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Published version

FORSTER, Rosanna, FETEIRA, Antonio, SOULIOTI, Dimitra, GRAMMATIKOS, Sotirios A, WALSH, Yvonne and KORDATOS, Evangelos (2024). Non-destructive evaluation of 3D-printed fibre-reinforced composite materials mechanical behaviour. In: AVDELIDIS, Nicolas P, FERRARINI, Giovanni and LÓPEZ, Fernando, (eds.) Proceedings Volume 13047, Thermosense: Thermal Infrared Applications XLVI; 1304718 (2024) https://doi.org/10.1117/12.3013730. SPIE.

Non-destructive evaluation of 3D-printed fibre-reinforced composite materials mechanical behaviour

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ABSTRACT

Fused filament fabrication (FFF) is the most widely used additive manufacturing (AM) technique to produce fibre-reinforced polymer matrix composites, due to their low wastage, geometric flexibility and ease of use. Composite materials generally have superior properties such as being stiffer and more robust than conventional materials at a reduced weight leading to their application in a wide variety of sectors (aerospace, automotive etc). However, composites manufactured in this way are highly susceptible to defects such as high void content and poor bond quality at the fibre and matrix interfaces. These defects stop fibre-reinforced composite materials manufactured this way meeting industry standards and being used for structural applications. In the present work, a combination methodology of acoustic emission (AE) alongside tensile testing has been developed to investigate the structural integrity and mechanical performance of AM fibre-reinforced composites. Pure polymer samples and short carbon fibre reinforced composites were manufactured, and their mechanical properties were observed.

Keywords: Fibre-reinforced composites, Acoustic Emission, Tensile Testing, additive manufacturing, Non-destructive Evaluation, 3d printing, polymer matrix composites

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1. INTRODUCTION

Polymer matrix composite materials use for industrial and structural applications has increased in recent years due to their advantage over metals such as design flexibility, lower weight, higher specific properties [1], therefore they have applications across a multitude of sector including aerospace, automotive, biomedical and architecture [2]. However, wider use of these materials has been restricted due to the current cost of manufacture, complex fabrication techniques and difficultly in damage inspection [1]. The use of additive manufacturing (AM) to produce these composites has been rapidly developing [3] [4] specifically Fused filament fabrication (FFF) to produce fibre-reinforced composites (FRPs). FFF allows for dimensional and geometric flexibility, low material wastage, minimal post-processing required and low cost [5]. However, composite parts produced this way are susceptible to defects such as porosity, cracks and a poor fibre-matrix interface. This is a large concern for these parts as the strength of composite materials is dependent on this interface [6], however these defects are difficult to detect during production due to the nature of the manufacturing process. Once printing begins, layers are printed sequentially, with a layer deposited on the print bed, allowed to cool, then another layer is deposited onto where they fuse together. This is repeated until the part reaches its desired shape [7]. Once the process has started, if interrupted, it may have to be abandoned and restarted dependent on the printers programming.

To allow for the structural assessment of FRPs, tensile testing has been employed [8] [9] to provide information on the mechanical properties. Acoustic emission (AE) testing has been used alongside tensile testing to allow for more information on these properties [10] and to show break locations and damage progression although most studies using AE with tensile testing do not apply AE directly during the tensile test, instead evaluating the printing process of the samples itself such as machine errors (nozzle blockage, print path errors) [11] and possible failure in the first printing layers [12]. There has been research into the impact of the infill patterns and density have on the mechanical properties of AM FRPs [9] but the use of AE has not been widely explored. Therefore, in this paper, the mechanical properties of AM FRPs were assessed across different infill patterns. The mechanical testing results were also compared to pure polymer samples printed within the same infill patterns and printing parameters with a combination method of tensile testing and acoustic emission.

