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Lonnie J. Love

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UTILITY OF BIG AREA ADDITIVE MANUFACTURING (BAAM) FOR THE RAPID MANUFACTURE OF CUSTOMIZED ELECTRIC VEHICLES

Author
Lonnie J. Love

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CONTENTS

LIST OF FIGURES

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ABSTRACT

This Oak Ridge National Laboratory (ORNL) Manufacturing Development Facility (MDF) technical collaboration project was conducted in two phases as a CRADA with Local Motors Inc. Phase 1was previously reported as "Advanced Manufacturing of Complex Cyber Mechanical Devices through Community Engagement and Micro-manufacturing" and demonstrated the integration of components onto a prototype body part for a vehicle. Phase 2 was reported as "Utility of Big Area Additive Manufacturing (BAAM) for the Rapid Manufacture of Customized Electric Vehicles" and demonstrated the high profile live printing of an all-electric vehicle using ORNL's Big Area Additive Manufacturing technology. This demonstration generated considerable national attention and successfully demonstrated the capabilities of the BAAM system as developed by ORNL and Cincinnati, Incorporated and the feasibility of additive manufacturing of a full scale electric vehicle as envisioned by the CRADA partner Local Motors, Inc.

1. PHASE 1: ADVANCED MANUFACTURING OF COMPLEX CYBER MECHANICAL DEVICES THROUGH COMMUNITY ENGAGEMENT AND MICRO-MANUFACTURING

Phase 1 of this CRADA project demonstrated the integration of components onto a prototype body part for a vehicle. The project demonstrated that it is possible to use ORNL's Big Area Additive Manufacturing system to manufacturing vehicle body parts with attachment fixtures suitable for automotive applications.

1.1 PHASE 1 BACKGROUND

A key element to Local Motors' (LM) business model is the ability to rapidly manufacture lightweight, highly customized electric vehicles. This project was necessary to demonstrate the ability to rapidly manufacture a custom vehicle using additive manufacturing. ORNL's Big Area Additive Manufacturingtechnology enables the direct digital manufacture of complex structures very rapidly (targeting manufacturing a 500 lb. vehicle body in under two days). The goal is massive part consolidation to enable the development of an electric vehicle with using less than 30 parts. The first phase of this project focused on key enabling technologies such as quantifying the mechanical strength of the materials and integration of fasteners into the structures. The team successfully demonstrated the ability to manufacture a subsystem of the vehicle and conducted load testing to validate the integrity of the materials and structure.

1.2 PHASE 1 TECHNICAL RESULTS

Prior work on large scale polymer additive manufacturing demonstrated the ability to rapidly manufacture large polymer structures using ORNL's Big Area Additive Manufacturing system (Fig. 1). Prior work in filled materials (Fig. 2) enables "out-of-the-oven" additive manufacturing. Note that the addition of carbon fiber (CF) to standard ABS material results in increased stiffness and reduced warping. By working out of the oven, BAAM enables integration of other components onto the system. As an example, it is possible to integrate a machining head (Fig. 3) onto the BAAM to enable fine surface finish and details.

Fig. 1. Big Area Additive Manufacturing at the ORNL MDF.

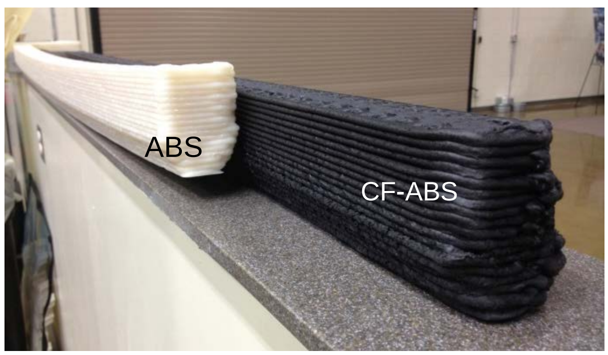

Fig. 2. Impact of carbon fiber filled material.

Fig. 3. Integrated machining head into the BAAM system.

In order to develop a system with integrated components, there were two fundamental tasks executed during this investigation. First, the team focused on manufacturing components with over hangs. A variety of support structures for overhangs were evaluated. Support structures included a pellet bed (Fig. 4) where the parts were surrounded by unmelted pellets, movable fixtures and break away supports. The unmelted pellets proved difficult to use due to the movement of the material during extrusion, leading to poor accuracy in deposition. Movable fixtures consisted of emplacing fixtures into the workplace for support, then removing after the build is complete. This process works extremely well but requires hands on operations. The final approach was break away support. This approach worked best. A support structure was designed into the structure (the front right quarter body wheel well in Fig. 5) then removed after the build was complete.

