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Cincinnati Big Area Additive Manufacturing (BAAM)

Oak Ridge National Laboratory

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ABSTRACT

Oak Ridge National Laboratory (ORNL) worked with Cincinnati Incorporated (CI) to demonstrate Big Area Additive Manufacturing which increases the speed of the additive manufacturing (AM) process by over 1000X, increases the size of parts by over 10X and shows a cost reduction of over 100X. ORNL worked with CI to transition the Big Area Additive Manufacturing (BAAM) technology from a proof-of-principle (TRL 2-3) demonstration to a prototype product stage (TRL 7-8).

1. CINCINNATI BAAM

This CRADA project (NFE-2014-04957) was begun in February, 2014 and was completed on January 2015. The collaboration partner Cincinnati Incorporated is a small female owned business. The results of this project was the development of a new product line, the BAAM-CI, for Cincinnati Incorporated which represents the world's fastest and largest additive manufacturing technology.

1.1 BACKGROUND

In February of 2014, ORNL initiated a new partnership with Cincinnati Incorporated focusing on large scale polymer additive manufacturing. This work was first undertaken under an Oak Ridge National Laboratory (ORNL) Laboratory Directed Research and Development (LDRD) program. The overall goal of the project was to demonstrate "out of the oven" additive manufacturing at a size (>2 m) and rate (>50 cc/min) that is more than one order of magnitude greater than the current state of the art (figures 1 and 2). The project was extremely successful and resulted in a Cooperative Research and Development Agreement (CRADA) between ORNL and Cincinnati Incorporated for work supported by US Department of Energy (DOE) Advanced Manufacturing Office (AMO) at the ORNL Manufacturing Demonstration Facility (MDF) focusing on maturation and transition of the technology. The BAAM system is based on extruding pellets, rather than a polymer wire, significantly reducing cost ($1/kg compared to $50 to $100/kg) and expanding the supply chain leveraging the injection molding industry.

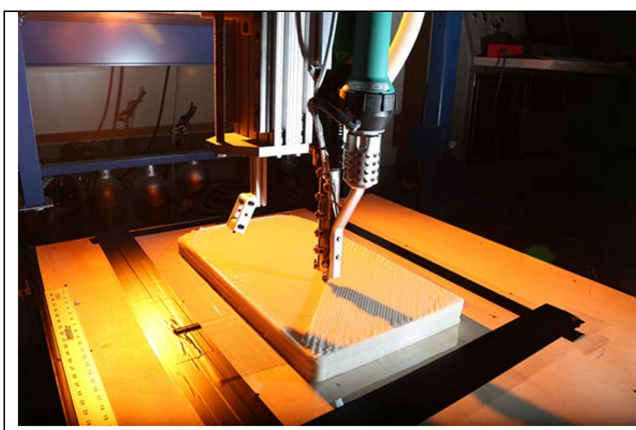

Figure 1: Extruder

Figure 2: Direct part manufacture

Cincinnati Incorporated is a 116 year old family owned U.S. machine tool manufacturer. Their product lines include press brakes, shears, powder metallurgy and laser cutting systems. Their laser cutting technology uses a high speed gantry system with linear electric motors that can achieve high speeds, high resolution and high acceleration with a payload that exceeds 100 pounds. This configuration is ideally suited for BAAM. The goal of this CRADA was to transition the BAAM technology onto CI's existing linear electric gantry systems currently used for laser cutting. Specific areas of focus were the development of a heated table for growing parts, software integration (controls and toolpath generation), and development of preliminary processing parameters and material properties. By the end of the CRADA, ORNL and CI transitioned the technology (designs and software) to CI leading to their first commercial sale of a BAAM system to Sabic Inc.

