In-line monitoring of the fused filament fabrication additive manufacturing process for fibre-reinforced polymer matrix composites.

FORSTER, Rosanna, FETEIRA, Antonio <http://orcid.org/0000-0001-8151-7009>, SOULIOTI, Dimitra, GRAMMATIKOS, Sotirios and KORDATOS, Evangelos <http://orcid.org/0000-0002-5448-3883>

Citation:

FORSTER, Rosanna, FETEIRA, Antonio, SOULIOTI, Dimitra, GRAMMATIKOS, Sotirios and KORDATOS, Evangelos (2024). In-line monitoring of the fused filament fabrication additive manufacturing process for fibre-reinforced polymer matrix composites. In: BINETRUY, Christophe and JACQUEMIN, Frédéric, (eds.) Proceedings of the 21st European Conference on Composite Materials. Volume 5 - Manufacturing. The European Society for Composite Materials (ESCM) and the Ecole Centrale de Nantes., 503-512. [Book Section]

IN-LINE MONITORING OF THE FUSED FILAMENT FABRICATION ADDITIVE MANUFACTURING PROCESS FOR FIBRE-REINFORCED POLYMER MATRIX COMPOSITES.

Authors: R. Forster[1] A. Feteira[1] D. Soulioti[1] S. Grammatikos[2] E. Kordatos[1]

[1]Materials and Engineering Research Institute, Howard Street, Sheffield Hallam University, Sheffield S1 1WB, UK
Email: R.forster@shu.ac.uk , e.kordatos@shu.ac.uk
[2]ASEMlab – Laboratory of Advanced and Sustainable Engineering Materials, Department of Manufacturing and Civil Engineering, Norwegian University of Science and Technology, Gjøvik, 2815, Norway

Keywords: In-line monitoring, additive manufacturing, non-destructive evaluation, infrared thermography, acoustic emission, fibre-reinforced composites, continuous fibre.

Abstract
In the present work, a novel combination in-line monitoring methodology including Infrared Thermography (IR) and acoustic emission (AE), benchmarked against micro-computerised tomography was developed for the monitoring of the FFF AM process manufacturing pure polymer, short fibre-reinforced and continuous fibre reinforced polymer matrix composite samples. The method allows for the detection of anomalies during the printing process and the verification of their presence after printing without the need for destructive testing. For both the in-line monitoring, the correlation between the printing parameters and the presence of defects and anomalies was investigated.
It was found that the in-line monitoring method can detect anomalies during the printing process and can provide information on the efficacy of the printing. This is substantiated by the presence of defects found during the offline assessment. It was also concluded there was a correlation between the structural integrity and print quality of the printed samples and their printing parameters which was identified during the in-line monitoring work.

1. Introduction

Fused filament fabrication (FFF) is an extrusion based additive manufacturing (AM) technique used to produce fibre-reinforced polymer matrix composites (FRPs) due to its resource efficiency, part geometric flexibility and ease of use [1]. 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 such as aerospace, biomedical and automotive [2]. 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 and these defects are hard to detect during the manufacturing due to the printing method [1]. Early defect detection for issues such as missing layers and excess vibration causing the print head to divert from its program can be detected by some FFF machines, but the technology isn't consistently reliable and cannot detect smaller defects such as voids or porosity in the printed samples. These defects stop fibre-reinforced composite materials manufactured this way meeting industry standards and being used for structural applications [3].

In this paper, we propose a methodology for in-line monitoring of the printing process with IR and AE to detect the presence of abnormalities which can lead to the formation of defects. This methodology was applied in full to both pure polymer and short FRPs and benchmarked against Micro-CT to ensure efficacy. The methodology was then applied to continuous fibre printing.

2. Experimental Setup

2.1. Printing

Printing of the pure polymer and short-fibre reinforced polymer samples was performed on an Anisoprint Desktop Composer A3 printer, through the plastic nozzle with a nozzle diameter of 0.4mm. The samples printed were 10x10x10mm cubes with a 5 loop brim and skirt to aid adhesion and material deposition alongside Magigoo PA adhesive glue. The filament of the pure polymer samples was CFC PA with a filament diameter of 1.75mm [4] and the short-fibre reinforced filament was Smooth PA with a filament diameter of 1.75mm [5]. CFC PA is a non-filled nylon PA12 and Smooth PA is a pre-impregnated PA12 filament reinforced with 10% dispersed 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 printing profiles as well as some of the key parameters are listed in Table 1.