Fig. 4. Pellet bed support for overhanging structures.

Fig. 5. Break away support for overhanging structures.

The second task focused on attachments. When making a system, mechanical elements such as motors, sensors, etc. must be attached to the body. There are a number of different ways to attach parts to the structure. One approach is to drill and tap holes into the material. However, it was found that the threads were relatively weak and could strip over time. The method that showed the greatest promise was threaded inserts (see Fig. 6). A pilot hole is drilled in the plastic body, and then the insert is heated with a solder iron and pressed into the structure. The material around the insert melts and flows into the insert giving an extremely strong bond. Samples were manufactured using ¼-20 threaded inserts and pulled to measure the holding strength. The polymer has a yield strength of approximately 10 ksi. The inserts pulled out between 1145 and 1355 lbs. A ¼-20 bolt has a stress area of 0.031 in^2. Therefore, the yield stress is between 37.0 ksi and 43.7 ksi, comparable to aluminum. This is due to the fact that the insert spreads the load out over a greater surface than the bolt by itself. This approach to applying fasteners should provide a reliable, strong interface for components to parts manufactured on the BAAM system.

Fig. 6. Threaded insert for component attachment.

1.3 PHASE 1 IMPACTS

The ORNL BAAM system has tremendous potential in terms of manufacturing. The present application area for BAAM is focused on tooling. However, many of the fundamental questions addressed in this project expand the capabilities of the system well beyond making simple structures. Having the ability to manufacture overhanging structures as well as defining reliable methods of attaching BAAM manufactured parts to other components expands the potential application area. This project is focusing on the enabling technologies required for rapidly manufacturing custom electric vehicles. However, success goes well beyond automotive applications. Other applications that are of interest are wind turbine blades. Is it possible to manufacture complex structures for the wind turbine industry at large scale and low cost? More advanced tooling applications require the ability to integrate cooling passages into the structure or integrate actuation for rapid part removal. The major contribution of this project is the demonstration of a path towards large scale manufacturing of systems as well as parts.

1.4 PHASE 1 CONCLUSIONS

The primary metric for success in phase 1for this project was the ability to manufacture a complex structure indicative of what will be developed for Local Motors vehicles. Two specific issues that needed solutions were 1) how to handle overhanging structures and 2) how to securely attach other components to the printed structure. The team successfully demonstrated that structures could be manufactured reliably with overhangs under 45 degrees, and that break away supports were perfectly suitable for manufacturing overhangs that exceeded this limit. The team also quantified the pull out force associated with threaded inserts and measured the yield stress between 37.0 ksi and 43.7 ksi, comparable to aluminum. This approach to embedding mechanical attachment points is reliable, low-cost and rugged.

The next phase of the project was to manufacture a full scale car body. The BAAM system will require advancements in the area of lattice in-fills for weight reduction, actively embedding structures within the build process (motors, sensors, wiring harnesses etc.). The overall objective would be to manufacture a full scale vehicle system by the end of the project. If successful, it will not only demonstrate the feasibility of true additive manufactured vehicles but will also demonstrate the path forward for additively manufactured systems.

2. PHASE 2: UTILITY OF BIG AREA ADDITIVE MANUFACTURING (BAAM) FOR THE RAPID MANUFACTURE OF CUSTOMIZED ELECTRIC VEHICLES

Oak Ridge National Laboratory worked with Local Motors, Inc.and Cincinnati Incorporated to demonstrate additive manufacturing of an all-electric vehicle using ORNL's Big Area Additive Manufacturing technology. The team demonstrated that it is possible to manufacture a full electric vehicle using under fifty parts through BAAM in less than two days by printing and assembling a car live at the International Manufacturing Technology Show (IMTS) in Chicago in September, 2014

2.1 PHASE 2 BACKGROUND

Conventional automobile manufacturing is very centralized. Typically a single car is manufactured on a large complex assembly line integrating tens of thousands of parts into a single vehicle. Tooling costs are extremely high, limiting the consumer to only a few options in terms of color, body style and interior features. Local Motors hopes to radically change automobile manufacturing through the use of BAAM technology. Rather than manufacturing a car through a complex assembly line, Local Motors is pioneering a vision of using BAAM technology to reduce the part count from tens of thousands to less than fifty parts. BAAM enables the customer to have full freedom in terms of body style, either selecting from a wide area of designs or customizing the car to fit their own requirements.

