INFLUENCE OF FIBER RINGS ON IMPACT STRENGTH OF 3D PRINTED FIBER REINFORCED POLYMER COMPOSITE

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Abstract: 3D printing is the fabrication technique where parts are made layer-by-layer. Fused Deposition Modeling (FDM) technique is a promising 3D printing process that can be used as an alternative to the traditional process of manufacturing Fiber Reinforced Polymer Composites (FRPC). However, a significant issue with the correct use of FDM composite parts is the influence of impact destruction on the physical reliability compared to traditional composites components. The aim of the present work is to investigate the influence of number of fiber rings on the impact strength of 3D printed continuous high strength high temperature glass fibre reinforced onyx composites. It is observed that impact strength increases as the number of fiber rings increases in 0°/90° fiber angle samples. However, it decreases in ±45° fiber angle samples as the number of fiber rings increases.
Key words: Fused deposition modeling, fiber reinforced polymer composites, glass fiber, build orientation, fiber angle, fiber rings.

1. INTRODUCTION

The 3D printing processes are extensively used for manufacturing the polymer prototypes and, in some cases, functional structures. 3D printing provides advantages over conventional manufacturing processes by providing a more capable and cost-effective means to produce complex geometries yielding more functional designs, and an efficient means of customization (Wang et al., 2017). Fused Deposition Modeling (FDM) is an extensively used 3D printing technique because of its relatively lower cost and low material wastage. (Chacon et al., 2017). In the FDM process, the wire filament is extrudate from the nozzle and successive layers are laid down on the bed, and thus 3D structure is created as per CAD model. Various polymer filaments viz. Polylactic Acid (PLA), Polycarbonate (PC), Acrylonitrile Butadiene Styrene (ABS) and Nylon (Polyamide-PA) can be used in FDM as a feedstock material.

Though, the major of 3D printed polymer components made from these polymer materials are still only used as prototypes parts because of the lower mechanical strengths of these components. To increase the mechanical properties of these polymer components made from FDM process, many researchers have considered optimizing the process parameters of the FDM. Tymark et al. (2014) studied the tensile strength of the ABS sample made by FDM machine. Dave et al. (2019a) investigated the effect of infill properties on the tensile strength of 3D printed parts. Mazurchevici et al. (2019) investigated the influence of infill percentage and infill pattern on the tensile properties of FDM printed parts. Qattawi et al. (2017) studied the influence of processing parameters such as print speed, orientations and layer thickness of 3D printed components. Dave et al. (2019b) studied compressive properties of scaffold components made using PLA and found that higher infill density resulted into higher compressive strength.

It was observed that researchers were able to improve the mechanical properties of polymer parts by optimizing the FDM process parameters by some extent. Still, the research on the development of new materials and new methods to improvise the FDM process are very limited. 3D printing of fiber reinforced polymer composites using FDM can improve the performance of the components by adding fiber reinforcements into the thermoplastic polymer matrix. By combining polymer and fiber materials having distinct physical properties can create the functional purpose materials which are extremely different having higher mechanical and physical properties (Nedelcu and Carcea, 2012). The addition of long continuous fibers into the polymers not only improves the mechanical properties but also useful for advanced applications due to their light weight and lower cost compared to conventional metals (Roy et al., 2019).

Various researchers used FDM to make 3D printed composite parts of a polymer as matrix and fiber as a reinforcement and studied its mechanical properties. Akhoundi et al. (2018) made 3D printed fiber reinforced composites of PLA with glass fiber. They studied the influence of process parameters such as fiber size, fiber pattern, raster width and layer thickness. By printing with different flow percentage and extrusion width, they have achieved 478 MPa tensile strength for glass fiber reinforced composites where glass fiber volume fraction was about 49%. Tian et al. (2016) investigated the performance of continuous fiber reinforced composites where carbon fiber reinforcement was used in PLA matrix. They have found that at higher nozzle temperature, maximum flexural strength can be obtained; however, it is resulted into higher surface roughness. Li et al. (2016) designed a novel 3D printer nozzle that can print carbon fiber with the polymer. They used PLA as a matrix material to print the carbon fiber reinforced composite parts. Perez et al. (2014) studied the effect of the addition of a jute fiber as a reinforcement material on the tensile strength of ABS. It was observed that tensile strength was reduced by 9%, but the main improvement of the addition of the jute fiber was that it reduced the amount of warping which leads to dimensional stability. Baumann et al. (2017) developed the fiber reinforced composites with fibers directly laid down on the printed layers. They used ABS as a matrix material and carbon fibers and glass fibers as reinforcement material. They concluded that the tensile properties of all carbon fiber specimens didn't increase much. In contrast, glass fiber specimens resulted into higher strength compared to the pure ABS specimen. Ferreira et al. (2017) made the carbon reinforced polymer composites parts. The tensile strengths of the specimens printed with pure PLA and composite filament were identical. There were no sudden change on the tensile properties when 15% of carbon fiber added to the polymer filament.

