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A REVIEW ON DEVELOPMENT AND MANUFACTURING OF POLYMER MATRIX COMPOSITES USING 3D PRINTING TECHNOLOGIES

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Abstract: *Additive manufacturing or 3D printing becomes one of the most swiftly growing and generally utilized innovation and technology in various engineering industries such as aerospace, automotive, medical and architecture. In the most recent couple of years, these innovative technologies have created to such an extent that permits us to offer the production of the final products. When this technology employs in the manufacturing and production of the composite materials (polymer matrix composite), its importance increases. In this review, we briefly examine the advancement of product improvement and development of polymer-based composites structures through additive layer manufacturing technologies, its processes, key advantage and disadvantages. Moreover, the major challenges faced in the 3D printing of the composite materials are also presented and discussed.*

Keywords: *Additive manufacturing, 3D printing technologies, polymer matrix composite materials, fiber reinforced polymers.*

1. INTRODUCTION

Composite materials have been broadly utilized as lightweight components in several industries including aerospace, automotive, nuclear, marine, and biomedical industries. They offer high mechanical strength and high performance for explicit applications due to high strength to weight ratio. Lightweight composites, including Polymer Matrix Composites (PMC) (i.e. fiber-reinforced polymers) are typically used in several industries. The efficient fabri-cation of these composite materials is a significant chal-lenge [1]. Traditionally, the fiber-reinforced polymers composites are manufactured by various methods i.e. transfer molding, injection molding, pultrusion, filament winding technique etc. Now, due to introduction of addi-tive manufacturing, most of the composite materials are been manufactured by this process, because 3D printing technology offers 'design freedom' that empowers the designers and engineers to create a product that can be fabricated at low volumes in economical way and are not able or difficult to fabricate through traditional processes. Reinforcements can be divided into two main groups: con-tinuous and discontinuous. Most common materials for reinforcement materials are carbon, glass, Kevlar, silicon and others.

Fiber reinforced polymers (FRPs) provide magnif-icent mechanical properties and let it for significant struc-ture adaptability. Besides, the reinforcement might be able to enhance further functionality to the material perfor-mance such as electro-conductivity, heat conductivity or biocompatibility [2]. The combination of the reinforcement fibers into the polymer matrix with adequate alliance, control of fiber orientation and low cost is challeng-ing. FRPs composites can be divided into two main groups: reinforced with short fiber and continuous fiber. Fig.1 shows the printing filament example with continuous car-bon fiber reinforced (CCFR) and short carbon fiber rein-forced (SCFR) thermoplastic.

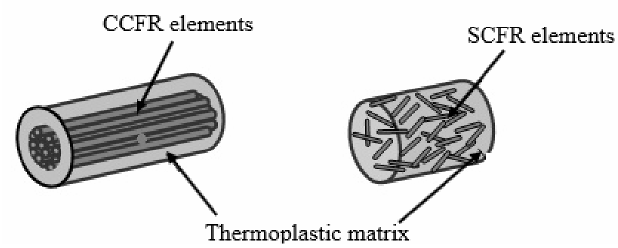

Figure 1. Types of orientation of fibers

Short fibers have better printing properties and are appropriate for use with standard printing techniques to increase the stiffness of the parts. However, compared to pure thermoplastics, the slight increase in mechanical properties still limits the increase in strength, as fiber pull out may occur before fiber breakage, providing an iso-tropic property. Continuous fibers give significant increas-es in mechanical performance over unreinforced poly-mers. However, this limits the freedom of design, since brittle and durable fibers cannot be easily separated by small turning radii and sharp corners [2].

The main aim of the article is to review additive layer manufacturing technologies for the production of polymer matrix composite structures. Table 1 shows the overview of results of printing of different reinforcements with the matrixes.

