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ORIGINAL ARTICLE

An assessment of additive manufactured molds for hand-laid fiber reinforced composites

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Abstract Composite materials are currently in high demand because of their unique properties, such as high stiffness, light weight, and distinctive appearance. A composite material composed of fibers and a resin can be manufactured through a variety of methods. One such method typically used for low production volume and custom applications is the hand layup method, which involves manually combining fibers and resin on a mold surface. For large quantity manufacturing and production of composites, molds are typically made out of a highly durable material like aluminum or steel. The initial investment of the mold is recovered through the manufacturing of numerous parts. However, in low volume and one-off productions, molds are typically handmade by a composite technician, which increases the cost to manufacture a part. The objective of this project was to use large area additive manufacturing, commonly known as 3-D printing, to create molds for these small scale production runs and assess the ability to use them for hand layup composites. After printing, some molds were treated with various surface coatings, and others were machined by a CNC mill. The finished molds were used for hand laying of fiberglass parts in order to assess the durability and resulting surface quality. It was found that printed molds could be an effective approach for limited production runs (4–5) of fiber reinforced composite parts, depending upon the mold shape, surface finish, and coating composition.

Keywords Additive manufacturing · Composite materials · 3-D printing · Manufacturing techniques · Molds

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1 Introduction

Fiber-reinforced composite materials serve a vital role in creating light weight and high-performance materials for modern applications. The rapid prototyping and cost-efficient production of limited volume composite parts are both vital to the success of competitive business practices [1–3]. In order to reduce design cycle and production times, companies must produce highly representative prototypes, plugs, and molds. Rapid tooling and prototyping can be made from a variety of computer-aided manufacturing processes like stereo lithography [3]. For large-scale tools, one-of-a-kind female molds are constructed from a male plug that is traditionally handmade by skilled technicians over the course of several weeks. In addition, the accuracy and design of both the mold and plug are inherently limited by the skill and experience of the artisan worker, which can be highly variable across the industry. One way to improve reliability and decrease the tooling cost and production time associated with developing a mold is through additive manufacturing [4, 5].

Additive manufacturing (AM) is the process of building a part through the deposition of multiple layers. Parts are designed with computer aided design (CAD) tools and virtually

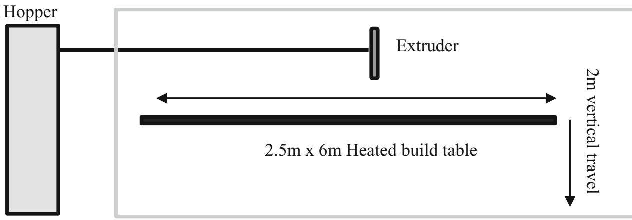


Fig. 1 Block diagram of Big Area Additive Manufacturing. The 300-kg capacity hopper uses forced air to convey pellets to a smaller hopper at the top of the extruder. Pellets are heated through a five zone heating element and shear energy, and beads are deposited onto a heated platen

sliced into layers suitable for AM processing using specialized software. Generally, AM has more freedom for advanced geometric patterns and designs when compared to subtractive manufacturing, like machining [6]. Some studies have examined the use of AM in the composite industry by rapid prototyping a plug, which is then coated in silicone to obtain a soft mold [5, 7]. Case studies have also shown that companies like John Deere are using AM for printing sand casting molds [8]. However, no other studies have used AM to directly print molds or plugs for hand layup or vacuum resin transfer of composite materials because traditional 3-D printers are typically restrained to small print beds and slow deposition rates. Cincinnati Incorporated's Big Area Additive Manufacturing (BAAM) system in the Manufacturing Demonstration Facility at Oak Ridge National Labs (ORNL) overcomes these restraints.

BAAM is a large-scale, industrial grade approach to additive manufacturing, similar to Fused Deposition Modeling (FDM™) that uses a gantry-mounted, high-throughput single screw extruder. Figure 1 illustrates how the BAAM system typically operates.

