the powder. The free form processes are a broader category and the types addressed here include electron beam deposition of metal wire, arc deposition of powder and wire, and ultrasonic consolidation of metal layers.



Concept Laser



EOS DMLS®



Arcam EBM®



**Optomec
LENS®**



MTT SLM®



Sciaky



**MTS Aeromet LAM
(No longer in
business)**



Phenix Systems

Figure 2. Laser powder, EB powder and wire, and blown powder AM systems

Each of the processes has its own unique characteristics for speed of manufacturing, post deposition treatment required, porosity and level of impurities in the as-built part. In each technology category and for each individual manufacturing process, there are tradeoffs between build rate and maximum build size with surface quality and between deposition of excess material and overall deposition accuracy, Figure 3.

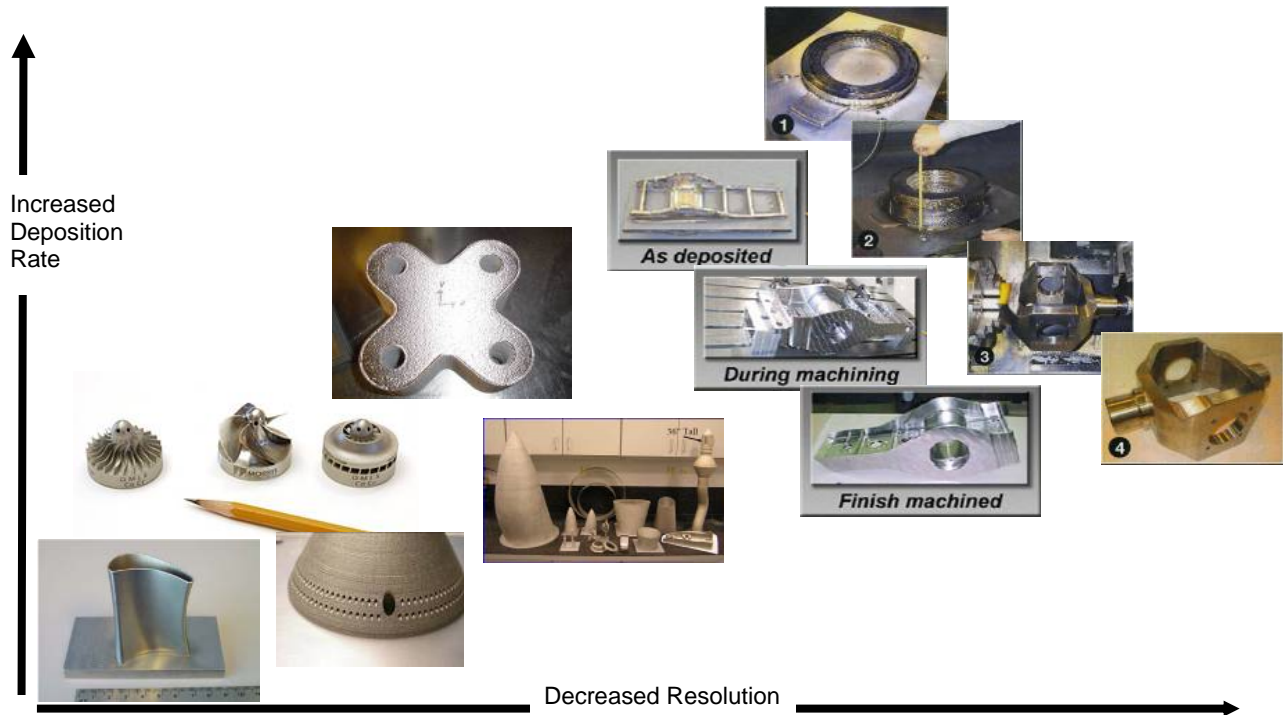


Figure 3. Trade-off of part resolution and deposition rate for small and large parts

