HYBRID MANUFACTURING TECHNIQUE USING LARGE-SCALE ADDITIVE MANUFACTURING AND COMPRESSION MOLDING FOR HIGH PERFORMANCE COMPOSITES

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ABSTRACT

Additive Manufacturing (AM) or 3-D printing has moved from small-scale prototypes to large-scale functional structures. With the introduction of large-scale 3D printers into the market a new industry has been born. For the first time, we are presenting the idea of preparing large-scale 3-D printed β-stage preforms to be used in traditional compression molding (CM) manufacturing technique to prepare final functional structures. Short carbon fiber (CF) reinforced material acrylonitrile butadiene Styrene i.e. ABS with 20% CF is used in present work. It is shown that highly aligned 3D printed short carbon fiber composite maintains its orientation after compression molding. A sandwich panel is prepared to show the capability to prepare complicated parts by integrating AM and CM. Interphase of the prepared dissimilar material is also studied using SEM. Samples prepared using AM-CM integration showed 11% and 79 % improvement in tensile strength and tensile modulus respectively compared to the traditional extrusion compression molding (ECM) process.

Keywords: Additive Manufacturing, Integrated Composite Processing, Compression Molding
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1. INTRODUCTION

3D printed boat, 'built' by the world's largest 3D printer (Ingersoll Inc.) [1], largest 3D printed trim tool for Boeing 777x winglet (Oak Ridge National Laboratory, ORNL) and first 3D printed Car (ORNL and Cincinnati Inc) are some of the examples of large-scale polymer additive manufacturing (AM) using extrusion deposition process. Extrusion deposition process involves

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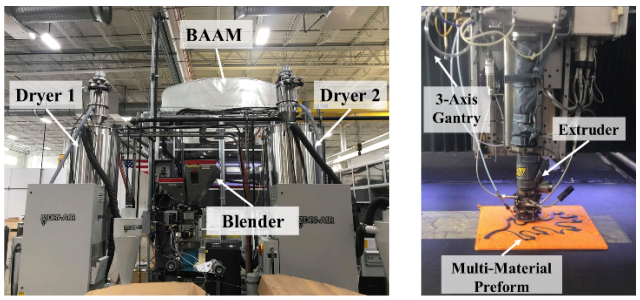
thermoplastic pellets melted through a heated extruder and deposited layer by layer via a nozzle. By producing these life-size functional structural components, large-scale polymer AM has changed the way 3D printing industry was used to be seen few years back. ORNL and Cincinnati Inc. introduced Big Area Additive Manufacturing (BAAM) system in 2014 [2]. Since then, there is huge advancement in this area [3]. The additional breakthrough in this series is the addition of dual material feeding mechanism to the BAAM system to print multi-materials in a single structure. Two dryer unit located next to the BAAM system keeps two types of different materials ready for deposition through extrusion nozzle. Nevertheless, the choice of multi-material used is not only limited to two material and can be extended to many different materials. Feedstock materials in the form of pellets provides the flexibility of using a larger variety of polymer systems in BAAM.



(a) (b)

Figure 1. (a) Multi-material printing setup on BAAM system, and (b) Extruder setup showing multi material deposition

With the additional ability to print multi-materials using BAAM technique, AM can offer new opportunities to reduces cost, weight and can improve functionalities of the printed parts [4,5]. A good aesthetic is a bonus of multi-material printing as shown in **Figure 1**. The compatibility of different materials with each other, function-driven design, desired printing cost and weight decides the combinations of the materials to be used in BAAM. For present study, the most common material for large scale printing acrylonitrile butadiene Styrene (ABS) and carbon fiber (CF) have been used. An idea of integrating AM technology with Compression Molding (CM) manufacturing technique is laid within this work. Large-scale polymer AM has advantages such as reduced cost, reduced waste and ability to make complicated structures, but still possess serious drawbacks such as high porosity levels and relatively low mechanical properties across the deposition direction (Z-direction). Present work focuses on the capability of BAAM system to produce multi-material parts and use them as β-stage preforms for the CM technique. For demonstration, a complicated structure like a sandwich panel, ABS/CF on top and bottom and neat ABS in middle, was printed and compressed to obtain a final structure whose mechanical performance was compared with the traditional Extrusion Compression Molding (ECM) process.

