FEASIBILITY STUDY OF NOVEL MAGNETIC COMPACTION FORCE ASSISTED ADDITIVE MANUFACTURING (MCFA-AM) METHODOLOGY FOR CONTINUOUS CARBON FIBER REINFORCED POLYMER (C-CFRP) COMPOSITES

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ABSTRACT

Composite parts manufactured by the current additive manufacturing (AM) methods are inferior in strength and stiffness compared to traditional composite manufacturing. Major issues include voids, physical gaps at layer/layer interface, and low reinforcing fiber content. This paper experimentally examined the feasibility of a patent-pending novel method, Magnetic Compaction Force Assisted-Additive Manufacturing (MCFA-AM), that utilized a magnetic compaction force to print and support curve-shaped continuous carbon fiber reinforced polymer (C-CFRP) composites in free space without any mold. C-CFRP prepreg tapes were fed through a magnet-assisted roller-like-setting, which was a part of the 3D printing head, and consolidated with a magnetic compaction pressure of 0.21 MPa in this feasibility trial. Short beam shear tests (ASTM D2344) showed that the 0.21 MPa MCFA-AM samples' interlaminar shear strength (ILSS) was 8 % and 9 % stronger and 7% weaker compared with the C-CFRP samples manufactured by the hand layup, the Tension-Tape-Placement-Without Compaction-AM, and the Out-Of-Autoclave Vacuum-Bag-Only (OOA-VBO) methods, respectively. Microscopic observations showed the size and number of voids were significantly reduced by the magnetic compaction. Finally, it demonstrated that printing stiff, strong, and complex shaped C-CFRP parts with great freedom can be done within a few minutes with this exciting AM-Composites technology advance.

1. INTRODUCTION

According to ASTM F42 Technical Committee, Additive Manufacturing (AM) or 3D printing is defined as "process of joining materials to make objects from the three-dimensional (3D) model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [1]. Rapid prototyping, the ability to manufacture complex structures, maximum material savings, and personal customization are some of the advantages of AM over traditional techniques [2-3]. In the

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past, AM technologies were only devoted to the production of low structural responsibilities parts and prototyping, but in the last decade, researchers started to investigate the possibility to implement AM into the manufacturing of functional parts [4].

Continuous fiber reinforced thermoplastic composites (CFRTCs) possess superior mechanical performance, versatilities, and light-weight capabilities, which makes it a suitable substitute for steel and conventional thermoset polymers in automotive, aerospace and marine applications [12, 13]. AM of pure polymers exhibits low mechanical properties, which are not suitable for high-stress-bearing engineering applications. Many recent AM studies have been worked on polymers with fiber reinforcements (i.e., short or long fiber) and showed an increase in strength and stiffness [2, 6, 7, 8, 9]. With respect to the reinforcement of polymers with short fibers, long fiber reinforcement has been found more effective to enhance mechanical properties [6,9]. 3D printing of continuous- fiber reinforced polymer composites (C-FRPCs) offers better mechanical properties over un-reinforced polymer composites [14]. However, process complexity also increases with numerous issues like fiber printing resolution, agglomerate formation, voids, heterogenous composite formation, blockage of printer heads, non-adhesion, and increased curing time. [10]

Traditionally, CFRTPCs have been developed by compression molding, pultrusion, vacuum forming, filament winding, and bladder-assisted molding. High costs of mold, inferior to produce complex geometry and inability of special fiber alignments are some of the limitations of these manufacturing methods and hinder the wide application of CFRTPCs in industrial practices [12-15]. Hence, there is a need of AM technique, which can print in a shorter time, without a mold, and offers equal or better mechanical properties in the printed parts than the traditional composite manufacturing processes. This paper presents a feasibility study of the novel magnetic compaction force assisted additive manufacturing (MCFA-AM) [31] to print and support continuous carbon fiber reinforced polymers (C-CFRP) parts in free space in a short amount of time. Furthermore, interlaminar shear strength (ILSS) for the printed parts was performed, and the results were then compared with other different manufacturing methods. Figure 1(a) shows the schematic of the novel MCFA-AM printing head proposed in the patent publication [31]. A block diagram, Figure 1(b), shows its several main components to be considered in the initial development stage and their relationships under a modularized system construction plan. In this paper, some of the high priority components' functions (or equivalent) will be experimentally evaluated and demonstrated.

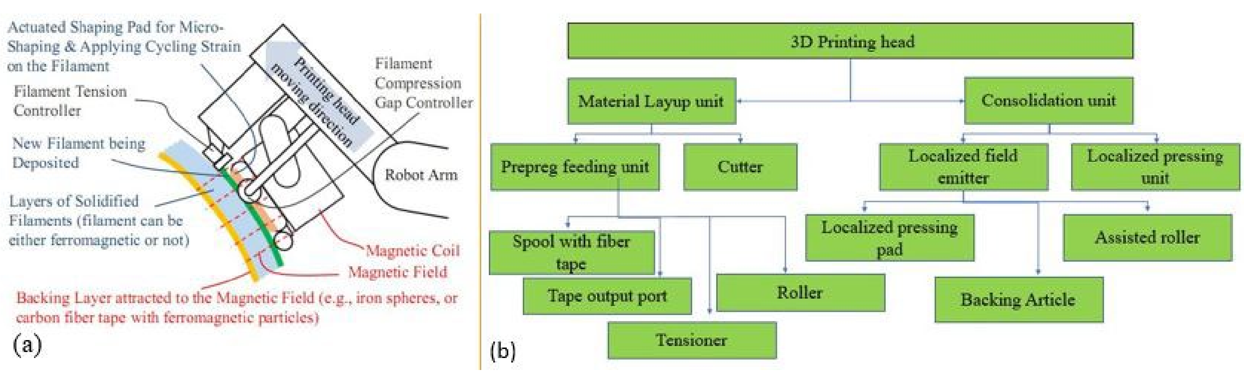


Figure 1. (a) The novel 3D printing head for the patent-pending MCFA-AM method [31] and (b) the block diagram shows the printing head's main components to be considered in the initial development stage and their relationships under a modularized system construction plan.

