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Research Article

3D Printed Composite Materials: Innovations In Additive Manufacturing And Mechanical Performance

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ABSTRACT

The advent of additive manufacturing has revolutionized the production of composite materials, enabling the creation of complex geometries and tailored properties that traditional methods cannot achieve. This paper explores the innovations in 3D printed composite materials, focusing on advancements in both materials science and printing technology. We examine various composite formulations, including polymer, metal, and ceramic matrices reinforced with fibers and fillers, highlighting their mechanical performance across diverse applications. The study emphasizes the role of optimization in print parameters and material selection, which significantly enhance mechanical properties such as tensile strength, durability, and impact resistance. Furthermore, we discuss the challenges and future directions in the field, including the integration of smart materials and sustainability considerations in the design of next-generation composite components. This comprehensive overview provides insights into the potential of 3D printed composites to transform industries ranging from aerospace to biomedical engineering.

Keywords: 3D Printing ,Additive Manufacturing, Composite Materials, Mechanical Performance, Material Innovation, Polymer Composites, Filament Types, Structural Integrity ,Lightweight Design ,Mechanical Properties ,Layer-by-Layer Fabrication, Advanced Manufacturing, Thermoplastic Composites, Strength-to-Weight Ratio, Customized Manufacturing, Printability ,Sustainable Materials, Carbon Fiber Reinforcement, Performance Testing, Application in Industry.

1. Introduction

Additive manufacturing techniques offer the possibility of developing materials from the nano-scale to the macro-scale in an ordered sequence and position. This opens new opportunities for advances in the design of scientific instruments and technological systems. 3D printing, or additive manufacturing, is used to create solid objects from digital models. A range of materials can be used for 3D printing, including metals, plastics, ceramics, composites, and food. Rather than continuing to build layer by layer on the same materials in the final printed part, composite 3D printing allows selective layering of different types of materials, each offering specific benefits, on top of each other.

While composite 3D printing is still under development, in particular regarding 3D printed composite materials, it offers several advantages, such as lightweight, high specific strength, enhanced material properties, and the production of high-performance, complex-geometry parts. The performance of components fabricated by three-dimensional printing depends on the choice of input materials, which are limited to a few materials such as polymers and thermoplastics.

To expand applications to hardening metallic or strengthening ceramic materials, composites have been prepared containing 3D printing polymers or polymer-based ceramics. This review summarizes recent developments in 3D printed composite materials, as well as focusing on technologies used to make composite materials, with possible future research directions.

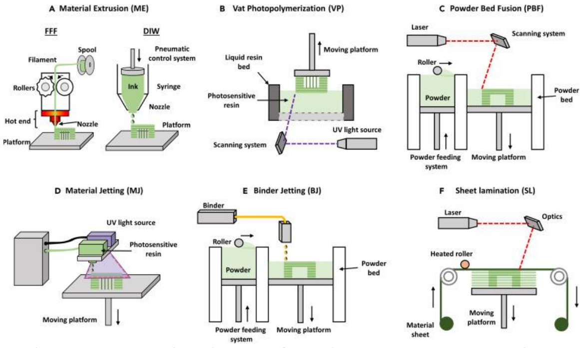

Fig 1: 3D printing of polymer composites

2. Fundamentals of 3D Printing and Composite Materials

Additive manufacturing offers unique opportunities for the production of composite materials that have typically been limited to more traditional methods of manufacture, including tape casting, lamination, film stacking, and plasma spraying. In recent research efforts to develop 3D printing of composite materials, various matrix materials, and reinforcement strategies have been employed, with the majority of work focusing on 3D printing with ceramics and ceramics reinforced with carbon nanotubes or graphene, leading to a variety of novel applications such as thermal protection systems for re-entry vehicles. While the mechanical performance of these innovative 3D-printed composite materials was high and extremely stable in ultra-high temperature environments, the adapted printing processes were highly specialized and typically associated with low throughput and low geometric freedom. The rapidly advancing field of 3D printing shows great potential in realizing optimized fiber architectures for improving mechanical performance and designing 3D printed composite materials, which serve as the focus of this article.
Additive manufacturing, known as 3D printing, has revolutionized how components and devices with complex geometries have been fabricated. Characterized by its versatile design and manufacturing process and its potential to reduce the time and cost of manufacturing products, AM technology is now readily available in the consumer market with end users capable of fabricating devices of interest with a wide range of functional materials. However, the focus of research in most commercialized 3D printing systems is on polymer and metal printing, and the 3D printing of composite materials, especially those reinforced with continuous fibers usually fabricated through traditional subtractive manufacturing approaches, is relatively less mature and less clearly classified.