For plastics, work on automated near-net-shape additive manufacturing of components dates back to the 1980's. Work on metals is more recent, and by far the bulk of metal AM research has focused on fusion processes, where successive layers of metal are deposited by melting. Several energy sources (e.g., laser, electron beam, arc) and material forms (e.g., metal powders, wires) have been employed. Powder bed processing has dominated this research over the last decade. Powder bed processing includes variants integrating electron-beam or laser power systems. Commercial systems have been introduced which are capable of producing components of limited size. End-users have recognized a number of limitations of this technology, including inconsistent results and poor productivity. More recently, considerable research has been expended on so-called freeform fabrication (FFF) approaches. Such processing has incorporated a range of power input types (electron beam, laser, gas tungsten arc, plasma arc) to allow development and manufacture of a broader range of product sizes at higher deposition rates. Early precursor work using robotic arc welding, Figures 4 and 5, achieved similar results but was not truly an AM process by definition.



Figure 4. Large component made with robotic arc welding

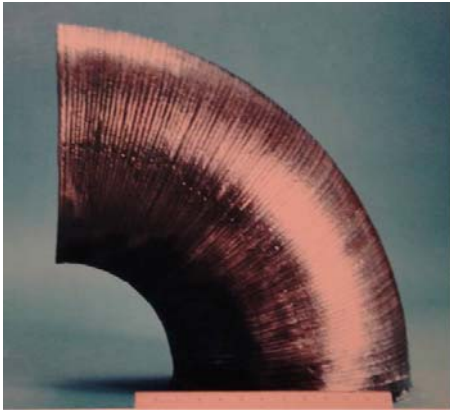


Figure 5. Large pipe elbow made with robotic arc welding

The State of the Art in AM

The tangible efforts in research are also aligned with the practical realities of cost, and it is known that the present embodiment of metals AM for combat aircraft now meet cost requirements compared to conventional manufacturing technologies, even if a simple approach to replace a casting or forging is taken, as long as the deposition rate of the process is high enough. In short, the clear buy to fly ratio advantages of metals AM, reducing from 20:1 or 12:1 to even 2:1 can still be insufficient, if the deposition rate of the manufacturing technology is not high enough, and cost components of finishing technologies is high, affecting the overall cost. One result is that the clear direction is for AM to address a ‘mind to fly’ approach embodying the unique advantages of AM to produce parts that are otherwise unmanufacturable for one or more reasons, along with integrated rather than parasitic functionality, and including functionally gradient metals. The latter offers considerable potential for transition pieces between joints in otherwise dissimilar materials.

Much of the emphasis of additive manufacturing research around the world, including the USA is focused on laser and electron beam processes, especially laser and electron beam powder bed processes such as DMLS and EBM through commercialized equipment such as EOS M280 and Arcam A2, and electron beam with wire addition, known as EBFFF, respectively. These powder bed systems are closed architecture and made in Germany and Sweden, respectively.

A notable exception is an emerging solid-state technology known as ultrasonic additive manufacturing (or ultrasonic consolidation). This technology employs ultrasonic vibrations and pressure to deposit successive layers of metal strips. Work to date has been primarily with soft aluminum alloys. Inconsistent bond-quality and poor through-thickness properties has limited application for higher strength alloys, such as titanium.

In addition to AMC leadership, and capability in many emerging additive manufacturing processes for metals, EWI has developed technology thrusts in ultrasonic additive manufacturing (UAM) based initially on work with Solidica. This technology development has increased available power by fivefold from 2kW to 10kW, and down force tenfold from 500 lbs to 5000 lbs. This capability, developed by EWI and funding through the Ohio Department of Development (ODOD) and an industry consortium including Boeing and GE (both AMC members), has delivered a new very high power UAM (VHP UAM) capability to the EWI shop floor and enabled a new company, Fabrisonic (jointly owned by EWI and Solidica), to be spun off, providing new jobs in Ohio based on U.S. manufacturing of custom VHP UAM machines for industry, and low cost machines for innovative university research. EWI was recently awarded a project under the Ohio Third Frontier Program to develop and build a laser-based system to augment VHP UAM bond integrity with the aim to substantially increase the technology readiness of this emerging solid state AM technology.

