Journal of
Polymer & Composites
https://journals.stmjournals.com/jopc

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Special Issue 3, 2026
DOI (Journal): 10.37591/JoPC

Review JoPC

Dual Nozzle 3D Printing of Basalt Fiber–Reinforced Polymer Composites

Y. Premraj[1],*, S. Dhandapani[2], Murugan[3], Ramanan[4]

Abstract

Additive manufacturing or 3Dprinting involves building a three-dimensional object by layering materials based on a computer-created design. Generally, 3D printing using single nozzle process where as strength, quality, wastage, and post reinforcement are drawback of this system. To eliminate and to enhance strength, precise control of fiber reinforcement, good bonding, no need of secondary reinforcement the dual nozzle 3D printing is an emerging additive manufacturing technique. In this process the thermoplastic resin matrix and basalt fibre reinforcement are enables in-situ fabrication of fiber-reinforced polymer composites by independently depositing reinforcement and matrix materials within a single build. This Layer-by-layer deposition promotes effective fiber–matrix bonding and controlled load transfer, and improved stiffness, thermal stability and eliminates the d raw back of single nozzle systems. The standard nozzle size for most 3D printers is 0.4 mm as it strikes a balance between printing speed, precision, and resolution. However, printing larger compounds at a faster rate can be challenging with a single nozzle, which extrudes the filament, is responsible for melting the material with the thermal energy supplied by the heating cartridge and block. Adding multiple nozzles can speed up the process, but it also increases the complexity of the coding. In this project the design of dual nozzle is carried out using the software integration and tensile, flexural, impact and microstructure are carried out and compared with single nozzle. The parameters are identified to improve the dual nozzle system. Using a double nozzle is an excellent option for printing medium to large-sized compounds. It offers a balance between printing speed, precision, and resolution while also allowing for dual-color or dual-material printing. This type of printers also suitable for printing several smaller compounds.

Keywords: Dual-nozzle 3D printing, Basalt fiber, polymer resin, additive manufacturing, composite materials

***Author for Correspondence**
Y. Premraj

[1]Principal. Department of Mechanical Engineering, T.J.S. Polytechnic College, Puduvoyal, Gummidipoondi, Tiruvallur District, Tamil Nadu, India
[2]Professor, Department of Mechanical Engineering, Rajalakshmi Engineering College, Thandalam, Chennai, Tamil Nadu, India
[3]Assistant Professor, Department of Mechanical Engineering, Gojan School of Business and Technology, Redhills Chennai, Tamil Nadu, India
[4]Associate Professor, Department of Mechanical Engineering, Sri Jayaram institute of Engineering and Technology, Gummidipoondi Tiruvallur District, Tamil Nadu, India

Received Date: January 28, 2026
Accepted Date: March 21, 2026
Published Date: May 19, 2026

Citation: Y. Premraj, S. Dhandapani, Murugan, Ramanan. Dual Nozzle 3D Printing of Basalt Fiber–Reinforced Polymer Composites. Journal of Polymer & Composites. 2026; 14(Special Issue 3): S620–S630p.

INTRODUCTION

Solid, three-dimensional (3D) objects can be fabricated using 3D printing processes. Plastics are popular materials for 3D printers due to their low cost and ease of use, though metals and ceramics can also be printed at higher expense.

The term "additive manufacturing" (AM) refers to production techniques that build 3D objects by sequentially depositing materials layer by layer. The essential characteristics [1–4] should exhibit to qualify as an AM technology.

Three-dimensional (3D) objects are visualized and designed using computer-aided design (CAD) software in additive manufacturing workflows. Proficiency in these CAD programs is essential for technicians to effectively create complex3Dproduct models. The resulting designs are exported as G-code files, which 3D printers interpret to control material extrusion rates and build times for accurate replicas.

The CAD 3D model must be oriented and prepared in slicing software for additive manufacturing to generate tool paths. Slicing software divides the model in to discrete layers, enabling the machine to trace the 3D geometry accurately during fabrication.

With the aid engineering materials such as polymers, metal powders, and composites the additive manufacturing machines convert 3D CAD models into physical objects using G-code tool paths by Slicing software. Which control the melting and deposition of materials to construct the part layer by layer.

Additive manufacturing encompasses various techniques classified by materials and machine technologies, [1, 2] as outlined in ASTM F42 standards from 2010, which identify seven distinct processes.

- Powder bed fusion (including methods using a powder bed).
- VAT photo polymerization.
- Material and Binder jetting methods.
- Directed energy deposition (DED) and Sheet lamination.

Extensive research covers these processes, which utilize diverse materials and machines for 3D printed components.

- Reduced material waste compared to subtractive machining, thereby enhancing efficiency.
- Elimination of the need for auxiliary tooling such as fixtures, improving resource utilization.
- Ability to manufacture highly complex geometries without tooling constraints.
- Greater production flexibility across applications.

Despite these advantages, limitations include high equipment costs, size restrictions, surface/micro structural defects, and slow speeds unsuitable for mass production. Among these, material extrusion also known as fused deposition modeling (FDM) is the most accessible and cost-effective for polymer-based parts, which are applied more in industries [5–7].The following sections detail FDM fundamentals, applications, parameters, and quality factors.

FDM Research and Its Practical Uses

The feedback stock for the fused deposition modeling (FDM) method is the thermoplastic polymers. A thermoplastic filament is feed continuously by two rotating rollers into the extruder and nozzle, where the material melts and is extruded layer by layer onto the build plate [8–10]. The nozzle head Follows precise three-axis paths defined by G-code to deposit material, forming the desired geometry as shown schematically in Figure 1 [8–10].