1.2 TECHNICAL RESULTS

1.2.1 Cincinnati Alpha BAAM

To initiate the project, CI installed one of their gantry systems (2m x 4m) in ORNL's MDF. ORNL sized and procured a pellet handling system, material conveyance system and extruder. The pellet handling system (figure 3) is sized to require approximately four hours to dry the material if the system is running at full capacity. The system also has an external feed system that enables continuous feed of material into the drier from a larger supply of material (figure 4).

Figure 3: Pellet handling system

Figure 4: Continuous feed

To expedite technology transfer, ORNL designed components and sent the models and drawings to Cincinnati for fabrication. The first examples are the brackets needed to interface the extruder to the gantry (figure 5). ORNL provided Cincinnati detailed designs for the z-table (figure 7) on which the parts are grown. ORNL made the required modifications and installed the system (figure 6). The new z-table provides approximately 36" of vertical displacement. Cincinnati fabricated and integrated the table and shipped it to ORNL (figure 8). This system's build volume is approximately 273 cubic feet. The next closest commercial system is the Stratasys Fortus 900 mc that has an 18 cubic feet build volume. Therefore, the Cincinnati BAAM system has a 15X increase in build volume over the largest commercial systems.

Figure 5: Extruder

Figure 6: Modifications to Cincinnati system

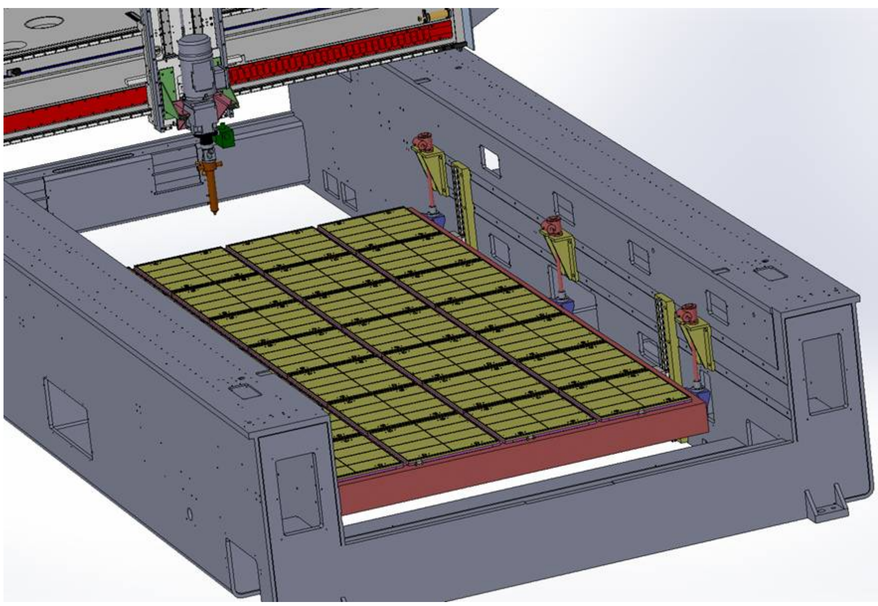

Figure 7: Cincinnati BAAM Z-table design

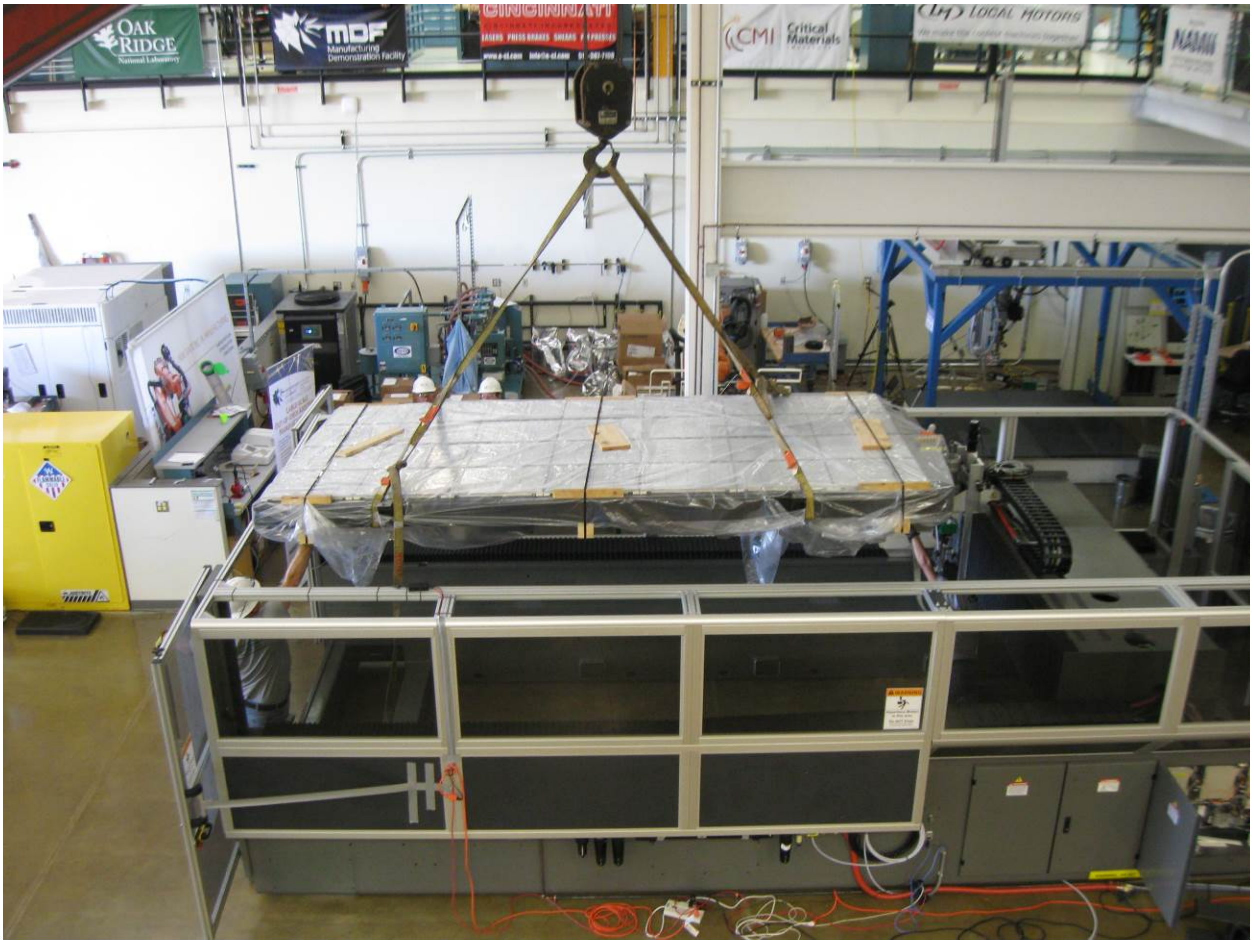

Figure 8: Cincinnati BAAM z-table delivery to the ORNL MDF

1.2.2 Support Strategies

To address of stabilizing overhanging structures during the build stage, ORNL developed a new powder applicator system for printing support structures. The system was successfully installed and tested on the Cincinnati BAAM system (figures 9 and 10). Efforts focused on application patterns that would provide sufficient bonding to stabilize the build, yet yield easy removal of the support from the part. A pattern that applied a powder every 1" provided a nice balance between holding the structure stable, yet enabling easy support removal. In addition, the slicing software was modified to include automated application of the support. The software is adjustable to enable interweaving support material between multiple layers enabling a "layered cake-like" structure for easy support removal (figure 10).

