Additively Manufacturing Molds for Low Cost, Geometrically Complex Fiber-Reinforced Resin Structures

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With their increased usage in industry, composite structures are gaining traction in student projects. Along with high strength-to-weight ratios, one of the largest benefits of fiber reinforced plastics is their ability to take the shape of any mold they are placed on. A large design constraint is the production of the mold, which is traditionally created using subtractive manufacturing techniques. Student groups do not always have access to the computer controlled machining capabilities necessary to produce geometrically complex profiles, and hand manufacturing the molds often deviates from the desired geometries. Due to falling prices, 3D printers are more commonly being purchased by student groups for rapid prototyping and manufacturing with plastics. However, the plastic additively manufactured components have low strength-to-weight ratios and are susceptible to deformation with rising temperatures. By laying up composite over additively manufactured molds, the manufacturability and precision of rapid prototyping is combined with the mechanical properties of composites to provide student groups an accessible, low cost way to produce components for flight vehicles. This paper explores the history, capabilities, limitations, and benefits of additively manufactured molding for composite structures, along with its implementation on a liquid propelled flight vehicle.

I. Introduction

In recent history, composite structures have revolutionized aerospace design for their high strength-to-weight ratio. Across industry, materials such as carbon fiber and fiberglass have been increasingly used on mass sensitive vehicles, such as planes and rockets, to allow for increased payload capacity without leaps in propulsion development. With its rise in industry, University groups began introducing composite structures into their flight vehicles. Once raw materials for composites are purchased, the largest barrier to student use is the manufacturing of molds. If the only mold production methods considered are the standard techniques seen in amateur and industrial use, precision or cost must be sacrificed. However, there is another process revolutionizing industry: 3D printing. Due to expiring patents, 3D printers are increasing in capability and falling in price. Additionally, a plethora of printers are easily available to purchase through mass market retailers and require little assembly and knowledge. Because of this, many student groups have purchased 3D printers and now have a machining solution that is reasonable cost with acceptable precision. These printers are used to create prototypes or create components where the strength-to-weight ratio can be low.

In student applications of composite molding, the molding materials typically are not required to have a high strength-to-weight ratio. However, the mold does often need to match a specific geometry optimized via computer modeling. Computer modeling is one of the best methods for validating designs of single components, as it is low cost and reduces the number of design concepts manufactured and tested. Because 3D printers operate on code derived from 3D models, the printed part closely matches the simulated geometry. Laying up fiber composites over an additively manufactured component would allow the composite to form to the required geometry, effectively solving the problem of mold manufacturing for small groups.

II. Background

Fiber-resin composites first saw use at the end of World War II; in the following decades, many groups have developed methods for molding the composites. From multinational companies to amateur hobbyists, the cost and precision of molding is widely varied from use case to use case.

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A. Traditional Molding in High Power Rocketry

In amateur high power rocketry, most solutions for the creation of molds have been developed to combat the primary drawbacks of industrial methods. Methods are meant to be both low cost and accessible to groups with limited manufacturing capabilities; they primarily rely on common materials and simple power tools available at local hardware stores. With the exception of cylindrical mandrels, most molds constructed for high power rocketry applications are female, as male molds do not provide as much control over the aerodynamic surface. These female molds are traditionally the negative of a hand-shaped male part, called the plug. The plug is made of low cost material and typically manufactured with additive sculpting, subtractive sculpting, or woodturning. Another material is used to encase the plug and create the female mold. The final composite material is then layered into the female mold and left to cure. While the handmade plug greatly reduces machining and material costs, the molds and final parts often deviate from desired geometries due to human error. While this is not typically a large concern for hobbyists, student groups rely on consistent profiles to match the flight performance predicted in simulations, because they are using the vehicle to achieve a specific goal. The tolerance of error cannot be quantified due to the inherent inconsistency of hand making the plug, leaving student groups unable to predict performance.

Fig. 1 Hobbyist Profiling Male Plug on Woodlathe [1]

B. Standard Molding in Industry

In standard industry applications, molds are constructed using advanced, computer controlled subtractive manufacturing techniques. As with amateur molding, the molds can either be male or female, depending on the geometries required by the part. However, the mold typically must be strong enough to withstand more aggressive layup techniques, such as autoclaving; to withstand the conditions, materials such as steel, aluminum, or Invar are employed. The mold then must last through thousands of use cycles to offset the high upfront cost of the mold material. If less aggressive manufacturing techniques are planned, molds can be made out of composite billet stock or high temperature plastics; however, the molds then run a higher risk of breaking and having to be remanufactured at additional cost.

