BREAKING BARRIERS IN POLYMER ADDITIVE MANUFACTURING

Lonnie J. Love, Chad E. Duty, Brian K. Post, Randall F. Lind, Peter D. Lloyd, Vlastimil Kunc and Craig A. Blue
Oak Ridge National Laboratory
Manufacturing Demonstration Facility
2370 Cherahala Blvd, Knoxville TN 37932

ABSTRACT

Additive Manufacturing (AM) enables the creation of complex structures directly from a computer-aided design (CAD). There are limitations that prevent the technology from realizing its full potential. AM has been criticized for being slow and expensive with limited build size. Oak Ridge National Laboratory (ORNL) has developed a large scale AM system that improves upon each of these areas by more than an order of magnitude. The Big Area Additive Manufacturing (BAAM) system directly converts low cost pellets into a large, three-dimensional part at a rate exceeding 25 kg/h. By breaking these traditional barriers, it is possible for polymer AM to penetrate new manufacturing markets.

1. INTRODUCTION

The largest market share for AM belongs to the polymer extrusion technology, commonly referred to as Fused Deposition Modeling (FDM) [1]. The FDM technology is based on extruding a thermoplastic filament through a heated orifice, depositing material in a layer-by-layer pattern building up to a final part. For the past twenty years, the primary application of this technology has been the prototyping industry. Models could be manufactured quickly for testing the form and fit of specific applications. Traditional FDM materials have not been suitable for end use parts because of insufficient mechanical properties, specifically poor strength and elongation. Low-temperature thermoplastics, such as polylactic acid (PLA), acetyl-butyl styrene

(ABS), and polycarbonate (PC), have conventionally been used. Recent materials efforts have focused on the development of new classes of engineering polymers for AM such as polyetherimide (Ultem^{TM}), polyphenylsulfone (PPSF), nylon, polyether ether ketone (PEEK), and polyether ketone ketone (PEKK) [2]. These materials offer improved specific bulk properties, but are often limited by defects inherent to FDM technique, namely, a layered structure with heavy porosity between adjacent beads.

Aside from mechanical performance, the traditional FDM extrusion process imposes some fundamental limitations on speed, cost, and scale. An FDM structure results from the deposition of thermoplastic materials through a small heated nozzle with an orifice on the order of 0.5 mm in diameter. Although this generally results in precise control of material flow-rate and reasonable surface finish, the orifice is a bottleneck that inhibits high flow rates and limits the deposition rate for FDM systems to about 20 cm^3/h. Since the flow rate of the material through the orifice is directly related to the filament diameter and the linear feed rate of the filament into the deposition head, the filament geometry must be carefully controlled to maintain a high part quality. For this reason, large commercial entities that rely on FDM for precision components place tight controls on the feedstock material, which can inflate the cost of seemingly low-cost thermoplastic materials well above $100/kg. The manufacture of precise parts also drives the need for a controlled thermal environment. Since many thermoplastics have a high coefficient of thermal expansion (CTE), it is important to carefully control the temperature of the deposited part. Therefore, the highest precision FDM systems on the market offer a heated build chamber which maintains the temperature within the entire build volume just below the glass transition temperature of the deposited material. Although building parts in an oven can help minimize thermal distortions, it is very difficult to accurately control temperatures

over increasingly larger areas, thus limiting the build volume for FDM systems. Currently, the largest commercial FDM system offers a build volume of approximately 0.5 m^3. At a build rate of 20 cm^3/h, it would take almost 3 years to completely fill this volume with printed material.

1.1 Going Bigger

The Big Area Additive Manufacturing (BAAM) system being developed by Oak Ridge National Laboratory (ORNL) and Lockheed Martin dramatically increases the available build volume for 3D printed parts [3]. The current BAAM system has a build volume of 2.4 m x 2.4 m x 2.4 m. The deposition head is a single screw polymer extrusion nozzle that is mounted on a large gantry (Figure 1). The deposition head can move in the x-y plane at a rate of 12.7 cm/s and increment vertically in the z-direction.