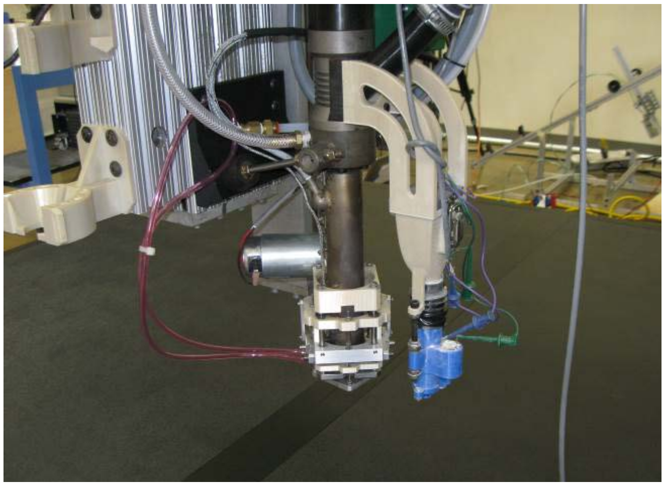

Figure 9: Applicator

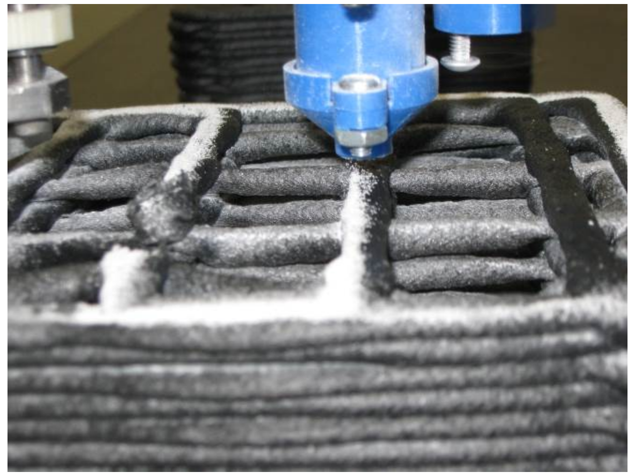

Figure 10: Applicator deployed on ORNL BAAM

1.2.3 Flow Rate

The team next focused on the integration and testing of a higher flow rate feed screw (figure 11). There are a few basic differences between the standard screw and the new screw developed by the team. First, the old screw was designed to feed both pellets and thermoplastic wire and was designed to enable chopping of the wire feedstock at the inlet. At the outlet, the original screw had two mixing pins that enabled blending of feedstock materials. The new screw eliminated both the wire feed and the mixing pins. These modifications significantly reduce throttling of the pellet flow at the inlet and extrusion at the outlet, enabling flow rates exceeding 40 lb/hr which is equivalent to 1000 cubic inches per hour. As a point for comparison, most conventional AM systems have a build rate of 1 to 5 cubic inches per hour. The new screw is also approximately 2” longer, enabling improved metering of the flow at the outlet. The new screw was successfully integrated into the existing Cincinnati BAAM system.

Figure 11: New screw (top) vs. old screw (bottom)

1.2.4 Slicing Software

A key element of BAAM is the slicing software that translates three dimensional geometry of the part design into the tool paths used for printing the part. There were three primary upgrades to the

existing slicing software (figure 12). First, the existing open source software was very unstable. ORNL staff rewrote approximately 80% of the software providing a stable platform. Secondly the team added features to the software including the ability to reslice the code from a paused configuration, the ability to log and archive all slicing conditions and select from either BAAM (ORNL or Cincinnati) with multiple material settings. Finally, the team also developed a new organic support structure that reduced material usage and enables automated powder dispensing as discussed above.

One advantage to BAAM is the ability to visualize effects easily that aren't possible on conventional fused deposition modeling (FDM) systems. In many cases, tool paths are defined assuming a closed path (e.g. an even number of bead widths). However, this leads to gaps when the actual part width is an odd factor with respect to the bead width. With conventional FDM, this effect isn't as noticeable as it is on BAAM. Therefore, ORNL developed "skeletons" which enable automated tool path generation with both even and odd increments in tool paths. This leads to a more uniform fill density when manufacturing thin walled sections.

