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3D PRINTED HYBRID COMPOSITE STRUCTURES – DESIGN AND OPTIMIZATION OF A BIKE SADDLE

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Abstract

As designers and engineers continue to push the boundaries of high performance and lightweight design, the use of complex geometries and composite materials is growing. However, traditional composite manufacturing often requires the use of additional tooling and molds which can significantly increase the cost. In this study, a carbon fiber reinforced composite bike saddle is designed and manufactured to demonstrate a newly developed hybrid composite manufacturing process. Using a dual curing 3D printed epoxy to print the final part geometry and co-cure pre-impregnated carbon fiber reinforcement, the bike saddle can be optimized, designed and manufactured in less than 24 hours without tooling.

Introduction

With the introduction of AM, more and more intricate parts can be made. By combining 3D printing with composite materials, complex structures with desirable mechanical properties can be achieved. A relatively new addition in AM technology is Digital Light Synthesis (DLS) by Carbon, Inc. (Redwood, CA). DLS, shown in Figure 1, involves a UV light source projecting through an oxygen-permeable window. In this process, layers can be generated continuously, producing parts with close to isotropic mechanical property and excellent surface properties [1]. Many of the resins used in the DLS process are dual curing resin with a UV and thermal curing stage.

Due to the resin being used in the DLS process, a two-stage curing process is required to produce the final part. During the printing process, only the UV portion of the curing is completed, resulting in a partially cured part. Next, the part is removed from the build platform and placed in an oven, where the heat from the oven activates the thermally cured stage.

A new process has been developed to utilize this two-stage curing process for hybrid composite fabrication. First, the part is 3D printed to activate the UV cure, resulting in a semi-rigid, but only partially cured part. This part still has chemical potential and bonding availability when it is then integrated with pre-impregnated fiber reinforcement. This assembly is then heated to activate the thermal curing reaction of both materials and co-cure the assembly.

Previous work has been done to co-cure lattice structure with pre-impregnated carbon fiber. The result is a sandwich structure where carbon fiber reinforcement is integrated on the top and bottom of the 3D printed lattice structure. It was shown that with this co-curing process, there is an increase in strength and stiffness and a strong bond between the 3D printed part and fiber reinforcement [2]. In this paper, we further develop the idea of creating such hybrid structures and demonstrate the possibility of incorporating such design with a more complex geometry. In order to explore the practical application of such a process, we have chosen to 3D print a bike saddle with the DLS process and co-cure the saddle with pre-impregnated carbon fiber. This demonstration shows that in addition to simple planer surfaces, carbon fiber composites can also be co-cured with surfaces that have more complex geometry using this process.

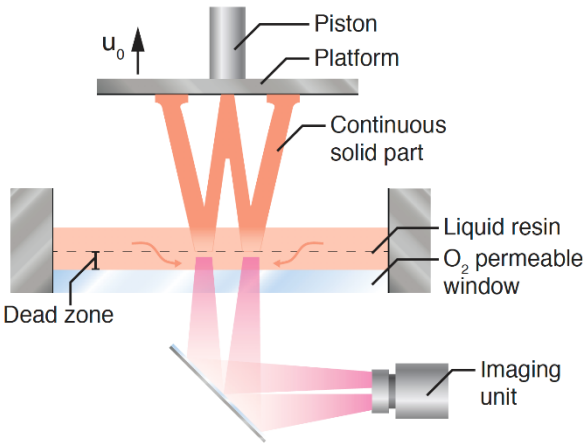


Figure 1. Schematic diagram of the DLS Process [3]

Finite Element Analysis

One important reason to make the saddle a hybrid structure is to increase the mechanical performance by placing the carbon fiber reinforcement in high stress regions. In order to determine the high-stress regions of a bike saddle in typical applications, Finite Element Analysis (FEA) is utilized.

A previous study has demonstrated that the loading on the saddle depends on the riding position [4]. There are two common riding position, drops and tops. When the rider is in tops position, the rider's center of gravity is farther backward. The stress on a saddle mostly concentrates around both sides of the posterior and in the middle due to the anatomical structure of the human pelvis. On the other hand, when the rider is in drops position, the rider leans more forward, resulting in a more forward center of gravity. The forward center of gravity will increase the load on the middle of the saddle compared to the tops position.

