Review Article

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Additive manufacturing (3D printing) technologies for fiber-reinforced polymer composite materials: A review on fabrication methods and process parameters

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Abstract: In recent years, additive manufacturing (AM) has seen extensive exploitation in the research areas for the processing of fiber-reinforced polymer composites (FRPCs). Existing reviews on AM have recommended either sustainable production methods or have introduced new processing methodologies. A relationship between materials used, manufacturing processes, process parameters, and their properties is essential in any manufacturing process. Accordingly, this review focuses on the manufacturing of FRPCs in relation to process parameters and properties of the polymer composites. Various studies dealt with the lightweight materials and parts that were manufactured through AM and which could retain the mechanical and other properties without compromising the strength and weight of the final product. The technologies involved in the major AM processes and the constituents used for the fabrication of FRPC parts, their advantages, and drawbacks are also deliberated. This review combines the material selection for AM technologies along with the choice of proper AM technique for printing FRPCs. This review further illustrates the recent research and technology that aims at embracing FRPCs into a circular economy. In summary, this review opens the door for new opportunities and for meeting challenges in the manufacturing of FRPCs by AM methodologies.

Keywords: additive manufacturing, 3D printing, fiber-reinforced polymer composites, fabrication methods, process parameters

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1 Introduction

Additive manufacturing (AM) is an emerging technique in the manufacturing sector competing against a hundred years of enduring conventional manufacturing methods. In the nineteenth century, prototyping or manufacturing was ultimately handmade by skilled craftsmen or labor entailing several days for the development of the product with a huge volume of input material being processed. Substantial tooling and a number of iterations are needed for crafting certain forms, fits, and, functions of the designed parts since it is expensive (1–5). Rapid technological development allows for a pathway to a circular economy through recycling and modification of the production process (6). Therefore, novel processes have come into existence with increased productivity, reduction in wastage, cheaper price, and enhanced parts functionality described as AM process (4,7). AM ordinarily recognized as 3D printing derived from significant attentiveness is the result of immense applications in numerous fields. This adaptable methodology has applied tangible and ground-breaking innovations throughout the manufacturing sector catering to the huge rise in demand for customized products (8,9). This method widely used as the next industrial revolution has its roots in the number of processes developed in the late 1980s under uninterrupted progress and advancement (10). This is a process of conversion of a computer-aided design (CAD) model with part geometry due to the conversion of the digital information to the final product through successive layer-by-layer (LBL) deposition of material with high precision (11).

Focused on the “design global, manufacture local” model has been found as a platform to bridge digital and conventional knowledge with existing physical infrastructures, for mass production. Initially, AM refers to various synonyms established in literature like layering, rapid prototyping (RPT), desktop manufacturing, CAD-oriented manufacturing, design-controlled automated fabrication, 3D printing, instant manufacturing, materials deposition, etc. (1,4,5,10,12). RPT is also known as the process of assembling material for the creation of a piece from 3D prototypical values, frequently LBL, as opposed to subtraction approaches and manufacture of the final product (13). In 2009, ASTM F42 International Technical Committee defined AM in terms of CAD to build object LBL for highly precise and complex structures. Twinset quotes to differentiate the manufacturing techniques, “what you see is what you get” – conventional method, “what you see is what you built” – AM (14).

It is a feasible process related to conventional manufacturing processes like milling, casting, etc., and requires less human involvement and liberty to produce a physical model of a drawing. Even the CAD model can be upgraded at any time, just a minute before the initiation of printing (15). Most of the researchers are focusing on pure polymer-based AM products and their composites (16–27). Also, they did not concentrate much on the wide range of composites, or precise AM technologies; consequently, there is no exhaustive review of AM technologies for FRPCs based on sustainability principles. The aim of this review is merging appropriate findings, and reachable literature, with the delivery of perception into the field of material science, mechanics of the AM process, and their composites in terms of processing and properties. The main objective of this review is to enhance the production process and its applications of FRPCs and endorse essential encounters, empowering methodologies to accelerate this changeover. It contributes to the maximum possible extent for the improvement of additively manufactured FRPCs for real-world manufacturing problems. Many experiments were conducted to find some of the preceding investigations in this domain, with encounters and the acquired existing material characteristics. In specific, the influence of the fiber content, dimension/alignment distribution, and fiber-matrix interface on the properties of additively manufactured FRPCs are deliberated to the hypothetical and investigational study.

1.1 Benefits of AM

The impactful benefits of AM on the environment, societal and economic welfare of the industry with zero scrap management, and no skilled craftsman all day long, have been built. Manufacture of FRPC parts via AM has numerous benefits comprising the capability to build multi-faceted sized parts with squeaky lengthy dimensions and swifter processing (28). AM products benefit through a wide range of applications even from medical kits like face masks, multiple split ventilator nozzles, and nasal strips for frontline workers in no time during pandemic situations, reaching several applications and interplanetary bodies, with the potential to create intricate parts by AM related to traditional machining processes (8). The following are the major benefits of processing FRPCs through AM.

(i) Freedom of design (visualization): The designer uses CAD for the creation of a 3D model of his design concept. Some blemishes could still evade the engineers and originators. Physical touch on the parts reveals the hindrance and produces an improved design (13).
(ii) Verification and optimization: In conventional manufacturing, authentication or enhancement of the design is frequently time-consuming and expensive. But it is possible in AM due to the absence of tooling or labor cost. Multiple iterations of design is also conceivable (13,39,30).
(iii) Producibility: The design can provide a physical product at an early stage with process planning and tooling design possible.
(iv) Feasibility: Marketing process, ease of demonstrating a concept, design ideas, and company’s ability to manufacture is within reach.
(v) Repairing: It economizes the energy required for repairing, using the technology for surface patching (31,32).
(vi) Cost-effective and time consumption: The manufacture of customized and complex structures is effortless, economically effective, and time-saving (33).
(vii) Societal wellbeing: Deliverable extraordinary eminence, gainfully effective healthcare product to increase the vigor and wellbeing of the people that has become the significant societal trial in this century.
(viii) Energy consumption and environmental impact: AM technologies have the prospective to diminish the lifecycle of mass material and energy disbursed relative to subtractive industrialized methods by abolishing persuaded scrap and the usage of risky subsidiary process inputs (31).

The prime advantages of AM include high reproducibility, quick manufacturing, and low cost with a focus on specific areas that include manufacturing processes, materials, design, management, organization, and implementation (29–33).

1.2 Materials and their classification

A large group of atoms agglomerate to form a structure of materials according to the property of the material, they are classified. It is independent of material shape and size, the response to external stimuli changes for each material. Materials have been categorized into two types based on their chemical contents such as metals and non-metals (25,26). Figure 1 depicts the generic classification of engineering materials and the subclassification of those materials. AM technologies currently use only thermoplastic materials and the research works are in full swing to develop AM technologies for metals and composite materials.

1.2.1 Composite materials

Composite materials rely on the inherent property of their constituents which have been made up of matrix and reinforcement. Matrix forms the outer layer and they are classified as thermoplastics and thermosets. The final properties of the composites are majorly dependent on reinforcement orientation in the matrix and the types of resins used for composite fabrication. Different properties of the composites can be obtained when thermoplastics and thermosets are used as matrices since they have many inherent differences (1,2,16,18).

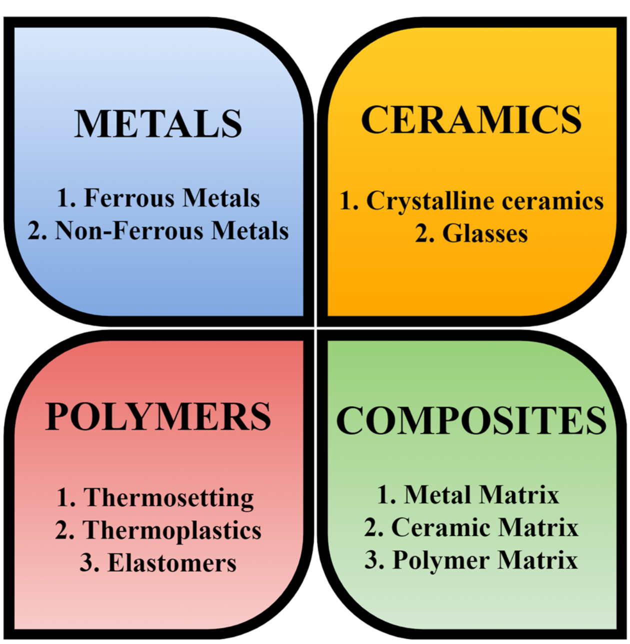

Figure 1: Classification of engineering materials.

1.3 Sustainability in manufacturing

The term cleaner production or sustainable manufacturing is a method to recycle waste materials and resources (34). Clean/sustainable manufacturing involves the effort to shift the production and the use of materials from linear to cyclical use of resources that do not generate waste materials and cannot be used as feedstock for any other method or manufacture for making a material that is used and disposed of. Clean technologies have the ability to apply the hop leads to manufacturing industries, combined with full consideration of the product life-cycle (35). An eco-friendly solution is required to minimize and eradicate environmental pollutants from composites processing, as well as repair requirements. Recycling is one phase in the movement toward a circular economy which is seen as the solution to environmental sustainability and security (36). Solutions that involve the use of emerging technology and materials for the elimination of emissions from composite processing are suggested through AM process (37).

Research on AM from circular economy perspective was conducted by Colorado *et al.* (38). They examined innovative practices adopted to ensure the AM for sustainable manufacturing and found polymers, ceramics, and composites as the subject of a major research toward circular economy. They suggested a significant reduction in the limitations of AM in relation with recycling of materials, health issues, and sustainability processes to ensure suitability of composites for circular economy due to recyclability. Sustainability in the selection process of materials is becoming an ever more persuasive point. From the viewpoint of end users, practitioners and policy makers have misgivings about the relationships between sustainable manufacturing and dimensions of sustainability such as ecological, economical as well as social (39).

FRPCs are solid, light-weight, and durable materials that find use in transportation, building, renewable energy, and many other sectors. Sustainability is also a primary driver for the choice of composites over conventional materials during their usage. In addition to the low maintenance requirements, composite structures provide a long service life and are lightweight resulting in lower energy consumption throughout the product life relatively has researched the road mapping of the composite processing methods to solve the problems related to sustainability (40). It is found that the theoretical findings consider more resource recycling and regeneration to provide more guidance for sustainability research in FRPCs. From all the above points, it could be understood that a review of sustainable manufacturing technology for fiber-reinforced composites is very important. In order to have quality products, the focus of the review has to be placed on the process parameters and application of the technology. Accordingly, Section 2 discusses the AM technology for fiber-reinforced composite materials.

2 AM

In the manufacturing sector, AM can help the generation of innovative products, advancement in the eminence of parts functioning, and reduce manufacturing costs and threats. AM has a boundless perspective to improve substantial progress in resources, printer technology, and processes (41). A numerical chain-based design for AM technology was introduced by researchers (4,7). The parts are modeled and arithmetically segmented (sliced) into many parallel cross-section portions, in the stereolithography (SLA) format. Most of the solid parts are made either by acrylic or epoxy resin and are modeled using some modelling software like ACES, STARWEAVE, and Quick cast (3). The commercially used software for the topological optimization in all the AM processes is TOPOSTRUCT and the transition of the topological skeleton of the part section from the geometry of the initial design is performed using the MATLAB implementation tool (4,42). This procedure involves the printing one or other materials in the LBL fashion and, by fine-tuning each discrete layer, a multifaceted, dense object can be molded from a digital prototypical model (3,9,13). Irrespective of the transformation seen in the material deposition process, primarily a CAD diagram is prepared for the preferred model, the printer follows the guidelines of the CAD system and physiques the entity in pre-defined outlines by the movable print head in a 3D coordinate system (Figure 2). Binding and curing lanes are created for each subsequent layer for the solidification of the part material. Subsequently, a layer is deposited on the preceding layer. The model has assembled LBL from the bottom-most to the upper-most (15).

The conceptual framework for AM applications is based on both the external forces and internal strategy driven subjectively by factors, and grouped into five theories shown in Figure 3 (13). The 4D printing is also introduced mainly on the natural fiber-based materials, which signifies the capability of 3D printed materials to excite when a peripheral stimulus is employed despite these materials having very low thermal resistance and moisture sensitivity. The suggested manufacturing rules are as a set, for precise physical shape such as the minimization of the number of the path ends in the product maximized curvature and minimized the number of discontinuity points (19,21). There are various stages in AM, based on the raw material, process parameters, layering methods, etc. This has been classified as a revolutionary set of processes for product development and manufacturing (2,10,43). Detail of various AM technologies is presented in Table 1.

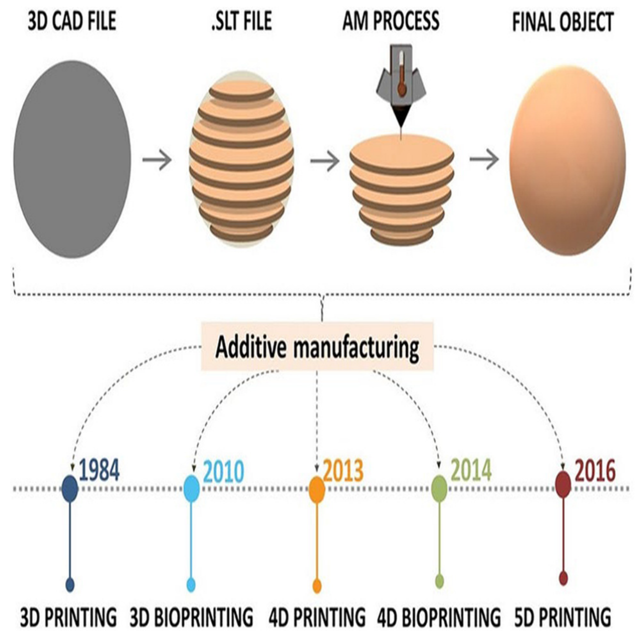

Figure 2: AM progression and development over the ages (9).

