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An Evaluation on the Effectiveness of a 3D Printed Composite Compression Mold

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***Abstract*—**The applications of composite materials within the aviation industry has been increasing at a rapid pace. However, the growing applications of composite materials have also led to growing demand for more tooling to support its manufacturing processes. Tooling and tooling maintenance represents a large portion of the composite manufacturing process and cost. Therefore, the industry's adaptability to new techniques for fabricating high quality tools quickly and inexpensively will play a crucial role in composite material's growing popularity in the aviation industry. One popular tool fabrication technique currently being developed involves additive manufacturing such as 3D printing. Although additive manufacturing and 3D printing are not entirely new concepts, the technique has been gaining popularity due to its ability to quickly fabricate components, maintain low material waste, and low cost. In this study, a team of Purdue University School of Aviation and Transportation Technology (SATT) faculty and students investigated the effectiveness of a 3D printed composite compression mold. A 3D printed composite compression mold was fabricated by 3D scanning a steel valve cover of an aircraft reciprocating engine. The 3D printed composite compression mold was used to fabricate carbon fiber versions of the aircraft reciprocating engine valve cover. The 3D printed composite compression mold was evaluated for its performance, durability, and dimensional stability while the fabricated carbon fiber valve covers were evaluated for its accuracy and quality. The results and data gathered from this study will determine the effectiveness of the 3D printed composite compression mold in a mass production environment and provide valuable information for future understanding, improvements, and design considerations of 3D printed composite molds.

***Keywords*—**Additive manufacturing, carbon fiber, composite tooling, molds

I. Introduction

THE rapid increase in popularity of composite materials in the aerospace industry today is mainly due to the composite material's superior capability over traditional aerospace alloys such as aluminum and titanium. The aerospace industry has continuously invested in numerous research and advancements to further improve the understanding of these composite materials [1]. As the aerospace industry's demand for utilizing composite material increases, the demand on manufacturing tooling also rises. Manufacturing tools such as production molds account for a large portion of the cost involved in the production chain of composite components. The manufacturing tools also play a large role in determining the overall quality of the resulting composite component. Therefore, the rising demand on manufacturing tools heavily emphasizes the importance of the aerospace industry's ability to produce and maintain tooling to the highest quality while effectively controlling the associated cost. The tooling and mold's quality, cost, and lead times will severely affect the cost of manufacturing, especially in large volume productions [2].

Traditionally, manufacturing tools are generally fabricated from metals such as aluminum and steel. Fabricating these metal tools usually involves time consuming and expensive conventional metal fabrication techniques such as milling, machining, and expensive computer numerical controlled (CNC) equipment [3]. Today, conventional metal fabrication techniques' time and cost drawbacks led to alternative techniques of tool fabrication like 3D printing gain substantial attention in the aerospace industry. 3D printing's advantage over conventional metal fabrication techniques includes its ability to print an entire tool or mold with intricate detail, minimal material required to print the tool or mold, minimal waste generated from the printing procedure, and shorter amount of time required for tool or mold fabrication. These advantages are some of 3D printing's major contributions that led to a large reduction in terms of manufacturing tooling cost [4].

In order to evaluate the effectiveness of a 3D printed composite compression mold, the study utilized a traditional steel valve cover from an aircraft reciprocating engine. By employing 3D scanning and reverse engineering techniques, a 3D model of the steel valve cover was created. The 3D model of the steel valve cover was then used to create an actual 3D printed composite compression mold [5]. The 3D printed composite compression mold was used to fabricate carbon fiber versions of the steel valve cover, which were evaluated for dimensional accuracy and quality. The 3D printed composite compression mold was also evaluated for its performance, durability, and geometric stability.

II. Methodology

A steel valve cover component from an aircraft reciprocating engine was used as the sample component to be fabricated for this study. In order to create a composite compression mold, the original steel valve cover was 3D scanned for design and dimensional data utilizing a FARO arm 3D scanner as shown in Fig. 1. The design and dimensional data collected from the 3D scanner were then processed for noise reduction, smoothing, and data filling to generate a surface. The resulting surface as shown in Fig. 2 was generated using CATIA by processed mesh.