The printer nozzle follows G-code paths derived from the CAD model's geometric coordinates, traversing back and forth iteratively to deposit material and achieve the desired part size and shape. Certain FDM systems employ multiple extrusion nozzles to create compositional gradients by depositing different polymer variants layer by layer. Most affordable FDM printers are optimized for polylactic acid (PLA) filament, as its properties determine extrusion resolution and efficiency; the build plate, often detachable or coated with adhesive, secures components during printing. Post-processing techniques like cleaning, sanding, painting, or milling improve surface finish and functionality [11].

Although a wide range of materials, poly lactic acid (PLA) is the most used filament in both domestic and industrial 3D printers due to several advantages in the fused deposition modeling (FDM) can process. The safety materials for both humans and the environment friendly polymer [11, 12] such as corn, sugarcane, wheat, and other carbohydrate-rich materials has been used to make PLA is a bio plastic, as it is derived from renewable resources. Making it an PLA has a melting temperature in the range of 180–220 °C and a glass transition temperature between 50–70 °C, which allows it to be extruded using most low-cost and energy-efficient 3D printers. Unlike conventional plastics that pose significant disposal challenges, PLA is biodegradable and decomposes relatively quickly under appropriate conditions.

As a biopolymer, PLA breaks down into harmless gases, water, biomass, and inorganic salts when subjected to burning, hydrolysis, or natural environmental exposure. In its semi-crystalline form, PLA exhibits high tensile and flexural strength, along with high flexural modulus. Additionally, PLA often does not require a heated build plate to ensure proper adhesion, which further contributes to its popularity among 3D printing users. However, grapheme-doped PLA may exhibit poor print quality on non-heated build plates, posing a limitation for printers without heated beds. PLA filaments are also available in a wide variety of colors and surface textures [13, 14].

The wide range of materials, including nylon, polycaprolactone, polyethylene, polybutylene terephthalate, wood-filled filaments, polypropylene, metals, carbon fiber–reinforced composites, graphene-doped PLA, and many others [11, 12] in the fused deposition modeling (FDM) technique

Owing to its versatility and capability to fabricate complex geometries, FDM is widely used in modern applications. Common uses include the production of personalized toys, automotive components, interior design elements, medical implants, cosmetic packaging, and various other consumer and industrial products [12].

Using FDM) the medical field for the fabrication of implant casting molds, medical device prototypes, and even functional implants. One of the most notable applications is the use of 3D-printed molds for casting medical implants through investment casting processes [15, 16]. Traditionally, investment casting relied on metal molds and sacrificial patterns to produce the complex geometries required for implants. The adoption of 3D-printed molds significantly reduces production time, manufacturing costs, and material waste by eliminating the need for sacrificial patterns [5, 8].

Beyond these applications, FDM has been employed in the fabrication of micro-truss structures for energy storage devices, drug delivery systems, biomedical scaffolds, rapid prototyping of electrochemical cells in the pharmaceutical industry, and the direct printing of conductive components in the electronics sector [17–20].

Polycarbonates are known as carbonate groups within their molecular structure in the thermoplastic polymers. In engineering applications, polycarbonates are valued for their high strength, durability, and, in certain grades, optical transparency [21]. These materials are easy to process using molding and thermoforming techniques.

The three primary monomers: a crylonitrile, butadiene, and styrene [22–24] is in the ABS which is impact-resistant engineering thermoplastic and is classified as an amorphous polymer.

MATERIAL AND METHOD

The manufacturing journey of a 3D printing machine (Figure 1) is a multifaceted process that encompasses various critical steps, each contributing to the creation of a functional and reliable product. At the outset of this endeavor lies the pivotal phase of design. Here, engineers and designers meticulously craft the blueprint of the 3D printing machine using Computer-Aided Design (CAD) software. This initial stage demands a comprehensive understanding of the machine's in ended application, dimensions, weight considerations, and material requirements. By meticulously laying out the design parameters, engineers ensure that the ensuing prototype will embody the envisioned functionality and performance [25–27].

Following the design phase, the journey progresses to prototyping, a crucial stage where the theoretical blueprint is translated into tangible reality. Utilizing cutting-edge 3D printing technology, a prototype of the machine is materialized layer by layer, offering a tangible manifestation of the design's potential. This prototype serves as a testing ground, allowing engineers to scrutinize its performance, identify potential flaws or inefficiencies, and refine the design iteratively. Through this iterative process of testing and refinement, the prototype gradually evolves, inching closer towards the realization of a robust and efficient final product.

Integral to the success of any 3D printing machine is the judicious selection of materials. Material selection is a meticulous process that demands careful consideration of factors such as durability, heat resistance, and mechanical properties. By selecting materials that exhibit optimal performance characteristics, engineers ensure that the resulting machine will withstand the rigors of sustained usage, delivering reliable performance over its operational lifespan [28].

As the design is refined and the materials are selected, the manufacturing phase commences, marking a pivotal juncture in the journey towards realizing the final product.