Another challenge is vertical extrusions of excess material left when moving the extruder from one location to another. With the carbon fiber reinforced materials, very hard and stiff bulges of excess material can lead to a collision potential between the part and extruder. Experience with the system demonstrated that this could lead to part failure on the z-leveler through multiple collisions. A solution is to modify the tool path such that, at the end of each path, the pump turns off and the head does a slow circular motion while slowly rising. This smears the excess material and levels it out while pulling away. Once this modification was incorporated into the slicing routine, the system never experiences a collision and led to hands free operation.

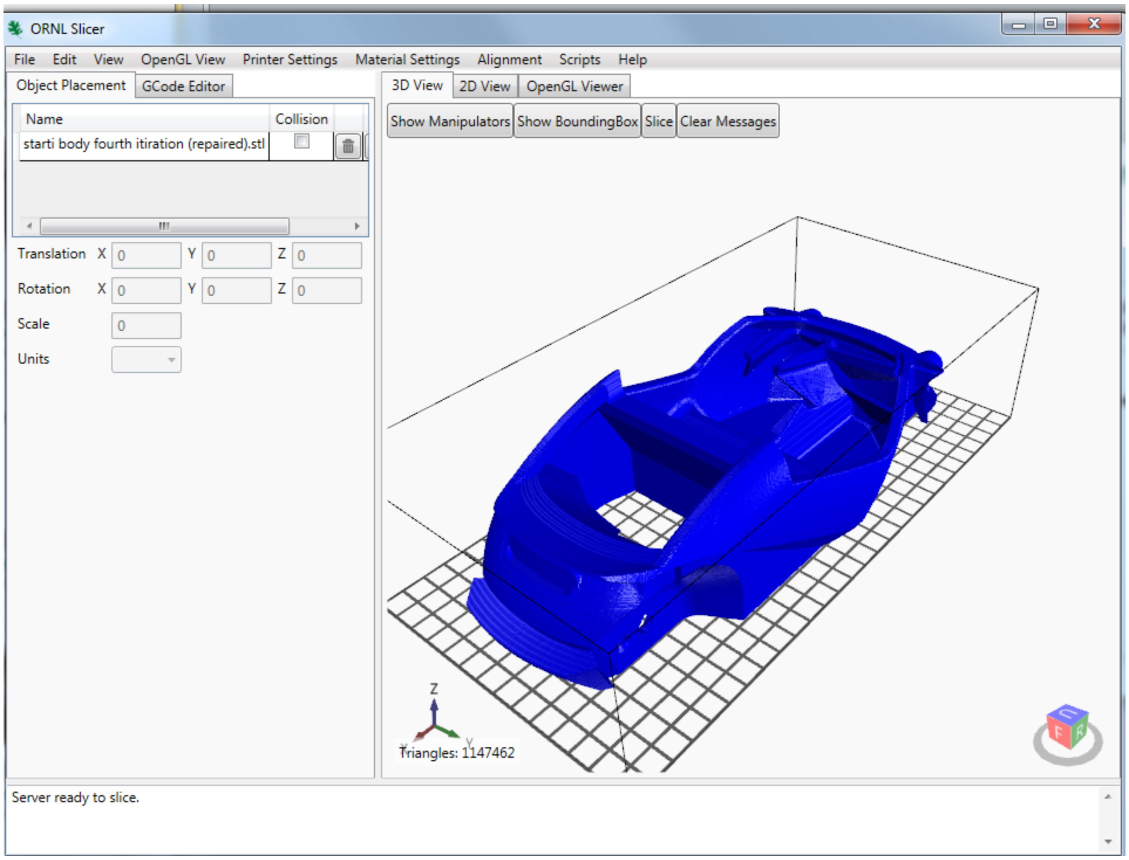

Figure 12: ORNL Slicer software

1.2.5 BAAM Material Testing

The mechanical strength of BAAM components will depend heavily upon the processing conditions as well as the tool path defining the bead orientation of the individual layers. The material deposited by BAAM is expected to have anisotropic properties dependent upon the bead orientation. As shown in Figure 13, the material being used will have a reference strength that is based on either a compression molded or an injection molded reference (the spec sheet value). The material properties that we measure from a single BAAM extruded bead will most closely match this reference value, but will likely be degraded in some fashion due to non-optimal extrusion processing with the BAAM system. As shown in the right side of the figure, the BAAM extruded beads often have internal porosity. This is believed to be a result of the poor screw design referenced in the above section. As the beads are deposited to form a component, there will be inter-bead porosity that develops as a result of incomplete filling of the extruded material as one bead is deposited next to another (as shown in the center right of the figure). These pores can be significant and will reduce the strength of the material, even in the direction of the deposited beads. This is illustrated in Figure 13 as the Part (Aligned) strength value. Furthermore, as the beads are pulled in directions normal to their deposition direction, the majority of the force must be transmitted across the interface between beads, which is much weaker than the parent material due to incomplete bonding and reduced contact area. This minimal strength is shown below as Part (Transverse) strength and represents the lower bound strength of a BAAM structure.