The hopper outside the machine dries approximately 300 kg of material and delivers the material to a pellet fed extruder inside of an enclosed environment. The environment is not actively heated, but maintains temperatures of up to 50 °C because the deposition surface is heated to 130 °C [9]. Two of the key features unique to BAAM is the use of a single screw extruder and high speed linear drives. Whereas most existing commercial polymer extrusion machines melt continuous filament strands and extrude the melted plastic in a bead ranging from 0.1 to 0.3 mm diameter at a rate of approximately 20 cm^3/ h, BAAM deposits beads that range from 4 to 7.6 mm diameter at a rate of 5000 cm^3/ h. The build area of BAAM is 2.5 m by 6 m by 2 m. Additionally, BAAM uses pellets instead of continuous filament, which allows the system to utilize a variety of materials, including carbon fiber reinforced acrylonitrile butadiene styrene (CF-ABS), polyethermide (Ultem™), and polyphenylene sulfide. These pellets are commonly used in the injection molding and extrusion industry and as a result, are approximately six times cheaper than continuously wound filaments [6, 10]. Because of these cost savings and faster production times, BAAM is ideal for rapidly producing tools.

This study examines the durability and expected life cycle of molds printed on the BAAM system for hand layup of fiberglass composites. A variety of surface treatments was applied before making a composite part from the printed mold.

2 Experimental procedure

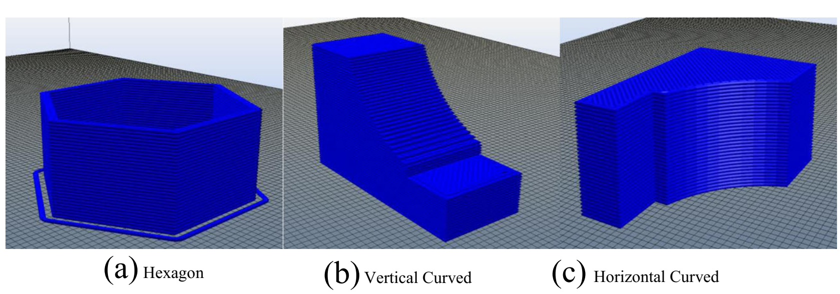
2.1 Molds

The BAAM system was used to print out two types of molds using CF-ABS. Carbon fiber-reinforced ABS pellets were chosen because of its ease of processability and relatively low cost. At the time of this research, the extruder on the BAAM was limited to a maximum of 350 C, which is too low for most high performance plastics. In addition, CF-ABS costs around $10 per kilogram, whereas high performance plastics can range between $20 and $100 per kilogram.

Two identical, hexagons with 10 cm by 15 cm molding surfaces (Fig. 2a) were printed to test durability of various coatings on simple flat surfaces. In addition, two identical, 30 cm by 20 cm "curved molds" were printed to test the effect of machining molds with curves and sharp angles at different orientations (Fig. 2b, c). Figure 1 shows the planar and curved molds as designed and sliced in the CAD software, and Fig. 3 shows the geometrically curved molds during and after the printing process.

The extruded CF-ABS is deposited in a "bead." The bead is then pressed onto the existing surface through a vibrating tamper. The tampering process flattens the circular cross

Fig. 2 CAD diagram of planar mold, vertical curved mold, and horizontal curved mold



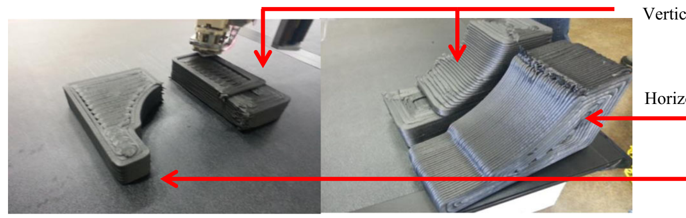


Fig. 3 During and after printing of the curved molds

section into an oval cross section, which minimizes the voids between layers of materials [11]. To achieve a smooth outer surface on the fiber reinforced composite (FRC) part, each of the printed surfaces of the first hexagon were treated with a different commercially available epoxy. Table 1 lists these coatings by manufacturer and appearance. The coatings on the surfaces of the second hexagon were identical to the first, but the mold was also treated with an adhesion promoter between the printed surface and the coating. After the coatings cured, they were sanded and polished.

