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NON-PLANAR LARGE-AREA EXTRUSION-BASED ADDITIVE MANUFACTURING OF COMPONENTS OF A LUNAR ROVER USING HIGH-TEMPERATURE THERMOPLASTIC COMPOSITES

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ABSTRACT

Space exploration vehicles require structures with lightweight materials and low thermal conductivity. Sandwich panels consist of two skins bonded to either side of a core. Those structures exhibit high flexural modulus and strength. Fused Filament Fabrication (FFF) enables manufacturing of such complex structures using high-performance thermoplastic composites such as carbon fiber-reinforced polyether ether ketone. Current printing methods are either limited in size, speed, temperature, or degrees of freedom (DOF). In this work, we develop a novel custom 3D printing setup using a 6 DOF robot for large-area additive manufacturing (0.9m × 0.7m × 0.6m) of high-temperature thermoplastic composites with non-planar deposition toolpaths for space applications.

1 INTRODUCTION

Space exploration requires lightweight, high-strength structures to maximize the payload delivered by spacecraft beyond Earth's gravity. Additive manufacturing (AM) allows us to shape intricate structures that are topologically optimized, thus resulting in lighter structures. Fused Filament Fabrication (FFF), one of the most popular AM technologies, consists of a print head in which filament of a polymer or a composite is melted, extruded and deposited layer by layer on a printing bed synchronously with the print head displacements. Recent works on the use of high-temperature composite materials for space applications presented the importance of a heated chamber to reduce thermal deformation [1] and to improve inter-layer adhesion [2]. Pierre et al. [3] developed an experimental setup to 3D print small specimens of carbon fiber-reinforced polyether ether ketone (CF-PEEK) using a print head on a robot. However, this setup is limited in size and printing speed. Duty et al. [4] used pellets instead of filament to create large structures without heated chamber to facilitate reptation. In the present work, we combine the advantages of high-temperature composite materials, of large-area AM and of non-planar toolpath to manufacture functional parts of a composite lunar rover. We also show our results on the effect of nozzle temperature and printing speed on the quality of the printed specimens.

2 METHODOLOGY

2.1 Experimental setup

Figure 1a presents the experimental setup used to achieve large-area additive manufacturing. A 6 DOF robot (Fanuc) mounted with a high volumetric flowrate filament-based extruder was used to precisely print the frame of a lunar rover within a day. The first few layers of sandwich panels with a honeycomb core and with a solid attachment ring were fabricated on a heated bed. This setup enables the anisotropy control with a custom slicer. Figure 1b presents the additional setup required for high-temperature thermoplastic composite AM. The additional setup consists of a heating enclosure composed of a radiative element and an insulated blanket that allows the robot to deposit material at a temperature where reptation occurs between layers, therefore enabling the use of these materials.

