Charpy Impact Test Result Comparison on Reinforcing Materials used in Continuous Filament 3D Printing

Balazs Molnar
Szechenyi Istvan University, Zalaegerszeg Innovation Park, Zalaegerszeg, Hungary
molnar.balazs@sze.hu (corresponding author)

Robert Magai
Szechenyi Istvan University, Zalaegerszeg Innovation Park, Zalaegerszeg, Hungary
magai.robert@sze.hu

Received: 14 August 2024 | Revised: 12 September 2024 | Accepted: 20 November 2024

 DOI: https://doi.org/10.48084/etasr.8740

ABSTRACT

With the growing industrial demand for materials that can withstand dynamic loads, composite 3D printing, particularly utilizing continuous fiber reinforcements, presents a promising solution. This study investigates the toughness of three fiber-reinforced materials, namely carbon fiber, Kelvar, and fiberglass, by conducting Charpy impact tests. The results reveal that fiber-reinforced 3D materials significantly outperform standard 3D printed components, with fiberglass showing the highest toughness. These findings demonstrate that fiber-reinforced 3D printed materials offer a viable alternative for applications requiring high toughness and dynamic resistance.

Keywords-3D printing; Charpy impact test; continuous fiber-reinforced materials

I. INTRODUCTION

As technology evolves at an unprecedented pace, industries are experiencing a shift in how products are designed and manufactured [1-2]. One of the most influential developments in this transformation is Additive Manufacturing (AM), often known as 3D printing, which is the layer-by-layer creation of an item from 3D model data utilizing raw materials including powder, liquid, and solid (filament) [3]. In recent years, AM has made significant development and is now regarded as a creative solution to many of the difficulties that traditional manufacturing methods confront [4-6]. This transformation is further supported by advancements in raw materials, with composite printers now widely available and metal 3D printers gaining traction in the market [7]. One of the key advantages of 3D printing is the minimal waste generated during production, which has contributed to its growing popularity and made it one of the leading methods for cost-effective manufacturing [4-5].

However, the layer-by-layer stacking mechanism of AM has inherent weaknesses that can lead to mechanical failure under loading. Process parameters and the mature of AM are among the most significant contributors to these failures. To address this issue, researchers are exploring several strategies, such as consolidation during or after the printing process, the use of reinforcement composite materials (nanoparticles, chopped fibers, and continuous fibers), and optimization of process parameters [8, 9]. For instance, to improve the mechanical performance of 3D-printed continuous fiber composites, authors in [10] utilized the annealing process, serving as a heat treatment technique. This treatment involves annealing the 3D printed part below its melting temperature for a specified time, which causes transformations in the polymer. Composite materials generally, offer significant benefits, such as up to 60% weight reduction, alongside improvements in mechanical properties [11, 12]. Fiber-reinforced continuous 3D printing is an extrusion-based technique in which two separate print heads work together to build the part. This method uses two distinct materials to ensure excellent properties: the matrix and the fiber reinforcement. Sine these materials have different thermal properties, two separate filaments are used, each processed by a dedicated print head [13-18].

Charpy impact testing is a widely used method for evaluating the toughness of materials, including 3D-printed parts. This test involves striking a notched sample with a pendulum and measuring the energy absorbed by it as it fractures. In [19], authors compared two plastic materials of Fused Deposition Modeling (FDM) technology, polylactic acid (PLA) and acrylonitrile-butadiene-styrene (ABS) using Charpy testing. Other studies have examined how the filling direction affects energy absorption [20]. Similar tests have been performed in continuous fiber reinforced 3D printing, observing the effect of filling direction on specimens. However, a comprehensive comparison of fiber-reinforced materials in dynamic applications has not yet been conducted [21]. The aim of the current study is to compare the energy absorption capacity of carbon, glass fiber, and Kevlar reinforcement materials, using a Charpy hammer.

II. METHODOLOGY

A. 3D Printing Method

The samples were manufactured using the Markforged Mark Two printer (Figure 1). Both the printer and the matrix material used belong to the same manufacturer, with the matrix material being part of the Onyx product family. Onyx is a composite filament designed for fiber-reinforced printing, serving as the enclosing material for the reinforcing fibers.