1.1 Literature review and motivation

3D printing of CFRTPCs is currently conducted by fused deposition modeling (FDM), laminated object manufacturing (LOM), selective laser sintering (SLS), stereolithography (SL), and extrusion (modified FDM). AM has not reached its full potential in the field of composites manufacturing for many reasons. Some of its limitations (e.g., lack of structural strengths and properties) holding the technology back to compete with composites manufactured by traditional methods. Fiber reinforcements have been used by many researchers to improve the mechanical properties of 3D printed parts, and their results are presented in the literature review below.

1.2 Fused deposition modeling and extrusion

According to Wohler's report [16] from Stratasys, Inc., FDM is the most widely used AM technique and holds 41.5% of the market share. Compared to traditional composite manufacturing, FDM provides the possibility of manufacturing complex functional and structural CFRTPCs. Recently, most of the research has been conducted to develop filament with short fiber additives or use of continuous fiber as reinforcement. Zhong, Weihong, et al. [18] overcame the deficiency of conventional Acrylonitrile butadiene styrene (ABS) polymers (i.e., low strength and hardness) by modifying ABS with the incorporation of short glass fiber (SGF), plasticizer and compatibilizer. They found that the strength of glass fiber reinforced ABS filament improved significantly at the expense of reduced flexibility and handleability. However, two key issues (i.e., extrusion force, and potential tool wear) were spotted during the process. Ning et al. [9] incorporated carbon fiber of different length and content into ABS to prepare FDM-fabricated parts. Their tensile tests and flexural tests showed the effects of carbon fiber content and length on mechanical properties and porosity. The authors concluded (i) the tensile strength and Young's modulus of fabricated part increased by 22.5 % and 30.5 % for 5 wt.% and 7.5 wt.% carbon fiber content, respectively, (ii) incorporation of 5 wt.% carbon fiber in ABS increase flexural stress, flexural modulus, and flexural toughness by 11.82 %, 16.82 %, and 21.86 % respectively, and (iii) porosity was severest with a 10 wt.% carbon fiber content. However, the fiber volume fraction achieved by this study was on 3-15 wt.%, which is significantly lower than conventional continuous-fiber reinforced polymer (C-FRP) by liquid molding processes of about 50-70 %. Nevertheless, the addition of short fiber reinforcement into polymer showed an improvement above neat polymer and paved a path for continuous or long fiber reinforcement.

Matsuzaki, Ryosuke, et al. [17] developed an innovative technique for three-dimensional printing of continuous fiber reinforced composites. The authors used unidirectional carbon fibers and Polylactic acid (PLA) matrix to prepare the fiber reinforced composites and observed an increase of 435 % and 599 %, respectively, compared to pure PLA specimen. Moreover, scanning electron microscopy (SEM) on fracture surface and cross-sectional surface indicated the insufficient adhesion between the fibers and thermoplastic resin and the presence of voids. Yang, Chuncheng et al. [7] proposed a mechanism for 3D printing for CFRTCs and investigated the performance of fabricated parts. The results showed that the flexural strength and tensile strength of 10 wt.% continuous carbon fiber (CCF)/ABS specimens were improved to 127 MPa and 147 MPa respectively, far greater than pure ABS parts produced by FDM (64 MPa and 29 MPa, respectively) and close to the one of CCF/ABS (injection molding) (140 MPa and 197 MPa, respectively) for the same fiber content. However, the tests also exhibit very low ILSS of 2.81 MPa and inferior interface performance. They also felt the need for optimizing the printing process parameters through this result. Justo, J. et al. [5] printed CF/Nylon and GF/Nylon composites using a MarkOne 3D printer, manufactured from the Markforged, and investigated the mechanical properties of the 3D printed parts. The study reported CF/Nylon composites with 40 % fiber volume fraction have a tensile strength and modulus of 701.05 MPa and 68.08 GPa, respectively, whereas GF/Nylon composites exhibited 574.58 MPa and 25.86 GPa of tensile strength and modulus, respectively. The values are promising compared to the other FDM results but under microscopic observation revealed a porosity of around 12 % and 17% for carbon and glass fiber reinforced composites respectively. It was suspected that mechanical properties could be enhanced by reducing the porosity in the parts.

It is important to notice that in all the reported FDM processes, no pressure was applied during the deposition step and the deficiency of solely-relying on fusion mechanism in the atmosphere on the highly viscous matrices can directly relate to the presence of large defects (pores and matrix-dominated zones) [5]. Thus, the presence of pores and no proper adhesion between layers resulted in weaker mechanical properties of the printed sample. It is also worthy of noting that traditional manufacturing methods (such as injection molding, autoclave curing, liquid composite molding, etc.) for polymer and composite parts typically rely on high injection pressure to collapse the trapped air bubbles or use vacuum to remove the air thus reduce the porosity in the parts.