Fig. 1: ORNL BAAM system

The build volume for the BAAM system is not constrained by an oven enabling this technology to be unbounded in size. As mentioned previously [3], this configuration allows the gantry platform to be extended in any direction without changing the fundamental technology. Alternatively, several of these systems could be linked together to make a massively parallel deposition system that spans hundreds of feet. Although it's possible to build an extremely large oven that could enclose the BAAM system, this would limit the flexibility of the system to scale for certain applications. As oven size increases, it's difficult to maintain accurate temperatures across the build volume, especially as the internal geometry of the oven changes as the part is being built. Even commercial units experience temperature differences across the platen (up to

5°C) and chamber (up to 23°C). Figure 2 demonstrates how such temperature differences can lead to significant distortion in relatively simple shapes. The 5 cm diameter cylinders shown on the left was manufactured in one area of the oven and has less than 3% distortion whereas if manufactured in a different region of the oven resulted in greater than 12% distortion.

Fig. 2: Part distortion due to temperature variations

2. EXPERIMENTATION

2.1 Enabling Materials

In order to minimize distortion of printed parts, ORNL has developed carbon fiber reinforced materials for FDM. Initially, the focus was on fiber integration and extrusion of the composite material for various loadings of carbon fiber for use with desktop FDM units. The addition of 10 to 40% carbon fiber (5 to 7 microns in diameter, 1 to 3 mm long) to ABS was able to more than double the strength of ABS and increase the stiffness by a factor of 4-7 (see Fig. 3) [4]. For sufficient strength and stiffness, the aspect ratio of the fibers (length to diameter) should be greater than 100:1. The processing conditions of the carbon fiber composite directly impact the final size of the fibers in the matrix materials. Aggressive compounding with high shear rates breaks the fibers down, reducing the fiber length by up to an order of magnitude reducing the

strength of the composite material. ORNL has developed a process where fibers are compounded into the host polymer through an extrusion process that reduces the shearing action and retains much of the original fiber length [5].

