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Evaluation of Mechanical Properties of Carbon Reinforced Composite for Different Process Parameters Using FDM

Ananda M.N.[1,*], Sudheer Reddy J.[2], Vijay Kumar S.[3], Vikram K.V.[4], Mahesh Kumar[5]

Abstract

Fused Deposition Modeling (FDM) stands as an advanced rapid prototyping technique, widely appreciated for its efficiency in constructing functional components within a reasonable timeframe. In this experimental exploration, a comparative analysis of mechanical properties was conducted on components manufactured through the FDM technique, specifically with a 20% concentration of SCF-PLA. The study considered process variables like layer thickness, infill pattern, and infill density. Employing diverse process parameters, a standard sample was printed, followed by multiple assessments for parameters such as roughness, tensile strength, fatigue, and more. The goal is to understand how changes in process parameters impact the mechanical properties of the manufactured components.

Keywords: Carbon fiber, Poly lactic acid, Fused deposition modelling, Layer thickness, Infill pattern, Infill density, Tensile, fatigue.

INTRODUCTION

The field of 3D printing is rapidly expanding, witnessing a surge in popularity as its applications continue to grow. This technology proves invaluable for creating prototypes, manufacturing replacement parts, and contributing significantly to the production of prostheses and medical implants [1, 2]. With the increasing accessibility of 3D printers, their impact on our world is set to intensify [3]. In the 3D printing process, a print head nozzle deposits heated plastic material layer by layer to construct the (ABS), carbon fiber polylactic acid (CFPLA), and polyamide have been the materials of choice for these components [4, 5]. However, the inherent low mechanical performance of pure polymer structures, characterized by low strength and rigidity, has prompted initiatives to enhance their mechanical properties.

Addressing these limitations, various approaches involve reinforcing polymers with fibers or nanomaterials to create Fiber-Reinforced Polymer Composites (FRPCs). These composites, produced through Additive Manufacturing (AM) technology, exhibit improved mechanical characteristics, making them highly desirable for high-performance applications [6]. The term "additive manufacturing" or "3D printing" refers to the process of creating 3D objects from Computer-Aided Design (CAD) or digital 3D models [7, 8]. This entails applying, binding, or solidifying a

***Author for Correspondence**
Ananda M.N.

[1,4]Assistant Professor, Department of Mechanical Engineering, Nitte Meenakshi Institute of Technology, Visvesvaraya Technological University, Bengaluru, Karnataka, India
[2]Professor, Department of Mechanical Engineering, Nitte Meenakshi Institute of Technology, Visvesvaraya Technological University, Bengaluru, Karnataka, India
[3]Associate Professor, Department of Mechanical Engineering, Nitte Meenakshi Institute of Technology, Visvesvaraya Technological University, Bengaluru, Karnataka, India
[5]Student, Department of Mechanical Engineering, Nitte Meenakshi Institute of Technology, Visvesvaraya Technological University, Bengaluru, Karnataka, India

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material onto a 3D object, typically adding layers, and can involve various materials such as plastics, liquids, or powdered grains fused together [9, 10]. In the 1980s, the technology, initially referred to as rapid prototyping, was primarily utilized for creating aesthetically pleasing or functional prototypes [11, 12].

In 2019, the terms "additive manufacturing" and "3D printing" became largely interchangeable due to significant improvements in the accuracy, repeatability, and material versatility of 3D printing technologies. These advancements have positioned certain 3D printing techniques as viable options for industrial production. A key advantage of 3D printing is its capacity to fabricate intricately designed shapes or geometries that would be challenging to produce manually, including hollow structures and items featuring internal truss configurations for weight minimization [13]. As of 2020, fused deposition modelling (FDM) emerged as the most widely adopted 3D printing technique, utilizing a continuous filament of thermoplastic material. Research conducted in 3D printing, or additive manufacturing (AM), involves the creation of three-dimensional objects from a computer-generated model or electronic data source. This is achieved through the successive layering of materials under computer control. The exploration encompasses the historical evolution of 3D printing, an analysis of suitable materials for 3D printing presses, and an understanding of the advantages offered by 3D printing over traditional additive manufacturing [14, 15].