2. EXPERIMENTAL SETUP

2.1 Printing

The tensile samples were printed on an Anisoprint Desktop Composer A3 printer with a nozzle diameter of 0.4mm and were Dogbone 1B samples as per BS EN ISO 527-4:2023. The samples were printed with a 5 loop brim and 5 loop skirt to aid with adhesion alongside the application of "Magigoo" PA adhesive glue to the print bed. The filament of the pure polymer samples was CFC PA with a filament diameter of 1.75mm [13] and the chopped fibre filament was Smooth PA with a filament diameter of 1.75mm [14]. CFC is a non-filled nylon PA12 polymer and Smooth PA is a nylon PA12 filament reinforced with 10% chopped carbon fibre. The smooth PA material profile provided in AURA was used for the chopped fibre printing settings, a custom profile was created for the CFC PA as one was not provided in the software. The tensile samples were printed at 50% infill with a total of 18 samples split across the two materials and 3 patterns provided in AURA [15] as shown in Figure 1. The dogbones were printed in sets of 3 shown in Figure 2 and the printing parameters are listed in Table 1.

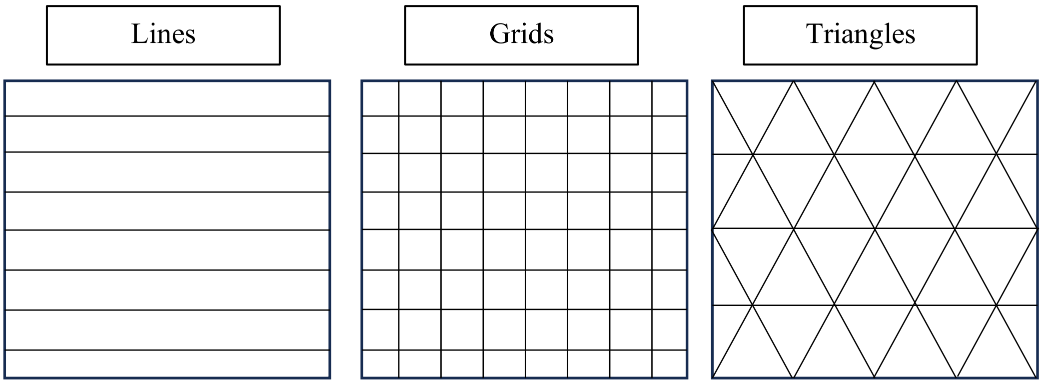

Figure 1 - Fill pattern options provided in Anisoprint AURA software [15].

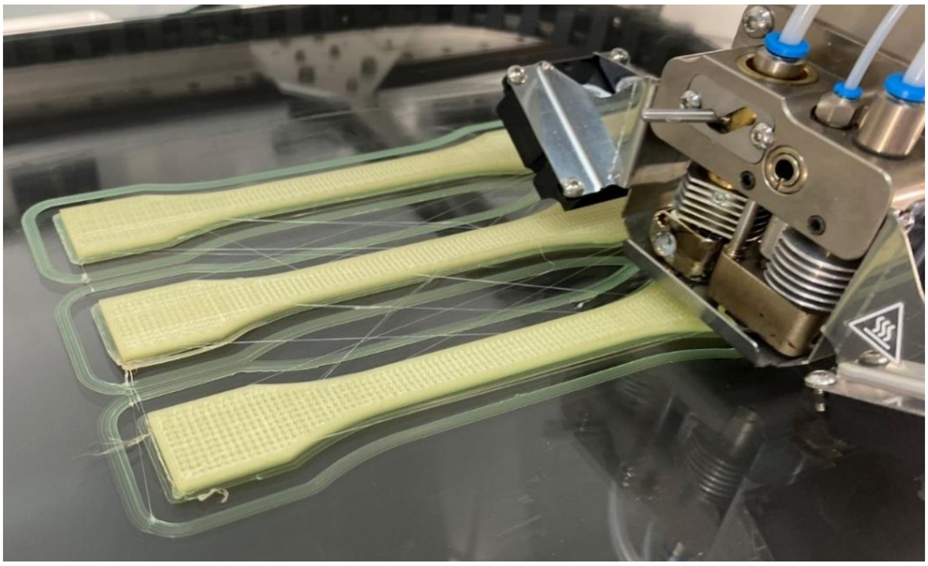

Figure 2 - CFC PA Dogbone 1A samples during printing with the 50% infill grid pattern.