Table 1. Studies on printing of different reinforced filaments [2]

Matrix	Reinforcement	Reinforcement's Amount	Result
ABS	Carbon fiber powder	3-15 wt%	Maximum Strength 42 MPa Maximum Stiffness 2.5 GPa
ABS	Short carbon fibers	10,20,30,40 wt%	Maximum Strength 65 MPa Maximum Stiffness 14 GPa
PLA	Continuous carbon fibers and jute fibers	V_f of 6.5%	Maximum Strength 185 MPa, Maximum Modulus 20 GPa
ABS	Continuous carbon fiber	10 wt%	Flexural strength 7127 MPa Flexural modulus 7.72 GPa
Epoxy resin	Short glass fibers	8 wt%	Flexural modulus 6.3 GPa

2. ADDITIVE MANUFACTURING

Additive manufacturing (AM) is defined as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to sub-tractive manufacturing methodologies" [3]. Large range of prototypes and functional components having complex geometries are problematic to be fabricated by conventional methods are now possible to build by AM technologies [4]. Compared to conventional methods, AM can shorten the development (design and manufacturing) cycles, thus reduce the manufacturing cost, increase competitiveness and enhance the overall production efficiency [5-7]. AM technology produces products by adding materials to reduce waste and achieve satisfactory geometric precision [8]. Key mechanical properties of materials manufactured by AM include strength, stiffness, ductility and flexibility. AM offers several advantages over conventional manufacturing methods include:

– Rapid product development process

– High degree of customization

– Designs Complexibility

– Highly automated [1].

AM technologies have been engaged in various engineering applications in the previous three decades and now being seriously considered to produce materials for several applications, namely, electronics [9], aerospace [10], robots [11], medical industries [12-14], military [15] and others.

AM processes are categorized according to the condition of the raw materials as input that includes, powder, liquid, molten and solid layer processes. 3D printing can be classified into four main categories: (i) extrusion; (ii) photopolymerization; (iii) lamination; and (iv) powder based. Fig.2 shows the classification of different 3D printing techniques.

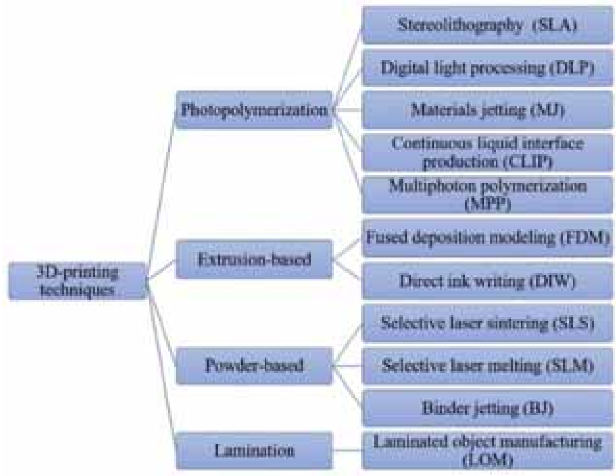

Figure 2. Classification of 3D printing techniques [16]

In recent years, AM technology has developed rapidly and is evolving due to its flexibility and low cost of prototyping and rapid production. All these features, along with AM's ability to produce the 3D printing structure and geometry production capacity and ability to achieve micron-level resolution, have contributed to the development of AM technology in a billion-dollar industry [17,18].

2.1. Description of 3D printing technologies

In the development of the additively manufactured product, it consists of three basic steps:

1. 3D CAD model converted to a standard file format (.STL).
2. Standard file sent to machine for printing.
3. Built-up of the part layer by layer [19]

Fig.3 illustrates the overall 3D printing process of materials step by step. Several 3D printing techniques have been utilized to fabricate the polymer-based composites. Each technique has its own advantages and limitations. The selection of such technique mainly depends on the input of material types, its processing and performance.

2.2. 3D printing of polymers

Polymers have been the center of attention due to their availability, attractive characteristics, ease of production and simple technological process of printing and therefore, occupies a major role for printing materials [20]. The 3D printing industry mainly involves polymers in various forms, such as filaments, liquid solutions and thermo-plastic melts. AM techniques used in the fabrication of plastics include fused deposition modelling (FDM) from plastic filaments, stereolithography (SLA) from photo-polymer liquid, laminated object manufacturing (LOM) from plastic laminations, and selective laser sintering (SLS) from plastic powders [21].