The transformative impact of 3D printing on the manufacturing industry is a focal point. It introduces the utilization of additive manufacturing processes, such as fused deposition modelling (FDM) and selective laser sintering (SLS), to produce graphene-based composites. This exploration provides an introductory understanding of various additive manufacturing techniques [16, 17]. An alternative to traditional polymers and metals, continuous fiber-reinforced thermoplastic composites exhibit promise. These materials enable the creation of lightweight structures with superior mechanical performance [18, 19]. The three-dimensional (3D) printing realm, particularly in material extrusion additive manufacturing (MEAM), is experiencing a surge in popularity. For the fabrication of test specimens, both commercial polylactic acid (PLA) filament and PLA filament reinforced with short carbon fibers (PLA/CF) were utilized. The ensuing evaluation involved subjecting annealed specimens to tensile strength tests at varying temperatures, coupled with examinations of their internal microstructures. The study delves into the impacts of annealing on polymer crystallinity and mechanical characteristics, as well as the influence of short-carbon fiber fillers on the mechanical properties of 3D-printed PLA [20–22].

MATERIALS AND METHODOLOGY

In the current research work, a composite material comprising 20% carbon fiber with PLA (Polylactic Acid) was employed, guided by insights from prior research indicating superior water absorption capacity and tensile strength at this percentage. The initial step involved designing a specimen using CATIA software, characterized by dimensions of 13.9mm width, 5.9mm thickness, and 70mm length. The 3D design model was then exported to a .stl file. After this, the file underwent importation into slicing software, where distinct process parameters were specified. Following parameter configuration, the file transformation into a G-code file enabled the production of nine specimens utilizing a 3D printer and the designated composite material. The printing phase encompassed exploration of diverse process parameters, including various layer thicknesses (0.1mm, 0.2mm, and 0.3mm) and infill density variations (50%, 60%, and 90%). Infill patterns were set as lines, triangles, and hexagons, offering a comprehensive examination of their impact on the printed specimens.

FUSED DEPOSITION MODELLING (FDM)

In the Fused Deposition Modelling (FDM) process [23], thermoplastic materials undergo extrusion through a heated nozzle tip, reaching a semi-molten state before being deposited onto a substrate. This sequential layering technique results in the formation of a solidified 3D object. FDM stands out as one of the most extensively employed methods for layer-by-layer 3D manufacturing. During FDM, a heated and movable printer extruder head guides the filament from a sizable spool, depositing it onto the evolving workpiece. The movement of the printhead is precisely controlled by a computer to define the shape of the print. Typically, the printhead moves in two dimensions, creating one horizontal plane or slice at a time. Subsequently, a slight vertical movement of the workpiece or printhead initiates the formation of a new layer. The speed of the extruder head can be regulated to facilitate the interruption and resumption of material deposition [24, 25], allowing for the creation of distinct planes between sections without issues such as stringing or dripping. The term "fused filament fabrication" was coined by members of the RepRap project, aiming to create an acronym (FFF) that would be legally unrestricted in its application [26].

EXPERIMENTAL PROCEDURE

The process initiates with the creation of a specimen in CATIA software [27], featuring dimensions of 13.9 mm width, 5.9 mm thickness, and 70 mm length. This 3D design model is then exported to a .stl file, subsequently imported into slicing software. In the slicing software, specific process parameters are defined, and after configuring these parameters, the file is converted into a G-code file. Following the preparation stage, a total of 9 specimens are printed using a 3D printer [28] and a wire-form material. Various process parameters are applied, including layer thicknesses of 0.1 mm, 0.2 mm, and 0.3 mm, along with infill densities of 50%, 60%, and 90%. The infill patterns include lines, triangles, and hexagons. Post-printing, testing is conducted on the specimens (refer to Figure 1 and Figure 2) to assess their performance and characteristics. Based on the present investigations some of the few parameters were considered to determine the mechanical properties of the prepared samples i.e. Nozzle temperature, Infill density, Filament diameter, Extrusion multiplier/flow rate, Layer height etc. The same has been considered for the present investigations.

Figure 1. Raw carbon fibre with PLA.

Figure 2. Printing of the Specimens.

Figure 3. Tensile Testing.