3 AM of composites

AM techniques have similarities of long-established composite constituents intrinsically grounded on heaping a sequence of distinct layers. It is then equitable to acclaim that a prosperous version of AM technologies to fused materials could help effortless composites' engineering through secondary fabrication processes and a higher grade of computerization. With the ability to precisely positioned fibers, the plastic-coated structure of merged components can be optimized in an individual layer, permitting for an upsurge in design/model liberty and different output (44). The development of the AM product onsets from the design/standard triangle language (STL) part file at the site of the customer. (i) To sign into the AM account: The manufacturing company needs the use of exclusive internet software to log onto the site provided to the customer. (ii) Data authentication: The STL file of the client is robotically checked for fault with the use of the client communication software. (iii) Quotation for the customer: The price of the material and capability of planning are estimated according to the CAD/STL file which has been transmitted to the server, automatically. Production

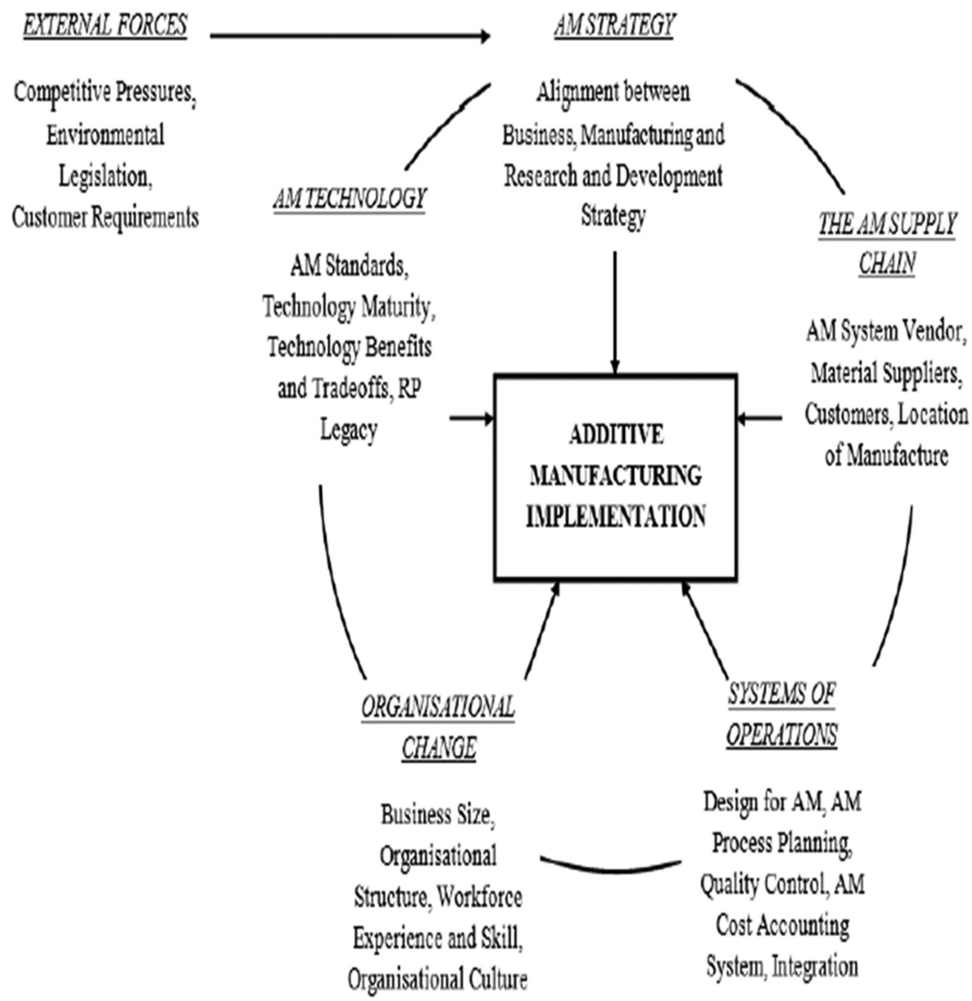

Figure 3: Conceptual framework of AM (13).

planning includes detailed input parameter, order delivery date, selection of AM process, process planning like part design, part slicing digitally, CAD, and selection of the parameters like layer thickness, laser power, scanning speed, etc., as obligatory. Delivery of the AM product is always customized according to the requirement (1,3,10,14).

3.1 Without reinforcement

AM printed with polymer has a unique behavior toward its functional property, melting processable plastics such as thermoplastics which are liquefied at high temperature and solidified under reduced temperature for getting the desired shape but, toward the degradation, the temperature is close to the melting point causing depolymerization. When a polymer-based material is used as a raw material for AM, then shrinkage of the final product becomes inevitable owing to the alternative heating and cooling cycles and this poses a great challenge during the 3D printing process. Hence, polymer-based raw materials are specifically used where high rigidity, high strength, and high resistance toward elevated temperatures.

3.2 With reinforcement

Ceramic matrix composites and metal matrix composites (MMCs) are widely used in aerospace, biomedical, electronic applications due to their superior properties such as high wear resistance, chemical inertness, and superior properties at high temperature (45). The solidification, micro-structure, and mechanical properties of composite parts produced using selective laser melting (SLM) is investigated by Vrancken *et al.* (46). They found that the AM was more effective method in achieving engineered parts from powder mixtures. Krakhmalev and Yadroitsev (47) applied SLM for the development of metallic coatings and SiC

Table 1: Comprehensive detail of various AM technologies

AM technology	Year of invention	Type of material used	State of feedstock	Layering techniques	System involved	Phase changes	Developer	Major applications	Ref.
VAT polymerization	1984	Photo polymers, ceramics, photo curable resins, Acrylates	Liquid resin	Layer scanning/ projection	Laser based	Photo polymerization	USA, Germany, UK, Italy	Surgical learning tools, hearing aids, facial prosthetics	(3,10,14)
Material extrusion	1988	Polymers	Filament	Continuous extrusion and deposition	Nozzle based	Solidification by cooling	USA, China	Building construction, printing human organs	(3,10,14)
Powder bed fusion	1990	Metals, polymers, ceramics	Powder	Extrusion process	Laser based	Fused by high power laser	Germany, France	GE9C engine, injector head in aerospace engine, seat belt bracket in automobiles	(3,10,14)
Direct writing	1993	Photo polymers	Viscous solution	Extrusion process under pressure	Printer based	Hardened by post curing process	Canada, Germany	Photovoltaics, photosensors, nanofluidic device manufacturing, tissue engineering	(10,14)
Binder jetting	1994	Polymers	Liquid binder	Inkjet printing	Printer based	Hardened by post curing process	USA, Germany	Printing full color prototypes, large sand molds, 3D printed metallic parts	(10,14)

powder mixtures based composites and investigated the relationship between the composition and microstructure. They found that the hardness, indentation fracture toughness, and abrasive wear resistance were significantly improved. Composites fabricated through SLM and the cell attachment, morphology, and proliferation of these composites have been evaluated (48). The MMC layers were formed through the laser cladding and the interface characteristics are found good.

3.2.1 Synthetic FRPCs

Over the years, the number of products manufactured by AM has improved by a hefty magnitude. A specific kind of material that has been in the focus recently is the FRPCs. The determination to design FRPC parts using AM started in recent years and scientists are working for the production of FRPCs with a range of renowned fibers that include carbon and glass fibers (28,49). Additively manufactured FRPCs are cost-effective, and have replaced the conventionally manufactured composites which have societal as well as environmental impact of an increase in carbon footprint during their span of life (50). While polymer-based AM has progressive significance over the past years, boundaries in the material properties, swift manufacturing, and size of the part have relegated this technology to RPT relatively over traditional manufacturing (26). There are numerous advantages observed in the FRPCs, with enrichment of the properties of polymer matrix materials. The primary difference between the synthetic and natural fiber-based composites lies on the parameters such as bio-chemical composition, micro-structure, the physical property of the fibers, and processing constraints such as rate of shear, and temperature. Fibers like carbon, glass, aramid, kevlar, etc., are manmade fibers whereas plant-based fibers are naturally available, and classified based on their extractions from animals, plants, and minerals (16,21,51).

AM has acquired distinct fascination due to its competency and ability to expand and alter the strength of manufactured composites by reinforcing fibers (52). Printing orientation is a key factor for the tensile properties of the material. Further, optimization of the bio-composite fabrication process is required to enrich actuation performance, robustness for enhancement of the bond strength, and selection of fiber and matrix (4,16). Investigation on AM of FRPCs can be segmented into particulate and FRPCs. Particulate composites that have been formulated using AM technologies include material extrusion or fused filament fabrication (FFF) and direct writing, VAT polymerization or

SLA, additive laser manufacturing, and laminated object manufacturing (LOM). Fiber-reinforced composites are produced through powder bed fusion, selective laser sintering (SLS), and other AM technologies, most frequently material extrusion is used worldwide (4,26,53).

Synthetic fibers offer a low thermal expansion coefficient, high thermal conductivity, and low density. Synthetic FRPCs extend the utmost comprehensible pathway toward wide-ranging, reasonable, and efficient AM composites (42,54). The usage of carbon fiber can help the expansion of material characteristics, reduce the manufacturing time for composite parts related to conventional/subtractive methodologies, and diminish warping, facilitating a superior possibility to shaping the envelope (55,56). Consequently, the inclusion of carbon fiber into AM methodologies is the current topic of research in manufacturing (26,57). Polymeric materials are the familiar components produced in 3D printing, delivering an array of combinations and capability to amend their inner structure and exterior surface and necessities solicited for precise components, inclusive of additives for enhancement of the strength of materials and anti-microbial compounds (58–61). Fibers and single-walled carbon nanotubes (SWCNTs) are bonded with acrylonitrile–butadiene–styrene (ABS) copolymer, developed in AM technology with a great dispersal capacity and dissemination of fibers in the matrix and an insignificant porosity.

Improvement of load-resisting properties requires optimization and modification of fiber to ensure improved fiber/matrix bonding that simultaneously improves the ductile behavior of the composite materials and their mechanical properties (51,62). Continuous fiber composites provide high mechanical strength, expensive composite part production, the particulate reinforcements with realistically upgraded mechanical strength, and these are extruded by injection molding and extrusion processes. The mechanical strengths of these composites are based on the fiber dispersion and directional orientation in the composite parts (63). Integration of AM technology for carbon fiber composites has shown improved strength, less weight, and precision of industrial components. Blending of carbon fiber with ABS polymer feedstock increased the stiffness and strength of the parts. The insertion of carbon-based synthetic fiber improves the thermal conductivity and reduces the coefficient of thermal expansion considerably (54).

The processability, micro-structural and mechanical performance of carbon fiber incorporated composites were reviewed in contrast to the traditional compression molded composites. The review indicates improvement in the strength, modulus, and porosity of additively manufactured composite samples by a larger percentage compared to conventionally fabricated composites (64). Carbon-reinforced ABS composites are manufactured through AM by changing the content of fibers and their length (65). Characterization techniques such as thermo-gravimetric analysis for assessment of the mass loss, Fourier transform infrared spectroscopy for approximating the functional groups of the material, and capillary rheology techniques were used. The outcomes helped determination of the correlation between the existence of additives and wt% of carbon fiber, thermal stability, and definite fiber wt%. However, rheological characteristics seemed generally unpretentious.

3.2.2 Bio-composites

The notable revolution in the materials world is the usage of plant fibers with synthetic and bio-polymers. In the chronicle of composites' practice across years, the utilization of plant fibers has proved to be an appreciable substitute to synthetic fibers like glass, carbon, aramid, and kevlar, due to the benefits which include lightweight, inexpensive, encompassing deep-rooted supply-chains, trouble-free recyclable and bio-degradable nature (66,67). Despite a few deficiencies, researchers found a blessing in disguise like the moisture sensitivity of a plant fiber which turns out to be a verdict of hygromorph (self-shaping of the material through moisture as an actuator). The major plant fibers are extracted from the parts of the plants like fruit, leaf, bast, seed, and stalk (51). The common constituents of plant fibers are cellulose 60–80%, others are hemicellulose, lignin, and a minor portion of wax, pectin, moisture, and water-soluble organic components. Plant fibers like sugarcane bagasse, rice husk, kenaf, corn husk, coir, hemp, cotton, banana, bamboo, jute, kapok, milkweed, and wheat straw have proved to be good acoustic absorbers. Plant fiber-reinforced composites provide good acoustic coefficients from the low, mid, and high-frequency spectrum. These fibers are used in acoustic panels, to convert absorbed sound energy into heat which can be used for solar applications (68). In summary, AM technologies use a wide range of materials for manufacturing various parts with intricate shapes and sizes rendering parts with a wide spectrum of properties catering to the needs of various industries. It could be understood from all the above discussions that AM technologies for fiber-reinforced composites were meager and attention has to be paid to AM technologies that render quality composites for a variety of applications. 3D printing of biocomposites with bio-based fibers and biopolymer matrix needs more attention owing to various manufacturing difficulties. The following section is dedicated to various AM technologies for manufacturing fiber-reinforced composites.

4 AM methodologies

The customary AM methodologies available for the processing of FRPCs are discussed in this section. Each methodology has its exclusive sketch and industrialized restrictions associated with the printing technique, preferred material, and prospects (appealing, mechanical performance, etc.) using a visco-elastic model relating the essential requirements for the effective printing of FRPC material (69). The model has four factors, namely, bead formation, material flow, bead function, and component function. Apart from the fiber stacking and orientation, AM process constraints influence the micro-structural and mechanical properties of the AM components. As the fibers get inclined to the path of the printed beads, they attain the maximum strength, correspondingly, polymer matrix composites (PMCs) manage for enhancement of the ductility in the direction where matrix properties are higher, with the resultant sequence of strength and ductility in the inclined orientation. The parts printed at low temperatures have poor interfacial adhesion among the layers, and the temperature constructed voids diminish the strength, whereas an average nozzle temperature creates the maximum strength, modulus, and ductility (70).

AM technology has a lot of individual processes based on their method of layer manufacturing, input material, and machines used (4,10,14,16,43,61,71,72). They are formulated by the ASTM F42 committee and include (i) FFF, (ii) VAT polymerization, (iii) SLS, (iv) direct writing, and (v) binder jetting. Some of the other AM technologies for fabricating metal-based composites are laser metal deposition (LMD), laser beam melting (LBM), laser deposition welding, laser metal fusion, metal laser sintering, laser cladding, and electron beam melting (EBM). LMD is a process for melting the surface and applying metal powder using a coaxial or multi-jet nozzle for building parts. Melt stock is protected against oxidation through a supply of gases such as argon or helium produced by carbon dioxide laser. LBM is based on the metal powder spread in the form of a thin layer for the creation of a part. EBM is a powder bed type with similar characteristics to LBM in which the metal powder is fed through a hopper and distributed through a rake across the build platform (73).

4.1 FFF technique

FFF is a 3D printing technique that permits LBL build-up of an AM part of thermo-plastic material via nozzle (44). This is a very popular AM technique, with the ability of the polymeric material to be extruded in the shape of a filament or pellet, as exploited in huge configure printers (3,14,16,74–82). It is also known as fused deposition modelling (FDM) and one of the viable commercially known techniques of material extrusion processes in AM (26,57). This technique is more suitable for the production of parts with intricate and complex internal shapes (83). This technique has been used in the fabrication of FRPCs, varying from particles to continuous fibrous form. The fibers are reinforced with thermoplastic liquid crystalline polymers in the particulate or continuous form and fabricated through the use of the FFF technique (78,84,85). Even hemp and harakeke FRPCs are also fabricated using this method (86).

