1. Introduction

Additive manufacturing (AM) is a growing method that promises to unlock creativity and freedom in design. The original additive manufacturing technique, stereolithography (SLA), is a subset of vat photopolymerization (VPP) that allows rapid builds of complex components. VPP systems use ultraviolet radiation (UV) to cure photopolymer resins stored inside a tank onto a build plate. Resin systems are highly customizable, allowing for new configurations and tuning for a desired response. Unfortunately, the performance of the finished product is affected by multiple variables that are not always well understood. Additionally, final part performance rarely (if ever) achieves full bulk properties. Many groups have sought for ways to improve the strength and performance of different material systems and techniques. These tactics range from varying print settings to complex post-processing and from topology optimizing designs to material additives. Other AM families, particularly material extrusion, have sought to improve part performance by creating composites instead of monolithic structures. Composites are often used to optimize strength to weight ratio but can also improve electrical characteristics and thermal stability. Combining the tolerances and prototyping ability of VPP with the increased performance from composites could unleash the full potential of VPP for end use parts. Much work has been done in this area, but several challenges remain.

2. Background

2.1.1 Vat Photopolymerization

In 1986, Charles Hull made 3D printing history when he submitted the first patent application for a 3D printing technology for his stereolithography machine. His company, 3D Systems, would be the pioneers in Vat Photopolymerization for decades to come. VPP systems work by curing resins onto a build plate using UV either in the form of a laser, projector, or individual photons. The resins are comprised of monomers (which will form polymer chains), oligomers, and photoinitiators. The monomer part is generally acrylate or epoxy. Acrylates cure faster, show more deformation, and have lower material properties whereas the epoxies cure slower, have less shrinkage, and display better properties. Given this material makeup, the upper limit for material properties is limited by the properties of thermosets. Generally, thermosets don't get above a maximum modulus of 10 GPa whereas aluminum (a common material for end use parts) is around 70 GPa. Cure depth in VPP printing is given by the working curve formation of the Beer

Lambert law: $C_d = D_p \ln\left(\frac{E_{max}}{E_C}\right)$ where C_d represents the cure depth, D_p is the depth of penetration into the resin, E_{max} is energy dosage per unit area, and E_c is the critical energy.

2.1.2 *Stereolithography*

Stereolithography (SLA) systems cure resins on a point-by-point basis by using a laser directed at the area desired to be cured. Resolution of this process is based on the precision with which the laser can be pointed. A typical SLA machine is shown in Figure 1.

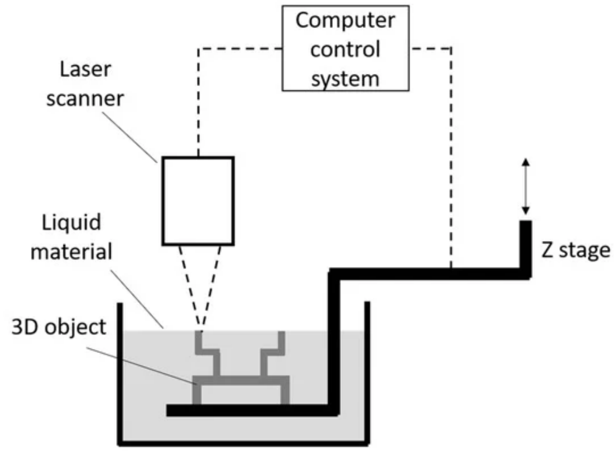

Figure 1: A standard SLA printer

2.1.3 *Digital Light Processing*

Digital Light Processing (or DLP) uses a digital micromirror devices (DMD) to project an entire layer for curing at once. This makes the process faster than SLA but lagging in resolution. Because it is inherently faster, DLP has taken the interest of those wishing to move beyond hobby trinkets, one-off parts, and prototyping into full scale manufacturing. As such, improving DMD resolution and increasing material properties are pressing challenges. A standard DLP machine is displayed in Figure 2.

