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ADDITIVE MANUFACTURING AND MECHANICAL BEHAVIOR PREDICTION OF MULTIFUNCTIONAL AEROSPACE COMPOSITES

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ABSTRACT

This paper presents select scientific and technological achievements from Dr. Therriault's team at Polytechnique Montreal relating to non-planar additive manufacturing (AM) of relatively large composite structures for aerospace applications. The team has developed software, modeling tools, and a 6-axis robotic infrastructure for multi-material AM. As a proof-of-manufacturing-capability, we designed a non-planar AM method for the creation of a technological demonstrator consisting of seven layers of different geometries and materials including 5 layers of thermoplastic martials (i.e., support, adaptive layer skin, plain skin, core of the sandwich structure and microscaffold) and 2 layers of thermosetting-based microscaffold, featuring multi-functionalities (e.g., abradable, acoustic) for aircraft engines. To enable printing of the non-planar technological demonstrator, two custom tools including the programming of mesh-mesh non-planar slicing for printing of thermoplastic-based materials and a Multinozzle Toolpath Generator for printing of thermosets multinozzle printing were developed. In addition, our new predictive tools including a phase-field model for the investigation of damage and failure of printed parts enabled us to accurately capture the location of crack initiation and predict the peak load with a relative error of 2%. Lastly, our novel and powerful open-source software, OpenFiberSeg, allowed us to fully characterize composite materials or printed structures from high-resolution X-ray micro-CT scans. The software can precisely identify the aspect ratio and orientation of the fibers and quantify the various defects and porosities that allowed predicting thermo-viscoelastic behavior of structures within ~5%.

1 INTRODUCTION

Additive manufacturing (AM), also known as 3D printing, allows the layer-by-layer fabrication of parts featuring complex geometries that usually cannot be achieved using conventional manufacturing methods (e.g., injection molding) [1,2]. Research results released in 2020 by Essentium showed an increasing interest for the purchase of industrial-scale AM machines [3]. However, these machines use a Cartesian 3 degree-of-freedom (DOF) positioning system with limited printing capabilities and largely operate in a closed-source environment. In addition, choices of printing materials are still limited, and the process is not economically viable yet.

Recent efforts by the industry (e.g., CEAD, ABB, Electroimpact) have focused on the utilization of high DOF robotic systems with an arm reach of several meters as a printing platform to enable large printing envelopes and printing over non-planar surfaces [4,5]. To increase the material extrusion rate, pellet-extrusion printing heads that use thermoplastic pellets instead of filaments are being used. It should be noted that the current open-source and closed-source printers usually rely on a single printing process with one or two printing heads. This drawback limits their applications for manufacturing of multi-material multi-functional components.

Another main issue is relatively low mechanical performance of the printed part which mainly stems from the porosities created at the different scales, and also the weak interface between the filaments in a layer, as well as between the neighboring layers [6]. Several works have been reported in the literature to predict interface properties, crack propagation and mechanical failure of the printed parts [7,8]. In addition to the process and mechanical behavior simulation, the detection of process-induced flaws is also necessary to achieve high-quality parts that can be qualified for industrial applications. X-ray tomography, a non-destructive imaging method [9,10], has been recently used to inspect the parts' microstructures for defects, porosities and the direction of reinforcements like carbon fibers [11]. Note that the microstructure of printed short fiber composites is challenging to characterize due to the presence of the dual scale porosity and the highly dense distribution of fibers [11].

This paper presents select scientific achievements from Dr. Therriault's team at Polytechnique Montreal relating to the AM of short-fiber reinforced polymer composites. In Section 2, we explain the development of our 6-axis robotic multi-material AM infrastructure. Section 3 describes the development of two custom nonplanar slicing methods for FFF printing of thermoplastics and multinozzle direct-ink writing of thermosetting materials. Next in Section 4, we present nonplanar AM of a technological demonstrator featuring multifunctionalities (e.g., abradable, acoustic) for aircraft engines. Finally in Section 5, some other related topics such as the development of visualization tools and the investigation of damage and failure of printed parts are discussed.