2.1. Overview of Additive Manufacturing Technologies

The first step in 3D printing typically involves the preparation of the 3D file. This could be prepared from scratch using CAD software, or a 3D scan could be performed to convert a physical object into a 3D file. Once the 3D file has been prepared, it is converted into a form that allows the printing process to start. The next phase involves choosing the desired printing parameters like temperature, nozzle size, and speed, and then the 3D printer will be started up. The 3D materials of choice could be fed into the 3D printer, and the production cycle would commence. We will treat some of the most widely used 3D print technologies. Photopolymerization-based 3D printing is based on the use of light to solidify a 3D object. It can be further divided into SLA, DLP, and MUSE technologies, all of which constitute vat polymerization.

Fused deposition modeling (FDM) is a widely used 3D print technology where a thermoplastic filament is heated until it becomes molten, and then it is deposited in layers to form a solid object. Direct ink writing (DIW) 3D printing consists of depositing ink strands in a layer-by-layer mode to form a robust 3D construct. Inkjet 3D printing is the 3D issuance of materials in small droplets through the action of an actuator. It has been revised to include a range of systems distinct from continuous inkjet printing and drop-on-demand inkjet printing.

With material jetting, the build is extruded as a droplet and then cured by intense illumination. Powder bed fusion 3D printing uses a bed of powdered material as the print medium. An energy source, such as a laser or an inkjet print head, is then used to fuse the powdered material.

The 3D printer would be used in a layer-by-layer fashion to print a full 3D object, with the raw material acting as a support structure. After printing, the unsintered powdered media is removed. Finally, the solid part is presented with the support structure. The most common materials of choice for 3D print technologies include polymers, ceramics, glass, and metals.

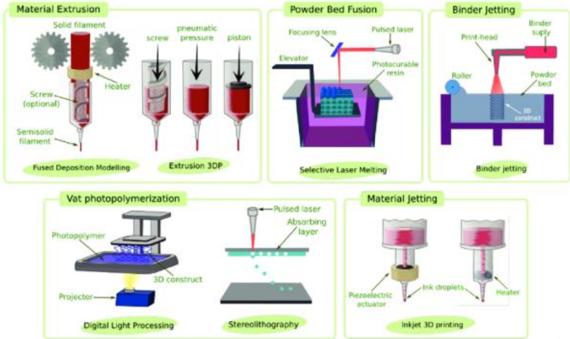

Fig 2 : 3D printing techniques classified based on their additive manufacturing

2.2. Types of Composite Materials Used in 3D Printing

Even for composite materials, an exciting range of options is available. In the field of 3D printing with composite materials, such as carbon fibers, glass fibers, or polyethylene fibers, various thermosetting and thermoplastic polymers have been embedded. It is essential to differentiate between thermosetting and thermoplastic polymer matrices. Such materials have often been developed to significantly improve the mechanical performance of 3D printed parts as well as stimulate the growth of 3D printing with continuous fibers. Significant improvements in the mechanical properties of the produced composite parts have been achieved, most notably for continuous carbon fiber-reinforced composites. Now, 3D-printed continuous composite materials offer excellent mechanical performance comparable to parts obtained with conventional composite manufacturing technologies.

When compared to short fibers, continuous fibers offer superior mechanical performance to composite materials. Therefore, additive manufacturing via composite-based materials with continuous fibers may provide benefits while enabling complex shapes, which is one of the key advantageous features of 3D printing. While continuous reinforcement of intricate thermosetting polymers has been a key obstacle in the pursuit of the vast potential of continuous fibers for advanced functional applications, significant progress is continuously being made. These considerations also apply to continuous short polyethylene fiber integration in combination with FDM printing, leading to major improvements in the mechanical performance of the prints. In any event, it is worth noting that in contrast to carbon fibers, composite combinations of PLA and PE fibers are typically considerably less expensive but also experience tension and rupture when 3D printing.