This method is also convenient for short FRPCs, due to their extrusion without the need for an extra layer. This technique has gained a reputation due to its reliable nature, harmless and effortless fabrication, low-priced feedstock material, and its accommodation of a range of thermo-plastics as a feedstock for building structures (77). These materials are environmentally stable and part accuracy can be obtained (87). Major elements of the process are presented in Figure 4 (26). The technique permits multi-faceted contour modelling with flexibility in design, unattainable with conventional industrialized methods. This technique is shown in Figure 5 (44). In this LBL fashion, the print head spills out the material, distinct for a particular plane, transports its Z axis, and the process is repeated (69,70). The support structures, predominantly using solvents, can enhance the potentiality and develop the surface roughness (77–80).

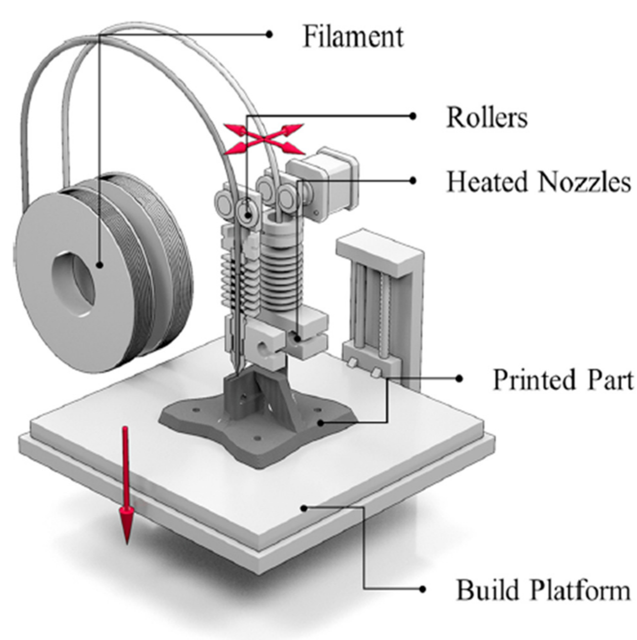

Figure 4: Scheme of FFF using two materials (26).

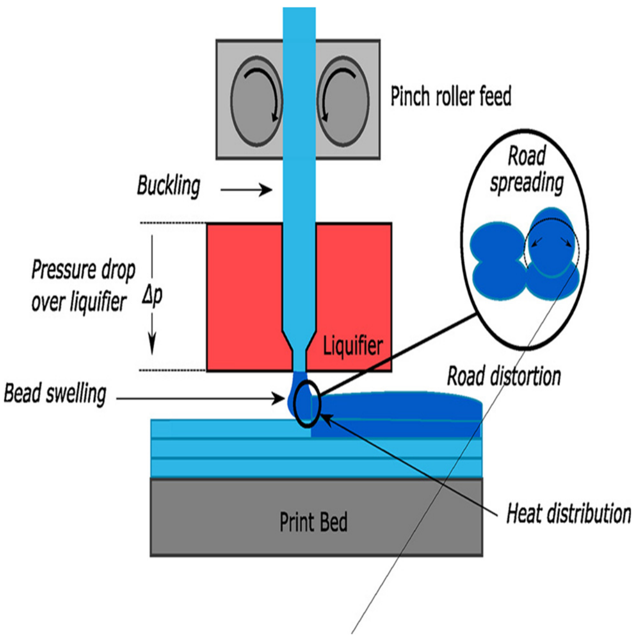

Figure 5: Key elements of the FFF process (44).

It is a fully customizable printer with various key parts of the equipment such as the extrusion head, framework, build platform, and build location. The process is based on a compact extruder, with variations in material devouring mechanism, and types of extruders and nozzle. The 3D movement of the head and printer bed depends on the lead drive and belt mechanism. The printer bed performs a vertical movement while the head moves in other directions. The built plate is covered underneath with a bed consisting of an embedded resistor. The plate gets heated up with electricity, and while passing through the resistor, the power is dissipated in the form of heat due to the Joule effect. This is the control system consisting of all-electric components, performed through the Arduino (88,89).

4.1.1 Fabrication process

Composite material in the form of filament is used as a feedstock to the system for designing a part in this technique. The initial feedstock materials are in three states as solid (in the form of pellets, wire, and laminate), liquid, and powder. The feedstock material should be flexible, stiff, viscous, and conductive in nature, for obtaining a pre-requisite of an effective model. Initially, FFF was used to fabricate parts, majorly made up of elastomers, ABS, and wax. The property of the thermoplastic material is needed as it is heated at nozzle temperatures up to a semi-liquid state and extruded. Quick slice software is used in the determination of the precise volume of ingredients and can be used by the CAD prototypical volume (79). The volume of fibers required is determined by the size of the CAD model. The constituents of composite materials like matrix and reinforcement are calculated using the relationship below:

$$W_{\text{composite}} = \frac{W_{\text{Matrix}} + W_{\text{reinforcement}}}{[1 - (W_{\text{plasticizer}}\% + W_{\text{surfactants}}\%)]} \quad (1)$$

where $W_{\text{composite}}$, W_{Matrix}, and $W_{\text{reinforcement}}$ are the weight of the composite material, matrix, and reinforcement. $W_{\text{Plasticizer}}$ and $W_{\text{Surfactants}}$ are the wt% of plasticizer and surfactant. In the combination, an insignificant % of plasticizer and surfactant are added for better flow, scattering, and robustness of the composites. The purpose of the softening agent is to reduce inter-molecular friction between the polymer matrix molecules. The purpose of the surfactant is to disperse the reinforcement in the polymer matrix for obtaining a homogenous mixture. The surfactant precipitate is dusted on the nano-particles to decrease the elevated energy. The coated nano-particles can give an upright link to the lower energy surfaces of polymeric particles (90).

The filaments depleted in this process should have accuracy in size and moderate strength. A screw type extruder is the most preferred type for extrusion of feedstock filaments for FFF. Its significant benefits include cost-effectiveness, simplicity, reliability, ruggedness, and favorable performance (91). The filaments are stored in the feedstock container and supplied to the system which is controlled by the computer program. The particular manufacturing devices use their peculiar software and processing for the input data. Despite the diverse producers, these programs have identical distinguishing features such as layer resolution setting, model, and density of the support material, and STL processing to layer mode (92). Representation of process is presented in Figure 6 (74). The materials used for process are steel, titanium, aluminum, and their alloys, nickel-based super alloys, Co, Cr and other numerous metallic as well as polymeric materials (73). An overview of the materials used for fabrication in this process is provided in Table 2.

4.1.2 Process parameters

The parameters to be considered for fabricating quality parts are: (i) fill pattern, (ii) air gap between the layers, (iii) slice or layer thickness: increment in the layer thickness tends for stimulation of the enhanced impact strength. Shear stress decreases with increase in the layer thickness, (iv) nozzle diameter, (v) regulation in the amount of

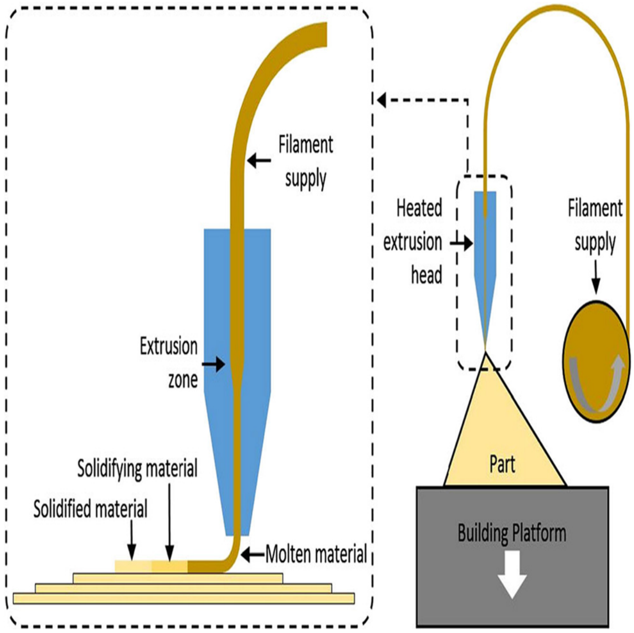

Figure 6: Schematic representation of FFF (74).

plasticizer, (vi) the orientation of the filament or build orientation: it affects the impact resistance with an incredible anisotropy property of the material. Resistance to the load is seen when the load applied is parallel to the adjacent layers. The sample breaks when the load applied is perpendicular to the adjacent layers. Optimization of this parameter can help increase the mechanical strength of thermo-plastic AM parts fabricated with the use of conventional methods, which are inherently poor. (vii) Printing time: it is based on the build orientation, layer thickness, type of fiber-reinforced and fiber volume content. The duration varies according to the type of edges like flat or curved. The thickness of the layer has a noteworthy effect on the printing process, since the sum of the layers is proportional to the thickness as well as printing time (75,76). The effects of process parameters on tensile strength, Young's modulus, yield strength, ductility, and toughness of carbon fiber reinforced composites are evaluated and the raster angle, infill speed, layer thickness, and nozzle temperature are considered as major process parameters (93).

There are four major types of printers used based on the material extrusion system include cartesian, polar, delta, and robot hand type (Figure 7). In the cartesian 3D printer, the movement of the extruder depends on the general cartesian coordinate system, also labelled by the *x*, *y*, *z* axes along the three conventional degrees of freedom (94,95). The major drawback of this system lies in its lower mechanical strength, layering in one constant building direction. In a polar 3D printer, the movement is in the direction of the polar coordinate system. This type has a movable head of predetermined length and angle between the points drawing apart. The delta 3D printer is initiated from the pick and place application. Its use is found in minimizing production time by moving the printer head fast. Robot hand 3D printer is used mainly for enhancement in production. It can produce a large number of complex structures, due to its flexible nature. The printer head is attached to the robot arms (94,95).

4.2 VAT polymerization/SLA

It was the first emerged method of AM in the late 1980s developed by Charles Hull of 3D System Inc. (1,10). This technique is also known as SLA (10,14,16). The basic principle is the initiation of photons where monomers are divided into a number of molecules (2). It is adaptable due to its freedom in designing a structure and to scaling. The design structure varies from the size of the sub-micron level to the decametric level (96,97). The most commonly used materials are liquid photo-curable resin and acrylate (82,98,99). FRPCs are primed using both continuous and discontinuous nanoscale as well as microscale fibers through the SLA process (98). A few examples in this category include glass fiber, alumina powder, silicon carbide, titanium carbide, ferromagnetic fibers, bio-glass, graphene, and silicate oxides. The most common matrices used for fabrication include epoxy, polyester, and photo-sensitive polyacrylate resins (52,98,100).

4.2.1 Fabrication process

This process begins with the CAD file through a mathematical equation or from scanning data of imaging technologies like magnetic resonance imaging or computer tomography scanning. The STL file format consists of local coordinates for the creation of the surface of the intended 3D model (1,5). The parts are sliced into a number of layers, and the information is fed into the SLA apparatus. The layer pattern projected on the resin is filled at the computer-building stage, either by a laser beam or digital light projection. The layer is solidified by photo-polymerization by ultraviolet (UV) light. The elevator table is just underneath the liquefied surface whose intensity is a light absorption limit of the polymer and then the elevator table drops in the user's specific distance underneath. Like digital light processing (DLP), the resins/ink used for printing are photo-curable and reactive diluent materials, which require careful selection to ensure effective printing. However,

Table 2: Overview of material used for different AM fabrication process

AM process	Composite materials	Outcomes	Observation	Ref.
FFF	Carbon fiber into ABS plastic	Measurement of tensile strength, yield strength, ductility, and Young's modulus	Carbon fiber reinforced ABS showed enhanced tensile strength and Young's modulus with reduced toughness, yield strength, and ductility compared to neat ABS film	(70)
	Thermotropic liquid crystalline polymer and fiber	Measurement of tensile properties	The modified composite's tensile modulus is four times greater than ABS with greater functionality	(78)
	Polylactic acid and tricalcium phosphate	Measurement of mechanical properties	Nozzle temperature becomes the factor of mechanical property of the product	(77)
	ABS with CNTs	Measurement of dimensional stability	Environmentally stable, better functionality application, biocompatible	(129)
	ABS with copper and iron particle	Measurement of mechanical and thermal properties	Stronger metal-polymer bonds, improved thermal properties, higher mechanical strength on AM products	(79)
	Polyamide (nylon type) with iron particle	Measurement of tensile properties	The tensile elongation is based on the content of the nanoparticle	(90)
	Continuous glass, carbon, and kevlar reinforced nylon composites	Measurement of impact strength	Impact performance of the autoclave manufactured materials are better compared to the 3D printed carbon fiber reinforced composite materials	(75)
	Continuous glass, carbon, and kevlar fibers reinforced nylon composites	Measurement of shear properties	Inter-laminar shear strength decreases with layer thickness due to higher porosity nature	(76)
SLA	Acrylic ester photopolymer with CNTs	Measurement of electrical, electronic, and printability of 3D printed parts	Microwave absorption, printability, electro-magnetic properties measurements provide positive connection and concentration of CNTs, representing improvement of absorption performance with increasing filler concentration	(82)
	Short glass fibers with urethane acrylic based photo-polymer	Measurement of tensile properties	Fiber-reinforced material yields higher elastic and ultimate tensile strength. The amount of shrinkage obtained by the reinforced samples during post curing will be lesser than non-reinforced counterparts	(98)
	Synthesized graphene oxide with ABS	Measurement of physical and thermo-mechanical properties	Decrease in pore size of the resin with increased annealing temperature. SLA is capable of producing nano-composites with sophisticated structures with good thermo-mechanical properties compared with the traditional casting methods	(96)
	Photocrosslinkable poly(e-caprolactone) resin with bioactive glass	Measurement of compressive properties	Adverse polymer layer covering the bioactive glass particles on the scaffold surface can be successfully avoided through SLA. Addition of BG enhances compression modulus of the scaffolds which is a desired property on bone applications	(99)
	Combination of nano-silicon dioxide, montmorillonite, and attapulgite with SLA resin	Measurement of tensile properties	Due to inadequate mechanical properties and inaccuracy of SLA, nano-fillers are used to enhance the young's modulus of SLA. The organic modified nano-SiO_2 shows escalation tensile strength. Nano-silica dioxide is a best reinforcement for SLA among three varieties of considered nanoparticles	(98)
Direct writing	Polyamine-polyallylamine hydrochloride (PHA) and polyacrylic acid (PAA) sodium salt	Measurement of mechanical properties	Linear backbone along with ionizable group is distributed uniformly that has direct effect on mechanical property of the product, adoptable ladder like architecture during complex structural form printing	(106)
SLS	Zirconia and alumina-based ceramics	Measurement of various properties like mechanical, thermal and electrical properties	Enhanced the properties of ceramics by inclusion of nano-filler and crack free material	(130,131)

(Continued)

Table 2: *Continued*

AM process	Composite materials	Outcomes	Observation	Ref.
	Nylon-12 powder (polyamide) and carbon black	Measurement of mechanical properties	SLS-based part shows higher strength and modulus compared to parts formed conventionally. The neat sample had high impact strength than blend due to agglomeration of particle. Even flexural modulus is less might be an indication of imperfect bonding between successive SLS layers	(117,119)
	Polyamide 12 with CNTs	Measurement of optical and mechanical properties	Density of neat is varied from density of blend due to the laser absorption capacity of particle and also its powder morphology to be optimized in order to enhance mechanical property	(119)
	High density polyethylene (HDPE) with hydroxyapatite (HA)	Measurement of bonding strength	HA ceramics bonds with bone, when it combines with binding polymer, it forms a bioactive composite. The laser power and scanning speed affects the property of composites' bioactive nature	(98,120)
	Polyether ketone (PEK) and HP3 PEK	Measurement of recyclability and mechanical properties	PEK always requires high preheating temperature. HP3 PEK powder is specifically manufactured for the use of AM. Reuse of PEK powder seems to be possible with slightly compromising mechanical property	(120)
Binder jetting	Stainless steel	—	Application of bone scaffolds	(29)
	Crystalline ceramic alumina powder encapsulated with amorphous alumina particle	Measurement of physical properties	Encapsulation enhanced powder sintering ability and compressive strength. Density of parts has direct influence over the mechanism property of the material and sintering also plays a vital role in the density	(132)
	Titanium alloy Ti-6Al-4V (Ti64)	Measurement of physical properties	Density throughout the part after sintering shows non-uniformity due to the interaction of binder with powder bed and nature of powder	(123)

there are significant variations in the composition of resin/ink for both SLA and DLP and therefore, comparing both processes is found to be difficult according to studies (15).