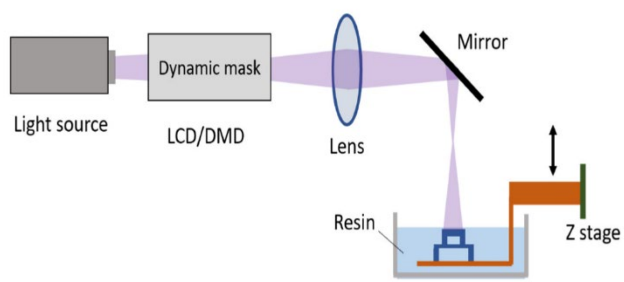

Figure 2: Schematic of a DLP printer

2.2.1 *Traditionally Manufactured Composites*

Composite materials are popular in industries such as automotive, aerospace, marine, and sports where a high strength to weight ratio is important. Other advantages include corrosion resistance, thermal stability, and fatigue resistance. Composites are created by combining two (or more) different materials to achieve desired properties. Often there is a "matrix" material that surrounds a "reinforcement" material. For example, what we usually call "fiber glass" is really a polymer matrix composite (PMC) with reinforcing glass fibers inside a polymer matrix. There are many ways to manufacture composites depending on the materials being used and equipment available. Many high throughput users cure parts in an autoclave. However, expensive equipment isn't necessarily required as many hobbyists use other "out of autoclave" methods in workshops or garages.

2.3.1 Composites with Other AM Methods

Several other AM methods have incorporated composites with varying levels of success. The most notable is material extrusion. Chopped fiber can be added to the filament before printing. Dickson et al [1] used this method to demonstrate an increase of ultimate tensile strength of around 2-3x and an increase in Young's modulus of ranging from 6-14x. Much research has been done to optimize factors such as adhesion between fiber and matrix or filament alignment in material extrusion. Differences in fiber alignment samples can cause variability in ultimate tensile strength and Young's modulus of 30% or greater [2]. Better adhesion between fiber and matrix increases the force required for fiber debond failures [3]. Incorporating similar ideas into VPP (and other methods) is non-trivial and still in its infancy especially for fillers longer than small particulates.

3. Different Types of VPP Composites

In traditionally manufactured composites, part performance is highly dependent on fiber length. Typical classifications include milled (<200 um), chopped (up to 6mm), and continuous (>6mm, often the entire length of the part) as shown in *Figure 1*. Longer fibers generally result in better material properties. Thus, to optimize printed composites it is advantageous to maximize the printed fiber length. However, this presents several challenges to printing regardless of additive manufacturing method. The following sections will highlight methods being used to print composites using VPP methods including several experimental techniques to overcome some of the problems printing composites with VPP poses.

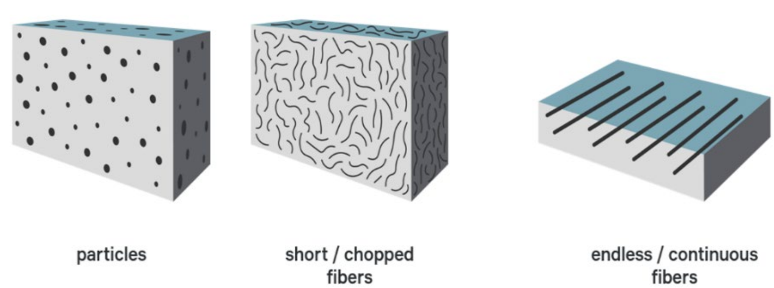

Figure 3. Comparison of fiber sizes in composites

3.1.1 Nano and Powdered Composites

Nano-scale and powdered particles are least challenging for incorporation. In fact, several VPP resin manufacturers already sell products with particles in them. Examples include Formlabs' Rigid series which is glass filled or 3D Systems Accura Composite resins. Particles in the nano scale to ~100 micron range can be mixed into the resin slurry and cured in place with the part. Methods as well as challenges in this process are highlighted below.

3.1.2 Nano Composites

Nano composites are defined as composites with one of the materials having a dimension around 100 nm or less [4]. One of the most recognizable nanocomposites by name is carbon nanotubes (CNTs). Sandoval et. al [5] successfully printed SLA parts with CNTs added to the resin using a 3D Systems 250/50 SL machine. However, while they achieved some slight strength gains, their work highlights a couple of problems nano-composites present. First, due to the CNTs' absorption of light, the "critical exposure" or E_c is increased. This resulted in longer print times for higher concentrations of CNTs. Also, several of this team's samples displayed crack initiation around an agglomeration of CNTs. These agglomerations were more frequent at higher concentrations of CNTs within the resin. The group did succeed in achieving load transfer between matrix and reinforcement as displayed in their microscopy images in Figure 4.