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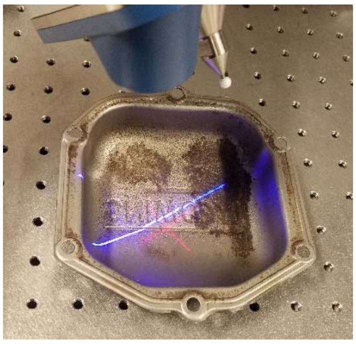

Fig. 1 Steel aircraft valve cover 3D scanning

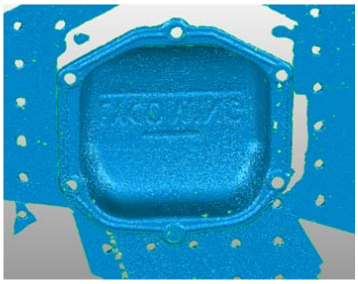

Fig. 2 Mold surface generation

With the CATIA generated surface, additional features of the compression mold were then added to design the 3D printed composite compression mold. The resulting CATIA designed 3D printed composite compression mold is shown in Fig. 3. The Composite Additive Manufacturing Research Instrument (CAMRI) of Purdue University's Composite Manufacturing and Simulation Center (CMSC) was used to accomplish the 3D printing of the composite compression mold as shown in Fig. 4. The composite compression mold was 3D printed through a 4.0 mm nozzle with Polyphenylene Sulfide (PPS) and 50% carbon fiber by weight. The printing beads were 6.15 mm wide and 1.5 mm thick. Total printing time for the 3D printed composite compression mold was 98 minutes and 5221.23g of total material was used. The post processing of the 3D printed composite compression mold involved annealing the mold in an oven at 120 °C for a total of 4 hours and final machining using a CNC. The post processed 3D printed composite compression mold can be seen in Fig. 5.

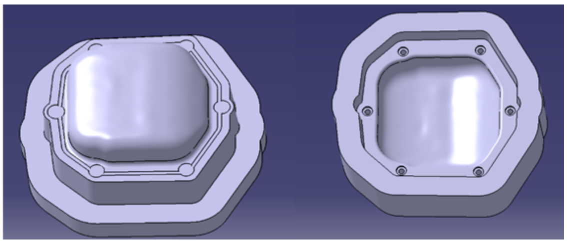

Fig. 3 CATIA designed compression mold

With the post processing completed, the resulting 3D printed composite compression mold was sealed with mold sealer followed by the application of semi-permanent mold release onto the mold surface. For additional demolding performance, a single pull mold release was also applied to the mold surface before every part layup. The main sections of the valve cover layup consist of four plies of carbon fiber, with two additional plies added for the flange area to improve the carbon fiber valve covers' durability as shown in Fig. 6.

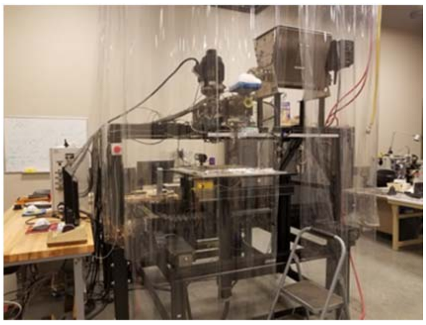

Fig. 4 CAMRI machine used for 3D printing

Fig. 5 Completed 3D printed composite compression mold

Fig. 6 Carbon fiber valve cover layup

With the layup of the carbon fiber completed, the positive side of the 3D printed composite compression mold was inserted into the negative side of the mold to complete the mold assembly as shown in Fig. 7. The completed mold assembly was then loaded into a heated press and compressed under 3 tons of pressure. To effectively control and contain the heat from the heated press, thermocouple and insulating material was added as shown in Fig. 8. The carbon fiber valve covers were cured at 250 °C for 5 hours.

After curing in the heated press, the carbon fiber valve covers were demolded, sanded, and finished to achieve the same dimensions of the original steel aircraft reciprocating engine valve cover. Mounting locations were also drilled on the carbon fiber valve covers to match the original steel valve cover. A completed carbon fiber valve cover after post processing can be seen in Fig. 9.

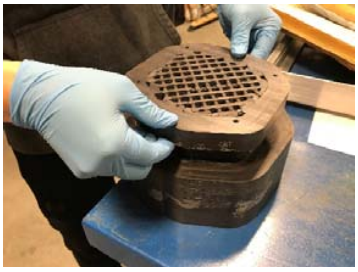

Fig. 7 Completed compression mold assembly

Fig. 8 Mold assembly loaded in heated press

Fig. 9 Completed carbon fiber valve cover

A total of 6 individual carbon fiber valve covers were fabricated from the same set of 3D printed composite compression mold. After each of the six demolding process, the 3D printed composite compression mold was 3D scanned for dimensional data and visually inspected for physical defects resulting from each demolding process.

III. Results

The fabrication process of the study resulted in a set of 3D printed composite compression mold and six individual carbon fiber valve covers. The 3D printed composite compression mold was evaluated for durability and dimensional stability. Similarly, the carbon fiber valve covers were also evaluated for their dimensional accuracy and quality.

In terms of the 3D printed composite compression mold's durability and dimension stability, a combination of visual evaluation and 3D scanning was utilized. All six carbon fiber valve covers were successfully fabricated and demolded from the same 3D printed composite compression mold as expected. However, the results did point towards durability issues as the 3D printed composite compression mold sustained increasing amounts of defects after every part demolding process. The main defects observed during the visual inspections between every part demolding process includes chipping and cracking on the mold surface. Chipping of the mold surface appeared to be random while the cracking concentrated between bead interfaces from the 3D printing process. The chipping defects are shown in Fig. 10 and the mold surface cracking can be seen in Fig. 11.