1.3 Laminated object manufacturing

LOM is one of the first developed AM methods for Carbon Fiber (CF) reinforcement. Klosterman, Donald, et al. [6] investigated the fabrication of polymer matrix composites with LOM. Unidirectional E-glass fibers at approximately 52-55 vol % with an epoxy matrix was used as prepreg to fabricate parts. Good interfacial contact between layers and good interfacial bonding between fiber and matrix was observed. The mechanical properties of specimens fabricated by LOM with suitable post-cure cycle were comparable to those obtained by conventional processing methods. Post LOM consolidation cycle was found effective for strengthening the layer-to-layer interface and void contents below 5 %. However, it was found that Polymer matrix composites (PMC) parts were not fully consolidated and cured directly in the LOM process. During post-processing challenges like significant shrinkage, warpage, delamination and /or shape deformation may arise. Laser-assisted tape placement (LAPT) is a promising technique for producing continuous fiber reinforced composites. Comer et al. [11] fabricated CF/PEEK laminates by LATP (with in-situ consolidation) and by autoclave. The mechanical properties of two different process were compared. Overall, the laminates produced by LAPT performed better than autoclaved laminates in terms of interlaminar toughness (134 %), but other properties were subpar like flexural strength (68 %), ILSS (70 %), flexural stiffness (88 %) and open-hole-compression strength (78 %). LATP cooling rates are extremely rapid, and melting of pre-prepreg tape may not occur in through-thickness direction.

Recently a novel laser assisted AM methodology [8] utilized glass fiber-polypropylene to fabricate 3D objects by implementing laser assisted bonding and laser cutting. It was able to minimize the waste materials than LOM process, as it used prepreg tape instead of pre-cut prepreg sheet. The author reported continuous glass fiber reinforcement increases tensile strength, tensile modulus, flexural strength, and flexural modulus by 547%, 247%, 253%, and 750% respectively compared to un-reinforced polymer composites. The bonding strength of the proposed method was evaluated through lap shear strength (LSS) and peel strength testing which showed 96 % higher for lap shear strength and 50 % higher for peel strength than compression molding (CM) using GF/Polypropylene (PP) and CF/PP for LSS and peels strength respectively. This method was able to achieve superior tensile strength and modulus compared to FDM with short fiber reinforcement and similar tensile strength but lower modulus relative to traditional composite manufacturing methods. The microstructure analysis demonstrated no visible voids contents and superior interfacial bonding. Though this technology showed great improvement in some mechanical properties, the values are significantly low compared to the autoclave manufacturing process.

1.4 Selective laser sintering

SLS is a powder-based AM process. Yan, Chunze, et al. [19] performed pre-modification of carbon fibers for good interfacial adhesion and uniform dispersion of carbon fiber within the polyamide-12 matrix. The CF/Polyamide (PA) sintered components with 30 wt.%, 40wt.%, and 50 wt.% carbon fibers exhibit the enhancement of flexural strengths by 44.5 %, 83.3%, 114%, and flexural modulus by 93.4%, 129.4%, 243.4% respectively compared with pure polyamide-12 sintered parts. Zhu, W. et al. [34] proposed a novel method based on SLS to prepare complex and high-performance carbon fibers/polyamide12/epoxy (CF/PA12/EP) ternary composites. It was reported that the mechanical tests on the composites fabricated by this method yield an ultimate tensile strength of 101.03 MPa and flexural strength of 153.43 MPa, which is higher than most of the reported SLS materials. Although the technology showed a great promise with short fiber reinforcement, SLS is not capable of producing composites parts with long or continuous fiber reinforcement [19-20].

1.5 Stereolithography

SL is based on a photoinitiated polymerization printing mechanism [21]. Parts shrinkage and weak mechanical properties are some of the major issues [22]. The use of carbon fiber is not suitable for SL process due to its opacity to UV light, causing delamination in the fabricated parts [23]. However, photo-polymer mixed with glass fibers have produced an improvement in both mechanical properties and dimensional accuracy [22]. Cheah, C. M., et al. [22] studied the effect of the addition of short glass fibers into acrylic-based photo-polymer (De Solite SCR310) in SL process. The study reported specimens reinforced with 20 percent fiber concentration were found to be double the stiffness and 33 % higher strength than non-reinforced. The author used the fiber volume fraction of 5, 10, 15, 20 % and the results showed the mechanical properties increased with increasing the fiber content. Improvement in shrinkage and accuracy of the overall part was also improved using short glass fibers reinforcement. However, the presence of air bubbles was observed with the increase in fiber content which limits the improvements in mechanical properties. Zak, G., et al. [24] used the short glass fiber (1.6 mm in length) to SL5170 photopolymer resin and reported an enhancement of mechanical properties, where 80 % higher modulus is reported for reinforced layered specimens. Karalekas, D. E. [25] investigated the mechanical properties of two stereolithography resins (i.e. acrylic and epoxy based) reinforced using commercially available nonwoven fiber mats and reported specimens reinforced with glass fiber mat (17 gm^{-2}) increased stiffness by 50 %, increased tensile strength by 48 % while strain to fracture decreases by 51 % compared to the corresponding properties measured for pure acrylic-based resin specimen. It was also observed compared to acrylic based the epoxy-based reinforced specimens do not show a significant increase in elastic modulus. The reason for not so much improvement in the epoxy-based resin was later investigated and found that after laser curing also there were many uncured resin spots at the reinforcement-pure resin interface and close to the edges of the specimens. The improvement with this process is too low to compare with the conventional composite manufacturing process and another AM of Continuous FRTPs.