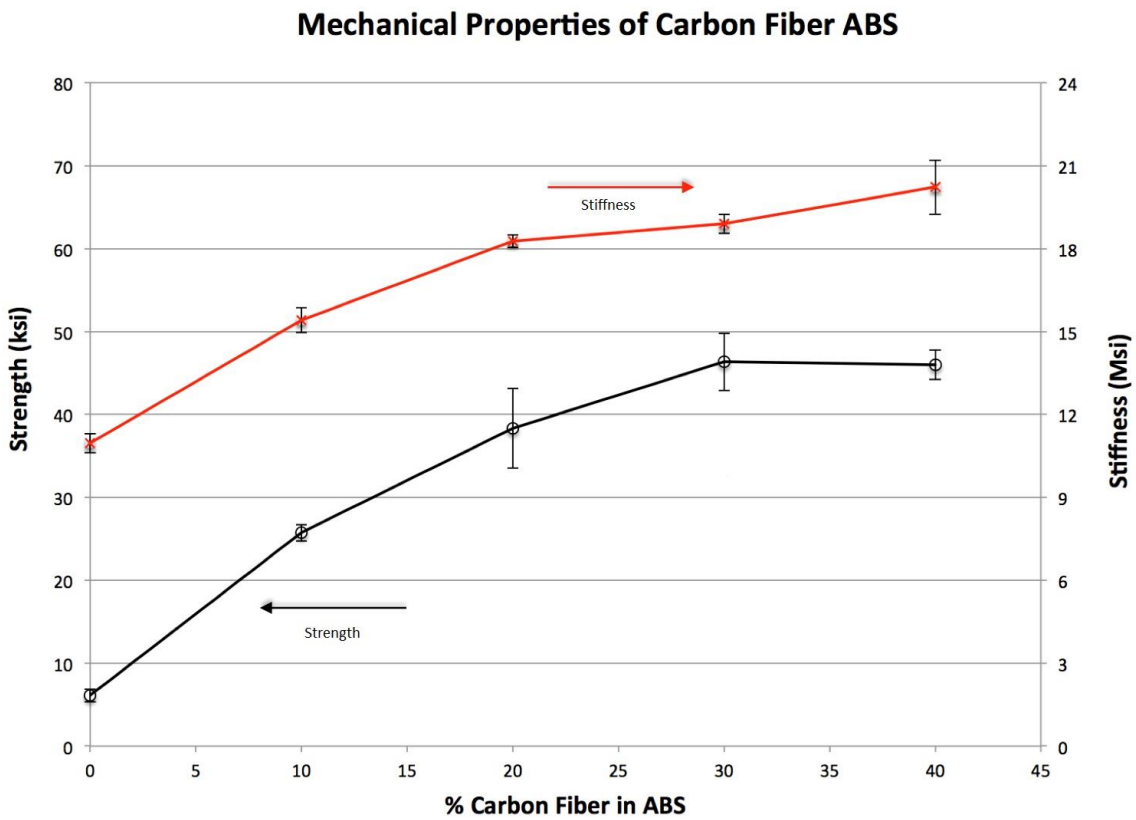

Fig. 3: Strength and stiffness as a function of fiber loading

Carbon fiber filled thermoplastics have also been printed with the BAAM system in order to increase stiffness and strength. As shown in Fig. 4 below, the tensile strength of 13% carbon fiber filled ABS is >50% stronger when the printed material is aligned in the direction of the applied force. Note that the strength of the neat ABS material is ~14% lower than the specified strength when the printed beads are aligned to the force (0-0), and drops another ~15% when the deposited beads are normal to the applied load (90-90). By contrast, the strength of the aligned carbon fiber filled is ~30% lower than the specification sheet reference for this material, and

drops another ~50% when oriented normal to the deposited beads. This result is not surprising, given that the extrusion process will shear align the carbon fibers along the primary axis of the deposited bead. When the beads are oriented normal to the applied force, the load is carried through the matrix material. The carbon fiber filled material is much more rigid during the deposition process which reduces contact area between adjacent beads and significantly reduces the apparent strength.

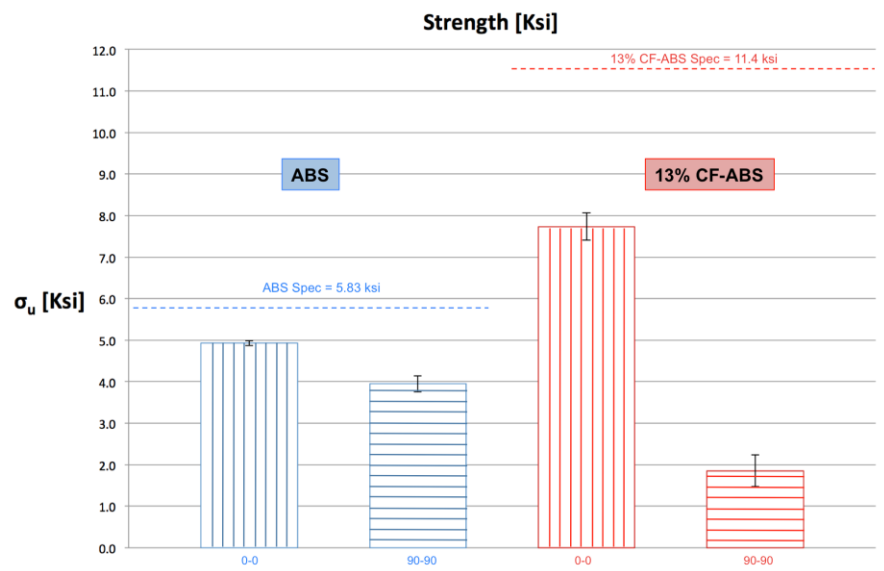

Fig. 4: BAAM ABS strength as a function of deposition

The stiffness of the same materials printed on the BAAM system is equivalent to the reference specification value when printed in the direction of the applied load. As seen in Fig. 5, the stiffness of the neat ABS material is not statistically different from the specified values for this material. On the other hand, the carbon fiber filled material exceeds the specification sheet value of 7.72 GPa. The increase in stiffness is due to the alignment of the carbon fibers during the BAAM deposition, whereas the specified value for this material assumes a quasi-random orientation of the carbon fibers.