2. EXPERIMENTATION

BAAM system used in this study consists of a vertical extruder attached to 3 axis gantry system. Extruder is attached to two feeding hoppers. The extruder on a 3-axis gantry crane allows material deposition at very high rate and can control the direction of the depositions. In this technique the part is first modelled using computer added design (CAD) software or other methods and further sliced using another software namely “slicer” to convert the CAD model into layer-

wise representation of the model. This slicer file is fed into the BAAM system which produce the final part layer-by-layer. It is already established that in this extrusion process the fiber orientation within the deposited bead tends to have a higher alignment at the deposition direction [6].

Neat ABS and 20% by weight CF filled ABS pellets were provided by Techmer PM. The pellets were dried for 8 hours at 70°C. The AM preforms were manufactured with a designed deposition path in order to align the orientation of the CF in a desired direction. Three panels were manufactured; (1) Neat ABS, (2) ABS/CF, and (3) Sandwich ABS/CF -ABS- ABS/CF (See **Figure 2**). Each panel had three layers printed in 0° orientation (i.e. direction of the bead deposition). Hot-press (Carver Press-30 Ton) was utilized for the CM process of the AM preform. The compression parameters for the AM-preform were carefully optimized to obtain desired thickness of the panels. Over heating or excess pressure could be detrimental for the AM-preform, see **Figure 3**. The platens of the hot-press were set to 135°C and the pressure was increased incrementally from 1 to 10 Ton. The molded plates were hold under pressure for 10 minutes before removing the pressure. The AM preforms panels mechanical properties were compared against the properties of panels made by conventional ECM process. In this process the same feedstock, neat ABS and ABS/CF, material was fed through a single screw extruder to produce a viscous charge. The charge was then transferred to a closed mold press in a fast-acting press to produce the composite panels. 30 Ton pressure was applied, and dwell time of 3 minutes was maintained. Printed direction in AM preforms and the charge direction in CM molded parts will be referred as "X-direction" in this manuscript. Size of all panels was 279.4 mm × 279.4 mm (11" × 11"). Samples for tensile test were cut from the prepared panels.

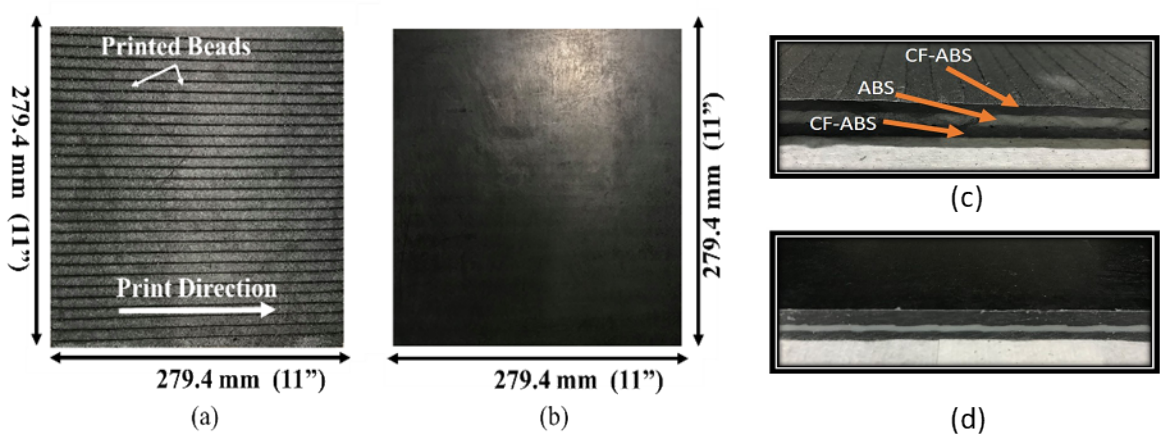
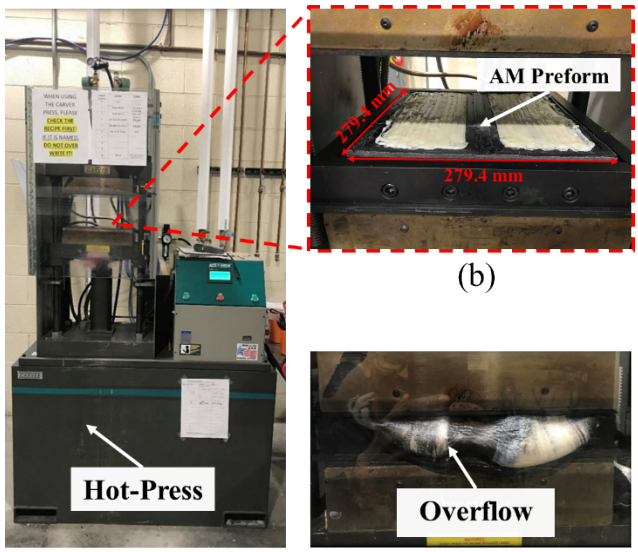


