Customized Vacuum Valve Developed by Multi-material 3D-Printed Processes for Carbon Fiber Lamination

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Abstract

3D printing technologies are proving to be an increasingly useful tool not only for the creation of prototypes, but also of finished components. 3D printing has become a mature technology able to product finished objects and non finished parts intended to support the production. This is possible because of the continuous innovation in materials that are now able to achieve specific requests. Moreover the lowering of the hardware's costs played a central role in the expansion of 3D printing technology. Another important aspect of 3D printing processes is in fact their application within the production process of other components, for example, by considering less inexpensive technologies such as FDM and mSLA. The goal of this research is to take advantage of the great variety that 3D printing offers in order to implement this process across different mechanical and prototyping applications to emphasize the importance of spreading this technology. This is achieved studying specific application.

Keywords

3D printing, FDM, MSLA, vacuum valve, carbon fiber lamination

1. Introduction

This research considers 3D printing as a tool for the creation of accessory components for the construction of final objects. This assumption is of fundamental importance because it shifts the attention from the finished product to the production of the product itself. In fact, reference is often made to 3D printing as a means of prototyping or final production, forgetting that it can allow the reduction of costs and times even in the production phase. The realization of molds, accessories, tools of various kinds in plastic material can in fact be able to perform the same function as components made with conventional technologies and at extremely competitive prices, especially on very small batches.

In this case, FDM and MSLA technology were used to create a vacuum valve with integrated check valve that can be used within the vacuum lamination process of carbon fiber components. The aim is to lower the production times of the valve in order to make the vacuum lamination technique for fiber composites more accessible.

1.1 Objectives

To develop a customized design of a vacuum valve intended for carbon fiber lamination by means of a combination of 3d-printed processes.

2. Literature Review

Additive manufacturing processes, most known as 3D printing is an expanding beneficial manufacturing technology, which allows to portray 3D structures at high speed at a rather low cost (Wang et al., 2017), (Warner et al., 2016), (Esmaeilian et al., 2016), (Pyo et al., 2017), (Ge et al., 2020). These processes have proved to have great potential in diverse industries from automotive (Way et al., 2012), robotics (Kim et al., 2018), (Kuang et al., 2018), towards materials (Zheng et al., 2014), (Tan et al., 2019), electronic devices (Wei et al., 2018), (Lewis & Ahn, 2015), and even bioengineering (Jansen et al., 2005), (Ventola, 2014), (Qiu et al., 2018), (Markstedt et al., 2015) and even food production (Yang et al., 2017), (Mantihal et al., 2020). This manufacturing method has been widely accepted in the construction of polymeric-sourced parts, for which 3 typologies for additive manufacturing concepts are extolled: Fused Deposition Modelling (FDM), Powder Laser Sintering (SLS), and liquid resin-sourced modelling (SLA, DLP, inkjet), (Edgar & Tint, 2015). The latter is widely known as stereolithography, it is a photopolymerization process, in which a reservoir containing UV-curable liquid resin is exposed to UV light in order to form chains between the molecules and creating a chemical crosslink. Moreover, a solid 3D geometry is built through resin photocuring of each layer. This process could be applied to a wide range of materials, including shape-memory polymers, ceramics, glass, biomaterials, and electronics (Layani et al., 2018). Moreover, it offers high accuracy due to its high printing resolution measured up to a nanometer scale. SLA process sourced from a laser beam is generally slow, since a single laser beam must move around the printing area; other processes like digital light processing (DLP) and masked stereolithography (MSLA) proved to be faster, as they use a light projector with LED arrays and LCD photomasks (Pagac et al., 2021). Additionally, MSLA could overcome the limitation of laser sourced modelling of not able to deliver heterogeneous, functionally graded material properties by controlling the light intensity through grayscale masks (Lu et al., 2006), (Na et al., 2016), (Xue et al., 2019), (Kuang et al., 2019).

Moreover, other important factor in the choice of this technology is the possibility of manufacturing the component in any part of the world, without the need to depend on a specific supplier and therefore to manufacture the product on site, avoiding the expected waste of time as well as costs of transport and supplier logistics, and such flexibility makes the design to be shared worldwide thru augmented reality (De Amicis et al., 2018), that could be used to integrate product and process assessment (Frizziero et al., 2019).