Although it is possible to achieve the desired surface roughness by machining the printed components, machining also exposes large voids at the intersection of deposited beads. The frequency and size of these voids depends on the print orientation. Because the beads of the BAAM system have an oval cross section, the orientation of the bead changes the amount of contact area across the layers. When the beads have more contact area, the machined surface is less likely to have voids. As shown in Fig. 4, the direction of the machined surface relative to the spacing and orientation of the deposited bead can have a significant impact on the quality of the resulting surface. If the machined surface is parallel to adjacent beads, the size and frequency of the voids can be minimized, such as with "horizontal" or "vertical" cuts. However, machine paths that cross deposited layers at shallow angles can generate large surface defects. In this study, the machined surface of the vertical curved mold cuts across layers at a shallow angle while the machine path for the horizontal curved mold consistently intersects the center of the outermost deposited bead (similar to the vertical cut sketched below). This should result in the horizontal curved mold having a significantly better surface finish in the "as machined" state. The CF-ABS was machined with carbide bit at a machine feed rate of 10 cm per second, a spindle speed rate of 1450 RPM, and without cooling fluid. The time to machine both molds was approximately 4 h. After the curved molds were machined, the surfaces were scanned with a FARO Arm 3-D scanner in order to document the mold's surface dimensions.

Table 1 List of surface coatings on planar surfaces

Manufacturer	Product
Valvoline PlioGrip	Plastic Repair 3
Valvoline PlioGrip	Finishing Cream
Valvoline PlioGrip	Panel 60
Clausen	Z-Chrome Z-Glass
3 M	EZ sand Flexible Parts Repair Adhesive
3 M	Dent Filling Compound Body Filler

2.2 Layup procedure

Six plies of fiberglass chopped-strand mat were cut to cover the mold and slightly overhang for easy removal. Before each layup, the molds were waxed with 5 layers of TR 104 high temperature mold release compound. Orca 555 Vinyl Ester resin was initiated with methyl ethyl ketone peroxide (MEKP). Because the purpose of these experiments was to determine the durability of the molds, the resin and MEKP were combined in a ratio that increased the heat exerted by the exothermic reaction, while also retaining a workable pot-life. For this experiment, MEKP composed 6 % of the total resin volume for the planar molds, and 5 % of the total resin volume for the curved molds (Fig. 5).

The mixed resin was brushed directly onto the mold and between each layer of fiberglass mat. Once all the fiberglass plies were placed, a roller was used to evenly distribute the resin. After the part returned to room temperature, the mold was placed in a vice, and the part was removed, or "pulled," by hand.

3 Results

Because the objective of this project is to observe the durability of an additive manufactured mold, the results are quantified as the number of pulls completed for each surface treatment. The requirements for a tool are generally derived from

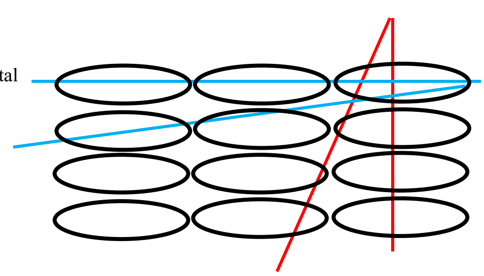


Fig. 4 Cross section of a printed part, where the *dotted line* represents machining path

Fig. 5 Fiberglass composite cured on a planar mold

the unique part specification. For example, a tool with a surface finish better than a 0.25-μm RMS is generally required for smooth parts; however, fenders for agricultural or construction equipment may also have molded step areas that require a specific texture to create a non-slip area. This market has historically been driven less by scientific specification and more by experience and results. As such, a mold is acceptable if the parts it produces are acceptable. A successful pull was defined as a pull that did not cause any adhesive or cohesive failures in the surface coating. An adhesive failure is the de-bonding of one material from a different material. In our test, the epoxy coatings generally failed adhesively by completely pulling apart from the printed surface (Fig. 6 left). Cohesive failure is characterized by the de-bonding of a material from itself. During the pull tests, some of the coatings cohesively failed by having small portions of the coating pull apart from itself. This process left most of the epoxy on the surface, but the missing pieces caused an uneven molding surface that was not suitable for further use without mold repair (Fig. 6 right). All of the coatings on the planar mold without adhesion promoter adhesively failed on the first pull. The results of the pulls

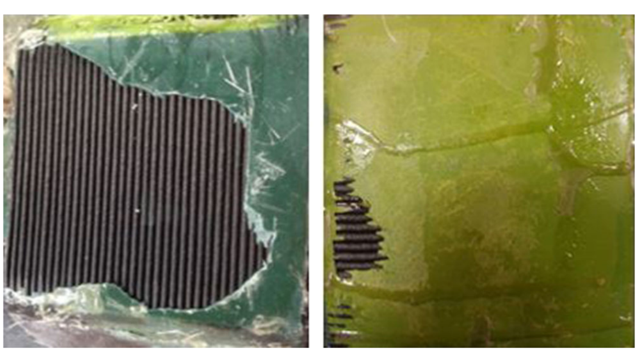


Fig. 6 Adhesive failure of 3 M dent filing compound (left) and cohesive failure of Clausen Z-Chrome Z-Glas (right)