3. Innovations in 3D Printing of Composite Materials

Considerable growth has been facilitated by the introduction of nanoparticle fillers. While the addition of nanoparticles has enabled these innovative approaches, it is important to ensure that the synergy the nanoparticles can achieve is not brought to a threshold limit in optimization. In some cases, this threshold limit can be attributed to nanoparticle agglomeration, which is commonly observed when nanoparticles are incorporated into a polymer matrix. If the tendency toward agglomeration is not sufficiently mitigated, some of the benefits provided by nanofillers are attenuated significantly after a critical nanoparticle concentration. The addition of second-phase nanofillers, such as carbon nanotubes or graphene oxide, can greatly diminish the stresses generated during processing and reduce local defects and deformation, ultimately enhancing the flexural modulus and strength. However, when these approaches do not resolve the challenges associated with the viscosity of the matrix, the inherent extrusion forces coming from matrix viscosity can damage the fibers and ultimately lessen the expected improvements in mechanical properties.

3.1. Multi-Material and Multi-Property Printing

The fusion of different types of materials in the same structural or functional system can give rise to emergent behaviors, functionalities, and performances, which can exceed the sum of the constituent parts. Additive manufacturing technologies have enabled the fabrication of composite materials and multi-material, multi-physical properties products, which could not be realized conventionally or easily. Mechanically reinforced polymers, conductive dielectric systems, and other hybrid material combination products can be fabricated within hours using multi-material inkjet printers and aerosol jet printers. These products rely on a discrete phase blend principle, where two or more distinct materials coexist, typically at the macroscale.

For structural improvement of solid structures, the lightweight of products is a cornerstone for functional performance, such as in transportation and aerospace. 3D geometry optimization is a potential way to boost the strength of lightweight structures. Design for Additive Manufacturing always looks into complex geometry to enhance the functionalities of a product to increase customer satisfaction. Nevertheless, these solutions largely missed the opportunities to increase structural resistance by crafting the material combination via spatial heterogeneous material design. This is a new frontier in improving manufacturing design and material performance. Indeed, the designs with non-homogeneous characteristics are omnipotent human creations in nature, represented by biological examples, from the cellular structure of bone to plant stems and spider webs.

The evolved structures have demonstrated optimized mechanical performances, including density reduction, structural sparsification, intertwined hierarchical porous features, and spatial anisotropy. The significant mechanical properties, including but not limited to stiffness, strength, toughness, or energy absorption, are designed to meet the prominent biological requirements by exploiting such material heterogeneity. It is fair to assume that similar strategies may be useful for additive manufacturing. The tantalizing thought is to realize a new generation of functionally graded materials and complex components with enhanced mechanical functionalities.

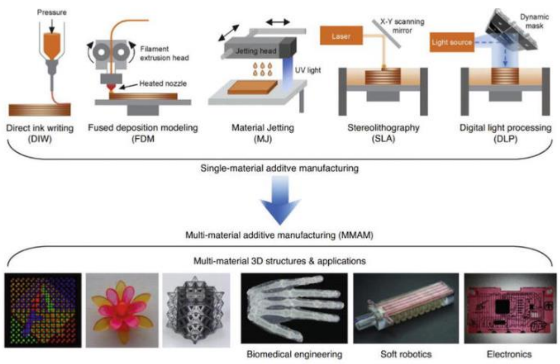

Fig 3: Multi-Material in 3D Printing for Engineering Applications

3.2. Embedded Sensors and Functional Components

Printed circuitry and transistors are essential in bringing 3D printing to the next level of smart manufacturing. Although there are many mature circuit printing technologies, such as screen printing and inkjet, they are still used as standalone processes. Embedding electronics within the 3D structure of a part would enable increased functionality without compromising the form of simple objects. For instance, LED-embedded 3D-printed models have a unique combination of appearance and function. Furthermore, there is a growing demand for functional printing or 3D printing for functional components. These applications require characteristics that the part has a desired electrical, thermal, or magnetic property beyond its visual appearance. With the embedded 3D printing concept, the circuitry can be distributed within the whole 3D geometry, as opposed to two-dimensional, and the 3D structure around the circuitry has unlimited design freedom, which may not be possible in conventional connecting wire design in 2D circuit boards.