In order to gain a better understanding of the stress distribution on a saddle, both the loading condition of tops and drops were modeled. For the loading condition when the rider is in tops position, a 200 N force is placed on both sides of the posterior and 200 N force is placed in the middle of the saddle (Figure 2). The model is constrained based on fixture geometry that resembles the metal rail for which the saddle rests on.

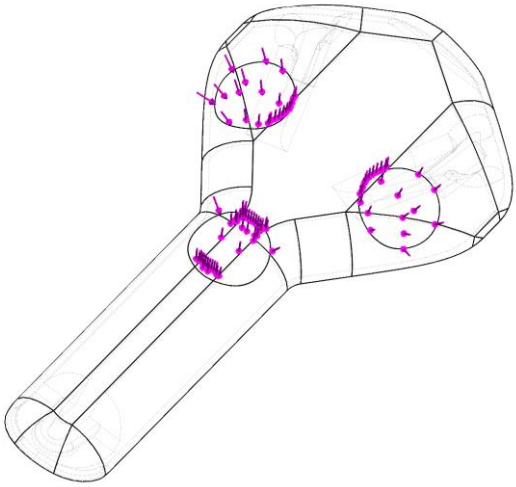


Figure 2. The loading condition of tops riding position

SolidWorks is used to complete the FEA simulation. The result shown in Figure 3 indicate that there is a stress concentration at the center of the saddle due to the load applied to the middle. In addition, there is also stress concentration occurring in the posterior region.

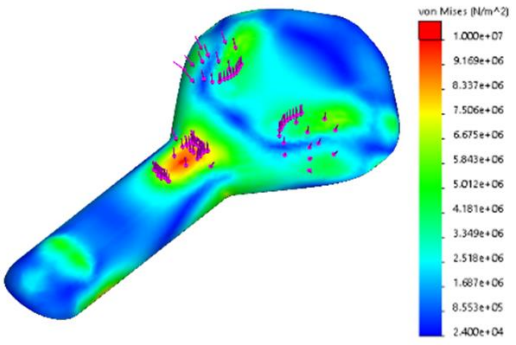


Figure 3. The FEA result of tops riding position

Next, the loading condition when the rider is in drops position is modeled. When the rider is in drops position, the load on the posterior of the saddle is decreased and more load is concentrated in the middle of the saddle. Therefore, a 600 N load is placed in the middle (Figure 4).

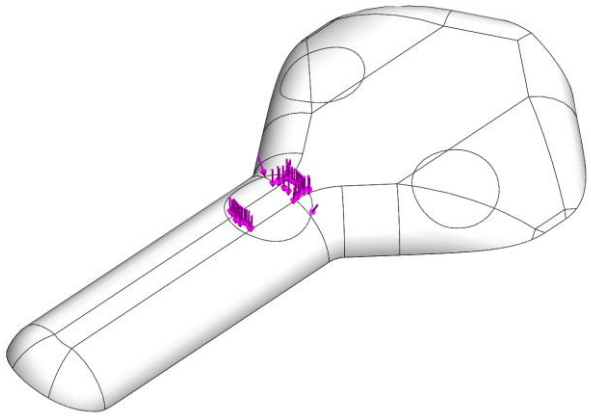


Figure 4. The loading condition of drops riding position

The result from drops position shown in Figure 5 indicate that there is higher stress concentration around the center of the saddle. In addition, stress around the saddle also experienced an increase compared to the tops position.