RESULTS AND DISCUSSION

Tensile Test

The assessment of a 3D-printed material's quality and mechanical properties often involves conducting a tensile test to anticipate its response to various loads [29]. This testing methodology is employed to pinpoint key characteristics, including the elasticity modulus, yield strength, ultimate tensile strength, elongation to fracture, and the reduction in specimen area post-deformation. Tensile testing, depicted in Figure 3, is a form of destructive testing wherein controlled stress is systematically applied to the specimen until it reaches the point of total fracture.

Figure 4 presents two distinct graphs: (a) Load vs. Time and (b) Stress vs. Time. These graphs provide a dynamic representation of the behaviour of a material during a tensile test.

(a) *Load vs. Time:* This graph illustrates how the applied load on the specimen changes over the duration of the test. The horizontal axis, representing time, reveals the timeline of the tensile test, while the vertical axis displays the corresponding loads exerted on the specimen. The graph may exhibit various phases, such as an initial increase as the load is applied, potential plateaus or fluctuations indicating specific material responses, and a final decline as the specimen reaches its breaking point. Analyzing this graph helps in understanding the temporal evolution of the applied load during the tensile test.

(b) *Stress vs. Time:* The Stress vs. Time graph demonstrates the relationship between stress and time throughout the tensile test. Stress, typically calculated as force divided by the cross-sectional area of the specimen, is a crucial indicator of a material's mechanical behavior. Similar to the Load vs. Time graph, this graph may reveal distinctive phases in stress evolution, offering insights into the material's deformation characteristics over time. Understanding stress variations provides valuable information about a material's ability to withstand external forces and its overall structural integrity during the testing period.

Surface Roughness

Surface texture and surface roughness analysis is performed to evaluate the outer characteristics of a material, particularly in the context of 3D-printed parts [30]. The surface of a 3D-printed component exhibits two primary attributes: surface roughness and surface polish, each with distinct characteristics. Surface roughness refers to the irregularities or variations in the surface profile across the entire surface of a specimen. Figure 3, 2, 1 likely illustrates the surface roughness of a 3D-printed part, showcasing the deviations, peaks, and valleys present on the surface. Analyzing surface roughness is crucial as it

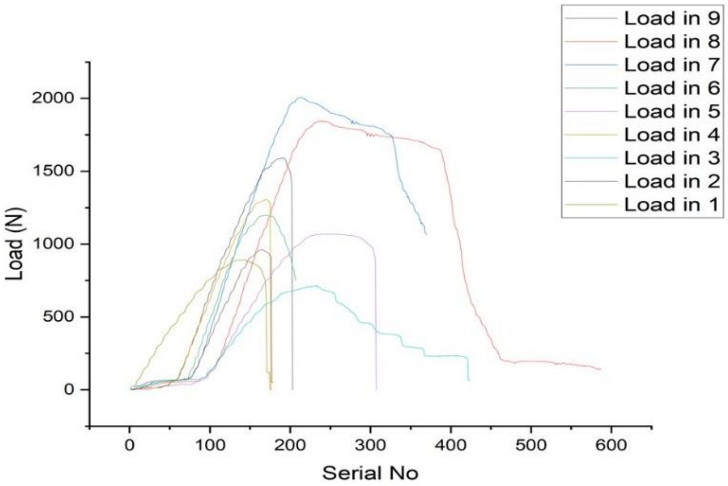


Figure 4. (a). Load Vs. Time.

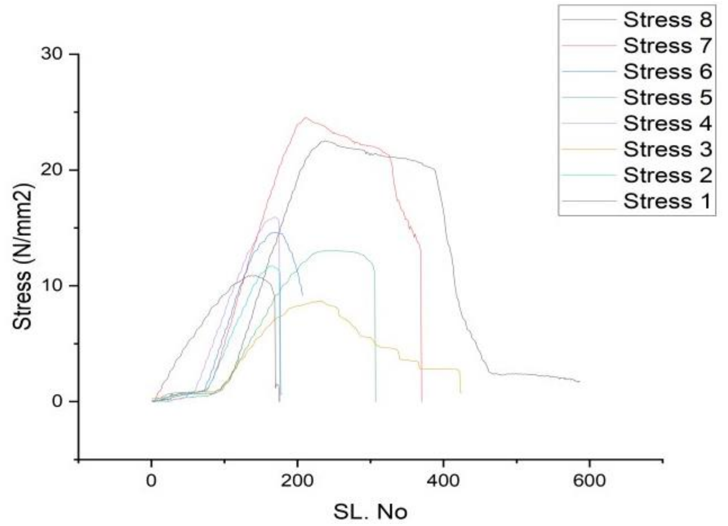


Figure 4. (b). Stress Vs. Time.