Although short fiber and long fiber reinforced composites provide better mechanical properties compared to unreinforced counterparts, there is a significant gap between the mechanical properties of the additively manufactured composites and the conventional methods manufactured composites. For instance, tensile strengths of additively manufactured short fiber reinforced composites are in the range of 70 MPa [27,28,29], additively manufactured long fiber reinforced composite in the range of 800 MPa [5,8] while the strength of fiber-reinforced composites manufactured by conventional methods is in the range of 200-2500 MPa [30,26]. Composite parts manufactured by current AM methods are inferior in strength and stiffness by an order of magnitude compared to traditional composite manufacturing [11]. Voids, physical gaps at layer/ layer interface, low reinforcing fiber content, are some common problems associated with current additive manufacturing [2-10]. The one thing to note in the current additive manufacturing method is the absence of application of compaction pressure in the printed parts. This paper aims to use novel MCFA-AM method [31] to print the continuous carbon fiber reinforced polymer (C-CFRP) composite parts in free space without using any mold. Feasibility of this new AM method, capable of printing in free space without any mold will be verified by conducting short beam shear tests of the MCFA-AM printed samples, and by comparing the results with samples produced by other manufacturing methods including the hand layup, the tension-tape-placement-without compaction-AM (TTP-WOC-AM), and the Out-Of-Autoclave Vacuum-Bag-Only (OOA-VBO) methods. Furthermore, printing of additional two complex shaped C-CFRP parts that cannot be conveniently produced with any molding processes but can be produced by this MCFA-AM method within a few minutes will be demonstrated; and the stiffness and strength of the complex shaped C-CFRP parts will also be demonstrated. Optical microscopic images will be taken to give a general idea of the size of voids in the MCFA-AM C-CFRP parts and compared with the other manufacturing methods.

2. EXPERIMENTATION

2.1 Materials

Four samples of continuous CFRPs were prepared by four different methods for the purpose of the study. The different methods used were: 1. Hand layup, 2.TTP-WOC-AM, 3. MCFA-AM and 4. OOA-VBO. The carbon fiber used to create C-CFRPs was a Toray T700S unidirectional fabric (680 g/m^2 areal weight, 1.8 g/cm^3 fiber density, 12k tow size) and polymer matrix used was two-part: EPIKOTE^{TM} Epoxy Resin TRAC 06170 and EPIKURE^{TM} Curing Agent TRAC 06170 obtained from Hexion Inc. High-pull rare earth magnetic disc, nickel-plated Neodymium magnets were used for magnetic compaction.

2.2 Hand layup and OOA-VBO samples manufacturing

During hand layup manufacturing of C-CFRPs, four prepreg plies were stacked on a flat aluminum plate, and a hand layup roller was used to apply the pressure to lay the one plies over the other and to squeeze out excessive resin and air bubbles. The laminated prepreg stack was kept in a nylon bag and stored in the freezer for curing at a later time.

For OOA-VBO samples, a laminated prepreg stack consisting of four plies was created the same way as the hand layup method. A peel ply, distribution media (DM) were placed on top of the prepreg stack, and vacuum tubes were connected and placed on the top of DM before sealing the whole assembly with a vacuum bag as shown in Figure 5 and described in [32]. The curing cycle is presented in Table 1. Both the OOA-VBO sample and the hand layup sample were cured with the same cure cycle.

Table 1. OOA-VBO cure cycle.

Time (min)	Temperature (ºC)	Vacuum pump
10	Room temperature (23)	On
30	45	On
60	120	On
30	140	Off

2.3 C-CFRP prepreg preparation for MCFA-AM and TTP-WOC-AM

To optimize the process, the resin was preheated at 60 ºC and mixed with the curing agent in the ratio of 100:16 by weight. Resin and hardener were mixed thoroughly until no clouding is visible. For hand layup and OOA-VBO, Toray T700S unidirectional carbon fabric was cut into the dimension of 100 mm (L) by 100 mm (W). For the TTP-WOC-AM and the MCFA-AM, the carbon fabric was cut in the dimension of 300 mm (L) by 15 mm (W). During the manufacturing of C-CFRPs prepregs, the fiber was preheated on a hot plate, and the resin was poured on top of the fabric and spread out with a roller for uniform resin impregnation of the fiber fabric. The prepreg was heated on top of the hot plate at 60 ºC for 8-10 minutes to achieve the desired B-stage curing level (i.e., good prepreg handleability and tackiness) and was transferred to nylon bagging and stored in the freezer at -18 ºC for later use.