2 Development of additive manufacturing infrastructure

Figure 1 shows photos of our custom-built 6-axis robot-assisted printing infrastructure and a schematic to illustrate the modified workflow to operate it. Printing heads of different technologies (e.g., Fused Filament Fabrication (FFF), direct-ink writing, UV-assisted 3D printing) can be mounted on the robot arm for printing of planar and nonplanar structures. Figure 1a shows a photo of the AM platform with the multinozzle installed to print abradable thermosetting materials inside the nonplanar surface of half of an actual 1:1 scale aircraft engine fan case. As shown in Figure 1b, we also designed and built a heating enclosure to enable printing of high-temperature resistant thermoplastic (HTRT) composites. The heat is provided by an infrared lamp. Figure 1c shows the AM workflow which is custom designed for the AM infrastructure. The toolpath is sent to a robotic simulation software (RoboDK, version 5.4.1) while printheads are synchronized with the robot's motion.

3 Development of non-planar slicing methods

3.1 Thermoplastic composite printing

We developed a non-planar slicing method and its associated code for non-planar printing of large components using the 6-axis robot platform [12]. The method works by controlling the layer shape by defining the top and bottom surfaces of the print, then automatically generates a surface defining the layer shape of each layer. This layer shape control is the additional control that permits complex non-planar printing. Then, like a typical slicer, a 3D model in STL format and the relevant printing parameters are defined by the user, and a G-code file for the manufacturing of that 3D model is automatically created. When the slicing surfaces established, mesh-mesh intersection operations compute the intersection lines between the slicing surfaces and the STL mesh model. The

Figure 1. (a) Photo of the AM infrastructure for nonplanar multinozzle AM of thermosetting materials on the inner surface of half an aircraft engine fan case, (b) Photo of the AM infrastructure with a custom-built heating enclosure for FFF printing of high temperature resistant thermoplastics, and (c) Workflow of the robot motion system customized for multinozzle printing of thermosets and FFF printing of thermoplastics.

resulting intersection lines are collected to generate the outline toolpaths. Once a G-code file is generated for the specimens, it is imported into the robotic simulation software (RoboDK, ver. 5.4.1) to solve the inverse kinematic problem for each coordinate of the toolpath [12].

3.2 Thermoset composites printing

Our multinozzle printhead composed of 26 cylindrical nozzles of 250 µm inner diameter was custom-built for the rapid AM of microscaffolds made of parallel lines using thermosetting materials [13]. Then, we developed a custom software programmed in Python, called Multinozzle Toolpath Generator (MTG) [14] that can be used to generate non-planar AM toolpaths, on any curved surfaces, suited for multinozzle printheads mounted on a 6-axis robot. Figure 2 presents the developed workflow for 3D printing of non-planar microscaffold networks using the multinozzle printhead. First, a non-planar printing surface is scanned using a structured light 3D scanner (GOM Atos Core 200, GOM Metrology, Germany). Then, using the developed MTG, the microscaffold network toolpath is generated on the non-uniform rational B-spline (NURBS) and imported to the robot controller. Finally, the print is fabricated in a layer-by-layer fashion by keeping the printhead oriented with the calculated surface normal at each coordinate, and by alternating the printhead rotation from 0 to 90°. The multinozzle AM along with the MTG method developed by the team enables the fast 3D printing of large periodic structures (up to an area of ∼5.2×10^4 mm^2 within 20 min) consisting of interconnected epoxy composite microscaffolds on a single curvature sinusoidal surface (as shown in Figure 2.3) and a double curvature surface (e.g., fan case), with an error of ~15 µm, without causing any collisions between the printhead and the substrate. As comparison, our multinozzle AM enabled printing a large microscaffold network with an overall dimension of ∼402 mm × 130 mm × 4.25 mm in ∼20 min which would have taken more than 8.5 h using a single nozzle with the same characteristics [14].