Fig. 2 Industrial Male- Female Mold [2]

Once stock is purchased, material must be removed with CNC manufacturing techniques, which allow for very tight production tolerances. With the increasing use of 5 axis CNC mills or mill turns, manufacturing time for these components has dropped in recent years. However, the machines capable of these complex operations are expensive, and the additional costs of subtracted material quickly rises as complexity rises, making this option difficult to implement for small, less funded groups. There also can be significant difficulty in the machining molds due to special tooling requirements, especially molds made from Invar or composites. These costs and difficulties serve as a barrier to entry for student organizations and small companies, as most cannot afford the high prices of materials and do not have ready access to the facilities or the personnel required for CNC machining.

C. Additively Manufactured Molding in Industry

Companies have long sought to reduce the costs and design limitations of subtractively manufactured molds. The increase in the resolution and material variety for additive manufacturing machines has led to many different companies in the aerospace and automotive fields experimenting with additively manufactured molds for composites. Foremost among the companies improving additive manufacturing is Stratasys, whose fused deposition modeling technology forms the backbone of most commercial 3D printers available on the market today. Outside of obvious material savings, 3D printers offer two large advantages. The first is the quick turnaround time between parts. If the first iteration of a part is faulty, then it can be reprinted as soon as it is redesigned. With traditional manufacturing techniques, there is a high lead time on replacement stock and additional design processing for the manufacturing of iterative parts. The second advantage of additive manufacturing is its precision. Affordable desktop 3D printers can create parts with tolerances that are well within acceptable ranges.. Printers can also easily create geometries that would otherwise require complex, multi-axis CNC operations, as well as some geometries that would be otherwise impossible to machine using subtractive techniques.

Fig. 3 3D Printed Molds from Stratasys Tooling Design Guide [3]

Stratasys, a company leading the development of 3D printing, has recently developed a new method of mold construction called sacrificial tooling. Male molds are printed from water or acetone soluble material, and fiber composites are laid up over the mold. After the composite is cured, the printed mold is washed out. This allows for geometries that were previously impossible to manufacture without connectors, such as converging-diverging shapes. The primary barrier to entry for utilizing sacrificial additive manufacturing techniques is the cost of large, high end printers. To have a successful sacrificial mold, the print needs to be a single piece that doesn't require epoxies for joining or additional filler for sanding. While the price of desktop printers is quickly dropping, they lack the required build volume and resolution for large-scale molding projects using the sacrificial technique. Sacrificial molding requires the usage of much larger industrial scale printers, which present the same problems to student groups as CNC capable machines. Their high cost and complexity serve as formidable barriers to student organizations and small businesses seeking to implement their usage.

III. Using Additive Manufacturing to Reduce Mold Costs

With the benefits and limitations of previous techniques in mind, a new method combining more precise manufacturing with the cheaper amateur molding was developed using additively manufactured components as the mold. For female molds, the plug is 3D printed, and fiber-resin composite is used to make the mold. The composite mold is then laid up into to create the final part. For male molds, a 3D printed component is used as the mandrel for laying up the part. By basing geometry on additively manufactured parts, the final part matches the geometry of its 3D modeled parent component.

A. Process

To begin, the use case of the desired part must be considered. While female molds provide smoother surfaces, male molds are easier to compress through wrapping or vacuum bagging. If the part must perform both aerodynamic and structural roles, a combination of male and female mold may be required. Once the mold method is determined, a 3D model of the mold is created. 3D printers operate using G-Code, which can be created from the 3D model using any number of free programs. An example of a free program with user-friendly interface is shown in Figure 4.

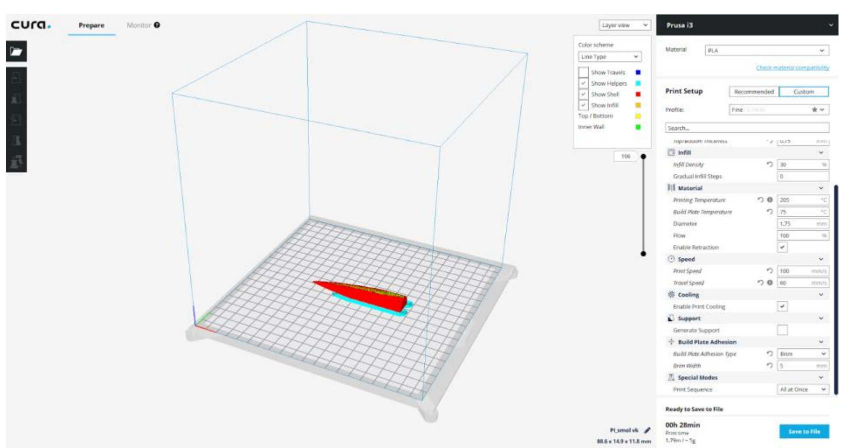

Fig. 4 Workspace of Cura, a free to use 3D printing slicer[5]