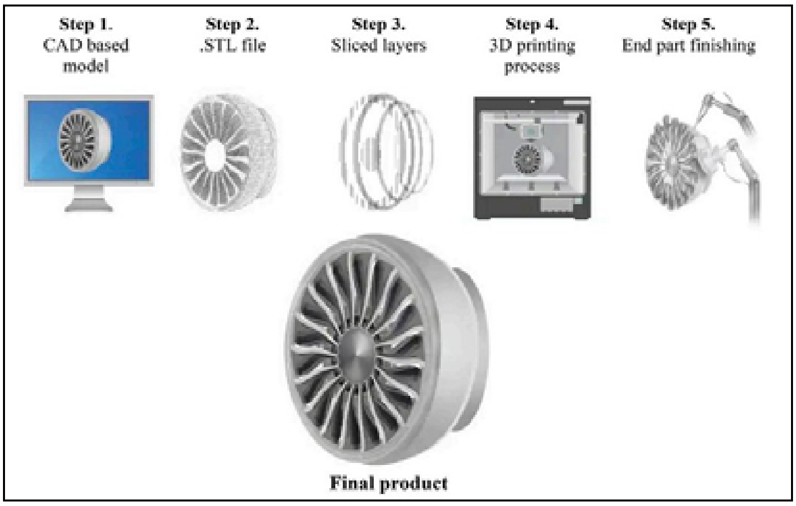

Figure 3. 3D printing process flow [19]

Table 2. A summary of reputable rapid prototyping methods [24]

Technique	State of materials	Polymer materials	Working principle	Advantages	Disadvantages
FDM	Filament	Thermoplastics materials i.e. PC, ABS, PLA, and nylon	Extrusion and deposition	Cheap, good strength, multimaterial capability	Anisotropy, nozzle blockage
IJP	Powder	All materials in the form of powder, binder can be supplied	drop-on-powder printing	Low cost, multi-material capability	Congestion of binder jet, binder contamination
SLS	Powder	Polycaprolactone (PCL) and polyamide powder	Laser scanning and heat induced sintering	Adequate strength, ease of removal of support powder	High cost, powdery surface
SLA	Liquid photopolymer	Photocurable resin (epoxy or acrylate based resin)	Laser scanning and UV induced curing	High printing resolution	High cost, Material limitation, cytotoxicity
3D Plotting	Liquid or paste	PCL, PLA, hydrogel	Pressurized syringe extrusion, and heat or UV-assisted curing	High printing resolution, soft materials capability	Low mechanical strength, slow process

3. 3D PRINTING OF FIBER REINFORCED POLYMER COMPOSITES

Composite materials are commonly used for lightweight structures and components due to their good mechanical properties, structural flexibility, relatively low cost, and high performance. Hence, are commonly used in many areas for lightweight structures and components, particularly in the transportation, construction, automotive, and aerospace industries. Composite materials are widely used in the aerospace industry, for fabricating several aircraft components. Currently, approximately 50% of the airframe of aircrafts are fabricated from composite materials [22].

In recent years, great attention has been considered to the 3D printing of polymer-based composite materials. Fiber reinforcement can significantly increase the efficiency and performance of 3D printed parts with a polymer matrix. The orientation of the composite fibers and the void contents are the key issues for 3D printing of these compositions. [18]. Fiber reinforcement can be used with either thermoplastics or thermosets to increase and enhance the mechanical properties in the parts [23].

In this paper, AM processes for polymer reinforced benefits and limitations in producing composite parts. The selection of production process depends on the requirements for raw materials, processing speed, resolution, costs and performance of the final product. [24].

3.1. Fused Deposition Modelling (FDM)

Fused deposition modelling (FDM) printers are the most usually utilized 3D printers for the manufacture of polymer matrix composites. Thermoplastics materials such as PC, ABS and PLA, are commonly used due to their low melting temperature. This technology is based on the controlled extrusion of thermoplastic filaments through nozzle. Fig. 4 shows the schematic process of FDM. FDM innovation can be utilized for printing composite structures, regardless of short fiber reinforced polymer (SFRP) or continuous fiber reinforced polymer (CFRP) [20].

In a typical FDM process, the filament on the spool is fed to the fluid head by applying pressure. By inserting the filament material, which is heated to the glass transition state and extruded through an extrusion nozzle at constant temperature, plastic parts can be arranged layer by layer.