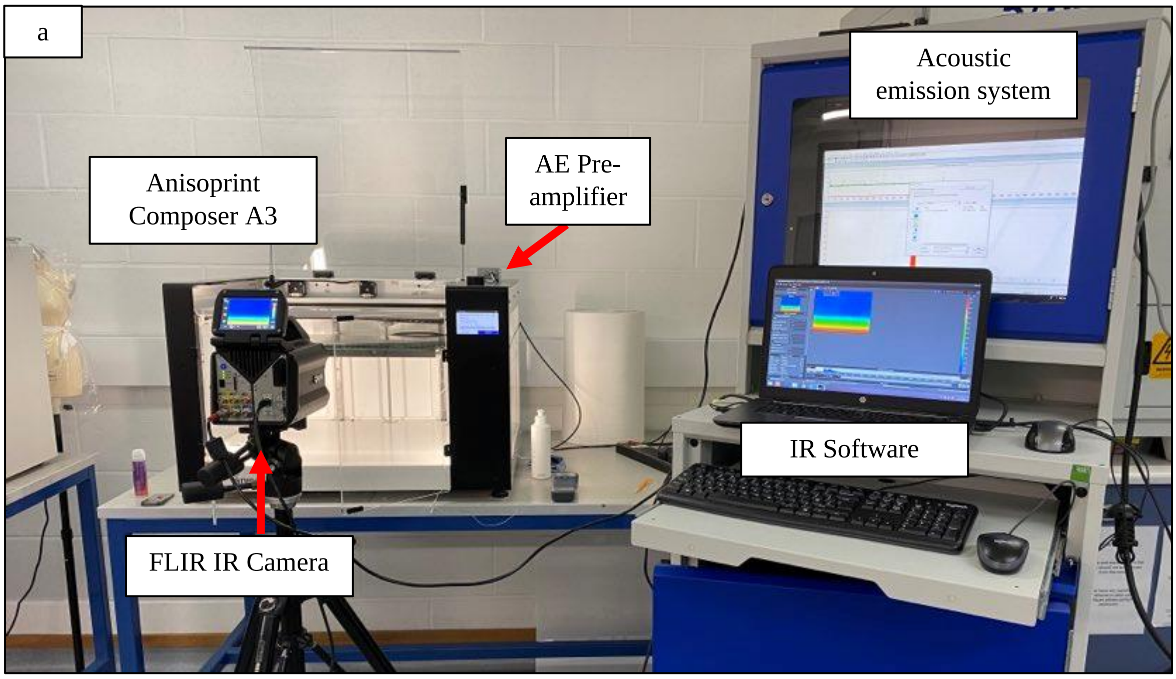
Printing of the continuous fibre samples was also performed on the Composer A3 through the composite and plastic nozzle. The samples prtined were 30x30x30mm cubes with a 2 loop skirt and a 5 loop brim to aid adhesion and material deposition alongside Magigoo PA adhesive glue. The combination printing used CFC PA filament for the plastic infill and the co-extrusion medium, the fibres used were Anisoprint CCF [6]. Anisoprint CCF consists of continuous carbon fibre spools, with a carbon volume fraction of 60% and a diameter of 0.35mm. A custom profile was created for the printing in AURA, using the pre-designed settings for the composite nozzle (CFC 1.5k + CFC PA), and the custom settings created for the CFC PA during the pure polymer printing. The printing profiles and parameters are listed in Table 2.

Table 1 - Table showing the printing profiles for the CFC PA and Smooth PA cubed samples.

	0.1mm Macrolayer	**0.3mm Macrolayer**
Macro Layer Height (mm)	0.1	0.3
External Shell Layer Height (mm)	0.05	0.15
Plastic Perimeters Layer Height (mm)	0.05	0.15
Infill Layer Height (mm)	0.1	0.3
Thick support layer height (mm)	0.1	0.3
Infill Density (%)	100	100
First Layer Height (mm)	0.25	0.25
Cube Print Time (mins)	57	19

Table 2 - Table showing the printing profiles for the continuous fibre reinforced samples.