MarkForged® Company made a remarkable improvement in the field of composite making using FDM. They employed dual extrusion method in which one nozzle deposits polymer material and another nozzle deposits continuous fiber. Several researchers have studied different aspect of the Markforged make Markone and Marktwo 3D printers. Caminero et al. (2018) studied the effects of three process parameters, viz. build orientation, fibre volume fraction and layer thickness for the continuous fibre reinforced composites made using MarkTwo 3D printer. They have carried out the charpy impact tests to determine impact strength. Nylon was used as a matrix material while they also studied a different type of fiber reinforcement viz. carbon fiber, Kevlar fiber and glass fiber. Dickson et al. (2017) evaluated the tensile and flexural properties of continuous glass, Kevlar and carbon fibre reinforced composites. They found that maximum nylon composite strength was achieved with carbon fiber while the composites with kevlar fiber gave minimum strength. Malenka et al. (2016) evaluated the tensile strength of continuous fiber reinforced 3D printed parts. They printed the composite parts with a different number of fiber rings. Giannakis et al. (2019) investigated the fatigue properties of composites part made using nylon matrix and carbon fiber. They have found that strength increased by adding carbon fibers into nylon polymer matrix, however the composite sample had elastic deformation. Pertuz et al. (2020) studied the effect of Isotropic layers of different types of fiber as reinforcement material. Mei et al. (2019) studied the mechanical properties of carbon fiber reinforced composites and further investigated the effect of hot press on the composite.

The literature review shows that some efforts have been made by the researchers to improve the mechanical properties of composite parts made using FDM process. However, mostly tensile and flexural properties were thoroughly studied. The impact properties of the fiber reinforced composites made using FDM were not yet thoroughly researched. The higher impact strength of materials is needed for a variety of applications such as aviation and automobile sector. Manned space vehicles require a level of protection against micrometeoroid impact. Similarly, high performance materials are desired for body and vehicle armour to stop projectiles while minimizing weight.

The goal of the present research work was to carry out the experimental investigation for a better understanding of how essential parameters were affecting the impact strength of 3D printed composites part. The MarkForged® MarkTwo 3D printer was used to make composite parts. The influence of processing parameters, viz. build orientation, fiber angle and number of fiber rings were analysed.

2. EXPERIMENTAL DETAILS

2.1 3D Printer and Materials

The 3D printed fiber reinforced composites parts were fabricated using a MarkForged® MarkTwo 3D printer as shown in Figure 1. This machine can print polymer and fiber materials independently as the printer has two extruders.

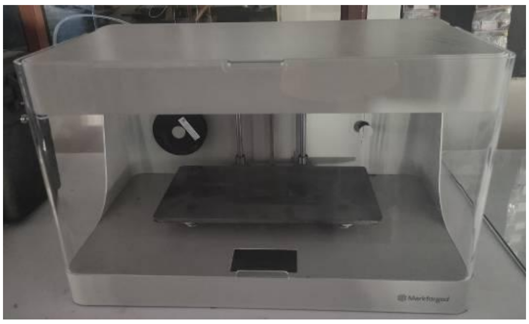


Fig. 1. MarkTwo 3D Printer

Onyx filament was used as a matrix material having a diameter of 1.75 mm. Onyx filament is the mixture of Nylon polymer and chopped carbon fibers. HSHT (high temperature high strength) fiberglass having 0.3 mm diameter, supplied by Markforged® was used as a fiber reinforcement.

2.2 Specimen Preparation for Impact Testing

Impact testing subjects material to a quick blow by a swinging pendulum. This impact measures the energy absorption of the material, which is an indicator of material toughness. In this study, the izod impact test method (ASTM D256) was applied for the impact testing. Specimen conforming to ASTM D256 standard contains a v-shaped notch, which provides a stress concentrator on the material. The notch tests the component's resistance to crack propagation. The dimensions of the 3D printed specimen are shown in Figure 2. The specimen was modelled using Auto Desk Inventor software, exported as an STL file and imported to the eiger software.

