In-line monitoring of the fused filament fabrication additive manufacturing process.

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 (2023). In-line monitoring of the fused filament fabrication additive manufacturing process. Nondestructive Characterization and Monitoring of Advanced Materials, Aerospace, Civil Infrastructure, and Transportation XVII, 12487. [Article]

In-line monitoring of the fused filament fabrication additive manufacturing process

R. Forster, A. Feteira, D. Soulioti, S. Grammatikos, E. Kordatos

R. Forster, A. Feteira, D. Soulioti, S. Grammatikos, E. Kordatos, "In-line monitoring of the fused filament fabrication additive manufacturing process," Proc. SPIE 12487, Nondestructive Characterization and Monitoring of Advanced Materials, Aerospace, Civil Infrastructure, and Transportation XVII, 124870M (18 April 2023); doi: 10.1117/12.2658374

Event: SPIE Smart Structures + Nondestructive Evaluation, 2023, Long Beach, California, United States

In-line monitoring of the Fused Filament Fabrication additive manufacturing process

R. Forster*[a] A. Feteira[a] D. Soulioti[a] S. Grammatikos[b] E. Kordatos*[a]

[a]Materials and Engineering Research Institute, Howard Street, Sheffield Hallam University, Sheffield S1 1WB, UK
[b]ASEMlab – Laboratory of Advanced and Sustainable Engineering Materials, Department of Manufacturing and Civil Engineering, Norwegian University of Science and Technology, Gjøvik, 2815, Norway

ABSTRACT

In the present work, a novel combination method of in-line monitoring and offline non-destructive evaluation was developed for the detection and monitoring of defects in additively manufactured specimen. The new methodology includes Infrared Thermography, Acoustic Emission and Micro-computerised Tomography to allow for the detection of anomalies during the printing process and the verification of their presence after the printing process without the need for destructive testing. It was found that the in-line monitoring can provide information on the efficacy of the printing process which is substantiated by the offline assessment.

Keywords: In-line monitoring, additive manufacturing, non-destructive evaluation, infrared thermography, acoustic emission

*R.Forster@shu.ac.uk, E.Kordatos@shu.ac.uk

1. INTRODUCTION

Additive Manufacturing (AM) is the overarching term for technologies which are based on the successive application of materials to create a physical 3D model for a part based on a computer-based design [1]. This technology has undergone rapid advancements in recent years where material and resource efficiency, low waste, part geometry flexibility and low production cost are key benefits. The most used method of AM for printing polymer materials is fused filament fabrication (FFF) which is an extrusion deposition based process. Parts manufactured through FFF cover applications across many sectors including automotive, aerospace, biomedical and civil [2] however when manufactured this way, the parts can contain defects which are hard to detect due to the nature of the printing method. Once started the print process, if interrupted, will have to be abandoned and restarted. This is due to the layer by layer nature of the build process. As the printed filament is extruded from the nozzle, it is deposited on the print bed which then hardens and becomes the first layer. The next extruded layer is layered on top of the previous one and fuses with it, with the process repeated until the desired shape has been achieved [3]. There are several forms of defects that can be created during this printing process such as porosity or cracks [4] and the parts can have highly anisotropic qualities which, dependant on application, could be a disadvantage. These defects can be formed in numerous ways including defects or porosity in the filament, nozzle clogging, uneven layer deposition or an uneven thermal profile during the printing process. Early defect detection 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.

The application of non-destructive evaluation (NDE) techniques to both polymer and polymer matrix composites can be challenging [4]. However, when applied to the FFF printing process, these techniques can be effective in determining the presence of defects in printed parts. Specifically Infrared Thermography (IRT) and Acoustic Emission (AE) are effective when applied as in-line monitoring techniques to this process, AE because there are various mechanical components and actuators which cause vibration and noise during the printing process. If an anomaly occurs or a defect is formed, the acoustic emission of the process will change [5]. IRT can be used to determine the temperature across layers of printed material and any unexpected thermal variations during the printing process [6].

In-line monitoring of the FFF process can deliver information which falls into two overarching categories, the monitoring of the 3D printer's health condition and the analysis of the printed product itself. In this paper, we propose an innovative method of in-line monitoring of the FFF printing process looking specifically at the product quality using multiple NDE techniques benchmarked against Micro-computerised tomography (Micro-CT) findings. This methodology will be transferable to FFF printing of composite materials as well as to pure polymer builds.