	CCF 1.5k + CFC PA Anisogrid 30%
Macro Layer Height (mm)	0.36
External Shell Layer Height (mm)	0.09
Plastic Perimeters Layer Height (mm)	0.09
Infill Layer Height (mm)	0.18
Thick support layer height (mm)	0.18
Reinforced Pattern Infill Density (%)	30
First Layer Height (mm)	0.25
Cube Approximate Print Time	4 hrs 27mins



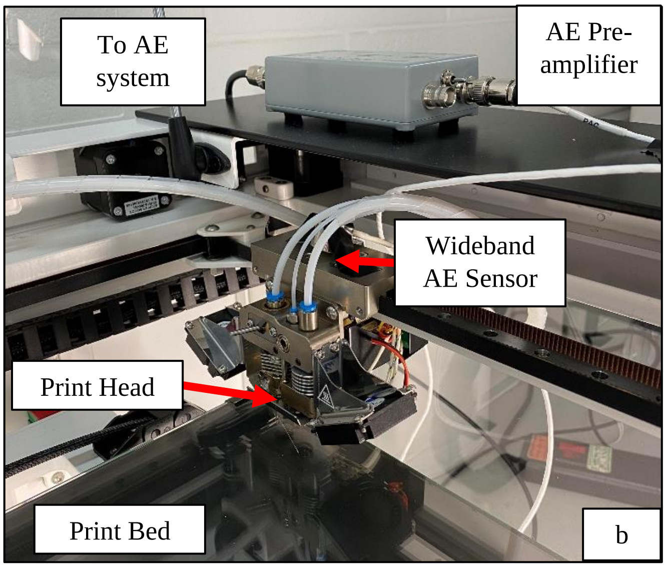


Figure 1 - (a) Experimental setup for the in-line monitoring process with the Composer A3; (b) Setup of the AE sensor attached to the print head with the alignment of the pre-amplifier.

2.2. In-line Monitoring

The experimental setup for the printing process can be seen in Figure 1. The IR results were recorded with a FLIR X6540sc camera with a cooled Indium antimonide (InSb) detector. The capturing frame rate was 101.0Hz with a range of 5-300.0°C, and a field of view (FOV) of 11ºx8.8º. The sensitivity was of >25mK. The camera was connected to a laptop which was recording the output data through FLIR IR software.

The AE data was collected with MISTRAS Micro-II express digital AE equipment, with a 20db gain pre-amplifier (2/4/6) to enhance the AE signals. A wideband AE sensor with a frequency range of 100-900kHz [11] was attached to the print head of the Composer A3 with tape as seen in Figure 1b with ANAGEL ultrasound gel applied to aid in the acoustic coupling. The data was processed in AEWin software.

2.3. Offline Assessment

The equipment used for the offline assessment of the CFC and Smooth PA samples was Micro-CT performed on a Bruker Skyscan 1272 equipment. It was used to analyse the internal structure of the printed cubes by loading them onto a raised surface, fixed in place with dental wax and rotated, with images being taken at a set rotation step layer by layer. The filter applied was AL = 0.25mm with an elevation of 12mm. The test selected was a source current of 200µA and a source voltage of 45kV. The pixel resolution was 10µm with averaging frames of 3 and a 0.7° rotation step. The samples were scanned about 180° with a 2016x1344 camera. Once scanning was finished, the images are loaded into NRecon using GPUReconServer where any scanning artifacts such as circle artifacts are removed, and smoothing is performed. The images were then aligned using DataViewer, rendered as a volume render in CTVox and analyses in CTAn where they underwent custom post-processing to allow for porosity percentage measurements.

3. Results

3.1 In-Line Monitoring

Figure 2 shows the temperature profiles for the CFC PA during the printing process (left) with the results presented graphically (right) in a plot of the temperature (°C) across the pixel plots. The IRT revealed anomalies in the thermal distribution of the printed material in figure 3b as well as loose material which has peeled away from the bed and obscured the cameras view. There is also an increase in retained heat in the 0.3mm macrolayer from the 0.1mm macrolayer.

