Large-Scale Additive Manufacturing

Introduction

In its most general form, manufacturing is a series of steps that transforms raw material into a final product. Additive manufacturing (AM), also known as 3D printing, is a technology that produces 3D parts from a metal or composite, layer-by-layer. The process begins by splitting a computer-aided design (CAD) model into horizontal layers of a fixed thickness. The file is then sent to a 3D printer to be understood and created using a controlled flow of material through a small nozzle, such that the product is fabricated from the bottom layer upwards. With the emergence of AM, the methods through which products are created has the potential to revolutionize means of manufacturing for labor-intensive, complex, and costly components.

Currently, 3D printed parts are limited in size by the volume of the printer, typically enveloping less than a cubic foot. However, researchers at Oak Ridge National Laboratory (ORNL), along with many industry partners, are highlighting the innovative technology capabilities of additive manufacturing by utilizing a build volume of nearly 1000 cubic feet. Defined as the ability to print parts at least 1 meter along any given axis, large-scale additive manufacturing can be used in industries that were originally thought out of reach such as aerospace, automotive, and renewable energy technologies. Ideal applications include high-value, complex, low volume parts such as large tooling components, lightweight components for the transportation industry, and low-cost parts for the energy industry [1].
In this paper, the material choice and analysis process will be given, leading into a discussion of applications where AM technologies are optimal. Substantial large-scale additive manufactured projects will be explored, highlighting key benefits and challenges that were encountered. Because the most recent technologically advanced projects have taken place within ORNL, the scope of this paper will primarily focus on projects collaborating with and spearheaded by this lab.

Materials, Printing Methods, and Challenges

Although there are many materials used in additive manufacturing, the most common used in large-scale production are plastics, metals, and composites. With each different set of material comes varying coefficients of thermal expansion, melting point, strength, and other properties which pose unique challenges through part warping and residual stresses, printability/application, and overall value [1], [2]. Therefore, various methods of printing are outlined to describe achievable mechanical and functional material properties.

Arguably, the most successful method utilized in large-scale additive manufacturing is fused deposition modeling (FDM), where a printing head attached to a 3-axis gantry extrudes a continuous bead of material along a guided path to complete each layer of the printed part. When using FDM for large-scale additive applications, the choice in materials is restricted to plastics and composites, including concretes or matrix-reinforced plastics [1], [2].

The first commercial success of large-scale plastic FDM was shown through the Big Area Additive Manufacturing (BAAM) printer, developed by Cincinnati Inc. and ORNL. The printer has a printing rate of up to 100 lbs/hr by simply melting and extruding pellets of material. As opposed to a heavily processed, pre-extruded filament that must be flexible enough to wind
around a spool, composite pellets are low-cost and may contain a significantly large amount of reinforcement, which is directly translated to a higher final part strength. The print head of the BAAM therefore vacuums the pellets from a container, heats, compounds, and extrudes the composite out of a high-flow 0.3” diameter nozzle. The first layer is deposited and chemically bonded to a heated bed to reduce internal stresses from temperature gradients. As each bead is laid, an actuating stamp softly tamps the freshly laid material to ensure that each layer is a uniform height and each subsequent layer will have a smooth surface for bonding. Depending on desired outer surface finish of the final part, a milling step can be added to smooth out visible layering [3].

The material of choice for most BAAM applications is currently a carbon fiber-reinforced acrylonitrile butadiene styrene (CF-ABS) plastic, and this material was chosen after initial testing with standard ABS showed extensive warping [2], [4]. As previously eluded to, CF not only decreased visible warping but also served as a material reinforcement that increased final part strength and stiffness. The in-plane strength of ABS increases by roughly 200% and in-plane modulus by 400% with a CF matrix; however, the strength in the z-direction is still nearly halved due to imperfect bonding between layers, which proves problematic for forces applied in this direction [2].

If a metal is desired instead, the process becomes increasingly more complicated. Metal deposition techniques can be classified into either a powder bed system or direct energy deposition (DED). Large-scale powder systems are extremely complex, involving not only a massive amount of required powder but also an actuating bed, powder delivery, and melting/sintering systems. DED instead delivers material directly onto the hot spot of a laser or
arc weld pool. A successful method has been to attach a metal-inert gas (MIG) welding torch to a robotic printing head, continuously extruding and welding standard weld wire to form consecutive layers [1]. Material costs are very low as standard weld wires can be used in combination with different welding styles (Gas Tungsten Arc Welding or TIG) to make steel, iron, aluminum, nickel, and even titanium feasible for production.

