THE TRENDS AND CHALLENGES OF FIBER REINFORCED ADDITIVE MANUFACTURING

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ABSTRACT: In the last few years, utilizing fiber reinforced additive manufacturing (FRAM) based components in several industries has become quite popular. Compared to conventional AM technologies, FRAM offered complementary solutions to their needs. In general, fibers have been traditionally used in many manufacturing processes for various reasons. However, using conventional methods, there are obstacles in obtaining the desired complex geometries and low setup costs. AM offers possible avoidance of these limitations. Shape complexity, infill density, and manufacturing lead times are no longer barriers. Bridging AM with fiber reinforced materials offers a vast opportunity for lightweight and strong parts. Depending on the affinity, fibers with different structures can be mixed with different matrix materials and, thus, create stronger parts with improved mechanical properties. Process parameters like raster angle, infill speed, layer thickness, and nozzle temperature also strongly impact physical properties of FRAM products and are considered carefully. FRAM-based components are used in many industries such as aerospace, motorsports, and biomedicine, where the weight, strength, and complexity of parts are critical. Hence, numerous industrial companies and research facilities are investigating the implementation and adaptation of FRAM to their requirements. Studies are generally conducted on new materials, new FRAM technologies, the effect of fiber orientations and fraction on the performance of parts, improving the printing parameters, and other subjects. This study reports the current trends and challenges that FRAM is bringing to AM ecosystem.

KEYWORDS: *Fiber Reinforced Additive Manufacturing; Composite; matrix; reinforcement; polymer*

1. BACKGROUND

Since the mid-19th century, new materials have been discovered that have replaced traditional ones and have enabled realization of new products. These materials are groups of polymeric materials, such as plastics, fibers, and elastomers [1]. The first plastic material was obtained by Parkes in 1862 and Hyatt in 1866. It was based on nitrocellulose [2]. People have used fibers for thousands of years. For illustration, sheep wool has been used for clothing since 5000 BC [3]. Just until the 1930s, all fibers were produced by natural sources. During these years, people started producing synthetic fibers instead of using natural ones [4]. Subsequent technological advancements also saw the emergence of new fibers with high strength-to-weight ratios. Such fibers include glass fibers discovered in the 1940s and carbon and aramid fibers discovered in the 1960s [5].

2. FIBER REINFORCED POLYMERIC COMPOSITE MATERIALS

Fiber reinforced composite materials are materials produced by taking polymer as the matrix with fiber as the reinforcement. The fibers mainly used are fiberglass (FG), carbon fibers, fabrics, Kevlar, basalt, etc. [6]. Wood, paper, and asbestos are some of the natural fibers which can be used in this process depending upon the requirements. Nylon, polyester, vinyl ester, epoxy, aluminum oxide, aluminum alloys, titanium alloys, etc. are some of the matrix materials used in making composite materials [7]. Properly selecting the volume, length, type, and orientation of fibers is vital because these parameters strongly influence physical and mechanical properties of composite materials (CMs) [6].

Additive manufacturing (AM), also known as 3D printing, is one of the latest manufacturing processes and uses layer-by-layer fabrication to build parts [8]. Selective laser sintering (SLS) [9], fused deposition modeling (FDM) [10], stereolithography (SLA) [11], laminated object manufacturing [12], and multi jet modeling are some of the AM technologies that enable the creation of light weight and strong fiber reinforced products. AM uses a computer aided design (CAD) model to structure three-dimensional parts, convert parts into series of thin layers, and produce G-Code for the particular type of 3D printer. Many researchers used AM to fabricate CMs for a wide range of applications. Masood et al. also used FDM to develop a polymer/metal-based CM by taking nylon as the matrix material and iron as the reinforcement [13]. The study concluded that by increasing the volume fraction and particle size of iron filler particles, thermal conductivity of the AM specimen increases. Brooks et al. introduced design methodology, which is used to integrate the AM polymer parts with continuous reinforcements [14]. To investigate the applicability of this method for tensile, torsion, and bending, three case studies including pulley housing, universal joint, and hook were used, respectively.

3. Overall, FRAM combines the advantages of composite materials and the flexibility of AM. It simultaneously allows the production of complex shaped parts without the manual aspect of the conventional composite manufacturing alongside with mold preparation. AM makes it possible to produce customizable parts in a short time period with minimal human intervention. Furthermore, robust and lightweight parts are achieved by the addition of fibers to the polymer matrix. The strong interfacial adhesion assists in stress and load distribution between fibers and matrix materials.MATERIALS CLASSIFICATION IN FIBER REINFORCED ADDITIVE MANUFACTURING (FRAM)

Parts fabricated with FRAM consist of a matrix and reinforcement elements, as shown in Figure 1. The chart presented in Figure 1 is a collection of materials used in recent FRAM studies. There are numerous research projects under development to produce lightweight, low-cost, and sustainable matrices by selecting the appropriate combination of matrix and reinforcement materials [7]. A collection of FRAM materials and their mechanical properties is shown in Table 1.

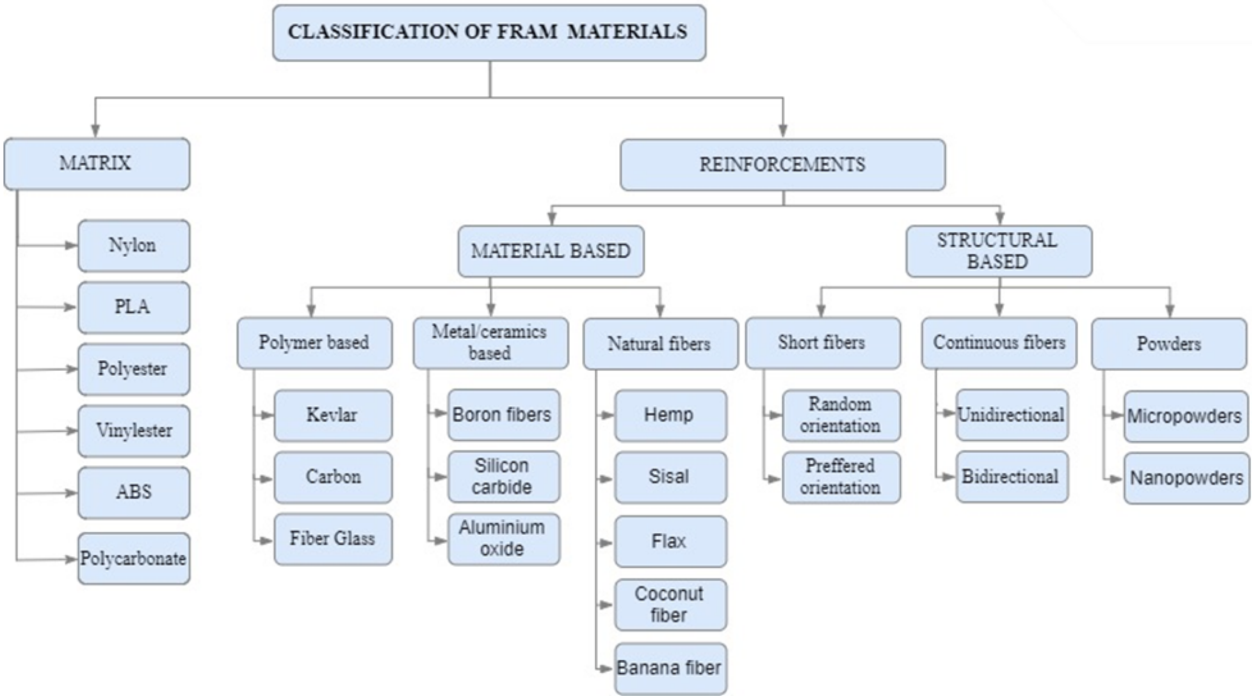

Figure 1: Classification of FRAM materials

Fibers in FRAM can be used in the form of short, continuous, and powder-based. In the short fibers group, the most common ones are carbon and glass fibers [15]. Short fibers are easier and cheaper to produce than continuous ones. Until 2014, continuous fibers were used with conventional manufacturing methods. In 2014, continuous fibers started to be used in additive manufacturing, as well [16]. Several studies have shown that short (discrete or chopped) fibers extruded as one filament successfully integrated with matrix material are applicable in several AM techniques [17], [18]. Newly developed FRAM machines printing the fibers and matrix materials continuously layer-by-layer have presented successful research, development, and industrial results [19], [20]. Similar to short fiber technologies, matrix and filament materials could also be reinforced in micro- and nano-level using powder bed technologies' fiber binding with laser or adhesives [21], [22]. The schematic representation of the FRAM process is illustrated in Figure 2.

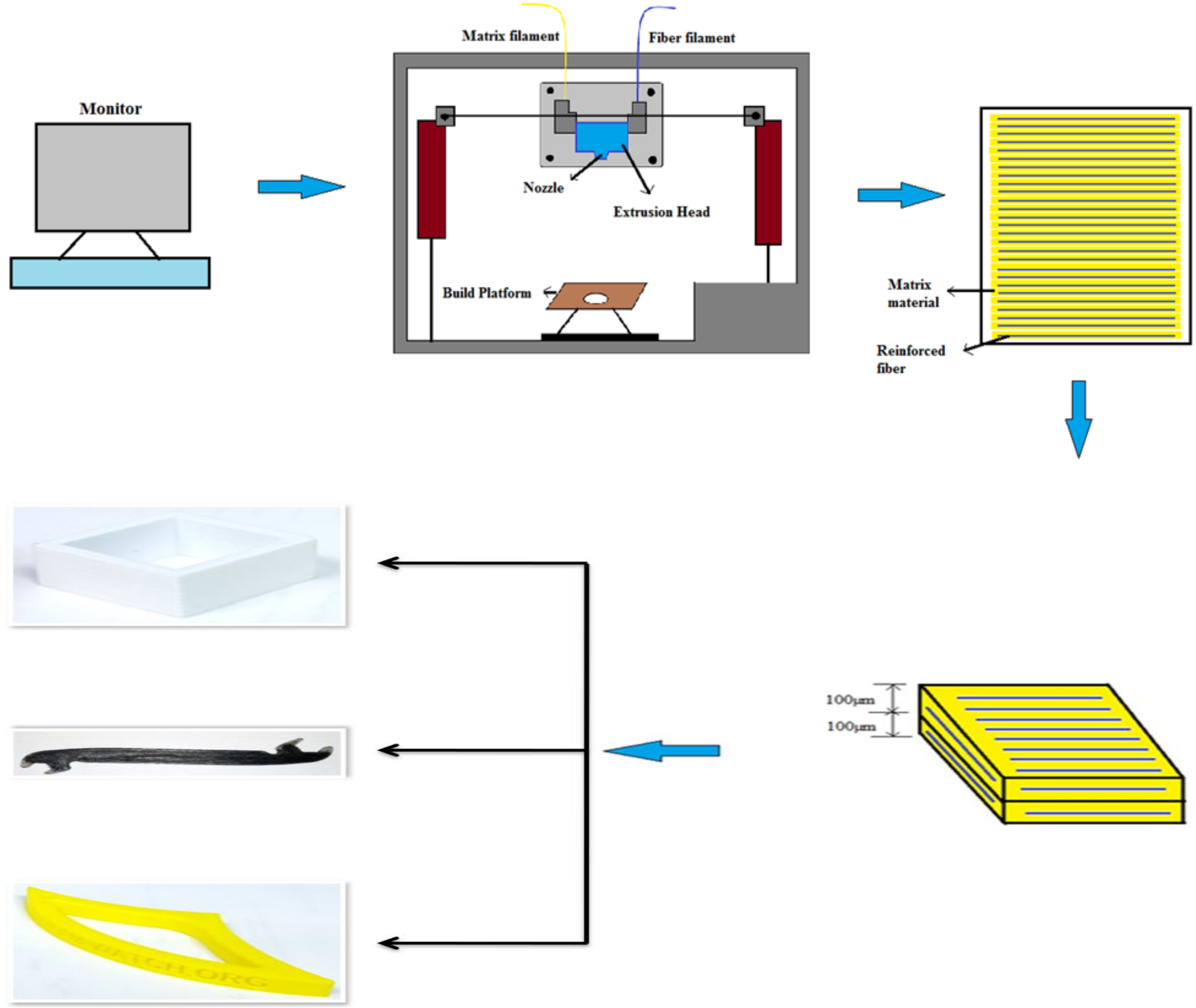

Figure 2: Schematic layout of FRAM

3.1 *Matrix/base materials*

Matrices, in this case polymers, play a vital role in CMs by (a) keeping fibers in place, (b) transferring stress between fibers, (c) protecting fibers from adverse environmental conditions, (d) preventing surface abrasion, and (e) supporting fibers under compression loading [6]. The matrix materials also strongly influence shear and compressive properties of CMs. The matrix material should be thermally, physically, and chemically (matrix should not react with fibers) compatible with the reinforcements.