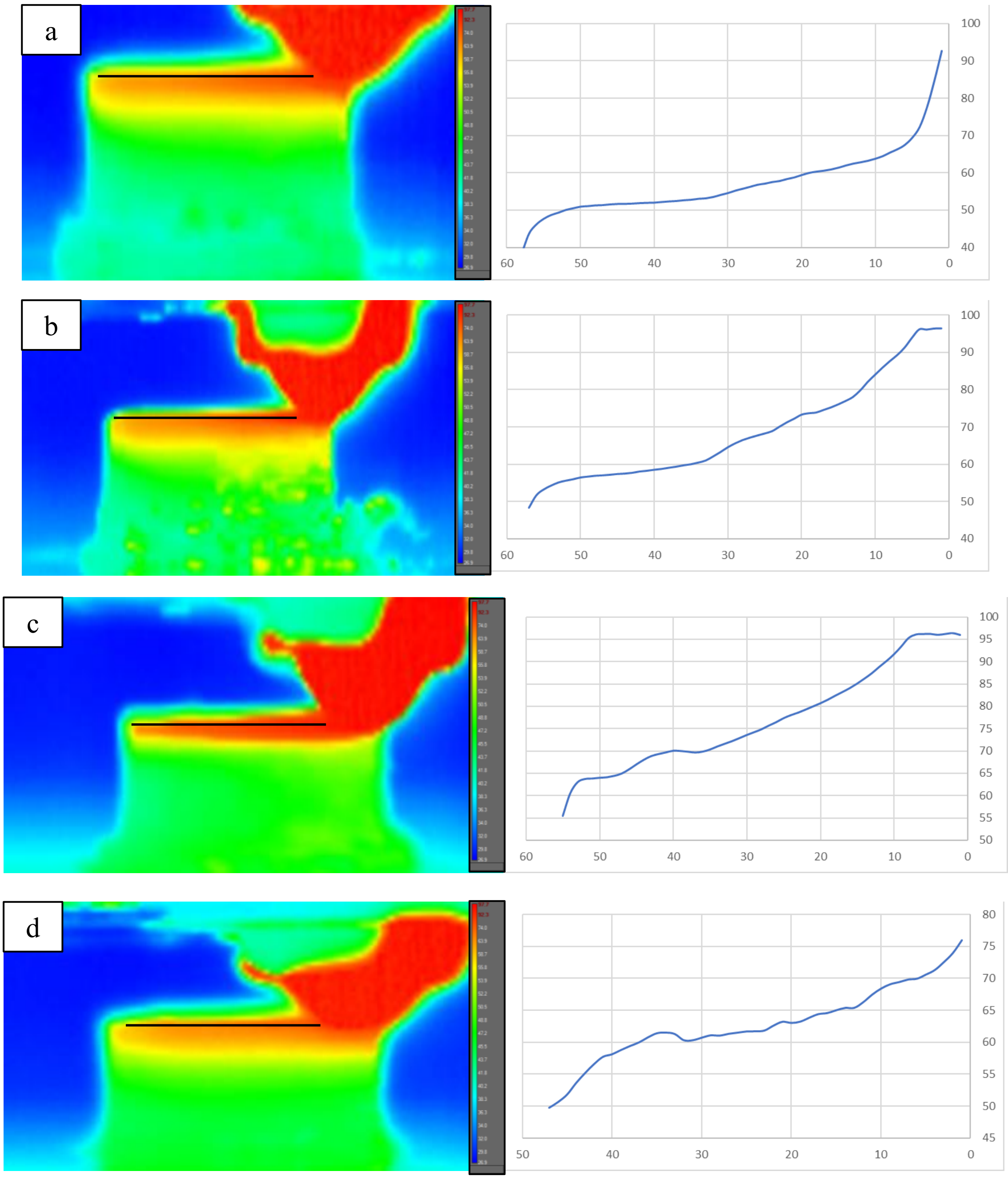


Figure 2 – IR thermographs and pixel plots for CFC PA a) 0.1mm and b) 0.3mm. for Smooth PA c) 0.1mm and d) 0.3mm.