The LBL of the parts is fabricated to form a 3D object through polymerization at room temperature. SLA parts are built with the use of two methods: (i) bottom-up fashion, and (ii) top-down fashion. In both approaches, the parts are common, which include a reservoir filled with liquid photo-curable resin, a source of light, either a controlled laser beam for a bottom-up approach or digital light for a top-down approach. The system controls the horizontal and vertical movement of a light beam, building a support platform. In the case of a bottom-up approach, support platform structures rest below the resin layer. The thin layer is irradiated from overhead and treated on the

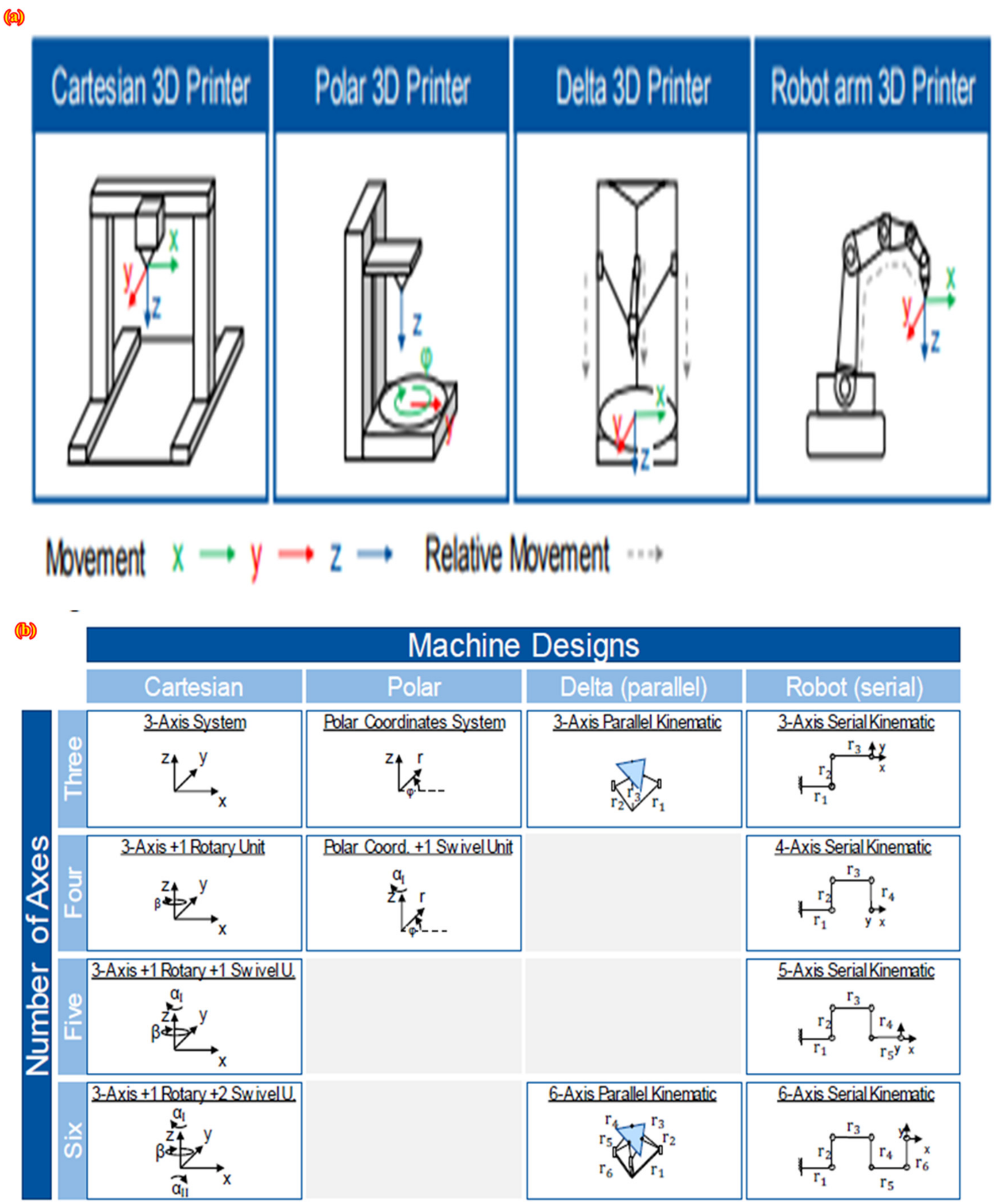

Figure 7: (a) Types of printers based on the extrusion system; and (b) classification of printers based on the number of axes (94).

topmost of the surface built as is usual in an LBL manner. Whereas, in the case of a top-down approach, the digital light is projected from the bottom of the surface to illuminate the resin. Various optical devices such as digital mirror devices and LCDs are used in the projection of light. The process of SLA is given in Figure 8. The materials used for fabrication in the SLA process are listed in Table 2.

4.2.2 Process parameters

Tailoring the process parameters according to the requirement plays a major role in deciding the quality of the final product obtained. AM is considered to be a flexible manufacturing technique that can render customized products as per the need. Understanding the process parameters involved in AM technologies plays a vital role in the same. Shrinkage in both the horizontal and transverse direction of the material is the work of laser power and pitch. Shrinkage changes with variations in laser power and layer pitch. Intensification of the laser unveiling density, and subsiding the pitch, helps upgradation of the load-bearing property of the finished FRPC component (98). The intensity of the light source has influence and control over shrinkage, e.g., acrylate structure, photo-initiator, curing kinetics, internal stresses, etc. In this process, the parameters such as exposure time, layer thickness, and time span between two consecutive exposures, printing structures, slicing methods, etc., have a significant influence on the surface roughness, printing accuracy, and mechanical properties of the additively manufactured composite parts (102). The other parameters that include warpage, light source, wavelength of light and their intensity also have effect on the printing process of SLA than DLP (15).

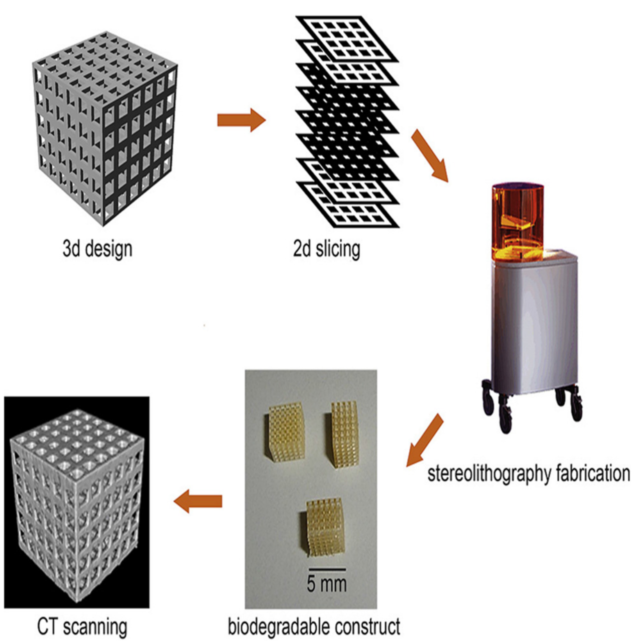

Figure 8: Process of SLA (101).

4.3 Direct writing

Direct writing technique, well-known as direct ink writing robocasting or 3D plotting (16,103), finds use for conductive inks, printing of bio-materials, and various composites (14,104–106). It is a method that comprehends a computer-assisted transformation stage transporting ink build-up nozzle for designing a material with well-ordered structural design and constitution (107). It is a powerful way to create a 3D micro-scale structure of subjective design and functionality. It uses viscous ink as feedstock materials which are composed of materials containing ceramics particles, metal particles, polyelectrolytes, hydrogel, polymeric, and extracellular matrices (108). For active polyelectrodes used biologically, electrically, or optically, various ink compositions with polyelectrolyte mixture are used (108). Multi-material 3D printing using micro-fluidic print heads has the ability to switch rapidly between multiple inks with the same single nozzle print heads which has the advantages of tool path planning and programmable assembly of functional materials (109). The scheme of the direct writing process is depicted in Figure 9 (26).

4.3.1 Fabrication process

A CAD model using various derivatives is required for the building of a model in direct writing. A liquid feedstock material or slurry or hydrogel is stored in the container of the syringe. The computer-controlled syringe applies the required mechanical or pneumatic pressure for the extrusion of the feedstock solution. The extruded solution gets deposited on the building platform in an LBL manner. The extrusion of feedstock is a bit difficult, due to the absence of any heating or solidification involved. The ink solidifies through the use of various mechanisms like visco-elastic recoil, reservoir coagulation, repulsive force suppression, UV polymerization, post-fabrication heating, and using reactive feedstock (99). Bio-active glass-hydroxyapatite, calcium phosphate, calcium sulphate, hydroxyapatite-TCP, TCP-silicon dioxide, calcium phosphate-collagen, Vaseline-titanium dioxide, CNTs with gellan and xanthan, poly(2-methaoxyaniline-5-sulfonic acid) with CNT, polymers and quantum dots, polymers with CdSe/ZnS and quantum dots are some of the combinations of the direct writing process materials. An overview of the materials used for fabrication using the direct writing process is provided in Table 2.

4.3.2 Process parameters

The following parameters are considered in the manufacture of quality parts by using the direct writing process. (i) Feedstock property: the solution must have specific fluid properties like ink rheological and visco-elastic properties. (ii) Visco-elastic property: the viscosity maintained should be from low to moderate since the solution needs extrusion through the capillary micro-nozzle under applied pressure. This property is also determined by varying polymer concentration, flow behavior, and the rigidity of the extruded filament. There are two cases based on the viscous nature. Case 1: when the fluid is highly viscous in nature, higher nozzle pressure is needed for extrusion. Case 2: when the fluid is low viscous in nature, lower nozzle pressure is required, as it flows easily through the nozzle but requires more time to dry (110).

4.4 Big area AM

Industrial-scale parts from thermoplastic and thermoset polymers can be processed at an excessive rate. This method helps to print larger components in large numbers with a low processing cost (111). The deposition head of the big area AM (BAAM) setup has the capacity to move at 12.7 $cm \cdot s^{-1}$. It is an extrusion-based method for thermoplastics and their composites, similar to customizing a material in the pellet form. The build quantity and print integration have greater orders of magnitude than the FFF units. This method is based on a screw-type conveyor system, enabling the direct feeding of material and converting it into filaments (Figure 10). This AM technology exploits nozzle diameters from 5.1 to 7.6 mm and allows 25–50 $kg \cdot h^{-1}$ deposition rate (112,113). Extensive reactive extrusion procedures enable the AM of thermoset composites, at higher rates than BAAM (112,114,115). The deposited material is cross-linked during the process and confirms the formation of strong bonding at the interface (110,116).

4.5 SLS

It is one of the promising methods of building AM parts by LBL using powder laser sintering materials with the help of a radiant heater and computer-controlled laser. It is also known as laser bed manufacturing or powder bed manufacturing (14,16). Polyamides are used as laser sintering material (10,117,118). The powder is fused with a laser beam or binder whereas a laser is used with a lower melting/sintering temperature of powder, otherwise, binder is used. SLS is suitable for polymer, metal, and alloy powder while SLM is mostly suited for metals like steel and aluminum than composites (22).

4.5.1 Fabrication process

In the same way as other techniques, the process starts with a CAD replica of the parts built LBL at distinct intervals of time. The model is sliced into a number of layers,

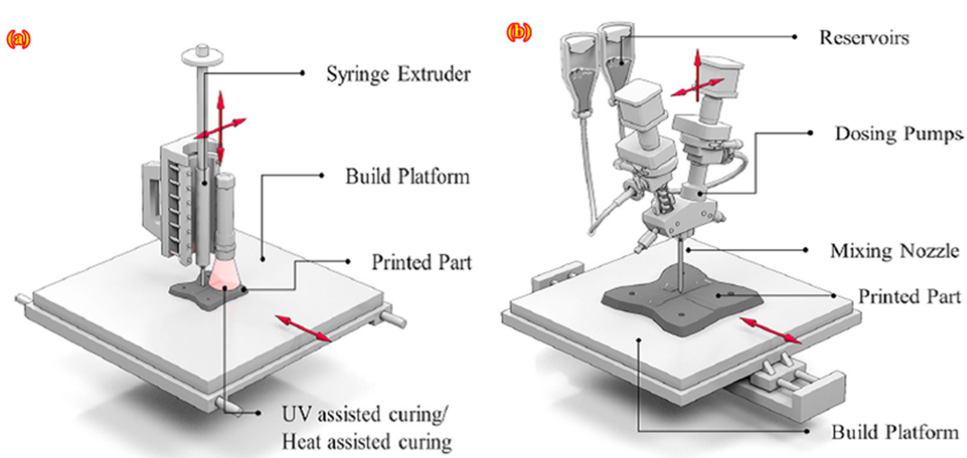

Figure 9: Schematic representation of 3D printer: (a) direct write; and (b) reactive extrusion (26).