One approach to realizing 3D-printed embedded sensors is based on extrusion-based 3D printing, where a multi-nozzle system can print both structures and wiring layers. Basalt fibers are used as both a conductive material and a non-conductive filler to manufacture a marble-like sensing platform and layered fabrication can be achieved seamlessly. The final marble block demonstration showed that the fabricated prototype can be used to monitor in-plane stress. More interestingly, printed masonry samples with embedded power and data transmission lines for in situ monitoring of the health of the structure. A segmented uniform resistive sensor made of conductive filament was embedded in the printed limestone sample. After adequate bending tests, the cross-section of one anchorage point was gradually reduced while keeping the others intact. The sensor showed a strong correlation between its electrical resistance change and the evolution of bending damage. There is also the potential of enhancing electric sensitivity with other types of resistive sensors.

4. Mechanical Performance and Testing of 3D Printed Composites

The development of new composite materials for novel AM technologies is a complex multistage process, including the choice of the basic material for printing and the optimization of its geometric and mechanical characteristics. The effectiveness of 3D printing technologies determines the possibility of creating composite elements with the specified high-strength properties. This goal is achieved through a combination of the mechanical properties of the reinforcing materials and the polymer matrix and, in general, the optimal direction of the reinforcing fibers in the main structural load-bearing elements of the printed products, or non-uniform and spatially heterogeneous formation of the polymer matrix. After studying the AM technologies and developing thermoplastic and thermosetting composite materials, we found a wide range of polymers, fibers, and other types of nanofibers, carbon nanotubes, graphene, soft and hard machinable materials, non-combustible and flame-retardant composites, and bio-natural-fiber composites. In addition, we present and discuss the current state of the strength properties of thermoplastic and thermosetting 3D printed composite materials with the introduction of various types of reinforcing and hollow fillers into polymers and their experimental results. Summarized mechanical properties of thermoplastic and thermosetting composite materials printed with different 3D printing techniques and types of fabrics can be useful information for producing printed items with specific high-strength properties.

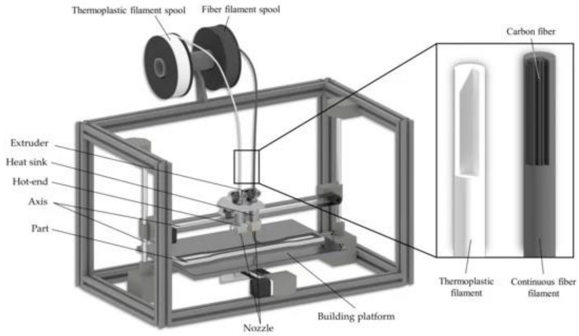

Fig 4 : Mechanical Properties of 3D-Printed Hybrid

4.1. . Tensile, Compression, and Flexural Testing

The most basic aspect of mechanical testing is tensile testing, which measures the performance of a 3D printed material or part under applied tensile force, or tensile strength. Mechanical properties of materials are typically determined through uniaxial tensile and compression testing, applying a force at two opposite ends of a specimen to stretch or compress the material until it fails. For 3D printed composites, it is important to test the anisotropy of the strength, as the material behaves differently in layer, lateral, and transverse directions due to complex interactions at the interfaces. Tensile testing is particularly important in the development of continuous fiber-reinforced composites. Compression testing measures the force and displacement of a material under compressive loads. It is an essential method to evaluate the load-bearing capacity and strain limits of a 3D printed structure, which is also crucial for comparing different 3D printer composites in their potential uses, such as lightweight bearing supports, impact-resistant helmets, and robust sandwich panels. Considering the lack of full support for overhanging layers from the printer, the tensile strength seems to be the most critical, while the flexural strength should also be noted in the lightweight printing of certain structure types. Unlike tensile testing, compression testing is difficult to carry out on all the layers, as cracks usually form and expand below the applied pressure. On the contrary, besides printing direction, the span-to-thickness ratio and loading rate determine the strength and stiffness of a 3D-printed material tested in a time-dependent manner.