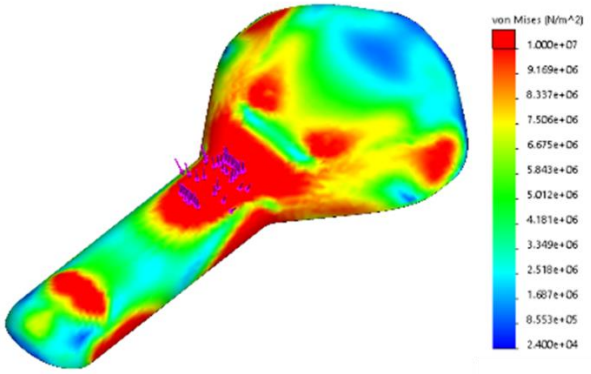


Figure 5. The FEA result of drops riding position

The result from drops position showed that there is higher stress concentration around the center of the saddle. In addition, stress around the saddle also experienced an increase compared to the tops position.

Materials

The hybrid structure was manufactured with two materials. The carbon fiber composite is woven epoxy resin prepreg HexPly W3T282-F263, from Hexcel. The material properties are listed below in Table 1 [5].

Table 1. Material data of HexPly W3T282-F263 [5]

Material Properties	Value	Unit
Nominal Ply Thickness	0.18	mm
Tensile Strength	570	MPa
Tensile Modulus	60.7	GPa
Glass Transition Temperature	188	°C

For the 3D printed base, the epoxy-based photopolymer resin EPX 82 from Carbon was manufactured with DLS. The UV curing process from the printer completes the first stage of the curing process. In typical applications without creating hybrid structures, the printed part will then be taken into an oven to fully cure using heat. After being fully cured, the material properties of EPX 82 are listed in Table 2 [6].

Table 2. Material data of EPX 82 [6]

Material Properties	Value	Unit
Ultimate Tensile Strength	82	MPa
Tensile Modulus	2800	MPa
Elongation at Break	5.9	%

Manufacturing

Design

Although the DLS process can produce parts with nearly isotropic mechanical property and high surface quality, good model design is important to prevent printing failure and reduce the need for excessive support. In addition, the design of the saddle also needs to incorporate the carbon fiber reinforcement.

The geometry of the saddle (Figure 6) is designed to be best suited for AM. A flat area on the rear is created such that during printing, there is a firm base for the model to stick to the build plate. There can be significant pulling force generated during the print due to the small gap between the part and the oxygen permeable window. The smooth flat area prevents the model from being pulled off from the build plate. When printing parts with a high overhang angle, DLS requires support to be paced at regions with high overhang angle. Therefore, most of the features of the model follow a smooth incline angle. The incline angle leads into the feature smoothly, reducing the overhang angle of the part, which eliminates the need for supports most support material.

The goal of this design is to utilize the ability of the of DLS printed parts to co-cure with pre-impregnated carbon fiber. Making such hybrid structures will improve the mechanical property, however, due to geometry and the ability to use vacuum bagging, carbon fiber cannot be place everywhere on the part. Therefore, the FEA results serve as a good guideline for placing the carbon fiber at the region where stress is the highest. According to the FEA result, there are high stress area at the center and the posterior region. For simplicity in this demonstration, fiber is placed in the textured region shown in Figure 7. In addition, grooves were designed to allow a smooth finish after placing the reinforcement.

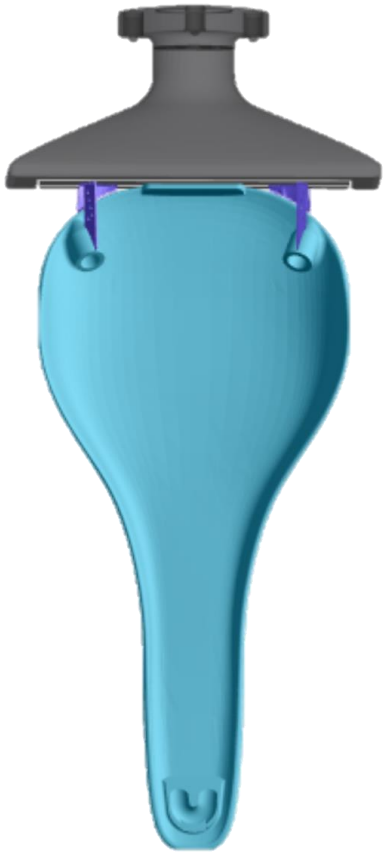


Figure 6. The final geometry of the saddle with the supports (in purple) and connection to the build platform



Figure 7. The placement of carbon fiber for this demonstration

Slicing and Printing

Common to all 3D printing technologies, DLS also requires slicing the model into layers and printing based on the sliced model. The Carbon cloud based slicing software is used to prepare the model. The model is printed with Carbon M1 3D printer. The print took approximately 11 hours to complete. After printing, the part is washed with solvent to remove excess resin and the support was removed.