3.1.1 Polyester

Table 1: Mechanical properties of materials used in FRAM [7], [23]–[28]

Reinforced Fibers	**Density (g/cm^3)**	**Tensile Modulus (GPa)**	**Tensile Strength (MPa)**	**Thermal conductivity (W/m*k)**	**Linear Coefficient of thermal expansion (10^{-6}/ºC)**	**Diameter (μm)**
Polymer Fibers						
Carbon	1.8	230-270	3600	21-180	4-8	5-10
Kevlar	1.4	70.5-112.4	3620	0.04	-4.86 to -3.96	11.9
Glass	2.54	50-90	3000	3.21	4-9	10
Metal Ceramics Fibers						
Boron	2.45	450	3500	3.22	4.5	140
Al_2O_3	3.4-3.9	215-413	2100-3100	25.08	8.1	10-12
SiC	2.55-3.08	450	2750-3440	120	2.77	14.5-140
Natural Fibers						
Jute	1.3-1.45	39.4	320-800	0.059	-0.6	20-200
Flax	1.4-1.5	62.4	345-2000	2	-0.8	12-600
Sisal	1.33-15	21.9	373-700	0.25-0.38	-3.9	8-200
Matrix Materials						
Nylon	1.15-1.85	2-4	40-60	0.2	80	14-24
ABS	1.01-1.21	1.4-3.1	25-50	0.15-2	72-108	50-53
PLA	1.252	1.28	59	0.11-0.19	85	60
Polyester	1.2-1.5	3-3.5	40-90	0.2	124	12-25
Vinyl ester	1.12-1.32	3-3.5	73-81	0.3-0.4	16-22	240
Polycarbonate	1.06-1.2	2.6	45-70	0.2	65-76	150

Polyester is widely used in biomedical applications due to its low viscosity, gravity, cost, and ease of use. Glass fiber reinforced polyester is also popular in the boating industry [29]. The primary limitations of polyester are its unrestrainable volumetric shrinkage and consequent depression on the surface, which is caused by the difference between the shrinkage values of matrix and fiber materials [6]. Pereira et al. successfully built porous cubes of poly (3-hydroxybutyrate), a natural thermoplastic polyester produced by microorganisms via SLS with minimal dimensional discrepancies [30]. Shape and dimensions of the resulting model are very close to the virtual model. Further, as an example for biomedical applications, Oliveira et al. performed experimental analysis to build scaffolds of polyester and nylon using SLS [31].

3.1.2 Acrylonitrile butadiene styrene (ABS)

ABS is a versatile thermoplastic polymer that exhibits good mechanical characteristics under a varying temperature range (75-85ºC), [32]. The material is generally associated with impact resistance, rigidity, low creep, low weight, good dimensional stability, and toughness, hence considered suitable for CMs [32]. Several experiments were performed on ABS to further improve toughness, impact resistance, and heat resistance. Boparai et al. performed a comparison analysis of tribological properties of ABS and Nylon 6-Al-Al_2O_3 parts made with FDM [33]. The experiment used three different compositions of Al and Al_2O_3 for tribological investigations and concluded that wear resistance behavior, thermal stability, and stiffness were more for CMs prepared with different proportions compared to parts produced with only ABS. Mori et al. developed a 3D printer to manufacture die-less forming of carbon fiber reinforced polymer (CFRP) parts [34]. CFs are sandwiched and heated between the upper and lower plates of ABS made by 3D printing. Results showed that fatigue and static strength increased due to thermal bonding between the fibers and the reinforcements. Ajinjeru et al. identified valid processing conditions for high-performance thermoplastics on large format additive manufacturing and compared the rheological behavior of high-performance thermoplastic, polyphenylsulfone with that of low-temperature polymer (ABS) [35].

3.1.3 Nylon

A variety of engineering applications use nylon, such as gears, screws, and tool casings, to name a few. Nylon is an exceptionally high-strength material with good temperature resilience, abrasion resistance, and chemical stability. Reinforced with glass fibers, nylon is also considered a good substitute to cast iron and aluminum (previously used for intake manifolds of automobile engines) by virtue of its low weight, improved efficiency, and reduced cost [32]. Nylon is easily extruded via designated 3D printing and injection molding machines. Despite this, it displays low impact strength compared to polystyrene, ABS, and polycarbonate. Masood et al. presented a produced CM using iron particles as the filler and nylon to formulate and characterize tensile properties of the final product [36].

3.1.4 PLA

Polylactic acid (PLA) is a thermoplastic and biodegradable material usually considered to be the most suitable material for FDM. Due to low glass transition temperature, it is considered unsuitable for high-temperature applications. To enhance its mechanical properties, PLA can be annealed, [37]–[39], reinforced with fibers, nanoparticles [40]–[42], or undergo chain extending [43]. PLA has a wide array of applications including medical devices where PLA scaffolds have shown biocompatibility potentials [44] with controlled and interconnected porosity [45].

3.1.5 Polycarbonate

Polycarbonate is a thermoplastic polymer that has extensive applications in engineering domains due to its physico-mechanical properties. Low creep resistance and low thermal stability limits its use in structural applications [6]. It can be easily worked, thermoformed, and molded, which makes it a valuable material in AM. Nelson et al. used SLS to fabricate a 3D product of bisphenol-A polycarbonate powders to study the effect of the process and properties of material on fusion depths [46]. Berzins et al. used amorphous polycarbonate powders for thermal modeling of selective laser sintering [47].

3.1.6 Vinyl ester

Vinyl ester is known for its excellent chemical resistance and high tensile strength. Good adhesion with glass fibers and low viscosity makes it a valuable matrix material in AM [6]. Generally, discontinuous and randomly oriented E-glass fiber reinforced vinyl ester has found its application in radiators for support [6]. Heller et al. used SLA to fabricate 3D cellular scaffolds for regenerative medicine and tissue engineering [48]. Results of this study showed that the vinyl ester is an excellent biocompatible material.

3.2 Fiber reinforcement materials

Fibers reinforcement materials used in polymer composite fabrication should be thin and flexible with high modulus, strength, and elastic properties. They should be several times stronger than the matrix to impart valuable improvements in the final properties of CMs. Reinforcing fibers are used as discontinuous phase. They also have high load carrying ability, strength, stiffness, and Young's modulus.

3.2.1 Polymer-based fibers

3.2.1.1 Carbon fibers

Carbon fibers (CFs) are usually combined with other materials to produce CMs. When they are mixed with plastic polymers, it is named a carbon fiber reinforced polymer (CFRP). CFs have several advantages like high stiffness, low elongation, ability to withstand high temperature, low specific gravity, high tensile strength, low weight, low thermal expansion, chemical resistivity, etc., which helps in finding its reinforcement applications [49]. Low strain to failure, high electrical conductivity, high cost, and low impact resistance limit its use in some engineering applications [6]. Aerospace and nuclear engineering, military, civil engineering, and motorsports are some popular areas where CFs are widely used. Now, in some cases, these can replace standard materials that have previously been used. For instance, aluminum was replaced by CFRP in aerospace applications because of its excellent properties [50]. Ning et al. investigated mechanical properties of FDM modeled parts [18]. The parts consist of CFs (different content and length) and ABS. The study concluded that a CFRP with 150 μm fiber length has better tensile strength and Young's modulus but less toughness and ductility compared to a CFRP with 100 μm fiber length. Ivey et al. investigated mechanical properties and microstructure of CMs with PLA filament reinforced with short CFs fabricated using material extrusion additive manufacturing [17]. Annealing was also performed after the experiments, which helped increase the specimen crystalline behavior with no significant effect on its mechanical properties.

Liao et al. investigated mechanical and thermal properties of CF reinforced polyamide-12 CM fabricated using FDM [51]. Laser flash diffusivity analysis showed the greatest improvement in thermal conductivity (277.8%) of the CF/PA12 composites compared to pure PA12. Zhong et al. fabricated a short CF reinforced CM by taking ABS as the matrix material via FDM and then studied critical material property issues related to that [52]. Results showed that the strength and hardness of the 3D printed samples increased, but flexibility and handleability reduced. To overcome these limitations, the authors proposed adding a small amount of plasticizer and compatibilizer in the prepared resin. Love et al. demonstrated blending of CCF with polymer matrix to analyze mechanical properties of the final product [53]. Results concluded that by adding CCF to polymer matrix, strength, stiffness and thermal conductivity of the samples increases significantly and there is no need to put the samples in the oven for minimizing distortions.

3.2.1.2 Kevlar

Kevlar fibers are generally aromatic polyamide fibers that exhibit crystalline behavior. They have low density, high impact, high tensile strength-to-weight ratio, and low thermal expansion, which all make them a successful reinforcement in CMs [6]. They are not used in areas that require high compressive strength and easy machinability [6]. Kevlar found its use in armor vehicles, the biomedical field, bullet proof jackets, etc. Caminero et al. studied inter-laminar bonding performance of 3D printed composite samples in regard to layer thickness and fiber volume content [54]. Inter-laminar shear strength increases with increasing fiber content, but this increase was moderate in the case of Kevlar fiber. It was also observed that the CFRPs have better inter-laminar shear performance than Kevlar fiber reinforced composites due to poor wettability of Kevlar fibers.