Figure 2. Example of single material AM-preform (ABS/CF); (a) Before compression molding, and (b) After compression molding**.** Example of multi-material AM-preform; (c) before compression molding, and (d) after compression molding. Sandwich panel is an example that cannot be prepared using conventional ECM or injection molding processes easily.



(a) (b) (c)

Figure 3. Optimization of compression molding parameters of the AM-preforms; (a) Compression molding setup, (b) Close up for the mold and the AM preform, and (c) Material Overflow resulted from un-optimized parameters.

3. RESULTS

3.1 Mechanical Properties

Tensile test results are shown in **Figure 4**. Tensile strength and modulus of AM-CM samples in X-direction are 11% and 79 % higher, respectively, than that of ECM samples. Tensile strength and modulus of neat ABS was same in both manufacturing techniques, but tensile strength and modulus of ABS/CF samples were significantly high in AM-CM compared to ECM only. The improvement can be assigned to the highly orientated CF in the AM-CM samples compared to ECM samples. High porosity in the AM produced parts and poor adhesion of the adjacent printed layers in Z-direction are the main reasons for poor mechanical properties of 3D printed structures [7]. As the extrusion process involves the melting and mixing of the feedstock material, this thermal process generates gases which may causes heterogeneous micro/meso pores in the structures [8]. Air trapping during feeding process, moisture in feedstock material or volatile additives increase chance of porosity. These heterogeneous pores create concentrated stress during loading on the polymer structure making them inherently weak. Although extrusion of melted polymer through a small orifice help to align the filler fibers into the deposition direction due to the applied shear force in the nozzle during extrusion (i.e. shear flow phenomena). By controlling the deposition direction, preferred fiber alignment can be achieved.

On the other hand, traditional ECM technique is composed of two method, extrusion of the charge and compression in a mold. Compression under pressure help to reduce porosity in CM produced parts[9]. However, due to the absence of the control over the material flow in the mold, fiber orientation is highly heterogeneous in the CM produced structures. Using the AM preform in place of the extruded charge for compression molding all the advantages of AM are combined with all the advantages of the CM processes. CF orientation in AM samples makes it a good candidate

to prepare samples with enhanced mechanical properties compared to ECM process. Tensile properties shown in **Figure 5** of AM-CM samples confirm that the low porosity and high fiber alignment assisted in the improvement of the mechanical properties.