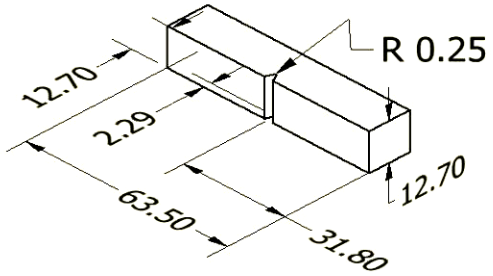
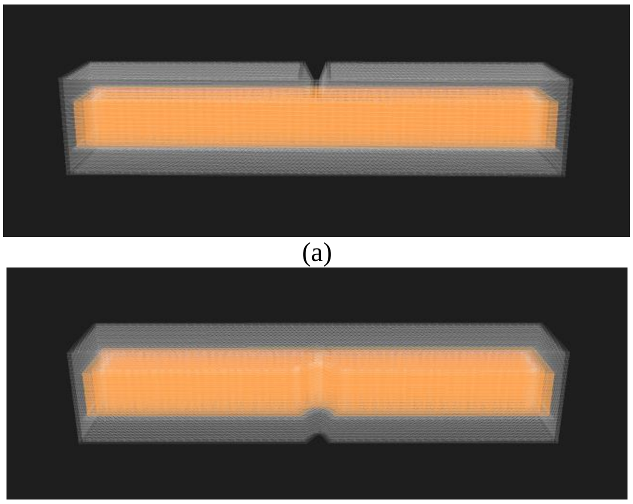


Fig. 2. Impact test specimen as per ASTM D256 (All dimensions are in mm)

In this experimental investigation, three different process parameters, viz. build orientation, fiber angle and number of fiber rings were considered. Flat and on-edge orientation were used to print the parts as shown in Figure 3. In the impact specimen, 60 layers of HSHT fiberglass were selected out of total 127 layers. In the specimen, there were 34 layers of onyx placed at the bottom, then 60 layers of HSHT fiberglass set in the middle and again 33 layers of onyx placed at the top. Due to this type of fiber and matrix arrangement, in all the specimens, the fiber volume content was around 30%.

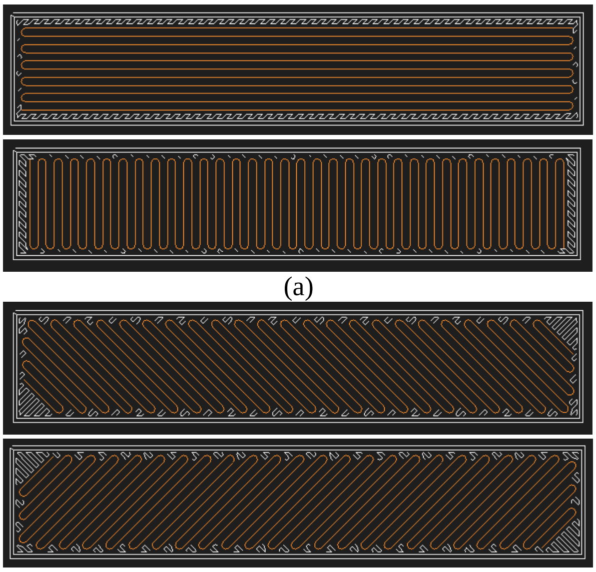


(a)

(b)

Fig. 3. Build orientation: (a) Flat and (b) On-edge

In the Figure 3, orange colour shows the fiber arrangement where at the top and bottom of fibers, onyx material is placed. In addition, two different fiber angles were assessed for the fiber reinforcement: 0°/90° and ±45° as shown in Figure 4. The orange colour lines show the fiber arrangement while the white colour lines show the onyx material arrangement.