3.2.1.3 Glass fiber

Glass fiber as a reinforcing material consists of many extremely fine fibers of glass. It is considered to be the most common reinforcing material for polymer matrix composites [6]. When glass fibers are blended into polymer materials, the resulting material is called a glass reinforced plastic or fiberglass. Glass fibers are strong in tension when they are combined with plastic, which is strong in compression and weak in tension, thereby creating a CM with high compressive and tensile strength. Parandoush et al. implemented laser assisted bonding and laser cutting to fabricate objects with prepreg continuous composites (glass fiber-polypropylene) [55]. Results showed that peel strength and lap shear strength increase significantly compared to traditional methods of AM (hot compaction method and compression molding). Chung et al. fabricated a CM by taking nylon-11 as the matrix material and glass beads as the reinforcement using SLS and performed theoretical modeling, numerical analysis, and experimental investigation [56].

Zhong et al. used short glass fibers with ABS to improve mechanical properties and found issues in fabrication related to using short fibers as reinforcements [52]. Results showed that glass fibers enhanced the strength of the CM but reduced flexibility and handleability. These limitations were overcome by adding a plasticizer and compatibilizer. Invernizzi et al. performed experimental analysis on glass and CF reinforced dual core polymer composites made using UV-3D printing [57]. The resulting material showed good mechanical and thermal properties. Further, the fibers were efficiently reinforced by using this printing technique. Goh et al. examined microstructural characteristics, tensile, and flexural and quasi-static indentation characteristics of continuous carbon and glass fiber reinforced thermoplastic composites made with fused filament fabrication [58].

3.2.1.4 Natural fibers

Jute, hemp, sisal, flax, coconut fiber, and banana fiber are some examples of natural fibers [59]. Automobile industries are now starting to make use of natural fiber reinforced polymers for many reasons, including that it (a) is environment friendly (biodegradable) (b) has low density (c) has higher acoustic damping than carbon and glass fibers, and (d) is inexpensive [6]. However, natural fibers also have several limitations like low tensile strength, low melting point, and moisture absorption. Matsuzaki et al. developed a method of 3D printing continuous fiber reinforced thermoplastics (CFRTPs) via FDM, which requires no usage of molds [60]. For this study, PLA was used as the matrix material and twisted yarn of jute (natural fibers) and CF as the reinforcement. The study showed improvement in tensile strength compared to values shown by conventional 3D printed polymer composites.

3.2.2 Metal/Ceramics-based fibers

Boron fibers are also used as reinforcements in polymer CMs because of their high tensile modulus (379-414 GPa) and high compressive strength, which exhibits excellent resistance to buckling [6]. The main limitation of boron fibers over CFs is high cost, which hinders their use in some engineering domains [6]. Generally, boron fibers are used in turbine blades and transmission shafts. Silicon carbide (SiC) and aluminum oxide (Al_2O_3) are common ceramic fibers used in polymer-based CMs for high-temperature applications. Singh et al. performed wear analysis of polymer-metal CMs produced with FDM [61]. This study used nylon and Al_2O_3 powder to produce continuous filament for product development. The authors highlighted that adding Al_2O_3 in the nylon matrix helps to increase wear resistance for the final product and make the product useful in grinding applications. Kenzari et al. investigated the compatibility of AlCuFeB quasicrystals filler particles with SLS [62]. Results of this study showed that the produced parts have low friction and wear characteristics compared to other composites used in SLS. Parts can be made porosity-free by using quasicrystals as filler materials and this also enhances its chances to be used in fluidic applications. Falck et al. introduced Addjoining of FDM to produce layered hybrid structures [63]. Two combinations (aluminum 2024-T3 with ABS and aluminum 2024-T3 with alternate layers of polyamide-6 and CF reinforced polyamide-6) were taken to study their effect on microstructure and mechanical properties.

3.2.3 Nanofibers/Nanoparticles

Carbon nanofibers are popular additives to CMs. Incorporating carbon nanofibers into thermoset and thermoplastic polymers can improve material properties. High strength and modulus is achieved by incorporating carbon nanofibers in thermoplastics, but small improvements are seen by incorporating them in a thermosetting polymer [6]. Carbon nanotubes, the allotrope of carbon, have outstanding thermal, mechanical, optical, and electrical properties and their elastic modulus is much higher than that of CFs [6]. Incorporating them in polymer composites improves one or more material property such as modulus, strength, thermal conductivity, and electrical conductivity. Carbon nanotubes are active participants as reinforcements in polymer matrices due to (a) more dispersion in polymer matrices, (b) strong bonding with the matrix material, and (c) higher solubility in solvents with functional groups [6]. Kim et al. investigated the effect on material viscosity and mechanical properties by adding clay nanoparticles in a polyamide 6 composite [45]. This study concluded that adding nanoparticles increases the material's viscosity and mechanical strength and decreases the final density of the sintered product, which makes it useful in lightweight applications. Ivanova et al. proposed a theory to introduce nanoparticles (metal, ceramic, and carbon) to AM [64]. Adding nanoparticles helps improve thermal and electric conductivities, mechanical properties, etc. The authors also mentioned the limitations of using nanoparticles in AM such as nozzle clogging, rough surface finish of printed parts, etc. Zheng et al. investigated distribution of nanoparticles inside a matrix material [65]. The authors suggested that emulsion polymerization should be done to avoid agglomeration of nanoparticles and to produce good interfacial bonding between the reinforcements and the matrix material. Kim et al. compared homogeneous and heterogeneous dispersion of BaTiO3 nanoparticles in polyvinylidene fluoride matrix materials [66]. The parts produced by FDM have a low degree of agglomeration, porosities, and cracks compared to traditional ways of building composites.

4. FRAM PROCESS IMPROVEMENT STUDIES

The raster angle, print speed (speed of nozzle), layer thickness, repeated heating and cooling, print platform temperature, infill speed, nozzle temperature, and nozzle diameter are some processing parameters in AM. Among these properties, the raster angle, infill speed, layer thickness, and nozzle temperature are the major parameters that need to be considered very carefully before creating any product with AM. Print and infill speeds control the volume of extruded filament and cross-sectional geometry of the specimen. Nozzle temperature influences fluidity and solidification characterization of the extruded filament. The raster angle indicates the direction of wire printing regarding the longitudinal x-axis of the specimen. The raster angle and layer thickness have direct effects on mechanical properties of the final product such as Young's modulus, toughness, ductility, strength, etc. In addition, post-processing methods can also influence the mechanical performance of the FRAM parts. While support removal is inherent to FRAM, processes like sanding and polishing are primarily applied for aesthetics and dimensional accuracy. Furthermore, some post-processing methods like gap-filling and hot-pressing decrease porosity and increase interfacial bonding of the part.

Zhang et al. worked on characterizing deformations and residual stresses induced after fabricating a layer-by-layer structure of polymer-based CMs [67]. ABS, carbon nanotube reinforced ABS, and short CF reinforced ABS were used for this study. Displacement fields, shrinkage, porosity, and microstructure analysis were performed to study the effect of processing parameters like raster angle and printing speed. Results showed that as printing speed increases, porosity, shrinkage, and residual stresses increase for the final product. 45º raster angles showed the minimum shrinkage and porosity compared to 0º and 90º. Matsuzaki et al. [A] performed 3D printing of a CFRP circle to examine the effects of set radius of curvature and fiber bundle size on the precision of the radius of curvature. It was demonstrated that with a larger fiber bundle size or a smaller set radius, the printed radius decreased from the set value. Also, analytical models to predict the actual printed radius were constructed and validated based on the experimental study [68]. Ning et al. studied the effects of FDM process parameters on tensile properties of CFRPs [69]. Raster angle, infill speed, layer thickness, and nozzle temperature were considered as major process parameters and their effects on tensile strength, Young's modulus, yield strength, ductility, and toughness were investigated. Tian el al. studied performance characteristics and interfaces of 3D printed composite parts by investigating the effect of process parameters on pressure and temperature [70]. At 200-230ºC, good impregnation of fibers and plastics was achieved, and bond strength also improved by taking the layer thickness from 0.4-0.6 mm and hatch gap of 0.6 mm. The authors also concluded that maximum flexural strength and flexural modulus were achieved at 27% fiber content.

These process parameters should be carefully controlled, otherwise they lead to unwanted defects on the surface of specimens. Due to porosities, more stress concentration takes place, which ultimately reduces the strength of the final product. Researchers have performed experimental analyses in an attempt to reduce porosity. Tekinalp et al. fabricated CFRPs using AM to investigate the effect of fiber orientation, dispersion, and void formation on the final product [71]. The results showed that by increasing the carbon-fiber content in ABS, a significant increase in porosities was observed. Yamawaki et al. fabricated continuous CFRTPs for mechanical characterization [72]. Hot pressing was also performed on the 3D printed product to further improve mechanical performance of the final specimen by reducing porosities. This experiment showed that tensile strength (700 MPa) and Young's modulus (53 GPa) for the 3D printed specimen increases up to twice as much after performing hot-pressing. Leong et al. constructed porous polymetric matrix drug delivery devices with SLS [73]. This study focused on SLS processing parameters such as laser power and laser scanning speed to control the porosity of the product. SEM and mercury porosimetry were performed to analyze surface morphology and porosities, respectively. From morphology analysis, the authors revealed that the channel width increased with increase in scanning speed and decrease in laser power. The porosity level showed a linear relationship with laser power. Shofner et al. fabricated CMs with vapor-grown carbon fibers and ABS material by FDM and studied issues related to porosity, dispersion, and alignment of fibers [74].

Papon et al. studied the effect of nozzle geometries and nanofiber concentrations on void contents of CMs [75]. Square nozzle geometry showed increased tensile strength and reduced void formation in cellulose nanofiber/PLA CMs. TEM analysis showed that there was uniform dispersion of carbon nanofibers with aligned orientation. Eichenhofer et al. introduced continuous lattice fabrication (CLF) for manufacturing fiber reinforced thermoplastic composites and demonstrated its ability to exploit anisotropic material properties [76]. The authors proved that CLF enables orientation in all the X, Y, Z coordinates and continuous deposition of high fiber volume fraction along the building trajectory. Farina et al. employed 3D printing to design reinforced particles in the cement mortar [77]. Rough and smooth reinforced particles were selected to compare the load carrying capacity of the final product. Results of this study showed that the matrix reinforced with rough fibers (Ti6Al4V) exhibited shear failure and high interfacial bond strength compared to the matrix reinforced with smooth fibers (photopolymeric), which eventually increases its load carrying capacity. Hill et al. analyzed the dependency of material properties on raster angle [78]. Tensile strength, yield strength, elastic modulus, hardness, and density of the material were experimentally measured as functions of raster angle.

5. FRAM PRODUCTION TECHNOLOGIES

AM is probably the most versatile technology for manufacturing complex structures, as it is difficult to fabricate complex structures of 3D printed composite products using conventional methods like hand layup, spray up, pultrusion, filament winding, compression and injection molding, etc. [79]. Since AM does not require any special tooling, there is a potential for less cost, labor, and production time. In this regard, FRAM produced parts are likely to be lighter, sustainable, and lower cost than traditionally made parts [80]; however, most AM-produced parts require post-processing like sanding, trimming, infiltrating, and polishing.