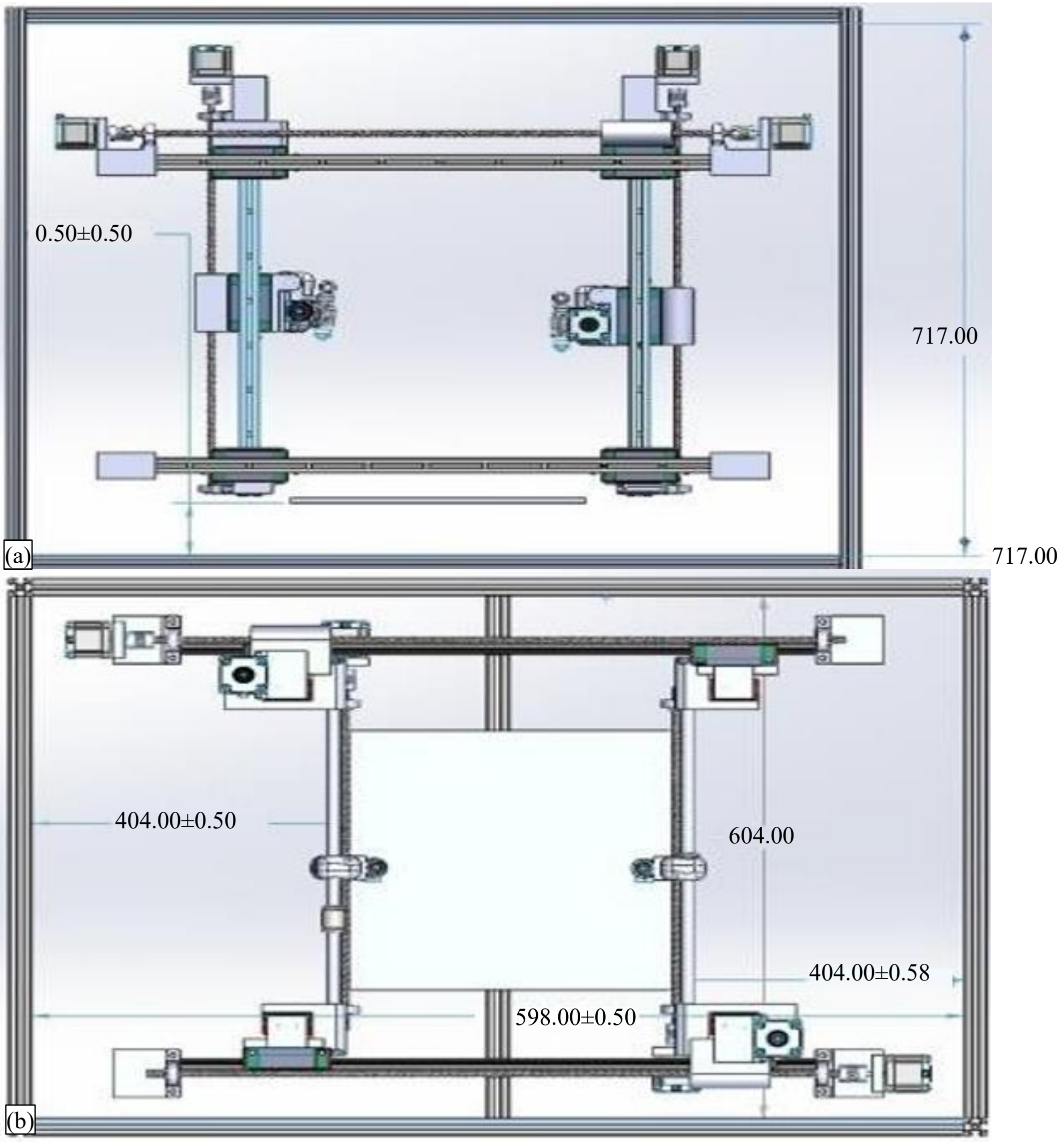

Figure 1. (a) Front view and (b) top view of 3D printing machine.

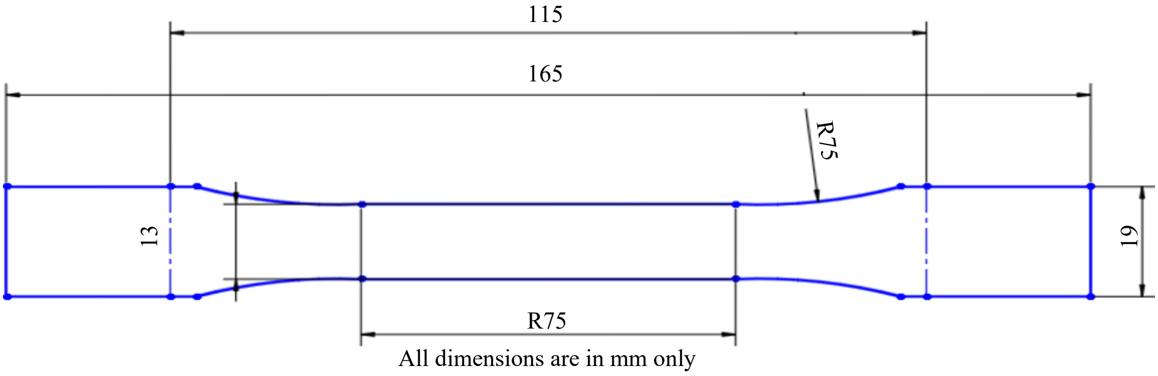

Figure 2. Tensile test specimen [ASTM:D638].

Table 1. Single nozzle and dual nozzle tensile strength.

S.N.	Ultimate load in KN in dual nozzle	Ultimate load in KN in single nozzle	Ultimate stress in N/mm2 in dual nozzle	Ultimate stress in N/mm2 single nozzle	% of elongation in dual nozzle	% of elongation in single nozzle	Displacement in mm in dual nozzle	Displacement in mm in single nozzle
1	5.81	6.82	103.215	108.225	6.667	8.67	5.52	6.52
2	4.47	5.63	79.566	89.255	3.33	5.33	3.88	4.88
3	6.04	9.04	107.77	110.45	6.667	8.67	5.03	6.03

DESIGN AND ANALYS IS USING SOFTWARE

Entail a combination of in-house manufacturing capabilities and outsourcing certain components to specialized manufacturers. Whether through precision machining, injection molding, or additive manufacturing processes, each component is meticulously crafted to exacting standards, ensuring seamless integration and optimal performance within the 3Dprintingmachine [29].