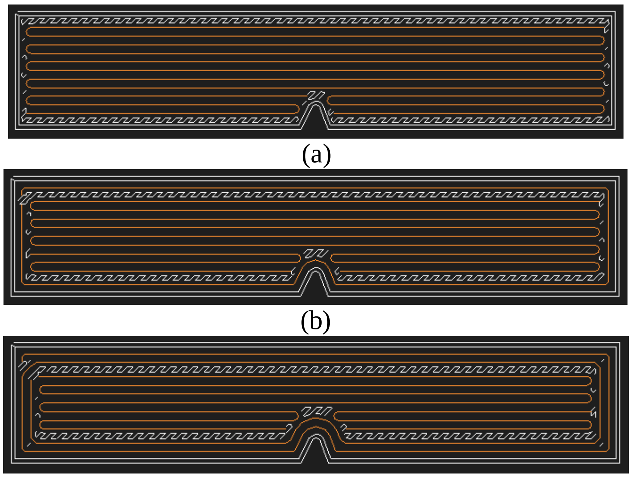


(a)

(b)

Fig. 4. Fiber Angle: (a) 0°/90° and (b) ±45°

The fiber angles were arranged in a criss-cross pattern such that if one fiber layer is printed in 0° fiber angle and then the other subsequent fiber layer is printed in 90° fiber angle. The same arrangement was followed for +45° and -45° fiber angle. Furthermore, three different numbers of fiber rings viz. 0, 1 and 2 were selected. The arrangement of fiber rings in on-edge build orientation is shown in Figure 5. Process parameters and their range are tabulated in Table 1.



(a)

(b)

(c)

Fig. 5. Number of fiber rings; (a) 0 ring, (b) 1 ring, and (c) 2 rings

Table 1. Process Parameters

Process Parameters	Value
Build Orientation	Flat, On-edge
Fiber Angle	0/90, +-45
Number of fiber Rings	0, 1, 2

Certain parameters viz. matrix fill pattern, matrix density, roof & floor layers, wall layers were fixed for all the samples.

3. RESULTS & DISCUSSION

The impact strengths are tabulated for all 12 samples in Table 2. The specimen printed with ±45° fiber angle and without fiber rings in the flat build orientation was having maximum impact strength of 2457.25 J/m. Figure 6 shows the image of the specimen after impact testing. This particular specimen was printed having on-edge build orientation, 0°/90° fiber angle, and 2 number of fiber rings. It was observed that during the impact loading, the outer onyx material was failed suddenly having a brittle fracture; however, the inside fiber arrangement of the HSHT fiberglass withstood the maximum loading giving higher strength to the composite specimen.

Table 2. Experimental data of impact strength

Sr. No.	Fiber Angle (°)	Build Orientation	Number of Fiber Rings	Impact Strength (J/m)
1	0/90	Flat	0	1779.88
2	0/90	Flat	1	2087.75
3	0/90	Flat	2	2318.13
4	0/90	On-Edge	0	754.53
5	0/90	On-Edge	1	767.69
6	0/90	On-Edge	2	903.02
7	±45	Flat	0	2457.25
8	±45	Flat	1	2455.49
9	±45	Flat	2	2347.69
10	±45	On-Edge	0	905.77
11	±45	On-Edge	1	894.41
12	±45	On-Edge	2	770.94

It is important to note that, during the printing of the fiber reinforced composite component, no pressure was applied to fibers and fiber nozzle simply lay down the fiber on the layer of polymer matrix as per desirable pattern selected in the software. For the conventional fiber reinforced composite making process, the pressure plays a vital role in reducing the defects related to pores in the components. While in this case, fiber and polymer arrangement plays the fundamental role.

Figure 6(b) shows the higher magnification image in which fiber breakout is clearly seen. It was observed that, in the case of composite part made from the conventional methods, majorly fiber pull out and delamination were the mode of fracture. While in this case, as observed from the image, no delamination has occurred. As no external pressure was applied to increase the bonding between the matrix material and fibers, the fiber pullout was observed as shown in the Figure 6(b). The fibers were broken at the notch area. Also, individual fibers were clearly seen as the fibers were only distributed on the layers from the fiber nozzle without any other bonding agent.