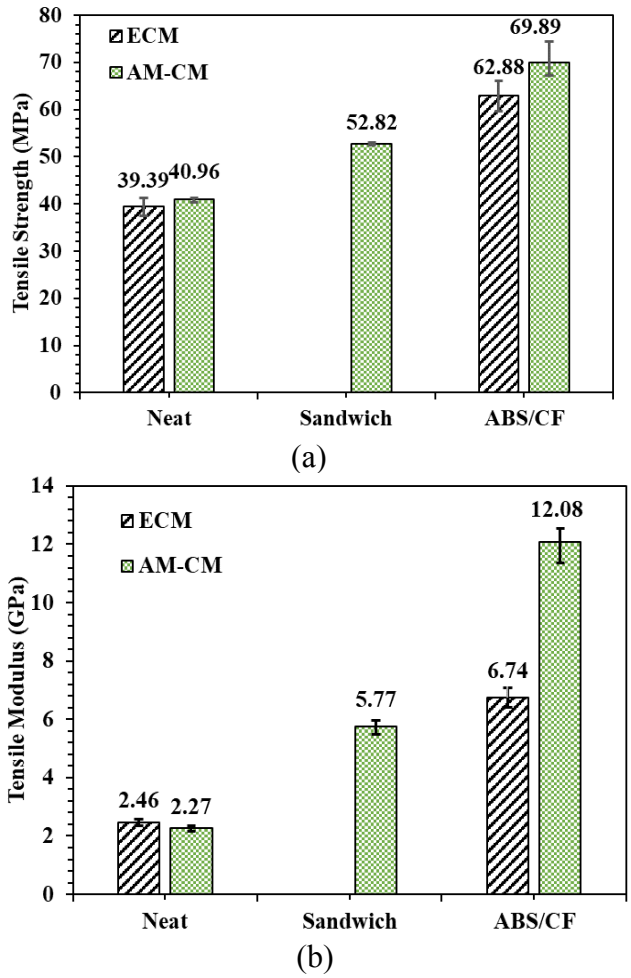


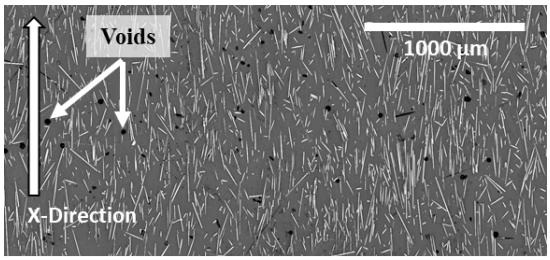
Figure 4. (a) Tensile strength (b) Tensile modulus of various samples prepared by CM and AM-CM integrated system.

Flexibility to prepare complex parts, which are not possible with convocational ECM process is another benefit of using AM preform. With AM-CM complex geometries, with specific properties in predefined directions can be obtained. This property can be an advantage over the over-molding processes or in cases where weight saving is needed. Combination of AM with conventional CM technique can produce complicated multi-material structures that cannot be produced by any other conventional processes easily, hence the lack of the data points in **Figure 4**, tensile strength and stiffness, for sandwich structures made by ECM process.

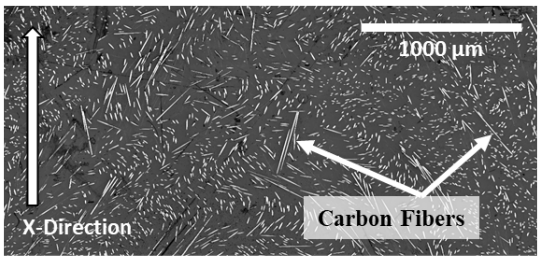
3.2 Morphology

Optical microscopy and Scanning Electron Microscopy (SEM) images were utilized to study the porosity, interphase and CF orientation. **Figure 5a** shows AM preforms before compression.

