Additive Manufacturing:
A Transformational Advanced Manufacturing Technology

Additive manufacturing (AM) is receiving increasing attention around the world. It is also called three-dimensional (3-D) printing, while the military prefers direct digital manufacturing (DDM). The process can be used for metals, polymers, and ceramics, and on emerging applications ranging from medical, aircraft parts, and parts for space vehicles to home furnishings and clothes. An allied small-scale AM area known as Direct Write is used to develop electronic circuitry.

AM grew from the early days of rapid prototyping, and as a dynamic field of study, acquired a great deal of related terminology. Recently, the ASTM F-42 Committee formed to standardize AM terminology and develop industry standards. The committee’s first standard, ASTM F2792-10, defines AM as “The process of joining materials to make objects from 3-D model data, usually layer upon layer, as opposed to subtractive manufacturing technologies.”

Currently, the AM industry is emerging on an international scale. It is recognized as a key advanced manufacturing technology for high value-added products—important for a future first-world economy and high-paying jobs.

The idea of building a part from scratch on a single machine is a radical departure from the norm of traditional manufacturing. AM is already a suite of processes. For example, there are not many processes that can be used to eliminate tooling and also be used to build tooling, the latter of interest to automotive and other markets. AM is applied to a wide variety of materials including metals, polymers, chocolate, and even experimental human body tissue.

Applications under development range from the micro-scale to large structural parts. The investment required to realize a tangible product is proportional to the application, ranging from highly original decorative sculpture at one end, to structural and rotating aerospace parts at the other. In the medical industry, AM is leading to a revolution in customized medical applications where dental implants, orthopedics, and hearing aids are manufactured to fit an individual’s unique physiology.

For nonrotating aerospace parts, the development and qualification costs for each new combination of material and process can easily exceed $10M. Precompetitive collaboration is attractive in this market. Potential benefits of AM include new product design features (make items you cannot make any other way), making parts at lower cost due to fewer operations and simplified supply chain (consider total life cycle costs and an holistic approach), reducing time to innovate and launch new products, supporting lean/agile manufacturing, producing replacement parts for legacy systems, reducing material waste and energy use, and supporting environmental sustainability.

The industry is on the threshold of a transition from a rapid-prototyping heritage to one requiring robust manufacturing production for eventual widespread commercial exploitation. This transition requires large-scale changes and investment to overcome barriers, from the development of standards, qualification of materials for design data, and establishment of supply chains; to robust, repeatable manufacture of products and consistent part tolerances produced from one machine to another.

AM can be used for new parts, repair, and production of legacy systems.
parts, particularly those where old tooling is no longer available. Possibilities and applications are available in most industries and market segments based on the particular paradigm at hand. The “mind-to-part” nature potentially allows for functionally gradient parts, parts with embedded features, physical channels (for example created in a part during build), sensors, and other features.

Figure 1 shows that available processes cover a wide range of deposition rates (from a few oz/hr to 40 lb/hr) and feature size resolution, balancing productivity and net-shape capability with machining cost and other finishing requirements including:

- Electron beam welding freeform fabrication, or EBFFF, with wire from Sciaky Inc., Chicago (lb/hr)
- Laser powder FFF from companies such as POM and Optomec using laser engineered net shaping (LENS)
- Laser and EB powder bed, from companies such as EOS and others, and Arcam in confined envelope (oz/hr)
- Emerging arc processes including cold wire gas tungsten arc welding (SMD), plasma arc welding (PAW), hot wire gas tungsten arc welding (GTAW–HW), pulsed gas metal arc welding (GMAW–P), and plasma transferred arc (PTA) based on commercially available equipment for directed energy deposition, or DED (lb/hr)
- Emerging: very high-power ultrasonic AM (VHP UAM) of strip (lb/hr) from Fabrisonic LLC

Within the past 20 years, additive manufacturing evolved from stereolithography used for rapid prototyping in nonstructural resins to sophisticated rapid manufacturing, which can be used to create parts directly without the use of tooling. Most work to date was conducted using plastics, but significant effort is now focused on metals.

The global market for AM exceeded $1 billion in 2009, and is expected to exceed $2.5B in 2011, with direct revenues for systems and materials sales of over $500 million. Nearly 90% of AM machines sold are 3-D printers for making polymer-based parts and models.

AM technology and industry is growing. In early 2010, the company Materialise (Leuven, Belgium) formed a group of companies to conduct collective marketing for AM. A recent issue of The Economist magazine (UK) addressed the potential of AM as a revolutionary manufacturing technology. Researchers and industry leaders in the European Union (EU) identified AM as a key emerging technology.

Teams have been formed among university, industry, and government entities within and across countries. The overall level of activity and infrastructure in this technology is greater in the EU than in the U.S. Several large cooperative projects worth of millions of dollars were funded in Europe, including the Rapid Production of Large Aerospace Components (Rapolac). Though much of the original research in developing these technologies was carried out in the U.S., much of the subsequent development was done elsewhere, particularly in Europe.

Figures 3 and 4 illustrate application areas for aerospace, which show the potential for weight reduction and the array of candidate parts being considered in an aero engine. Cost savings are important; a flaperon spar for the Joint Strike Fighter is being qualified using EBFFF with an anticipated overall cost savings of 40 to 50% compared to a forging.

Implementation in the aerospace industry could lead to a reduction of required raw materials; that is, an improved “buy-to-fly” ratio. AM could also lead to innovations for lightweight structures that could see application in unmanned aerial vehicles. Legacy parts required to sustain aging aircraft are becoming increasingly difficult to source as many fabricators are no longer in business. Here, AM can be used to create parts directly from a CAD file created by reverse engineering using CMM.