Previous research has compared the physico-mechanical properties of conventional methods and AM methods of making CMs. Kuldeep Agarwal et al. performed a comparison study between conventional composite processes and composite filament fabrication (CFF) [79]. Elastic modulus, tensile strength, and fatigue life were compared for the different processes and the effect of process parameters like fiber volume fraction, fill pattern, etc. were also studied in this work. Results in this study showed that parts produced with CFF have better mechanical properties compared to conventional techniques. Van Der Klift et al. fabricated CFRTPs with a Mark One 3D printer using direct digital manufacturing (DDM) [81]. The aim of this study was to compare tensile properties of 2-layer and 6-layer CFRTPs made by DDM and by conventional methods. The 2CF specimens came close to the rule of mixing for composites made by conventional methods due to the formation of many voids in the 6CF composites. Sugiyama et al. used a continuous carbon fiber 3D printer to manufacture CFRTP sandwich structures with various core shapes and surface as a single piece. The study investigated increasing the flexibility of core shape design. It was demonstrated that continuous carbon fiber 3D printers could be applied for flexible design of core shapes matching the required strength and stiffness [82]. Justo et al. reported experimental characterization of fully-made nylon-based additive layer manufactured (ALM) CMs [83]. Results of this study showed that mechanical properties of ALM produced CMs were not yet comparable with autoclave manufacturing of CMs due to high porosities and low fiber volume. Dhariwala et al. designed a scaffold using hydrogels combined with cell-encapsulation to provide mechanical strength and access to nutrients for new tissue using SLA, which was not quite achievable by traditional cell-seeding techniques [84]. Results showed that SLA is highly useful in producing complex constructs and the cells were viable and proliferating within the constructs.

6. MECHANICAL PROPERTIES OF FRAM

6.1 Tensile strength

Mechanical properties of FRAM have been thoroughly investigated. Starting with tensile properties, different studies have been conducted on different factors. Generally, testing was done to investigate improving the maximum carrying load capacity and the effects of different printing parameters on this aspect. Van der Klift et al. conducted a brief study on CF reinforced nylon specimens using Japanese standard JIS K 7073 [81]. Dickson et al. extended the study by investigating the effect of volumetric fraction and fiber orientation angles on tensile properties of Kevlar, CF, and FG reinforced nylon specimens [85]. Results showed that CF reinforced specimens performed 6.3 times better than non-reinforced nylon specimens in tensile testing. Melenka et al. evaluated and predicted tensile properties of Kevlar reinforced nylon by using volume average stiffness [86]. The elastic moduli for specimens with fiber volume of 4.04, 8.08 and 10.1% were 1.76, 6.92, and 9.00 GPa, respectively. Model results differed by 57.5, 6.2, and 0.1% for the 4.04, 8.08, and 10.1% fiber volume fraction specimens, respectively. Li et al. manufactured a polymer-based CM using FDM by taking polylactic acid (PLA) as the matrix material and continuous carbon fiber (CCF) as the reinforcement and investigated the mechanical strength and thermodynamic properties of the final product [87]. Chen et al. and Imeri investigated the effect of fiber orientation to tensile properties by changing the number of rings to the specimens [88], [89]. From these results, CFs with two rings isotropic infill showed the best results with 419 MPa ultimate strength. Stress-strain curves of different specimens with different fiber reinforcement materials (Kevlar, FG, and CF) and infills are shown in Figure 3. It can be seen that the most deformed specimens were the fiberglass reinforced ones (FG5 RC, FG2 RI) regardless of the fiber direction. All of the specimens showed brittle behavior. However, carbon fiber reinforced specimens (CF2 RI) were the stiffest ones.

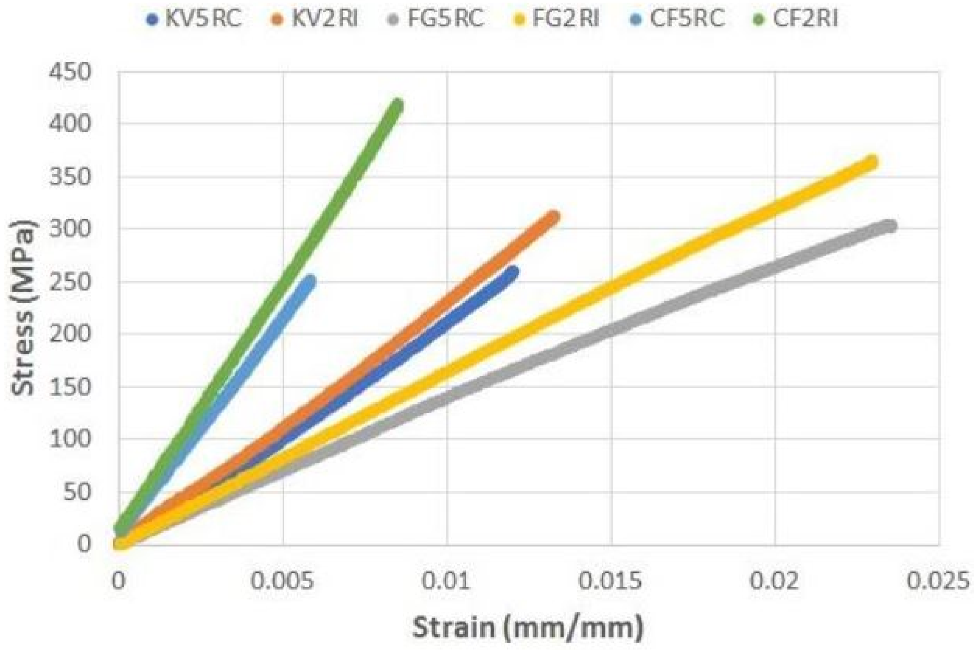

Figure 3: Stress-strain graph of tensile specimens with different fiber reinforcement materials and different infills (CF, KV, and FG) [88]

Further, Alwabel investigated the effect of fabrication process parameters on mechanical properties of CF reinforced specimens [90]. Factors included build time between successive layers, arrangement of fiber and nylon layers, fiber start location, and the use of supporting material. It was concluded that the effect of fiber start location and the use of supporting material had no significant negative impact on tensile properties. However, arrangement of fibers had a negative effect on ultimate tensile strength.

In general, FRAM parts performed much better than plain 3D printed parts with ABS, PLA, nylon, and others. In addition, the effect of fiber orientations is thoroughly understood, but there is still more work to be done in attempting to predict tensile properties of these parts. Specifically, parts can be assumed to consist of laminas and then analyzed using classical laminate theory [91].Still the model will not take into account surface and internal defects which come from the toolpath of the printer. This remains an open problem for researchers to solve. On the other hand, the better tensile properties lead to a higher cost. Thus, FRAM is more expensive than PLA and ABS as shown in Figure 5.

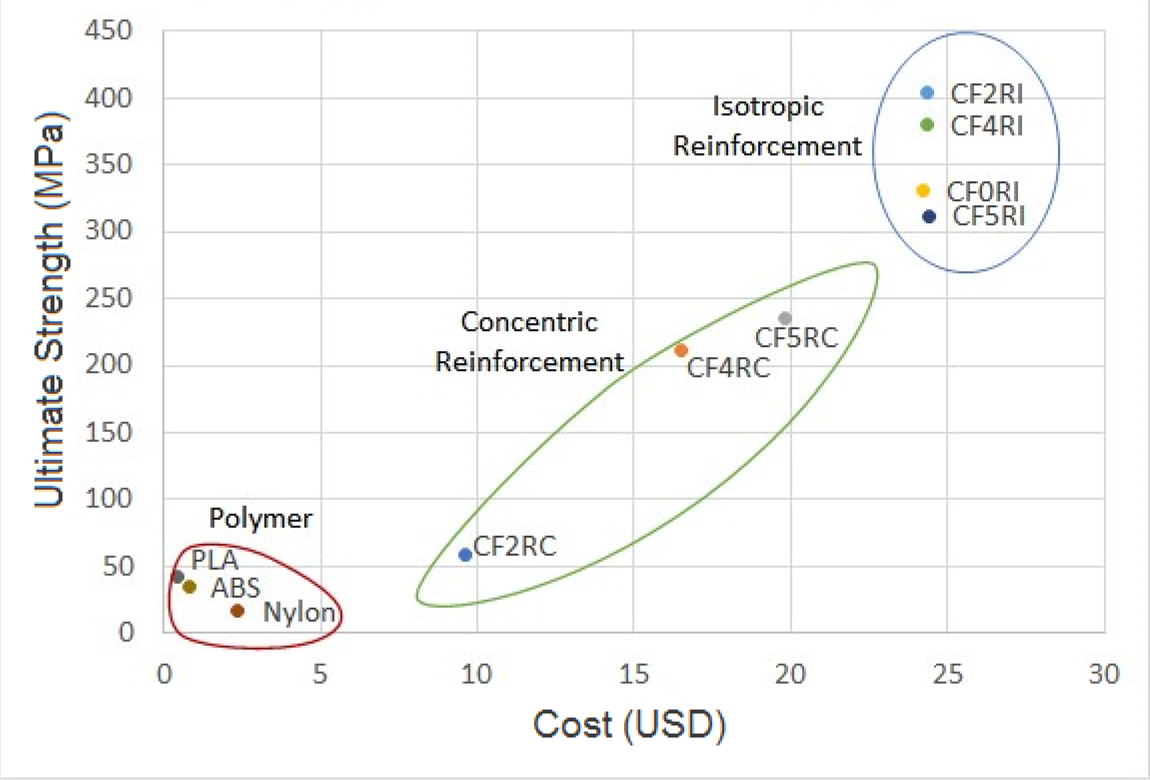

Figure 5: UTS-cost comparison of FRAM and conventional 3D printing materials [89].

6.2 *Fatigue strength*

Fatigue failure constitutes 50-90% of all mechanical failures [92]. Hence, it is important to know how a part would react under cyclic loading. In FRAM parts, it is also important to know how the parts can be made stronger with varying fiber volume, direction, and other significant parameters. On the subject of fatigue properties, Kuchipudi investigated the effect of volume fraction of fiber to the number of cycles up to failure [93]. Specimens of 25 and 50% fiber volume with 0°, 45°, and 90° fiber orientations, respectively, were fatigue-tested at different loads. In terms of strength, 0° specimens proved to be the strongest while 90° ones were the weakest. In terms of ductility, compared to 0° and 90° orientations, 45° specimens elongated more.

Imeri et al. investigated the effect of fiber orientation on fatigue properties [94]. Specimens were tested at different loads with a load ratio R=0.1. Fiber orientation was divided into two groups: concentric and isotropic. Concentric specimens with two and three rings failed in the first load of 3.33-0.33 kN and were much weaker than the isotropic ones. Isotropic infill implies the way the fiber is laid down, not mechanical properties. CF specimens with zero and one rings proved to be the strongest. Imeri et al. performed analysis of variance (ANOVA) on the experimental data to understand the effect of load, material, number of rings, and the interaction of load and material [95]. From ANOVA, it was found that the interaction of load and material was not significant. However, load, material, and rings with very small p-values, as shown in Table 2, proved to have a significant effect on the number of cycles.

Table 2: ANOVA results of FRAM fatigue specimens [95]

	Df	Sum Sq	Mean Sq	F value	p value
Load	3	46.542	15.5141	31.894	3.58E-09
Material	2	33.521	16.7607	34.4567	2.82E-08
Rings	3	27.645	9.2149	18.944	6.57E-07
Load *Material	2	4.331	2.1653	4.4514	0.02096
Residuals	28	13.62	0.4864		

Overall, the conducted studies create a base knowledge about fatigue properties of FRAM components, but there is still research to be done on this subject.