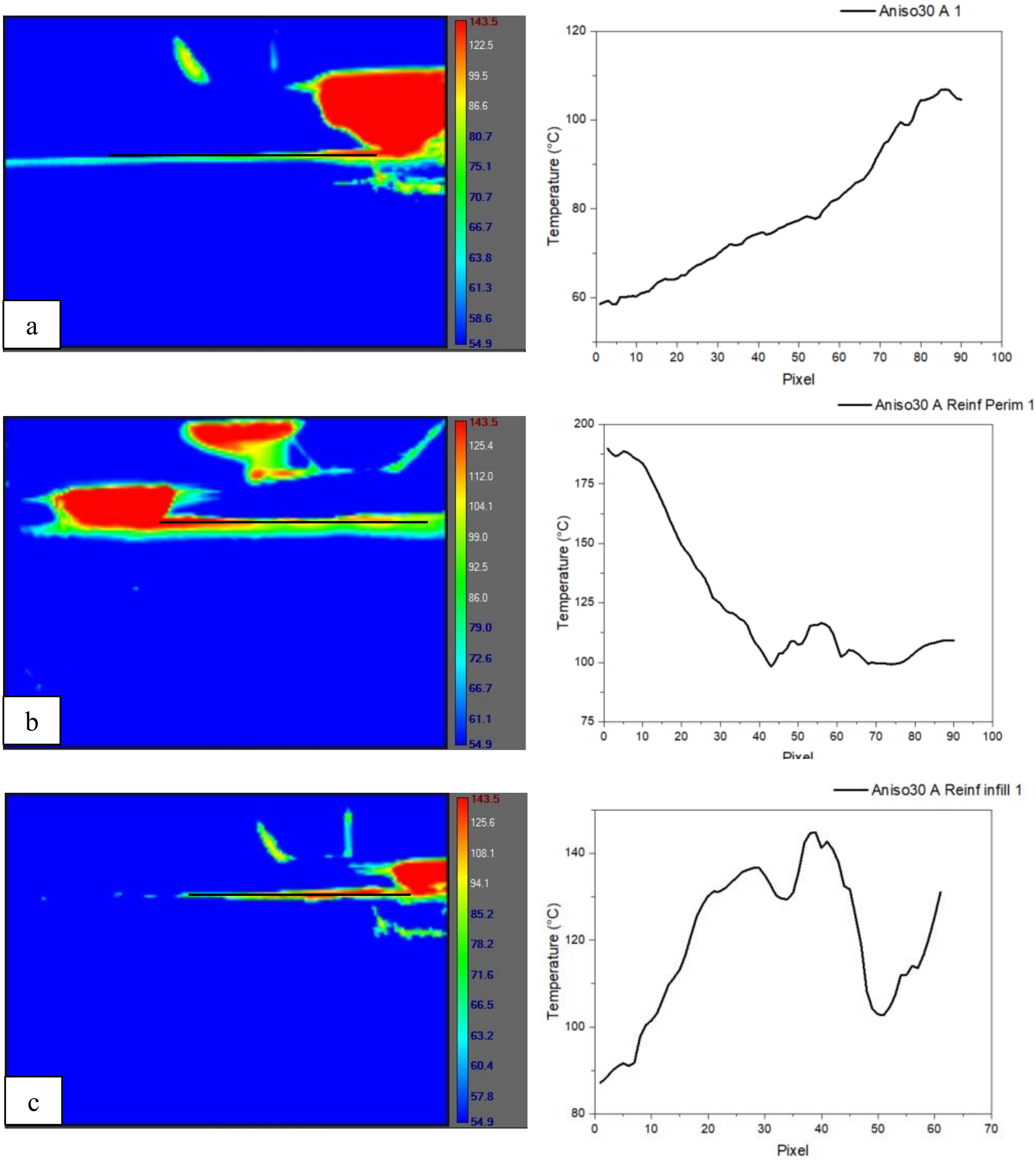


Figure 3 - IR Thermographs for the continuous fibre printing. a) Plastic perimeter, b) Reinforced perimeter and c) Reinforced infill.

Figure 3 shows the IR thermographs for the continuous fibre sample. Due to the nature of the layup, the IR readings were split into three sections: the plastic perimeter printed through the plastic nozzle (3a) and the reinforced perimeter and infill printed through the composite nozzle (3b,3c). Figure 3a shows the most consistent cooling curve, with minimal indicators of defects. Figure 3b and 3c show variations from the expected cooling curves with uneven material deposition in the perimeter and uneven themal distribution in the reinforced infill.

Table 3 - Acoustic emission results for printing of the cubed samples showing hits per minute.