In 2009, a workshop was held in the U.S. to form a roadmap for research in AM for the next 10 to 12 years. 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.

Additive Manufacturing Consortium

Based on results from the roadmap developed in 2009, EWI organized an Additive Manufacturing Consortium (AMC), bringing together technology leaders to address the large number of needs for technology maturation (MRLs and TRLs) for metals AM. The AMC now consists of 30 industrial members and partner organizations, representing both large and small industry members, government agencies, other partner organizations, and key universities active in the field of AM research. The main goals of the AMC is to advance the manufacturing readiness of AM technologies and to advocate for investment.
in AM on a national basis to move these technologies into the mainstream of manufacturing technology from their current emerging position. AMC produced a report on the state of the art for metals AM\cite{6}.

By combining the attributes of EWI with the collective human and equipment capabilities of AMC members and partners, a distributed capability called the National Test Bed Center (NTBC) is in place for metals additive manufacturing processes, which also includes considerable expertise in metallurgy, modeling, NDE processes, and AM part finishing.

AMC meets quarterly to network, exchange information on public domain research conducted, and discuss plans and implementation for program-defined 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 multinational corporations and small businesses including Boeing, Lockheed Martin, General Dynamics, GE, Rolls-Royce, Goodrich, Honeywell, Morris Technologies, Sciaky, EOS, 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. Universities active in the AM research field include Ohio State University, which is mentioned in the context of AM engine control and accessory component candidates in GE Aviation’s turbine engine.
University, University of Dayton Research Institute, University of Texas – El Paso, University of Louisville, North Carolina State University, and South Dakota School of Mines and Technology. Other partners include Lawrence Livermore National Labs, TechSolve, National Center for Manufacturing Sciences, and Wohlers Associates.

The AMC partnership operated by EWI combines industry, government, and university expertise in relationships with other consortia to provide a comprehensive national capability to advance additive manufacturing to create jobs and build a national competitive advantage. These organizations, most of which are also EWI member companies, possess a thorough knowledge of the AM landscape, and are actively conducting research in the field.

AMC provides an innovation ecosystem for both mature and transition technology to industry. It provides what is sometimes referred to as the “missing middle” of technology transition (Fig. 5). Within the consortium, there are over 50 machines for metals AM, and more for plastics AM. All the industry primes are interested in metals and polymeric materials, as well as hybrid AM, providing a National Test Bed Center. The university partners provide a strong capability for education in AM in addition to R&D capabilities. There are currently more needs than funding, so working together to advance these precompetitive topics is very important.

Modeling, sensors, and controls

As a relatively new, emerging technology, there is a need to understand the basic science of each particular AM process, as most of the processing parameters to this point have been empirically derived. Specifically, it is necessary to understand the material microstructure resulting from a particular thermal processing cycle, and develop highly validated modeling, which can be used to define operational windows to develop required microstructure and thus, material properties. Therefore, physics-based modeling for additive manufacturing processes is a strategic area of development. DARPA and others are funding work in this area for Advanced Vehicle Make (AVM) as part of the Open Manufacturing program. 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.

Closed-loop feedback control sensing systems and intelligent feed-forward schemes must 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. As part of the continuum of “productionizing” AM parts build, many companies are interested in in-process monitoring and control, particularly the development and implementation of real-time feedback control on AM builds. Currently, this exists in small islands of capability for weld pool vision or parameter monitoring/reporting. In the future, this will exist (at least as options) in most machines intended for production use. Real-time feedback control is also required for an R&D environment, and is being developed in several universities and institutes around the world.

Summary and future vision

AM represents a new paradigm and offers a range of opportunities for design, functionality, and cost. Opportunities for many industries largely remain to be identified. AM is a dynamic, 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. Factors increasing the potential suitability for commercial and government applications include:

• Nominally unmanufacturable components
• High added value, long lead-time items
• Repair and replacement of legacy aircraft components

However, much work is required across many fields to realize the promise of AM and overcome the barriers of cost for materials property data, qualification, and certification costs, particularly for aerospace parts. Some items on the horizon that will overcome current barriers and en-
able this promising technology to be deployed in production include:

- Development of design databases in MMPDS to allow aerospace designers to select the AM process with confidence
- Use of modeling and simulation at the design stage to optimize for performance at an early stage and compress the development timeline in the manufacturing process
- Established industry standards that facilitate the business processes for parts production
- Education and training for designers, engineers, and technician staff
- Lower cost machines (ubiquitous like CNC machine tools), although some posit that the cost of AM machines is not necessarily an impediment to those who purchase multi-million dollar CNC equipment
- Open architecture machines with embedded sensors and controls for parts certification and reduced cost of nondestructive inspection
- Development of the supply chain leading to the commoditization of AM, which will drive the need for lower cost processes
- AM in space and mission to Mars based on the work of NASA and others
- Morphing UAVs and MAVs with hybrid metallic/composite structure and embedded Direct Write electronic circuitry
- Mobile parts hospitals for field use by the Army, Navy, and Air Force
- Combined functionality and functionally gradient materials

References

For more information:
Dr. Ian D. Harris, director AMC Technology Leader
Arc Welding, EWI
1250 Arthur E. Adams Dr.
Columbus, OH 43221-3585
tel: 614/688-5131
614/440-1277 (mobile)
email: iharris@ewi.org
www.ewi.org.