4.2. Impact and Fatigue Performance

Mechanical performance is an important issue for highly manufactured composite materials, not only for product development but also for part design and engineering. Raw individual continuous fibers have good tensile and compressive strength; the incorporation of matrices and interfacial interactions has improved the toughness of CMCs. 3D printed composites, especially short carbon fiber reinforced thermoplastic composites, can also have high strength and stiffness, but the interfacial properties can affect the weakness of the lateral strength. In this part, the significant impact of the composite materials and the poor interlayer adhesion caused by the tensile test, delamination, and fractal area represent the crack initiation and propagation of the 3D whole part printed by the short carbon fiber reinforced PEEK. The presence of a layer interface with a 45° arrangement between two adjacent layers could significantly reduce the mechanical properties of SLA-printed ceramic films and was even worse than that of a monolithic film. Serious stress concentration was observed near the crack tip and also increased due to the layer interface. No significant variation in the interface-finite element length or corresponding enhancement was found when the layer displacement was over the interface length. In contrast to the layered architecture, the interface periods of the two fiber-reinforced SLA printed tensile specimens were far longer than the independent segments of a stiff fiber, suggesting that the parts with fiber-reinforced segments had better fatigue resistance. In addition, the fatigue life of the fiber printed specimens was mainly affected by the properties of the resin and fiber joint, and the continuous extrusion of resin along the fiber plies near the crack tip could inhibit crack propagation, thus significantly enhancing the mechanical performance. From our research, we found that even though interlaminar weakness would reduce the properties of the 45° printed CA film, it performed better than the C1 monolithic material within a certain layer sequence or printed direction. Therefore, designing an optimal 3D printed part with minimized primary structures in the lift direction and no apparent interface weakness to present better mechanical performance is an inevitable trend.

5. Applications and Future Directions

It is important to look at the applications of 3D printing materials for a better understanding of how close we are to using these materials daily. It is also important to look into the challenges that are currently restricting the applications of these 3D-printed materials in industry and other research fields. As permanent solutions to these challenges are identified through extensive research, it will open up the possibilities to develop more functional 3D printing materials. One of the greatest needs currently is for 3D printing composite material, which can overcome some of the challenges and drawbacks of the materials currently available. A major benefit of 3D printing is that there is greater freedom in design. Some of the limitations of traditional manufacturing methods are not seen in 3D printing. It allows for a new dimension of design freedom.

Polymer composite materials are used widely because they have high resistance, lightweight, and good mechanical properties. The usage of composite materials in manufacturing, such as in traditional manufacturing, has limitations because of complex shapes or lack of purposes; it may be an expensive choice. The employment of 3D printing techniques enables the opportunity to overcome this limitation. To produce composite materials with different functionalities, 3D printing techniques have been applied as follows: many types of printable polymers are available at a low cost for printing machines. A large range of composite filaments can be prepared and printed without the need for specialized equipment and costly components. High-performance composite materials with complex geometries replace the lightweight parts made of polymer. Special multi-material 3D printing methods can be appropriately applied to fabricate composite structures with gradients of materials; this has the benefit of gradually switching the mechanical characteristics of the materials.

5.1. Aerospace and Automotive Applications

In the aerospace industry, owing to the miniaturization trend of electronic devices and the lightweight design schemes of UAVs and UCAVs, electromagnetic shield bodies with thin-wall and thin-thickness sandwich composite structures are widely required. The utmost difference between the additive manufacturing method and the traditional manufacturing technique is the fabrication principle. For the traditional manufacturing approach, the removal method, which cuts the part of the structure that is not needed, is adopted, such as lathe processing, milling, and sawing. Material addition is the process of forming the required structure through the accumulation of materials, and the layer stack creates the final structure. For this reason, additive manufacturing technology has some advantages that traditional manufacturing lacks. The automobile industry is one of the key driving forces for mold and tool innovations. Mold manufacturing in various processes of car production involves casting, stamping, forging, and vacuum forming of bumpers, dashboards, interior parts, automotive lighting parts, etc., and tool manufacturing for injection molding of plastic, aluminum, and magnesium alloy. Due to the requirements concerning the surface roughness of molds, tool production requires expensive post-treatment such as CNC milling, polishing, and photochemical treatment processes that involve additional resources and time to meet the final requirement. Owing to the complex design of automotive parts, it is hard to apply efficient fabrication via high-speed CNC milling, and it takes close to 20 days for the fabrication of structures. Therefore, the hybrid fabrication process reduces fabrication time and part costs by optimizing CAD for 3D printing and CNC machining. In the case of fabricating complex shapes by the hybrid fabrication process, it is easy to apply CNC strategies such as Z-axis machining and layer pocket finishing in the remaining sections.