Sample Name	**Hits/ Min (with 34&36db)**
CFC PA 0.1mm	57.719
CFC PA 0.3mm	60.94736842
Smooth PA 0.1mm	59.40350877
Smooth PA 0.3mm	66.10526316
CCF 1.5k + CFC PA 30%	59.69704918

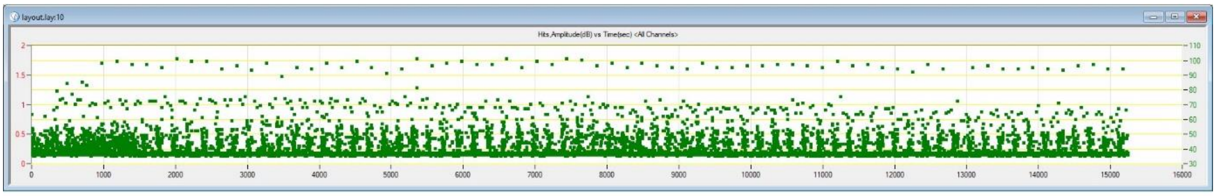


Figure 4 - Map of hits vs amplitude (db) vs time for the continuous fibre sample during printing.

Table 3 shows an increase in Hits/min as the macrolayer height increases in both the CFC PA and Smooth PA. In the CFC PA there was a 5.6% increase in hits/minute between 0.1mm and 0.3mm macrolayer, and in the Smooth PA there was an 11.28% increase between the 0.1mm and 0.3mm macrolayer. This indicates there are more events which could be indicators of defects with the larger Macrolayer settings compared to the smaller ones. For the continuous fibre samples, Figure 4 shows a repeated and consistent event at around 60db at 200 second intervals. This was determined to be the acoustic event of the printer cutting the continuous fibre to prepare for printing.

3.2 Offline Assessment

Due to the different thresholding required in the custom post-processing of the samples, the CFC PA and Smooth PA infill porosity percentages are not directly comparable however, the trends shown can be discussed.

Figure 5 shows the CTVox renderings for the CFC PA and Smooth PA samples, with an image slice taken from the middle of the cubes showing the infill. There is a very similar quality in the wall print for all prints across both materials excluding the Smooth PA 0.3mm where there is porosity and air visible in the image. In the Smooth PA 0.1mm, the "webbed" infill shows a consistent pattern with minimal detectable porosity. In the Smooth PA 0.3mm, there is porosity visible in the webbed infill. This is concurrent with the increase in AE events across these samples and the IRT during the in-line monitoring. The trend of porosity increasing as the macrolayer height increases is present across both materials.