Table 2 Surface coatings results

Manufacturer	Product	Pulls endured	Failure type
Valvoline PlioGrip	Plastic Repair 3	4	Adhesive
Valvoline PlioGrip	Finishing Cream	4	Cohesive
Valvoline PlioGrip	Panel 60	1	Adhesive
Clausen	Z-Chrome Z-Glass	4	Cohesive
3 M	EZ sand Flexible Parts Repair Adhesive	4	Adhesive
3 M	Dent Filling Compound Body Filler	3	Adhesive

from the hexagon with adhesion promoter are given in Table 2.

After the first pull on both the horizontal and vertical curved molds, the pattern of the fiberglass mat was imprinted onto the machined surface, as shown in Fig. 7. The imprinting of the fiberglass mat resulted from the exothermic reaction of the MEKP initiator, which reached temperatures of 93 °C during the curing process [12].

If surface quality were the deciding factor for a given FRC product, then the machined molds tested here would only last one pull. For applications where the surface quality of the part is not a decisive factor, the machined molds could last longer. In our experiment, molds were deemed too rough for further FRC production after five pulls due to a degradation of the ABS. Figure 8 shows the molding surface of the FRC parts after each pull. The first part is characterized by a smooth surface with miniscule amounts carbon fiber and ABS. Some of the carbon fibers from the printed mold were removed with the second part. The amount of removed mold material increased after each additional pull.

After five parts were pulled from the molds, each of the molds was scanned again with the FARO Arm and a deviation analysis was generated for the machined surface compared to the surface after experimentation. Fig. 9 plots the geometric deviation across the mold surface for the vertical curved mold. The average deviation between the machined surface and the used surface was +/− 0.165 mm, and the RMS finish was 294.64 μm. In general, the tool had one large area on the curved surface where material was removed and smaller areas where vinyl ester resin compiled. The horizontal curved mold had similar deviations and surface finish.

4 Conclusions

The goal of this research was to establish the potential of direct production of a hand-laid composite tool using Big Area Additive Manufacturing. A more traditional approach for producing a similar male tool would involve layering a tooling

Fig. 7 Machined surface of ABS-carbon fiber "horizontal curved mold" (*left*), pattern of fiberglass (*middle*), and imprint of pattern onto machined surface