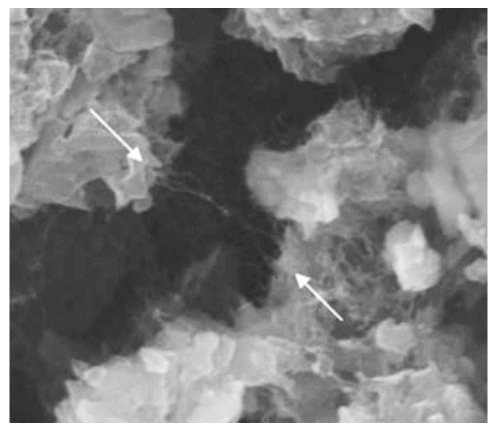
Figure 4 SEM image showing microcrack bridging

Other groups have sought to use particles that don't absorb light as much as CNTs. Weng et al [6] added Silica (SiO_2), attapulgite (ATP), or organic montmorillonite (OMMT) to their resin and printed samples using a homemade SLA printer. They performed rheological testing on each of the mixtures they fabricated. Their results showed that two competing mechanisms are at work in curing nanocomposites. First, the particles can promote crosslinking of the polymer – speeding up the reaction. Alternatively, the particles may block light energy which slows down the reaction. SiO_2 sped up the reaction and tended not to block the light as it is transparent. This makes SiO_2 and other transparent particles favorable for printing.

Another team, Kobayashi and Ikuta [7], overcame the agglomeration issue by increasing the viscosity of the printing resin. This inhibited the movement of the suspended particles which stopped them from aggregating towards each other. For their team this was especially important as they are attempting to print microactuators – small scale mechanical actuators to be used in consumer electronics or medical devices. These would only function properly if the particles are distributed properly throughout the part. The actuator would be printed using SLA and a resin with a magnetic additive called FA-700. The magnetic characteristics of the printed components were tested. Higher concentrations of magnetic particles resulted in higher magnetic flux values when placed inside an applied magnetic field. However, higher viscosity resins may not be compatible with the mechanical components of some printers and additional mixing may be necessary to undo sedimentation if it occurs.

Another major area of research within VPP nanocomposites is optimizing particle adhesion to the matrix as poor matrix to particle adhesion inhibits load transfer from the matrix to the reinforcement. Song et. al [8] studied the effect of different coatings on aluminum oxide particles in composites fabricated via SLA. The coatings were then evaluated for rheological and structural properties. What the group found was that higher strength, hardness, and rheological properties were tied to better chemical bonding adhesion between coating and matrix. This idea matches with previous work done in traditional composites and material extrusion composites. Continued investigation is needed to discover the best coupling agents for each new additive.

Additionally, nanoparticles can be added to improve thermal stability. Mabarak et. al [9] added ceramic metal oxide nanoparticles to SLA resins and tested thermal degradation using thermogravimetric analysis (TGA). They found a positive correlation between concentration of particles to temperature for a given degradation percentage. In other words, adding ceramic nanoparticles decreased the degradation of the composite. By utilizing a debinding and sintering postprocessing, CMCs containing multiple oxides can be printed [10]

3.1.3 Powdered Composites

Electrical properties can also be impacted and controlled by using composites. Some groups have even attempted to print battery components using different AM methods. Saccone and Greer [11] propose a method for creating Lithium Sulfur batteries that starts by DLP printing the battery cathode core using a traditional resin but adding an aqueous solution with suspended Li_2SO_4

particles. Then the printed part undergoes a pyrolysis process which creates LiS_2-C composite final parts. While Li-S batteries have high storage capacity they are notorious for degrading – particularly at the interfaces between components. The hope is that by utilizing 3D printing, the geometry can be tailored to maximize mechanical stability. This method showed promise as the feature size was significantly less (50 micron) than previous AM battery methods allowing freedom in design. It also retained charge capacity better than other AM methods as shown in Figure 5.