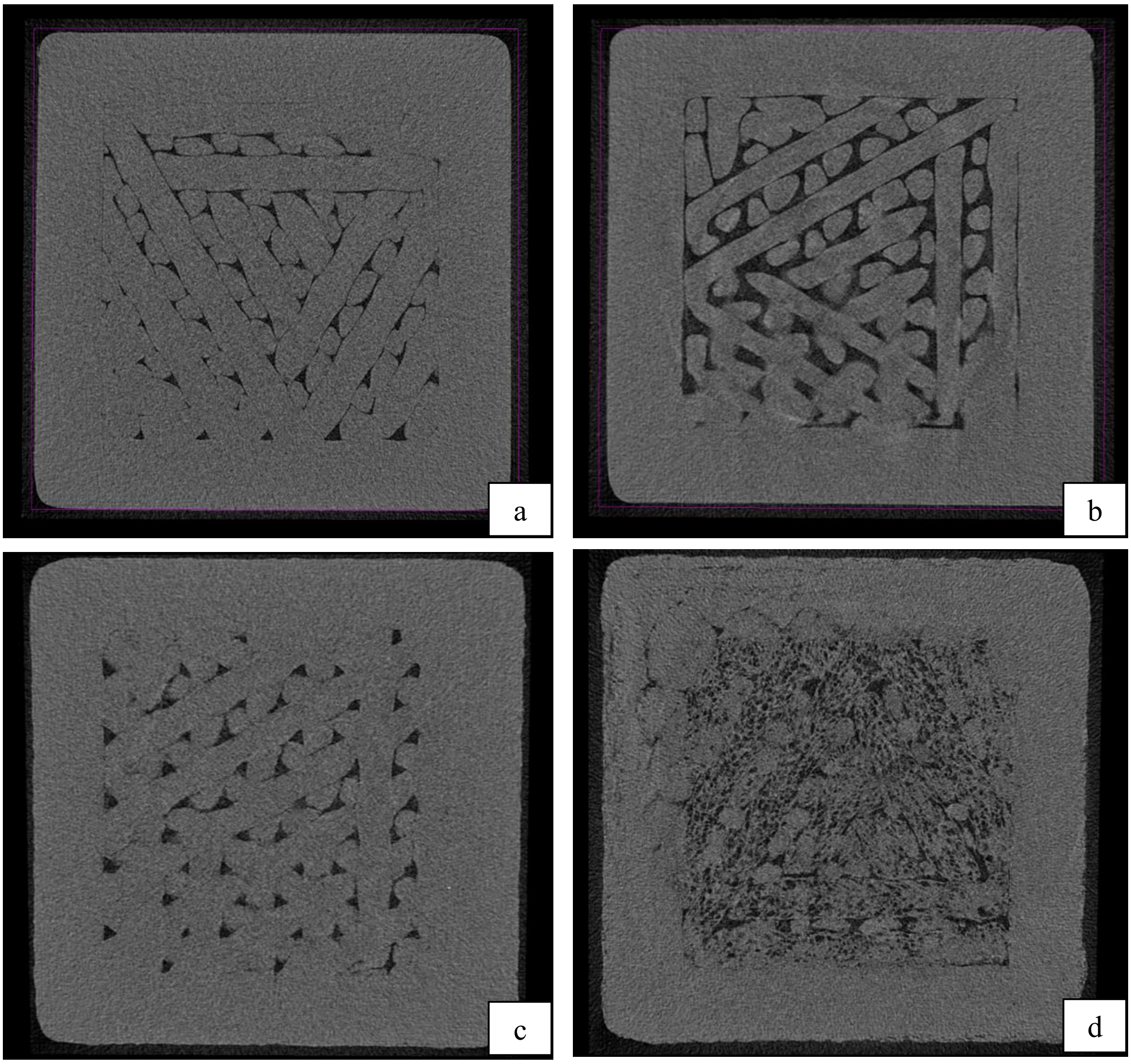


Figure 5 - CTVox renderings for CFC PA a) 0.1mm and b) 0.3mm and Smooth PA c) 0.1mm and d) 0.3mm.

4. Conclusions

In the present work, a novel combination in-line monitoring methodology including Infrared Thermography (IR) and acoustic emission (AE), benchmarked against micro-computerised tomography was developed for the monitoring of the FFF AM process manufacturing pure polymer, short fibre-reinforced and continuous fibre reinforced polymer matrix composite samples. This method was benchamarked against offline assessment through Micro-CT to determine its efficacy.

It was concluded that the combined methodology of in-line monitoring can detect abnormalities in the printing process and detect indicators of defects. This includes uneven material deposition, uneven thermal distribution and presence of porosity in both pure polymer and fibre-reinforced polymers. The findings for the pure polymer and FRPs were benchmarked against the offline assessment. Compared to current methods of detecting defects in these materials, it supplies a non-destructive methodology which is backed up by the offline assessment findings.

The findings of this new combined methodology benchmarked against the Micro-CT requires further study and testing however the methodology can be used to determine abnormalities in the printing process which led to the formation of defects.

Acknowledgments

For the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising from this submission.
This research was funded by the Sheffield Hallam University Graduate Teaching Assistant Scheme.

References

[1] O. Ahmed, X. Wang, M.-V. Tran and M.-Z. Ismadi, "Advancements in fiber-reinforced polymer composite materials damage detection methods: Towards achieving energy-efficient SHM systems," *Composites Part B: Engineering,* vol. 223, p. 109136, 2021.

[2] D. Fico, D. Rizzo, R. Casciaro and C. E. Corcione, "A Review of Polymer-Based Materials for Fused Filament Fabrication (FFF): Focus on Sustainability and Recycled Materials," *Polymers,* vol. 14, no. 3, p. 465, 2022.

[3] X. Wang , M. Jiang, Z. Zhou, J. Gou and D. Hui, "3D printing of polymer matrix composites: A review and prospective," *Composites Part B,* vol. 110, pp. 442-458, 2017.

[4] Anisoprint, "CFC PA Technical Data Sheet," November 2020.

[5] Anisoprint, "Smooth PA Technical Data Sheet," August 2020.

[6] Anisoprint, "Anisoprint Reinforcing materials: Composite Carbon fibre (CCF) and Composite basalt fibre (CBF)," 2020.

[7] MISTRAS - Physical Acoustics Corporation, "WD Sensor," 2011. [Online]. Available: https://www.physicalacoustics.com/content/literature/sensors/Model_WD.pdf. [Accessed 17 February 2023].