Solid Freeform Fabrication 2024: Proceedings of the 35th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

The Behaviour of First-Generation Bio-Composites in a Multi-Axis Material Extrusion Application

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Abstract

Environmentally friendly materials are becoming more prevalent in many industries and Additive Manufacturing (AM) is no different. In Material Extrusion (MEX), Wood Fibre Reinforced Polylactic Acid (WF-PLA) embodies a sustainable promising alternative to standard PLA and Short Carbon Fibre Reinforced PLA (SCF-PLA) because of its enhanced mechanical characteristics and full biodegradability. By aligning the wood fibres to the direction of the load, Multi-Axis Material Extrusion (MAMEX) could further enhance the capabilities of WF-PLA, but this has not been yet proven. To shed some light on this topic, this paper compares the mechanical behaviour of WF-PLA, PLA and SCF-PLA samples made using 4 and 5 axes MEX. In 4 axes MEX, the results show that WF-PLA samples display 27% poorer ability to resist the applied loading than PLA, and 37% poorer than SCF-PLA. Whereas in 5 axis MEX, WF-PLA samples were able to withstand the same amount of force as the PLA samples, but over a longer period. This research highlights that Wood Fibre-reinforced materials could be beneficial to the AM community and further development is required to fully exploit their opportunities.

Introduction

In MEX, composite materials are often used to create a desired aesthetic with some examples being illustrated in Figure 1; this is accomplished through the inclusion of particulates and fibres. Some MEX systems are capable of printing parts utilising composite materials in a structurally functional manner, again using polymers loaded with particles or short fibres. There are also MEX machines that are capable of printing using continuous fibres such as the systems developed by Markforged (1). As material innovation is a key driving factor in the AM industry, it is imperative to explore the potential benefits of new materials to determine how useful they can be and what areas need improvement. Markforged create machines that are capable of printing with pre-impregnated filaments; these machines focus on Polyamide composites with metal particulate and short carbon fibres (1). However, as composite materials become more accessible with the increasing availability of pre-impregnated filaments, other manufacturers have entered the market. WF-PLA is a fully sustainable and biodegradable bio-composite (2) and represents a shift in the AM industry towards being more environmentally responsible. In recent years, a trend that has influenced product adoption has been how sustainable the materials used to create the product are. This is an issue for the MEX industry as substantial waste material is produced due to failing prints and break-away support structures. It is possible to recycle this material, with research having been undertaken to explore this (3–7). However, the recycled material has been determined to have poorer mechanical properties than the virgin material. For MEX to be considered a sustainable manufacturing technique, more suitable materials would need to be developed. For this work, a novel material was sourced; it was a bio-composite filament consisting of a PLA derived from an organic source that has been reinforced with wood fibre.

Figure 1: Material Extrusion Samples Produced with Polymer Composite Materials

A common limitation of almost all commercial MEX machines, particularly when printing in fibre-reinforced materials, is the orientation of the extrusion paths. The planar nature of the printing limits the orientation possibilities. Research has shown that fibre orientation can be controlled by the orientation of the print surface and the layer offset direction (8–12). This approach can be adequate for components that undergo simple loading conditions with stress vectors limited to one or two dimensions. However, when the direction of the applied loading becomes more complex, the fibre reinforcement is must be orientated to resist stress vectors in all three axes. By using a multi-axis MEX (MAMEX) system such as the 5AxisMaker machine offered by 5AxisWorks, the fibres can be orientated to best resist these complex loading conditions (13). Previous work has highlighted how innovative path planning in a MAMEX printer has enabled improved mechanical behaviour over a conventional MEX printer (14,15).

The research reported in this paper uses the 5-axis capability of 5AxisMaker to build the curved geometries of a thin-walled dome and a "wave spring". These geometries are appropriate to investigate the optimisation of the mechanical performance of MEX parts by selectively orienting the deposition of the filament. The objective of this work was to determine how the incorporation of sustainable materials affects the mechanical behaviour of a sample when compared to conventional materials available to the AM industry.

