CANCOM2024 – CANADIAN INTERNATIONAL CONFERENCE ON COMPOSITE MATERIALS

THERMAL CONSOLIDATION EFFECTS ON FLEXURAL PROPERTIES OF CONTINUOUS REINFORCED 3D-PRINTED COMPOSITES

Barbuio, T[1], Kempers, R[1], and Melenka, GW[1]*
[1] Mechanical Engineering, Lassonde School of Engineering, Toronto, Canada
*Garrett Melenka (gmelenka@yorku.ca)

Keywords: *Continuous Fibre 3D Printing, Thermal and Mechanical Testing, Flexural Strength*

ABSTRACT

3D-printing of continuous fibre reinforced polymer composites has been shown to significantly improve strength and stiffness when compared with traditional 3D-printed parts. However, the manufacturing process results in voids between the printed polymer rasters, which limits component strength and stiffness by decreasing interlayer adhesion. The flexural properties of the material are the properties most affected by voids. This study examines the effects on flexural properties of a uniform thermal consolidation process by performing compaction and integrated ohmic heating on a 3D-printed polylactic acid (PLA) part reinforced with nichrome (NiCr) wire. A direct current was passed through the NiCr wire to induce ohmic heating while heated compaction force was applied to the top and bottom of the part using a heated press. The glass transition temperature (Tg) of PLA was used to determine the optimal consolidation temperature to sufficiently re-melt the PLA to fill in the voids, increasing the flexural properties. After consolidation, the parts were evaluated under a three-point bend test to determine the change in flexural properties due to void reduction, while optical microscopy was performed to quantify the void changes. Samples that underwent this consolidation post-processing technique exhibited reduced void content and, therefore, superior flexural strength.

1 INTRODUCTION

Additive manufacturing (AM) is a process used to create complex parts that would have been difficult and wasteful to create using traditional manufacturing methods. Fused filament fabrication (FFF), one of the most common AM methods, while widespread, is still mainly used for printing with thermoplastic materials. Typical 3D printing materials are thermoplastics, such as polylactic acid (PLA), polyethylene terephthalate glycol (PETG), thermoplastic polyurethane (TPU), and acrylonitrile butadiene styrene (ABS). PLA is the most often used because of its low melting temperature and accessibility. 3D-printing with PLA is used for rapid manufacturing of low-strength parts. However, the addition of other materials, such as metals and synthetic fibres in 3D-printed parts, can significantly increase their strength and versatility. Fibres in composite parts can be continuous (i.e., the fibre reinforcement of the parts is fully connected from one end to the other in one or more lamina layers) or discontinuous (i.e., the fibre reinforcements are broken up and disordered to reinforce the matrix material). Discontinuous 3D-printing filaments with carbon fibre PLA and metallic powder-infused PLA are commercially available, but they sacrifice strength because of the discontinuous nature of the composite filament [1]. Continuous carbon fibre/PLA 3D printed composite samples were shown to have a 40% higher flexural strength and a 10% higher flexural modulus than short carbon fibre/PLA 3D-printed composite samples [2]. While the 3D printing of continuous wire polymer composites

(CWPCs) yields parts with superior mechanical properties [3], they contained voids which reduced the adhesion between the polymer matrix and the metal wires [4]. Compaction using heated platens has been shown to provide approximately a 5.2% decrease in voids in continuous fibre and thermoplastic matrix composites, yielding a 46% in flexural strength and a 30% increase in interlaminar shear strength in traditionally manufactured composite parts [5].

This work presents a preliminary study to determine the effect of void content on 3D-printed CWPC samples. A novel consolidation technique is applied to the 3D-printed CWPCs, which uses a combination of compaction and ohmic heating. The consolidation technique aims to close the voids, increasing the strength of the parts. The samples undergo a three-point bend test to quantify their flexural strength, and optical microscopy is used to identify the effectiveness of the consolidation technique in reducing the voids.

2 METHODS

2.1 Sample Manufacturing

Samples with dimensions of 80 mm long x 13 mm wide x 4 mm thick (ASTM D 7264) [6], were printed using a modified FFF 3D printer (Prusa i3 mk2, Prusa Research, Prague, Czech Republic). A continuous metal wire with a diameter of 0.075 mm was integrated using a needle that guided the wire for co-extrusion with the polymer matrix through a 1 mm-diameter printer nozzle. A visual representation of the printing process is shown in Figure 1.