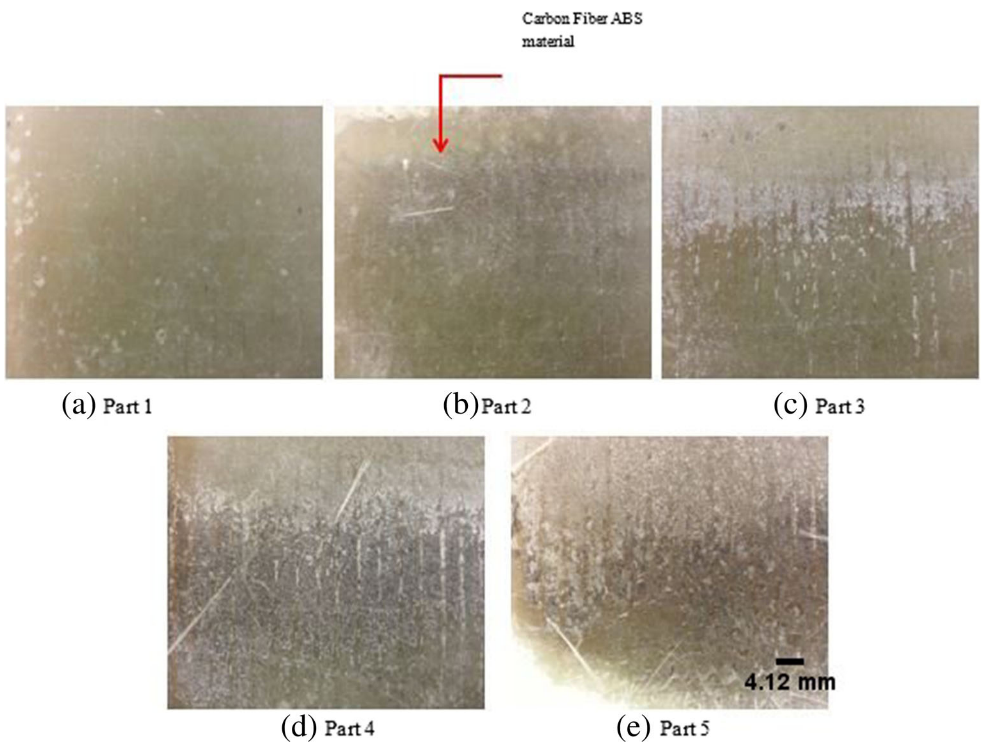


Fig. 8 Comparison of surface for FRC parts on the horizontal curved mold. The images illustrate a progression of the CF-ABS material removed after each successive pull. In the first pull (**a**), small amounts of mold material are removed. The fourth part (**d**) has the largest amount of CF-ABS build up. The bead width of the printed molds is 4.12 mm

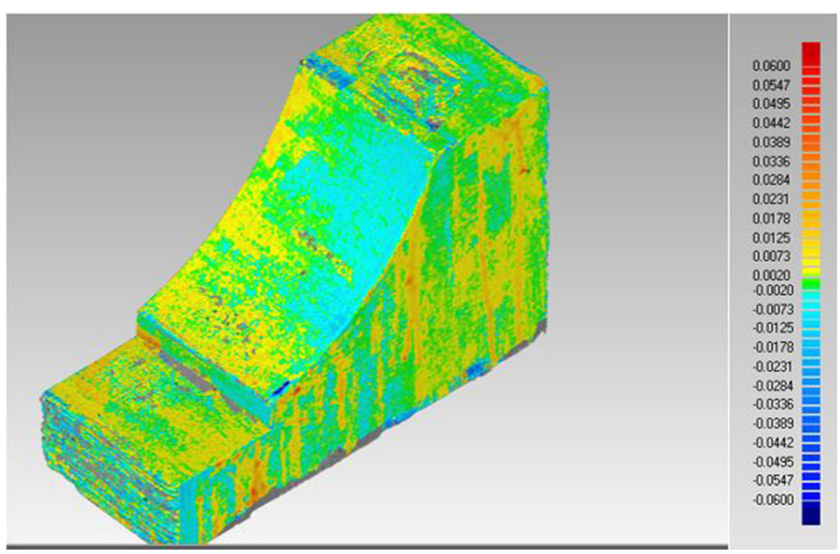


Fig. 9 Deviation analysis image of vertical print orientation from Geomagic 3-D modeling software

Fig. 10 Curved mold after pulls. The whitening of the surface indicates rough spots from FRC pulls

material such as urethane modeling board or medium density fiberboard, cutting the tooling preform to the required geometry with a CNC router or mill, or surfacing the tool with an appropriate epoxy or polyester surface. In this study, we 3-D printed planar and curved molds on the Big Area Additive Manufacturing system at Oak Ridge National Labs. The surface of the hexagon was treated with commercially available epoxies, and the surfaces of the curved molds were CNC milled. A 6-ply fiberglass composite part was hand-laid on the molds using an aggressive 6 % initiator proportion. After curing, the composite was pulled off the tool, and the process was repeated. The durability of the molds was characterized based on the number of pulls successfully completed. The integrity of commercial coatings on the planar surfaces was found to be significantly improved by first applying an adhesion promotor. However, none of the coated planar samples exceeded four cycles before adhesively or cohesively failing. The curved surface molds that were machined performed the best, each surviving five pulls without excessive surface damage—irrespective of print orientation. The total number of pulls per part was lower than that of a traditional mold, where hundreds or even thousands of pulls are required for cost recouping. Whereas traditional molds require weeks of hand labor, the curved molds were printed in 1.5 h and machined in 4 h. In addition, these molds used approximately $60 worth of material per mold. Assuming an aggressive cost of $250 an hour for both printing and machining [4], the cost to manufacturing one mold is below $1500. Another example of cost savings from BAAM printed tooling is the production of a wind turbine blade mold printed by Oak Ridge National Labs. Currently, a 30-m wind turbine blade mold has an estimated $1.5 million tooling cost [13]. A similarly sized mold was printed on BAAM for a total less than $200,000, including material costs and machine time for both printing and milling [4]. This study demonstrated that additively manufactured molds can be used for limited production of FRC parts as an alternative to traditionally manufactured molds (Fig. 10). Future work is being conducted to examine high performance plastics, like Ultem and PPS, for tooling in autoclave environments.

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