The head of the liquefier moves in the X-Y plane as a toolpath created by the software, and at the same time the first required plane is placed on the print plane to form the bottom of the part. At the end of this layer, the build platform moves down to form a layer with a thickness so that another layer of filamentous material can be created. Each single layer will be deposited frequently on the previous layer in the same way until the part is finished. The FDM printer with dual extrusion nozzles, two filament materials can be extruded simultaneously through the nozzle. After FDM fabrication, the support material can be easily removed at the end of the building process.

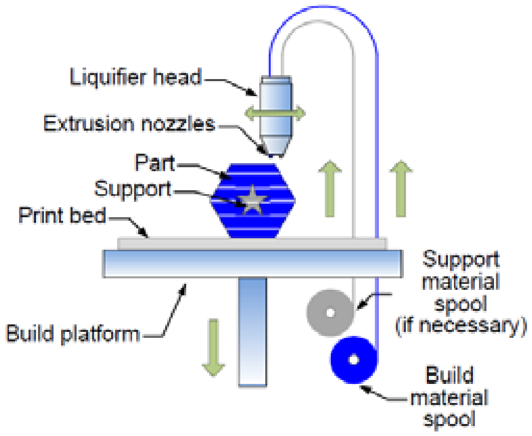

Figure 4. Schematic of FDM process [21]

Advantages:

– Low cost, high speed and simple process
– Allows simultaneous deposition of different materials
– Parts can be multi-functional with designed composition
– FDM equipment requires a very low maintenance.

Disadvantages:

– Difficult to disperse homogeneously reinforcements and remove the void formed.
– Low process and delamination caused by temperature fluctuation
– Material limited only for thermoplastic polymers with sufficient melt viscosity

3.2. Inkjet 3D printing (IJP)

This technology is based on powder processing used for SFRP printing, as shown in Fig. 5. The powder is first spread on a platform that attached to a standardized layer by depositing a liquid binder through an ink jet printhead that able to move in X-Y direction. After a desired 2D pattern is framed, the platform falls off and another layer of powder is deposited. This procedure is settled again lastly the unbounded powder must be evacuated to get the final products. The internal structure can be controlled by varying the amount of binder deposited. The dependency of the quality of the final part are the size of the powder, the viscosity of the binder, the interaction between the binder and powder and the binder deposition speed [24].

This technology is generally based on the powder processing and a nozzle has been used to deposit materials on paper. The amount of ink in the chamber is ejected from the gun by the piezoelectric system, which drastically reduces the volume of the chamber. The drop falls by gravity and dries, causing the solvent to evaporate.

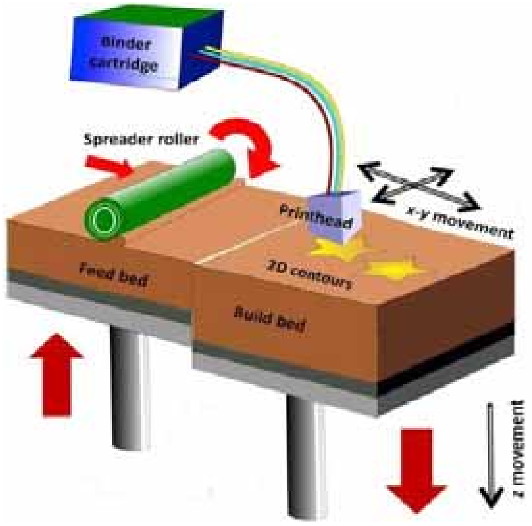

Figure 5. Schematic of working principle of IJP [25]

Advantages:

– Adaptability of material choices and room temperature processing environment.
– All polymer materials in powder form could be used for printing.
– The technique makes it easier to remove the support structure.

Disadvantages:

– Fragile print heads and expensive ink cartridges.
– Parts printed with an inkjet tend to have lower mechanical strength and fracture easier.
– Inkjet systems are generally applicable to specific materials that can be deposited at low viscosities.

3.3. Selective laser sintering (SLS)

This technology is based on a power laser source that is used to fuse small particles of polymers together. This technique is similar to IJP technologies also used for SFRP printing. The powders are heated slightly below the melting temperature to facilitate the joining of the different layers and to avoid thermal distortions. In the final product, unbounded powder removed to get the final part.