(a) (b) (c)

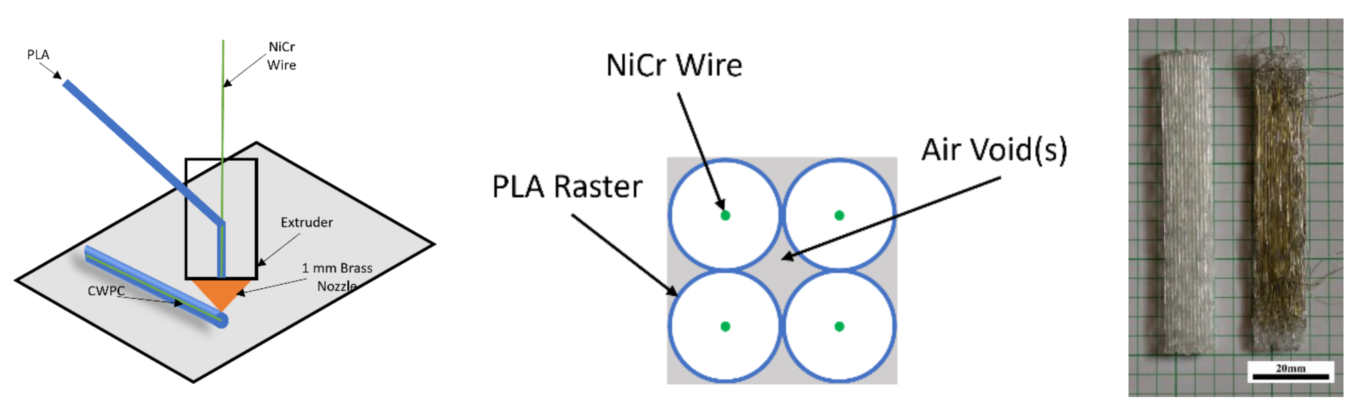


Figure 1: (a) Schematic of continuous wire polymer printing process, (b) Schematic of the expected interlayer adhesion after printing, (c) Image of PLA (left) and PLA+NiCr (right) samples

Transparent PLA filament (1.75 mm Transparent PLA, Eryone, China) was used as the matrix material, and NiCr wire (40 AWG NiCr Wire, Evanohm Alloy S, Pennsylvania, United States) was used as the fibre material deposited within every polymer raster. A custom G-Code (MATLAB 2023b, Natick, Massachusetts, The MathWorks Inc.) was used to unidirectionally print the samples in the dimensions required. Table 1 shows the printing parameters used. The dimensions used ensured the samples would maintain the span-to-thickness ratio outlined in the ASTM D7264 three-point bend test, while also having a suitable size for compaction by the aluminum plates. A total of eight samples were fabricated: four were PLA without reinforcement and four had continuous NiCr wire embedded. This allowed the mechanical properties of the compacted and non-compacted samples to be compared.

Table 1: Sample FFF printing parameters

Material Parameter	
Nozzle Temperature	200°C
Bed Temperature	50°C
Printing Speed	12 mm/s
Layer Height	0.5 mm
Raster Width	1 mm
Nozzle Diameter	1 mm
Wire Diameter	0.075 mm

2.2 Consolidation Procedure

A consolidation procedure was performed to heat and fuse the polymer matrix and fill in the voids in the samples by bringing the polymer matrix to above its glass transition temperature, then applying pressure using heated aluminum plates to force flow within the sample. The consolidation procedure was performed using a 3kN load cell universal testing machine (UTM; Electropuls E3000, Instron, Massachusetts, United States). The consolidation procedure consisted of multiple steps. First, the aluminum plates were fastened to the top and bottom grips of the UTM and heated to 70°C, which is 10°C above the glass transition temperature (Tg) of the PLA matrix. Next, samples were placed one at a time on the bottom plate, and the top plate was lowered until it contacted the top of the sample. A baseline transient 1-D conduction analytical model was used to determine the amount of time it would take for the center of the sample to reach just above the Tg of the PLA matrix, i.e., 65°C. The results from the analytical model suggested the time required was 120 s to reach 65°C. For the NiCr wire-embedded samples, a 24V DC power supply was connected to the ends of the continuous wire; supplying a constant voltage to heat the resistive wire, uniformly heating the samples. After 120 s, the UTM applied an 840 N compression force for 10 s to induce polymer flow to fill in the voids of the part. Once the consolidation procedure was completed, the sample was removed from the plate and was allowed to cool down naturally.

2.3 Three-Point Bend Test

A three-point bend test was performed to obtain the flexural stress and strain graph and determine its relation to the consolidation post-processing technique. A support span-to thickness ratio of 16:1 was used instead of the typical 32:1 [6], to keep the samples within the dimensions of the compacting aluminum plates. Given the sample thickness of 4 mm, the support span was set to 64 mm. The length of the samples was 80 mm, which was approximately 20% longer than the support span length. The samples were placed on the three-point bend fixture and on the same UTM used for consolidation, with a loading rate of 1 mm/min.