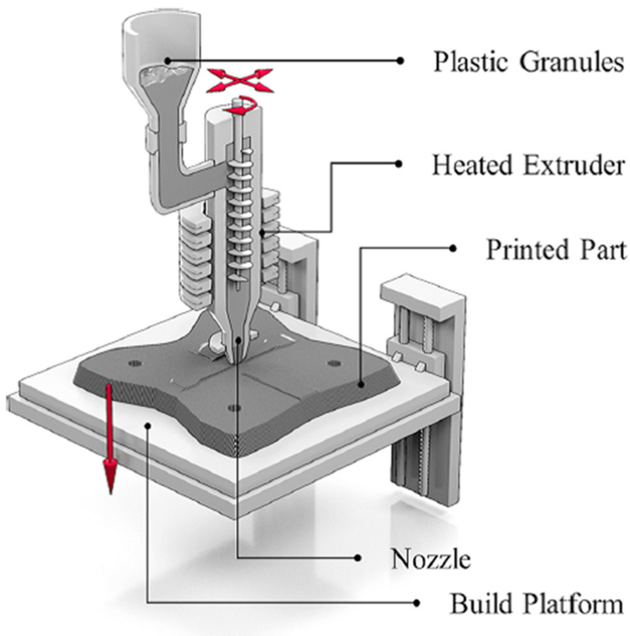

Figure 10: High-throughput BAAM extruder (26).

then the sliced layers are scanned onto a pre-heated powder bed. Very fine loose powder is spread and closely packed onto the build platform in a chamber filled with inert gas (10,16). The powder bed is pre-heated for a reduction in cracking, warpage, and fine surface finishing. When the powder is exposed to the scanning carbon dioxide laser of a high beam, it increases the temperature of the powder surface and solidifies a layer. Once the layer is printed, the bed is sunk by a gap identical to the carved layer thickness. Further layers of residue are accumulated by the roller mechanism and the newly laid layer is exposed. The laser and powder interaction generates enough heat to fuse the layers and to form a solid object or by sintering LBL, the entire part is fabricated. Then, the generated parts are kept in the cooling chamber at ambient atmosphere and residual loose powders are removed by vacuum, while processing (117,119,120). Not all polymers are used as laser sintering materials, since they do not meet with indispensable mechanical, electrical, and thermal properties (117,119–121). A wide range of polycarbonate, polyvinylchloride, ABS, nylon, polyester, polypropylene, polyurethane, and wax are used. The use of nano-sized particles/fillers in the improvement of the property of polymer is seen in recent times and the details are shown in Table 2.

4.5.2 Process parameters

The following are the parameters affecting the various properties of parts: (i) laser power: it affects the morphology of the structure. The fusion of the particles is increased with increasing laser power. The greater the energy imparted, the higher the particle fusion. As laser power increases, there is a substantial increase in particle fusion. The boundaries between particles become indistinguishable and larger voids occur. The polymer degrades gradually or vaporizes. As it vaporizes, the air trapped inside is released, and this leads to elevated temperature, an exothermic reaction, developing local burns. (ii) Scan speed: it has a considerable effect on the height of the particular sintered layer at the scanning speed ranges of 300–800 $mm{\cdot}s^{-1}$. Longer interaction time directly leads to a longer period of particle interaction and fusion. It is a high-energy absorption process and sets the way for the degradation of powder even in the oxygen-less environment at a higher scanning speed of about 4,800 $mm{\cdot}s^{-1}$. It provides a short interaction and the particles do not have sufficient time to interact. It is always better to use a moderate scanning speed, of around 1,200 $mm{\cdot}s^{-1}$ (94), (iii) Scanning space and pattern: small scan spacing and parallel pattern, (iv) laser beam size: LBL fashion is more suitable and the influence on properties is rather small, (v) temperature set point of parts: high for better finishing, (vi) powder feed temperature: properties increase with the increase in feed temperature, (vii) roller speed: medium to high is preferable, vii) powder layer thickness: as thin as possible; and (viii) powder size and shape: excess heat will damage the powder size and shape which has the least influence (122).

4.6 Binder jetting

Binder jetting process is the commonly used method for the manufacture of composite parts. It does not require any specific setup like an enclosed thermal chamber and laser beam, or energy beam for processing the material (110). In binder jetting, an inkjet printer is used for printing the binder. The materials used for the construction of parts are ceramics, metals, shape memory alloys, aluminum oxide, and alumina-silica ceramic powder (16,29,123,124). In recent days, binder jetting is the major process, often used for framing metal parts, micro-lattice, and nano-lattice structures (119,124,125).

4.6.1 Fabrication process

As per the CAD model of sliced layer format onto a powder bed, the platform moves evaporating moisture and getting the binding material to dry. The powder bed is pre-heated and the temperature is measured using a thermocouple.

It is motionless and covers the devouring chamber filled with the powder. Even the temperature can be amplified by a light source; values are monitored by a data acquisition device in the computer, and recorded in the LabVIEW environment (3,29,126,127). Precise consideration of drying part is imperative and can be done by spreading the binder deeper into the first layer. Following the completion of one layer, a fresh layer is recoated on top of it. The addition of one layer at a time and a binder to translate the model data to a 3D object is done. It is mandatory to evaluate the geometrical fidelity of the binder jetting prior to the process. It includes layer thickness, bestowing frequency of the binder as the regulating factor (119,123–125). In the binder jetting, a droplet of the binder is laid over the powder bed, partly shaped with the addition, gluing powder particles. The development of the part is trailed by dropping the power bed support, and a new layer is created. Careful handling is necessary for avoiding breakage and is allowed to cure the binder. The curing temperature is based on the type of binder used. Then, the parts are sintered in a heating chamber, where 99% of it is consolidated and shrinkage occurs up to 25% in most cases. It has been a big challenge in the binder jetting process (128).

4.6.2 Process parameters

The consistency of the binder jetting components is greatly influenced by parameters like the thickness of the layer, powder shape and size, distribution pattern, drop volume, binding materials' viscosity and saturation temperature, print head speed, number of layers printed, spraying velocity, drying speed, curing time, number of base layers, etc. Usage of powder mixtures shows enhanced parts properties, strength, and less shrinkage after sintering. Residual loose powder is removed after printing through the compressor (119). Based on the material used, the consolidation mechanism is classified as (i) solid-state sintering, (ii) full melting, (iii) melting at different phases, (iv) liquid-phase sintering, and (v) chemical binding. An overview of the material used for fabrication is given in Table 2.

4.7 Properties of additively manufactured FRPCs

Industrialization has been done for bracing manufacturers and designers through the entire product or process design for the evaluation of the characteristics and properties of the product (8). Properties of AM products can be increased with the addition of various reinforcements. Most of the AM polymer components are used as hypothetical models rather than as function-based modules since the products manufactured by AM have deficient strength (33). The properties of the additively manufactured FRPCs match those of ubiquitous, denser structural metals, and these properties show nearly isotropic behavior (49). Depending on the affinity, fibers with different structures can be mixed with different matrix materials, thereby creating stronger parts with improved mechanical properties. Parameters like raster angle, infill speed, layer thickness, and nozzle temperature also have a big influence on the properties of FRPC products. A combination of polyhydroxyalkanoate (PHA) matrix, recycled wood fibers, and polylactic acid (PLA) was tried by some researchers for property improvement of the composites.

AM process has the problem of void formation between the deposition lines, which turns out to be favorable for the acoustic characteristics since the pores and voids readily absorb the sound waves (133). Experimental work was carried out on synthetic and plant fibers reinforced hybrid PLA composites fabricated by using a 3D printing process in accordance with ASTM D638. The extrusion and direct deposition method exhibited greater tensile strength insignificantly, representing the feasibility of fabricating through AM (28). The promising prospect of the specimen strength is the effect of direct tensile loading on consistent fibers, which sustains this intensity, despite the trials not having process defects. Composite materials should be bonded properly at the interface for good performance. This plays a major role in the properties of FRPCs as it transfers load from the matrix to the reinforcing fibers and induces stress transfer between them. Good bonding at the interfacial region yields higher mechanical strength and stiffness while poor bonding provides lower strength and stiffness (134). The desired interfacial bonding in the 3D printing of FRPCs was achieved through the reinforcement of continuous fibers with PLA, which resulted in significant improvement in tensile and flexural strength (135).

The properties of wood-based composites are influenced by the printing width, and their microstructure is modified. Mechanical properties are seen as considerably lower than the samples prepared by the compression molding process, due to weak inter-laminar bonding (136). Foaming and fiber pre-stressing are feasible techniques for finding the density reduction and improvement in the mechanical strength of bio-based polymers. These utilize the intrinsically high stiffness and strength of plant fibers in the production of composites with superior performance (137). This has been elaborated as a bio-printed peptide, chemically united with sodium alginate scaffold for exterior tissue engineering applications (138).

The mechanical properties of carbon fibers and ABS composites fabricated by using the AM process were evaluated by Ning *et al.* (139). They found that the performance of a composite with 150 μm fiber length in terms of tensile strength, Young's modulus, toughness, and ductility was superior compared to a composite with 100 μm fiber length. Carbon fibers were reinforced with PLA and the composites were fabricated using the material extrusion AM process (140). The mechanical properties and microstructure of these composites were evaluated and no significant effect was seen on their mechanical properties. A study of the mechanical and thermal properties of carbon fiber-reinforced polyamide-12 composites fabricated by using the FDM process was made (141). The results showed the greatest improvement in thermal conductivity of the composites compared to neat polyamide-12 composites. Zhong *et al.* prepared carbon fiber-reinforced ABS composites and examined their properties (85). Results showed a significant increase in the strength and hardness of the composites.

The inter-laminar shear strength (ILSS) of 3D printed composite samples in regard to layer thickness and fiber volume content was examined by Caminero *et al.* (76). They found an increase in ILSS with increasing fiber content and better ILSS in the carbon fiber-reinforced composites than Kevlar fiber-reinforced composites. Chung and Das (142) fabricated glass fibers reinforced nylon composites using SLS and performed theoretical modelling, numerical analysis, and experimental investigation. Results showed that the glass fibers enhanced the strength of the composites considerably. Experimental analysis on glass and carbon fibers reinforced hybrid polymer composites fabricated by UV-3D printing was conducted (143). The results showed improvement in mechanical and thermal properties. Assessment of micro-structural characteristics, tensile, flexural, and quasi-static indentation characteristics of the carbon and glass fiber reinforced hybrid composites fabricated by FFF was made and a considerable increase in the above-mentioned characteristics was found (144).

Continuous jute and carbon fiber-reinforced PLA composites were fabricated and their properties were studied (145). The study showed a significant improvement in tensile strength compared to the results of polymer composites made with the use of conventional methods. The wear studies of Al_2O_3-incorporated nylon-based composites made by FFF were analyzed (146). The results showed the addition of Al_2O_3 with the nylon matrix causing an increase in the wear resistance of the materials. The compatibility of AlCuFeB nanoparticles as filler materials in the composites made up of SLS was investigated by Kenzari *et al.* (147). The results showed the produced parts had low friction and wear characteristics compared to other composites. The results further revealed the parts as porosity-free filler materials enhancing applications of the composites. Aluminum/ABS, aluminum/polyamide-6, and carbon fiber reinforced layered hybrid composites were prepared through the use of the add-joining process and their mechanical properties were studied (148). The results showed that the mechanical properties of the add-joining composite parts were comparable to the parts produced with conventional process.

4.8 Characterization of 3D printed composites

Additively manufactured FRP composites were usually characterized by various techniques to analyze their failure modes, gain structural information regarding the internal microstructure, the fracture behavior of the additively manufactured composites under various loading conditions, and fracture crack propagation to understand the internal characteristics of the 3D printed component. Numerous methods including optical microscopy, scanning electron microscopy (SEM), X-ray tomography, and transmission electron microscopy (TEM) are used for the structure analysis (149,150). Few experimenters studied the mechanical properties of continuous carbon fiber-reinforced polyamide composites manufactured through the FDM technique. The 3D printed specimen, after being subjected to tensile and flexural tests, was examined using SEM to understand the fracture surface morphology. Specifically, SEM was used to identify the fracture mechanism which was observed to be dependent on the fiber volume fraction, print quality, and internal structure of the 3D-printed specimen. It was also observed from various micrographs that fiber pullout was predominant due to the good interfacial adhesion between fiber and matrix (151,152). Figure 11a and b shows the SEM image of continuous carbon fiber polyamide composites.