Table 1 - Printing parameters for the Dogbone 1B samples

	0.2mm Macrolayer Lines infill	**0.2mm Macrolayer Triangle infill**	**0.2mm Macrolayer Grid infill**
Macro Layer Height (mm)	0.2	0.2	0.2
External Shell Layer Height (mm)	0.1	0.1	0.1
Plastic Perimeters Layer Height (mm)	0.1	0.1	0.1
Infill Layer Height (mm)	0.2	0.2	0.2
Thick support layer height (mm)	0.2	0.2	0.2
Infill Density (%)	50	50	50
Infill Pattern	Lines	Triangles	Grid
First Layer Height (mm)	0.25	0.25	0.25

2.2 Mechanical Testing

Tensile testing was carried out on an Instron Universal Testing machine (Model 3369) with a Digital Extensometer AVE2, with the setup displayed in Figure 3. The crosshead velocity was set to 50mm/min for the pure polymer samples and 2mm/min for the chopped fibre samples, each with a 5kN load cell. For the AE monitoring, two AE Pico sensors with an operating frequency range of 200-700kHz [16] were attached with tape to the samples. ANAGEL ultrasonic gel was applied to the surface to aid with acoustic coupling. A pre-amplifier gain was set to 40db and a threshold of 30db was applied to reduce the effect of background noise and equipment vibration. The data was captured and displayed in the AEWin software.

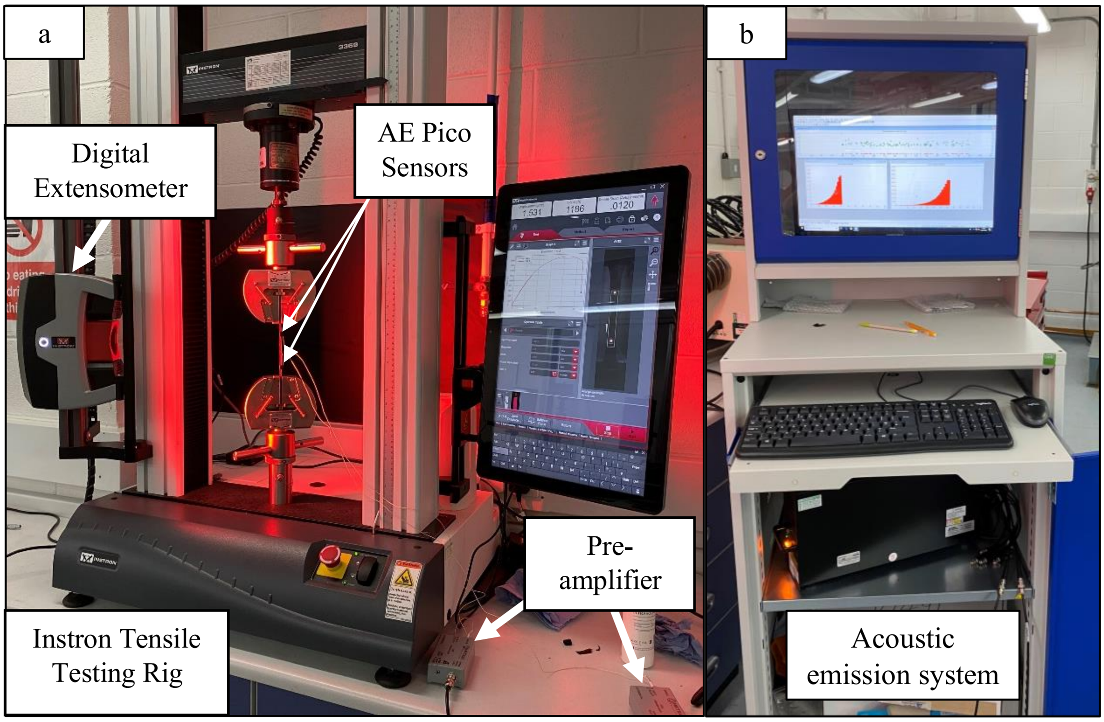

Figure 3 - Experimental setup for the tensile testing of the samples.