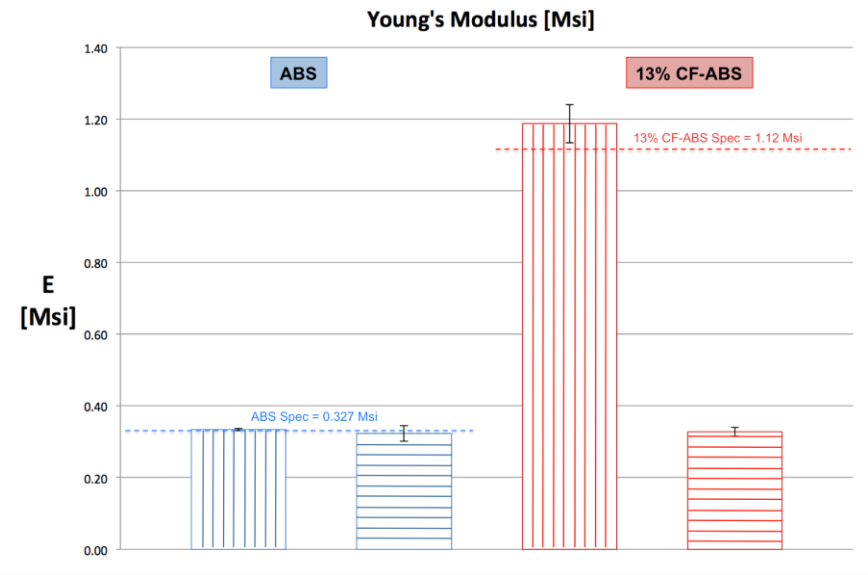

Fig. 5: BAAM ABS stiffness as a function of deposition

In addition to increasing the stiffness and strength, the addition of carbon fiber to BAAM thermoplastics also increases the thermal conductivity and dramatically reduces the CTE. Both of these properties are directionally dependent, since the carbon fibers are primarily aligned along the extrusion direction during processing [4]. For instance, the CTE of 13% carbon fiber in ABS was measured to be 106 μm/m/°C perpendicular to the extrusion direction, but as low as 9.8 μm/m/°C along the extruded bead where the fibers are aligned. In any additive process, temperature gradients in the part during the manufacturing process leads to residual stress that manifests as warp and curl in the finished part. The addition of carbon fiber benefits in two ways: by reducing thermal gradients through an increased thermal conductivity and by simultaneously limiting strain through a lower CTE and increased stiffness. The combination of these results is the ability to maintain part geometric without the need of an oven. For example, NIST test articles were manufactured on a commercial-scale FDM system using neat ABS and a desktop FDM system using carbon fiber ABS. It was found that the carbon fiber part distorted

significantly less than the neat ABS part, even though the neat ABS part was deposited inside of an oven [6].

Integrating carbon fiber into ABS material has also proven effective for reducing warping on the BAAM system. As an example, two long bars (5 cm x 10 cm x 1.8 m) shown in Fig. 6 were printed on the BAAM system with identical operating conditions. One part was made with unfilled ABS while the other had 13% chopped carbon fiber (5 to 7 microns in diameter, 50 to 100 microns long). The carbon fiber filled bar is shown on the left and unfilled bar on the right. The unfilled bar had a total distortion of 4.5 cm whereas there was no measurable distortion on the carbon fiber ABS bar.

Fig. 6: BAAM curl bars

By getting outside of the oven, the BAAM system offers tremendous flexibility. Not only does it allow the technology to scale effectively, it also provides direct access to the deposition zone. This allows sensors and analytical instruments (such as an IR camera) to be placed in close proximity to the extrusion nozzle without needing to be thermally protected. The open environment also makes it possible to perform ‘pick-n-place’ operations, for inserting additional materials, sensors, or control units directly into the part. Operation outside of an oven

also enables the use of low temperature robotics, motors, and controls, which decreases the cost and increases the reliability of these systems.

2.2 Going Faster

One of the primary criticisms of AM over time has been a slow build rate. The BAAM system uses an extrusion diameter of 7.5 mm which enables a deposition rate exceeding 5,000 cm^3/h (over two orders of magnitude increase in flow rate) for standard thermoplastic materials. The large nozzle also enables controlled extrusion of filled materials, such as long fibers, without clogging the extrusion head. Recently, ORNL utilized the BAAM system to build a large carbon fiber composite component (1.2 m x 1.2 m x 1.5 m) that weighed over 200 kg in approximately 40 hours.