However, it is not possible to change the manufacturing technology of a component without adapting its design. In fact, this must be adapted and modified following the best practices of the specific printing technology in order to obtain a component that allows the same performance, but can be made with the chosen technology, even if made through procedures that involve the use of 3D printing (Ferretti et al., 2021).

2.1 Multi-material sourced valve

Traditional valves are made from metallic materials such as aluminum and stainless steel and offer a high-performance element. These can tolerate high temperatures and pressures, but their cost is very high ($30 and $80), especially if a small number of components or even a single prototype is considered.

In special cases, there is no need of aluminum valves since carbon fiber components can be made with resins that do not require an autoclave post-cure cycle and can achieve complete cross-linking even at room temperature. This means that low-cost valves could be made from low-cost polymers and printed very easily. Total costs should be reduced compared to the aluminum counterpart, amortizing the cost per individual component (Ngo et al., 2018).

2.2 FDM challenges

One of the problems of FDM molded components is certainly the difficulty in obtaining parts that are watertight but above all gas tight. This is due to the deposition by layers and lines which involves the presence of voids and pores in the structure. Designers should decide on other additive manufacturing applications for air tight components (Ngo et al., 2018).

3. Methods

3.1. Part modelling process

All components were designed using PTC Creo. The modelling of the components is strictly related to the production process used, in this case FDM or MSLA. For what concerns the printing of components with FDM technology a particular attention was carried out to avoid the creation of overhangs to eliminate the generation of supports. For the components built with MSLA technology the thickness of the part was kept constant to avoid shrinkage.

3.2. Materials

The materials used are PLA FILOALFA® , TPU Filaflex 60A Pro Black Recreus® and ESUN® water washable resin. Table 1 shows the main mechanical properties as declared by the manufacturers.

Table 1. Main Mechanical Properties for Used Materials

PLA FILOALFA®		
Properties	**Value**	**Method and Condition**
Density	1,24 g/cm3	D792
Tensile Strength	53 Mpa	D790
Tensile modulus	3,6 Gpa	D882
Tensile Elongation	6%	D882
Heat Deflection temperature	55°C	E2092
TPU Filaflex 60A Pro Black Recreus®		
Properties	**Value**	**Method and Condition**
Density	1,07g/cm3	DIN en iso 1183-1-A
Tensile Strength	26 Mpa	DIN 53504-S2
Tensile Elongation at break	950%	DIN 53504-S2
Hardness	63 ShoreA	DIN ISO 7619-1(3s)
ESUN® water washable resin		
Properties	**Value**	**Method and Condition**
Density	1,10-1.14 g/cm3	GB/T 4472
Tensile Strength	19-46 Mpa	ASTM D638
Elongation at break	17-30%	ASTM D638
Hardness	74-82 ShoreD	ASTM D2240

The choice of materials is linked to the process temperatures of the carbon fiber composite lamination. In this specific case the temperatures are slightly higher than the ambient one, since this is a lamination process that does not require the use of an autoclave for the final cure of the part. A common PLA, which has a glass transition temperature (Tg) of about 55°C (Table 1) is enough for this application. Nevertheless, the main body of the valve requires to be airtight and an FDM part would be challenging for this purpose. It was therefore decided to combine two additive manufacturing technologies in the design of the vacuum valve, taking advantage of mSLA for the parts that need to be gas tight.

3.3. Case Study: Vacuum Valve With Integrated Check Valve For Carbon Fiber Lamination

The valves for the vacuum lamination process are usually made with an aluminum body, a rubber gasket and an aluminum ring nut that is tightened to ensure proper sealing. On the upper part of the valve there may be an additional thread for the attachment of sleeves equipped with check valve or sleeves for connection to the vacuum pump. Figure 1 shows an example of a lamination vacuum valve (Airtech Advanced Materials Group, 2021).

Figure 1. Example of Aluminum-sourced vacuum valves.