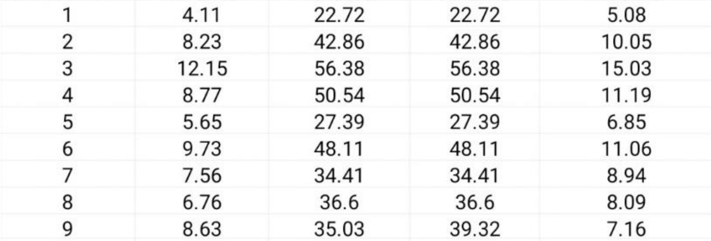
provides insights into the texture of the material, influencing factors such as friction, wear resistance, and aesthetic appearance. Different 3D printing processes and materials may result in varying degrees of surface roughness. It's worth noting that while surface roughness is concerned with the overall texture, surface polish pertains to the smoothness and reflective qualities of the surface. The two characteristics, surface roughness and surface polish, contribute to the overall visual and functional properties of the 3D-printed part. In summary, the examination of surface roughness in Figure 5 aids in understanding the topographical variations across the specimen's surface, which is essential for assessing the material's quality, performance, and potential applications. Table 1, presented alongside Figure 5, provides a detailed compilation of Surface Roughness Data, offering a quantitative perspective on the irregularities and variations observed on the surface of the 3D-printed part.

Fatigue Test

Fatigue testing as shown in Figure 6 (a) is a distinctive form of mechanical testing that entails systematically applying loads to a cross-section or structure over repeated cycles. This specialized testing method plays a crucial role in identifying critical points, validating the structural integrity of components susceptible to fatigue, and gathering essential data on fatigue life and fracture propagation [31]. Through fatigue testing, engineers and researchers gain valuable insights into how materials and structures withstand repetitive loading, contributing significantly to the design and evaluation of durable and safe constructions. In Figure 6(b), a Load vs. Time graph illustrates the dynamic relationship between applied loads and time during the fatigue test. This graph offers a comprehensive view of how the load on the specimen fluctuates over the testing duration, providing critical information about fatigue characteristics, potential stress cycles, and overall structural behavior. Analyzing this graph is instrumental in understanding the material's response to cyclic loading and predicting its fatigue life.

Figure 5. Surface Roughness Testing.

Table 1. Surface Roughness Data



SPECIMEN	Ra (µm)	Ry (µm)	Rz (µm)	Rq (µm)
1	4.11	22.72	22.72	5.08
2	8.23	42.86	42.86	10.05
3	12.15	56.38	56.38	15.03
4	8.77	50.54	50.54	11.19
5	5.65	27.39	27.39	6.85
6	9.73	48.11	48.11	11.06
7	7.56	34.41	34.41	8.94
8	6.76	36.6	36.6	8.09
9	8.63	35.03	39.32	7.16

Where Ra = Arithmetic mean deviation; Ry = max height of profile; Rz = Ten-point height of irregularities; Rq = Root mean square deviation of the profile.

Figure 6. (a). Fatigue Testing.

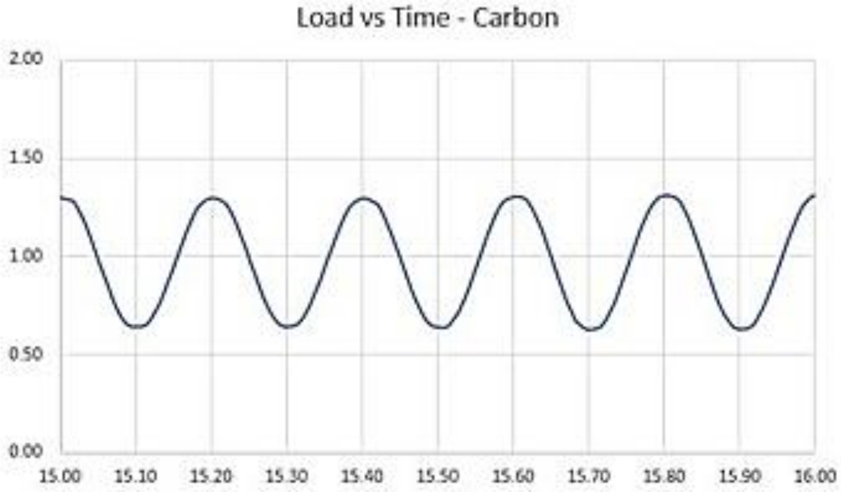


Figure 6. (b). Load vs. Time graph of Fatigue Test.