Throughout the manufacturing process, stringent quality control measures are instituted to safeguard the integrity and reliability of the final product. Quality control protocols encompass a spectrum of inspections, tests, and validations aimed at verifying dimensional accuracy, structural integrity, and functional performance. By adhering to rig or quality assurance standards, manufacturers mitigate the risk of defects or deviations, ensuring that each unit adheres to their quite specifications and standards [30].

TESTING OF COMPOSITES

Tensile Test

Universal testing machine were used to examine tensile properties. Tensile load is higher when laminate tension extends first and then breaks the specimen. The tensile specimen was prepared as shown in Figure 2. The specimen breaks at a given stage when loaded axially in either direction. Tensile testing follows ASTM D638. The composite laminate is blanked to tensile test dimensions, so it meets standards. Figure 3 shows ASTM composite sample tensile test standards.

The tensile testing results are presented graphically as shown in Figure 3.and the values of ultimate load, ultimate stress, percentage of elongation and displacement values are represented in Table 1 for Dual Nozzle and Single Nozzle. The single-nozzle specimen exhibited a higher ultimate tensile load of 110.45kN, where as the dual-nozzle specimen showed a slightly lower value of 107.48 KN. In comparison, the ultimate tensile strength of the dual-nozzle specimen was lower than that of the single-nozzle specimen.

This reduction is attribute do the extrusion process in the single-nozzle system, where filament deposition occurs uniformly, resulting in better material homogeneity and, consequently, improved tensile performance. In contrast, the dual-nozzle system involves separate deposition of the material and resin, leading to a non-uniform internal structure and weaker interfacial bonding. As a result, the tensile strength of the dual-nozzle specimen is reduced. However, with proper control of filament heating and processing temperature, the tensile properties of the dual-nozzle specimens can be significantly improved.

Flexural Test

Flexural or three-point bending test was done with Universal Testing Machine. Flexural test specimen could bear load under deformation. Flexural testing requires controlling inter-laminar shear strength using short beam shear tests. Figure 4 shows ASTM D790 composite sample flexural test standards.

The flexural test results values of ultimate break load, ultimate stress, and displacement values are represented in Table 2 for Dual Nozzle and Single Nozzle also the values are graphically visualized in Figure 5. The behavior of the specimen under flexural loading is influenced by the observed fracture. During fabrication, the fiber assumes a concave geometry, resulting in maximum tensile stress on the outer surface and minimum stress on the inner surface. Flexural strength is expressed in mega Pascal's (MPa). All flexural tests were carried out under controlled laboratory conditions at a constant temperature. Owing to the dual-nozzle characteristics previously identified in the tensile test, a similar response was also observed during the flexural test. Therefore, precise control of the processing temperature is essential to enhance the overall material properties.

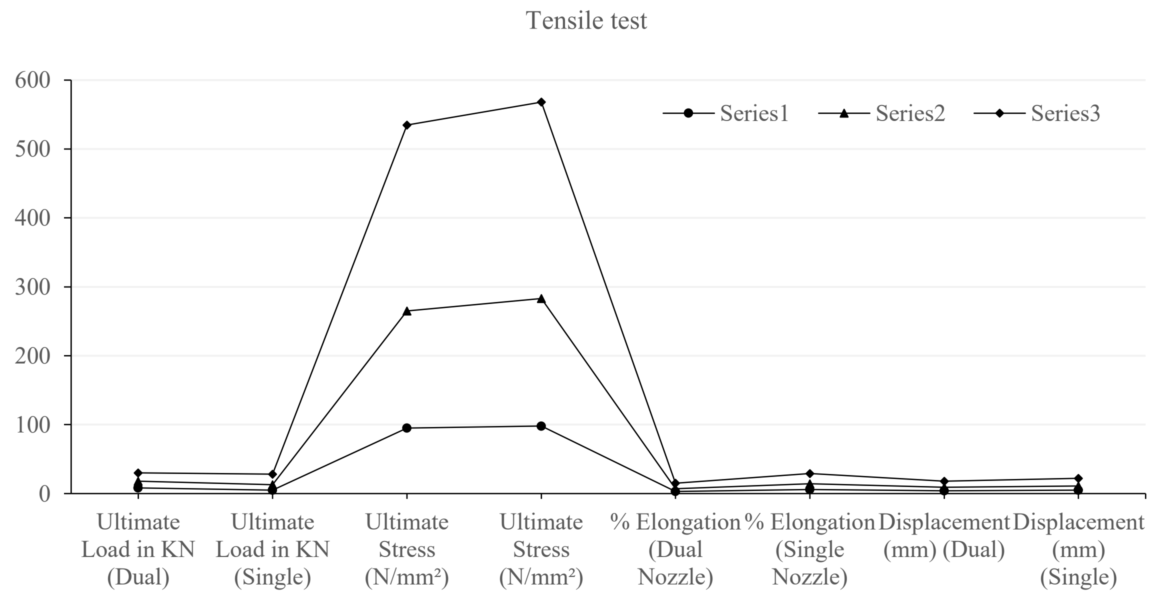

Figure 3. Tensile test compression.