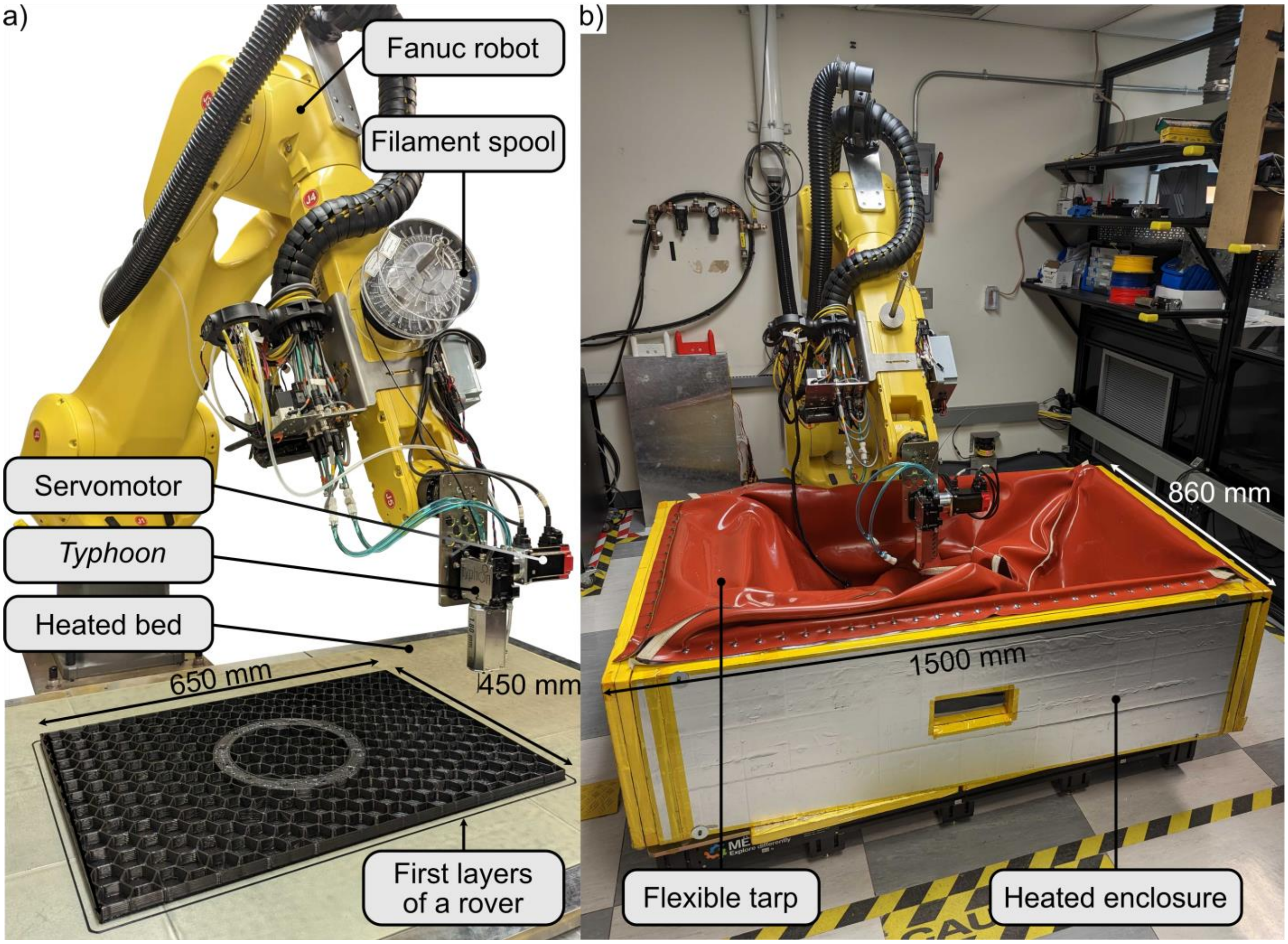

Figure 1 - a) Experimental setup for additive manufacturing of large-area components using a 6 DOF Fanuc robot with a high volumetric flowrate filament extruder on a heated bed and b) with a heated enclosure allowing the robotic arm to move during deposition of high-temperature thermoplastic composites.

2.2 Materials

CF-PEEK filament from 3DXTech with 2.85 mm in diameter is used in this study. Filament was dried according to the manufacturer's recommendations.

2.3 Mechanical criterion and printing variables

The objective of this experiment was to find the main printing parameters maximizing the flexural modulus and flexural strength of the printed material following ASTM D790. The print head diameter was fixed at 1.20 mm for CF-PEEK material. First, the printing speed was fixed at 5 mm/s and the nozzle temperature varied from 400°C to 450°C with 10°C increment. Second, the temperature was set at 440°C and the speed varied from 5 mm/s, then 10 mm/s to 50 mm/s with 10 mm/s increment to evaluate the mechanical properties of the flexural samples. Three samples for each set of parameters were printed and mechanically tested.

3 RESULTS

3.1 Mechanical properties

Figure 2 presents the average and 95% confidence interval of mechanical properties for three samples of flexural specimens according to ASTM D790 (88 mm × 12.96 mm × 4.8 mm) on an MTS Insight 50 EL electromechanical testing machine with a span length of 72 mm. Figure 2a) shows the flexural modulus with a print head displacement of 5 mm/s at various nozzle temperatures. The modulus reduces as the temperatures increases. The top surface becomes porous intra-beads and the mass decreases by 20% between the sample at 400°C and the one at 450°C. Figure 2b) presents the flexural strength for the same specimens. From 400°C to 420°C, delamination within the specimens were the failure mode, thus resulting in low repeatability. The tendency between the flexural modulus and the flexural strength lowering as the nozzle temperature increases might be due to degradation of an additive within the filament. Figure 2c) presents the flexural modulus with a nozzle temperature of 440°C and at various printing speeds. Printing faster results in higher flexural modulus. This might be due to the reduction of residency time, thus reducing the degradation of the additive causing the porosities within the material. The mass gain between 5 mm/s and 50 mm/s is 25%. Figure 2d) presents the flexural strength of the same specimens. The tendency is aligned with the flexural modulus. However, the failure mode of the samples is a neat fracture in the middle of the specimen, the result of the extreme fiber breakage.