Fig. 1. Illustration of the 3D printer used (Markforged Mark Two).

During the production of the sample parts, the Onyx matrix material was reinforced with Kevlar, fiberglass and carbon fiber materials. The samples were designed using CAD software, the dimensions of which correspond to the standard. Before printing started, the designed part was exported to Standard Triangle Language (STL) format. Figure 2 depicts the 3D model of the printed piece.

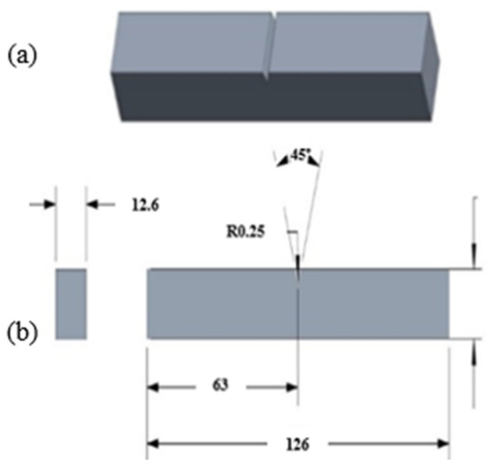

Fig. 2. (a) 3D model and (b) main dimensions of test specimens.

Fiber-reinforced materials possess varying properties, which can affect the required number of reinforcement layers. To ensure comparable measurements, the same fill ratio was applied to all reinforcing materials, thereby standardizing the layer count and avoiding discrepancies. Table I presents the printing parameters of the reinforced materials.

TABLE I. 3D PRINTING PARAMETERS OF FIBER REINFORCED MATERIALS

3D Printing Parameters	Material Specifications
Fill style	Linear
Wall layer number	2
Roof layer	2
Onyx layer number	4

During the 3D printing process, the samples were designed with a material distribution of 5-40-10-40-5 %. This means that the outermost 5% of the sample (at both the top and bottom) and the central 10% consist of Onyx matrix material. The remaining 40% in the intermediate structure is composed of various reinforcing materials (carbon fiber, Kevlar, or fiberglass). This design was necessary because the diameter of the reinforcing fibers differs between the materials, which affects the total number of layers required to construct the samples. Specifically, carbon fiber has larger diameter compared to Kevlar and fiberglass and as a result, carbon fiber reinforced sample contains 101 total layers, while the other two require 127 total layers to achieve the same reinforcement ratio. To ensure consistency in the reinforcing material, the number of reinforcing layers was adjusted. The carbon fiber-reinforced specimen has 40 reinforcing layers in the intermediate sections, while the Kevlar and fiberglass-reinforced specimens have 51 reinforcing layers each. This adjustment ensures fair comparison across the different materials." Figure 3 displays the structures of the test pieces created with the Eiger software.

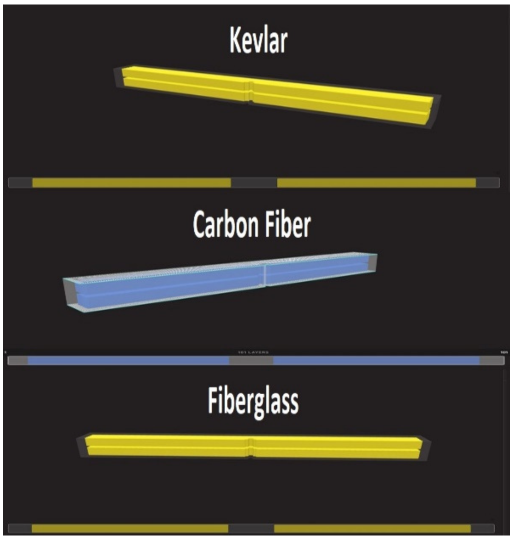

Fig. 3. Layer by layer construction of the test pieces using Eiger software.