6.3 *Creep deformation*

Creep is a continuing deformation of material under constant stress over a period of time. Studying FRAM properties is of great importance due to many applications of FRAM above the transition temperature. However, creep properties of FRAM have not been investigated thoroughly. Mohammadizadeh et al. intended to increase the knowledge base of creep behavior of fiber reinforced (CF, Kevlar, FG) specimens at room temperature and 100°C [96]. Nylon specimens without reinforcement deformed the most while CF reinforced specimens deformed the least. Statistical analysis with a 98% coefficient of determination verified there was difference in the creep models for different fibers. Strain of 3D printed polymer composites at two different temperatures is shown in Figure 6 for each FRAM specimen.

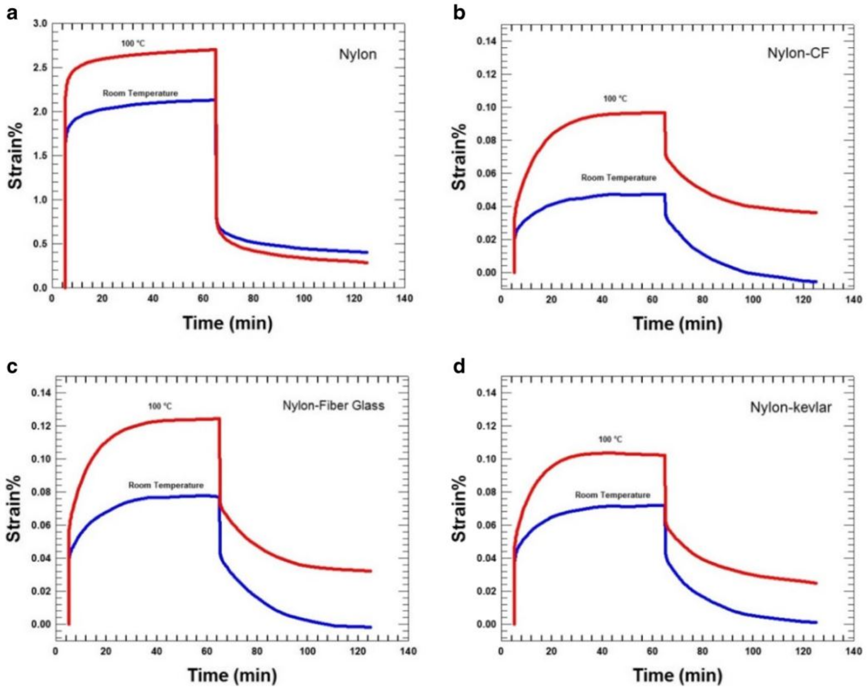

Figure 6: Strain of FRAM specimens at two different temperatures [96]

6.4 *Fracture toughness*

6.5 Fracture toughness is the ability of a component to resist fracture. In FRAM, the fiber orientation and interlayer bonding are crucial to the crack propagation of the part. There are a few studies that have attempted to increase fracture toughness of FRAM parts. Recently, Papon et al. have investigated inter-laminar fracture toughness of short carbon fiber filled PLA composites with different layer orientations (0°/ 90°and 45°/-45°) [97]. The authors have shown that square nozzle geometry improves the bond strength and enhances the contact surface areas between adjacent beads by conducting fracture toughness tests on the printed specimens. Furthermore, Young et al. has investigated the interlayer fracture toughness of additively manufactured unreinforced and carbon fiber reinforced ABS. The fracture toughness of the reinforced specimens was reduced due to poorly wetting of carbon fiber[98]. Since there are not many studies in the literature, this property of FRAM materials can be investigated further by varying fiber composition, fiber alignment, and process parameters.Topology optimization

Topology optimization (TO) is a mathematical method of structural optimization in which material is distributed depending on constraints of the design volume or area [99]. With the ability of AM to create complex parts, the possibility to bridge AM with TO rises for the purpose of reducing material use and mass [100]. In 3D printing of single materials, there have been applications of TO for AM [101]–[103]. However, when it comes to FRAM, applications of TO are fewer in number. Among various reasons, it could be that in addition to boundary conditions, design volume, and other constrains, optimizing for FRAM has more barriers. First, modeling of the part has to be for multi-materials. Next, fiber angle optimization has to be conducted, as well. Even though these constrains exist, there are some studies conducted in the literature. Jacome et al. have developed an analysis framework for TO of 3D printed reinforced composites [104]. The approach developed is a multi-step optimization. First, the structure is optimized in a design volume. The second step is dependent on manufacturability criteria and the design is explored in the fiber angle space. Since Jacome et al. do not have a specific FRAM hardware system, their focus is on the first step of this multidisciplinary design optimization framework. Hoglund et al. presented a TO method for continuous fiber angle optimization approach for fused filament fabrication parts [105]. Optimization is done in a two-dimensional area and the fiber angle after was shown to align along with the axis of the structural members formed after optimization. After testing, parts showed to be stiffer compared to the structures designed without accounting for fiber direction.

6.6 Machine Learning

Machine learning (ML) is a branch of artificial intelligence, which perceives or recognizes patterns from complex data sets [106]. This method has proved to be valuable in various research fields [107]. Researchers have just recently started to apply ML in the field of FRAM, as well. Gu et al. conducted a study designing bioinspired composite materials using ML [108]. Designs were simulated, 3D printed, and tested for tensile strength. This study showed that new materials with bioinspired microstructures can be designed using ML and their properties can also be predicted. These new microstructures can be printed using AM. ML is not only applicable in AM research but also in AM industry. AREVO Inc., based in California, has established a machine capable of printing fiber reinforced composites [109]. AREVO Inc. uses ML in the digital design and process software of FRAM with parameters including temperature, print path, warpage, shrinkage of the printed material, and residual stresses. Although ML is still in its early days, it is envisaged that its potential in FRAM could soon be realized. This may include improving efficiency, real-time control, and predictive maintenance of machines.

7. APPLICATIONS

FRAM has become the choice of a wide range of applications in automotive, aerospace, biomedical, and other industries [110]. In the automotive industry, Divergent 3D introduced one of the world’s first 3D printed CF-made lightweight cars [111]. This culminated in PSA Group’s strategic partnership with Divergent 3D to build carbon-based vehicle structures [112]. Reduced weight and high strength are imperative in aerospace industries [113]. NASA accomplished numerous studies in order to reduce emission and fuel burn and make lighter turbofans for business jets [114], [115]. Another application of composite-based AM is a jet engine that was developed by CFM with GE Aviation. This next generation engine called the “LEAP Engine” with durable and lightweight features offers 15% increased fuel efficiency, 50% reduced emissions, and 75% lower noise effect [116], [117]. Successful utilization of this process has relatively popular aircraft applications in various Airbus and Boeing airplane models [115].

Lightweight, high-strength, and individual parts like steering rack extensions, shown in Figure 6, wheel suspension, structural brackets, and other parts have been applied to Formula SAE and F1 cars, respectively [118], [119]. Apart from cars, AREVO Inc. prints composites using a robotic arm and has announced the world's first 3D printed CF eBike frame, which could be a promising alternative for bike manufacturers [109]. Successful results of these implementations have proven the functionality of FRAM in robust engineering applications. In general, conventionally machined aluminum parts could be replaced with FRAM ones out of CF with nylon, based on the evidence presented in this review [118]. Successful implementation of FRAM-made wrenches (Figure 8) has provided ergonomic, lightweight, affordable solutions to making tools for industrial applications. Further, Hofstätter et al. replaces injection molding inserts with FRAM ones and showed that lifetime and crack-propagation velocity were successfully improved [120]. Finally, FRAM has been applied to various industries and is growing day by day due to its advantages over traditional methods.

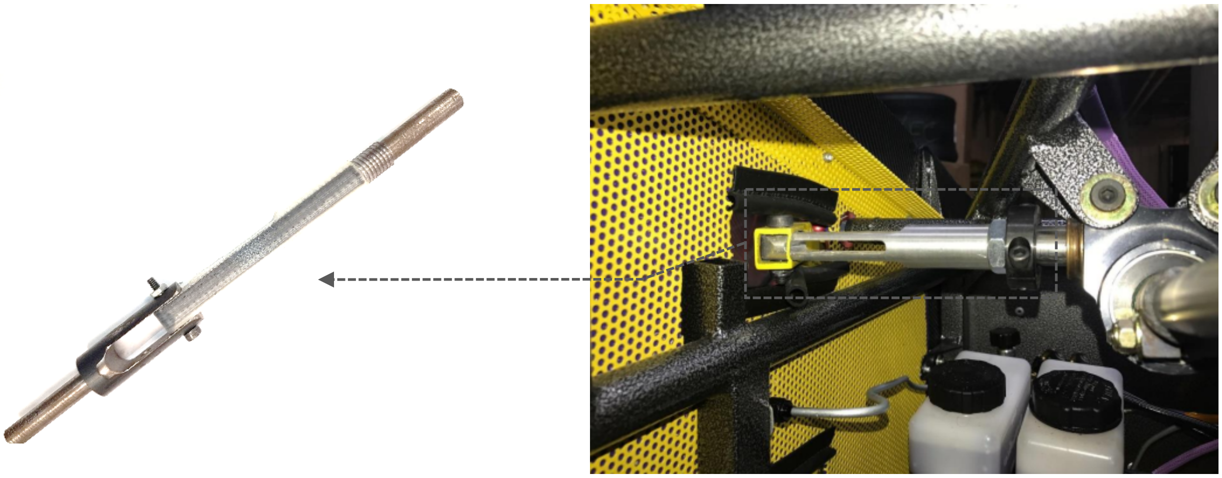

Figure 7: Steering rack and its location on Formula SAE car [118]

Figure 8: Aluminum, FRAM, and PLA wrenches

8. FUTURE OF FRAM

Numerous industries and institutions are investigating ways to utilize FRAM to print lightweight and sustainable products to compete with conventional techniques. Among these are Xi'an Jiaotong University (China), Eskisehir Osmangazi University (Turkey), Georgia Institute of Technology (USA), Rochester Institute of Technology (USA), and Tennessee Technological University (USA) [121]. Further, researchers at Oak Ridge National Laboratory have built car frames using AM and CF reinforced ABS to replace serial production [122], [123]. Boeing and Ford Motor Company provided funding for Stratasys' Robotic Composite 3D Demonstrator to print lightweight and low-volume parts [124]. Another potential application of FRAM could be in biomedical engineering for load-bearing composite orthopedic implants and prosthetic limbs [60]. Moreover, fiber-filled plastics are modified to have enhanced thermal and electrical conductivity, thus making it possible to utilize their full potential in product design [125].

There are other novel FRAM processes. One of them that was invented by Continuous Composites utilizes fast UV light-curing thermosets reinforced with continuous fibers to print 3D structures by means of a robotic arm [126]. Similarly, Eichenhofer et al. conduct extensive research on CLF, which is not based on layer by layer build up, but rather, extruding fiber in three dimensional space, which allows engineers to fully utilize load bearing capabilities of composites [127]. All in all, latest developments in FRAM will expand its application field to different industries such as concrete printing, dentistry, and architecture.