Method

The samples were created using the tool paths shown in Figure 2. The reason these toolpaths where selected was to aid comparison with previous MAMEX research that had been undertaken (14,15). Standard ISO test specimens would not suffice for this study as they are mainly 2-dimensional. Moreover, the mechanical behaviour of domes has been widely studied by other researchers, which is useful for comparison of results (16–22). Dome geometries are widely used in compression testing as they are suitable 3D dimensional geometry for incorporating rotational symmetry ad radial stresses.

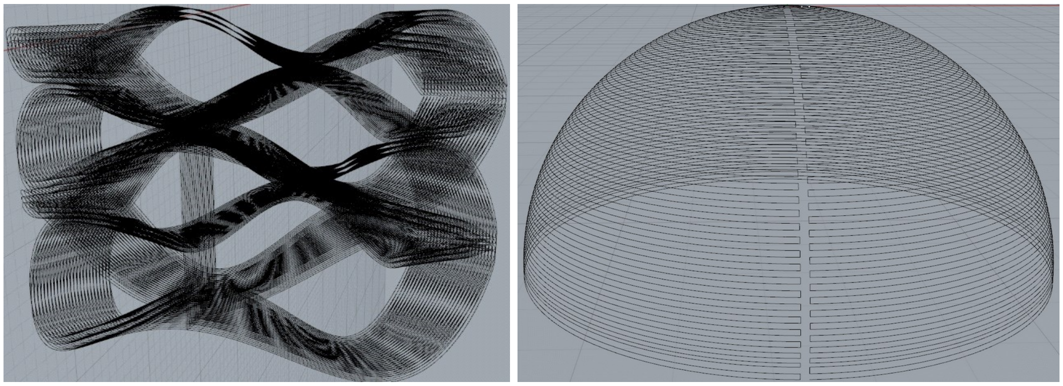

Figure 2: 4-Axis Wave Spring Sample (Left), 5-Axis Dome Sample First Layer (Right)

The samples for the comparative testing were fabricated using a commercial 5-axis MEX 3D printer (5AxisMaker 5xm600XL) from 5AxisWorks Ltd (13), as shown in Figure 3. This is the same machine that was utilised in previous studies and was used for creating all the composite samples for the present studies.

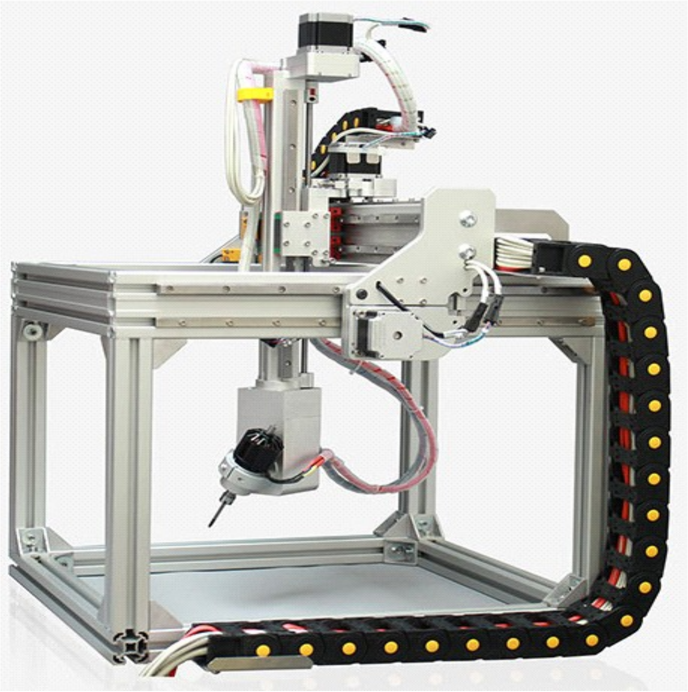

Figure 3: 5AxisMaker Multi-Axis MEX System (13)

Grasshopper for Rhinoceros v5 was used as the slicing software and to generate the G-Code from 3D CAD data. For processing, the filament was melted and deposited at an extruder temperature of 210°C using a hardened steel nozzle with an exit diameter of 0.6 mm. The reinforced samples were printed using the same tool path as the samples in previous studies, this was done to aid in comparison of results.