B. Charpy Test

The tests were conducted in accordance with ASTM D6110 standard [22], using a Charpy hammer (type MQ_PSD-50-2), as shown in Figure 4. The Charpy testing process began with Kevlar fiber-reinforced specimens, followed by carbon fiber-reinforced samples, and concluded with glass fiber-reinforced specimens. For each type of reinforcing material, three specimens were tested, and the average of the recorded values was calculated for evaluation.

Fig. 4. Charpy testing machine.

III. RESULTS AND DISCUSSION

Figure 5 illustrates the condition of all nine test pieces after Charpy test was completed.

Fig. 5. The results of the specimens after Charpy testing.

The results for Kevlar and carbon fiber specimens were consistent with expectations. However, the fiberglass specimens displayed unexpected results. Specifically, the fiberglass samples exceeded the measuring range of the machine, meaning that the test could not register their full resistance. Unlike the Kevlar and carbon fiber specimens, which experienced complete fractures, the fiberglass specimens only deformed without breaking under the impact.

Based on the results of the Charpy test, it was not possible to precisely determine the impact resistance of the glass fiber-reinforced samples. To illustrate their performance in the rest of this study, their values are denoted as +50 J, indicating that they surpassed the machine's maximum measurable limit. The results of the impact on the ither samples were clearly visible during the test and Figure 6 depicts the outcome values. The average impact of the carbon fiber-reinforced samples was 9.1 J and 12.2 J of the Kevlar fiber-reinforced samples. The analysis indicated that the glass fiber-reinforced specimens exhibited the highest resistance to dynamic forces, followed by Kevlar-reinforced specimens, with the carbon fiber reinforced specimens showing the lowest resistance.

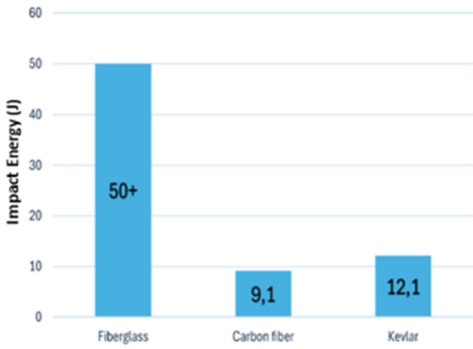

Fig. 6. Diagram of the impact energy (J) of the fiber-reinforced specimens.

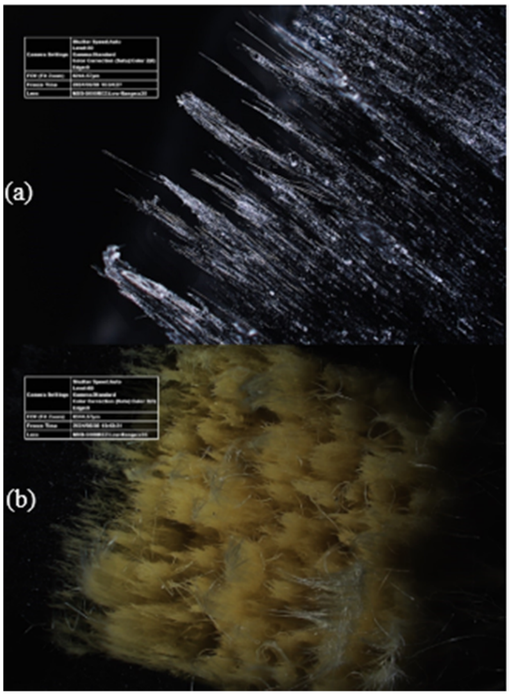

Fig. 7. Examination of fractured pieces of (a) carbon-fiber, and (b) Kevlar-fiber under a microscope.

After testing, the fractured pieces were examined under a microscope, revealing the layer tears caused by the hammer's impact. For the glass fiber reinforced specimens, no breakage occurred. Instead, the samples were deformed by the force of the hammer. Due to this, no micrographs were taken, and a detailed analysis of fiberglass deformation was not performed. Figure 7 highlights the layer-by-layer construction of the printed samples, showing the full structure of each layer. A closer look of these images clearly reveals the effects of the hammer's high-impact force on them, showing the thinning and tearing of carbon and Kevlar fiber reinforced specimens.