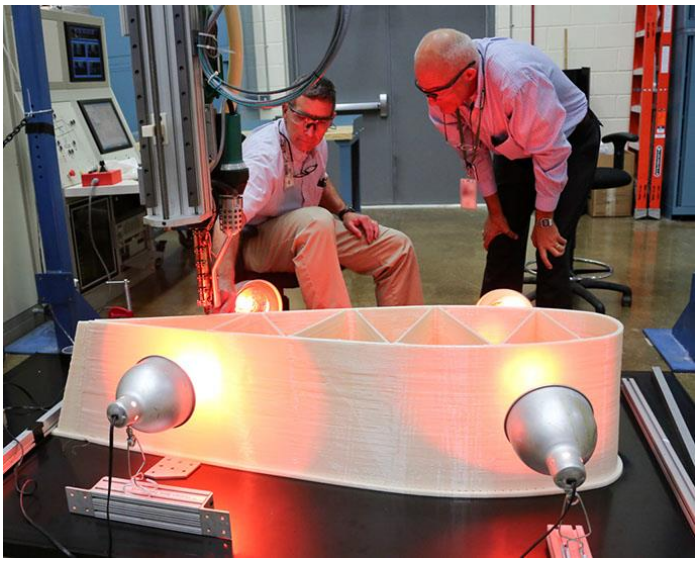

Fig. 7: BAAM manufacturing

2.3 Getting Smarter

The large extrusion nozzle enables high flow rates, but it sacrifices resolution and surface finish. In order to achieve smooth surfaces and accurate tolerances with the BAAM system, a machining step is required. To accomplish this, a ball-mill router has been attached to the

BAAM extrusion head and can be moved into place intermittently to machine specific surfaces and features (see Fig. 8). The current "machine-as-you-go" configuration enables the creation of complex geometries with fine surface finish on otherwise hidden faces. For certain applications, it may be more efficient and economical to separate the deposition and machining processes.

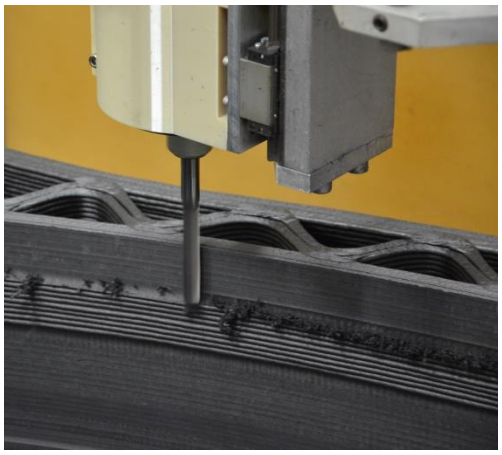

Fig. 8: BAAM in-situ machining

The increased diameter of the extruded bead also impacts the thermal behavior of the deposited structure. Since the surface area of a deposited bead is related to the extrusion diameter to the first power, and the volume of the bead follows the square of the diameter, increasing the extrusion diameter from 0.5 mm to 7.5 mm increases the volume to surface area ratio by a factor of 15. Since heat loss from the bead to the environment occurs across the surface area, a BAAM-deposited structure retains heat much longer than a traditional FDM-deposited structure. Notice in Fig. 9, the infrared image indicates that the underlying layers are retaining significant thermal energy as the new deposit is introduced. This produces a stronger bond between layers, as molecular chain mobility is directly correlated to temperature and, therefore, should result in a higher number of polymer chains crossing the interface and entangling.

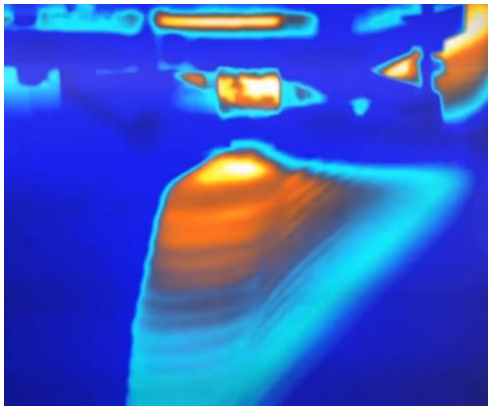

Fig. 9: Thermal imaging of BAAM extrusion

The internal structure of the BAAM printed components is very similar to the traditional FDM structure – aligned beads of extruded material in successive layers. Similar to the FDM process, structures deposited with BAAM exhibit porosity between adjacent beads and layers. Since BAAM utilizes a larger extrusion orifice than traditional FDM, both the extruded beads and resulting porosity are exaggerated (see Fig. 10). However, the much larger surface to volume ratio of the extrudate enables the material to stay hotter and softer longer, reducing the net porosity.