In further work, the team focused on characterizing the mechanical performance of carbon-fiber filled ABS material that has utilized the z-tamping deposition capability. The z-tamping technique

utilizes a pneumatically actuated ring around the extrusion tip to compress the top layer of the deposited structure as the bead is deposited. The concept behind the z-tamping technology is that the compression will force the molten bead into the previously deposited structure, which will decrease inter-bead porosity and increase bond area between adjacent beads.

The z-tamped carbon fiber filled (13%) ABS samples were deposited, machined, and dried. Figure 14 illustrates the relative strength of the z-tamped samples compared to the neat ABS and similar CF-ABS materials without the z-tamping system. Following the idea of the strength comparison chart figure 13, the bar charts show the strength of the deposited bead compared against the three primary strength directions of the deposited structure (x = aligned with the bead deposition direction, y = perpendicular to the beads in the deposition plane, z = perpendicular to the deposition plane). As expected, the strength of the beads for the ABS and CF-ABS materials exceeded the strength of the deposited structures, but falls below the spec sheet reference for these materials. The z-tamped bead material should have the strength as the non-z-tamped material, so there is concern that that particular test was flawed. The z-direction samples for the z-tamped material were evidently flawed because they all broke in the same layer in the shoulder section of the tensile specimens. However, the remaining samples seemed to fail in the expected manner. The aligned specimens (x) were the strongest for each case, but weaker than the bead material (as suggested in the figure above). The in-plan transverse loaded samples (y0 were the weakest of the specimens because the interlayer contact area between adjacent beads is much smaller than the interlayer contact area between successive layers (z). This is primarily due to the elliptical shape of the individual beads.