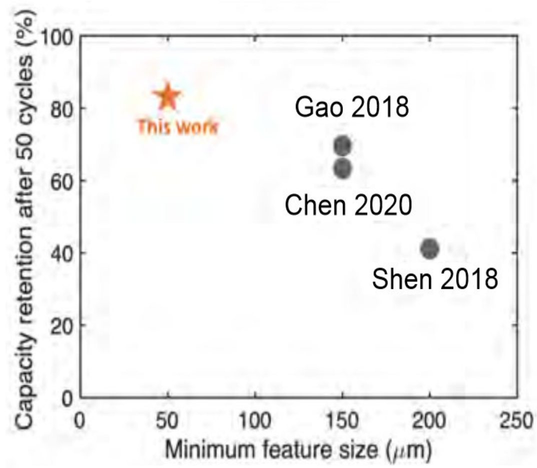

Figure 5 Saccone's printed battery charge capacity

Sano et. al [12] printed composite tensile bars using varying amounts of glass powder to test the effects on mechanical properties. They applied Halpin-Tsai and Eshelby-Mori-Tanaka equations to predict Young's modulus. Powdered samples were manufactured by adding glass powders to the resin, mixing it, and printing using a Nobel SLA printer. Experimental values were slightly lower than predicted as shown in Figure 6 but that is to be expected as additive properties generally lag more traditional methods. Additionally, they pushed the bounds on filler content to test the printer performance and found printing above around 50 wt% caused poor resolution and failed prints. This is important to consider moving forward as printer hardware may have to change to accommodate composite printing.

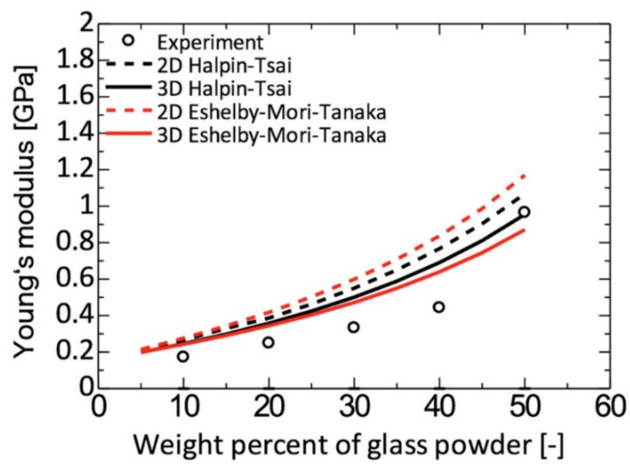

Figure 6 Experimental vs. Predicted Results from Sano et. al

3.2.1 Chopped Composites

Sano et. al [12] also printed differing lengths of fibers, including chopped fibers, by adding 30mm long glass fibers to the resin. While they do not report mechanical results for the chopped fiber samples they do provide pictures proving it is technically possible. However, imaging of the specimen showed that fiber alignment was completely random. In order to optimize the advantage of using composites fibers must be properly aligned.