Water Absorption Test

Polylactic Acid (PLA) is an organic substance known for its susceptibility to moisture absorption, displaying a high sensitivity to even minimal amounts of water. This characteristic can significantly impact the material's properties, particularly its diameter, when stored. To assess the extent of moisture absorption, it is essential to measure the change in weight after the material has been exposed to water. Understanding and quantifying this change in weight provides critical insights into PLA's response to environmental conditions, aiding in the evaluation of its performance and suitability for various applications. Figure 7(a) illustrates the Water Absorption Test, a method used to evaluate how a material absorbs water over a specified duration. This visual representation provides insights into the experimental setup and procedure employed to assess the material's response to water exposure. In Figure 7(b), a Weight vs. Specimen graph demonstrates the relationship between the weight of the specimen and specific conditions, likely during or after the water absorption test. This graph offers valuable information about the material's weight variations in response to water absorption, providing a quantitative measure of its susceptibility to environmental factors. Analyzing this graph aids in understanding the material's water absorption characteristics and potential implications for its applications.

Bending Test

The bending test is a methodology employed to ascertain crucial qualities of a material, particularly its bending strength [31]. This destructive testing technique is applicable to various materials such as polymers, fiber-reinforced plastics (FRP), metals, and ceramics. The procedure involves subjecting the material to controlled bending forces to evaluate its response under specific conditions. During the test, measurements of both the bending force and deflection are recorded. These recorded values are then used to establish essential material properties, providing valuable insights into its mechanical behavior and structural integrity. Bending tests are instrumental in gaining a deeper understanding of how materials respond to uniaxial bending stress. Figure 8(a) visually represents the methodology of the bending test, showcasing the setup and procedure involved in subjecting a material to bending forces. It provides an overview of the controlled conditions under which the test is conducted. In Figure 8(b), a representation of the tested specimen offers a visual insight into the physical characteristics of the material subjected to the bending test. Together, these figures provide a comprehensive understanding of the bending test process and its application to assess material properties.

The Figure 9(a) presents a Load vs. Time graph, illustrating the dynamic relationship between the applied load and time during the bending test. This graph captures the temporal evolution of the load on the material, offering insights into how the material responds under bending forces over the duration of the test. In Figure 9(b), a Load vs. Displacement graph demonstrates the correlation between the applied load and the resulting displacement during the bending test. This graph provides a visual representation of the material's deformation under the applied load, aiding in the analysis of its mechanical behavior and structural response to bending forces. Together, these graphs offer a comprehensive view of the material's performance during the bending test.

Figure 7. (a) Water absorption Test.

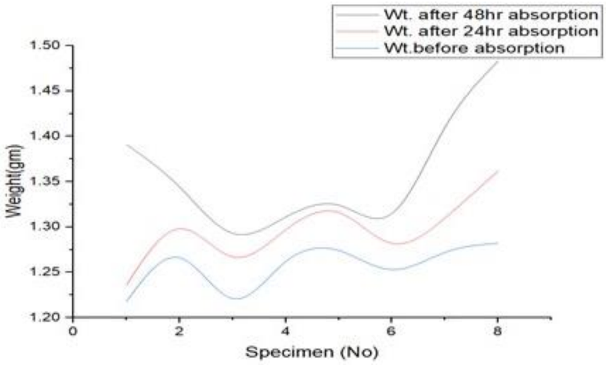


Figure 7. (b) Weight Vs. Specimen Graph.