This software allows users to easily control many aspects of the print, including layer height, build temperature, and fill densities. Creating a complex shape such as the one shown in Figure 4 for subtractive manufacturing would require an experienced machinist, expensive toolpath generating software, and excess material for clamping along the bottom edge. If the part is larger than the build space of the printer, the 3D model can be divided into multiple pieces. Additionally, indexing features such as tongues and grooves should be added so that the mold can be easily assembled once all pieces are complete. Any print intended to be used as a mold should have minimal layer thickness to reduce the deficits between layers and create the smoothest surface possible. While it may lengthen the print time, it greatly reduces the post-processing time for the mold.

Once the print is complete, the largest challenge of post processing is smoothing the print surface for layup. On high quality printers, the print is often smooth enough to layup onto with only a release layer. However, for lower quality prints with larger layer sizes, there are many ways to achieve a smooth surface. Depending on the print material, a chemical bath alone may be sufficient. If the material is not able to smooth itself, a filler is the next best option. A traditional filler used in amateur rocketry is wood filler, and it does a satisfactory job adhering to the surface of the print without deformation while remain workable. A thin layer of filler should be applied over the entire surface of the print and then sanded until the print layers are visible. This process should be repeated until all significant areas of loss are filled. Once the surface is filled, it should be primed and sanded. Spray primer provides an even coat without brush strokes or runs. The part should then be sanded a final time and sprayed with gloss paint, to create a smooth, non-porous surface.

If the part is acting as a male mold, the fiber-resin composite for the final part is laid up, compressed, and cured on the 3D printed part. If the part is intended to be a plug for a female mold, it is placed into a parting board, so that one half of the mold can be created. To create the first half of the mold, fiber-resin composite is laid up over the combined plug and parting board. Once the first half is cured, the parting board is removed. The second half of the mold is then laid up onto the first half of the mold with the plug. Once cured, the halves are separated, the plug is removed, and the final part is then laid up into the 2 part female mold.

Layup processes are not incredibly varied in rocketry and industry, with the largest differences usually being material, not procedure. Due to the similarities, many layup processes for both male and female molds could be implemented with equal success. The exception to this rule is any layup process involving excessive heat, such as autoclaving or high-temperature curing, due to the low glass transition points of most readily available additive manufacturing materials. If an additively manufactured mold must be heated, there are select heat resistant filaments that can be used

B. Case Study: Nose Cone on Student Manufactured Liquid Rocket

This theoretical process for mold manufacturing is currently being implemented for the liquid rocket airframe for Space Hardware Club (SHC) at the University of Alabama in Huntsville (UAH). To reduce weight while maintaining sufficient structural integrity, the team planned on creating their 6.125 inch by 33 inch nose cone with a fiberglass layup. Because the nose cone primarily sustains aerodynamic forces, a female mold was selected to control the finish of the aerodynamic surface as much as possible. To reduce cost and use existing materials, it was decided that the mold itself would also be fiberglass. When deciding on the material and method for manufacturing the plug, there were many viable options. These options are shown in Table 1.

Table 1 Analysis of Material Choices

Material	Stock Cost	Time Required	Machinability
Aluminum	~$450	1 Hour CAM 2 Hours Machine Prep 3 Hours Machining	Diameter Exceeds Dimension of CNC Lathe Workspace
Acetal	~$480	1 Hour CAM 2 Hours Machine Prep 2 Hours Machining	Diameter Exceeds Dimension of CNC Lathe Workspace
HMPE (High-Modulus Polyethylene)	~$320	1 Hour CAM 2 Hours Machine Prep 2 Hours Machining	Diameter Exceeds Dimension of CNC Lathe Workspace
Carbon Foam	Free to SHC	1 Hour CAM 2 Hours Stock Prep 2 Hours Machine Prep 1 Hour Machining	Diameter Exceeds Dimension of CNC Lathe Workspace
3D Printed	~$50	30 Minute G-code ~24 Hour Print (autonomous)	Can Be Printed In Multiple Sections