2. EXPERIMENTAL SETUP

2.1 In-line monitoring

The experimental setup of the in-line monitoring can be observed in Figure 1. The printed specimens were monitored by a FLIR IR camera (X6540sc) with a capturing frame rate of 100Hz, a sensitivity of >25mK and a cooled indium antimonide (InSb) detector. The camera was connected to a laptop which was recording the output data.

The AE data was recorded by MISTRAS Micro-II express digital AE equipment with a wideband AE sensor with a frequency range of 100-900kHz [7] attached to the print head using tape shown in Figure 1b. The characteristics of amplitude and cumulative hits were recorded during the print process and to enhance the AE signals, a 40db preamplifier (2/4/6) was selected. To ensure acoustic coupling, ANAGEL ultrasound gel was applied between the sensor and the print head surface. The data was analysed in AEWin software.

The 3D printing was performed on an Ultimaker S5 Pro bundle with a nozzle diameter of 0.4mm. The specimens printed were 10x10x10mm cubes with a 7mm brim to aid in build adhesion. PVA glue was applied to the print bed to aid adhesion. The filament used was transparent PLA with a filament diameter was 2.85mm ±0.1mm. Ultimaker Cura includes 5 default print profiles (extra fast, fast, normal, fine and extra fine) as well as the ability to create custom print profiles. An example of the differences of the properties in these print profiles can be seen in Table 1. The main thermal events for PLA are well recorded in published literature, with a low glass transition temperature (T_g=60-65°C) and melting temperature (T_m=170-180°C) [8] [9].

Table 1 - Print properties for the three different print profiles.

	Extra Fast	**Fine**	**Custom Extra Fine (0.04mm layer height)**
Layer Height (mm)	0.30	0.10	0.04
Initial Layer Height(mm)	0.27	0.20	0.20
Line Width (mm)	0.40	0.40	0.40
Wall Thickness (mm)	0.80	0.80	0.80
Top/Bottom Thickness (mm)	0.90	1.00	1.00
Infill Density (%)	100.00	100.00	100.00
Infill Layer Thickness (mm)	0.30	0.10	0.04
Print Time (mins)	4	15	32

2.2 Offline assessment

The micro-CT which was used to analyse the internal structure of the printed cubes was performed on Bruker Skyscan 1272 equipment. The specimens were placed on a raised surface, fixed in place with dental wax and rotated, with images taken layer by layer. The test selected used a source voltage of 55kV, a source current of 160 µA and a resolution of 9µm. The filter applied was Al = 0.5mm and the elevation of the samples were 11mm. The cubed specimens were scanned about 180° with a 0.7° step and the pixels were 2016x1344. The images were reconstructed in the NRecon software using GPUReconServer to remove artifacts from the reconstruction. The images were aligned using DataViewer then rendered as a volume render in CTvox where they were analysed.