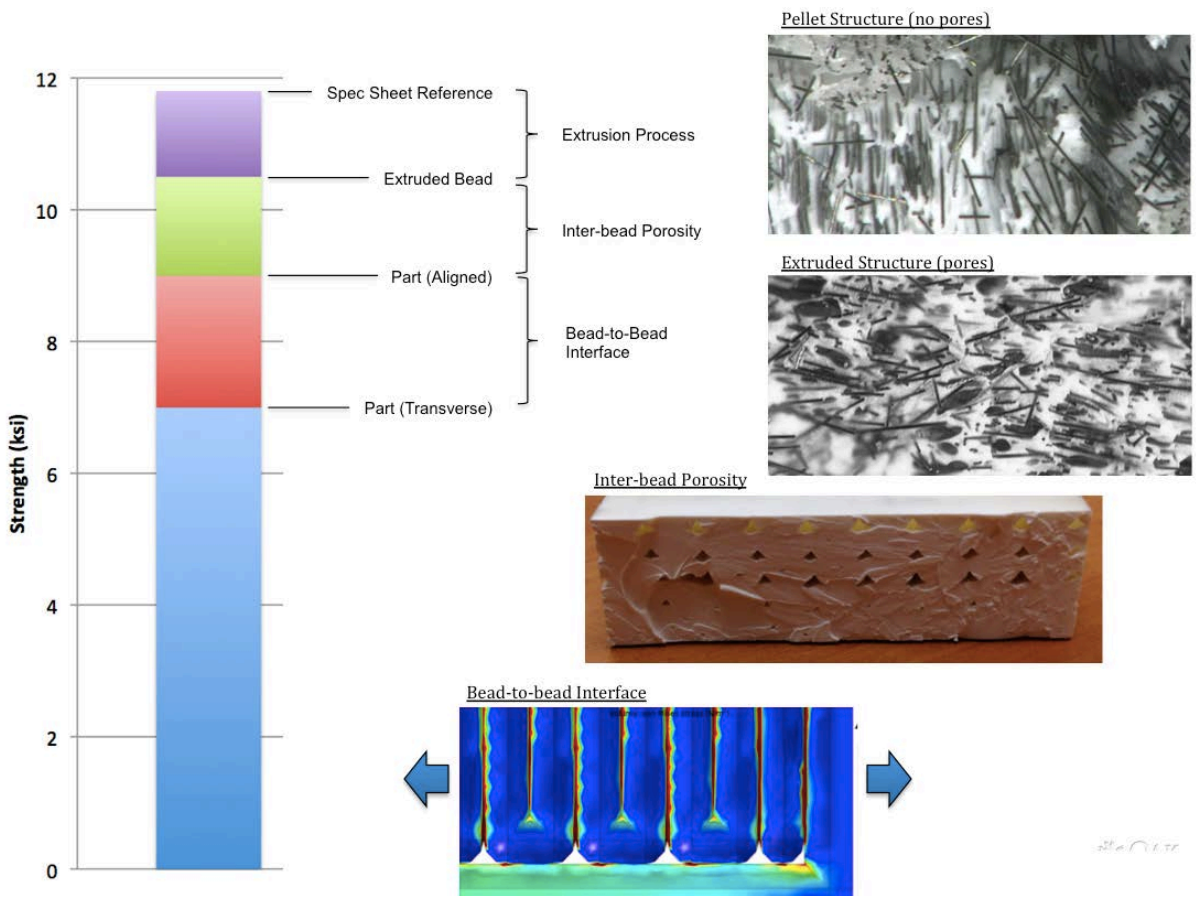

Figure 13: Material property breakdown

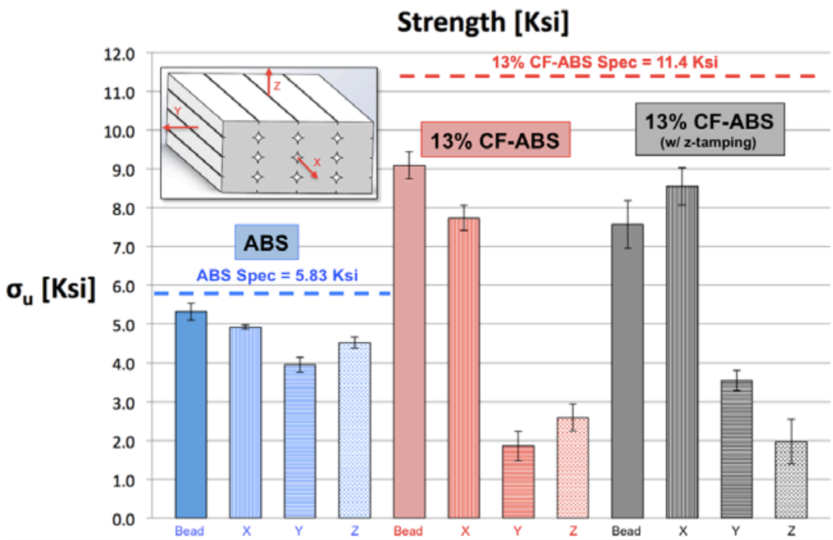

Figure 14: Strength as a function of deposition direction

1.3 IMPACTS

Additive manufacturing has the potential to reduce both the energy required for manufacturing as well as the embedded energy associated with systems manufactured additively. An energy intensity analysis of BAAM revealed that it is not only one of the most energy efficient additive processes, but the energy intensity and production rate of BAAM rivals many conventional manufacturing processes (figure 15). Furthermore, BAAM enables the production of large parts at a low cost at a high rate. The primary application of interest is the tooling industry, specifically focusing on molds for the automotive, aerospace and appliance industries.

There are three fundamental hurdles impeding additive manufacturing's market penetration: speed, cost and size. Conventional AM systems produce relatively small parts (less than 1 cubic foot) at very low rates (less than 5 cubic inches per hour) with high material costs (exceeding $100/lb). BAAM is a complete paradigm shift. It produces very large parts (in excess of 100 cubic feet) at very high rates (exceeding 1000 cubic inches per hour) with very low material cost (less than $5/lb). These shifts due to the technology are opening up many new applications. While ORNL was able to prove out the technology in the laboratory, the partnership with Cincinnati has enabled the technology to rapidly (in under a year) transition to the commercial market with CI having multiple sales (4) of these million dollar machines during the duration of the CRADA with applications ranging from aerospace, automotive and tooling industries.

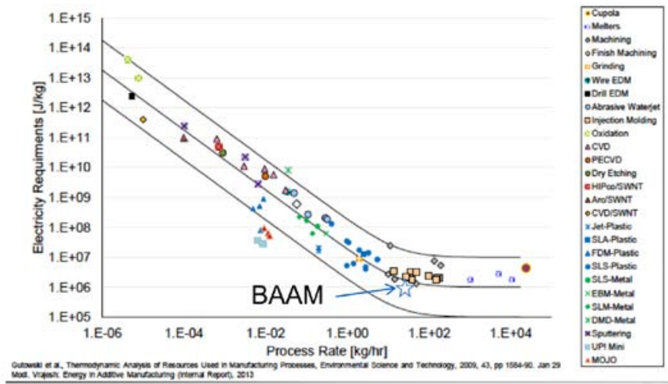

Figure 15: BAAM Energy Intensity

1.4 CONCLUSIONS