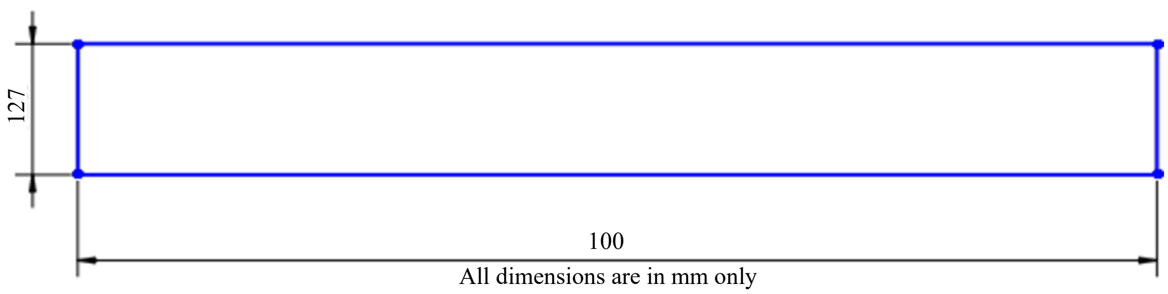

Figure 4. Flexural test specimen [ASTM:D790].

Journal of Polymer & Composites
Volume 14, Special Issue 3
ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

Impact Test

To perform the impact test, a machine equipped with a Charpy arrangement was utilized. The ASTM D256 standards are followed during the impact test. The total amount of energy absorbed at impact, measured in joules, during material fracture, is also evaluated in this test. In the end, the lifespan of the specimen composite will determine everything. In order to measure the greatest amount of energy absorbed after impact, the specimen is subjected to a violent hit using the oscillating pendulum to and fro.

The material's toughness determines the fracture. The specimen is hit until it breaks at a specific point. We have recorded the maximum amount of energy that can be absorbed in joules and produced there level graphs and the values are represented in Table 3 and the comparison values were graphically represented in Figure 7. Composites amplest must undergo impact testing in accordance with ASTM standards (Figure 6). Due to the dual-nozzle characteristics observed in the tensile test, a similar response was also evident in the flexural test. Therefore, proper control of the processing temperature is essential, as maintaining optimal thermal conditions directly contributes to the improvement of material properties.

Table2. Single nozzle and dual nozzle flexural test.

S.N.	Ultimate Break load KN in Dual Nozzle	Ultimate Break load KN in single Nozzle	Ultimate Stress KN/mm² in Dual Nozzle	Ultimate Stress KN/mm² in single Nozzle	Displacement in mm in Dual Nozzle	Displacement in mm in single Nozzle
1	0.490	0.651	0.009	0.158	3.80	5.60
2	0.620	0.852	0.012	0.162	5.80	8.20
3	0.495	0.685	0.010	0.189	3.60	5.60

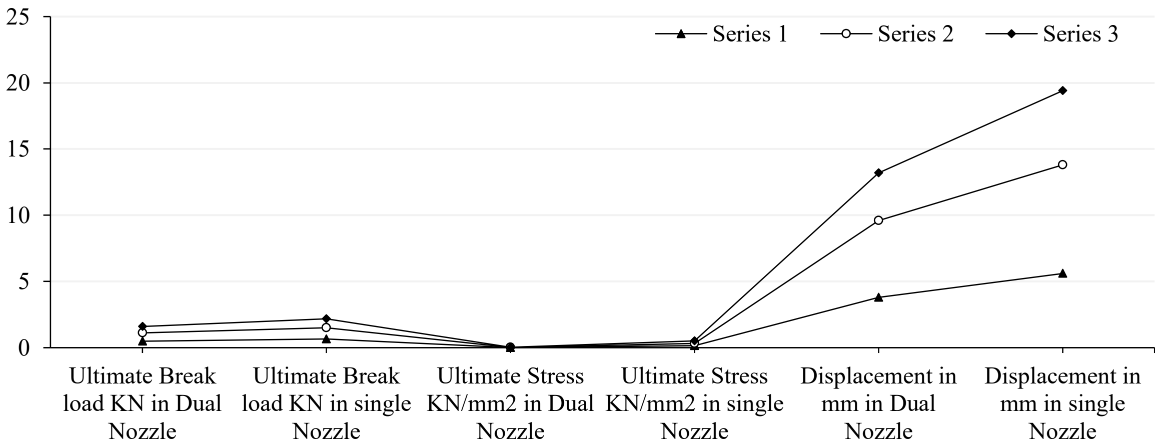

Figure 5. Flexural test graph.

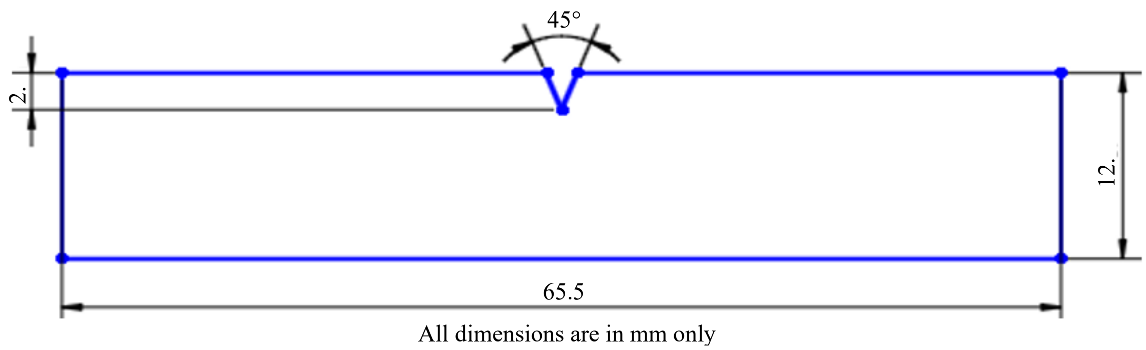

Figure 6. Impact test specimen [ASTM:D256].

Table 3. Impact test valve.