2.4 Printing MCFA-AM and TTP-WOC-AM samples

A simplified MCFA-AM 3D printing head, which follows the basic principle described in the patent-pending publication [31] was developed as shown in Figure 2. The simple printing head in this feasibility study was operated by hand instead of a robot (i.e., hand-printing). The robot-operated MCFA-AM system will be constructed in the future. To study the feasibility of this novel MCFA-AM for C-FRPCs, samples were hand-printed with and without the assistance of magnetic compaction force in free space without a mold. The samples were then let cure for an hour in this free hanging setup. Four plies of prepreg were used to print each sample. Then, each sample was subjected for post curing at 120 °C for 1 hour and then at 140 °C for 30 minutes in a hot press with a minimum gap between the sample and the top hot plate. Therefore, the hot press only controlled the temperature but didn't apply any compression on the sample during the post-curing process.

Figure 2. A simplified hand-hold printing head designed for this feasibility trial of MCFA-AM (left) and the MCFA-AM printing head schematic described in [31] (right).

2.5 Trimming samples for the ASTM D2344 short beam shear test and ILSS evaluation

Once all the samples were post cured, a computer numerical control (CNC) router, CNC Shark Pro HD from Next Wave Automation, was used to cut five specimens from each C-CFRP sample. Each specimen was cut and sanded to 2.5 mm thickness, 5 mm width and 15 mm length as recommended by the short beam shear test (ASTM D2344) for ILSS characterization. Figure 3 shows the overall samples fabrication plan for the four different methods.

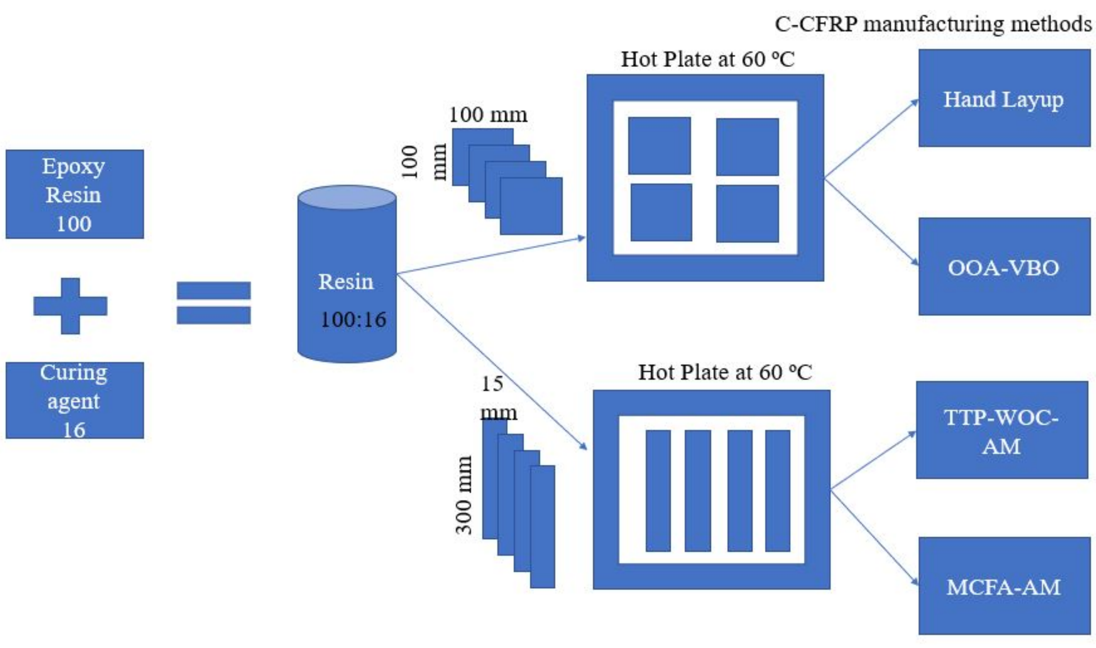


Figure 3. C-CFRP manufacturing process for different methods.

2.6 Short-Beam Shear (SBS) Test

According to the standard [33], specimen length, width, and span length should be 6,2 and four times the thickness respectively. For the thickness of 2.5 mm, width and span length for the specimen was sanded to 5 and 15 mm respectively (with an error of ± 0.01mm). The test was conducted on TINIUS OLSEN Super "L" Universal Testing Machine. The sample was centered on 3 mm diameter supports with 10 mm span length, and the load was applied through loading nose with 6 mm in diameter with crosshead rate of 1.0 mm/min till failure as shown in Figure 4. Five specimens for each sample was tested. The failure mode observed in the specimens was an interlaminar shear failure. So, short-beam strength was calculated using Equation 1.

$$F^{sbs} = 0.75 * \frac{P_m}{b * h} \tag{1}$$

Where F^{sbs} = short-beam (shear) strength (which represents ILSS), MPa
P_m = maximum load observed during the test, N
b = measured specimen width, mm
h= measured specimen thickness, mm

3. RESULTS AND DISCUSSION

Under naked-eye observation, the voids are large and clearly visible in the C-CFRP specimens manufactured by hand layup and by TTP-WOC-AM. Under normal observation, no voids were found in the C-CFRP specimens produced by MCFA-AM and by OOA-VBO, as shown in Figure 5. The large voids in the hand layup and TTP-WOC-AM specimens were due to the absence of either sufficient compaction force to collapse the voids or vacuum to remove the air and volatiles in the parts. The optical microscopic images of 10 different sizes of voids were taken for each sample type at 100X magnification using a Nikon Eclipse LV150. In Table 2, the statistical analysis shows the summation of the area of voids, where $A_{void,TTP-WOC-AM} > A_{void,Handlayup} > A_{void,MCFA-AM} > A_{void,OOA-VBO}$. In addition, it is observed that the size of voids also follows the same order. Figure 6 shows some example of microscopy images of the voids under a 100X magnificaiton.