A few experiments were carried out by reinforcing basalt fiber reinforced PLA composites and additively manufactured using conventional FDM technique with unidirectional fiber orientation and alternative LBL orientation. 3D X-ray tomography was used to characterize the anisotropic fracture behavior of the composites. It was stated in the results of the characterization that the fracture behavior of the multiscale hierarchal microstructure formed a single macro-matrix from the micro-sized fibers embedded within the filaments. This clearly portrayed that the alteration in printing direction could bring significant changes in the mechanical properties of the composites (152–154). Figure 11c and d depict the tensile fracture morphology of 0° and 0°/90° basalt fiber reinforced composites. The red and blue region indicates various failure modes in

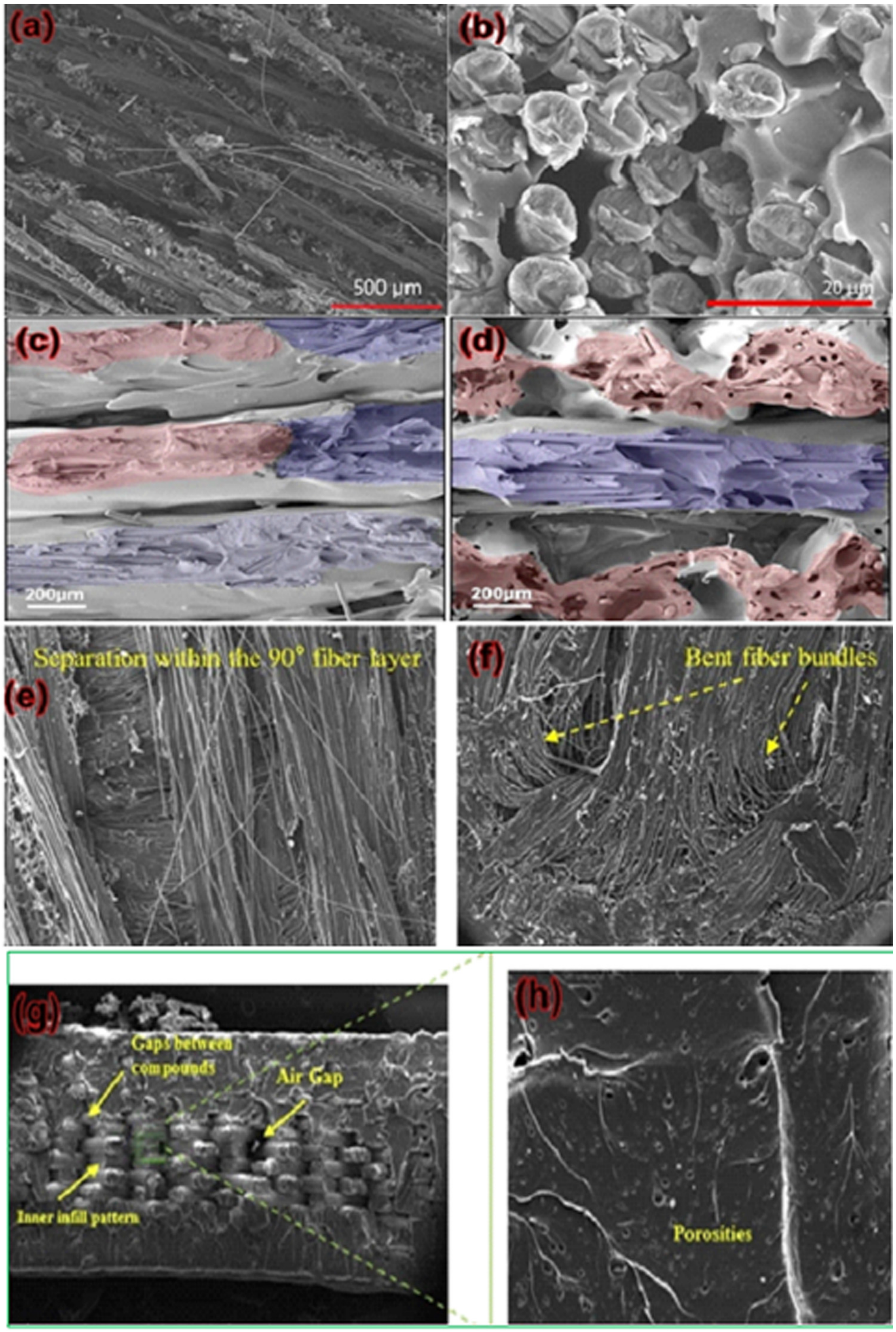

Figure 11: SEM images of 3D printed (a) and (b) carbon fiber reinforced polyamide composites (151), (c) and (d) basalt fiber reinforced composites (152), (e) and (f) interfacial characteristics of short carbon-reinforced polyamide composites (156), and (g) and (h) PLA and recycled PLA composites (159).

which the fiber and matrix have failed during tensile loading. Some other experiments focused on assessing the interfacial characteristics of short carbon fiber reinforced polyamide composites in various fiber orientation angles. The specimens were subjected to double cantilever beam and end notch bending tests and the fracture morphology was observed using the SEM technique. It was stated in the results that lower matrix content led to lower internal quality of the fiber bundle and low impregnation quality. It was also observed from the morphology that though the continuous filaments seem straight while printing, they appeared to be curved during the morphological analysis despite stable material stiffness (155,156). Figure 11e and f depict the SEM images of short carbon-reinforced polyamide composites and their interfacial characteristics.

Some other experiments were carried out by 3D printing of PLA and recycled PLA filaments and the specimens were subjected to mechanical property evaluation. Fracture surface morphology was analyzed using SEM and the results portrayed that PLA was subjected to some localized failures during loading due to its inherent brittleness which offered the roughness to the PLA filaments. Though some voids and air gaps were found in the morphology, the layer thickness was found to have higher influence over the mechanical properties of the composites (157–159). Figure 11g and h denotes the fracture surface morphology of 3D printed PLA and recycled PLA composites.

4.9 Process parameters-property relationships

The process parameters-property relationships of additively made FRPCs are explained in this section. The process parameters have a considerable impact on the properties of the composite parts. Most of the FRPC research works feature a significant number of mechanical tests on the maximization of the strength, modulus, and dimensional accuracy through variation in process parameters and employment of diverse design of experiments. Different process parameters such as build orientation, layer thickness, processing temperature, and printing speed were examined by several researchers (160). Chacón *et al.* (161) investigated the effect of build orientation, layer thickness, and fiber volume content on the mechanical performance of 3D printed continuous FRPCs fabricated with the use of the AM technique. Tensile and three-point bending tests were performed for the determination of the mechanical strength of the printed specimens. The influence of layer thickness on the mechanical performance of nylon samples was seen as marginally significant. Continuous FRPC samples have better strength and stiffness than unreinforced materials. Carbon fiber reinforced composites are known for the best mechanical performance, with higher stiffness, and flat samples have higher strength and stiffness values than on-edge samples, according to the findings. The results also showed increase in the strength and stiffness with the increase in fiber volume content, but the level of increase in mechanical performance is moderate with continual increase in fiber content, particularly in the case of kevlar and glass fibers, due to the weak bonding between the fiber/nylon layers as well as the presence of defects.

4.9.1 Influence of process parameters

The major influencing parameters in processing of composites through AM are raster angle, print speed, layer thickness, repeated heating and cooling, print platform temperature, infill speed, nozzle temperature, nozzle diameter, etc. Among these parameters, the raster angle, infill speed, layer thickness, and nozzle temperature need careful consideration during processing. Print and infill speeds control the volume of extruded filament and cross-sectional geometry of the specimen. Nozzle temperature has influence on fluidity and solidification of the extruded filament. The raster angle indicates the direction of printing regarding the longitudinal axis of the specimen. The raster angle and layer thickness have direct effects on mechanical properties such as Young's modulus, toughness, ductility, strength, etc., of the final product. In addition, post-processing methods can also influence the mechanical properties of the AM composite parts. The performance characteristics and interfaces of AM composite parts were analyzed through investigation of the effect of process parameters on pressure and temperature (162). The results showed the achievement of good impregnation of fibers and plastics, and improvement in bond strength by taking the layer thickness of 0.4–0.6 mm and hatch gap of 0.6 mm. The results further revealed the achievement of maximum flexural strength and modulus at 27% fiber content. The mechanical properties of parts fabricated with the use of conventional methods are inherently poor (163–166). Optimization of processing parameters such as build orientation, layer thickness, and feed rate has been investigated for improvement in the mechanical properties of the composite parts (167).

Figure 12a shows a rise in the tensile strength and elastic modulus rise and a subsequent fall with rise in printing temperature. Tensile strength increased by 4.5% and elastic modulus increased by 11% when the printing temperature raised from 200°C to 230°C. The tensile strength decreased by 1% and the elastic modulus fell by 3% when the printing temperature was increased from 230°C to 240°C. As a result of the printing temperature being too low or too high, the mechanical strength of the samples was not optimal. When the printing temperature was too low, the material did not melt, affecting the forming process of the sample. When the printing temperature was too high, the upper layer of material did not cool completely after melting, causing

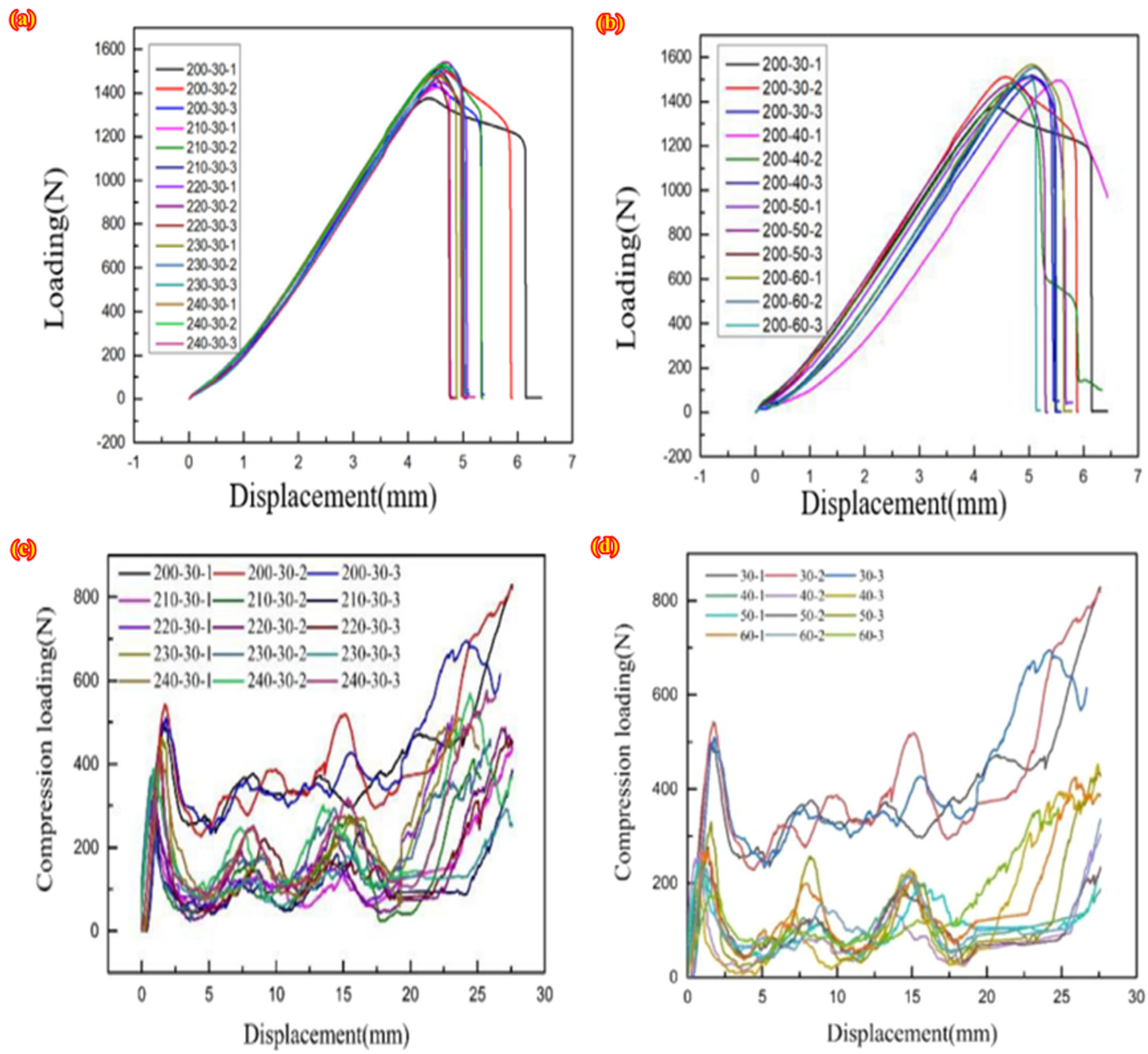

Figure 12: Load vs displacement curve represents effect of printing temperature and printing speed on (a) and (b) tensile strength, and (c) and (d) lattice structure (168).

errors in the forming process and decreasing the mechanical strength of the sample (168).

A rise in the tensile strength and elastic modulus was seen following the increase in the printing speed, according to the findings (Figure 12b). The highest tensile strength is 51 MPa, and the maximum elastic modulus was 5,100 MPa, with an average growth rate of 2.3% and 10.3% when printing at 60 mm·min^{-1} (168). The maximum load was 509 N, according to the load displacement curve, when displacement was loaded to 1.6 mm, and the load vs displacement curve was linear (Figure 12c). Following the displacement and increase in the linear elastic stage, the upper ring was deformed, and the lower ring experienced elastic deformation. The cell body deformed elastically when pressured. The cell wall collapsed quickly when the compression force approached the critical load for cell wall collapse. With an insignificant change in the load, there was a dramatic growth in displacement and the cell wall collapsed, resulting in a huge platform surface with good energy absorption. The load vs displacement curve for different printing speeds in Figure 12d shows a similar change trend to the load vs displacement curve for different printing temperatures in Figure 12c, which changed only at the maximum load and displacement at each stage. As a result, the conclusion drawn from the load vs displacement curve was comparable; hence no further explanation was required (168).

As previously stated, printing time is directly proportional to the manufacturing cost and likewise directly connected to the build orientation, as evidenced by the results reported earlier. The printing time for upright samples was the longest, while that for on-edge samples was the shortest. The primary process parameters that had the greatest impact on printing time were layer thickness and feed rate. A reduction in both on-edge and flat orientations, and printing time was seen following an increase in feed rate. However, for high feed rate values, printing time remained nearly constant, as explained in the case of the upright orientation (169).

4.9.2 Influence of build orientation

The mechanical properties, particularly ductility and failure behavior, had a strong impact on the build orientation. Tensile and flexural strengths and stiffness were the highest in on-edge and flat orientations, whereas they were the lowest in upright orientation. Inter-layer fusion bond failure and trans-layer failure are the two main failure types that can cause these disparities. The samples were pulled parallel to the layer deposition direction and the force was perpendicular to the fibers for upright orientation, resulting in inter-layer fusion bond failure. Inter-layer fusion bonds between neighboring layers or fibers, rather than the fibers themselves, survived the majority of the applied force in this scenario, layer or fiber-to-fiber adhesion had a substantial impact on tensile strength (169).

4.9.3 Influence of layer thickness

The number of layers required for printing an object and layer thickness is directly proportional to the printing time. Growth in layer thickness was seen, causing an increase in the printing time and yield of high production costs. The influence of layer thickness on mechanical properties due to build orientation was different for upright samples also on edge and flat samples. Better layer thickness appeared to create higher strength in upright samples (169). This impact can be explained by the fact that, as layer thickness increased, fewer layers were required for a given overall thickness, reducing the number of layer bonds and increasing strength. With the increase in the feed rate, this trend became more pronounced. In short, the results showed that, as layer thickness grew, tensile and flexural strengths increased in the upright orientation. Except in the case of low layer thickness, the variations in tensile and flexural strength were of minor consequence in on-edge and flat orientations. The response surface analysis graph in Figure 13 shows agreement with these findings (169).

4.9.4 Influence of feed rate

The change in ductility with the feed rate was more important than the fluctuations in tensile and flexural strengths in terms of ductile or brittle behavior of the samples. Increased feed rate resulted in a considerable reduction in printing time, with the implication of a fall in production cost following an increase in feed rate. The maximum tensile and flexural strength of the upright orientation sample dropped as the feed rate rose. Except in the case of high feed rate under tensile loading and two typical situations for on-edge oriented samples: tensile performance with feed rate of 20 $mm{\cdot}s^{-1}$ and flexural performance with feed rate of 80 $mm{\cdot}s^{-1}$ (169), the effect of feed rate on tensile and flexural strength was of minor significance in the case of on-edge and flat orientations. As the feed rate rose, the maximum tensile plastic strain at fracture fell, but to a lower extent than with increased layer thickness. With increased feed rate, the reduction in flexural strain at fracture was insignificant. In terms of stiffness, big variations in tensile and flexural moduli were seen depending on the feed rate. Finally, as the feed rate increased, tensile and flexural strength dropped in the upright orientation. Due to reduction in printing time, high feed rate values, with the need for avoiding in this circumstance.