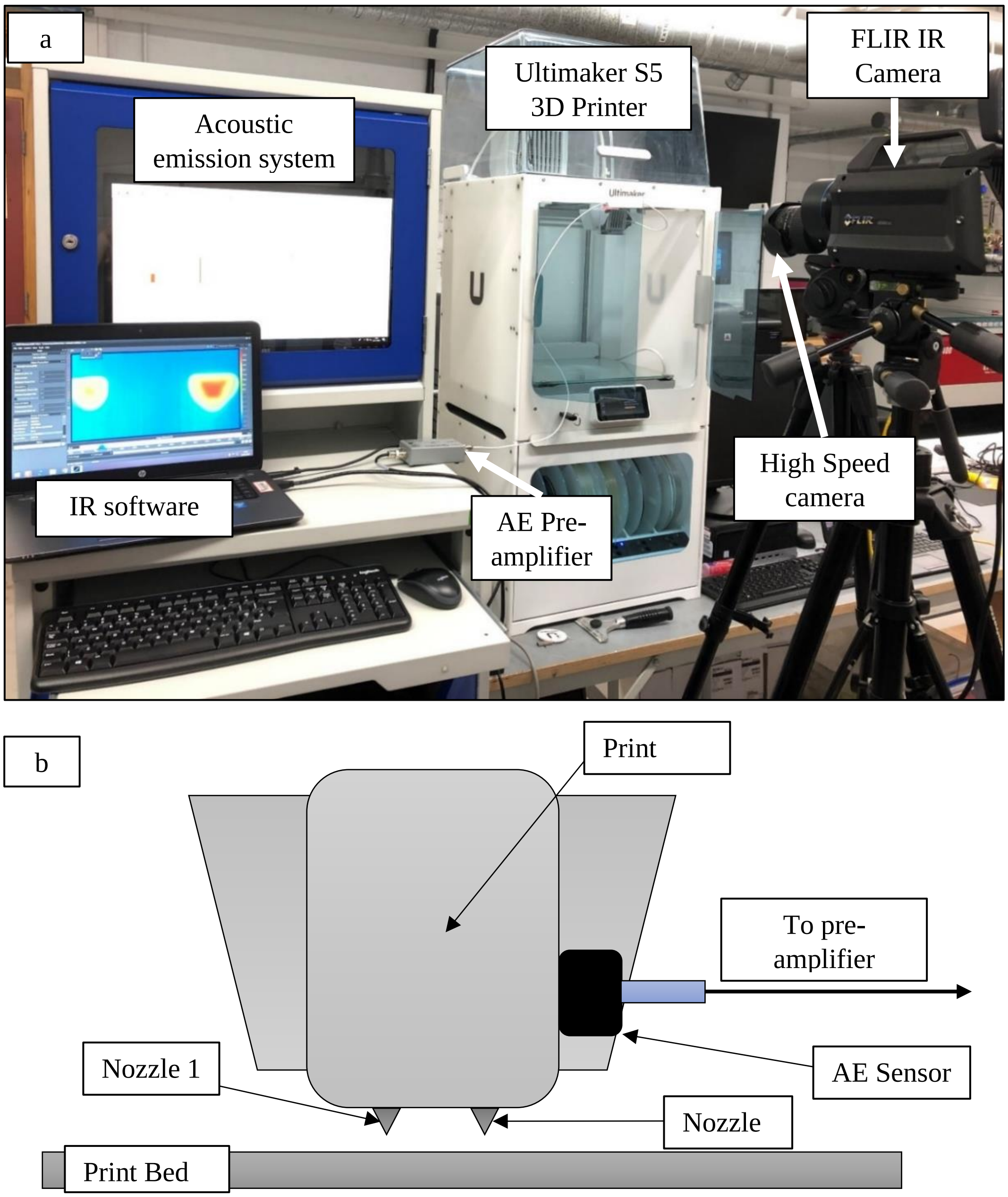

Figure 1 – (a) Experimental setup for the in-line monitoring process; (b) Setup of the AE sensor whilst attached to the print head.

3. RESULTS

The combined in-line monitoring method was applied to three printing profiles, two default profiles and one custom profile, the details for which are shown in Table 1. The custom profile was built from the Extra Fine default profile but with a 0.04mm layer height instead of 0.06mm. Figure 2 shows the temperature profiles during the printing captured by the infrared camera. The IRT revealed abnormalities in the printing process across all three prints with uneven and unexpected thermal distribution across the printed layer which is evidenced by the appearance of a darker red on the right side of the sample. This distribution goes against the variation of colour expected with cooler material towards the right side of the sample, and hotter material by the nozzle.