Fig. 10 Chipping defects of the mold surface

Fig. 11 Cracking defects of the mold surface

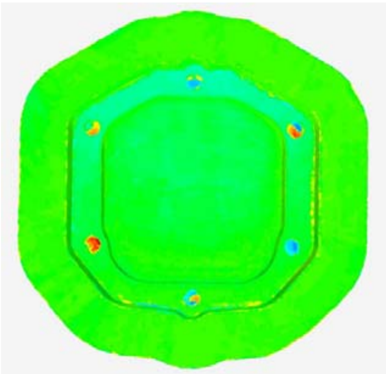

Fig. 12 3D scanning after first demolding process

The 3D printed composite compression mold's dimensional stability was evaluated with the help of 3D scanning. The 3D printed composite compression mold was 3D scanned before initial use and 3D scanned again after each demolding process of the carbon fiber valve covers. Between each demolding process, the mold had gone through a complete cycle of pressure and temperature changes required by the carbon fiber valve cover's curing process. For illustration purposes, the resulting 3D scans of the 3D printed composite compression mold after its first and sixth carbon fiber valve cover demolding process are shown in Figs. 12 and 13 respectively. Based on the 3D scanning results, there was no significant change in terms of mold geometry apart from a few minor noise and missing data in the 3D scan results.

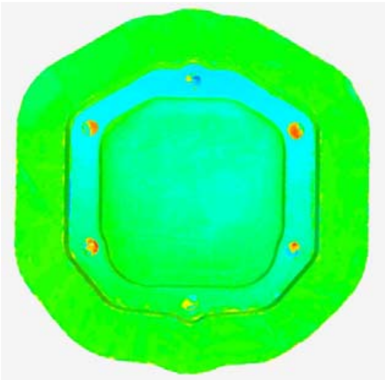

Fig. 13 3D scanning after sixth demolding process

Fig. 14 Mounted carbon fiber valve cover

Fig. 15 Carbon fiber valve cover defects

The carbon fiber valve covers' dimensional accuracy and quality were mainly evaluated visually. Dimensionally, all six of the carbon fiber valve covers were very consistent and mounted onto the aircraft reciprocating engine with no issues as shown in Fig. 14. Although in terms of quality, the carbon fiber valve covers were by no means defect free, the inconsistencies on the carbon fiber valve covers were associated with the defects sustained by the 3D printed composite compression mold after every part demolding process. However, the defects on the carbon fiber valve covers as shown in Fig. 15 were mainly cosmetic defects that can be corrected with minor manufacturing post processing such as sanding and applying layers or clear protective coating.

It is important to note that, due to the inconsistencies on the carbon fiber valve covers being associated with the defects sustained by the 3D printed composite compression mold, the quality of the carbon fiber valves covers will continue to deteriorate as the 3D printed composite compression mold continues to sustain defects. Eventually, the defects on the carbon fiber valve covers will no longer be correctable through post processing and fail to meet predetermine quality requirements; therefore, further highlighting the importance of the 3D printed composite compression mold's durability.

IV. Conclusion

With the results collected from this study, the effectiveness of a 3D printed composite compression mold was evaluated. All six carbon fiber valve covers were successfully fabricated from the same 3D printed composite compression mold. With the aid of 3D scan data collected after every demolding process, the study determined that there was little to no significant change in the geometry of the 3D printed composite compression mold. There were however, very slight deviations in the 3D scan data that were most likely caused by the chipping defects sustained by the 3D printed composite compression mold after every demolding process. Some of the deviations may also be caused by other factors such as the tool path used for the 3D printing process reacting adversely to thermal and other types of localized stresses [6].

The six carbon fiber valve covers were all installed with perfect fitment and no issues onto the original aircraft reciprocating engine. However, the carbon fiber valve covers suffered from surface defects that were caused by the gradual deterioration of the 3D printed composite compression mold's mold surface. This relationship raises concerns and highlights the importance of the compression mold's durability. Although the exact origin of the surface deterioration needs to be determined through further studies, there can be a few suggested causes such as porosity within the 3D printed composite compression mold, inadequate 3D printing tool path of the 3D printed composite compression mold, and weak interfaces between the printed beads [1]. The majority of these causes are rectifiable through changes in the 3D printed composite compression mold's design and fabrication techniques. Additional procedures such as heat treatments, application of surface coatings, and advanced approaches such as the utilization of gradient materials are all potential solutions [7]. A tool-path optimization for the 3D printed composite compression mold's printing process may also help with addressing the weak interfaces between the printed beads [8].

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