3. RESULTS

3.1 Mechanical

Figure 4 shows the stress strain curves for the materials. The CFC PA samples are significantly more ductile than the Smooth PA samples however the Smooth PA samples had higher yield strength and tensile strength at break than the CFC PA. They also followed a brittle curve with minimal deformation after yielding, where the CFC PA showed extended plastic deformation after yield. However, the amount of deformation shown by the CFC PA samples after yield was not consistent across the infill profiles.

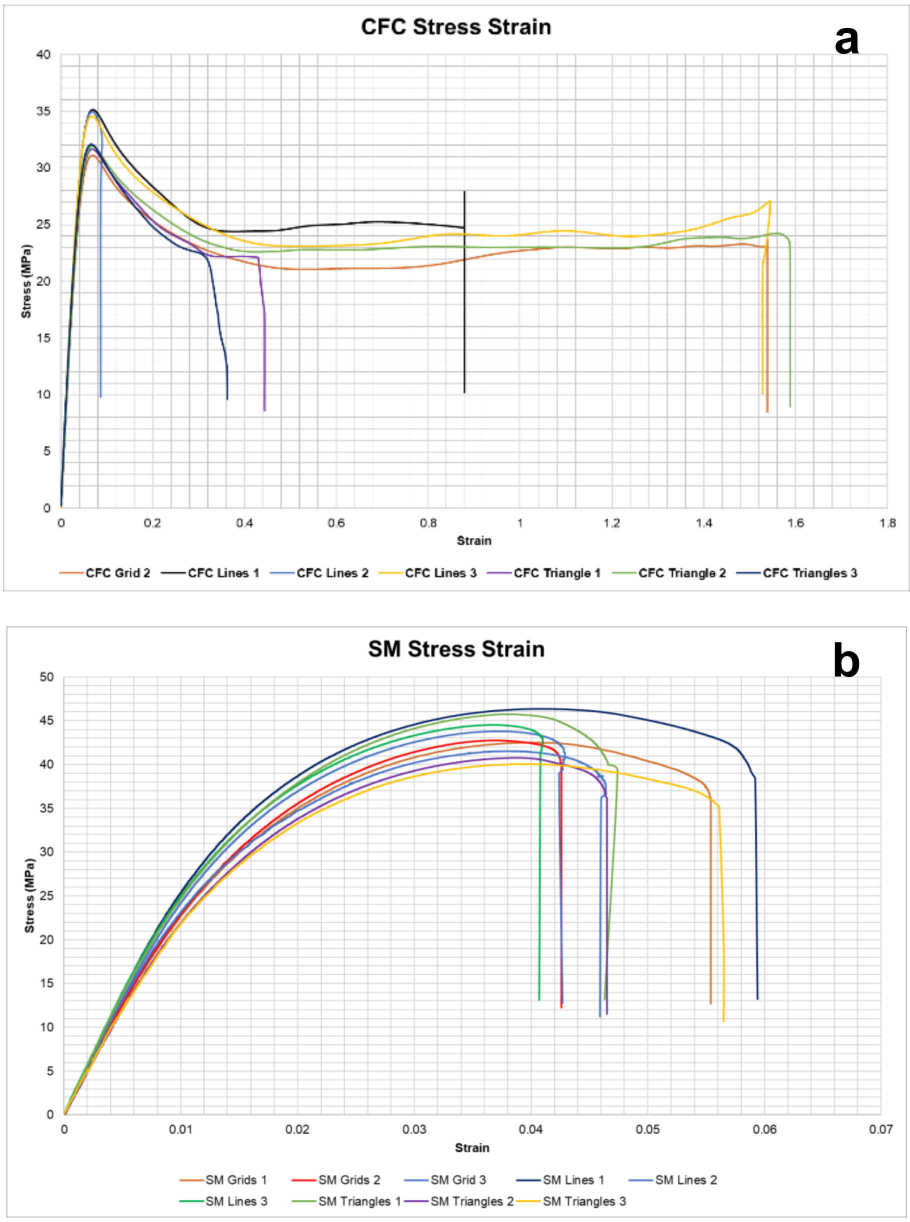

Figure 4 - Graphical representation of stress strain curves across the infill patterns from (a) CFC PA and (b) Smooth PA.