Large void content is clearly visible in the figure. It can be noticed in **Figure 5b** that the ECM resulted in random fiber orientation and porosity levels that are less than the ones observed in the AM preforms. It is found that the AM-CM process is highly effective in reducing porosity from the AM produced parts while maintain its high fiber orientation as shown in **Figure 5c**. To show the capability to modify the internal microstructure which eventually affect the mechanical properties, an ORNL word was printed using the fiber orientation by designing the deposition direction of the CF based PLA material through a 0.25 mm diameter nozzle as shown in **Figure 5d**.



(a)



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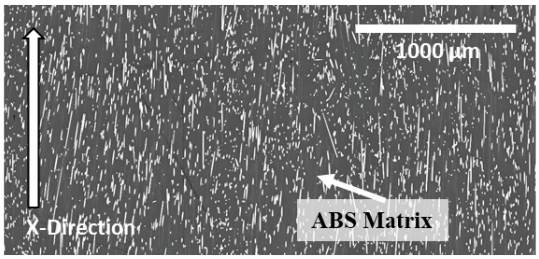

(c)

(d)

Figure 5. Optical microscopy showing the microstructure for; (a) AM preform, (b) ECM molded panel, and (c) AM-CM molded panel, and (d) Writing ORNL with fiber orientation in PLA Matrix.

A good interphase between ABS and ABS/CF was observed from SEM the images shown in **Figure 7**. Good interphase confirms the effective over molding process between neat ABS and ABS/CF materials. Over molding techniques are used to selectively reinforce part in targeted areas. Conventional over molding process uses a continuous unidirectional (UD) reinforced tapes, where they are strategically placed in a mold cavity then the mold is filled with (i.e. over molded) with short/long fiber-reinforced thermoplastics. In such techniques, slipping of the UD tapes during the mold filling, is a common risk. With our newly introduced concept of integrating AM and CM process, highly aligned short/long fibers can be integrated into the molded part and can be printed in a way (i.e. highly aligned fibers) to get the maximum strength and stiffness in the desired direction. In our proposed technique of over-molding parts, it was noticed that there is no slipping between the two dissimilar materials. However, direct comparison of mechanical properties between traditional over-molding technique and proposed technique has not been done yet and will be considered in the future work.

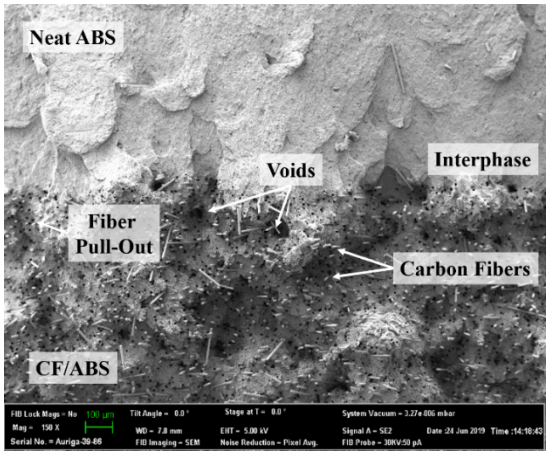

Figure 7. SEM image for the fracture surface of multi-material (neat ABS/CF-ABS) produced by AM-CM process showing the interphase.

4. CONCLUSIONS

In the present paper, we have demonstrated the ability to print multi-materials using Big Area Additive Manufacturing (BAAM) technique. We showed that the combination of additive manufacturing (AM) with conventional compression molding (CM) technique can produce complicated multi-material structures that cannot be produced easily by any other conventional processes. Integrating AM technology with an established manufacturing technique, CM, was used to demonstrate the manufacturing of sandwich panel. AM multi-material preforms were compressed to obtain the final molded components. Morphology of the composite were studied using optical microscopy and scanning electron microscope to understand the fiber orientation, porosity and interphase properties between multi-materials. The enhanced mechanical performance based on design are discussed with correlation to the fiber orientation in the AM-CM produced coupons. Tensile testing confirmed the effectiveness of AM-CM integrated technique over conventional CM technique.

5. ACKNOWLEDGMENTS

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