2.4 Optical Microscopy

Samples were cut and then mounted in clear epoxy (West Systems 105 Epoxy Resin, West Systems, Michigan, United States). The samples were sequentially ground using 120, 400, 600, 800, and 1200 grit sandpaper discs. Next, they were polished using 0.05µm alumina powder. After grinding and polishing, optical microscopy with 2.5x magnification was performed on the samples to obtain a visual representation of the rasters and reinforcement wires, and the location and size of the voids in the sample (ZEISS Axio Imager 2, Zeiss Group, Baden-Württemberg, Germany).

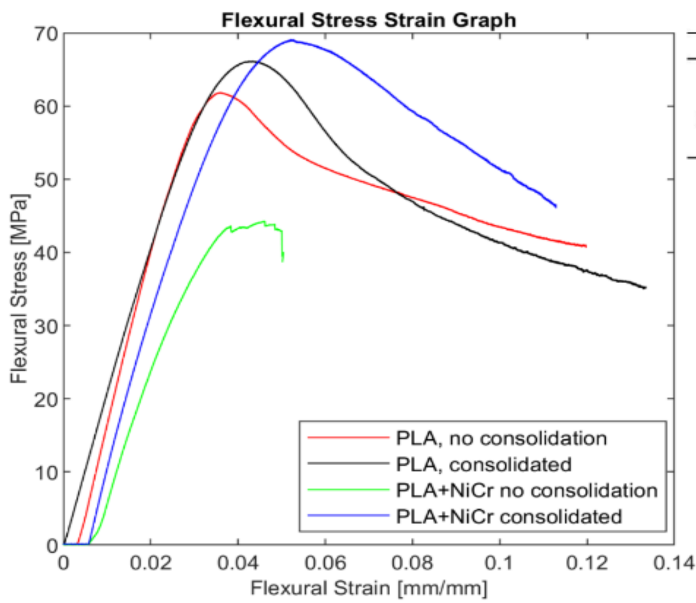
3 RESULTS AND DISCUSSION

3.1 Sample Manufacturing

Eight samples were printed and tested to determine the effect of void reduction on flexural strength and the validity of the consolidation procedure, using a three-point bend test and optical microscopy, respectively. Two preliminary studies were performed. The first study examined the three-point bending of four samples (two PLA, two PLA+NiCr). The second study examined the optical microscopy of the samples (two PLA, two PLA+NiCr).

3.2 Three-Point Bend Test

Raw load and displacement data from the three-point bend test were used to calculate the flexural stress and strain. The equations given in the ASTM D 7264 standard were used to plot the stress strain graph (Figure 2Figure 2). All samples, with and without reinforcement, behaved as expected. The non-consolidated samples failed earlier than the consolidated samples. The reinforced samples had large differences in their flexural strengths. The non-consolidated PLA+NiCr sample experienced delamination, while the consolidated sample only experienced matrix cracking as a failure mode.



Sample	Flexural Strength (MPa)
PLA, no consolidation	61.90
PLA, consolidated	66.20
PLA+NiCr, no consolidation	44.33
PLA+NiCr, consolidated	69.15

Figure 2: Flexural stress-strain results from 3-point bend test for all sample variations with flexural strength results

The flexural stress-strain graph shows the sample that had the NiCr reinforcement without the consolidation procedure had a flexural strength of 44.33 MPa, the lowest of the four samples tested. While the sample that had the NiCr reinforcement had the highest flexural strength, 69.15MPa, resulting in a 55.9% increase in flexural strength of reinforced samples after consolidation. The PLA-only samples as expected had a higher flexural strength when consolidated, compared to the non-compacted, resulting in a 6.9% increase in flexural strength of regular PLA samples after consolidation. Due to the increase in void content, the non-consolidated reinforced sample experienced delamination, causing the fibres to carry the resulting load. This resulted in failure of the CWPC earlier than the PLA samples because the void content of the composite samples was higher, the PLA rasters did not adhere to each other as well as the samples made from only PLA were. These results work with the hypothesis that the insitu printing nature of the CWPC samples increases the porosity, which decreases the flexural strength of the part. However, when the consolidation procedure is performed, the CWPC samples are stronger than the traditional PLA 3D printed samples.

3.3 Optical Microscopy

The optical microscopy performed shows that the samples that were compacted have reduced voids, see Figure 3 below. The samples with the wire reinforcement show the wires as bright white, it is seen they are relatively uniform within the rasters in the middle of the sample, but there is some misalignment near the top, which could also lead to delamination. Future work will include determining the neutral axis of the cross-sectioned sample, then performing image processing to find the difference in void and raster area before and after consolidation.

