ORNL/TM-2015/78
CRADA/NFE-14-05201

Material Development for Tooling Applications Using Big Area Additive Manufacturing (BAAM)

Chad E. Duty
Tom Drye
Alan Franc

March 18, 2015

Approved For Public Release

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

DOCUMENT AVAILABILITY

Reports produced after January 1, 1996, are generally available free via US Department of Energy (DOE) SciTech Connect.

Website http://www.osti.gov/scitech/

Reports produced before January 1, 1996, may be purchased by members of the public from the following source:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone 703-605-6000 (1-800-553-6847)
TDD 703-487-4639
Fax 703-605-6900
E-mail info@ntis.gov
Website http://www.ntis.gov/help/ordermethods.aspx

Reports are available to DOE employees, DOE contractors, Energy Technology Data Exchange representatives, and International Nuclear Information System representatives from the following source:

Office of Scientific and Technical Information
PO Box 62
Oak Ridge, TN 37831
Telephone 865-576-8401
Fax 865-576-5728
E-mail reports@osti.gov
Website http://www.osti.gov/contact.html

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ORNL/TM-2015/78
CRADA/NFE-14-05201

Advanced Manufacturing Office
Materials Science and Technology Division

MATERIAL DEVELOPMENT FOR TOOLING APPLICATIONS USING BIG AREA ADDITIVE MANUFACTURING (BAAM)

Authors
Chad E. Duty
Tom Drye
Alan Franc

Date Published:
March 18, 2015

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283
managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

Approved for Public Release

ORNL Manufacturing Demonstration Facility
Technical Collaboration **Final Report**

Material Development for Tooling Applications Using Big Area Additive Manufacturing (BAAM)[1]

Techmer Engineered Solutions

Project ID: MDF-TC-2014-053
Start Date: 06/24/2014
Completion Date: 02/28/2015
Company Size: Medium-sized business, with over 600 employees

Summary
Techmer Engineered Solutions (TES) is working with Oak Ridge National Laboratory (ORNL) to develop materials and evaluate ORNL's recently developed Big Area Additive Manufacturing (BAAM) system for use in tooling applications. The first phase of the project established the performance of some commercially available polymer compositions deposited with the BAAM system. Carbon fiber reinforced ABS demonstrated a tensile strength of nearly 10 ksi, which is sufficient for a number of low temperature tooling applications.

Background
ORNL has developed a Big Area Additive Manufacturing (BAAM) system that is capable of producing parts directly from pellets, on a large scale (8' x 8' x 8'), and at a rate of 10-20 lbs/h. Each of these capabilities represents a dramatic improvement over the existing state-of-the art in polymer additive manufacturing. The ability to deposit outside of a temperature-controlled environment requires the use of low coefficient of thermal expansion (CTE) materials that resist distortion and warping during the multi-layer deposition process. Initial trials at the ORNL Manufacturing Demonstration Facility (MDF) with carbon-fiber filled materials have demonstrated significantly reduced distortion, which is believed to be due to a combination of high stiffness and improved thermal conductivity. The nature of this behavior was initially unclear, which motivated this project to explore various additives and reinforcing materials that can be used with BAAM thermoplastics in order to provide sufficient mechanical performance while resisting distortion during the deposition process.

Techmer Engineered Solutions (TES) has significant experience with developing additives and engineered reinforcements for high performance polymers. TES has

[1] Research sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

extensive formulation technology using most engineering resins, from acrylonitrile butadiene styrene (ABS) to polyphenylene sulfide (PPS), to polyether ether ketone (PEEK) and many others. Through this know-how, TES is able to custom tailor materials to meet most end-use applications, such as electrical and thermal conductivity, lubricity, CTE, strength, modulus, electromagnetic interference/radio-frequency interference (EMI/RFI) shielding, dimensional stability, etc. The ORNL additive manufacturing team combined with TES compounding expertise brings together a team capable of producing innovative materials to address a significant market need and advanced manufacturing opportunity. The objective of this project was to deposit a variety of commercially available thermoplastic materials with the BAAM system and establish a baseline for mechanical performance that would be sufficient for low temperature tooling applications.