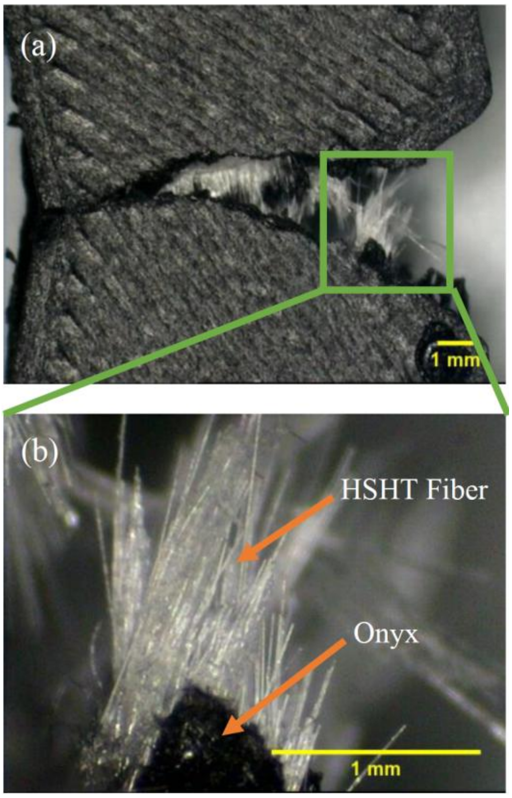
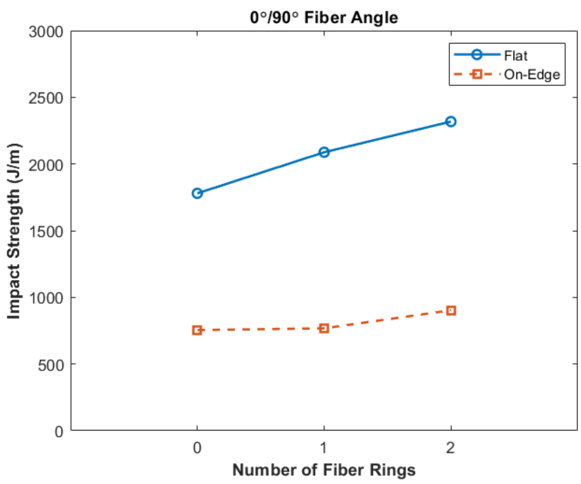


Fig. 6. Impact specimen after the fracture

3.1 Effect of process parameters on impact strength

Figure 7 shows the graphical representation of the relation between different processing parameters and the impact strength of the fiber reinforced polymer composites.



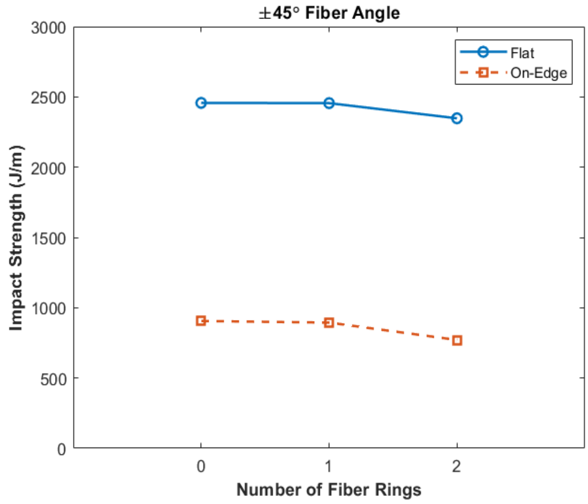


Fig. 7. Effect of the number of fiber rings on impact strength

A first glance at Figure 7 reveals that the number of fiber rings significantly affects the impact strength, particularly for the specimen printed with flat orientation. These graphs indicate that for both the fiber angles, parts printed with flat orientation have better impact properties as compared to on-edge specimens for the same number of fiber rings.