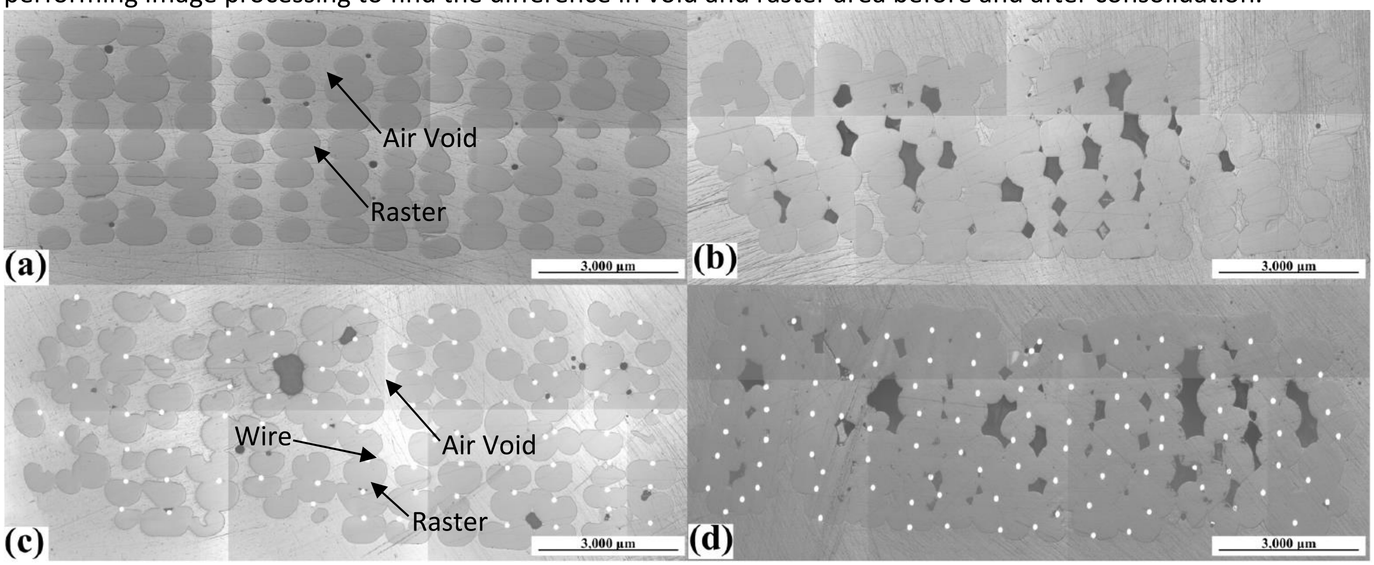


Figure 3: Optical microscope image of cross section of (a) PLA non-consolidated sample, (b) PLA consolidated sample, (c) PLA+NiCr non-consolidated sample, (d) PLA+NiCr consolidated sample

4 CONCLUSIONS

A preliminary study on the effect of void content on the flexural properties of 3D printed NiCr reinforced PLA samples was performed. A consolidation procedure to fuse the polymer matrix, filling in the voids was investigated. The consolidation procedure was evaluated using 3-point bend tests to determine flexural stress-strain behaviour and optical microscopy to visually represent the void content in these parts. The 3-point bend tests showed a 6.9% and 55.9% increase in flexural strength of the non-reinforced and reinforced parts, respectively, after the consolidation procedure was performed. Optical microscope images visually show the change in the void content in these samples before and after consolidation, for both the non-reinforced and reinforced samples. Future work in this study will quantify the void content using image processing techniques, investigate the effect consolidation parameters such as temperature and compaction pressure have on void content and the flexural properties. Interlaminar shear strength and void content will also be quantified.

5 REFERENCES

[1] I. M. Daniel and Ori. Ishai, *Engineering mechanics of composite materials*. Oxford University Press, 2006.

[2] J. M. Pappas, A. R. Thakur, M. C. Leu, and X. Dong, "A comparative study of pellet-based extrusion deposition of short, long, and continuous carbon fiber-reinforced polymer composites for large-scale additive manufacturing," *Journal of Manufacturing Science and Engineering, Transactions of the ASME*, vol. 143, no. 7, Jul. 2021, doi: 10.1115/1.4049646.

[3] Y. Ibrahim, G. W. Melenka, and R. Kempers, "Additive manufacturing of Continuous Wire Polymer Composites," *Manuf Lett*, vol. 16, pp. 49–51, Apr. 2018, doi: 10.1016/J.MFGLET.2018.04.001.

[4] Y. Ibrahim, G. W. Melenka, and R. Kempers, "Flexural properties of three-dimensional printed continuous wire polymer composites," *Materials Science and Technology (United Kingdom)*, vol. 35, no. 12, pp. 1471–1482, Aug. 2019, doi: 10.1080/02670836.2019.1630085.

[5] N. Van De Werken, P. Koirala, J. Ghorbani, D. Doyle, and M. Tehrani, "Investigating the hot isostatic pressing of an additively manufactured continuous carbon fiber reinforced PEEK composite," *Addit Manuf*, vol. 37, p. 101634, 2021, doi: 10.1016/j.addma.2020.101634.

[6] "Designation: D 7264/D 7264M-07 Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials 1." [Online]. Available: http://www.ansi.org.