The goal of the project was to mature and transition the BAAM technology from ORNL to Cincinnati Incorporated. The ORNL team worked with CI engineers to modify an existing product line to transition from a laser cutting technology to a large scale additive manufacturing machine tool. Specific areas of focus were on the extrusion technology, build platform, control software (both tool path generation and flow control) and processing parameters with material properties. All of the objectives for the CRADA were achieved. CI delivered the first gantry system to ORNL in March 2014. By April 2014, ORNL had incorporated the extruder onto the system. By May 2014, test articles were manufactured. In September 2014, ORNL/CI and Local Motors demonstrated the BAAM at the International Manufacturing Trade Show (IMTS) leading to the successful sale of CI’s first BAAM system. CI now sees the BAAM technology as a critical future product line and is pursuing a multi-year CRADA with ORNL for further refinement and development.

2. PARTNER BACKGROUND

Since Cincinnati's founding in the late 1890's as The Cincinnati Shaper Company, CINCINNATI Incorporated has built its reputation on three principles: innovation, performance and endurance. They built on their leadership with those early machines to begin manufacture of metal fabrication equipment in the early 1920's, and this remains their primary focus. They are one of a handful of U.S.-based, build-to-order machine tool manufacturers, and have shipped more than 50,000 machines in over 100 years of operation. From their modern 500,000-square-foot plant and technical center on a 600+ acre site near Cincinnati, Ohio, they engineer and build machines to the standard of ruggedness required in the North American market – with premium engineering features that stand up to years of rigorous use in demanding environments.