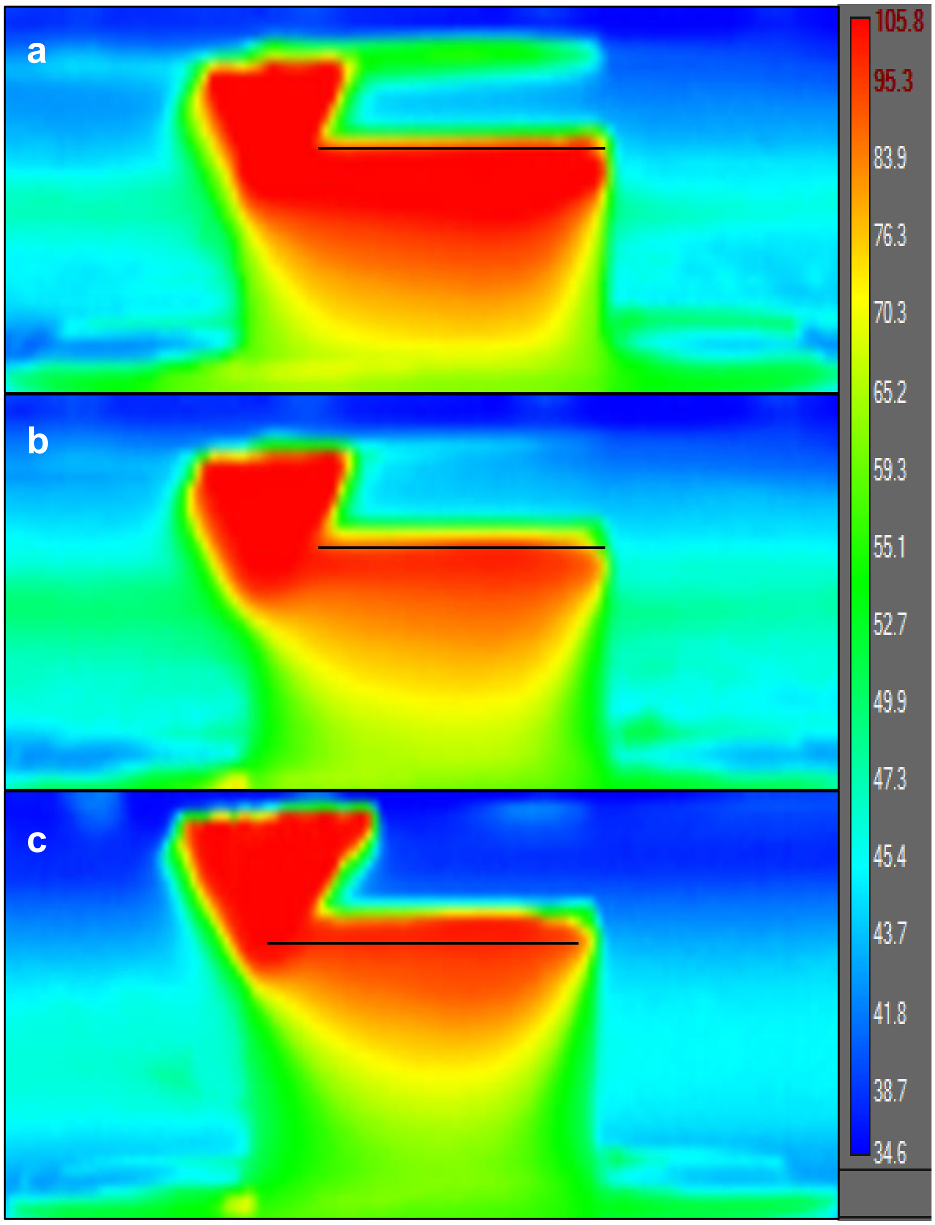

Figure 2 – IRT results a) Extra Fast b) Fine c) Custom Extra Fine with 0.04mm layer height. The black line across the samples represents the line used to draw the profile plot information.

This unexpected temperature variation did improve between the Extra Fast print in Figure 2a and the Fine in Figure 2b, however there was very little improvement in the distribution between the Default Fine and the Custom Print in Figure 2c although the average temperature of the print was lower in the Custom print indicating better cooling of the printed material. These differences in the temperature variations are displayed graphically in Figure 3.