Technical Results

ORNL and TES evaluated a number of commercially available thermoplastic materials that may be appropriate for deposition on the BAAM system. An unreinforced commodity material, acrylonitrile butadiene styrene (ABS), was selected as the baseline reference for BAAM material properties. Previous experience with the BAAM system demonstrated that neat (or unreinforced) ABS distorted significantly during the deposition process. However, since ABS is a terpolymer made by polymerizing styrene and acrylonitrile in the presence of butadiene, the proportions of A:B:S can vary significantly for different material suppliers, so it was important to have an unreinforced control material from the same supplier as a reference point.

Two reinforced ABS materials (glass fiber and carbon fiber) were also selected to evaluate the increase in strength and stiffness that typically accompanies fiber reinforcement. In each case, the feedstock material is delivered in a pre-compounded pellet form from TES, so the reinforcing materials are chopped fibers (~1 mm length). The fiber content for each sample was held constant at 20% by weight. A high temperature reinforced material, glass fiber reinforced polyphenylene sulfide (GF-PPS), was also selected due to potentially much higher stiffness and strength. The GF-PPS material was utilized as a pelletized feedstock, but the glass fiber content was increased to 40% by weight. Each of the materials is commercially available compounds available from TES. The product description is listed in the table below along with the mechanical properties taken from typical injection molded samples.

Techmer Engineered Solutions Thermoplastics

Abbreviation	Product Name	Strength (ksi)	Stiffness (Msi)
ABS	5 MFI High Impact ABS	6.09	0.37
20% CF-ABS	Electrafil J-1200/CF/20	14	1.8
20% GF-ABS	HiFill J-1200/20 NAT	12	0.9
40% GF-PPS	HiFill 1305 - 11007 NAT	23.6	2.1

Each of the materials were deposited using the single-screw BAAM extrusion system at ORNL at a feed rate of ~10 lbs/h and a deposition head speed of ~2 in/s. The BAAM extruder has a resistively heated thermal jacket around the extrusion screw. The extrusion temperature for all of the ABS materials was set at 250C, but was increased to 357C for the GF-PPS material. The deposited structure for each material was a thin

wall hexagon structure pictured below (Figure 1). Each of the wall segments measured roughly 28” long, 6.5” wide, and 1” thick (3 bead widths). Large dog bone specimens were machined out of five of the walls with the primary axis aligned to the deposited bead direction according to the specifications below (see Figure 2a). Smaller tensile specimens were cut from the remaining wall with the primary load axis running perpendicular to the layered deposit, in order to measure inter-layer strength (see Figure 2b).

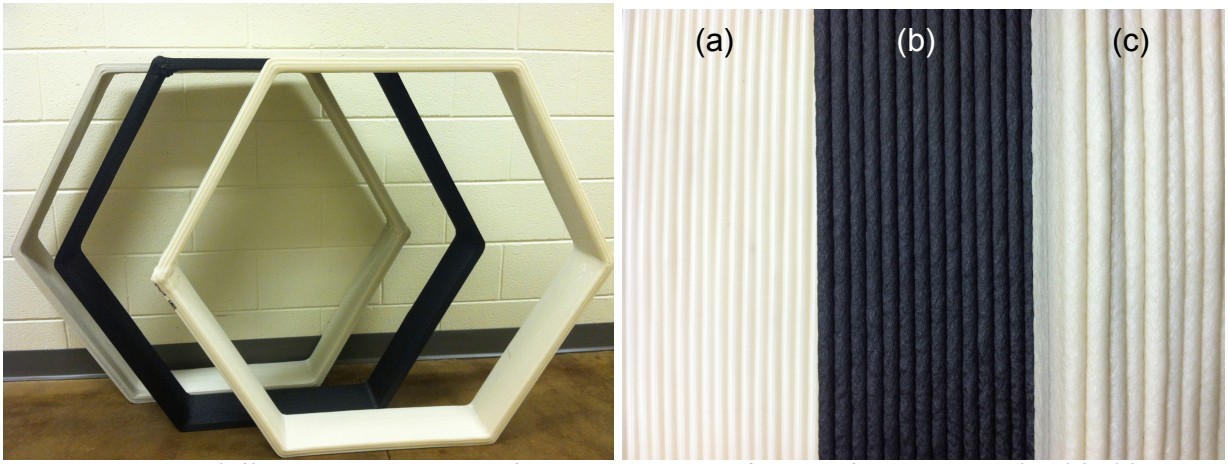

Figure 1. Hexagons (left) printed on BAAM system for mechanical testing. Close-up of deposited walls (right) for (a) neat ABS, (b) CF-ABS, (c) GF-ABS