4.10 Optimization of AM processes

Computational mechanics (CM) and deep neural networks (DNNs) are the optimization tools for solving several engineering problems. These tools have shown impressive results in areas such as visual recognition. There is great flexibility to define their structure and important advances in the architecture and the efficiency of the algorithms to implement them make DNNs a very interesting alternative to approximate the solution. In a research work, the mechanical problems are analyzed by Samaniego *et al.* (170) using CM and DNNs. They found that the energy of a mechanical system seems to be the natural loss function for a machine learning (ML) method to approach a mechanical problem. An opensource software, namely, PERMIX is used for modelling and simulation of fracture in parts manufactured through

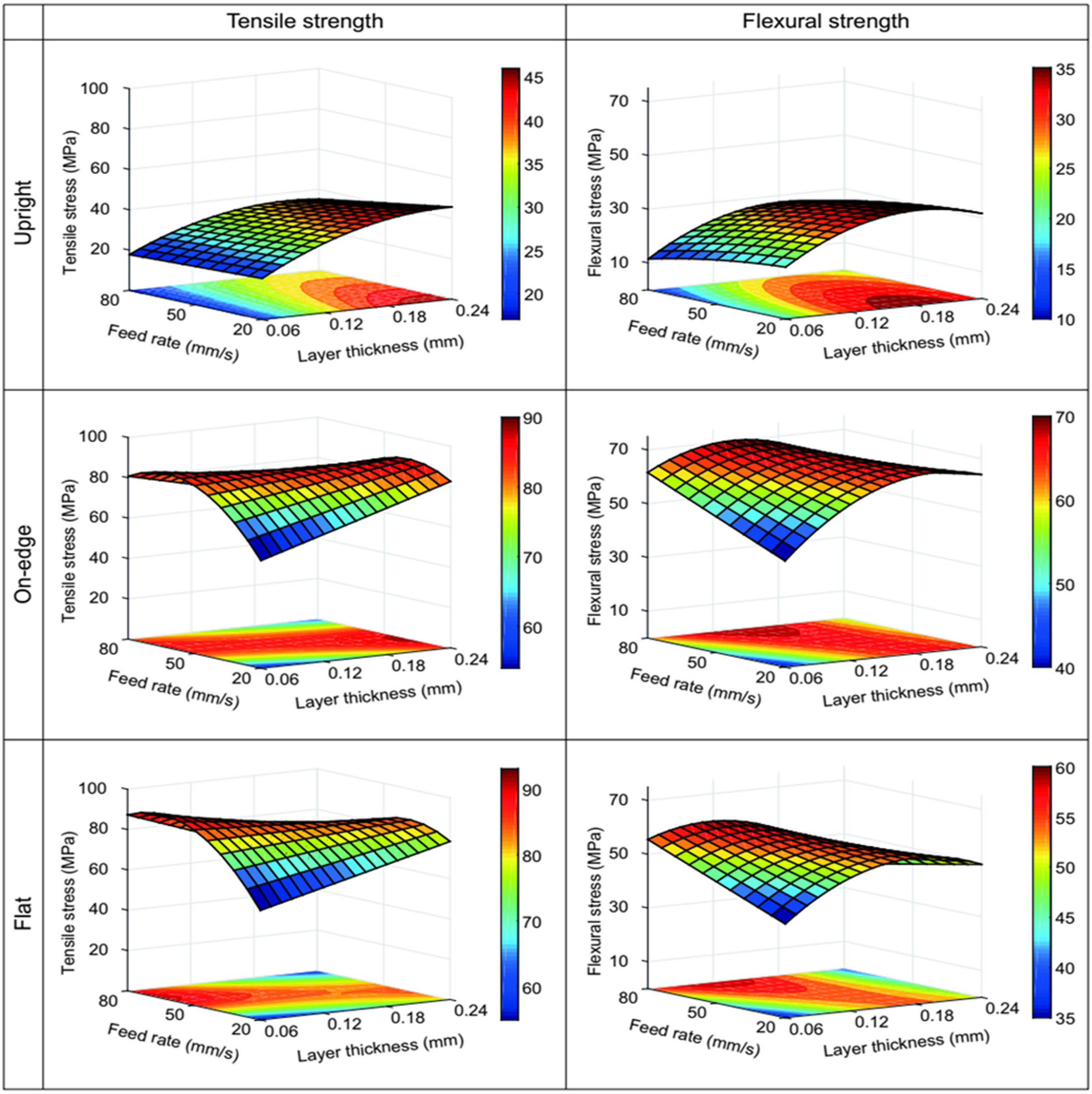

Figure 13: Response surface plots for mechanical properties (169).

AM process. The fracture in the part is modelled with the use of finite element method and the result showed that the efficiency of the developed software is good for modelling and crack propagation (171).

Among ML algorithms the neural network is most used model due to its computational power and sophisticated architecture. Convolutional neural network (CNN) as a deep learning (DL) tool has attracted the researchers due to its excellent performance in analyzing the image data. CNN for the prediction of part mass, support material mass, and build time of AM parts have been developed and found that the CNN was more accurate than the linear regression model for the prediction of the part metrics (172). The manufacturability of the designed part through AM have been checked with the use of CNN and obtained above 93% accuracy on results (173).

DL is a version of ML and used for any artificial neural network (ANN) with more hidden layers (174). A review has been conducted by Qi *et al.* (175) on the advantages of using neural network to the aspects of AM including part design, modelling, and quality evaluation. It is very difficult to maintain the quality of AM parts while neural network strongly relies on data collection. A novel ANN based optimization technique is used for the minimization in the geometric inaccuracies of the part produced through AM process. This method is used for the determination of optimal build orientation of the part with respect to part quality and manufacturability. Results showed significant improvement in the part's dimensional accuracy (176). ANN is used for the optimization of composite structure with the consideration of manufacturability to ensure the print quality of the part produced through AM. The result showed that the optimized composite structure can improve the stiffness of the model and the optimized design has been successfully implemented for the fabrication of parts through the AM process (177).

4.11 Comparison of AM processes

Material fabrication techniques are classified according to the form of the raw material such as powder, liquid, and solid. Some AM techniques use powder as a material with a single component and a combination of components with a binder. Liquids are used as raw material which needs solidification by melting, depositing, and resolidifying the material. These stages are followed by shape melting and ballistic particle manufacturing. Liquids are polymerized by a single frequency light in SLA, and thermal polymerization using heat. Solid-based raw materials are bound using grains by melting the components together in the interference melting, sheets are glued by LOM and also through foil polymerization (1). The comparative analysis of different AM processes is presented in Table 3.

4.12 4D printing

This section includes illustrations of some advances in 4D printing related to FRPCs exhibiting physical transformations of the printed pieces/structures. The main drawback of 3D printing is that the initial state of the printed structure is motionless and inert (189). A new-fangled concept called 4D printing was launched in 2013 to overcome this problem, allowing bioengineered paradigms to be pre-programmed for advancement in a specific way after lithography (190). 4D printing is the development of the construction of a touchable item using suitable AM technology, resting on the sequential layers of stimuli-responsive composite or multi-material with unreliable properties (191,192). 4D printing shows an amendment in product design and industrialized methods from stationary structures to vibrant structures like shape memory material with unified functionalities.

Unlike 3D technology, 4D printing has the capability of contour and functionality transformation when subjected to inherent/peripheral stimuli permitting an additional precise imitation of the dynamics of the instinctive tissues, based on the integration of smart bio-materials (193,194). The use of fibers has been seen in 4D printing while agreeing with additional strength for regulation and employment of variation in the shape or engorgement after 3D printing, instantaneously out of the printing bed (195). Moreover, as anticipated, 4D bio-printing or laser-supported bioprinting has currently emerged. 4D bio-printing is a specified extension of 3D bio-printing aiming at the reconstruction of the bio-chemical and bio-physical structure, as well as the ordered morphology of several tissues through the use of stimuli-responsive bio-materials and cells (196).

In 4D printing, accompanying properties are vital, and polymers or polymeric composites are used entirely in this technology. Subsequently, they are seen as extra miscellaneous in terms of both active shape-changing behavior and material designability (190). 4D printing is a new concept, there are limited technologies with appropriateness for printing flexible objects used in the manufacture of multi-material objects and created on accumulating curable liquid photo-polymers in a LBL fashion. SLM is used for generating metallic components. Lately, a technology appropriate for printing polymeric solutions termed direct write printing has been established for enabling 4D printing for bio-medical applications (110). As for 4D bio-printing, this technology has scarcely emerged, there are numerous important challenges seen in articulation such as (i) the 4D constructs involve synergy among cells and bio-ink; (ii) the cells requisite persist both the printing procedure and the stimuli essential for shape change, and (iii) the response competence of the 4D formulated paradigm must not be weakened by the insertion of cells (197). An assessment of the abovementioned lithography technologies is shown in Figure 14 (9).

5 Applications of AM polymer composite products

The usage of AM in various fields like aviation, bio-medical instrumentation, and electronics goods manufacturing increases day by day, as evidenced by Wohler's Report 2020. This has been proved through the data relating to money spent annually on

Table 3: Comparison of AM processes

Process	Commercial name	Merits	Demerits	Applications	Ref.
Material extrusion	Fused deposition modelling	• Well-known and efficient process • ABS plastic is used due to its advantageous structural properties and ease of accessibility • Effortless fabrication process • Multi-material usage feature • Various dimensional print heads can be easily personalized	• Controlled nozzle radius relegates quality of finished products, nozzles are in circular shape outlet and it is impracticable to make sharp peripheral corners and edges will also exhibit round shape • Speed of product development is low compared to other processes. At higher reinforcement loading condition, nozzle gets clogged • Precision of the end product is limited to nozzle thickness • Constant pressure applied on the material is vital in order to raise eminence of finish	All metal FDM parts are found to have reduced weight and improved time for part repairsAlmost 70 % manufacturing grade thermoplastic parts are executed in NASA's Mars rover because of capacities like lightweight and ability to withstand the inflexibilities of space	(52,164,178)
VAT Polymerization	Stereolithography	• Great level of accurateness and beneficial finish • Finer resolution • Moderate process • Large build areas compared to other process: object dimension is 1,000:1,000 × 800 × 500 and maximum model weight of 200 kg • Random alignment of fibers is possible	• Exclusive • Extensive post processing time and removal of resin • Formation of air bubbles • Limited material of photo-resins and sedimentation of fiber in resin • Need support structures till post curing for parts to be durable for structural component • Improved resin viscosity with the inclusion of fibers	Aircraft cabin accessories like functional knobs, full size panels, seat backs, entry doors, jigs, and transparent aircraft headlights	(52,179,180)
Directed energy deposition	Direct metal deposition, 3D laser cladding	• Main advantage of this process is commonly used to add material, overhaul work with excellence, functional parts • The surface quality and speed with restoration applications and a pre-determined microstructure	• Finishing of parts varies with respect to type of material like paper or plastic material, it is necessary to do a post processing to achieve anticipated effect • Inadequate material practice	Aerospace applications like overhaul of turbine blades, aerofoils, blisks engine, combustion chambers, and compressors	(181,182)
Sheet lamination	Ultrasonic additive manufacturingand LOM	• Speedy process at economical price • Effortlessness of material handling, strength and bonding of models is dependent on the bonding agent used • Parts with high strength can be produced	• Inadequate material practice • High power usage • More material wastage • It is moderately difficult to build parts with compound cavities	• Complex internal geometric part • Manufacturing of structures by using various materials • Fiber reinforcements during manufacture • Entrenching of electronics and other facets to create smart structures	(52,183)

(Continued)

Table 3: *Continued*

Process	Commercial name	Merits	Demerits	Applications	Ref.
		• Fast slicing due to the cutting route only on the shape outline, not the entire cross-sectional area • No requirement of post-processing and support structures			
Powder bed fusion	Selective laser sintering	• Fairly low-priced • Suitable for visual models and prototypes • Composites with huge amount of reinforcement can be attained • Ability to produce small scale using table top machine • Powder acts as a supporting structure • Wide range of material options • Unused powders can be reused	• Comparatively slow speed • Deficiency in materials structural properties • Size limitations and impossible to fabricate composites material with lengthy fibers • High power usage • Finishing of parts are rough and dependent on powder grain size • High porosity in the final parts	Non-functional parts and direct digital manufacturing of uncritical components	(52,184,185)
Binder jetting	3D printing	• Various colored parts can be prepared • Wide choices of materials like metal, polymers and ceramics • Comparatively faster process • The usage of wide range of material permitting number of different binder-powder combinations and other mechanical properties • Slurries with higher solid loadings is possible only through this method	• The use of binder material makes the parts unsuitable for structural parts • Additional post processing can increase the duration of the overall process	• Cooling chambers can be fabricated through this process • Impellers and turbine blades	(186,187)
Material jetting	Direct writing	• The process aids high accuracy of depositing material in droplets form, hence less materials are discarded • The process allows to prepare multiple material parts and wide range of colors under one process	• Support material is obligatory • A high precision can be attained based on limited materials like polymers and waxes	Semiconductors,dielectric plastics,conductive metals,repellent materials,piezo-electric battery components,capacitors, biotic materials can be fabricated using this method	(188)

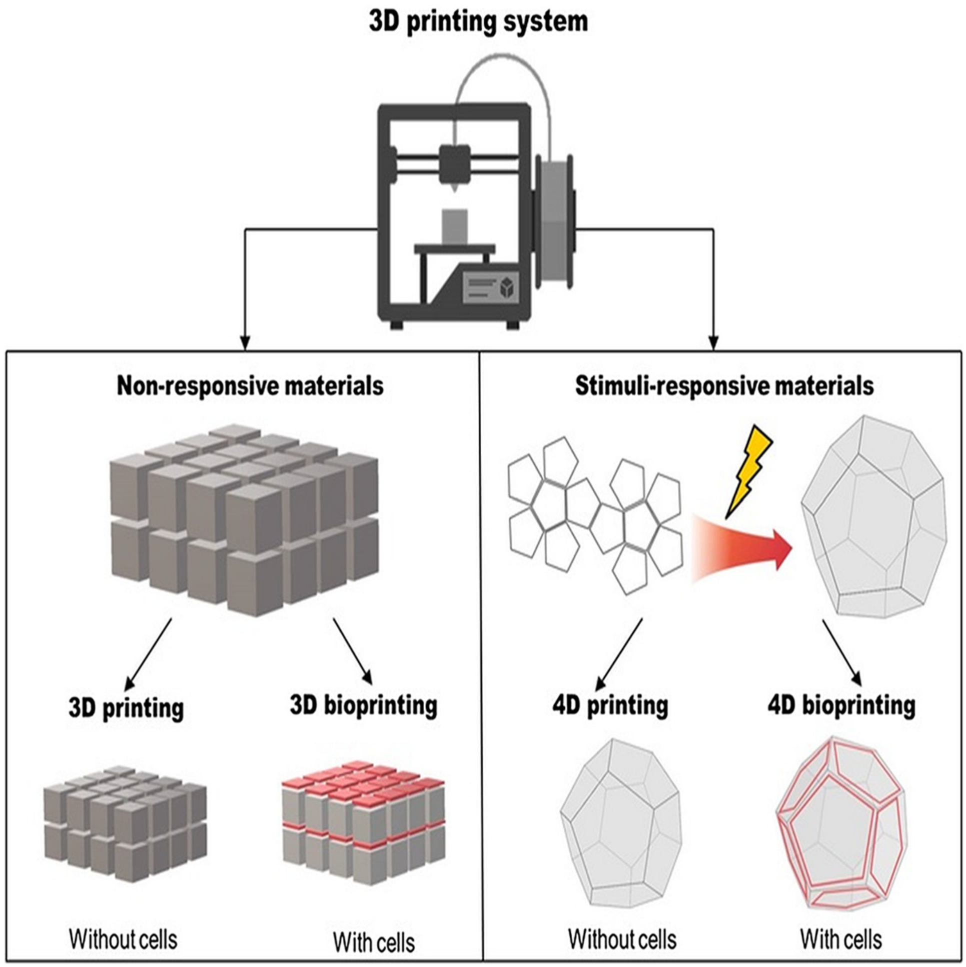

Figure 14: Schematic illustration indicating the foremost disputes among 3D and 4D printing (9).