IV. CONCLUSIONS AND FUTURE WORK

This study examined the impact resistance of three different fiber-reinforced materials used in composite 3D printing, with the goal of helping users select the most suitable material for various practical applications. Among the tested materials, fiberglass reinforcement demonstrated a ductile behavior, absorbing the most energy (+50 J), while the Kevlar and carbon fiber reinforcements presented a more brittle behavior absorbing a small amount of energy.

Future research should focus on investigating the effects of post-heat treatment on the materials discussed in this study. While previous studies have shown that post-heat treatment can enhance the properties of continuous fiber-reinforced 3D printed specimens, it remains to be determined how much improvement it can bring to the fiberglass, Kevlar, and carbon fiber-reinforced materials. Further studies should explore how structural modifications of the reinforcing material matrix influence the results, with the goal of understanding the potential performance gains and identifying optimal treatment methods for these materials.

REFERENCES

[1] K. S. Prakash, T. Nancharaih, and V. V. S. Rao, "Additive Manufacturing Techniques in Manufacturing -An Overview," *Materials Today: Proceedings*, vol. 5, no. 2, Part 1, pp. 3873–3882, Jan. 2018, https://doi.org/10.1016/j.matpr.2017.11.642.

[2] J. Huang, Q. Qin, and J. Wang, "A Review of Stereolithography: Processes and Systems," *Processes*, vol. 8, no. 9, Sep. 2020, Art. no. 1138, https://doi.org/10.3390/pr8091138.

[3] T. D. Ngo, A. Kashani, G. Imbalzano, K. T. Q. Nguyen, and D. Hui, "Additive manufacturing (3D printing): A review of materials, methods, applications and challenges," *Composites Part B: Engineering*, vol. 143, pp. 172–196, Jun. 2018, https://doi.org/10.1016/j.compositesb.2018.02.012.

[4] N. Shahrubudin, T. C. Lee, and R. Ramlan, "An Overview on 3D Printing Technology: Technological, Materials, and Applications," *Procedia Manufacturing*, vol. 35, pp. 1286–1296, Jan. 2019, https://doi.org/10.1016/j.promfg.2019.06.089.

[5] D. Godec, J. Gonzalez-Gutierrez, A. Nordin, E. Pei, and J. Ureña Alcázar, Eds., *A Guide to Additive Manufacturing*, Cham, Switzerland: Springer Nature, 2022.

[6] P. Lakkala, S. R. Munnangi, S. Bandari, and M. Repka, "Additive manufacturing technologies with emphasis on stereolithography 3D printing in pharmaceutical and medical applications: A review," *International Journal of Pharmaceutics: X*, vol. 5, Dec. 2023, Art. no. 100159, https://doi.org/10.1016/j.ijpx.2023.100159.

[7] M. Jiménez, L. Romero, I. A. Domínguez, M. del M. Espinosa, and M. Domínguez, "Additive Manufacturing Technologies: An Overview about 3D Printing Methods and Future Prospects," *Complexity*, vol. 2019, no. 1, 2019, Art. no. 9656938, https://doi.org/10.1155/2019/9656938.

[8] F. Ning, W. Cong, J. Qiu, J. Wei, and S. Wang, "Additive manufacturing of carbon fiber reinforced thermoplastic composites using fused deposition modeling," *Composites Part B: Engineering*, vol. 80, pp. 369–378, Oct. 2015, https://doi.org/10.1016/j.compositesb.2015.06.013.

[9] J. Wang, H. Xie, Z. Weng, T. Senthil, and L. Wu, "A novel approach to improve mechanical properties of parts fabricated by fused deposition modeling," *Materials & Design*, vol. 105, pp. 152–159, Sep. 2016, https://doi.org/10.1016/j.matdes.2016.05.078.

[10] D. G. Zisopol, A. I. Portoaca, I. Nae, and I. Ramadan, "A Comparative Analysis of the Mechanical Properties of Annealed PLA," *Engineering, Technology & Applied Science Research*, vol. 12, no. 4, pp. 8978–8981, Aug. 2022, https://doi.org/10.48084/etasr.5123.