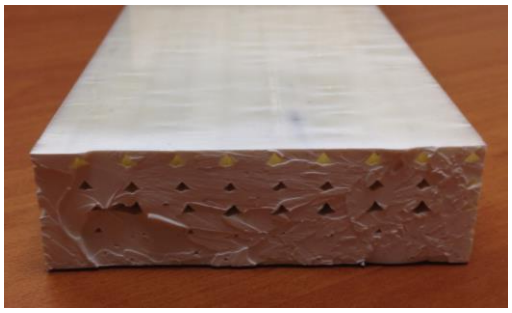

Fig. 10: Part porosity

2.4 Getting Cheaper

The single screw extruder utilized on the BAAM system is significantly different than the filament-based melt extrusion system used in traditional FDM systems. Typically, the FDM systems achieve high precision and flow control by carefully metering a very thin bead through a

small orifice (~500 μm). The feedstock material for FDM is carefully controlled at a diameter of 1.75 mm because the flow rate is dependent on the diameter variations to the second power, whereas it is only related to the linear feed rate of the filament to the first power. As a result, industrial FDM machines that are focused on precision and reliability require the use of a very expensive feedstock material that can cost up to $220/kg for ABS. Even the lower cost desktop FDM systems require a filament feedstock that costs approximately $31/kg.

By comparison, the feedstock material for BAAM is pelletized plastic that is commonly found in high-volume injection molding and extrusion industries. As a result, ABS pellets can be found commercially for approximately $1/kg. Even carbon fiber filled ABS can be obtained commercially for $5/kg. Since BAAM is designed to accept commodity plastic pellets as the feedstock material, the cost of producing components is dramatically reduced (~100x). Furthermore, the BAAM systems should be far more energy efficient than traditional FDM platforms because it does not utilize an oven. In initial testing with a commercial FDM system, the energy required to print a component with the oven active was 80-100 MJ/kg. When the oven was turned off, the energy consumption was reduced to 15-20 MJ/kg.

3. RESULTS

3.1 Tooling

The structure and properties of materials produced by BAAM have not yet been optimized for production parts. However, there is a near term opportunity to utilize the BAAM technology for tool and die applications. The capability to make tools, dies, and molds is rapidly disappearing from the US and much of it is being redirected to China. The tooling industry only produced $11.7 billion dollars in total sales in 2010, which is down significantly from previous years [7].

Between 1998 and 2010, over one-third of US tool, die, and mold establishments have gone out of business, closing at twice the rate of general manufacturers over the same time period. Employment in this industry has fallen nearly in half, with the average age of a toolmaker equal to 52 [7]. These are highly skilled jobs that form the foundation of a much larger manufacturing capability in the US.

ORNL has recently engaged with the NavAir Station at Cherry Point, NC to evaluate the use of BAAM tooling for sheet metal forming. In this preliminary study, ORNL manufactured stretch form and hydroforming tools, measuring about 35 cm x 63 cm x 7.5 cm. After deposition on the BAAM system, the parts were machined in place using the ball mill mounted on the BAAM extrusion arm. These parts took less than 4 hours to manufacture and were successfully tested in service (see Fig. 11 and Fig. 12).

Fig. 11: Printed ABS tool

Fig. 12: Shaped metal part

3.2 Surface Finish

Additive manufacturing rarely provides the surface finish that is needed for tooling or end use applications. There is a typical battle between deposition rate and surface finish. The faster the deposition rate, the poorer the surface finish. ORNL is currently working with multiple companies on material solutions that will enable rapid and efficient coatings between

the base material and a surface material that provides the target surface finish. Two examples were recently highlighted by ORNL. The first is a mold for a composite hood on a car. The mold was printed in eight hours followed by a rough machine cut that took four hours. The final surface finish is based on a gel coat that bonded well with the carbon fiber reinforced ABS. The final finish took four hours. The tool is fully functional, producing carbon fiber hoods (see the hood on the right of Fig. 13).