For both CFC & Smooth PA samples with the Lines infill pattern had the highest average Tensile strength at break and yield strength. This is shown graphically in Figure 5.

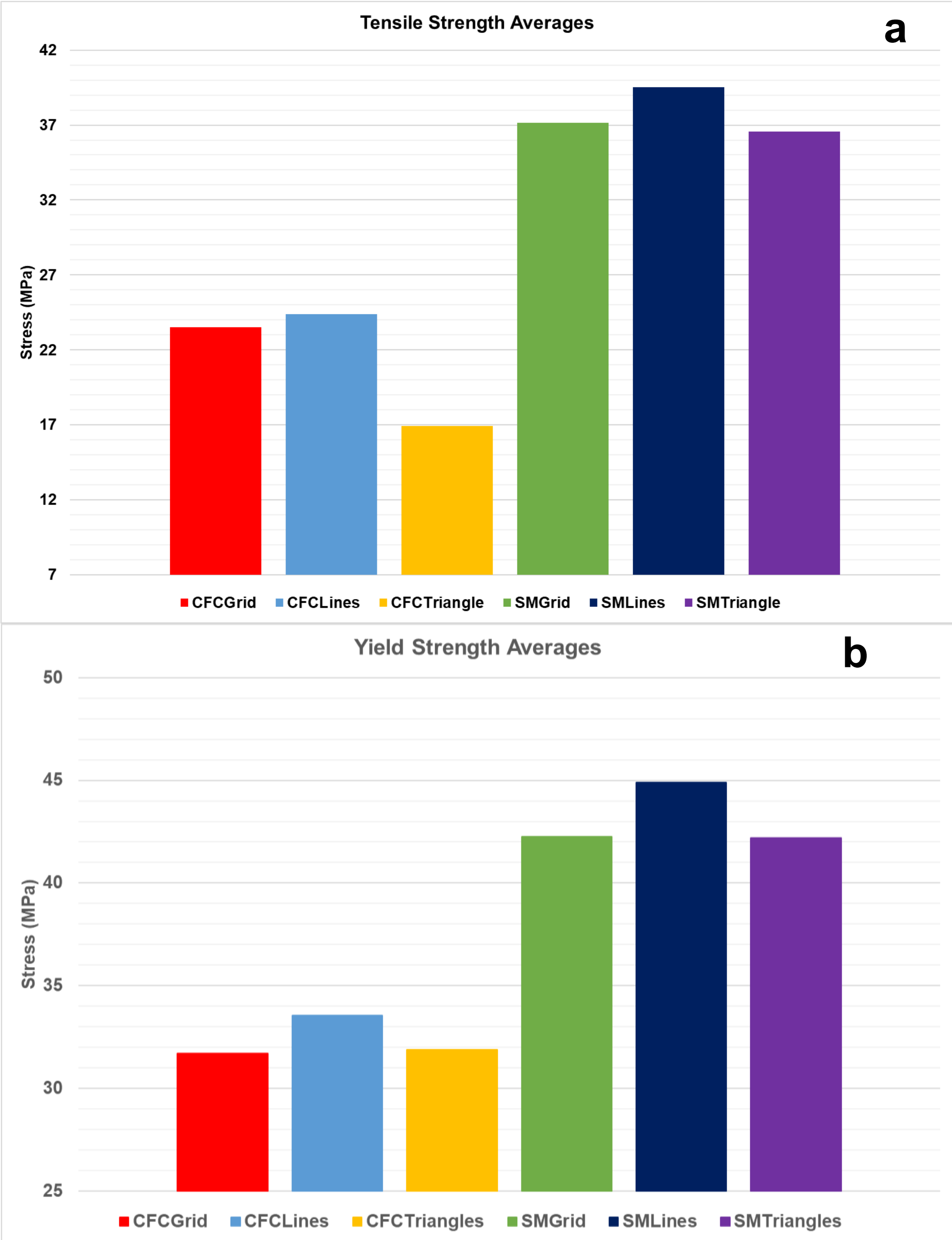

Figure 5 - Average (a) Tensile strength at break and (b) yield strength across the materials and infill patterns.