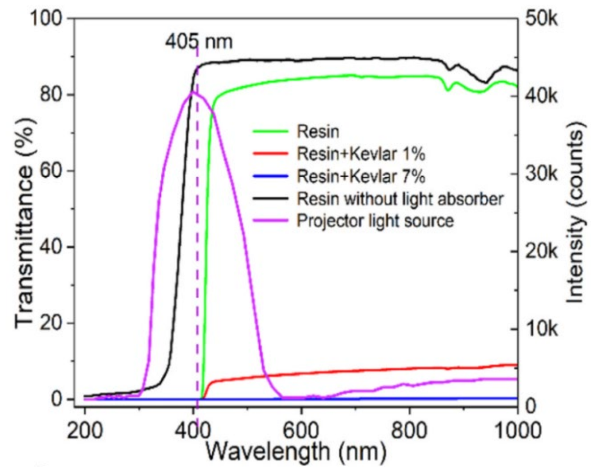

Figure 7 Transmittance for different concentrations of Kevlar

Composites using chopped materials other than glass have been printed using VPP as well. Zhao et. al [13] printed Kevlar composites using a DLP printer. They added 60 micron long, 10 micron wide Kevlar fibers to an epoxy/acrylate resin. Since Kevlar is scatters light and is hard to penetrate, Beer-Lambert law equations no longer hold. The addition of the Kevlar significantly decreased the transmittance of light which prevented the photopolymer from curing as shown in Figure 7. As can be seen in the figure, at 7wt% there is almost no transmittance of light which leads to very long print times. Exceeding 7wt% would be virtually impossible. To combat the loss of light energy, they added a second thermally cured polymer. The idea was to get enough curing in the stage one photo cure to hold shape and then achieve final properties with a thermally initiated cure using the curing agent benzoyl peroxide (BPO). This process resulted in an increase in ultimate tensile strength from ~30 MPa in neat resin to ~55 MPa at 7 wt% Kevlar. Modulus increased from ~0.1 GPa in neat resin to ~1.3 GPa for 7wt%. One interesting note is this team achieved better resolution with the Kevlar than without. They theorize that this is due to the reinforcement blocking light scattering within the plane of printing, decreasing unwanted curing.

3.2.2 Fiber Alignment Optimization

Several attempts have been made to solve the fiber alignment problem in VPP composites with varying levels of success. Each of the methods generally employs some external force to attempt to align the fibers. Several factors can affect the successful alignment of fibers inside a resin. If the resin is too viscous it will hinder the ability of the fibers to move and proper align. Fiber length also affects its ability to turn properly. Both experimental and modeling work is being done in these areas to optimize these parameters.

One major area of research is using ultrasound to align the fibers within the resin in a technique called “directed self assembly”. The idea is that the ultrasonic signal creates a standing wave

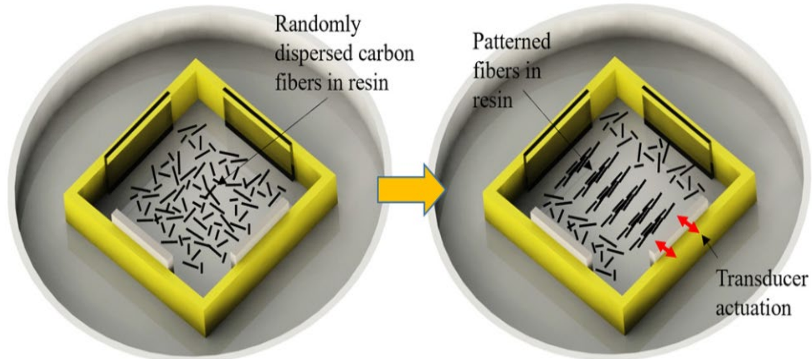

Figure 8. Transducer setup

inside the resin that would move the fibers into alignment. Asif et. al [14] attempted to print microtensile samples containing oriented 100-micron-long carbon fibers. To orient the fibers, they used 2 MHz ultrasonic transudcers placed perpendicular to each other as shown in *Figure 8*. This allows them to print with the fibers oriented at two different directions (0º and 90º). The fibers end up aligned separated by one half the wavelength. Wavelength can be expressed by the equation: $\lambda = \frac{c}{f}$ where λ is wavelength, c is material speed of sound, and f is frequency of the wave. As wavelength can be manipulated by transducer frequency it is thus possible to tune the distance between groupings of aligned fibers. A test matrix was created to test the difference between aligned and unaligned samples at concentrations of 0.5%, 1%, 2%, and 4%. Tensile strength improved 11%, 28%, 1%, and 4%, respectively. Printing in this method introduced extra variables needing optimization and issues to be solved. First, the resin was initially too thick and needed to be diluted using a solvent. For this to be a viable industry solution, resin systems must be tailored to accommodate the inclusion of composite fibers. Additionally, alignment of the fibers is not instantaneous and thus between switching alignments, a pause time was added. Furthermore, increasing the fiber length would require a greater force applied from the transducers.