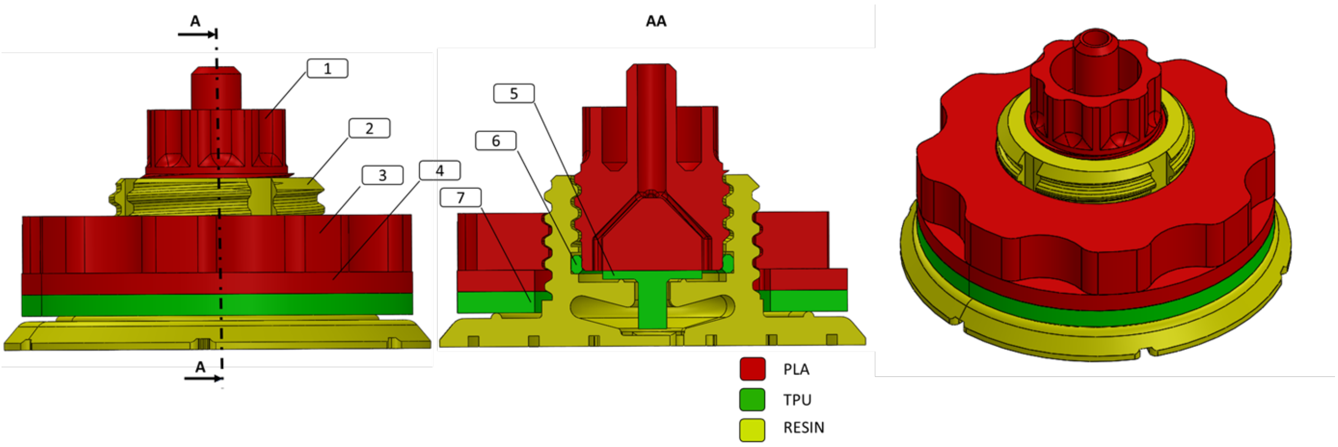

Figure 2: 1. check valve body; 2. main body; 3. threaded ring nut; 4. anti-rotation spacer; 5. valves; 6. gasket; 7. main gasket

Figure 2 shows the design of the new valve made with 3D printing approach. All the components are designed considering the 3D printing approach following the best practices of the Design for Additive Manufacturing. SP415 l-8 type thread was chosen since it proved to be the better solution for printability using FDM technology. The channels (part 1 of Figure 2) have the function of allowing the passage of air easily from the bag to the vacuum pump and their design it is only possible through the use of 3D printing. The alternative would be designing the vacuum valve and the check valve separately. In Figure 3 bottom view and section view of component 1 could be seen, which allow to better clarify the internal geometry.

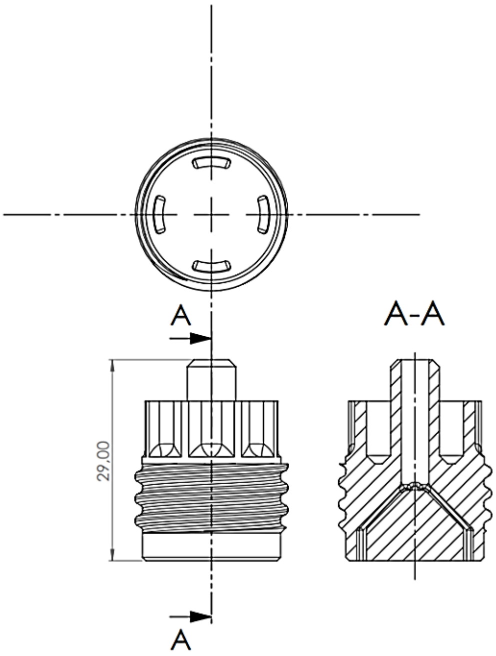

Figure 3: Top and Front views of component 1

Moreover, Part 3 in Figure 2 is a threaded ring nut, also in this case the use of a non-metric thread was chosen by using a sp410 l-8 thread. the ring nut then has a series of grooves on the external surface to ease closing and opening. Part 4, on the other hand, is a spacer as shown in below Figure 4, with the function of preventing that the spiral movement of part 3 creates wrinkles in the plastic vacuum bag during the closing operation.

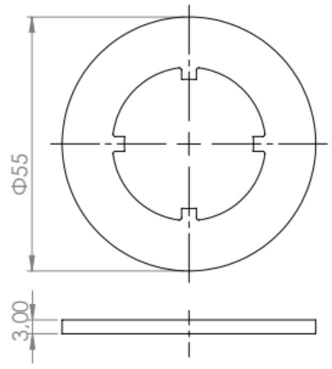

Figure 4: Spacer (component 4)

4. Data Collection

4.1. Printing Strategy and Settings

The main printing parameters used within the Ultimaker Cura to perform slicing before printing are now shown in the Table 2, applied to make components 1,3,4 with FILOALFA PLA.