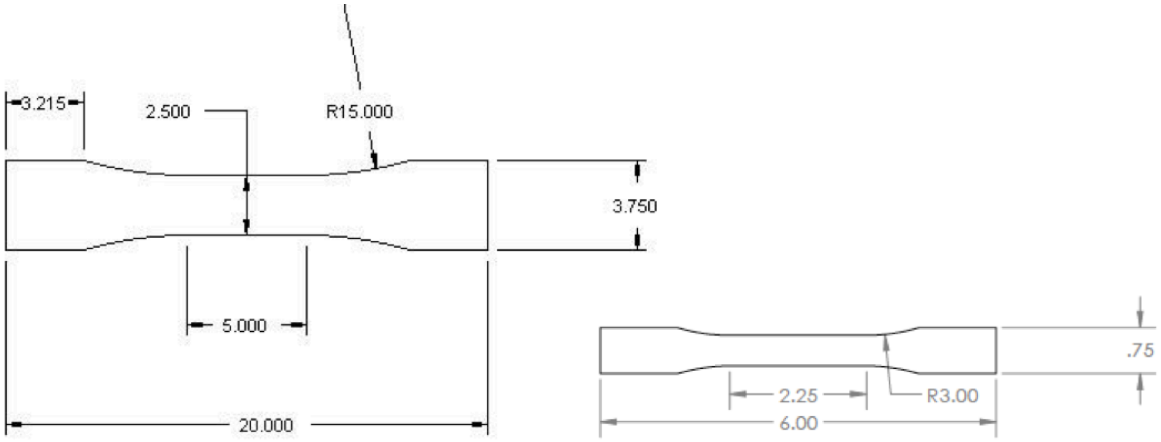

Figure 2. Test sample cut plan for BAAM dog bone tensile specimens (all dimensions in inches). The larger specimen (left) is 0.75” thick and the smaller sample (right) is 0.25” thick. Images are not to relative scale.

After the specimens were cut from the hexagons, they were placed in a large furnace at 50C to dry for at least 48 hours, then stored in a desiccant chamber at 23C for at least 15 hours, according to ASTM D618-B. The samples were subjected to mechanical testing within 30 minutes of being removed from the desiccant chamber according to ASTM D638. The mechanical strength, stiffness, and percent elongation for each of the samples are presented below in Figures 3-5. Note that for each sample, the properties are shown for the direction aligned to the deposition direction (x), in the cross-layer direction (z), as well as the typical injection molded reference data (if available).