SLS technique is almost similar to IJP technique as both technologies are based on powder processing. Instead of a liquid binder in IJP, the SLS uses laser beam to analyse the powder in a controlled manner to sinter it by heating, as shown in Fig. 6. The features resolution of the function is determined by parameters such as dust particle size, laser power, distance and scanning speed. Until now, polycaprolactone (PCL) and polyamide (PA),

polyethylene and PEEK are widely used laser sintering materials [19].

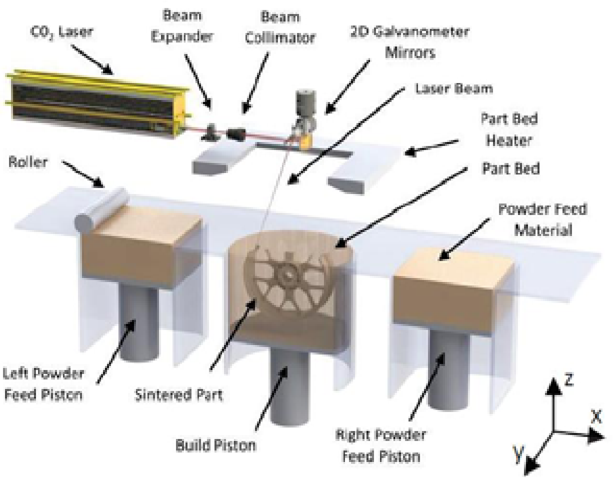

Figure 6. Schematic representation of the Selective Laser Sintering process. [26]

Advantages:

- SLS process do not need any support structure, all hollow spaces are automatically filled with unused powder.
- SLS has a characteristic to print virtually isotropic mechanical properties due to very strong layer adhesion
- SLS are capable of producing strong, functional parts with complex geometries.

Disadvantages:

- This technology also relies on limited polymers
- Complex merging behaviour and the molecular diffusion process during the process limited the choice of polymers used in the process.
- SLS prints have a comparable tensile strength compared to SLA prints, they are less flexible and can undergo less deformation before failure.

3.4. Stereolithography (SLA)

Stereolithography (SLA) technology used for creating prototypes based on UV light or an electron beam to generate a chain reaction from a polymer resin. The parts are manufactured by the selective UV curing of resin under a layer. In SLA, Acrylic and epoxy polymers are the main materials utilized. Additional processing such as heating has been used for parts printed with SLA to achieve the desired physical performance [27].

SLA uses photopolymers that can be cured with a UV laser. The UV laser controls the desired path technique in the resin tank and the photochemical resins polymerize in a 2D pattern layer. After each layer has hardened, the platform repeats and the next layer of uncured resin is prepared for the pattern [14], as shown in Fig. 7.

In order to analyze the quality of the final printed parts, it is very important to understand the curing reactions that occur during the polymerization process. The intensity of the laser power, the scanning speed and the exposure time influence the curing time and the print resolution

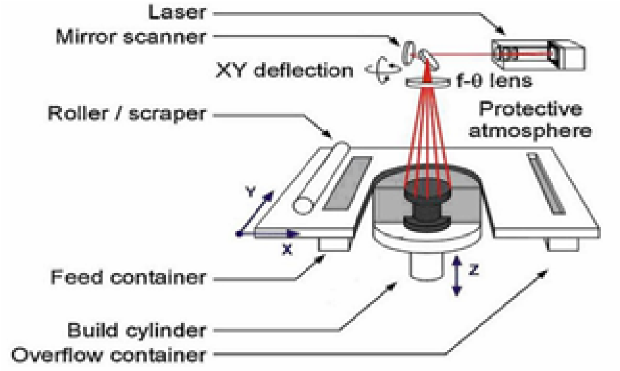

Figure 7. Schematic diagrams of SLS technology [28]

Advantages:

- Capability to print parts with high resolution and quality
- SLA have good functional surface quality parts.
- Resulting parts have a smooth finish

Disadvantages:

- High cost is a major concern for use in the industrial application
- Possible cytotoxicity of residual photo initiator and uncured resin is another concern
- Components are only UV-resistant to a limited extent

3.5. Direct-write 3D printing

Direct-write 3D printing has been offered as a promising technique for manufacturing fiber reinforced composites for high quality and strength. These methodologies essentially depend on the utilization of shear arrangement during the extrusion procedure to adjust fibers along the printing heading [29]. Direct-write printing uses viscoelastic materials, including polymer liquids hydrogels as printing ink to fabricate complex 3D parts [30]. 3D plotting is based on extrusion of viscous material from a compressed pressurized syringe to generate the 3D part, as shown in Fig. 8. The syringe has the ability to move in three dimensions, while the platform remain stationary and the extruded materials are combined together layer by layer. The curing reactions can be carried out by providing two reactive components using mixing nozzles or they can be either induced by heat or UV light.