Niendorf et. al [15-17] ran similar experiments using ultrasound assisted directed self assembly but focused on how electrical properties varied with degree of fiber alignment. Electrical conductivity could be tuned by influencing the alignment of current carrying fibers. They started by studying how changes in parameters correlate to alignment of fibers. The three main parameters studied were weight fraction, input power to the transducers, and distance between transducers. Several imaging datasets of printed samples were collected with varying values for each of the parameters. Regression was performed to tune weights for an equation relating fiber alignment to the three parameters. This allowed them to predict the probability of fiber alignment and assess which parameters were most influential in the alignment process. Next, they added

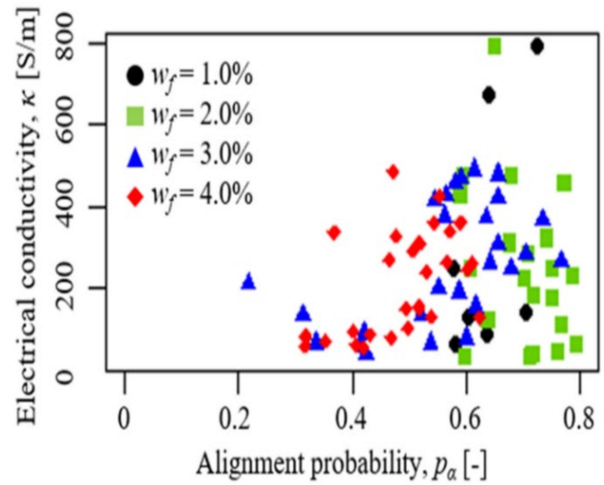

Figure 9 Conductivity vs Calculated Alignment Probability

15x130 micron silver coated fibers to the SLA resin for printing. They printed samples with 1wt%, 2wt%, 3wt%, and 4wt% at different transducer powers. Higher transducer power corresponded to better alignment which results in better conductivity. Also, higher weight fraction of fibers increased the likelihood of contact between fibers and thus also increased the likelihood of conductivity. Finally, they relate this conductivity back to their previous work of calculating the probability of alignment. Note in Figure 9 how much lower alignment probability values still showed conductivity for higher weight fractions. Although this team successfully proved the viability of printing electrically conductive composites with SLA, they also highlight future work in optimizing parameters to ensure desired conductivity is achieved. They have since been working on applying supervised machine learning algorithms to predict conductivity and fill in this knowledge gap. This process requires a significant amount of data however and results could vary from system to system. Additional work in modeling and experimentation would be necessary to accurately predict conductivity outcomes.

Lu et al [18] have performed similar sets of experiments on projection based vat photopolymerization systems to enhance heat dissipation. Heat dissipates more rapidly through the filler than the matrix. If the fillers are aligned they more efficiently dissipate the heat out of the part. Heat sinks were printed using varying patterns of oriented or non-oriented filler and matrix. These heat sinks were then heated to 90 degrees Celsius and moved to a thermally isolated chamber held at room temperature. They were then monitored using a thermal imaging camera (FLIR) to track how the composite cools. Ultimately, they found that samples with randomly oriented fibers slightly improved cooling, but oriented fibers improved cooling by greater than 25%. Additionally, cooling differed depending on pattern of fibers. Further work must be done to optimize cooling for a given structure by properly aligning the fibers to maximize heat transfer.

One of the more successful attempts at aligning fibers for printing using VPP is Martin et al [19] who first coat fibers (or particles) with a "magnetic-labeling" system (a superparamagnetic iron oxide). A magnetic force is applied to the resin aligning the fibers to the field. Unlike traditional DLP, only sections of the layer are cured at a time grouped by fiber alignment, decreasing print speed (average layer time of around 2 minutes). Their primary focus is using additive manufacturing to replicate reinforcement architectures found in nature such as shells and bones. Open hole tensile tests were modeled and performed to judge how fiber orientation influences damage propagation and strength. The greatest strength was in samples containing fibers oriented along the axis of tension. The second most effective method was orienting fibers in a circle around the initial damage. Patterned samples were also created to shape crack propagation by alternating squares of fiber alignment within the sample. This idea could be used to steer crack propagation away from critical areas and allow designers to control failure mechanisms.