Table 2. PLA FILOALFA® Slicing Parameters

Parameters	**Value**	**Unit**
Layer height	0.15	mm
Line width	0.4	mm
Wall line count	3	/
Z Seam alignment	Shortest	/
Top layers	3	/
Bottom Layers	3	/
Skin overlap percentage	20	%
Infill Density	20	%
Infill pattern	Lines	/
Infill overlap percentage	25	%
Printing temperature	205	°C
Flow	100	%
Print speed	60	mm/s

Table 2 shows that the components have a low infill of 20%, this is justified by the fact that these do not have to guarantee airtightness and therefore it is possible to make them without a 100% infill, significantly reducing costs and printing time. Figure 5 shows the components lying on the printing surface in the preview post slicing.

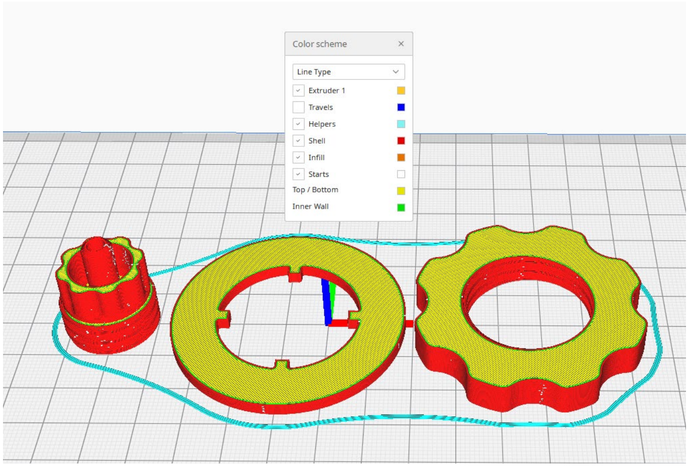

Figure 5. Components preview post slicing.

Moreover, the valve inner seal (part 5), and gaskets (parts 6, 7) of Figure 2 are vital for the functioning of the valve as they are responsible for its sealing. The TPU Filaflex 60 ° Pro Black Recreus filament is an extremely technical material, being extremely soft and flexible it is the ideal material for making gaskets. However, this type of material is very complex to print and requires special printing parameters. Table 3 shows the main printing parameters.

Table 3. Slicing Parameters for TPU Filaflex 60A Pro Black Recreus®

Parameters	**Value**	**Unit**
Layer height	0.2	mm
Line width	0.4	mm
Wall line count	2	/
Z Seam alignment	Shortest	/
Top layers	4	/
Bottom Layers	3	/
Skin overlap percentage	25	%
Infill Density	60	%
Infill pattern	Lines	/
Infill overlap percentage	25	%
Printing temperature	235	°C
Flow	118	%
Print speed	20	mm/s
Retraction extra prime amount	-0.064	mm^3
Coasting volume	0.064	mm^3

As can be seen from Table 3, the printing speed has been greatly reduced compared to the parameters used for PLA. The parameters Retraction extra prime amount and Coasting volume were also used to minimize the oozing problems inherent in very flexible material. The combination of a higher-than-normal flow rate and the increased overlap between the various areas of the print therefore allows to obtain seals without open porosity and therefore airtight.

The choice of the arrangement on the printing bed is also very important, as can be seen from Figure 6, a concentric arrangement allows not only to reduce the printing time, but also to reduce the length of the movements between pieces, minimizing the oozing of material from the nozzle.

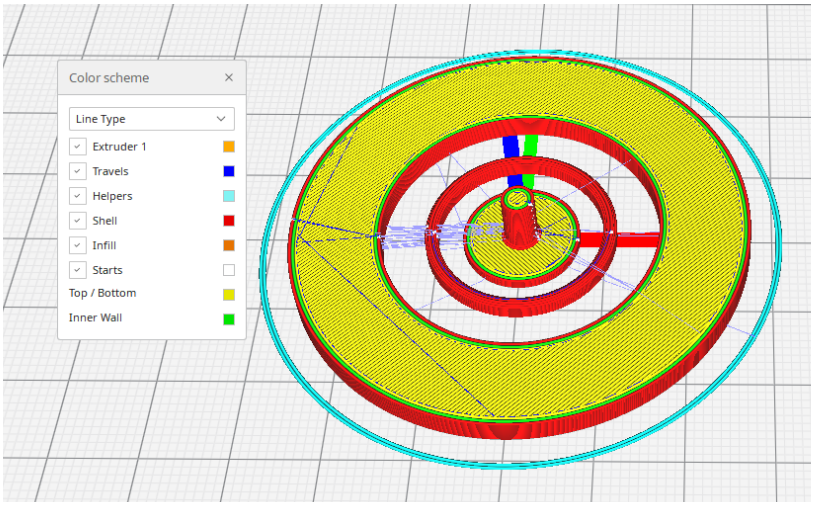

Figure 6. Concentric components arrangement preview.