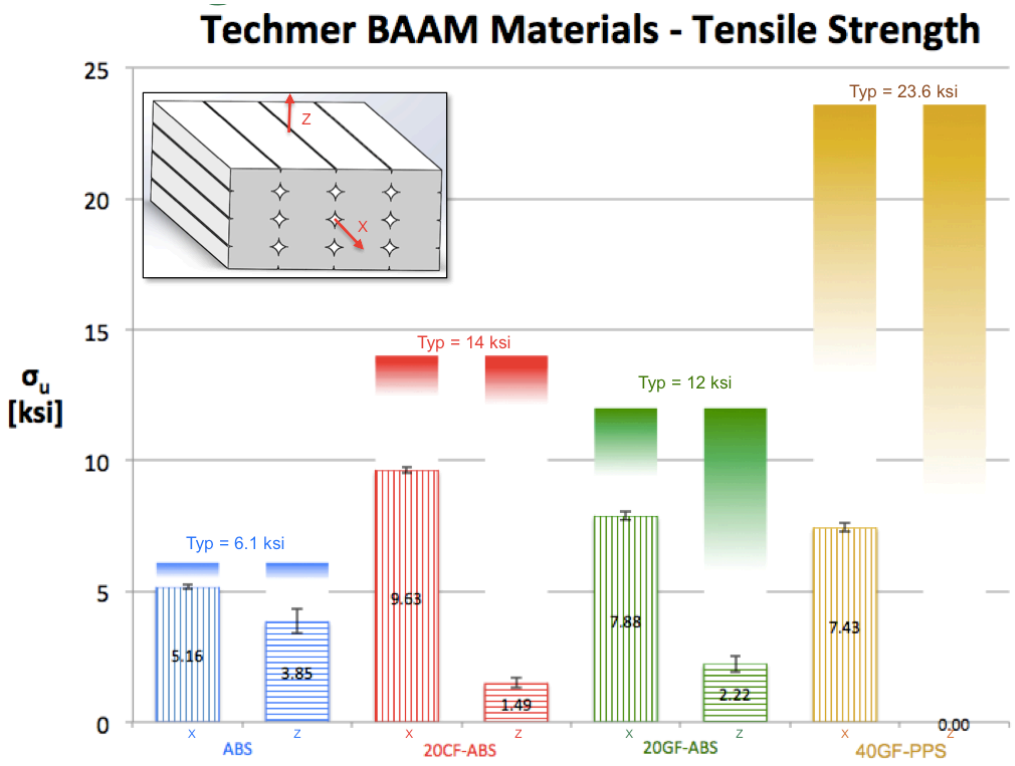

Figure 3. Tensile Strength of Techmer materials deposited on the BAAM system.

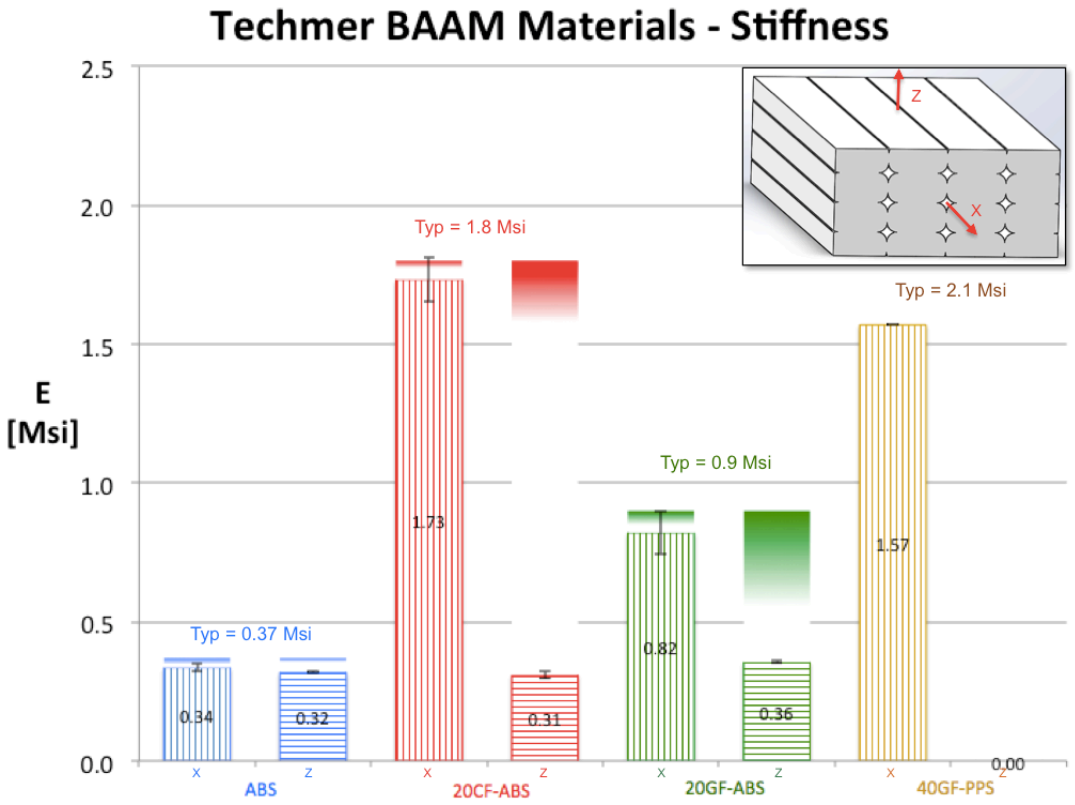

Figure 4. Tensile Stiffness of Techmer materials deposited on the BAAM system.