Post Processing

Making the hybrid structure with DLS printed epoxy and pre-impregnated carbon fiber involves several steps. The goal is to achieve a part with improved mechanical properties by co-curing the pre-impregnated carbon fiber with DLS printed epoxy. The first step is to prepare the carbon fiber. A rectangle segment is cut from a large roll of carbon fiber and trimmed to the proper dimension. Finally, the pre-impregnated carbon fiber is placed onto the part.

The next step is to place the assembly into a vacuum bag shown in Figure 8. The use of vacuum is to ensure there is enough compaction force for the carbon fiber to co-cure with the epoxy while reducing voids and ensuring the fully listed mechanical properties. When preparing for vacuum bagging, a layer of peel ply is place at the top of the part to prevent the carbon fiber from adhering onto the vacuum bag. Next, a layer of breather fabric is placed on top of the peel ply. Finally, the vacuum bag is used to fully cover both the top and bottom of the part and a vacuum pump connection is placed inside. After the vacuum bag is applied, a vacuum pump is connected via the connector. The final step is to co-cure the epoxy and carbon fiber in an oven.

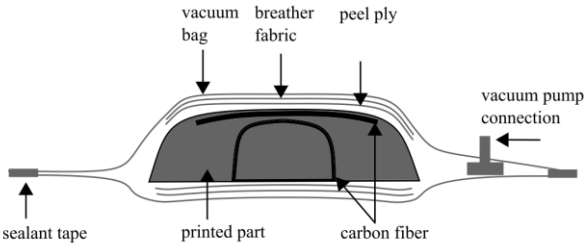


Figure 8. Arrangement for co-curing under vacuum

Finally, after the curing cycle is complete, the vacuum bag is removed, and excess resin residue is trimmed off. The steel rail is attached though the holes designed on the bottom of the saddle. The final part is shown in Figure 9.



Figure 9. The finished bike saddle after co-curing

Discussion and Conclusion

In the pursuit of manufacturing an epoxy-carbon fiber hybrid structure with complex geometry, a bike saddle is designed and manufactured. During the designing phase, FEA is utilized to determine the best placement for carbon fiber. In addition, optimization to the geometry of the saddle reduces the need of support materials and improves the success rate of printing. Finally, the carbon fiber is integrated with the printed part and co-cured in an oven.

This demonstration shows the possibility of co-curing carbon fiber and epoxy for parts with complex geometry. There are many benefits of this process. One such instance is that it can be used to reduce the cost of some carbon fiber parts. Even in full carbon fiber constructed parts, there are regions that are experiencing less stress and loading, and such region can be replaced with DLS printed parts. Furthermore, DLS printed part can be used as a base or mold for more complex geometry. As some hollow carbon fiber structure require intricate mold design, a DLS printed base can be used as a mold to reduce the cost of developing and machining molds. In addition, it can also potentially reduce the development time of composite parts as machining and production time for the mold can be reduced.

In this paper, we demonstrated the possibility of using 3D printed EPX 82 epoxy resin to manufacture end-use parts by co-curing with pre-impregnated carbon fiber. There are also many future improvements and research can be done for this process. The design used for this demonstration was very simple and it should be clear that generative design would produce a more optimized geometry by removing material from low-stress regions and reducing weight. Further, different designs can be made for specific riders or specific riding positions with more detailed FEA analysis.

Also, while previous work shows a strong cohesive bond between the fiber reinforcement and 3D printed part, after producing more examples of the bike saddle, loading tests can be conducted to determine the mechanical properties. Another aspect that is worth investigating is to explore the possibility of scale up production of such process. As it requires fewer man labor compared to traditional carbon fiber composite structure manufacturing.

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