Advantages:

- Material flexibility. Polymer solutions pastes, and hydrogels can be used.
- The process has the ability of advanced polymer design

Disadvantages:

- Temporary fulfilling material might be required to support the printed structure because untreated viscous

materials possesses low stiffness, that can result in the breaking of complex structures.

- 3D components printed by Direct-write 3D printing exhibit some mechanical property issues

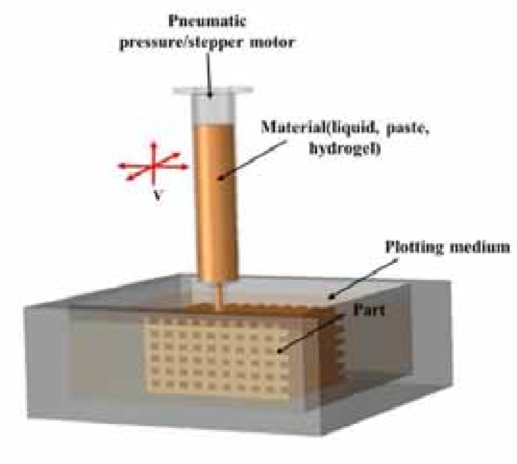

Figure 8. Schematic of 3D plotting technology [24]

4. MAJOR CHALLENGES FACE IN THE AM OF COMPOSITE MATERIALS

The fabrication of composite materials mainly FRPs composite materials exhibits number of advantages over the manufacturing through the conventional methods. But, on the other hand it also limits the productivity due to some major issue face during the 3D printing. AM of composite materials faces the following major challenges during the fabrication:

1. Maintaining the homogeneous distribution of reinforcement material in the matrix.
2. The availability of the raw material in a proper form (wire or powder) and the imperfections that can result because of chemical variations of the feedstock materials [1].
3. The selection of ideal process parameters to manufacture the composite materials. Inadequate process parameters can result in the change of microstructure of the material during the process and also the mechanical properties of that product [31].

Other major drawbacks of 3D printing technology are the void formation of printed parts. The created porosity reduces the mechanical performance of printed composites. The concentration of these voids depends mainly on the process selection and manufacturing. Although, reinforcement improves the performance of polymer composites, but compared to traditional manufacturing processes such as molding methods, most of the 3D print-ed composites parts still have low mechanical property and can't meet the practical prerequisite. The main reason for the low mechanical strength is that during the process the formation of voids is more common and is considered an important factor in reducing the mechanical and anisotropic properties and in the resulting delamination between the printed layers. Also, the anisotropic behavior was caused by the nature of layer by layer printing [19]. The addition of reinforcement can additionally expand the porosity because of the poor interfacial bonding with matrix. Most of the printing processes are time-consuming and often problematic to manufacture with large volume. Moreover, if an error occurs during printing, the process must be stopped, which leads to loss of time and material [24].

Hence, these challenges need to be considered for the long-term development of the additive manufacturing of polymer matrix composite materials.

5. CONCLUSION

The literature showed various attempts to additively manufacture of polymer matrix composites for the fabrication of complex designs and structures. In this review, five main AM technologies were examined, their processes, principle operation, key advantages and disadvantages were discussed for fiber reinforced polymer composite structures creation i.e. FDM, IJP, SLS, SLA and Direct-write 3D printing that are more appropriate for rapid, simple and complex composite structure manufacturing compared to traditional production methods. The main challenges in the fabrication of composite materials using AM technology, as well as the selection of process parameters to manufacture composite components with high mechanical properties, their issues during and after the manufacturing of the products were presented and discussed. Further research is still needed to recognize the optimum process parameters to fabricate composite materials through AM. But still, AM has very bright future for the fabrication of polymer composite structures.

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