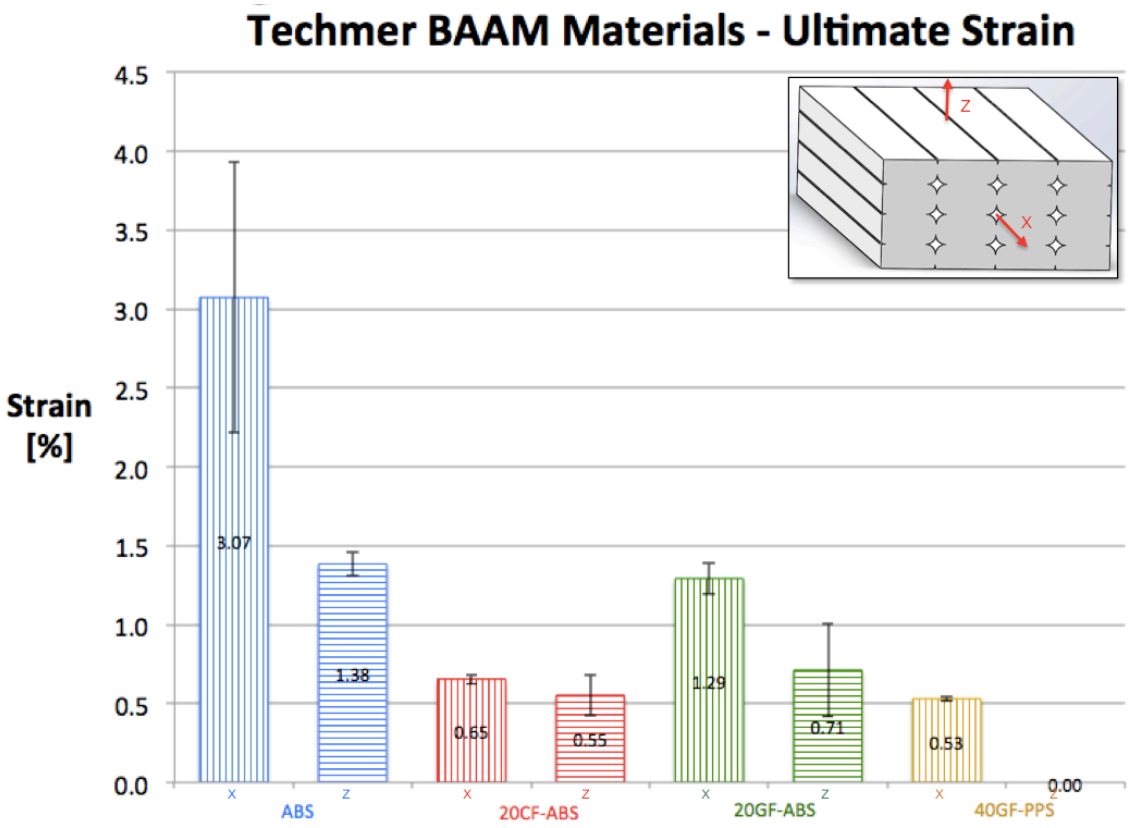

Figure 5. Tensile Elongation of Techmer materials deposited on the BAAM system.

A review of the tensile strength data in Figure 3 demonstrates that the neat ABS material is most isotropic and most closely matches the injection molded reference material, achieving 85% of the tensile strength in the aligned direction and above 63% in the cross-layer direction (z). The CF-ABS material is much stronger in the aligned direction (9.5 ksi), but loses almost 85% of that strength in the z-direction (1.5 ksi). This poor interlayer strength is due to a combination of the increased rigidity of the extruded bead, which reduces the contact area between adjacent beads, and the high concentration of carbon fibers near the surface of the extruded bead, which are poorly bonded and act as a type of mechanical release agents. The GF-ABS material has less strength in the x-direction (7.9 ksi), but significantly more strength in the z-direction (2.2 ksi).

The GF-PPS material has the potential of being incredibly strong (typical strength of 24 ksi), but the processing capability of the current extruding system limits the extrusion temperature to 357C. An inspection of the cross section of the PPS material (Figure 6) reveals a very porous structure that is likely due to improper processing of the high temperature material (extrusion temperature too low, possible “hot spots” that volatize certain components, or entrapped air). Each of these issues will likely be resolved in the next version of the extruder design (four heated zones, compression ratio = 2.93). The measured tensile strength (7.4 ksi) is still significant, but the interlayer adhesion was so poor for this material that the samples could not be machined intact.

Figure 6. Cross section of GF-PPS deposited bead demonstrating significant porosity.