The melted filament expands in diameter after leaving the nozzle, resulting in an approximate hatch distance of 0.6 mm and a shell thickness of approximately 0.2 mm. A printing speed of 70 mm/min was adopted for the fabrication process.

The images in Figure 4 depict the two sample types created wave spring and dome. Five specimens of each sample type were created and subjected to compressive testing. Due to the nature of the fibre reinforcement, the samples have a unique aesthetic with the colour being that of a dull wood tone, like Medium Density Fibre Bord (MDF), but with a “ridged” surface finish.

Figure 4: Bio-Composite Printed Samples

The axial compression testing was carried out on an Instron 3366 material test system with a 5kN load cell and a compression speed of 2mm.s^{-1}. The purpose of this test procedure was to establish the different mechanical behaviours of the test samples regarding their stiffness, ductile behaviour, and maximum compressive loading. The experimental setup is illustrated in Figure 5 (with a black PLA specimen from a previous study).

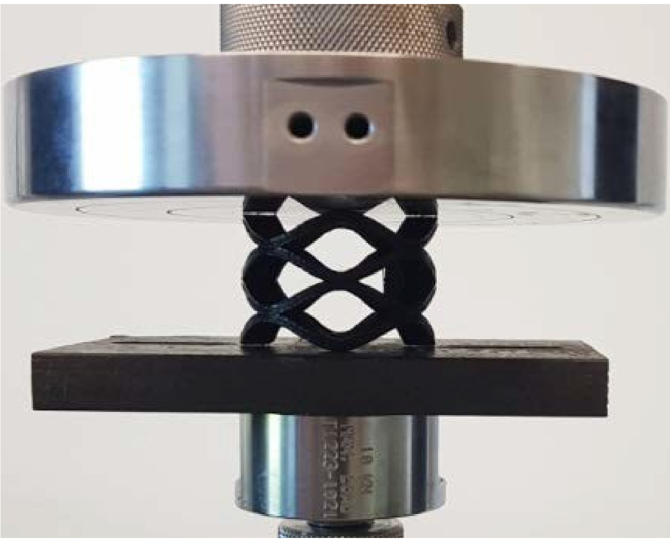

Figure 5: Compression Testing Setup

Results and Discussion

The results collected demonstrated some unusual mechanical behaviour of the samples. While they were not expected to withstand as much force as samples build previously with carbon fibre reinforcement, the 4-axis wave spring results showed that this material had even worse properties than standard PLA. Following up with the materials manufacturer it was discovered that the material sourced from them contained a different PLA than what was advertised on their website. This lower quality material matrix would explain the poor mechanical behaviour, highlighting the importance of the matrix material within composite materials. This is highlighted best within Figure 6, as the wood filled wave spring displayed 27% worse load-bearing capability than the PLA samples. Furthermore, the displacement before failure was only around 50% of that seen in both the PLA and SCF-PLA samples.