Statistical analysis of the mechanical datasets shows that there is more variance in the Smooth PA results than the CFC PA shown in Table 2. This is true for the data sets when compared by material and the data sets when compared by infill type, shown graphically in Figure 6.

Table 2 - Yield strength averages for the CFC PA and Smooth PA material

	Material YS Average (MPa)	Std dev
CFC PA	32.38354	1.4609
Smooth PA	43.11954	2.048584

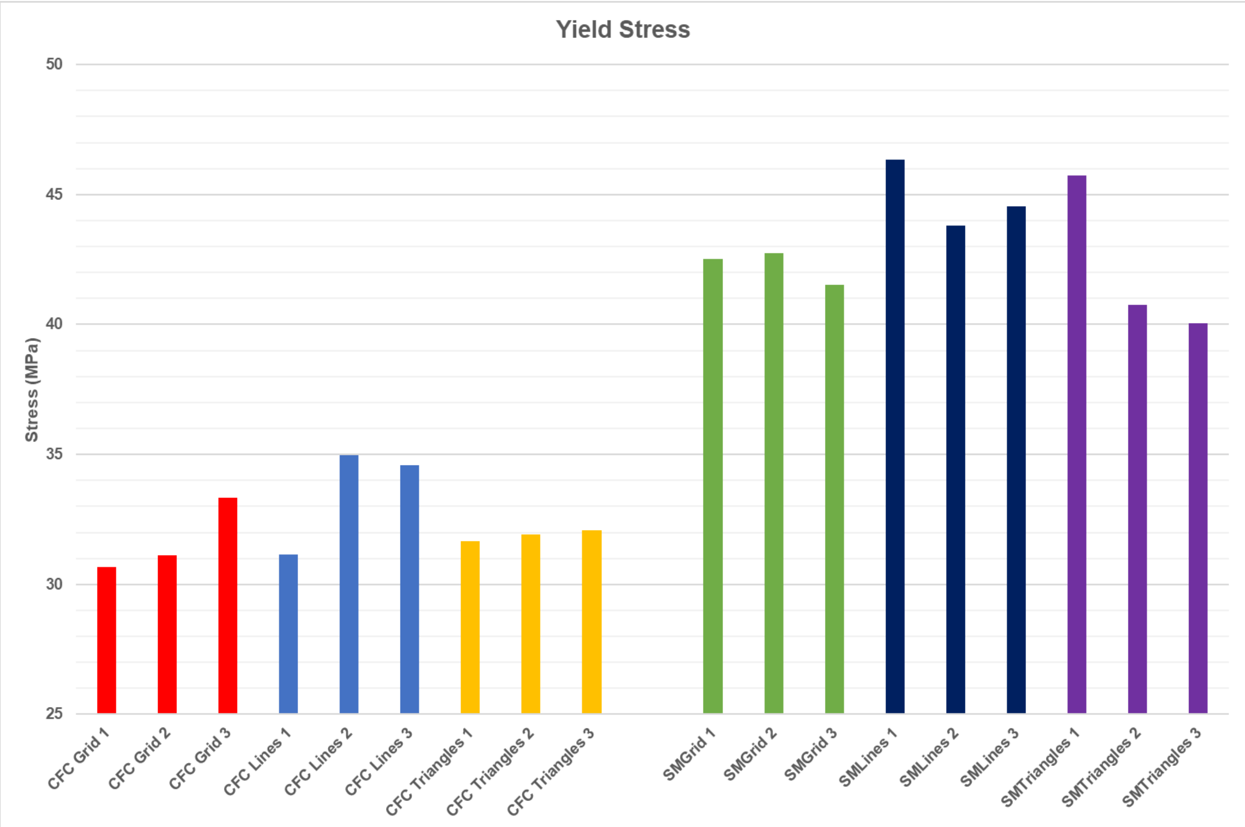

Figure 6 - Graphical representation of the yield strength of the individual samples grouped by infill type.