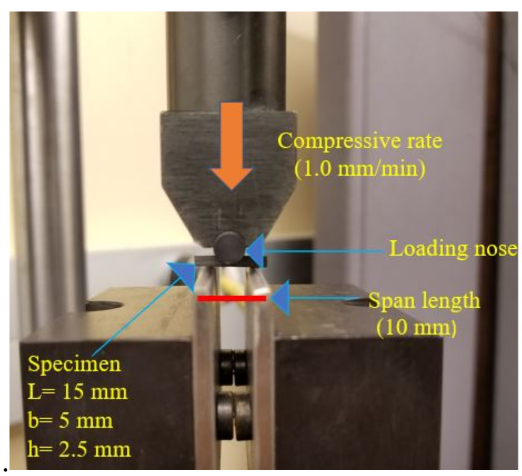


Figure 4. Short Beam Test set up.

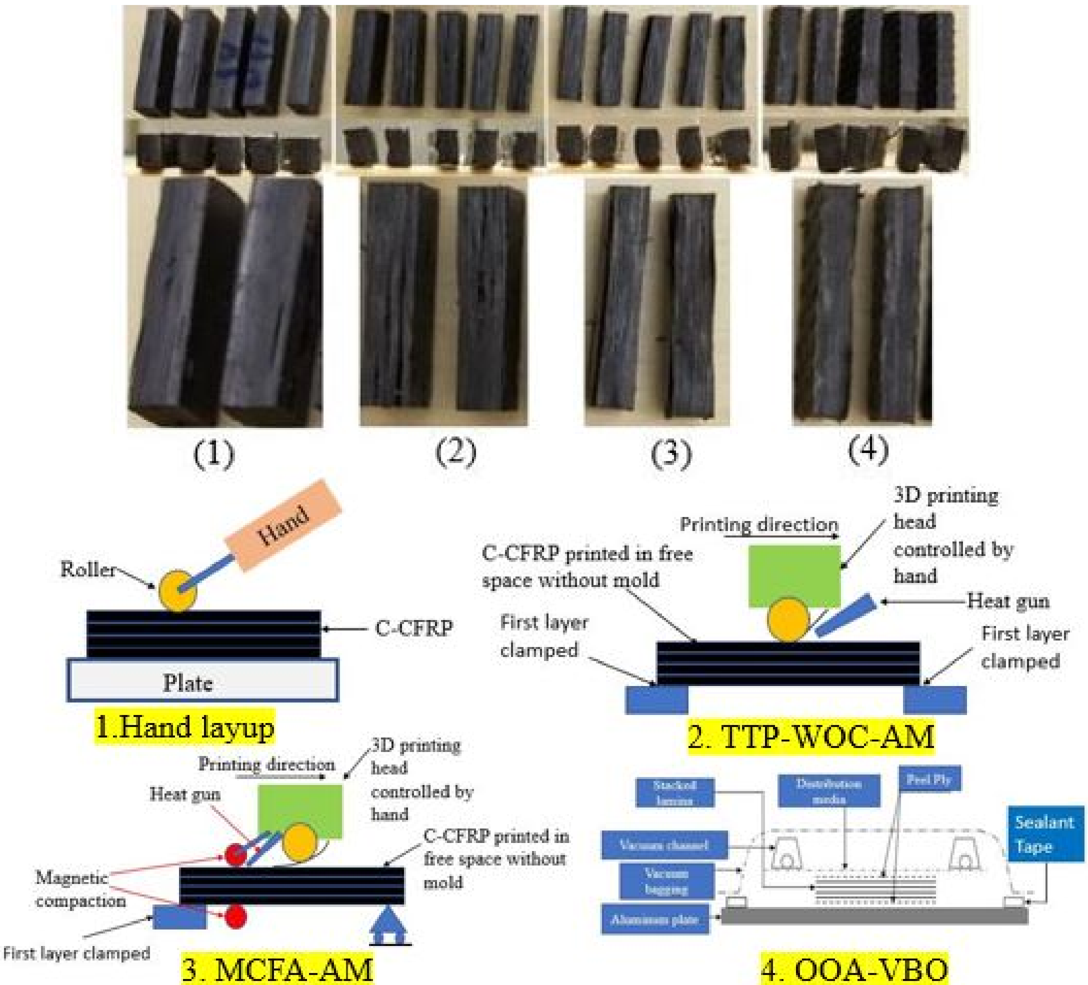


Figure 5. Specimens from different C-CFRPs manufacturing methods.