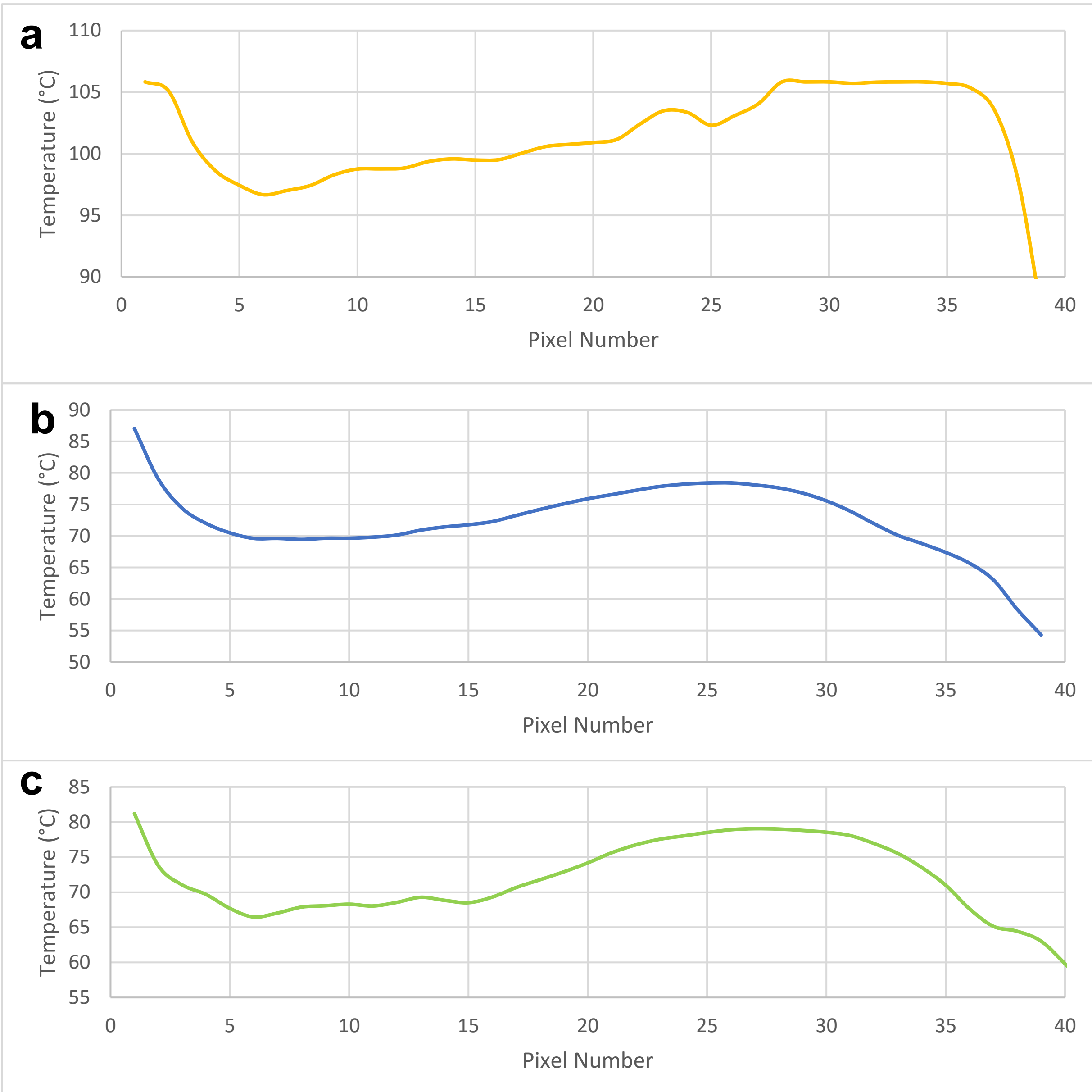

Figure 3 - Pixel Profile plots of the temperature across the printed material a) Extra Fast b) Fine c) Custom Extra Fine with 0.04mm layer height

The AE results revealed multiple events across the printing process, however the extra fast and fine samples showed more at a varied and higher amplitude, compared to the custom, shown in Figure 4 which presents plots of amplitude (db) vs time (secs) and cumulative hits vs amplitude (db). Figure 4a shows the extra fast sample with a maximum amplitude of 64db and Figure 4b shows the fine sample with a maximum amplitude of 75db. Figure 4c shows the Custom profile print which only displayed a maximum amplitude of 49db and had a much less varied hit amplitude across the print than the default prints. This indicates there are fewer acoustic events which could be indicators of defects in the Custom print compared to the default programs.