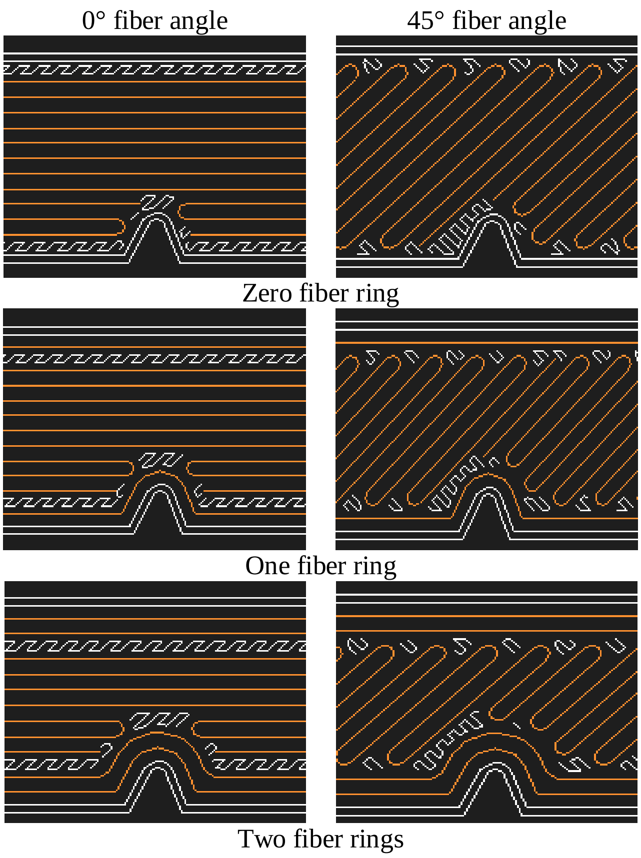


Fig. 8. Fiber arrangement at different number of fiber rings and fiber angle

However, the trends for the 0°/90° and ±45° fiber angles for the same build orientation are contrary. The impact strength is increasing as the number of fiber rings increases for both the build orientations for 0°/90° fiber angle. While for the parts printed with ±45° fiber angle, with the increment of the number of fiber rings, the impact strength in fact decreases. The possible explanation for this effect is that when the fiber angles are ±45°, as the number of fiber rings increases, the fiber length decreases as shown in Figure 8. The orange colour lines show the fiber arrangement while the white colour lines show the onyx material arrangement. The short fibers placed in the specimen are the reason for lower impact strength, particularly for the sample printed with 2 fiber rings and ±45° fiber angles. There was no significant difference in the impact strength of the parts built without fiber ring and made with one fiber ring when the fiber angle was ±45°. Although the impact strengths were slightly decreased when the parts were made with two fiber rings. It is because the decrement of fiber length was too high when there were two fiber rings as compared to the parts built with only one fiber ring.

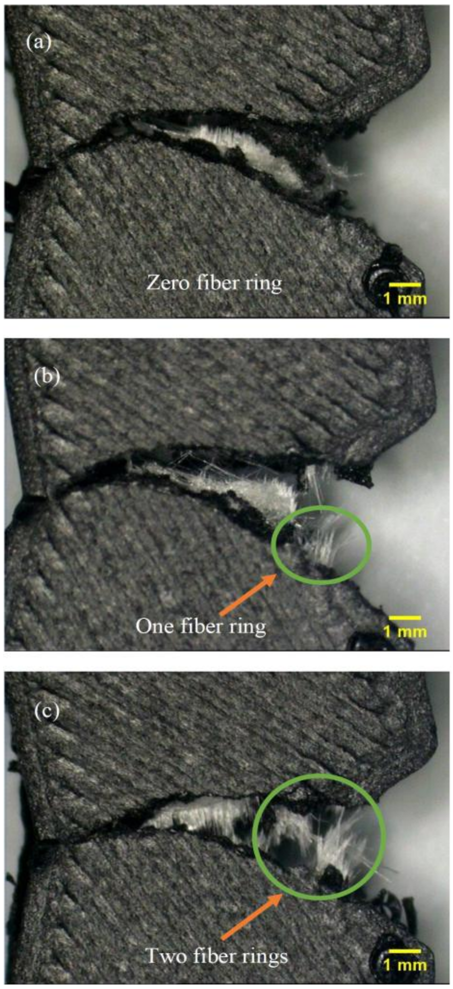


Fig. 9. fractured impact specimens having a different number of fiber rings

Though, for the parts printed with 0°/90° fiber angle, the length of the fibers for particularly 0° fiber angle did not reduce as compared to 45° fiber angle. Figure 9 shows the images of fractured impact specimens built with on-edge orientation and 0°/90° fiber angle having a different number of fiber rings. Figure 9(c) shows the fractured impact specimen having 2 fiber rings. As the fiber rings increases, the fiber around the notch area helps it to resist more impact loading for the parts printed with 0°/90° fiber angle.

4. CONCLUSIONS

The impact strength of fiber reinforced polymer composites having HSHT fiber glass as a reinforcement and onyx as a polymer matrix printed with Markforged Mark Two 3D printer was analysed. Impact tests were carried out to analyze the impact strength of the composite specimens. Three key process parameters were studied: build orientation, fiber angle and number of fiber rings. It was observed that parts made with flat orientation exhibit higher strength as compared to on-edge orientation. Also, the effect of number of fiber rings on the impact strength was different for 0°/90° and ±45° fiber angle. The impact strength is increasing as the number of fiber rings increases for 0°/90° fiber angle, while for the parts printed with ±45° fiber angle, with the increment of the number of fiber rings, the impact strength in fact decreases.

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