Looking at DED and FDM together, there are challenges that can be grouped based on the similar nature of these methods of 3D printing methods. The first is referred to as overhang, where one layer of material protrudes further than the previous. To address this problem, Cincinnati Inc. recommends a minimum angle of 60 degrees from the horizontal on the BAAM system which has 0.10-0.16” layer height [5]. At smaller scales, the issue of overhangs is solved by incorporating a support structure. At large scales, support structures have not been demonstrated with much success as there is no non-destructive method for the removal of these structures.

The second challenge involves thin walls, as the printing nozzle size restricts the minimum thickness of a part. Imagine printing a line: if its thickness is set at 0.2” and the manufacturing system has a 0.3” nozzle, the software may ignore any features below 0.3” since it cannot print a bead that thin. The same situation limits higher wall thicknesses: a wall thickness of 1” cannot be built with a 0.3” nozzle. Instead, either a 0.9” wall can be produced using three beads of 0.3”, or a 1” thickness can be created using two outer beads and a minimal amount of an infill structure [5]. These problems are inherent in all 3D printing yet are greatly exacerbated at such large scales.
The third and most prominent problem in all types of large-scale additive manufacturing are residual stresses and distortions. In welding (and therefore DED), literature indicates that it is physically impossible to eliminate residual stresses due to the nature of thermal gradients and any associated plastic gradients [1]. The same logic applies to the use of composites: although thermal management, reinforced materials, and high surface area contact between layers can mitigate stresses, there will always be some level of residual internal stress. However, these stresses can be managed with careful planning to ensure that compressive stresses are minimal to avoid part fracture or failure.

Evolution of Five Sequential Additive Manufacturing Projects

BAAM

In 2014, Cincinnati Inc. and ORNL signed a collaborative research and design agreement focused on furthering large-scale polymer additive manufacturing technologies and ultimately building parts weighing hundreds of pounds. All CAD model processing software had to be rewritten to slice models and create feasible tool paths for the printer system, since this project was the first of its kind. Technological developments involved extruder screw redesign and revamp, which allowed printers to produce up to 40 lbs/hr. Today, printers boast manufacturing capabilities of roughly 100 lbs/hr as a result of improvements stemming from these early BAAM developments [6].

An underlying goal of the first project was also to help Cincinnati Inc. build and commercialize BAAM technology, which was an overwhelming success. Commercial 3D printers at the time were limited to a 1 cubic foot in build size with material costs up to over $100/lb,
whereas BAAM technology showed >100 cubic feet of build space with approximately $5/lb in material costs [6].

**Strati**

Less than a year later, the BAAM technology was highlighted at the International Manufacturing Trade Show (IMTS) in collaboration with Local Motors to print a car known as the Strati. The Strati, shown in Fig. 1a, demonstrated how disruptive large-scale manufacturing could be: from its entirely additive manufactured frame and body, to the fact that the entire vehicle was printed and assembled within the week-long timeline of the trade show. The ability to produce a fully functional car quickly, without the need for many individual parts, and with a low material cost introduced a new business model. Instead of a manufacturer producing and sending cars to be standing capital investment in the parking lot of a car dealership (which is seen most commonly in the market today), Local Motors proposed combining the manufacturer and dealer. With components for the motor, drivetrain, and other non-3D printed components in inventory, a micro-factory could quickly print and assemble cars upon receiving a purchase order, then sell on site [7]. Previously, additive manufacturing was considered a technology strictly destined for prototyping, but the Strati proved to be a flagship example of the diverse advantages of large-scale additive manufacturing to advancing the automotive industry.

**Shelby Cobra**

Shortly afterward, an all-electric Shelby Cobra replica was printed to bridge the gap between the vehicle powertrain development process and vehicle systems integration. By developing hardware and directly incorporating it into working CAD models of a car frame and
body, the ORNL team could test the powertrain in parallel with chassis evaluation. Using means of traditional manufacturing, the two steps would instead be conducted sequentially, slowly building one set of components around the other [3].