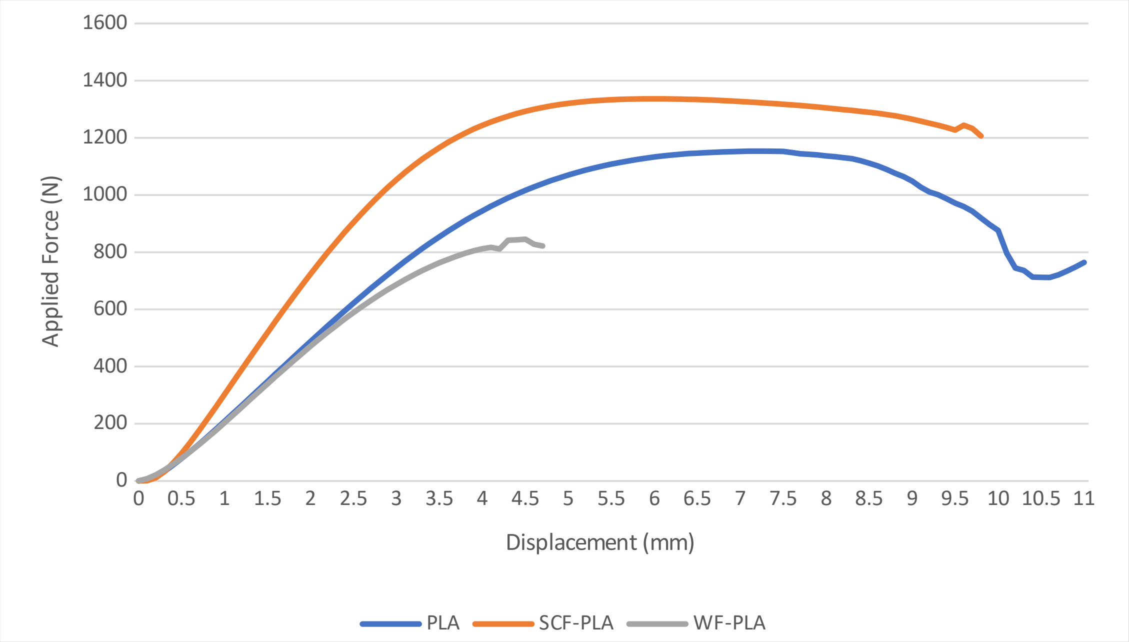

Figure 6: Wave Spring Material Comparison Average Results

For the 5-axis dome tests, the WF-PLA displayed increased displacement to failure behaviour compared to the pure PLA samples (see Figure 7). The wood-filled samples were able to withstand similar applied forces to the PLA sample but over a much larger displacement, indicating that the wood fibres were able to absorb more energy prior to failure. The SCF-PLA once again outperformed the WF-PLA material by a significant margin for these samples.