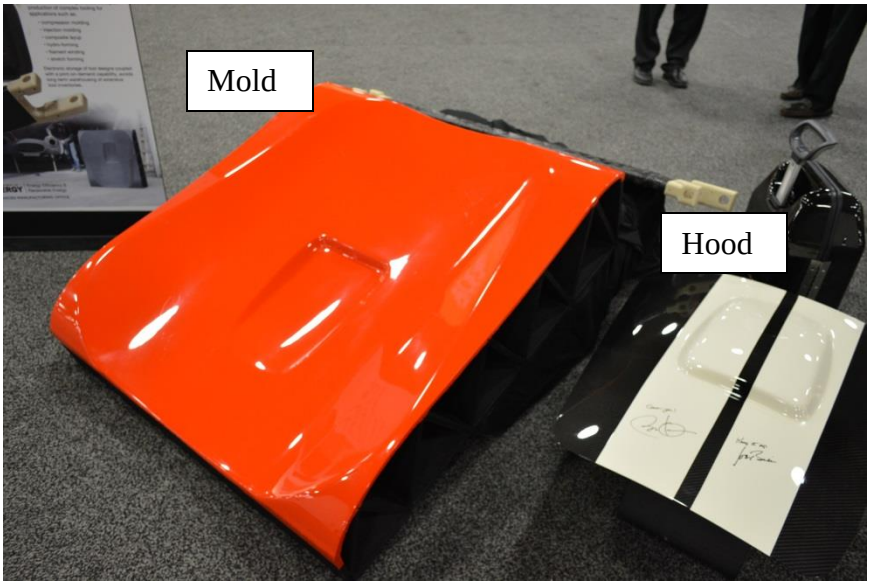

Fig 13: Mold and composite hood

A second example is the production of a prototype electric vehicle (see Fig 14). In a six week period, the car was designed (one week), printed (24 hours), assembled (one week), finished (two weeks) with final assembly and testing (two weeks). All of the body and frame is printed with 450 lbs carbon fiber reinforced ABS with a material cost of approximately $2000. The system also has wireless charging and demonstrates the ability for rapid innovation. The printed vehicle is not to suggest that we will be mass producing vehicles for the road but to highlight the speed at which the additive process can enable innovation.

Fig 14: Printed Cobra

3.3 Commercialization

ORNL has partnered with Cincinnati Inc. to develop the first commercial version of the BAAM technology. Cincinnati Inc is a leader in the manufacture of high productivity metal fabricating machinery. The initial embodiment of the BAAM system will leverage a gantry-based system that has been traditionally used for laser cutting. It will feature a build volume of 2.0 m x 4.0 m x 0.9 m. The goal is to have a commercial system available by 2015.

Fig. 15: Cincinnati Inc. BAAM

4. CONCLUSIONS

Polymer additive manufacturing using FDM has enabled the creation of very complex structures, but has been criticized for being a slow (20 cm^3/h) and expensive (>$100/kg) technology with limited build size (<0.02 m^3). ORNL has developed a large scale AM system that improves upon each of these areas by about an order of magnitude. The Big Area Additive Manufacturing (BAAM) system directly converts low cost pellets ($1-30/kg) into large, three-dimensional parts (8 m^3) at a rate exceeding 25 kg/h. Deposition outside of a thermally-controlled environment has enabled fabrication of large-scale components, but has also required the development of advanced carbon fiber filled materials to increase strength, stiffness, and minimize warping. Over the coming months, ORNL will be developing a commercial version of the BAAM deposition system along with key industrial partners.

5. ACKNOWLEDGEMENTS

This work was supported by ORNL's Laboratory Directed Research and Development program as well as the Department of Energy's Advanced Manufacturing Office.

6. REFERENCES

1. Wolhlers, T. (2013). *Wohlers Report.* Fort Collins, Co.: Wohlers Associates, Inc.
2. Wendell, B., Rietzel, D., Kuhnlein, F., Feulner, R., Hulder, G. and Schmachtenber, E., "Additive Processing in Polymers," *Macromolecular Materials and Engineering*, Vol. 293, pp. 799-809, 2008.
3. Holshouser, C., Newell, C., Palas, S., Duty, C., Love, L., Kunc, V., Lind, R., Lloyd, P., Rowe, J., Dehoff, R., Peter, W., and Blue, C. "Out of Bounds Additive Manufacturing." *Advanced Materials & Processes*, March 2013.
4. Kunc, V., Velez-Garcia, G., Ozcan, S., Tekinalp, H., Lindhal, J., Love, L., Duty, C., and Blue, C., "Microstructure and property of carbon fiber reinforced materials for fused deposition modeling" submitted to Composites Part A: Applied Science and Manufacturing, 2014

5. Tekinalp, H., Kunc, V., Velez-Garcia, G., Duty, C., Love, L., Naskar, A., Blue, C. and Ozcan, S., "Short Carbon Fiber Reinforced Composites via Fused Deposition Modeling: In Comparison to Compression Molding," *Composites: Part A,* in review
6. Love, L., Kunc, V., Rios, O., Duty, C., Elliot, A., Post, B., and Blue, C., "The Importance of Carbon Fiber to Polymer Additive Manufacturing," *Journal of Material Research,* in review
7. Bill Canis, "The Tool and Die Industry: Contribution to US Manufacturing and Federal Policy Considerations." *CRS Congressional Report*, March 16, 2012