The stiffness of the BAAM deposited materials is very close to the injection molded reference for each case (with the exception of the PPS material). It is interesting to note that for each of the ABS-based materials in the aligned direction, the stiffness was between 91% - 96% of the injection molded reference. The ratio of the stiffness in the aligned direction (x) compared to the cross-layer direction (z), was significantly higher for the neat ABS (94%) than it was for either the CF-ABS (18%) or the GF-ABS (54%) materials. Once again, this is likely a combination of the higher viscosity of the reinforced deposited beads or an increased concentration of reinforcing material near the bonded interfaces. Similar trends are apparent in the strain data.

Figure 7 shows the cross section of the fracture surfaces for each material at 20x magnification. The bead geometry is readily apparent for all of the reinforced materials, whereas the neat ABS material has far fewer defects.

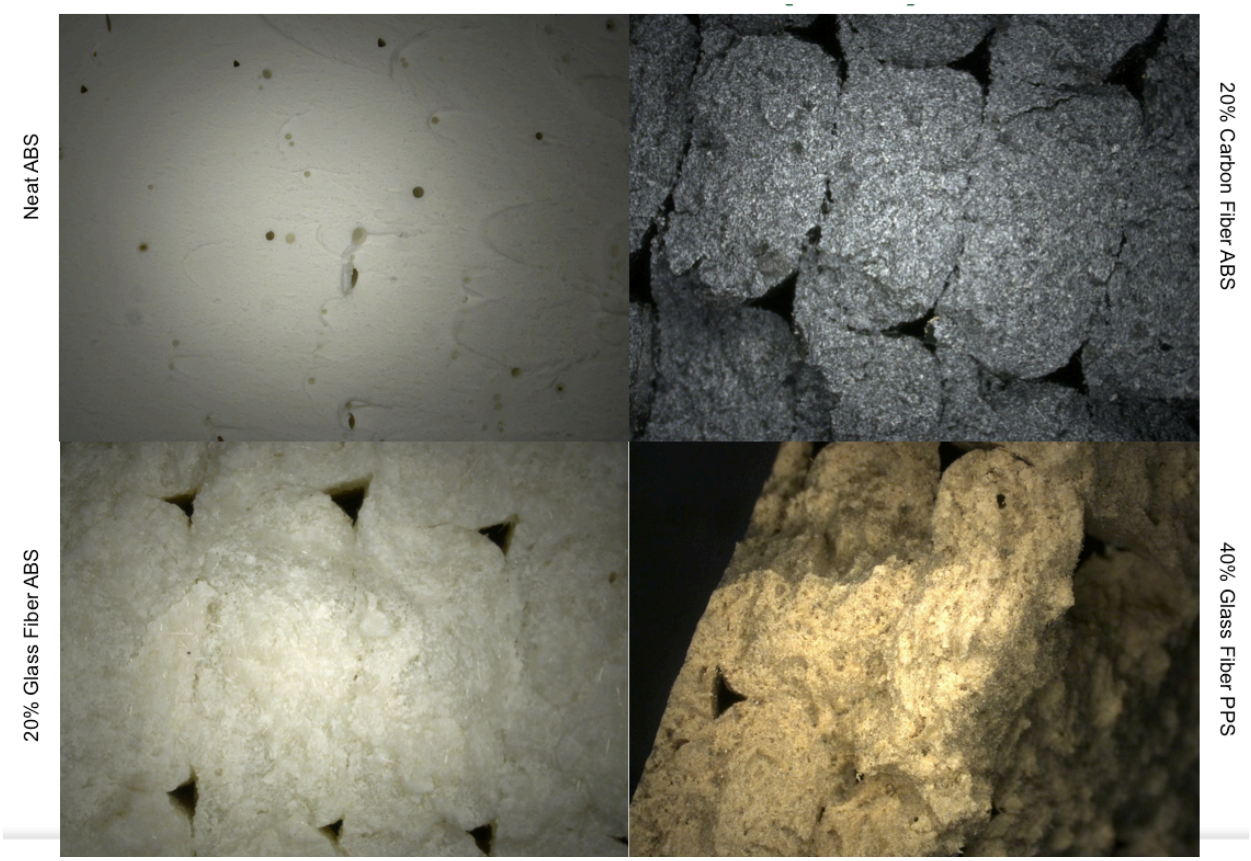

Figure 7. Fracture surface of BAAM deposited materials: neat ABS (upper left), CF-ABS (upper right), GF-ABS (lower left), GF-PPS (lower right).