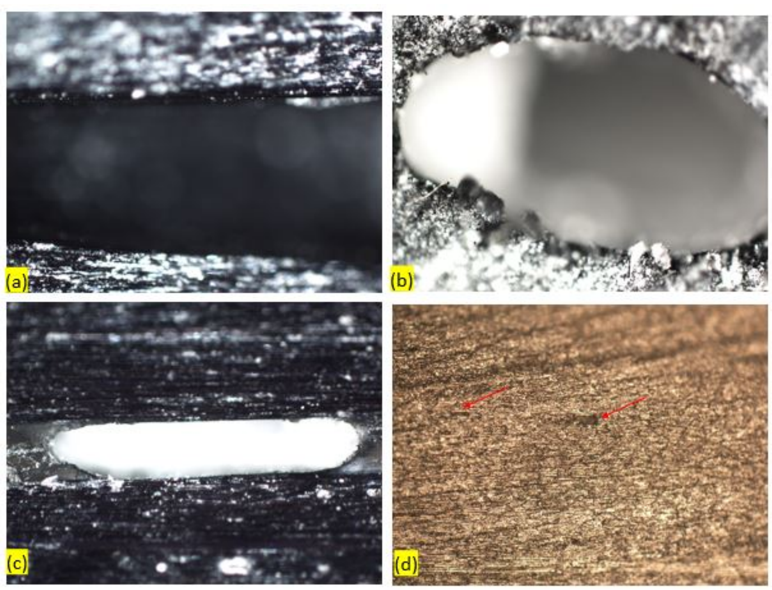
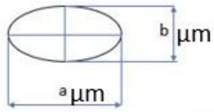


Figure 6. Voids image taken at 100X magnification (a) Hand Layup (b) TTP-WOC-AM (c) MCFA-AM and (d) OOA-VBO.

Table 2. Statistical analysis on the optical microscopy images of voids taken at 100X magnification.



Area=(Pi*a*b)/4	Hand Layup			TTP-WOC-AM			MCFA-AM			OOA-VBO		
SN	a	b	Area	a	b	Area	a	b	Area	a	b	Area
1	17.74	3.67	51.11	76.65	70.05	4214.93	3.21	3.00	7.56	1.50	1.23	1.45
2	87.01	73.17	4997.72	113.95	87.78	7851.99	6.12	5.55	26.66	3.66	3.13	8.99
3	90.78	87.94	6266.81	173.45	91.90	12512.94	8.08	7.56	47.95	4.18	3.49	11.45
4	97.44	93.84	7177.86	436.64	80.73	27671.21	13.32	5.62	58.76	1.67	1.43	1.87
5	187.57	82.74	12182.84	431.63	124.37	42140.23	9.90	8.76	68.08	1.84	1.41	2.04
6	197.38	145.40	22528.76	500.50	184.42	72457.23	10.70	10.47	87.94	1.68	1.58	2.08
7	654.45	141.27	72576.51	326.51	294.21	75409.07	18.67	7.73	113.29	3.45	2.50	6.77
8	558.98	182.14	79922.90	503.19	340.17	134368.56	20.76	10.39	169.32	8.42	2.81	18.57
9	1189.95	243.43	227390.58	1282.48	272.29	274127.09	61.15	18.50	888.05	13.69	4.86	52.23
10	1280.72	238.40	239679.06	1223.19	321.84	309032.10	84.17	21.46	1417.94	22.71	6.61	117.84
Maximum Area (μm^2)			239679.06			309032.104			1417.936			117.839
Minimum Area (μm^2)			51.11			4214.926			7.560			1.448
Summation of Area			672774.15			959785.350			2885.559			223.299

The magnetic compaction pressure was estimated by measuring the magnetic attracting force (~7.85 N) and the compaction area (~37.5 mm^2) when a printed C-CFRP part being placed between the magnet roller and the magnet backing article. The estimated compaction pressure was 0.21 MPa.

Next, short beam shear tests (ASTM D2344) were performed, and the short beam (shear) strength (i.e., ILSS) was calculated using Equation 1. The results are shown in Figure 7. The tests showed that the ILSS of the MCFA-AM samples with a 0.21 MPa compaction pressure was 8 % and 9 % stronger and 7% weaker compared with the C-CFRP samples manufactured by the hand layup, TTP-WOC-AM, and the OOA-VBO methods, respectively. The increase in the ILSS is due to the 0.21 MPa compaction pressure applied during the manufacturing of C-CFRPs parts. The compaction pressure significantly reduced the size of the voids in the MCFA-AM samples and increased the matrix-sensitive mechanical properties. It is also observed that the ILSS was indirectly proportional to the void content. The OOA-VBO samples have the highest ILSS average of 75.4 MPa while the size of the voids is smallest among all. The MCFA-AM samples have the second highest ILSS with an average of 70.5 MPa. However, the ILSS data for MCFA-AM samples were more consistent (i.e., with less standard deviation) than the OOA-VBO samples. It is observed under the microscope that the size of voids is almost the same in the OOA-VBO and MCFA-AM samples. However, the number of voids was much more in the MCFA-AM samples, which could be the cause of the reduced ILSS and will be a topic of future studies.

The novel MCFA-AM method was also implemented to see its capability of hand-printing complex parts without molds. The new AM methods successfully printed freeform CFRP parts ranging from simple to complex geometries within a short period of time. The different shapes of C-CFRP parts printed are shown in Figure 8(a). All three parts were printed in a total of 20-25 minutes and were post-processed afterward. Impressive stiffness (keeping the shape) and strength (without failure) against bending load were founded in repeatedly lifting various weights as shown in Figure 8(b) and 8(c).