EWI alone and in conjunction with AMC partners is working in most applicable research areas for processes, sensors and modeling. Active areas include modeling of residual stresses and distortion, and multi-functional and multi-material structure modeling for hypersonic vehicle structures with embedded functionality rather than parasitic functionality. Residual stress and distortion modeling has been used to predict the effect of continuous and semi-continuous AM for airfoil fabrication

and repair. Simulations accounted for combined thermal and resulting distortion prediction and validation. In terms of sensors and sensor fusion EWI and its AMC partners are active in visual, thermal, laser-based, and other sensor technologies and specialize in novel sensor integration.

EWI conducted over \$500K of research into arc-based titanium AM and titanium armor cladding for a Prime that is part of AMC. This work demonstrated a deposition rate of over 10 lbs/hour in Ti-6Al-4V using hot wire GTAW in air using a trail shield, Figure 6. The development work showed that the Ti-6Al-4V deposits produced met requirements regarding oxygen levels, thus opening up the possibility of production of large titanium parts without the constraints of a small powder bed working enveloped or a vacuum chamber and concomitant consequences including specialty overalloyed wire to compensate for aluminum vaporization in a vacuum chamber.

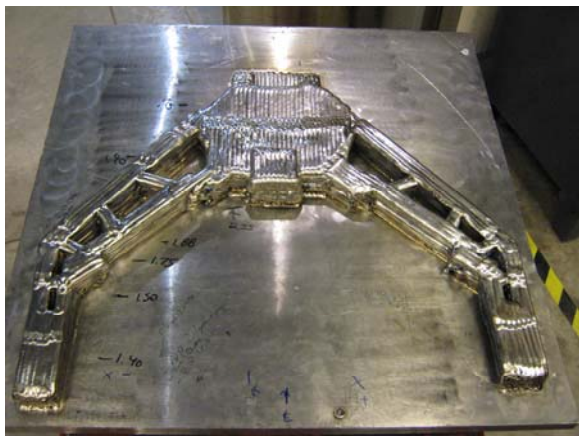


Figure 6. A large ground vehicle control arm made by robotic hot wire GTAW

The Additive Manufacturing Consortium (AMC)

By combining the attributes of EWI with the collective human and equipment capability of the AMC members and partners, a distributed capability presently called the National Test Bed Center (NTBC) is in place for metals additive manufacturing and joining processes that also includes considerable expertise in NDE processes and AM part finishing by machining, grinding, and other surface finishing technologies.

The Additive Manufacturing Consortium (AMC), formed in 2010 and led by EWI, is a consortium of 22 organizations in industry, government and academia that was formed to address needs in metals additive manufacturing on behalf of US manufacturing competitiveness for the advancement of the manufacturing readiness of this disruptive manufacturing technology. AMC meets quarterly to network, exchange information on public domain research conducted, discuss plans and implementation for program definition for lead candidate technology and data development associated with ultimate process qualification. AMC members, including EWI are represented on ASTM F42, the international standards committee for development of AM standards.

AMC members include both multi-national corporations and small businesses, Boeing, Lockheed Martin, General Dynamics, GE, Rolls-Royce, Morris Technologies, Applied Optimization, B6Sigma, and EWI. Government agency partners are U.S. Army (Picatinny, Benet), U.S. Air Force (WPAFB), U.S. Navy (NAVAIR), NIST, and NASA, and key universities active in the AM research field, namely The Ohio State University (OSU), University of Texas, El Paso (UTEP), University of Louisville (UofL), North Carolina State University (NCSU), and South Dakota School of Mines and Technology (SDSMT). Other partners include Lawrence Livermore National Labs (LLNL), TechSolve, NCMS, and SAE RTAM.

In short, the AMC partnership operated by EWI combines industry (both large and small), government, and university expertise and knowledgebase along with relationships with other consortia to provide a very comprehensive national capability to advance additive manufacturing, and other associated technologies in an integrated open manufacturing basis for the nation, jobs, and national competitive advantage in advanced manufacturing. These organizations, most of which are also EWI member companies, together possess a thorough knowledge of the AM landscape, and are actively researching in the field.