AM (10,19). The AM market is estimated to rise at 14.4% reaching USD 23.33 billion in 2026. Clients of aviation-related businesses show interest in composite materials due to their lightweight, acceptable strength, and easy transportation. In recent years, AM technology is widely used in the aviation industry in the design and fabrication of thin-walled composite parts based on a global design for AM methodology and also rib-structure with a large pocket, aiming for lightweight aircraft materials without compromising on mechanical strength (4). The functionally graded materials manufactured by AM for missile application offer better properties than the fabricated component (198). The composites used for this application are usually fabricated with the use of conventional methods such as heat or cold pressing. Only simple structural components are produced through the use of conventional methods, AM provides complex structural components with enhanced mechanical properties, is lightweight, and has achieved almost its near-net shape composites (199).

Aerospace components are mostly complex geometries and demand high performance like the leading edge of hypersonic vehicle and spacecraft propulsion systems, nozzle throat inserts, and missile nose cones to withstand high temperatures through the use of functionally graded materials (3,14,200), for improved performance of advanced gas turbine engines compressor blades, or blisks aerofoils (201). Hollow turbine blades are fabricated rapidly with a sintering temperature strength setup from 500°C (202) (Figure 15). Polymer-based materials like epoxy, ABS, and nylon are often used for the parts of aircraft engines and missile parts (203). The current trend of AM has been combined with the conventional casting techniques for the reduction in the density of material inevitably with the weight of the airplane components, helping in the reduction in carbon emission, and consumption. A few leading aviation giants have commenced using AM for manufacturing their parts and a few examples are shown in Figure 16 (200).

The process of AM used in health-care is generally known as bio-printing of FRPCs. It is a computer-assisted manufacture of tissues, scaffolds, and cells, for creation of organs through layering of cells. This is one of the ground-

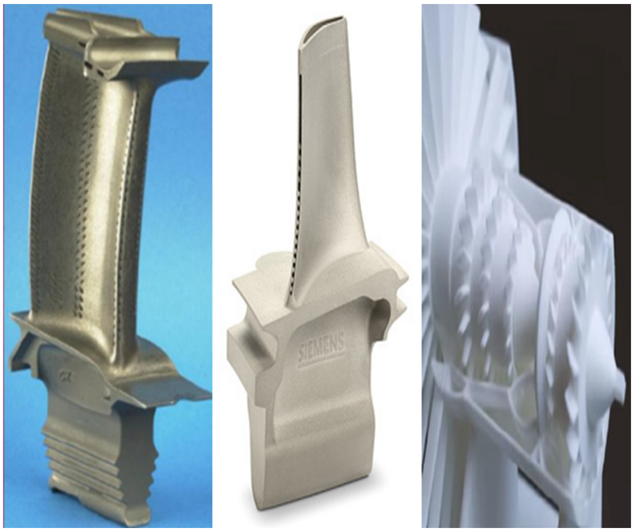

Figure 15: 3D printed high-pressure turbine blades (202).

breaking resolutions to the healthcare crisis for organ scarcity and transplantation (204). The major considerations of these products used in the bio-medical applications are bio-degradable, bio-compatible, enhanced bending property, mechanical strength and bio-mimicking nature, and for hard parts like bones, porosity, compressive strength, and few biotic properties such as osteo-conduction and osteo-integration (205,206). There are three approaches involved in bio-printing of FRPCs:

(i) Biomimicry:Creation of a structure similar to the natural structure of muscles and organs in the human body. It also needs imitation of shape, framework, and micro-environment of tissue.
(ii) Autonomous self-assembly: The process of embryonic organ development depends on histogenesis, influencing composition position, and properties of tissues.
(iii) Mini tissue: Structural and functional unit of tissue. Some of the energy system design components are manufactured using AM for seizing the benefit of AM capabilities. The major concerns are in the areas of maintenance and repair, in various industries as prospective applications, progress justifiable indicators for sustainability measurement in AM processes, products for recognition of viable industrial materials (207).

With the advent of enhanced AM technology, AM of 3D porous structures for the application in bone tissue engineering is emerging. Simultaneously, the integration of artificial intelligence for 3D printing of biologically complicated porous structures through laser-based techniques has also emerged. By careful optimization of process parameters, the 3D printing of porous structures can be fully ripened (208,209). Recently, the number of patients requiring organs has been doubled and the number of transplants has also increased. AM competes for a vital role in the medicinal field through the use of medical implants and medicinal kits. This is considered as the cutting-edge technology that crafts advance novelties and adopts multifarious medical issues. This is evidently validated by the outcomes attained in

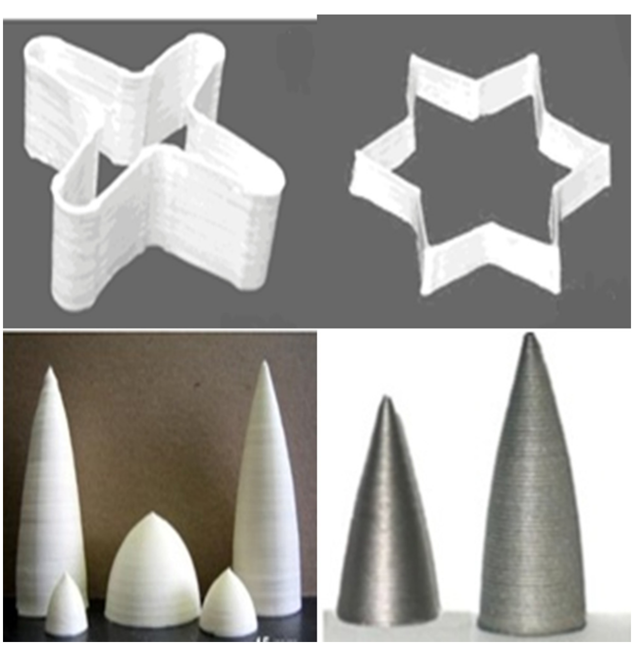

Figure 16: Aerospace parts fabricated using the FFF process (200).

Figure 17: The challenges and limitations of FRPCs manufactured through AM.

Table 4: Possible ways of improving the properties of parts produced by AM techniques

Properties that need to be enhanced	Possible ways	Ref.
Mechanical	Low printing speed and minimum layer thickness due to better bonding between layers	(216)
Shape memory	Addition of nano-filler into various printable resins increases the flexibility and also shape memory property by repeated stretching and bending	(217–219)
Morphing and visco-elastic property	Use of multi-material	(220)
Electrically active composite	Addition of carbon nano-fillers	(197,221,222)

regenerative medicine, diagnosis, implantations, and simulated organs (210). The usage of AM composite products in craniomaxilliofacial implants for severe head injury, tissue structures, tissue engineering scaffolds, 3D printed material for oral and maxillofacial surgery, bone tissue engineering, hearing aids, etc. (9,211,212).

Table 5: Drawbacks of AM in processing of FRPCs and suggestions

Drawbacks	Causes and possible ways to overcome	Ref.
Sizing limitations	Most common liquid polymers, powder, ceramic, and photo-polymers are used. These materials reduce AM to make massive sized products due to excess requirement of resources and also the properties are influenced. Large-sized objects take time to complete the production process	—
Fiber volume and orientation	FRPCs manufactured through AM suffer from low strength and stiffness as compared to their conventional counterparts due to the limitation of low fiber volume. Increasing the degrees of freedom of the fiber placement in the matrix in such a way that the properties may be improved in all directions	—
Interfacial bonding	Good bonding between the matrix and fibers is essential to enhance the properties of the composites	—
Property	Alternative trial tackled in the material type is the major constraint in the properties of the FRPCs	—
Electric and magnetic properties	Improvement of electrical conductivity and magnetic properties of PMCs by selecting the appropriate fibers and matrices	—
Budget	The deepest barrier for 3D printing is based on the consumption of money and the expected product quality from the users. AM equipment is contemplated to be excessive financing than conventional machinery. AM machine cost is estimated to be as high as 70% of the conventional machines	(223,224)
Blockage in printer nozzle	Contemporary 3D printing is friendly to particular resin inclusion of reinforcements like filler, particulate can damage the printer's nozzle through agglomeration, blockage in printer heads, and increased curing time	(225)
Design flexibility	Presently only limited materials are accessible for fiber-based composites, which has limited applications and design flexibility	(226)
Defects	Recent methodologies and material preferences escort to the establishment of substantial defects in the finished products, have an undesirable influence on the accessible strength	(227)
Discontinuities and flaws	Some of the AM parts contain discontinuities and flaws such as porosity and deficit of fusion are generally probable and they occur usually among the layers, decreasing the load-carrying extent and mechanical strengths of the parts. There is a linkage among unprocessed material, type of discontinuity, process parameters, and post-processing	(228)
Porosity	Preventing void formation inside the specimen by choosing proper process parameters like nozzle temperature, cooling speed, printing speed, etc.	—
	When direct writing techniques are used for printing multi-material part orientation of each nozzle and its jump and halt ink flow on-demand, without flaws or defects is hectic	—
Cost reduction of machines and materials	Due to the limited availability of the industrial-scale AM printers, it is necessary to develop new materials and printers in order to make them available at lower cost	—
Limited technology adaptation	Considering the advantages of AM fabricated parts in making lightweight and sustainable products, integration of the technology to other field of studies will have to grow	—

6 Challenges, limitations, and opportunities

While a significant quantity of evolution has been crafted in the field of AM, there are several investigations to be taken up for finding solutions to encounters seen. AM gives supreme flexibility in the manipulation around conventional methods, but numerous restrictions hampered the advancement of the marketplace (213). These include the impracticality of reproducing materials, slow print, inadequate accessibility, imprecise actuation, and expensive printer heads, with no prospect of printing additional materials (9). AM has numerous advantages for economic and environmental society. The major challenges and limitations of FRPCs manufactured through AM are depicted in Figure 17.

The limitations seen in the use of nanoparticles in AM include nozzle clogging, and rough surface finish of printed parts. The distribution of nanoparticles inside composite materials was investigated and the requirement of emulsion polymerization for avoiding agglomeration of nanoparticles and production of good interfacial bonding between the reinforcements and the matrix material has been seen (214). It is found the parts produced by AM have a low degree of agglomeration, porosities, and cracks compared to traditional ways of building composites (2,215). Shofner *et al.* (62) processed carbon fibers and ABS material by FDM and studied issues related to porosity, dispersion, and alignment of fibers. Drawbacks seen were the inefficient process and lack of proven techniques. Direct printing of natural fiber composites through the available 3D printing techniques was also not feasible due to the dispersion effects which have to be eradicated through suitable means. In recent times, self-printing 3D printers have been developed for the printing of functional materials based on real-time applications and parameters. The 3D printed materials post cures itself after 3D printing which can be put directly to application. The possible ways of improving the properties of parts produced by AM techniques are presented in Table 4. Researchers worldwide are working on the methods for overcoming the drawbacks of AM in processing of FRPCs, which are listed in Table 5.

7 Summary and conclusion

This review focuses on the different AM technologies involved in the processing of FRPCs and their process parameters for enhancement of the productivity, reduction in mass material usage, cost-efficient, and enhanced parts functionality. Besides, this technology is seen whirling into a multi-disciplinary arena, with the requirement of proficiency of researchers beyond their strategic province of study, including ecology, bio-medical, and bio-chemistry. This review also shows the bonding between fiber and the matrix material playing a major role in strength distribution and the strength of the additively manufactured continuous fibers reinforced composites is high compared with the short fibers reinforced ones. The practice of continuous improvement, health and safety standards, use of energy efficient methods, and utilization of machineries are the most influential factors for sustainable manufacturing processes of composites.

Several printing parameters have influence on the properties of the materials that include printing time, orientation, laser power, scanning velocity, power feeding rate, gas feeding rate, substrate material, printing speed, etc. Inter-layer failure has been seen in build orientation, which has resulted in decreased strength and stiffness. On the other hand, the maximum mechanical properties have been found in on-edge and flat samples, with the demonstration of trans-layer failure. Variations in the effect of layer thickness on the tensile and flexural strength of FRPCs have been seen depending on the construction orientation. Ductility was shown to diminish with a rise in layer thickness. A decrease in tensile and flexural strength was seen following a rise in the feed rate. A reduction in ductility was also seen following the increase in layer thickness, similar to the impact of layer thickness. With the best printing time, strength, and stiffness, ductile behavior is sought.

This review further reveals the mechanical properties of additively manufactured FRPCs as highly influenced by the fiber layer thickness inside the laminate and a significant increment due to the further addition of fibers. It suggests 3D printing as an evolving technology that is viable, momentary evolving, and expected to be a foremost concept in material technology. Perceptions in this field are deceptive in space, bio-medical, fabric processing, smart clothing, microchip technology, robotics, and beyond. The conclusion is that, in the next few years, AM will become a focal component in all the fields of manufacturing and progress strongly as a salient method of manufacturing covering all classes of materials including FRPCs.

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