Finally, part 2 of Figure 2 was made using MSLA technology with **E**SUN® water washable resin. The choice of this type of rapid manufacturing technology arises from the difficulty of obtaining completely airtight pieces with the use of FDM technology alone, without post processing. MSLA and SLA technology in general manages to achieve this goal very easily. Hence the choice to use this technology for the main body of the valve. The valve body design has therefore been adapted to this printing technology. Thanks to the high resolution of MSLA technology it is possible to create extremely small and complex details. The entire valve body could be seen in Figure 7, with some areas of interest are also highlighted.

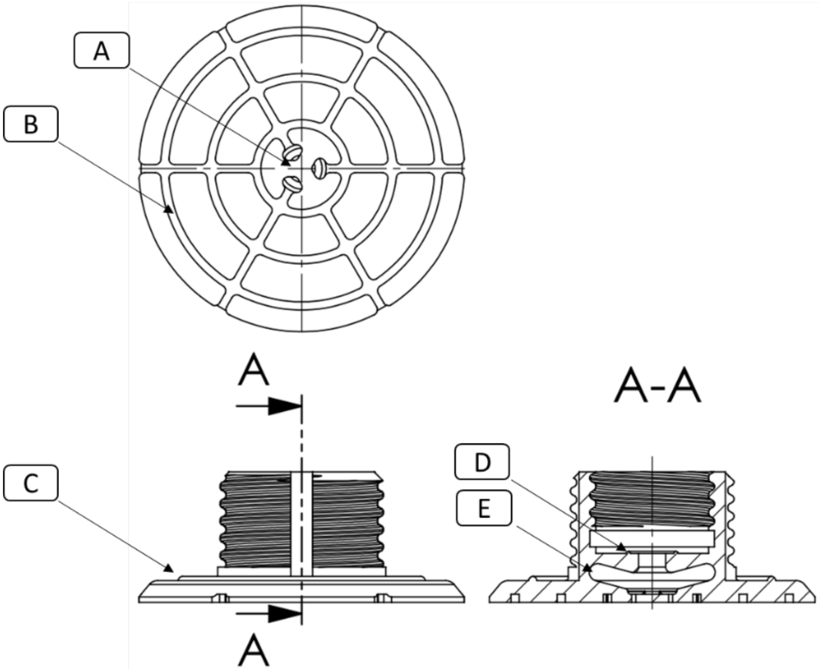

Figure 7. Valve main body: A. Anti-intrusion net; B. Channels; C-D. Bulge for sealing; E. Groove

Zone A includes a small anti-intrusion net that has been created in order to prevent the material of the vacuum bag from entering the suction hole and compromising the operation of the valve itself. Zone B, on the other hand, is made up of a series of very narrow channels, these guarantee the passage of air in the main channel, preventing the vacuum bag from stopping the flow of air. In C and D, on the other hand, there is a bulge which helps to guarantee the seal once the ring and the body of the check valve are sealed. The groove highlighted with E has the purpose of lightening the piece, in order to maintain more or less a constant thickness in all areas, this helps to avoid unwanted shrinkage deformation during printing. The geometry of the internal cave is such as to facilitate the escape of any resin trapped inside it. The printing parameters used within Lychee slicer for component slicing shown in Table 4

Table 4. ESUN® water washable resin parameters

Parameters	Value	Unit
Bottom exposure time	24	s
Normal exposure time	1.9	s
Lift distance	6	mm
Lift speed	40	mm/s
Retract speed	150	mm/s

Figure 8 shows four valve bodies ready to be printed. The huge advantage of mSLA technology is the ability to make multiple copies of the same component without increasing the overall print time.