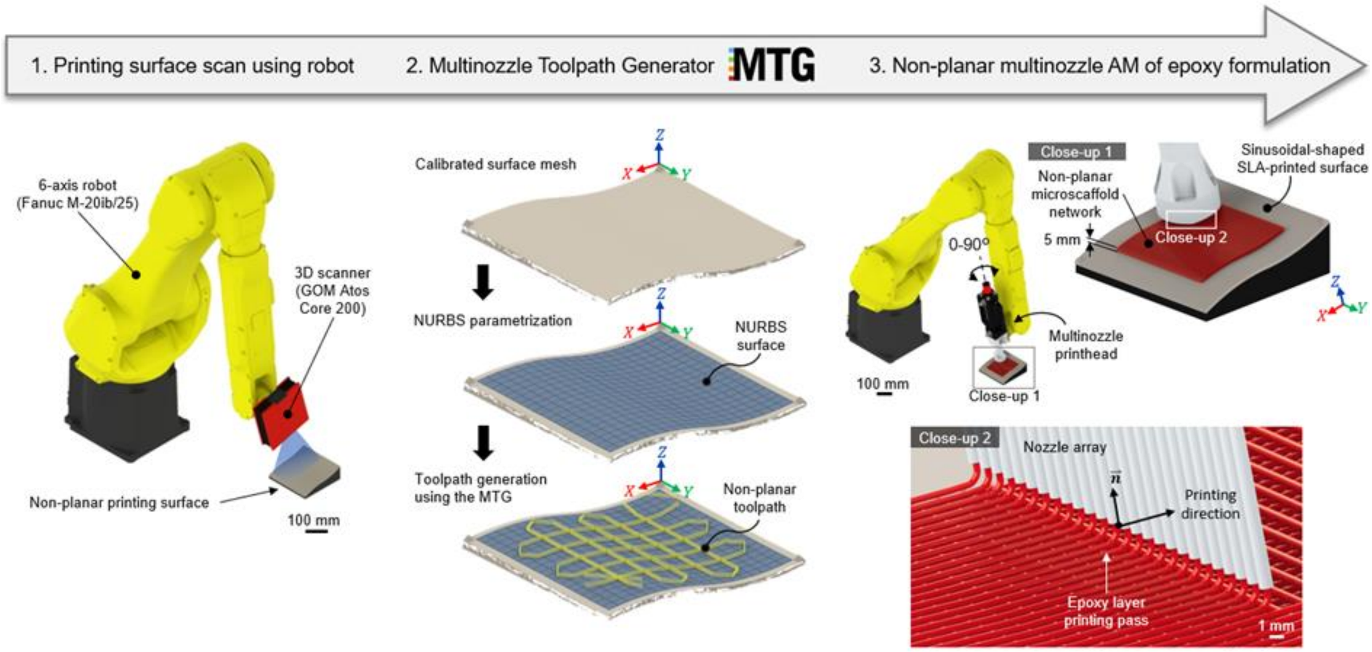

Figure 2. Non-planar microscaffold network manufacturing workflow. 1. Printing surface scan, 2. NURBS parametrization of the surface's mesh and multinozzle toolpath generation, 3. Non-planar multinozzle additive manufacturing using 6-axis robot [14].

4 Multimaterial AM of a technological demonstrator

In collaboration with Safran Group, we designed and manufactured a nonplanar multi-layer technological demonstrator (Figure 3) featuring multi-functionality: tailored acoustic performance for sound absorption of aircraft engines, top layers abradability, and lightweight [13,15]. The largest radius of the demonstrator is ∼996 mm which is at the bottom surface of the demonstrator and conforms to the aircraft casing curvature. The demonstrator consists of fiver layers (i.e., support, adaptive layer skin, plain skin, core of the sandwich structure and microscaffold) of thermoplastic-based materials and 2 top layers of abaradable thermosetting microscaffold with different geometries featuring multifunctionalities. The core of the demonstrator is made of trapezoidal structures of carbon fiber (CF)-reinforced PEEK (3D printing filament, Ensinger) and 2 layers of microscaffold networks with the same materials all with optimized geometries for efficient acoustic absorption. Figure 3 also shows an enlarged side view of the 2 top layers of the demonstrator made of the abaradable materials with our tailored formulation and fabricated using the multinozzle. The bottom porosity level has a thickness of 2.83 mm and a pore size of 726 µm, and on the top porosity level has a thickness of 2.74 mm and pore size of 183 µm. The successful manufacturing of such a complex multi-layer multimaterial component contributes to the large-scale integration of multifunctional materials into various applications and could potentially lead to the manufacturing of lightweight, sound-absorbing, structural parts beneficial for the automotive or aerospace industry.