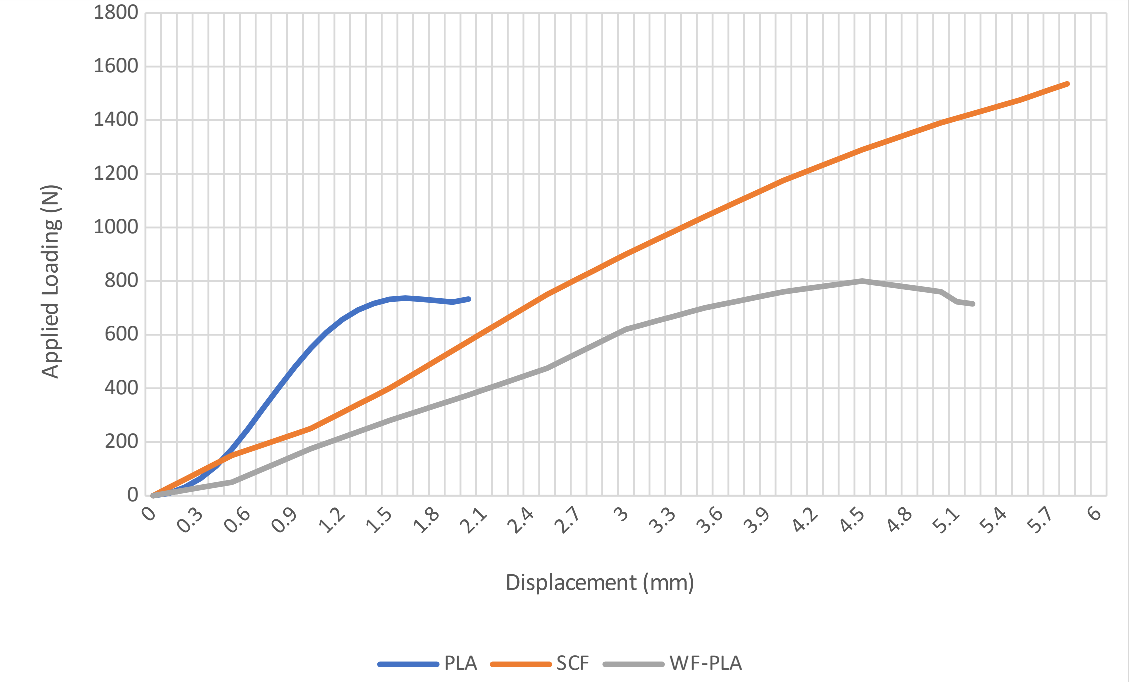

Figure 7: Dome Material Comparison Average Results

The apparent discrepancy between the two sets of results can best be explained with reference to Figure 8. These images show the failure behaviour of both the pure PLA and WF-PLA dome samples. The WF-PLA samples failed in the mode that was predicted by research on the crush behaviour of thin-walled domes (23). The authors propose that the lower hoop stiffness of the WF-PLA allowed the samples to stretch circumferentially thereby enabling further downward deformation. In contrast, the higher stiffness of pure PLA samples caused them to fail prematurely due to a catastrophic splitting along the "weld seam" of the dome. This is an important finding that will be considered when designing future tool paths.

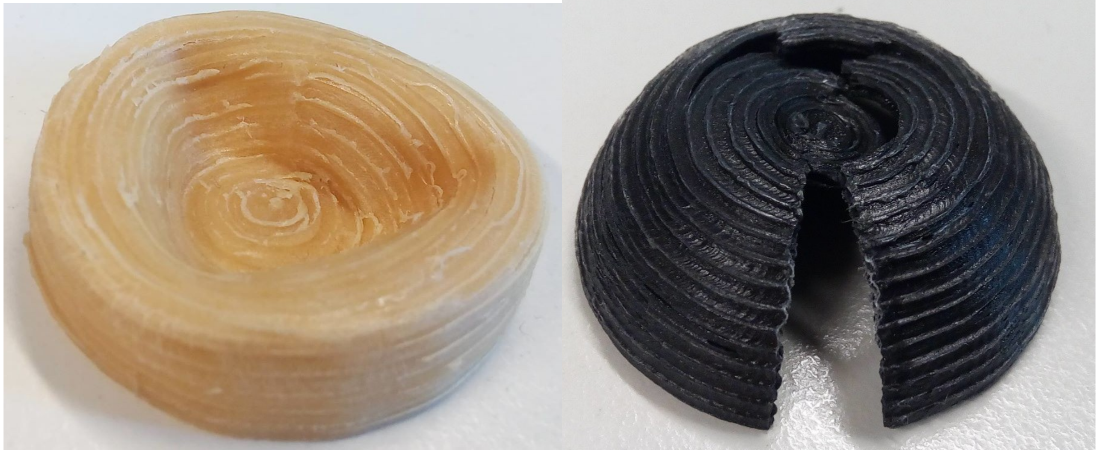

Figure 8: Compressed Thin Wall WF-PLA Dome (Left) Pure PLA Dome (Right)

Conclusion

While the WF-PLA did not compare favourably with either PLA or SCF-PLA, it does represent an important entry point into the field of AM. The reason behind its poorer performance is probably due to a poor-quality PLA used as the material matrix. With this being addressed, WF-PLA can aid the AM industry meeting consumer demand with more sustainable products.

While these results do not demonstrate the full capability of this material and reinforcement strategy, it is of importance as an example of the AM industry moving towards a more sustainable future. As these materials are relatively new, further research is required to improve their performance. This reflects the development path of many current and future AM materials.

Acknowledgements

The work was undertaken to support the Directional Composites through Innovative Manufacturing (DiCoMI) project, funded by the European Commission under grant agreement No 778068.

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