![Figure 1. (a) Local Motors Strati with 3D printed chassis and body without post-processing [8]. (b) ORNL Shelby Cobra with 690 lbs of printed chassis and body, including machined and painted body [9].](image)

It took 24 hours to print the entire body, frame and internal supports for the Cobra using CF-ABS as shown in Fig. 1b. A main takeaway of this project was the ability to produce a working vehicle in a safe, fast, and low-cost manner that was easily evaluated by EPA regulations and standards. While the project was considered to be successful, it was discovered that CF-ABS alone is not an ideal direct engineering material for vehicle frames due to its relatively low stiffness compared to steel. For more overall strength and point load support, an additional torsion bar system was incorporated into the frame and therefore did not maintain the same geometries as a chassis of steel [3].

**Integrated Energy Systems**

To maximize the use of renewable energy sources in building and automobiles, ORNL undertook the Additive Manufacturing Integrated Energy (AMIE) demonstration project. The project focused on reducing air pollutants and greenhouse gas emission through the
development of an integrated natural-gas-powered vehicle and renewable-energy building systems, as shown in Fig. 2.

![Image of ORNL AMIE demonstration project consisting of large-scale additive manufactured home, vehicle, and wireless charging system](image)

**Figure 2. ORNL AMIE demonstration project consisting of large-scale additive manufactured home, vehicle, and wireless charging system [9].**

At this time, the BAAM system applied its current capabilities of printing CF-ABS at 80 lbs/hr to produce both the building and vehicle. The vehicle, although larger than the Strati and Shelby Cobra, applied lessons learned from these previous projects to print a body and chassis that could be incorporated into a hybrid electric vehicle.

The house, which was constructed from roughly 80% 3D printed parts, included many novel technologies such as vacuum-sealed insulation panels which were created on the BAAM. Because of 3D printing limitations, anisotropic material properties were apparent as strength out of the print plane is weaker. To address this problem, tensioning rods run longitudinally across the length of the home, holding the layered prints in compression and ensuring each panel is adequately contacting the adjacent panel. Through the implementation of solar panels and a secondary energy storage system of batteries, the home had functional lighting, an HVAC system, and a microkitchen. By integrating a wireless charging station, the building demonstrates a hands-free method of energy sharing with the hybrid vehicle [9].
The entire AMIE project lasted 9 months from conception to conclusion, putting into perspective how large-scale additive manufacturing can expedite the building of energy-efficient homes that can be easily integrated with the grid or with vehicles.

**Additive Excavator**

Up to this point, most projects have highlighted the use of composites on the BAAM printer. However, industry feedback indicated a few key applications of metallic large-scale additive techniques that could be used for demonstrations in construction equipment, tooling, or additional energy systems. Construction equipment was ultimately the challenge undertaken by ORNL, as Project AME (Additive Manufactured Excavator) came to life at the CONEXPO-CONAGG convention in March 2017 as shown in Fig 3 [10], [11].

![Figure 3. Project AME, highlighting the printed excavator cab with complex, flowing features and printed stick made of low-cost steel weld wire [11].](image)

Although it is currently still under evaluation, the excavator is known to have two large printed components: the cab and the boom. The cab, printed out of CF-ABS on the BAAM printer, was designed to fulfill all safety requirements of a cab manufactured by traditional means and created in a total of 5 hours. The stick, a 400 lb part made with low-cost steel weld wire, was printed using MIG welding/DED and was the first successful application of metal 3D printing by ORNL. It was printed in only 5 days using a system built by Wolf Robotics [11].

These excavator components were designed to be direct drop-in replacements, proving that
part consolidation, cost, and time savings of additive manufacturing are hugely beneficial in low volume parts.

Summary and Conclusions

In this paper, a brief overview has been given to a limited selection of large-scale applications and projects to demonstrate the impacts that additive manufacturing technology can have. Large-scale additive manufacturing is redefining the manufacturing process by effectively consolidating parts, greatly reducing time to produce components, and significantly reducing costs associated with such large parts. Applying AM to low volume, highly complex parts can slash production times by months or even years. Instead of focusing efforts on how to reduce the number of parts, vendors, and individual part costs, resources can be funneled into part consolidation, troubleshooting, and raw material costs.

Through continued research and industry partnerships, increasingly more projects, ranging from printed wind turbine blade molds to printed concrete building, are being constructed in the realm of large-scale parts. While large-scale additive manufacturing has its limitations, it has the potential to be applied to key industries and revolutionize the manufacturing process.

References