The utilization of FRAM fabricated parts is growing in various manufacturing fields; however, the current studies report a certain number of barriers which are related to processes, materials, and machines. It is predicted that the upcoming research studies will focus on the improvements of parameters related to these factors. The authors of this paper identify the following core challenges provided in Table 3 that the researchers will be investigating to improve FRAM.

Table 3: Future challenges.

Challenge	Clarification
Enhancement of interfacial bonding	High interfacial bonding between the matrix and reinforcements is desirable in order to enhance the mechanical properties of the composite materials.
Minimization of porosities	Preventing the formation of voids inside the specimen by selecting the appropriate process parameters like inert atmosphere, nozzle temperature, fan cooling speed, printing speed, etc.
Refractory behavior of materials	Improving the thermal performance of the polymer matrix composite in order to use them in high temperature applications i.e. automotive and aerospace industries.

Electric and magnetic properties	Improvement of electrical conductivity and magnetic properties of polymer matrix composites by selecting the appropriate fiber type and composition.
Flexibility in fiber placement	Increasing the degrees of freedom of the fiber placement inside the matrix material in such a way that the mechanical properties get enhanced in all three directions.
Cost reduction of machines and materials	Due to the limited availability of the industrial-scale FRAM printers, it is necessary to develop new materials and printers in order to make them available at lower cost.
Limited adaptation of the technology	Considering the advantages of FRAM fabricated parts in making lightweight and sustainable products, integration of the technology to other field of studies will have to grow.
Generative design based on fiber orientation	TO software tools for FRAM parts along with optimization of fiber placement angle should be developed.

9. CONCLUSION AND FUTURE DIRECTIONS

The present paper examines the advanced studies held in the field of FRAM and proves that this technology has a potential to be used in various engineering fields successfully. The research studies conducted are mainly on evaluating and improving the mechanical properties of the FRAM parts. It has been shown that mechanical properties like strength, thermal and electrical conductivity, fatigue life, and creep resistance are greatly improved by using FRAM. Moreover, FRAM processes also reduce the time and cost associated in manufacturing the industrial complex workpieces.

Despite these improvements, FRAM faces challenges in the area of post-processing and porosities. Post-processing needs to be done in order to remove the support materials and maintain dimensional accuracies. The presence of porosities inside or on the surface of the part leads to more stress concentration and eventually reduces mechanical strength. Many researchers put significant efforts into experimental analyses to discover ways to reduce porosity.

Raster angle, infill speed, layer thickness and nozzle temperature have a significant effect on the porosity level, shrinkage, and microstructure of the material. These process parameters have direct effect on the ductility, toughness, Young's modulus and strength of the material. Careful consideration of these parameters will broaden the application of FRAM in several industries.

Furthermore, linkage of FRAM with topology optimization and machine learning is on its origin, but very promising. Compared to single material AM, where the topology optimization is concentrated in the structure mainly, fiber alignment in FRAM structures needs to be optimized. Not only research institutions but also industrial companies are starting to use the generative design for making stronger parts. However, significant efforts need to be done in the future to ease the implementation of topology optimization and machine learning in FRAM processes. Smart manufacturing system of FRAM will be established by a fusion of current manufacturing system and artificial intelligence technology in the near future. Thus, smart FRAM printers will predict defects of products and troubles of printing in advance and adjust process parameters to perform normal operation. Therefore, the field of topology optimization, machine learning, and big data analytics will be significant and be expanded rapidly.

Current possible applications of FRAM in multiple industries such as aerospace, automotive, and biomedicine are presented in this review. In conclusion, FRAM is a promising field with many challenges to be tackled and different areas to be explored more in the future. It is clear that the next generation of FRAM-related research will be closely tied to the advancement of computers, resources, and analytical tools.

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REFERENCES

[1] D. Feldman, “Polymer History,” *Des. Monomers Polym.*, no. 11–1, pp. 1–15, 2008.

[2] T. L. Szabo, “Introduction to plastics,” in *Plastics*, 3rd ed., Elsevier, 2005, pp. 1–20.

[3] W. J. ROFF and J. R. SCOTT, “POLYVINYL FORMAL, ACETAL AND BUTYRAL,” in *Fibres, Films, Plastics and Rubbers*, Elsevier, 1971, pp. 82–86.

[4] M. C. Thiry, “The customer is king!: Quality, performance, and the challenge of keeping the consumer happy,” *AATCC Rev.*, vol. 4, no. 3, pp. 35–38, 2004.

[5] T. Palucka and B. Bensaude-Vincent, “Composites: Overview,” *Hist. Recent Sci. Technol. жовтня*, 2002.

[6] P. Mallick, *Fiber-Reinforced Composites*, 3rd ed., vol. 20072757. CRC Press, 2007.

[7] M. J. Donachie and C. Zweben, *Mechanical Engineers’ Handbook*, 3rd ed. Hoboken, NJ, USA: John Wiley & Sons, Inc., 2005.

[8] B. Conner *et al.*, “Making sense of 3-D printing: Creating a map of additive manufacturing products and services,” *Addit. Manuf.*, vol. 1, pp. 64–76, 2014.

[9] J. P. Kruth, P. Mercelis, J. Van Vaerenbergh, L. Froyen, and M. Rombouts, “Binding mechanisms in selective laser sintering and selective laser melting,” *Rapid Prototyp. J.*, vol. 11, no. 1, pp. 26–36, 2005.

[10] S. H. Ahn, M. Montero, D. Odell, S. Roundy, and P. K. Wright, “Anisotropic material properties of fused deposition modeling ABS,” *Rapid Prototyp. J.*, vol. 8, no. 4, pp. 248–257, 2002.

[11] F. P. W. Melchels, J. Feijen, and D. W. Grijpma, “A review on stereolithography and its applications in biomedical engineering,” *Biomaterials*, vol. 31, no. 24, pp. 6121–6130, 2010.

[12] D. Klosterman, R. Chartoff, G. Graves, N. Osborne, and B. Priore, “Interfacial characteristics of composites fabricated by laminated object manufacturing,” *Compos. Part A Appl. Sci. Manuf.*, vol. 29, no. 9–10, pp. 1165–1174, 1998.

[13] S. H. Masood and W. Q. Song, “Thermal characteristics of a new metal/polymer material for FDM rapid prototyping process,” *Assem. Autom.*, vol. 25, no. 4, pp. 309–315, 2005.

[14] H. Brooks and S. Molony, “Design and evaluation of additively manufactured parts with three dimensional continuous fibre reinforcement,” *Mater. Des.*, vol. 90, pp. 276–283, 2016.

[15] C. Unterweger, O. Brüggemann, and C. Fürst, “Synthetic fibers and thermoplastic short-fiber-reinforced polymers: Properties and characterization,” *Polym. Compos.*, vol. 35, no. 2, pp. 227–236, Feb. 2014.

[16] Markforged, “https://markforged.com/about,” 2017. [Online]. Available: https://markforged.com/about. [Accessed: 12-Oct-2018].

[17] M. Ivey, G. W. Melenka, J. P. Carey, and C. Ayranci, “Characterizing short-fiber-reinforced composites produced using additive manufacturing,” *Adv. Manuf. Polym. Compos. Sci.*, vol. 0340, pp. 1–11, 2017.

[18] F. Ning, W. Cong, J. Qiu, J. Wei, and S. Wang, “Additive manufacturing of carbon fiber reinforced thermoplastic composites using fused deposition modeling,” *Compos. Part B Eng.*, vol. 80, pp. 369–378, 2015.

[19] "Mark Two | Markforged." [Online]. Available: https://markforged.com/mark-two/. [Accessed: 29-Sep-2018].

[20] "X7 | Markforged." [Online]. Available: https://markforged.com/x7/. [Accessed: 29-Sep-2018].

[21] D. Gu, H. Wang, and G. Zhang, "Selective laser melting additive manufacturing of Ti-based nanocomposites: The role of nanopowder," *Metall. Mater. Trans. A Phys. Metall. Mater. Sci.*, vol. 45, no. 1, pp. 464–476, 2014.

[22] D. Gu *et al.*, "Selective laser melting additive manufacturing of TiC/AlSi10Mg bulk-form nanocomposites with tailored microstructures and properties," *Phys. Procedia*, vol. 56, no. C, pp. 108–116, 2014.

[23] S. K. Bandyopadhyay, P. K. Ghose, S. K. Bose, and U. Mukhopadhyay, "The thermal resistance of jute and jute-blend fabrics," *J. Text. Inst.*, vol. 78, no. 4, pp. 255–260, 1987.

[24] T. Powell *et al.*, "Engineering Properties of Flax Fiber and Flax Fiber-Reinforced thermoplastic in Rotational molding," *J. Mater.*, pp. 1–7, 2008.

[25] S. Farah, D. G. Anderson, and R. Langer, "Physical and mechanical properties of PLA, and their functions in widespread applications — A comprehensive review," *Adv. Drug Deliv. Rev.*, vol. 107, pp. 367–392, 2016.

[26] DuPont, "KEVLAR ® ARAMID FIBER TECHNICAL GUIDE," 2017. [Online]. Available: http://www.dupont.com/content/dam/dupont/products-and-services/fabrics-fibers-and-nonwovens/fibers/documents/Kevlar_Technical_Guide.pdf. [Accessed: 12-Oct-2018].

[27] F. R. Cichocki and J. L. Thomason, "Thermoelastic anisotropy of a natural fiber," *Compos. Sci. Technol.*, vol. 62, no. 5, pp. 669–678, 2002.

[28] J. Thomason, L. Yang, and F. Gentles, "Characterisation of the Anisotropic Thermoelastic Properties of Natural Fibres for Composite Reinforcement," *Fibers*, vol. 5, no. 4, p. 36, 2017.

[29] D. W. Chalmers, "The Potential for the use of composite materials in marine structures," *Mar. Struct.*, vol. 7, pp. 441–456, 1994.

[30] T. F. Pereira, M. F. Oliveira, I. A. Maia, J. V. L. Silva, M. F. Costa, and R. M. S. M. Thiré, "3D Printing of Poly(3-hydroxybutyrate) Porous Structures Using Selective Laser Sintering," *Macromol. Symp.*, vol. 319, no. 1, pp. 64–73, 2012.

[31] M. F. Oliveira *et al.*, "Building tissue engineering Scaffolds utilizing rapid prototyping," *Matéria (Rio Janeiro)*, vol. 12, no. 2, pp. 373–382, 2007.

[32] E. A. Campo, "The Complete Part Design Handbook," *Hanser*, pp. 1–114, 2006.

[33] K. Boparai, R. Singh, and H. Singh, "Comparison of tribological behaviour for Nylon6-Al-Al2O3 and ABS parts fabricated by fused deposition modelling: This paper reports a low cost composite material that is more wear-resistant than conventional ABS," *Virtual Phys. Prototyp.*, vol. 10, no. 2, pp. 59–66, 2015.

[34] K. I. Mori, T. Maeno, and Y. Nakagawa, "Dieless forming of carbon fibre reinforced plastic parts using 3D printer," *Procedia Eng.*, vol. 81, no. October, pp. 1595–1600, 2014.

[35] C. Ajinjeru *et al.*, "Determination of melt processing conditions for high performance amorphous thermoplastics for large format additive manufacturing," *Addit. Manuf.*, vol. 21, pp. 125–132, 2018.