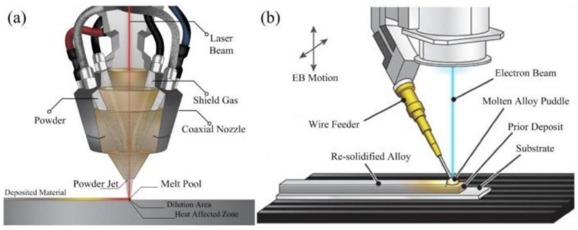

Fig 5: Additive manufacturing in the aerospace

5.2. Challenges and Opportunities in Scaling Up Production

The ability to fabricate multi-material composites with high spatial resolution, while maintaining the scalability and tunability of fiber-reinforced systems, is a significant advance in the evolving field of advanced manufacturing. At the same time, a limitation of current 3D printing processes in general is the relatively small-scale nature of parts that can be fabricated. Although the cost of additive manufacturing has greatly decreased in recent years, every unit built has a manufacturing cost associated with it, leading to high costs in the deposition of large components. The vision is that additive manufacturing will eventually replace large processes and, in doing so, reduce the costs of goods that are built with the processes. Reducing the cost of manufacturing through 3D printing will be key to enabling the fabrication of large components, especially for fiber-reinforced polymer MMCs. Recent progress in continuous deposition technologies could further enable this type of capability.

6. Conclusion

In this study, we reported and discussed recent advances and research trends in the 3D printing of composites. The focus was mainly on the fabrication of fiber/short fiber-reinforced and toughened polymers, functionally graded materials, ceramics, and multi-material composites. The review also analyzes the influence of processing parameters on the mechanical performance of printed composite parts. An appropriate selection of processing parameters plays a vital role in the properties of 3D-printed parts. Tailored 3D printing processing conditions for various types of composites are proposed to determine the accurate capabilities of novel 3D printing techniques. To further improve the mechanical performance of 3D printed composites, recent innovations are highlighted, including various 3D printing strategies, structures, additional materials, and post-treatments. These innovations offer useful design guidelines for effective strategies to address the key challenges arising from poor fiber orientation and insufficient load transfer. We also addressed the recent challenges and pointed out potential future opportunities. In summary, the current review will affect innovation in the burgeoning area of 3D printed composites, promote further applications, and show future research directions.

6.2. Future Trends

The success of 3D printing of composites made from the polymer matrix, especially due to the potential of core-shell systems, lays the groundwork for future developments, particularly when we consider strategic enhancements capable of promoting the replacement of conventional metallic materials in certain applications. It is possible to print complex devices in a single piece, worthy of the most demanding applications. Several advantages are associated with additive manufacturing; however, it is also necessary to develop mechanisms that promote properties similar to those of metallic materials, enabling their use for more applications. In this context, there has been considerable growth in recent years in the research and use of multi-headed printing techniques. Another important aspect is the need to improve the interlaminar strength of a composite, which guarantees the unions between the threads, promotes improvements in global mechanical strength, and increases the durability of the composite.

Its good mechanical and physical behavior is mainly associated with the material used to reinforce the interlaminar strength, material-system performances, or fabrication technology. It is possible to combine fillers in the polymer matrix until the desired improvement is achieved. However, in conventional manufacturing processes, the elaborate fiber alignment results in high processing temperatures. The metallic filler, while important from a structural point of view, when associated with a thermally sensitive polymer matrix, can promote thermal degradation and even the differential cooling behavior of the polymer matrix around the metallic filler. The new additive manufacturing technologies have excelled in selectively controlling the distribution of materials, from the alignment of the fibers outside the filament to the specific formulation of the vibrator, allowing for printing.

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