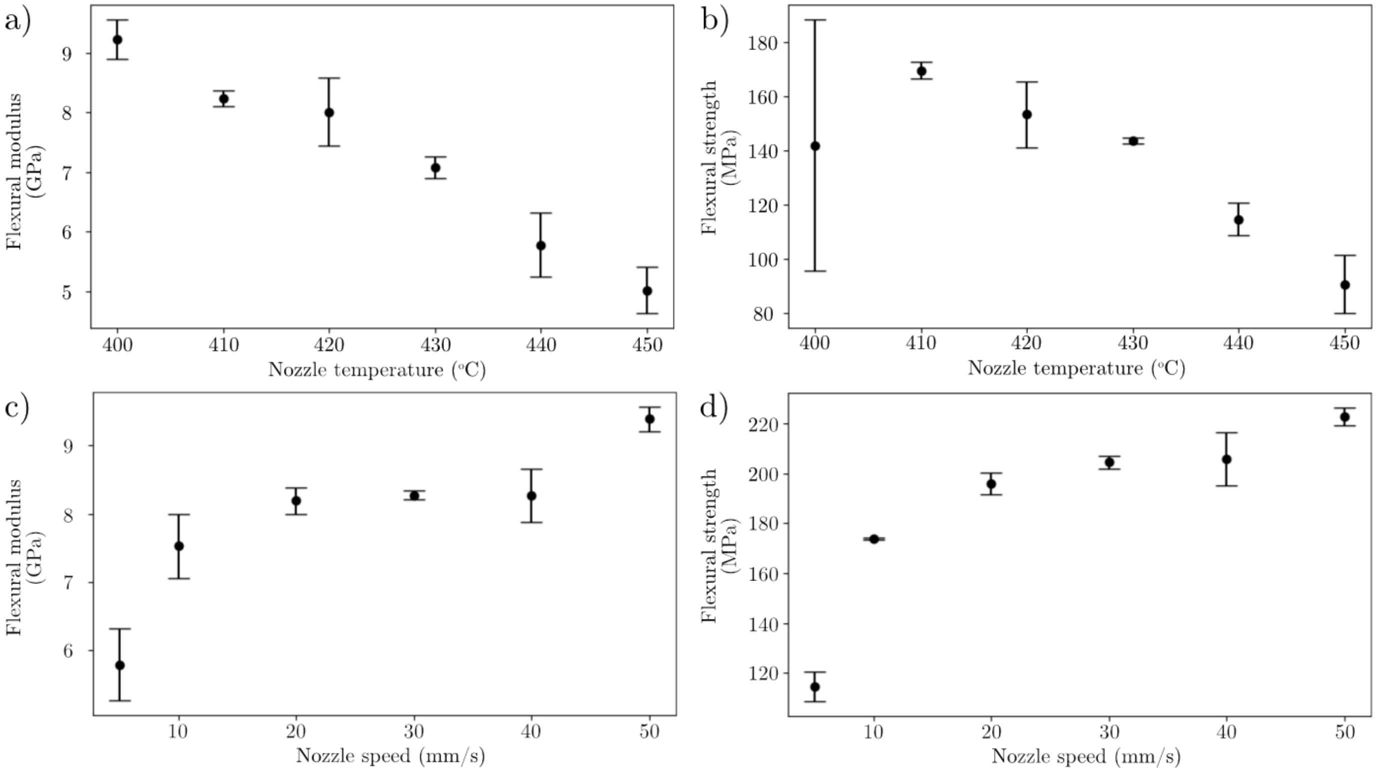

Figure 2 – Three-point bending testing results showing, for three samples at every set of parameters, an average and 95% confidence of a) the flexural modulus at various nozzle temperatures with the print head moving at 5 mm/s and b) the flexural strength at various nozzle temperatures with the print head moving at 5 mm/s and c) the flexural modulus at various printing speed with the nozzle fixed at 440°C and d) the flexural strength at various nozzle temperatures with the nozzle fixed at 440°C.

3.2 Non-planar samples and fully printed sandwich panels

Figure 3 presents three representative CF-PEEK structures printed using the high flowrate filament-based printhead. Figure 3a shows a sandwich panel of 212 mm in length with single beads walls as a honeycomb core. Some defects at the top corners are clearly seen and can be due to the bridging of large beads. The edges of the top skin are rough compared to the center, as the nozzle is dripping at lower speeds due to the robot's inertia and toolpath. This sandwich panel was printed within 2 hours. Figure 3b shows a 100 mm long curved flexural beam printed with planar layers without its support material. The corners are over extruded, and the staircase effect is predominant. Figure 3c presents the same geometry printed with a non-planar toolpath. The surface is very smooth with no presence of staircase effect.

Figure 3 – CF-PEEK printed part of a) a full sandwich panel with a length of 212 mm and a honeycomb core, b) a curved beam printed with a planar toolpath and c) the same curved beam geometry printed following a non-planar toolpath.

4 CONCLUSION

FFF 3D printing of high-performance composites is complex where many printing parameters have a direct effect on the print performance and geometrical tolerances. Using a robot to allow large-area additive manufacturing adds some opportunities and challenges, where experienced users could benefit from more control over the anisotropic behavior of a complex 3D printed part but needs to deal with the drips of a bigger nozzle mounted on a robot that has high inertia. Here, we have demonstrated that nozzle temperature and printing speed on a high flowrate filament-based printhead has a high impact over the material properties. We have shown the feasibility of 3D printing of high-temperature sandwich panels with a high flowrate on a large-area AM setup, and we have shown the feasibility of printing non-planar specimens to enhance mechanical performances. Additive manufacturing remains an interesting field of research with a huge potential for environmentally harsh destinations, such as space. For space application using FFF of CF-PEEK, the biggest challenge remains on the material processing of the filament to reduce its porosity content to meet space requirements.

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