[36] S. H. Masood and W. Q. Song, "Development of new metal/polymer materials for rapid tooling

using Fused deposition modelling," *Mater. Des.*, vol. 25, no. 7, pp. 587–594, 2004.

[37] P. Nugroho, H. Mitomo, F. Yoshii, and T. Kume, "Degradation of poly(L-lactic acid) by γ-irradiation," *Polym. Degrad. Stab.*, vol. 72, no. 2, pp. 337–343, 2001.

[38] H. Urayama, T. Kanamori, K. Fukushima, and Y. Kimura, "Controlled crystal nucleation in the melt-crystallization of poly(L-lactide) and poly(L-lactide)/poly(D-lactide) stereocomplex," *Polymer (Guildf).*, vol. 44, no. 19, pp. 5635–5641, 2003.

[39] H. Tsuji and Y. Ikada, "Properties and morphologies of poly(?-lactide): 1. Annealing condition effects on properties and morphologies of poly(?-lactide)," *Polymer (Guildf).*, vol. 36, no. 14, pp. 2709–2716, 1995.

[40] H. Urayama, C. Ma, and Y. Kimura, "Mechanical and thermal properties of poly(L-lactide) incorporating various inorganic fillers with particle and whisker shapes," *Macromol. Mater. Eng.*, vol. 288, no. 7, pp. 562–568, 2003.

[41] T. Trimaille, C. Pichot, A. Elaïssari, H. Fessi, S. Briançon, and T. Delair, "Poly(D,L-lactic acid) nanoparticle preparation and colloidal characterization," *Colloid Polym. Sci.*, vol. 281, no. 12, pp. 1184–1190, 2003.

[42] X. Hu, H. S. Xu, and Z. M. Li, "Morphology and properties of poly(L-lactide) (PLLA) filled with hollow glass beads," *Macromol. Mater. Eng.*, vol. 292, no. 5, pp. 646–654, 2007.

[43] Y. Di, S. Iannace, E. Di Maio, and L. Nicolais, "Reactively modified poly (lactic acid): Properties and foam processing," *Macromol. Mater. Eng.*, vol. 290, no. 11, pp. 1083–1090, 2005.

[44] C. X. F. Lam, R. Olkowski, W. Swieszkowski, K. C. Tan, I. Gibson, and D. W. Hutmacher, "Composite PLDLLA/TCP Scaffolds for Bone Engineering: Mechanical and In Vitro Evaluations," *IFMBE Proc.*, vol. 23, no. November 2014, pp. 1480–1483, 2009.

[45] S. Bose, S. Vahabzadeh, and A. Bandyopadhyay, "Bone tissue engineering using 3D printing," *Mater. Today*, vol. 16, no. 12, pp. 496–504, 2013.

[46] J. C. Nelson, S. Xue, J. W. Barlow, J. J. Beaman, H. L. Marcus, and D. L. Bourell, "Model of the selective laser sintering of bisphenol-A polycarbonate," *Ind. Eng. Chem. Res.*, vol. 32, no. 10, pp. 2305–2317, 1993.

[47] M. Berzins, T. H. C. Childs, and G. R. Ryder, "The Selective Laser Sintering of Polycarbonate," *CIRP Ann. - Manuf. Technol.*, vol. 45, no. 2, pp. 187–190, 1996.

[48] C. Heller, M. Schwentenwein, G. Russmueller, F. Varga, J. Stampfl, and R. Liska, "Vinyl esters: Low cytotoxicity monomers for the fabrication of biocompatible 3D scaffolds by lithography based additive manufacturing," *J. Polym. Sci. Part A Polym. Chem.*, vol. 47, no. 24, pp. 6941–6954, Dec. 2009.

[49] M. L. Minus and S. Kumar, "The processing, properties, and structure of carbon fibers," *J. Miner. Met. Mater. Soc.*, vol. 57, pp. 52–58, 2005.

[50] S. Chand, "Carbon fibers for composites," *J. Mater. Sci.*, vol. 35, no. 6, pp. 1303–1313, 2000.

[51] G. Liao *et al.*, "Properties of oriented carbon fiber/polyamide 12 composite parts fabricated by fused deposition modeling," *Mater. Des.*, vol. 139, pp. 283–292, 2018.

[52] W. Zhong, F. Li, Z. Zhang, L. Song, and Z. Li, "Short fiber reinforced composites for fused deposition modeling," *Mater. Sci. Eng. A301*, vol. 301, pp. 125–130, 2001.

[53] L. J. Love *et al.*, "The importance of carbon fiber to polymer additive manufacturing," *J. Mater. Res.*, vol. 29, no. 17, pp. 1893–1898, Sep. 2014.

[54] M. A. Caminero, J. M. Chacón, I. García-Moreno, and J. M. Reverte, "Interlaminar bonding performance of 3D printed continuous fibre reinforced thermoplastic composites using fused deposition modelling," *Polym. Test.*, vol. 68, pp. 415–423, 2018.

[55] P. Parandoush, L. Tucker, C. Zhou, and D. Lin, "Laser assisted additive manufacturing of continuous fiber reinforced thermoplastic composites," *Mater. Des.*, vol. 131, pp. 186–195, 2017.

[56] H. Chung and S. Das, "Processing and properties of glass bead particulate-filled functionally graded Nylon-11 composites produced by selective laser sintering," *Mater. Sci. Eng. A*, vol. 437, no. 2, pp. 226–234, 2006.

[57] M. Invernizzi, G. Natale, M. Levi, S. Turri, and G. Griffini, "UV-assisted 3D printing of glass and carbon fiber-reinforced dual-cure polymer composites," *Materials (Basel).*, vol. 9, no. 7, 2016.

[58] G. D. Goh *et al.*, "Characterization of mechanical properties and fracture mode of additively manufactured carbon fiber and glass fiber reinforced thermoplastics," *Mater. Des.*, vol. 137, pp. 79–89, 2018.

[59] M. F. Oliveira *et al.*, "Construção de Scaffolds para engenharia tecidual utilizando prototipagem rápida," *Matéria (Rio Janeiro)*, vol. 12, no. 2, pp. 373–382, 2007.

[60] R. Matsuzaki *et al.*, "Three-dimensional printing of continuous-fiber composites by in-nozzle impregnation," *Sci. Rep.*, vol. 6, no. 1, p. 23058, Sep. 2016.

[61] R. Singh, S. Singh, and F. Fraternali, "Development of in-house composite wire based feed stock filaments of fused deposition modelling for wear-resistant materials and structures," *Compos. Part B Eng.*, vol. 98, pp. 244–249, 2016.

[62] S. Kenzari, D. Bonina, J. M. Dubois, and V. Fournée, "Quasicrystal-polymer composites for selective laser sintering technology," *Mater. Des.*, vol. 35, pp. 691–695, 2012.

[63] R. Falck, S. M. Goushegir, J. F. dos Santos, and S. T. Amancio-Filho, "AddJoining: A novel additive manufacturing approach for layered metal-polymer hybrid structures," *Mater. Lett.*, vol. 217, pp. 211–214, 2018.

[64] O. Ivanova, C. Williams, and T. Campbell, "Additive manufacturing (AM) and nanotechnology: Promises and challenges," *Rapid Prototyp. J.*, vol. 19, no. 5, pp. 353–364, 2013.

[65] H. Zheng, J. Zhang, S. Lu, G. Wang, and Z. Xu, "Effect of core-shell composite particles on the sintering behavior and properties of nano-Al2O3/polystyrene composite prepared by SLS," *Mater. Lett.*, vol. 60, no. 9–10, pp. 1219–1223, 2006.

[66] H. Kim, T. Fernando, M. Li, Y. Lin, and T.-L. B. Tseng, "Fabrication and characterization of 3D printed BaTiO 3 /PVDF nanocomposites," *J. Compos. Mater.*, vol. 52, no. 2, pp. 197–206, Jan. 2018.

[67] W. Zhang *et al.*, "Characterization of residual stress and deformation in additively manufactured ABS polymer and composite specimens," *Compos. Sci. Technol.*, vol. 150, pp. 102–110, 2017.

[68] R. Matsuzaki *et al.*, "Effects of Set Curvature and Fiber Bundle Size on the Printed Radius of Curvature by a Continuous Carbon Fiber Composite 3D Printer," *Addit. Manuf.*, vol. 24, pp. 93–102, 2018.

[69] F. Ning, W. Cong, Y. Hu, and H. Wang, "Additive manufacturing of carbon fiber-reinforced

plastic composites using fused deposition modeling: Effects of process parameters on tensile properties," *J. Compos. Mater.*, vol. 51, no. 4, pp. 451–462, 2017.

[70] X. Tian, T. Liu, C. Yang, Q. Wang, and D. Li, "Interface and performance of 3D printed continuous carbon fiber reinforced PLA composites," *Compos. Part A Appl. Sci. Manuf.*, vol. 88, pp. 198–205, 2016.

[71] H. L. Tekinalp *et al.*, "Highly oriented carbon fiber-polymer composites via additive manufacturing," *Compos. Sci. Technol.*, vol. 105, pp. 144–150, 2014.

[72] M. Yamawaki and Y. Kouno, "Fabrication and mechanical characterization of continuous carbon fiber-reinforced thermoplastic using a preform by three-dimensional printing and via hot-press molding," *Adv. Compos. Mater.*, vol. 27, no. 2, pp. 209–219, 2018.

[73] K. F. Leong, K. K. S. Phua, C. K. Chua, Z. H. Du, and K. O. M. Teo, "Fabrication of porous polymeric matrix drug delivery devices using the selective laser sintering technique," *Proc. Inst. Mech. Eng. Part H J. Eng. Med.*, vol. 215, no. 2, pp. 191–192, 2001.

[74] M. L. Shofner, K. Lozano, F. J. Rodríguez-Macías, and E. V. Barrera, "Nanofiber-reinforced polymers prepared by fused deposition modeling," *J. Appl. Polym. Sci.*, vol. 89, no. 11, pp. 3081–3090, 2003.

[75] E. A. Papon and A. Haque, "Tensile properties, void contents, dispersion and fracture behaviour of 3D printed carbon nanofiber reinforced composites," *J. Reinf. Plast. Compos.*, vol. 37, no. 6, pp. 381–395, 2018.

[76] M. Eichenhofer, J. C. H. Wong, and P. Ermanni, "Continuous lattice fabrication of ultra-lightweight composite structures," *Addit. Manuf.*, vol. 18, pp. 48–57, 2017.

[77] I. Farina *et al.*, "On the reinforcement of cement mortars through 3D printed polymeric and metallic fibers," *Compos. Part B Eng.*, vol. 90, pp. 76–85, 2016.

[78] N. Hill and M. Haghi, "Deposition direction-dependent failure criteria for fused deposition modeling polycarbonate," *Rapid Prototyp. J.*, vol. 20, no. 3, pp. 221–227, 2014.

[79] K. Agarwal, S. K. Kuchipudi, B. Girard, and M. Houser, "Mechanical properties of fiber reinforced polymer composites: A comparative study of conventional and additive manufacturing methods," *J. Compos. Mater.*, vol. 52, no. 23, pp. 3173–3181, Sep. 2018.