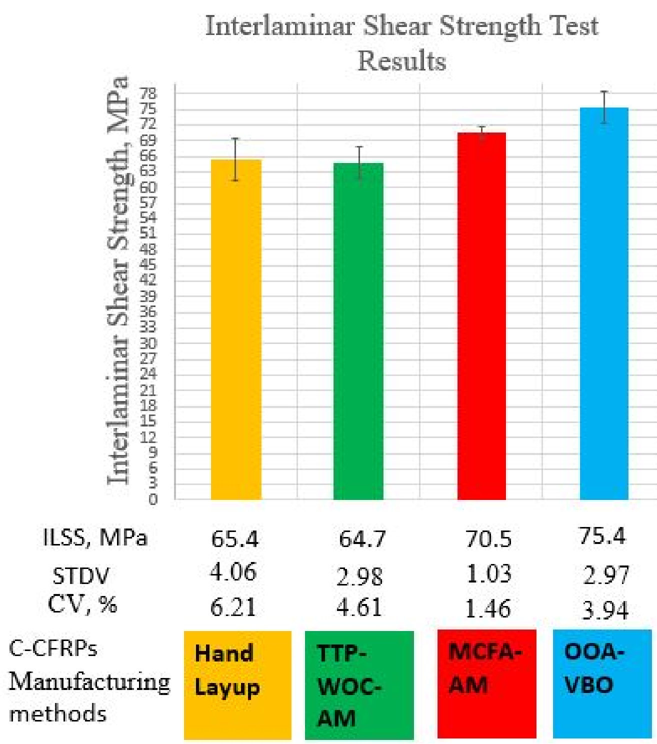


Figure 7. Statistical analysis of ILSS of samples

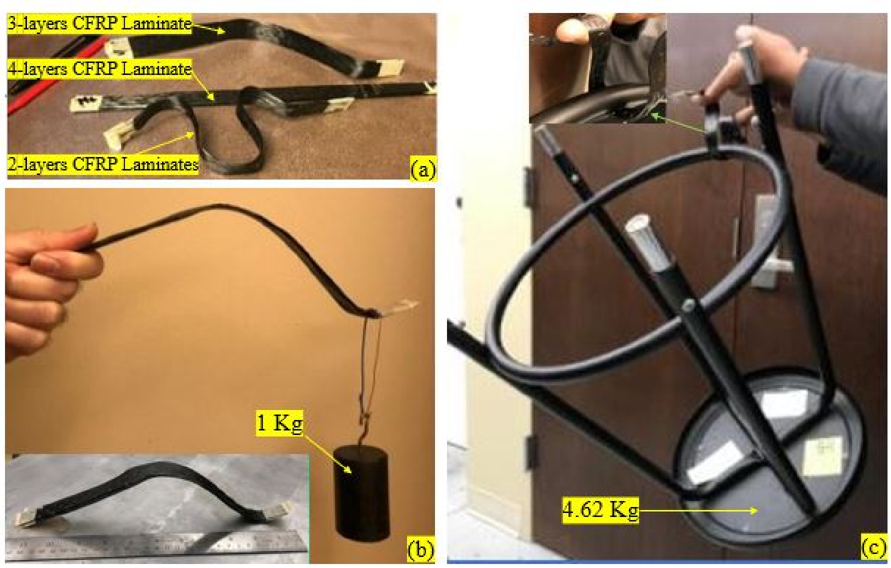


Figure 8. Freeform 3D hand-printed C-CFRP parts using the simplified MCFA-AM printing head.

4. CONCLUSIONS

The novel MCFA-AM method is able to print unidirectional C-CFRP composites in free space without a mold. In this feasibility study, a 0.21 MPa magnetic compaction pressure was applied to consolidate the samples. The compaction pressure significantly reduces the size and content of voids in the MCFA-AM printed parts into undetectable by naked eyes, which contrasts to the void issues by hand layup and TTP-WOC-AM methods. Furthermore, the MCFA-AM sample showed an improvement of 8 % and 9 % in ILSS compared to the hand layup and TTP-WOC-AM methods.

Compared to OOA-VBO, the MCFA-AM method is inferior in ILSS by around 7%. Under microscopic observation, it is revealed the inferiority is most likely due to a larger number of tiny voids compared to OOA-VBO, while the size of voids was almost the same between the two methods. The vacuum pressure in the OOA-VBO process was applied over the entire samples for a long period of time (120 minutes) compared to MCFA-AM, where the 0.21 MPa magnetic compaction pressure was applied only on the small area being consolidated over a very small time (20-30 seconds). The large number of voids (void content) in MCFA-AM samples may be due to the low compaction pressure and the short amount of time compaction pressure was applied.

The future work is to increase the compaction pressure and compaction duration to study the effects on voids size, void content and mechanical properties of the MCFA-AM printed C-CFRP parts. Moreover, various curvatures and thicknesses of parts will be printed in order to develop a better understanding of the curvature-property relationships. Temperature and time to heat the prepreg is also an important matter of topics, which will be studied in the near future. Another part of future works is to implement this novel method with different fibers and resin systems (thermoset and thermoplastic) in order to find the optimal fiber and resin systems. This MCFA-AM method could also be benefited by adding nanoparticles into the C-CFRP prepreg to further enhance the composite parts' electrical, thermal, and mechanical properties [32,35,36,37] beyond OOA-VBO's limits and further improve the printing speed and quality consistency.

5. ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support from Alabama Department of Commerce through the Alabama Innovation Fund (Award number: 150436), and the Graduate Assistantship from the Systems Engineering Program at the University of South Alabama. The authors are grateful for the carbon fiber materials provided by Toray, Resins supplied from Hexion Inc.

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