3.2 Acoustic Emission

Figure 7 shows that in the CFC PA, the grid samples show the most events within the gauge length, followed by the Triangles and the lines. In the smooth PA, the lines showed the most events in the gauge length, with the triangles and grids comparable after, shown in Figure 8.

Figure 7 - AE Events across the tensile sample gauge length for CFC PA a) Grid b) Line c) Triangle.

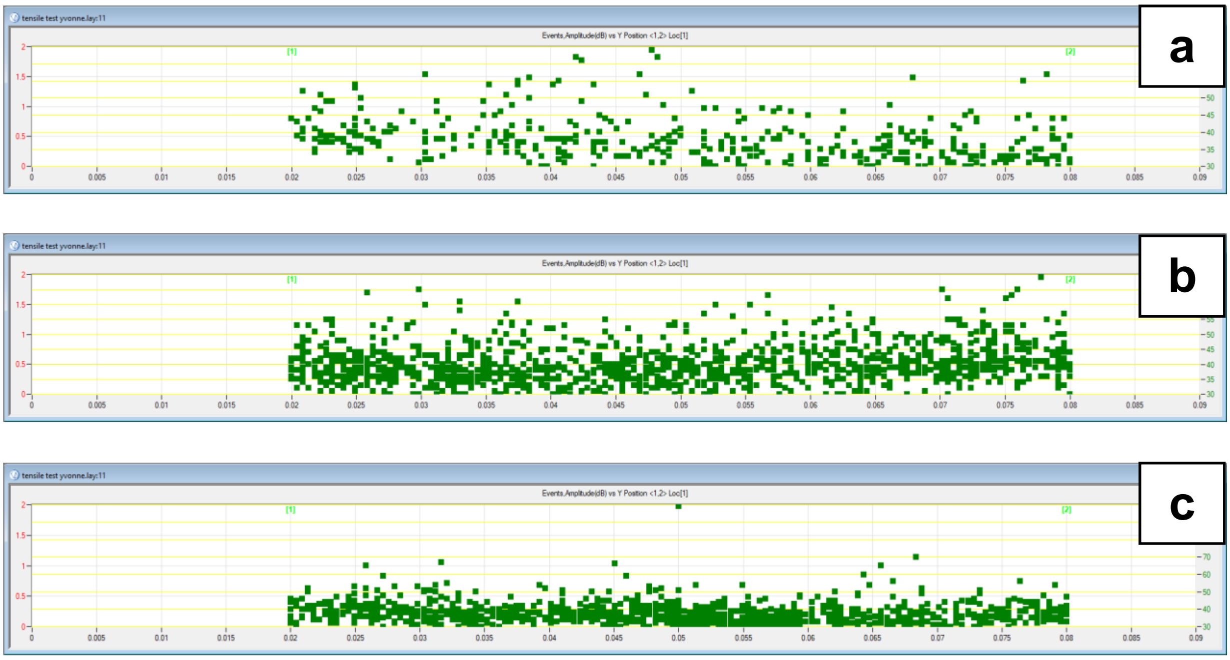

Figure 8 - AE Events across the tensile sample gauge length for Smooth PA a) Grid b) Line c) Triangle.

Across the materials, the behaviour is significantly different with the chopped fibre material showing substantial AE events across the sample compared to the CFC PA, shown in Table 3.

Table 3 - Average cumulative hits across the infill patterns.

Infill Pattern	Average Cumulative Hits
CFC Grid	2446.5
CFC Line	363
CFC Triangle	925.3333
SM Grid	11611.67
SM Line	13716
SM Triangle	11416.33

There is no comparison between the infill profiles across the different materials, with the CFC PA and Smooth PA showing opposite event behaviour – CFC PA Lines being lowest, whilst Smooth PA Lines being the highest, shown graphically in Figure 9.