Impacts

This project enabled a critical collaborative research partnership to be established between ORNL and TES for the development of thermoplastic materials for the BAAM deposition system. This project represented the first rigorous testing of Techmer materials on the BAAM system and proof that the carbon fiber reinforced ABS could provide sufficient strength for initial tooling and concept car applications. As a result, Techmer material was used to print the world's first 3D printed car, the Strati, in cooperation with Local Motors and Cincinnati Incorporated at the International Manufacturing Technology Show in Chicago in September of 2014. Techmer material was also used to produce the printed Shelby Cobra and a large mold for carbon fiber lay-up for the Detroit Auto Show in January 2015. President Obama and Vice-President Biden visited Techmer in January 2015 to view the Cobra and autographed the carbon fiber hood made on the printed tool.

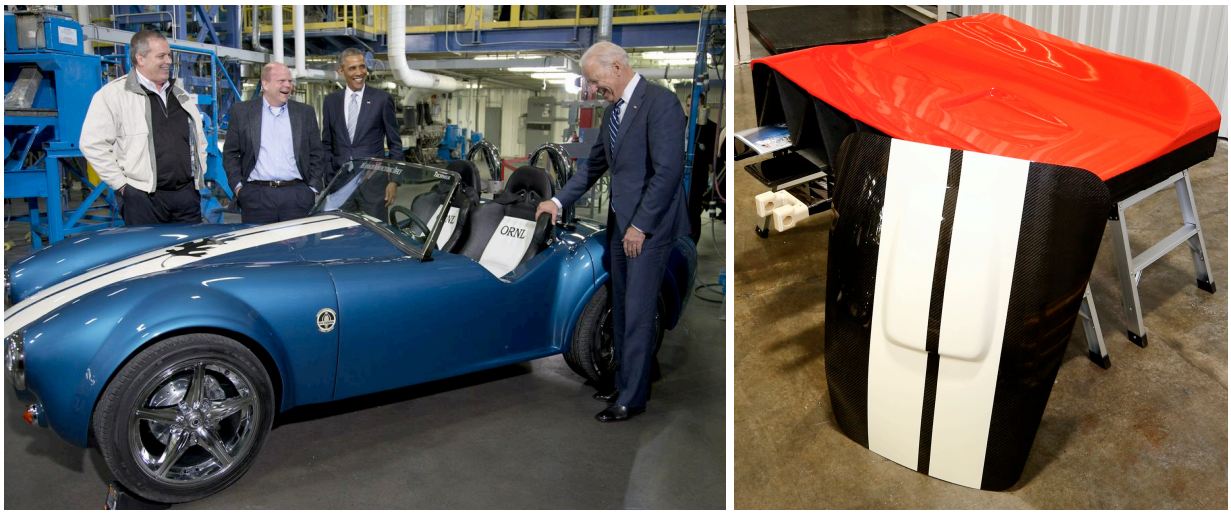

Figure 8. President Obama and Vice President Biden at Techmer ES admiring the 3D printed Shelby Cobra (left). The large printed mold using TES material and carbon fiber hood produced from the tool (right).

Conclusions

Aside from the publicity and technology impacts this project has enabled, it has also proven the commercial opportunity of the BAAM system for Techmer's line of high performance thermoplastic materials. Techmer is currently supplying 1,000's of pounds of CF-ABS material for the BAAM system and is looking to expand operations into the high temperature performance materials, such as GF-PPS. This project has already enabled a commercial venture with a large aerospace company for the use of carbon fiber reinforced PPS material.

About the Company

Techmer Engineered Solutions, LLC (TES) is part of the Techmer group with headquarters in nearby Clinton, TN. Through additive, reinforcement, and processing technology, TES custom formulates and produces plastic compounds used in a variety of industries and applications. Industries served include: automotive, aerospace, oil & gas, business machine, electrical & electronic, medical, etc. With seven manufacturing sites (3 dedicated to TES) and world class testing labs, Techmer is well positioned to bring leading edge custom solutions to market.

Points of Contact

Chad Duty, ORNL, dutyc@ornl.gov, 865-574-5059

Tom Drye, Techmer ES, TDrye@techmerES.com, 865-425-2121

Alan Franc, Techmer ES, AFranc@techmerES.com, 865-425-2121