C. Manufacturing Process

Each option using a subtractive manufacturing technique had similar drawbacks. The Haas TL-1 CNC lathe at UAH has a maximum workspace diameter of 6 inches, and the maximum diameter of the part was 6.125 inches. While creating a subtractively manufactured plug in separate parts or adding material after turning was considered, the cost in combination with respective complexity or inaccuracy drove the team towards using an additively manufactured mold. Because the workable area has to be so long, a support jig would have to be created and mounted on the tailstock of the lathe, which is why the machine prep time is longer than usual. The main setback of 3D printing was the time required; however, the printing hours are not man hours for the 3D printing, as the printer operates autonomously once the print begins and does not require supervision. Additionally, the dimensional issue on the 3D printer could be solved by printing the part in multiple sections whereas the dimensional issue with the lathe would require the use of an additional machine.

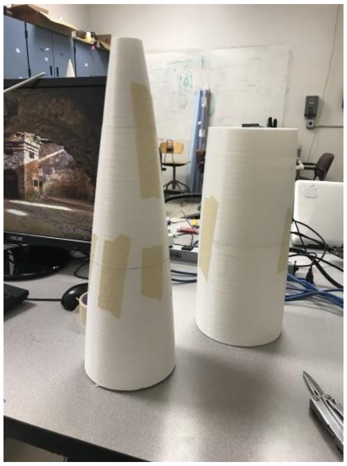

Fig. 5 Printed Plug During Assembly Process

Because the team was on a tight schedule and needed a proof of concept, a thin plug was printed in mid-December of 2017, with printer settings and component structure optimized for low cost and short print time. Using roughly $25 of filament, it had minimum fill and maximum layer height and is shown in Figure 5. At its thinnest, it was 1/10th of an inch. It was printed in 5 sections to fit within the printer, and the five sections were joined using epoxy fillets. Once the sections joints were cured, the plug was filled and sanded until smooth, then painted bright orange to highlight any remaining flaws and create a glossy, non-porous surface. The plug was then placed in the parting board as seen in Figure 6. The team ran into a problem when waxing the assembled plug and board in preparation for layup. Pure carnauba wax was used to smooth the surface of the plug and the parting board. As one of the hardest waxes available, carnauba wax requires heating to become workable. A mistake was made when the solid wax was placed on the parting board and then heated, causing the thin and delicate printed plug to deform due to the proximity to heat. The plug was

Fig. 6 Plug Placed in Parting Board

removed from the board, and a more robust plug was printed, now that the filling and smoothing processes had been demonstrated. As of February 2018, the new plug was in the smoothing process, with projected layup within the first week of March.

D. Limitations

Just as with any other machining technique, there are limitations on what additively manufactured molds are capable of. Because additive manufacturing works layer by layer, prints will often have pronounced ridges over the entire surface, especially if the print settings were optimized for speed or the printer was low quality. This leads to increased post processing time and more filling material required. In addition to this, the most affordable printers have build plates that may be too small for single piece prints in some applications. While creating indexing parts is easier with additive manufacturing, any joint between 2 prints will require more filling and sanding than a single piece print. As seen in the case study, the printed molds are also subject to deformation under thermal loads if a material with poor thermal qualities is used for the print.

The thermal issues can be combated by using an extrusion material with better thermal properties. On the cutting edge of additive manufacturing, metal 3D printing is gaining acceptance and lowering in price. If metal 3D printing follows the same trend as plastic 3D printing, it may be a better option for student groups needing a heat resistant mold. It would also increase the overall robustness of the mold, meaning it could be used across multiple projects and reduce costs for years after initial manufacturing, similar to the effects of industrial CNC metal molds. However, at this time, the cost presents the same barrier to entry of other industrial processes.

IV.Conclusion

Between industrial mold creation, amateur mold creation, and this method, additively manufactured mold creation is neither the cheapest nor the most accurate. However, it strikes the middle ground sought by student groups; reasonable accuracy at a reasonable cost. With additive manufacturing, a student only has to create a 3D model of the part, export it into a G-Code-creating program and input desired print settings, then export the G-code to the printer. This quick, simple process is conducive to student projects, where designs rapidly change as more knowledge is gained or testing shows inadequacies in prior designs. Additively manufacturing molding gives students capabilities not often seen in any other facet of student projects, lowering both the cost of and the knowledge required for precision manufacturing.

V.Acknowledgments

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