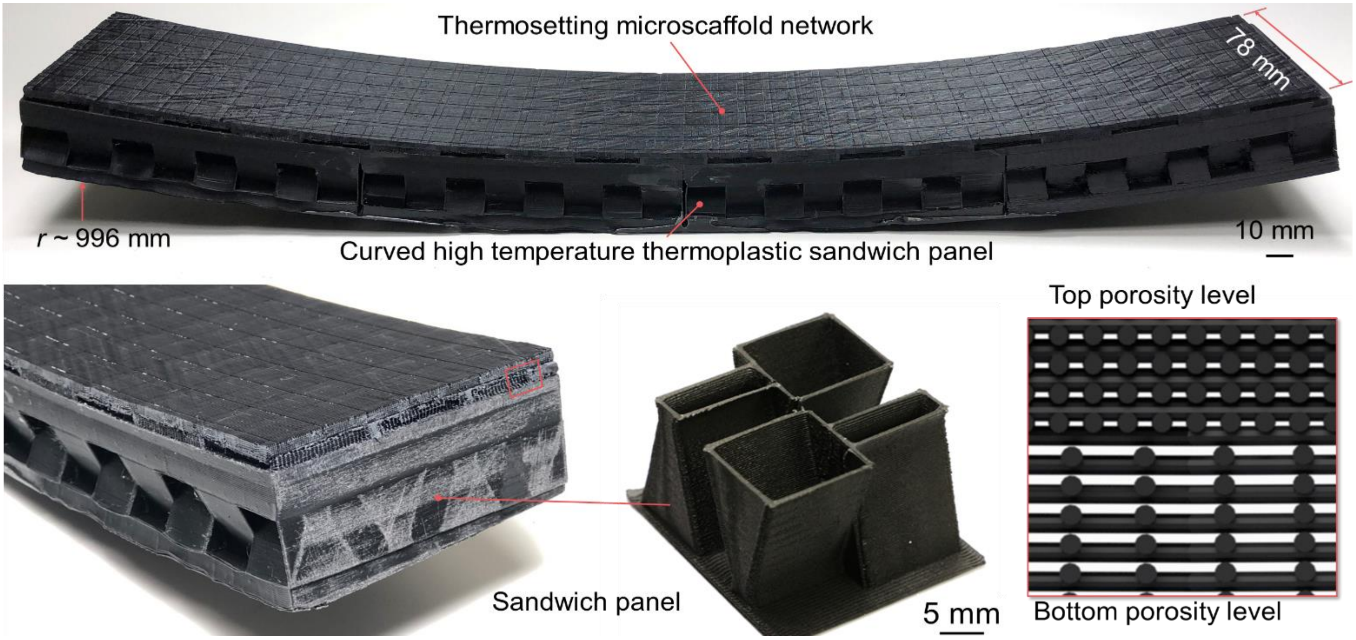

Figure 3. Images of a technological acoustic demonstrator for sound absorption in aircraft engines. The demonstrator is a multi-layer multimaterial structure fabricated by our custom six-axis robot-assisted additive manufacturing infrastructure [13].

5 Prediction of mechanical behavior of AM parts and development of visualization tools

In the field of AM of fiber-reinforced composites, the process-structure-property relation is still not fully understood. An important success of our recent research was creating a methodology to help investigate the morphological properties of CF-reinforced composites. We developed a powerful open-source software, OpenFiberSeg, to fully characterize composite materials or 3D printed structures from high-resolution X-ray micro-tomography scans [16]. The software can precisely identify the aspect ratio and orientation of the fibers and quantify the various defects and porosities. Using these detailed microstructure characteristics, our numerical models predicted thermo-viscoelastic behavior of FFF structures within ~5% [17].

We have also developed a phase-field model to predict the anisotropic fracture of FFF parts [18]. The model allows to capture the distinct fracture behavior of the FFF printed filaments and the interfaces. We applied the model to the FFF specimens with six different material orientations in two mechanical testing: three-point bending of single-edge notched bending (SENB). The comparison of the results showed that the model can predict the peak load for all material orientations with a maximum error of 11%. We also validated the capacities of the model using FFF compact-tension (CT) specimens modified with holes. Our model is able to accurately capture the location of crack initiation and predict the peak load with a relative error of 2%.

6 Conclusion

This paper presents some select achievements of the team of Prof. Therriault at Polytechnique Montreal on advanced additive manufacturing of polymer composites mainly for aerospace applications. The team has obtained an understanding of the main mechanical features of AM CF-reinforced polymers, namely stiffness, fracture toughness, and viscoelastic behavior, both through modelling and specialized experimental characterization. We developed a unique AM process for non-planar printing of geometrically-optimized acoustic structures using HTRT composites and for multinozzle direct deposition of abradable thermosetting materials with new formulations featuring high printability, abradability, and acoustic performance. Our future works will focus on further development of the prediction tools and AM infrastructure towards industrialization.

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