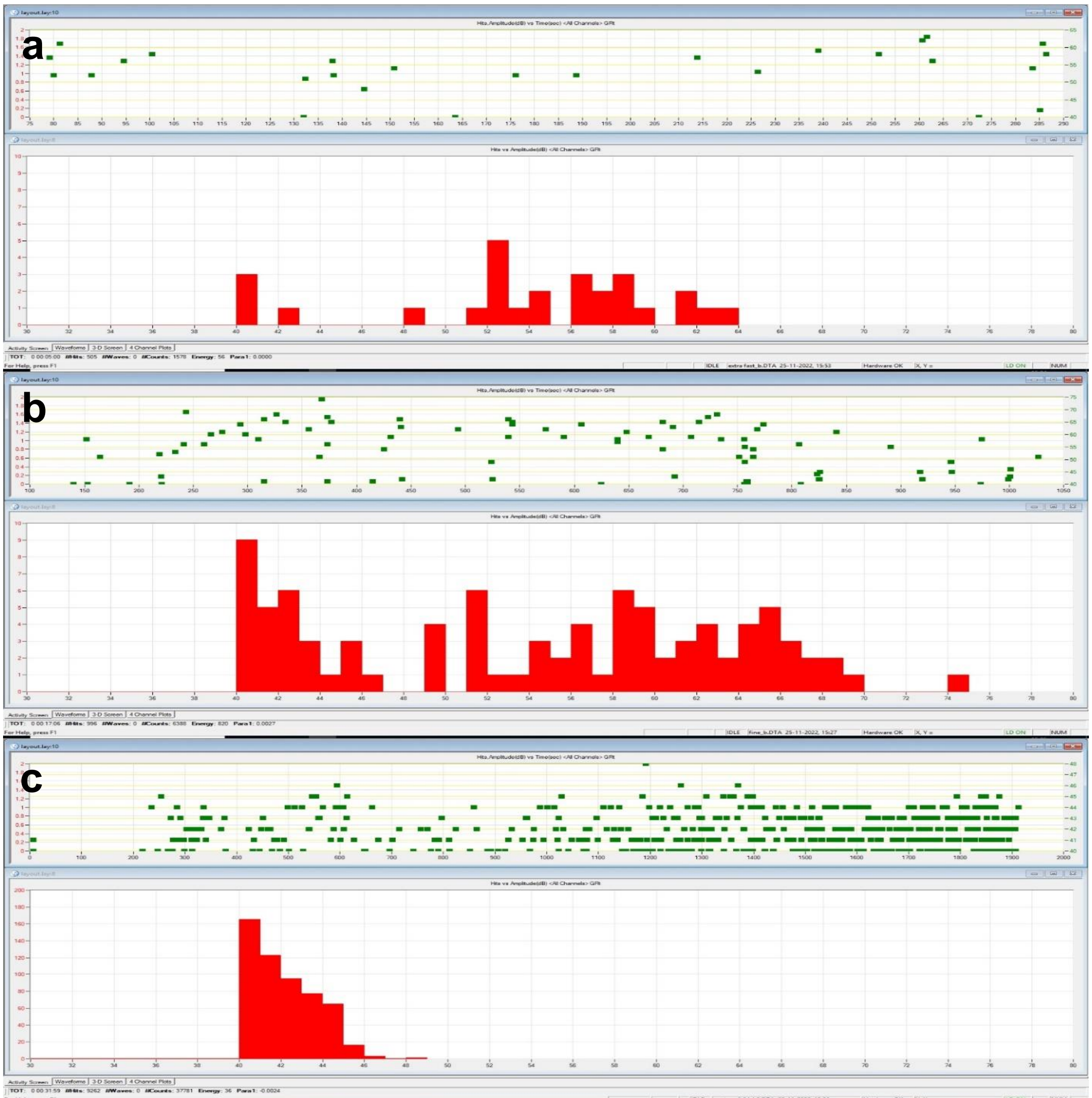

Figure 4 - Acoustic Emission results a) Extra Fast b) Fine c) Custom Extra Fine with 0.04mm layer height

The findings of the In-line monitoring are concurrent with the Micro-CT volume renderings. Figure 5a shows the render of the Extra Fast sample with systematic defects between the printed layers and poor bonding between the infill leading to major porosity. Figure 5b shows the Fine print which contains fewer defects between the horizontal wall layers but still includes systematic porosity where the infill layers haven't bonded properly creating defects through the print. Figure 5c shows the custom print volume render where there are almost no defects detectable in the wall layers and very few where the infill bonding has created porosity.