S.N.	Single Nozzle impact strength in Joule	Double Nozzle impact strength in joule
1	12	10
2	14	9
3	13	9

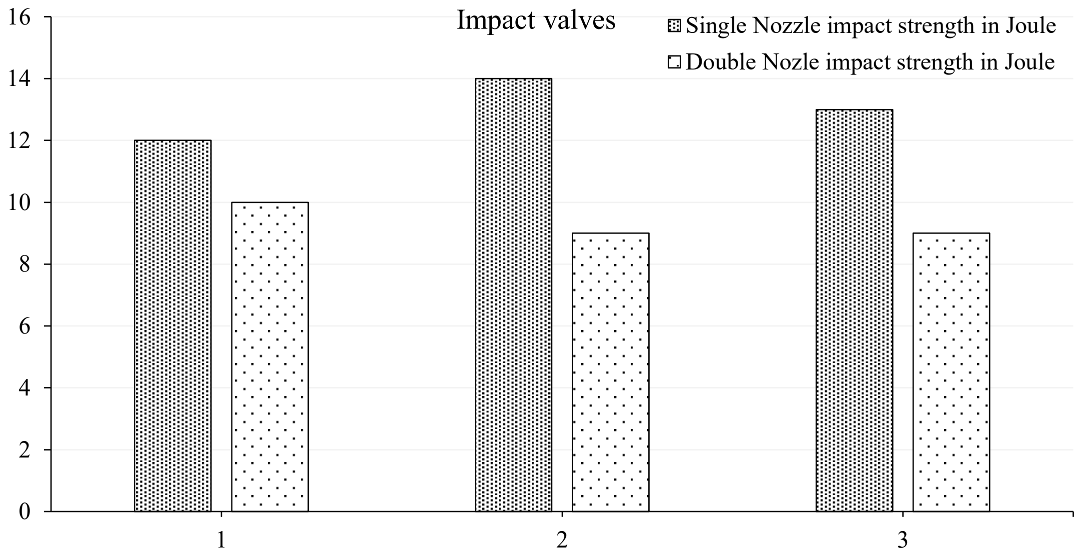

Figure 7. Impact test graph.

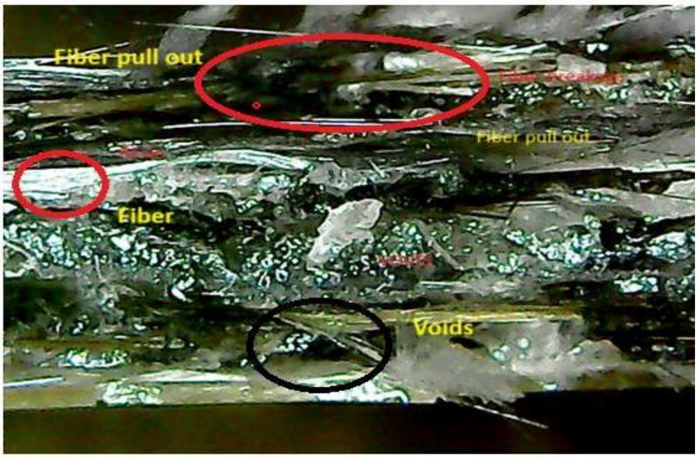

Figure 8. Macro image analysis image.

Macro Images

Macro images in material analysis issues close-up photography to reveal surface details, textures, defects (like cracks, pores), and microstructures (like grain flow, fibers) for quality control, failure analysis, and property assessment in industries from aerospace to textiles, often employing technique like focus tacking, panoramic stitching, and specialized lighting for high-resolution 3D visualization, complementing microscopy for larger-scale features.

The Macro images were shown in Figure 8. The image was shown as a voids and fiber facture. In this defect generally happened reason was the fiber was hexothermic heat generation happen in a process. But in this category the fiber and resin apply different channels. The process lack heat fusion was happened hence fiber was pulled out in a lesser load application. The heat source was happened rapidly may be quickly control the defects.

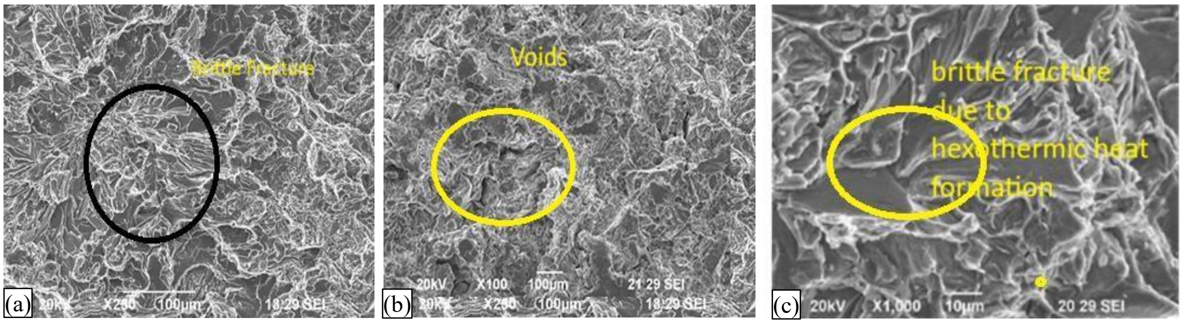

Figure 9. Fracture surface image tensile, flexural and impact test.

Morphological Examination with a Scanning Electron Microscope *(SEM)*

Morphological examinations were conducted using a scanning electron microscope (SEM) to scrutinize the interior surface properties of the sample material in detail. After removing and drying all test samples, a 25–30 nm thick gold layer was applied via an ion-sputter coater. The resulting SEM images clearly reveal the interfacial contact between the matrix and fiber.