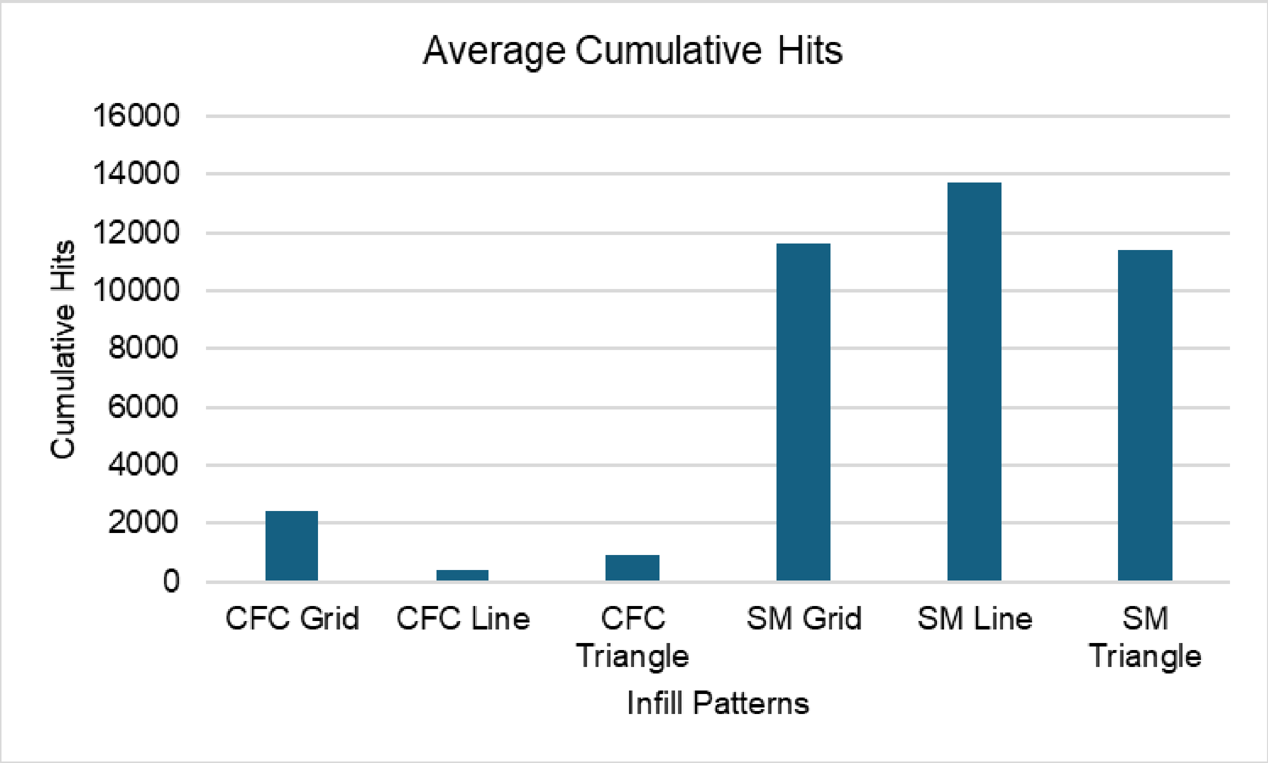

Figure 9 - Average cumulative hits across the infill patterns.

Statistical analysis of the cumulative hit datasets shows that there is more variance in the Smooth PA results than the CFC PA shown in Table 4. This is concurrent with the mechanical findings where the Smooth PA samples showed more variance in results than the CFC PA.

Table 4 - Cumulative hit averages per material.

	Material Cumulative Hit Average	Std dev
CFC PA	1094.75	872.8614
SM PA	12248	1215.996

4. CONCLUSION

In this paper, the effect of different infill patterns and material on the mechanical properties of additively manufactured samples was evaluated using tensile testing supported by acoustic emission testing. Pure polymer and short-fibre reinforced polymer matrix composite samples were printed at 50% infill across the three printing patterns allowed in the AURA software. The tensile test results were recorded and compared to the acoustic emission results to identify any correlations.

It was concluded that in both the pure polymer and FRP samples, the Lines infill pattern had the best mechanical properties, with the highest Yield strength and tensile strength at break. The presence of fibres greatly improved the Yield strength and tensile strength at break of the Smooth PA compared to the CFC PA, however also showed significantly more acoustic events during the test.

ACKNOWLEDGEMENTS

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This research was funded by the Sheffield Hallam University Graduate Teaching Assistant Scheme.

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