AMC Goals Accomplished in Year 1

1. Obtain broad industry and government support –achieved for A&D, reaching out to oil and gas, power, and heavy fabrication community

2. Organize “National Test Bed Center” research partners network – in place with extensive equipment and staff resource capabilities
3. Identify technology priorities and create development plan – priorities identified for Ti and Ni-based alloys. \$60M of proposals developed to government agencies.
4. Conduct state-of-the-art review of metal AM technology - Complete
5. Establish a database for collecting metal AM property information – will use MMPDS

The Future of AM

There is a rich landscape of available technologies and materials for metals AM. Parts in titanium alloys, nickel alloys, high-grade stainless steels, and many others are being produced using lasers, electron beam, and arc techniques with a variety of consumable forms. This is a dynamic, constantly evolving field with many researchers and industrial users continually improving the state-of-the-art while moving to develop and qualify combinations of material and process for commercial exploitation. Currently, the number of commercially made parts is low because of the high performance demands and associated costs for industry to qualify parts. Parts qualification costs relate to the demands of the applications and market environments.

Using AM to fabricate metal parts opens the possibility for reducing material usage that could enable overall reduction in cost and greenhouse gas emissions related to manufacturing. Promising case studies have been undertaken and there are a number of ongoing studies investigating how AM can enable “green manufacturing”.

The opportunities for the offshore oil and gas industry largely remain to be identified, but are considered to involve combined functionality and functionally gradient materials. 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. Applications where legacy parts are still necessary for operation and fabricators are no longer in business, could use AM to create parts direct from a CAD file. 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.

The 'digital thread' (fully computerized design to production using computer-based technical data packages), and 'moving manufacturing to the left' (integrated computer modeling of materials, process, distortion, metallurgical and mechanical properties) are visions implicit in the future of open architecture advanced manufacturing for AM.

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 need to be developed as many of the microstructures formed present inspection challenges.

Metals AM is still a relatively new and immature technology and there is a need for understanding the basic science of each particular AM process as most of the processing parameters to this point have been empirically derived. In particular, there is a need to understand the material microstructure resulting from a particular thermal processing cycle. There have been many studies on individual processes and resulting properties, but there is still a need for a comprehensive

material property database and testing methodology to be developed. Many studies have been carried out for tensile strength and elongation as a function of material compositions. Further 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.

Mechanical properties of parts can vary greatly depending on the process used, parameters of the individual process, loading direction, and post-fabrication heat and surface treatments. Furthermore, different part geometries require special design considerations such as supports and heat sinks that ensure built parts maintain geometric accuracy. And depending on the technology used, the deposition path can affect the final properties.

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 lower cost manufacturing and novel integrated parts designs that cannot be made using current technology. This is generating a great deal of enthusiasm around the world for future high-value manufacturing applications. Currently, there are niche applications; particularly in the medical field and to a lesser extent aerospace where parts made using plastics AM and some metals are being put into initial evaluation of service. To meet the full potential of these processes, continued development to 'productionize' the machines for full manufacturing readiness and further understanding of the materials properties is essential. With the pace of advancement, this key emerging field is poised to grow rapidly over the coming years.

Summary

In summary, AM represents a whole new paradigm and range of opportunities for design, functionality, and cost. The AM field represents an exciting and rapidly emerging industry.

1. AM for metals is rapidly developing through a range of powder bed and wire-fed technologies
2. Additive Manufacturing Consortium (AMC) is poised for growth into many manufacturing sectors
3. AMC offers collaboration for development of metals AM manufacturing readiness using Laser, EB, arc and other processes – consortium has 22 members and partners, and welcomes more
4. Looking for potential applications within the oil and gas market that fit one or more of the following scenarios and opportunities;
 - Nominally ‘unmanufacturable’ components
 - High added value, long lead time items
 - Adding features to low yield castings and forgings
 - Repair applications

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