To enable this vision, the team had to demonstrate the ability to successfully manufacture a single automobile body/frame and then integrate a handful of conventional components (battery, electric motor, steering column, wheels and brakes) on to the printed platform. The additive manufacturing process had to successfully print the car body (weighing over 1000 pounds) and include the integration of the conventional drivetrain components. The fundamental metric that defined success was the manufacture of first Strati electric vehicle at the International Manufacturing Technology Show in Chicago in September, 2014. ORNL, partnering with Cincinnati Incorporated and Local Motors, printed the car in 44 hours using ORNL's using ORNL's Big Area Additive Manufacturing technology. To complete the vehicle, the printed body was machined in less than 12 hours and fully assembled in less than 24 hours.

2.2 PHASE 2 TECHNICAL RESULTS

There were two fundamental problems that had to be overcome to enable demonstration of additive manufacturing (AM) of electric vehicles. The first challenge was the ability to integrate conventional components into an AM body. The second issue was the ability to successfully print a very large structure using BAAM.

To integrate conventional components, ORNL and Local Motors worked collectively to identify strong, reliable joining methodologies to merge metallic components with the AM composite (carbon fiber reinforced thermoplastic) parts. The primary joining method that proved successful was the combination of epoxy on dovetailed joints with fasteners to join two composite parts (Fig. 7). When joining metallic components to printed composite parts, the team found that threaded inserts proved extremely effective (Fig. 8).

Fig. 7. Dovetail joint to join two composite parts.

Fig. 8. Metallic bracket for integration of metallic components.

The second major achievement was the successful demonstration of the printing of the full car using BAAM. There were a few hurdles that the team had to overcome. First was the issue of the large thermal mass of the car. The first attempt at printing the vehicle was unsuccessful due to the slow rate of material deposition. The extrusion rate for the first printed car 1 was approximately 10 lb./hr., and printing of the car required six days. At this slow rate, each printed layer would cool down sufficiently enough that layer to layer adhesion was reduced, resulting in delamination (Fig. 9).

Fig. 9. Car 1, showing delamination.

In order to address the thermal, issues car 2 was printed in four segments. Multiple segments reduced the amount of cooling time between layers, enabled increased layer adhesion, and led to the successful print of the full car 2 (Fig. 10).

Fig. 10. Car 2, printed in four parts with no delamination.

However, the material deposition rate of the system used to print car 2 was still insufficient to complete the live demonstration planned for IMTS. Approximately two weeks prior to IMTS, ORNL received a new feed screw design for the BAAM system. The new screw design increased the flow rate from approximately 10 lb./hr. to 40 lb./hr. This increased rate provided the team with the belief that they could successfully print the full car in time. The final car was then fully printed at IMTS in approximately 44 hours (Figs. 11 and 12).

Fig. 11. Full car printed at IMTS.

Fig. 12. Fully assembled Strati at IMTS.

2.3 PHASE 2 TECHNICAL IMPACTS

The BAAM technology holds great potential in terms of low-cost, very rapid manufacture of large composite parts. Conventional additive manufacturing is slow (~1 in3/hr.), limited to small parts (< 1 ft3) and uses expensive feedstock (>$100/lb.). BAAM enables the rapid manufacturing (>1,000 in3/hr.) of large parts (>200 ft3) using low cost feedstock (~$4/lb.). To demonstrate this potential, ORNL partnered with Cincinnati Incorporated and Local Motors for a live demonstration of printing a full size vehicle at the International Manufacturing Technology Show . In front of 110,000 visitors, over a two day period, the team successfully printed the vehicle without any interruptions. This customized body cost less than $4,000 to manufacture. The demonstration received media attention from thousands of sources including the New York Times, Wall Street Journal, Popular Science, Scientific American, Forbes Magazine and the Washington Post, along with an appearance on the Today Show.

2.4 PHASE 2 TECHNICAL CONCLUSIONS

The fundamental metric for project success, demonstrating the printing of a full size electric vehicle, was successfully met. This effort demonstrated to Local Motors the ability of the BAAM technology to print vehicles, and the potential to make very low cost electric vehicles for the general population by additive manufacturing. Local Motors is now purchasing their first Cincinnati BAAM (Ci-BAAM) system and are making plans for building 100 microfactories over the next ten years, with three Ci-BAAM systems planned in each factory. The goal is that each of these factories will locally manufacture approximately 2000 electric vehicles/year. To achieve this goal, the team is exploring robotic emplacement of components, fault detection and increased deposition rate.

3. LOCAL MOTORS BACKGROUND

Local Motors (LM) was founded in 2007 to create a community-based co-creation facility both on-line and physically whereby members could freely collaborate and challenge each other to vet ideas and develop the most desired products as quickly as possible. Local Motors then tied this co-creative community and its ideas to a network of Micro-Factory + Lab spaces whereby it develops these ideas along with the participation of the community members. Development includes rapid product design and iteration in addition to small volume manufacturing. Their 3D printed car project resulted in over 200 detailed designs.