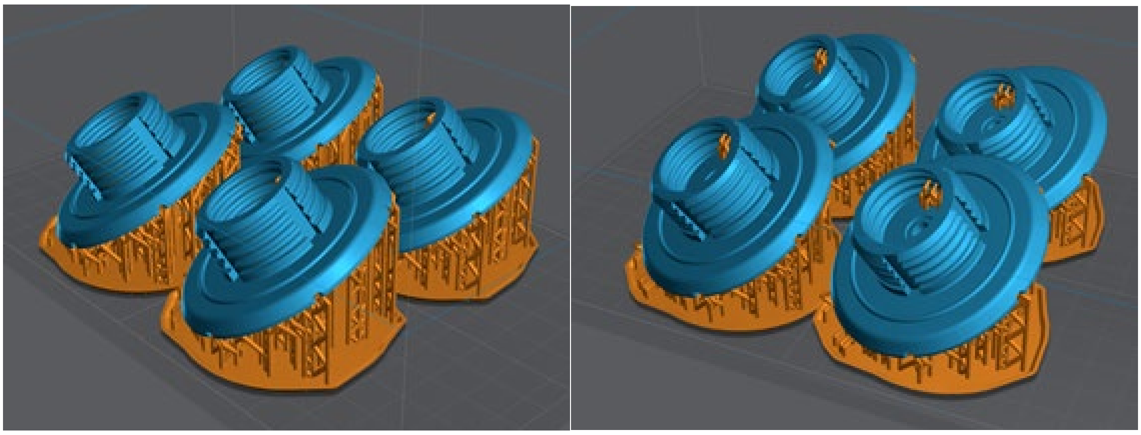

Figure 8. View of multiple component 2 laying on the build plate after slicing

5. Results and Discussion

Figure 9 shows the physical production of the main body built using MSLA technology. Figure 10 shows all the PLA parts and in Figure 11 the TPU printed components.

Figure 9. resin printed main body

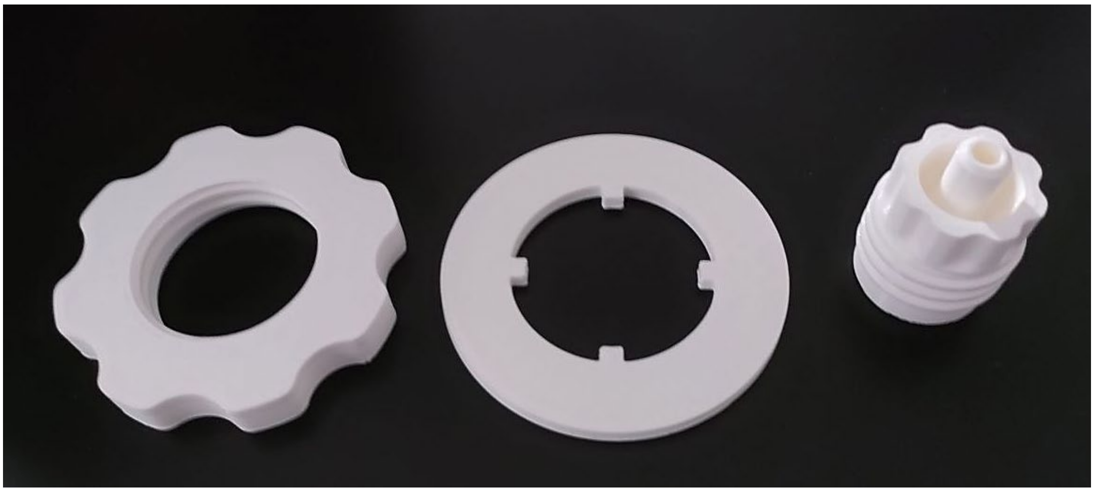

Figure 10. PLA FDM printed components

Figure 11. TPU FDM printed components

Figure 12 shows the final assembled component that takes advantage from the different additive manufacturing technologies.

Figure 12 Final Assembly

6. Conclusion

This study showed how 3D printing can be revolutionary not only to create finished components, but also to integrate within the manufacturing process of other parts. In this case study, the fabrication of a valve useful for producing carbon fiber components through vacuum technology was discussed. The ability to print the component independently demonstrated how versatile 3D printing technology can be. The combination of FDM and MSLA technologies could help to customize parts for better efficiency, especially on different geometries. A future development would be characterizing the materials used to reduce waste due to support and testing of finished components. This final step should be performed in order to adopt polymer's 3D printing as replacement for metal components.

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