The SEM morphological investigation of bio-composite materials is shown (Figure 6). Characterization of composite tensile-Flexural and impact test. Fiber surface specific breaking was shown after tensile testing sample (Figure 7) which shows the heterogeneous and layered microstructure and distinct fiber-rich and resin-rich zones. SEM images also reveal internal cracks, voids, interfacial characteristics, and most critically, composite material shattered surfaces' internal assembly (Figure 9). Increased interfacial area between reinforcement and matrix, Incomplete fiber wetting by molten resin. Figure showed the Basalt composite fiber matrix internal assembly. Figures show fiber linear breaking after impact load test. Impact testing fragmented bio-composite samples at the fracture point (Figure 9). Fiber end sand poorly bonded regions act as crack initiation sites

CONCLUSION

In conclusion, the 3D printer project has proven to be an innovative and versatile technology with numerous potential applications in various fields.

The results show tensile tested cline in value in dual nozzle systems.

The impact load also declined in value in dual nozzle systems, similarly flexural also shows weeks in dual nozzle.

- Here during experimentation, we are using heterogenous system so thermal stability is not maintained,
- Itisobservedthatpoorinterfacialbondingimpactinlowvalueinallmechanical
- testing.
- During transition of nozzle left to right or right to left, Cooling occurs and previous layer solidifies.
- Thermal mismatch hand residual thermal stress makes micro crack sand voids.
- Fiber deposition is discontinuous due to this fiber alignment may not follow principal stress direction
- Due delay in nozzle switch air entrapment

The decline in tensile, flexural and impact properties in dual-nozzle printing a rise from weak interfacial bonding, thermal mismatch, porosity, and reduced interlayer diffusion compared to the homogeneous deposition in single-nozzle printing. To overcome this issue further research can be carried out by addressing above issues their eliminating we can conclude the actual proof of improvement in dual nozzle system which is applicable in all areas including medical based elements. The ability to create custom and complex objects with ease has the potential or evolution manufacturing, medicine, aerospace, construction, education, and many other areas. As the technology continues to advance, we can expect to see more affordable and efficient 3D printers, as well as improved material sand software that will enable even more complex and precise printing. This will result in faster production times, reduced costs, and increased customization, which will benefit both businesses and individuals alike.

Furthermore, the future of 3D printing is not limited to its current applications. With ongoing research and development, there is no doubt that new and exciting uses for 3D printing will continue. Overall, the3Dprinterprojecthasgreatpotentialtotransform the way we create and manufacture objects, and it is an exciting technology to watch as it evolves in the coming years.

REFERENCES

1. Marouene Zouaoui, Julien GardanM Julien Gardan, Pascal Lafon, Ali Makk, Carl Labergere and Naman Recho. A Finite Element Method to Predict the Mechanical Behavior of a Pre-Structured Material Manufactured by Fused Filament Fabrication in 3D Printing, Appl. Sci. 2021; 11(11), 5075.
2. Rohde, S.,Cantrell, J. Jerez, A. Kroese, C. Damiani, D. Gurnani, R DiSandro, L. Anton, J. Young, A. Steinbach, D. et al. Experimental Characterization of the Shear Properties of 3D–Printed ABS and Polycarbonate Parts. Exp. Mech, 2018, 58, 871–884.
3. Ismail Ezzaraa,Nadir Ayrilmis, Mohamed Abouelmajd, Manja Kitek Kuzman, Ahmed Bahlaoui, Ismail Arroub, Jamaa Bengourram, Manuel Lagache and Soufiane Belhouideg. Numerical Modeling Based on Finite Element Analysis of 3D-Printed Wood-Polylactic Acid Composites: A Comparison with Experimental Data, Forests, 2023, 14(1), 95.
4. Gardan, J. Makke, A. Recho, N., Improving the fracture toughness of 3D printed thermoplastic polymers by fused deposition modeling. Int. J. Fract.2018, 210, 1–15.
5. AhnS.H.andC.Baek,. Anisotropic Tensile Failure Model of Rapid Prototyping Parts - Fused Deposition Modeling (FDM)International Journal of Modern Physics B, 2003, 17(8 & 9) 1510-1516.
6. Abueidda D.W,M.Elhebeary,C.-S.A.Shiang,S.Pang,R.K.A.Al-Rub,I.M.Jasiuk,. Mechanical properties of 3D printed polymeric Gyroid cellular structures: Experimental and finite element study, Materials and Design, 2019, 165, Article 107597
7. Song,Y,Y.Li,W.Song, K. Yee,K.-Y.Lee, V.L.Tagarielli,. Measurements of the mechanical response of unidirectional 3D –printed PLA, Materials and Design, 2017, 123 154–164
8. Yao T., Ye J., Deng Z., Zhang K., Ma Y., and Ouyang H., "Tensile Failure Strength and Separation Angle of FDM 3D Printed PLA Material: Experimental and Theoretical Analyses," Composites Part B: Engineering, vol. 188, 2020, Article 107894.
9. Kalita S.J,S.Bose,H.L.Hosick,A.Bandyopadhyay, Development of controlled porosity polymer-ceramic composite scaffolds via fused deposition modelling Mater.Sci.Eng. C, 2003, 23 (5)611–620
10. Rosenzweig D, E. Carelli, T. Steffen, P. Jarzem, L. Haglund, 3D-printed ABS and PLA scaffolds for cartilage and nucleus pulposus tissue regeneration Int. J. Mol. Sci., 2015, 16 (7), 15118
11. Gautam Tanikella N,B.Wittbrodt,J.Pearce, Tensile Strength of Commercial Polymer Materials for Fused Filament Fabrication 3D Printing, 2017.214–223
12. DaliaC, B. Rimantas, M. Daiva, M. Rytis, N. Audrius, O. Armantas, Multi-scale finite element modeling of 3D printed structures subjected to mechanical loads Rapid Prototyp. J.,2018,24 (1), 177–187
13. WittbrodtB,J.M.Pearce, The effects of PLA color on material properties of 3-D printed components Addit. Manuf., 2015, 8, 110–116
14. Farah S,D.G.Anderson,R.Langer, Physical and mechanical properties of PLA, and their functionsinwidespreadapplications—acomprehensivereviewAdv.DrugDeliv. Rev., 107 (Supplement C) , 2016, 367–392