[80] E. Yasa and K. Ersoy, "Additive Manufacturing of Polymer Matrix Composites," in *Aircraft Technology*, InTech, 2018, pp. 147–169.

[81] F. Van Der Klift, Y. Koga, A. Todoroki, M. Ueda, Y. Hirano, and R. Matsuzaki, "3D Printing of Continuous Carbon Fibre Reinforced Thermo-Plastic (CFRTP) Tensile Test Specimens," *Open J. Compos. Mater.*, vol. 06, no. 01, pp. 18–27, 2016.

[82] K. Sugiyama, R. Matsuzaki, M. Ueda, A. Todoroki, and Y. Hirano, "3D printing of composite sandwich structures using continuous carbon fiber and fiber tension," *Compos. Part A Appl. Sci. Manuf.*, 2018.

[83] J. Justo, L. Távara, L. García-Guzmán, and F. París, "Characterization of 3D printed long fibre reinforced composites," *Compos. Struct.*, vol. 185, pp. 537–548, 2018.

[84] B. Dhariwala, E. Hunt, and T. Boland, "Rapid Prototyping of Tissue-Engineering Constructs, Using Photopolymerizable Hydrogels and Stereolithography," *Tissue Eng.*, vol. 10, no. 9–10, pp. 1316–1322, Sep. 2004.

[85] A. N. Dickson, J. N. Barry, K. A. McDonnell, and D. P. Dowling, "Fabrication of continuous carbon, glass and Kevlar fibre reinforced polymer composites using additive manufacturing," *Addit. Manuf.*, vol. 16, pp. 146–152, 2017.

[86] G. W. Melenka, B. K. O. Cheung, J. S. Schofield, M. R. Dawson, and J. P. Carey, "Evaluation and prediction of the tensile properties of continuous fiber-reinforced 3D printed structures," *Compos. Struct.*, vol. 153, pp. 866–875, Oct. 2016.

[87] N. Li, Y. Li, and S. Liu, "Rapid prototyping of continuous carbon fiber reinforced polylactic acid composites by 3D printing," *J. Mater. Process. Technol.*, vol. 238, pp. 218–225, 2016.

[88] Y. Chen, C. Ortiz Rios, A. Imeri, N. Russell, and I. Fidan, "Investigation of the Tensile Properties in Fiber-Reinforced Additive Manufacturing and Fused Filament Fabrication," *Int. J. Rapid Manuf.*, no. Special Issue on 21st Century Manufacturing.

[89] A. Imeri, "Investigation of the Mechanical Properties for Fiber Reinforced Additively Manufactured Components," Tennessee Technological University, 2017.

[90] A. S. Alwabel, "Effect of Fused Filament Fabrication Process Parameters on the Mechanical Properties of Carbon Fiber Reinforced Polymers," Air Force Institute of Technology Wright-Patterson AFB United States, 2017.

[91] L. Li, Q. Sun, C. Bellehumeur, and P. Gu, "Composite Modeling and Analysis for Fabrication of FDM Prototypes with Locally Controlled Properties," *J. Manuf. Process.*, vol. 4, no. 2, pp. 129–141, Jan. 2002.

[92] R. Stephens, A. Fatemi, R. Stephens, and H. Fuchs, *Metal Fatigue in Engineering*. John Wiley & Sons, Inc., 2000.

[93] S. C. Kuchipudi, "The Effects of Fiber Orientation and Volume Fraction of Fiber on Mechanical Properties of Additively Manufactured Composite Material," Minnesota State University, 2017.

[94] A. Imeri, I. Fidan, M. Allen, and G. Perry, "Effect of Fiber Orientation in Fatigue Properties of FRAM Components," *Procedia Manuf.*, vol. 26, pp. 892–899, 2018.

[95] A. Imeri, I. Fidan, M. Allen, D. A. Wilson, and S. Canfield, "Fatigue analysis of the fiber reinforced additively manufactured objects," *Int. J. Adv. Manuf. Technol.*, vol. 98, no. 9–12, pp. 2717–2724, Oct. 2018.

[96] M. Mohammadizadeh, I. Fidan, M. Allen, and A. Imeri, "Creep behavior analysis of additively manufactured fiber-reinforced components," *Int. J. Adv. Manuf. Technol.*, pp. 1–10, Aug. 2018.

[97] E. A. Papon and A. Haque, "Fracture Toughness of Additively Manufactured Carbon Fiber Reinforced Composites," *Addit. Manuf.*, Dec. 2018.

[98] D. Young, N. Wetmore, and M. Czabaj, "Interlayer fracture toughness of additively manufactured unreinforced and carbon-fiber-reinforced acrylonitrile butadiene styrene," *Addit. Manuf.*, vol. 22, no. November 2017, pp. 508–515, 2018.

[99] E. Andreassen, A. Clausen, M. Schevenels, B. S. Lazarov, and O. Sigmund, "Efficient topology optimization in MATLAB using 88 lines of code," *Struct. Multidiscip. Optim.*, vol. 43, no. 1, pp. 1–16, Jan. 2011.

[100] W. Gao *et al.*, "The status, challenges, and future of additive manufacturing in engineering," *Comput. Des.*, vol. 69, pp. 65–89, Dec. 2015.

[101] T.-H. Kwok, Y. Li, and Y. Chen, “A structural topology design method based on principal stress line,” *Comput. Des.*, vol. 80, pp. 19–31, Nov. 2016.

[102] T. Zegard and G. H. Paulino, “Bridging topology optimization and additive manufacturing,” *Struct. Multidiscip. Optim.*, vol. 53, no. 1, pp. 175–192, Jan. 2016.

[103] J. Wu, N. Aage, R. Westermann, and O. Sigmund, “Infill Optimization for Additive Manufacturing—Approaching Bone-Like Porous Structures,” *IEEE Trans. Vis. Comput. Graph.*, vol. 24, no. 2, pp. 1127–1140, Feb. 2018.

[104] L. G. Bahamonde *et al.*, “An Analysis Framework for Topology Optimization of 3D Printed Reinforced Composites,” in *2018 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, 2018.

[105] R. Hoglund and D. E. Smith, “CONTINUOUS FIBER ANGLE TOPOLOGY OPTIMIZATION FOR POLYMER FUSED FILAMENT FABRICATION,” in *Solid Freeform Fabrication Symposium*, 2016, pp. 1078–1090.

[106] R. S. Michalski, J. G. Carbonell, and T. M. Mitchell, *Machine learning: An artificial intelligence approach*. Springer Science & Business Media, 2013.

[107] S. Ryszard Michalski, G. Carbonell Jamie, and M. Tom Mitchell, *Machine Learning*. Berlin, Heidelberg: Springer Berlin Heidelberg, 1983.

[108] G. X. Gu, C.-T. Chen, D. J. Richmond, and M. J. Buehler, “Bioinspired hierarchical composite design using machine learning: simulation, additive manufacturing, and experiment,” *Mater. Horizons*, vol. 5, no. 5, pp. 939–945, 2018.

[109] “AREVO Unveils First 3D-Printed Carbon-Fiber eBike - Arevo,” 2018. [Online]. Available: https://arevo.com/news_item/arevo-unveils-first-3d-printed-carbon-fiber-ebike/. [Accessed: 24-Sep-2018].

[110] J. Rodriguez and J. Lewicki, “A NEW COMPOSITE-MANUFACTURING Approach Takes Shape,” 2017.

[111] “Luxury Car Maker PSA Group Puts 3D Printing to Use for Car Chassis | 3DPrint.com | The Voice of 3D Printing / Additive Manufacturing,” 2015. [Online]. Available: https://3dprint.com/159574/peugeot-3d-printing-chassis/. [Accessed: 27-Sep-2018].

[112] T. Wohlers, I. Campbell, O. Diegel, J. Kowen, I. Fidan, and D. L. Bourell, *Wohlers Report 2018*. Wohlers Associates Inc, 2018.

[113] “3D Printing Applications | Markforged.” [Online]. Available: https://markforged.com/applications/. [Accessed: 12-Oct-2018].

[114] B. Soediono, “Summary for Policymakers,” in *Climate Change 2013 - The Physical Science Basis*, Intergovernmental Panel on Climate Change, Ed. Cambridge: Cambridge University Press, 1989, pp. 1–30.

[115] T. Hofstätter, D. B. Pedersen, G. Tosello, and H. N. Hansen, “State-of-the-art of fiber-reinforced polymers in additive manufacturing technologies,” *J. Reinf. Plast. Compos.*, vol. 36, no. 15, pp. 1061–1073, 2017.

[116] “LEAP Engines – CFM International Jet Engines CFM International,” 2015. [Online]. Available: https://www.cfmaeroengines.com/engines/leap/. [Accessed: 27-Sep-2018].

[117] "Additive Manufacturing – the future of manufacturing - THE GLOBAL MANUFACTURING & INDUSTRIALISATION SUMMIT." [Online]. Available: https://gmisummit.com/gmis-media/news/additive-manufacturing-the-future-of-manufacturing/. [Accessed: 27-Sep-2018].

[118] A. Imeri, N. Russell, J. R. Rust, S. Sahin, I. Fidan, and H. Jack, "3D printing as an alternative to fabricate the motor sports parts," *124th ASEE Annu. Conf. Expo.*, 2017.

[119] T. Hofstätter, D. B. Pedersen, G. Tosello, and H. N. Hansen, "Dimensional Accuracy and Surface Finish in Additive Manufacturing Challenges and opportunities of fibre-reinforced polymers in additive manufacturing with focus on industrial applications," no. October, pp. 3–6, 2017.

[120] T. Hofstätter, D. B. Pedersen, G. Tosello, and H. N. Hansen, "Applications of Fiber-Reinforced Polymers in Additive Manufacturing," *Procedia CIRP*, vol. 66, pp. 312–316, 2017.

[121] I. Fidan, "Academic Activities and Capabilities," in *Wohlers Report*, 2018, pp. 287–303.

[122] M. R. Talagani, S. Dormohammadi, R. Dutton, C. Godines, H. Baid, and F. Abdi, "Numerical Simulation of Big Area Additive Manufacturing (3D Printing) of a Full Size Car," *SAMPE J.*, vol. 51, no. 4, pp. 27–36.

[123] S. Curran *et al.*, "Big Area Additive Manufacturing and Hardware-in-the-Loop for Rapid Vehicle Powertrain Prototyping: A Case Study on the Development of a 3-D-Printed Shelby Cobra," in *SAE Technical Paper*, 2016.

[124] "3D printing takes-off," 2016. [Online]. Available: https://www.aerosociety.com/news/3d-printing-takes-off/. [Accessed: 25-Sep-2018].

[125] T. Mulholland, S. Goris, J. Boxleitner, T. Osswald, and N. Rudolph, "Process-Induced Fiber Orientation in Fused Filament Fabrication," *J. Compos. Sci.*, vol. 2, no. 3, p. 45, Aug. 2018.

[126] "Additive manufacturing industry got interested in fiber reinforced composites," 2017. [Online]. Available: http://basalt.today/2017/07/11611/. [Accessed: 25-Sep-2018].

[127] M. Eichenhofer *et al.*, "Analysis of Processing Conditions for a Novel 3D-COMPOSITE PRODUCTION TECHNIQUE," *20th Int. Conf. Compos. Mater.*, no. July, pp. 19–24, 2015.