Martin's team's idea has been patented and turned into a company called Fortify [20] that sells both resins and printers. Their printers incorporate mixing to prevent fibers and particles from "sedimenting" to the bottom of the vat. Another addition to their system that was needed was increased power in the plunging motor. This is due to the high viscosity of the resin containing additives. To optimize both plunge rates and mixing they first must thoroughly characterize the viscosity profile of the resin (typically done through rheology). Fortify offers a custom software that aids in the development of new filled photopolymers for use on their systems. The software allows users to input rheological data points and estimate sedimentation of particles. There are also calibration tests for cure depth and adhesion that print grids of squares at varying laser energies. The user measures the squares under a microscope and reports the depth at each grid point to create the cure depth working curve. This technology is already at work in the industry building RF devices, high thermal conductivity heat sinks, and more.

3.2.3 Continuous Composites

Some teams have attempted to introduced continuous fibers (or mats of woven fibers) directly into the resin. Karalekas [21-22] laid the groundwork for this idea starting in 2003. He placed fiber mats midway through the thickness of SLA printed dogbone tensile samples. The fibers were either E-glass, carbon or Kevlar and both acrylate and epoxy based resins were used. He examined the change in strength, modulus and strain at break and found slight improvements for the reinforced samples.

Sano et al [12] added fiber glass mats to the resin by placing a new mat after each 5 printed layers. Then the protruding fibers were cleaned off by sanding during postprocessing. The continuous glass fiber specimens showed an increase of nearly 10x in both strength and stiffness when compared to neat resin. They also were significantly stronger (~2-5x) than powder filled samples. While this study proved the benefits of adding continuous fibers over powdered/nano-scale additives, adding mats of fibers to the print is tedious work and not really a viable solution for manufacturing.

Some methods for printing continuous composites focus on printing “channels” for fibers to be added into during post processing. After the fibers are inserted, the entire part is dipped into a second resin and cured. Brooks and Molony [23] paired this idea with topology optimization and finite element analysis. They started with generic shapes such as pulleys, hooks and joints to be tested under various mechanical loading scenarios. Then the simulations informed final design shape by optimizing strength to weight ratio. The fibers were placed along (really inside) the areas carrying the greatest load – also known as the “load path”. They used carbon fibers, Kevlar fibers, stainless steel, and basalt. The structures showed gains ranging from 4x to 50x in load capacity. While they didn’t print using VPP techniques, their work forms the basis for several other teams attempting similar processes with VPP. It is important to note that load path is highly dependent on boundary conditions and loading scenarios would need to be thoroughly investigated for this to be successful for end use parts. Also, designing parts for this method is complicated as access ports for threading the fiber must be added and balancing manufacturability with strength increases is challenging.

Khatua et al [24] incorporated strategies from filament winding composite manufacturing and automatic fiber placement (AFP) to develop a robotic system that places “spatially-steered” fibers during the VPP printing process. In material extrusion composite processes, the fibers are generally single fibers. However, in this method an entire fiber tow can be used (i.e. 3000 fibers form a 3k tow). These tows can be laid down at a given layer at any orientation or


Figure 10 Leaf printed using robotic DLP system

pattern thanks to the help of a robot. This allows for printing of structures such as the leaf shown in Figure 10. They performed mechanical testing on two unique fiber patterns and compared them to samples without fiber and found increases in load carrying capacity of 25% and 50%. Upon analyzing the fracture surface they found fibers had been poorly impregnated and lacked adhesion to the matrix. This exposes a weakness in their method as fibers must properly adhere to the matrix to achieve load transfer. Understanding the matrix to fiber impregnation mechanism will be crucial for them going forward.

4. Outside the Box Ideas

Section 3 highlighted several teams working towards printing VPP composites with traditional fibers and slight modifications to their printer systems or resins. There are some groups thinking very outside the box when it comes to fibers and printing techniques. This section will cover a few of those unique ideas.

4.1.2 Natural Fiber Composites

Manufacturing composites using natural fibers (coconut fibers, paper fibers, etc.) is an appealing idea as the fibers are readily available, low cost, and are biodegradable while still providing many of the same benefits of unnatural fibers.

Boyala et al [25] printed samples containing human hairs using a DLP printer. Adhesion between natural fibers and matrix is often poor so the authors studied the effects of different processing methods by performing fiber pull out tests on three types of surface treatments – neat, MA-POSS grafted, and plasma treated (MA-POSS grafting is a chemical treatment in which special molecules bind to the hair - creating more locations for linking to the matrix). Untreated hairs performed the worst, grafted were slightly better and plasma treatment did the best. Tensile tests showed an increase in modulus and ultimate strength regardless of surface treatment, but plasma treatment did perform better than untreated or MA-POSS.