15. Pollard D, Ward C, Herrmann G, et al. The manufacture of honeycomb cores using Fused Deposition Modeling. Adv Manufacturing: Polym Composites Sci 3(1): 2017, 21–31.
16. Mamatha S, Biswas P, Das D, et al. 3D printing of cordierite honeycomb structures and evaluation of compressive strength under quasi-static condition. Int J Appl Ceram Technology 2020, 17(1): 211–216.
17. Jackson, RJ, W. A., and M. M., 3D Printing of Asphalt and its Effect on Mechanical Properties, Miner. Des., 2018, no. 160, pp. 486– 474.
18. Zhao, Y. Chen, Y. Zhou, Y. Novel mechanical models of tensile strength and elastic property of FDM AM PLA materials: Experimental and theoretical analyses. Mater. Des. 2019, 181, 108089.
19. Gardan, J. Makke, A. Recho, N., Fracture Improvement by Reinforcing the Structure of Acrylonitrile Butadiene Styrene Parts Manufactured by Fused Deposition Modeling. 3D Print. Addit. Manuf. 2019, 6, 113–117.
20. Raajeshkrishna CR, Chandramohan P, Saravanan D, Effect of surface treatment and stackingsequenceonmechanicalpropertiesofbasalt/glassepoxycomposites.PolymPolym Composites 2019, 27(4): 201–214.
21. Figueroa-Cavazos J.O,E.Flores–Villalba,J.A.DiaElizondo,O.Martínez-Romero, C.A. Rodríguez, H.R. Siller, Design concepts of polycarbonate-based inter vertebral lumbar cages: finite element analysis and compression testing, Appl. Bionics Biomech., Article 2016, 7149182
22. Cole,D.P.Riddick,J.C.Jaim,H.M.I.Strawhecker,K.E.Zander,N.E.,Interfacial mechanical behavior of3D printed ABS. J. Appl. Polym. Sci. 2016, 133.
23. Rodríguez, J.F. Thomas, J.P. Renaud, J.E., Mechanical behavior of acrylonitrile butadiene styrene(ABS) fused deposition materials. Experimental investigation. Rapid Proto type.J.2001,7,148–158.
24. Cole,D.P.;Riddick,J.C.;Jaim,H.M.I.;Strawhecker,K.E.;Zander,N.E.,Interfacialmechanical behavior of3D printed ABS. J. Appl. Polym. 2016, Sci. 133.
25. Sivasubramanian Palanisamy1,2,∗ , Mayandi Kalimuthu1 , Shanmugam Dharmalingam3 , Azeez Alavudeen1 , Rajini Nagarajan1,∗ , Sikiru Oluwarotimi Ismail4 , Suchart Siengchin5 , Faruq Mohammad6 and Hamad A Al-Lohedan ´' Effects of fiber loadings and lengths on mechanical properties of Sansevieria Cylindrica fiber reinforced natural rubber bio composites. Mater. Res. Express 10 (2023) 085503, https://doi.org/10.1088/2053-1591/acefb0.IOP publishing.
26. Karuppusamy Manickaraj [1], Ramakrishnan Thirumalaisamy [2], Sivasubramanian Palanisamy [3], Nadir Ayrilmis [4], Ehab El Sayed Massoud [5], Murugesan Palaniappan [6], S Lakshmi Sankar [7]Value-added utilization of agricultural wastes in biocomposite production: Characteristics and applications.Ann N Y Acad Sci 2025 Jul;1549(1):72-91. doi: 10.1111/nyas.15368. Epub 2025 May 16..https://doi.org/10.1111/nyas.15368.
27. Rajkumar Ramasubbu , Arumugam Kayambu , Sivasubramanian Palanisamy , Nadir Ayrilmis"Mechanical properties of epoxy composites reinforced with Areca catechu fibers containing silicon carbideFebruary 2024BioResources 19(2):2353–2370, DOI:10.15376/biores.19.2.2353-2370.
28. Palaniappan, M., Palanisamy, S., Murugesan, T., Tadepalli, S., Khan, R., Ataya, S., and Santulli, C. (2024). "Influence of washing with sodium lauryl sulphate (SLS) surfactant on different properties of ramie fibres," BioResources 19(2), 2609–2625.
29. Utilizing waste manhole covers and fibreboard as reinforcing fillers for thermoplastic composites**,** Nadir Ayrilmis https://orcid.org/0000-0002-9991-Journal of Reinforced Plastics and Composites 4800 nadiray@iuc.edu.tr, Gürdal Kanat, ,and Alireza Ashori+**2** View all authors and affiliations,Volume 44, Issue 17-18, https://doi.org/10.1177/07316844241238507.
30. Bhuvaneshwaran Mylsamy, Karthik Aruchamy, SenthilKumar Marudhamuthu Shanmugam, Sivasubramanian Palanisamy , Nadir Ayrilmis Improving performance of composites: Natural and synthetic fibre hybridisation techniques in composite materials – A review-Materials Chemistry and Physics, Volume 334, 1 April 2025, 130439