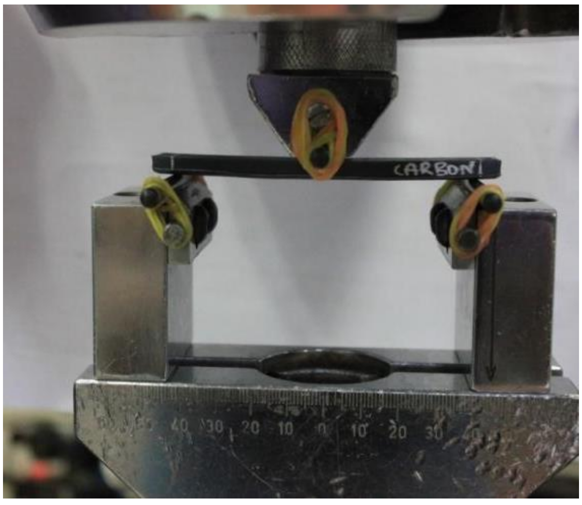


Figure 8. (a) Bending Test Method.

Figure 8. (b) Tested Specimen.

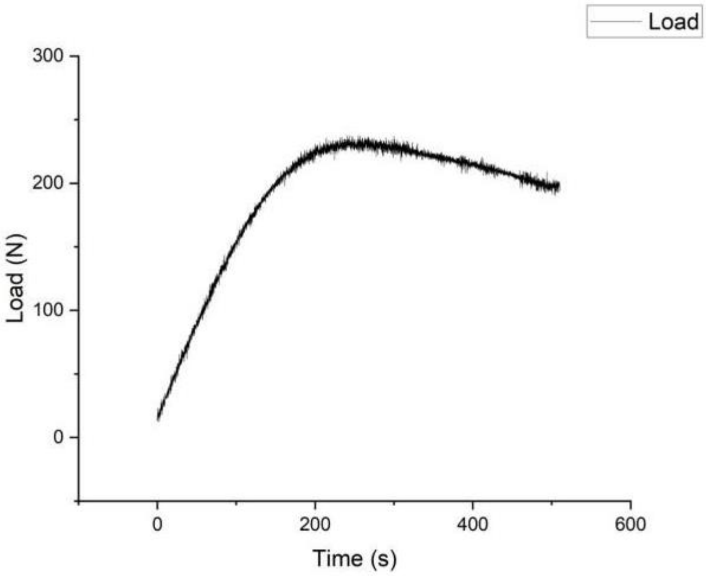


Figure 9. (a) Load vs. Time graph.

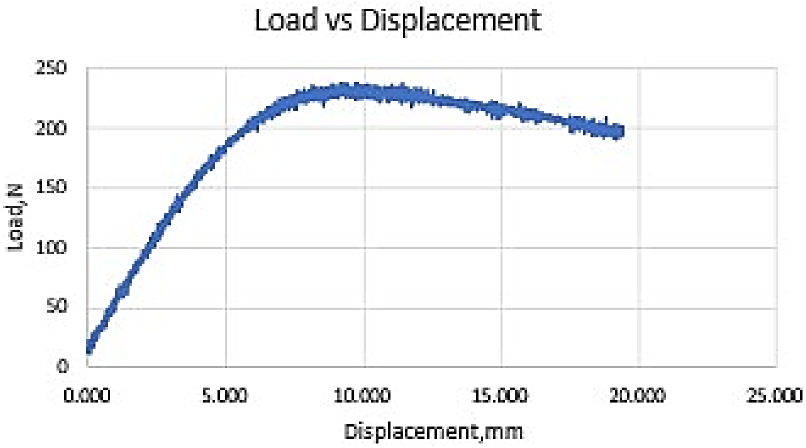


Figure 9. (b) Load vs. Displacement Graph of Bending Test.

CONCLUSION

The following encapsulates the key conclusions drawn from the presented research findings.

- Specimen 7, produced with 0.1 mm layer thickness, 90% infill density, and linear infill pattern, exhibited superior tensile strength in the carbon fiber-reinforced PLA composite. Specimen 7 emerged as the choice for enhanced tensile strength, contributing to the overall goal of improving composite strength.
- The research aimed to identify optimal process parameters for achieving the best strength, water absorption capacity, and tensile strength in lightweight yet high-strength composites. Mechanical property analysis included tensile strength, bending, and bending tests on specimens prepared according to ASTM requirements.
- Critical observation of results highlighted that the 20% carbon fiber with PLA composite provided desirable mechanical strength.
- Additive manufacturing (AM) techniques, particularly FDM, have gained prominence due to improved raw material management, environmental considerations, and the capacity to create intricate items. The intriguing mix offered by AM in composite materials presents a unique opportunity for exploration by businesses, researchers, and consumers.

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