4.1.3 Continuous Liquid Interference Production

As has been highlighted throughout this paper, speed is a massive barrier to printing composites with SLA or DLP. In 2014, a patent was filed for a faster VPP technique known as continuous liquid interference production (CLIP). CLIP uses an oxygen permeable window that inhibits curing in the bottom of the tank. Since there is still resin in this “dead zone” the part doesn’t need to be raised in between each layer to replenish resin. Instead, the part is raised continuously through the vat. Like DLP it uses a DMD but instead of a picture being projected a “video” is played as the part is raised. While highly protected under patents and IP restrictions by its company Carbon, some have begun attempting to print composites using CLIP.

Zhang et al [26] have incorporated electric field assisted directed self assembly with CLIP to create ordered graphene PMCs. Graphene nanoplatelets underwent surface treatment and were added to dual curing resin. To successfully print, light intensity was increased from 1.9 to 3.3 mW/cm^2. The 2wt% samples showed over 100% gains in tensile strength, elongation, flexural strength, and fracture strain. The team also tested the sensitivity of platelet alignment to electric field intensity, demonstrating that DSA technology could be applied to CLIP printers. Unfortunately, due to the high viscosity of the resin, max printing speed decreased from 200 mm/hr to 14 mm/hr – still much faster than traditional SLA/DLP but not fully utilizing the speed of CLIP.

4.1.4 Continuous Fiber 3D Printing

While not technically “Vat” Photopolymerization CF3D printing employs a robotic arm that extrudes fibers alongside photopolymers and a UV curing laser. The fiber is passed through the photopolymer, impregnated prior to extrusion, and cured upon leaving the nozzle. The system can print composites with minimal supporting material underneath due to the tension applied to the fiber and its ability to hold its shape. Researchers at the Air Force Research Laboratory [27] studied the properties of these composites and report a modulus of 122 GPa and strength of 1599 MPa – purportedly the highest recorded values for AM composites ever. One main advantage of this approach is weight and volume fractions are not limited by printability factors such as light penetration and resin viscosity.

4.1.5 Lattice Structure Filling

While not directly printing a composite, another popular technique is printing lattice structures and then filling the structures. Xiao et. al [28] printed lattice structure jaw prosthetics and coated them in titanium using radio frequency magnetron sputtering. Since the structure is open the titanium penetrates inside the lattice acting almost like a reinforcement inside a matrix. Finite element simulations informed the design of the lattices to strengthen areas of highest stress while still allowing sputter coating to occur.

Zhang et al [29] printed SiC matrix composites with embedded carbon fibers using this method. They first printed carbon fiber filled “preforms” which undergo a reactive debinding and sintering process during which they are infiltrated with silicon powder. The result is a CMC with complex patterned reinforcement placement. This process involves precise control over temperature and chemical interactions requiring further equipment and full characterization of the constituent materials. Without this, the preforms would deform, the ceramics would crack, and adhesion between ceramic matrix and fiber would be poor.

4.1.6 Two Phase Composite SLA Printing

Xu et. al [30] designed an automated printer that contains multiple resin vats, a washing vat, a fiber extruder, and a mixer for distributing fibers. The system can create multimaterial SLA prints with carbon fiber (or other fibers) added. By pairing stiff CFRPs with more ductile polymers, damping coefficients can be tuned as needed.

5. Future Work

Printing composites with VPP is an emerging technology being developed. For it to come to market in future years several challenges need to be overcome. First, full-scale manufacturing industries won’t make the jump to VPP composites at the current printing speed. Incorporating technologies like CLIP, CF3D, or other novel printers will be crucial for scaled manufacturing. Second, interactions between resins and additives will require careful study and characterization to ensure proper adhesion between them. This research may be driven by industry players seeking design flexibility or by research laboratories experimenting with novel combinations. Finally, VPP will need to catch up to material extrusion in its research on fiber alignment. The primary advantage of composites comes with the added strength of aligned fibers. Research in material extrusion has proven this to be especially true in AM. VPP strategies for properly aligning fibers need to be developed to a marketable level.

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