[11] X. Tian *et al.*, "3D Printing of Continuous Fiber Reinforced Polymer Composites: Development, Application, and Prospective," *Chinese Journal of Mechanical Engineering: Additive Manufacturing Frontiers*, vol. 1, no. 1, Mar. 2022, Art. no. 100016, https://doi.org/10.1016/j.cjmeam.2022.100016.

[12] Y. Yang, B. Yang, Z. Chang, J. Duan, and W. Chen, "Research Status of and Prospects for 3D Printing for Continuous Fiber-Reinforced Thermoplastic Composites," *Polymers*, vol. 15, no. 17, Jan. 2023, Art. no. 3653, https://doi.org/10.3390/polym15173653.

[13] F. Safari, A. Kami, and V. Abedini, "3D printing of continuous fiber reinforced composites: A review of the processing, pre- and post-processing effects on mechanical properties," *Polymers and Polymer Composites*, vol. 30, Jan. 2022, Art. no. 09673911221098734, https://doi.org/10.1177/09673911221098734.

[14] X. Tian *et al.*, "3D Printing of Continuous Fiber Reinforced Polymer Composites: Development, Application, and Prospective," *Chinese Journal of Mechanical Engineering: Additive Manufacturing Frontiers*, vol. 1, no. 1, Mar. 2022, Art. no. 100016, https://doi.org/10.1016/j.cjmeam.2022.100016.

[15] Y. Yang, B. Yang, Z. Chang, J. Duan, and W. Chen, "Research Status of and Prospects for 3D Printing for Continuous Fiber-Reinforced Thermoplastic Composites," *Polymers*, vol. 15, no. 17, Jan. 2023, Art. no. 3653, https://doi.org/10.3390/polym15173653.

[16] M. Mohammadizadeh and I. Fidan, "Tensile Performance of 3D-Printed Continuous Fiber-Reinforced Nylon Composites," *Journal of Manufacturing and Materials Processing*, vol. 5, no. 3, Sep. 2021, Art. no. 68, https://doi.org/10.3390/jmmp5030068.

[17] M. Khosroupour Arabi and N. Kordani, "3D-printing of Continuous Fiber: A review of processes, materials and properties," *Polymer-Plastics Technology and Materials*, vol. 62, no. 12, pp. 1525–1559, Aug. 2023, https://doi.org/10.1080/25740881.2023.2222793.

[18] X. Shen, B. Jia, H. Zhao, X. Yang, and Z. Liu, "Study on 3D printing process of continuous carbon fiber reinforced shape memory polymer composites," *IOP Conference Series: Materials Science and Engineering*, vol. 563, no. 2, Apr. 2019, Art. no. 022029, https://doi.org/10.1088/1757-899X/563/2/022029.

[19] D. G. Zisopol, N. Ion, and A. I. Portoaca, "Comparison of the Charpy Resilience of Two 3D Printed Materials: A Study on the Impact Resistance of Plastic Parts," *Engineering, Technology & Applied Science Research*, vol. 13, no. 3, pp. 10781–10784, Jun. 2023, https://doi.org/10.48084/etasr.5876.

[20] S. Korga, M. Barszcz, and Ł. Zgryza, "The effect of the 3D printout filling parameter on the impact strength of elements made with the FDM method," *IOP Conference Series: Materials Science and Engineering*, vol. 710, no. 1, Sep. 2019, Art. no. 012027, https://doi.org/10.1088/1757-899X/710/1/012027.

[21] D. R. Hetrick, S. H. R. Sanei, O. Ashour, and C. E. Bakis, "Charpy impact energy absorption of 3D printed continuous Kevlar reinforced composites," *Journal of Composite Materials*, vol. 55, no. 12, pp. 1705–1713, May 2021, https://doi.org/10.1177/0021998320985596.

[22] *Standard test method for determining the Charpy impact resistance of notched specimens of plastics,* ASTM-D6110-18, 2018.