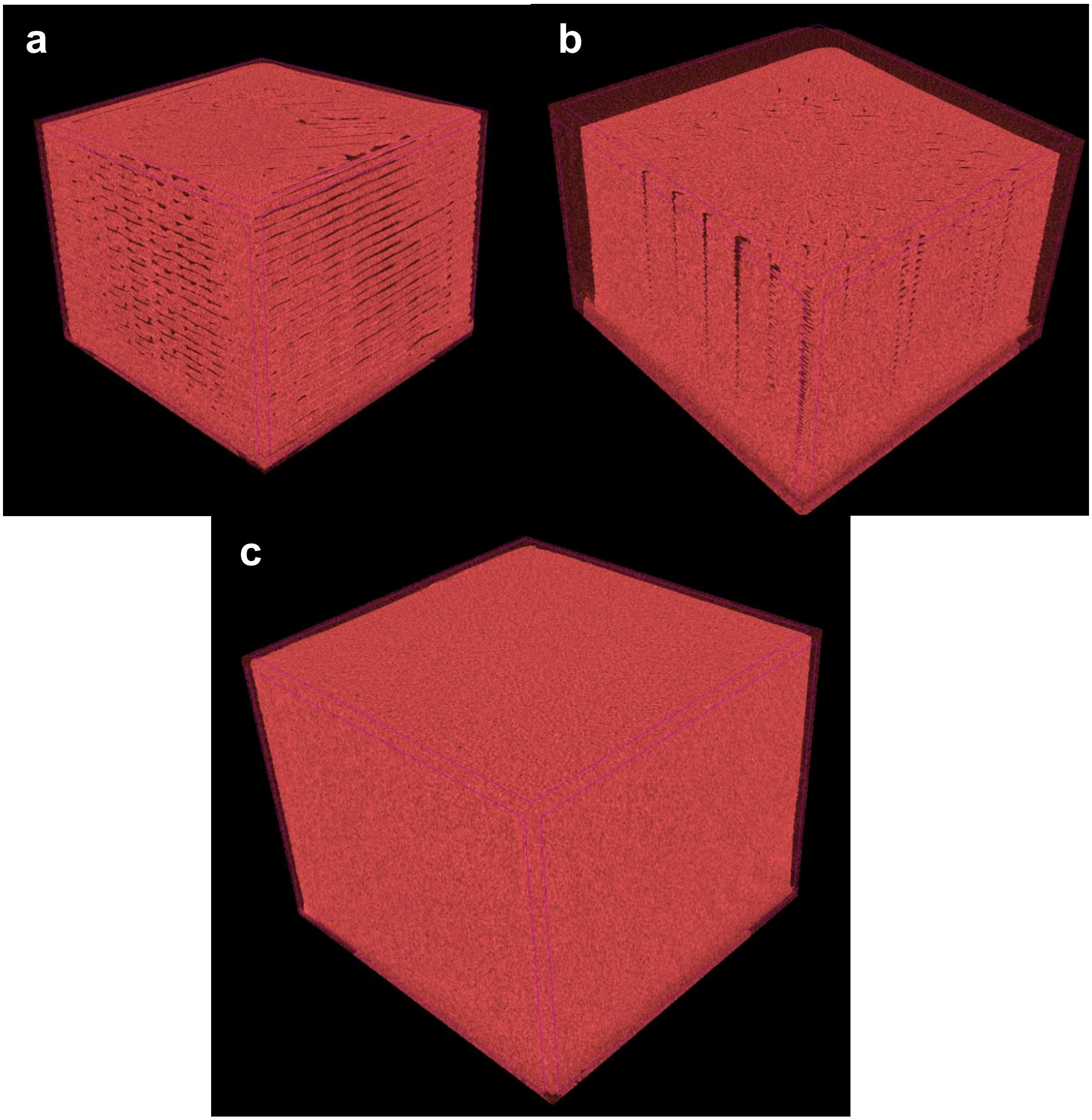

Figure 5 – Micro-CT CTVox renders a) Extra Fast b) Fine c) Custom Extra Fine with 0.04mm layer height.

4. CONCLUSIONS

In this paper, a novel combination of NDE methods was employed to create an effective in-line monitoring methodology for the detection of defects in additively manufactured parts. The method includes the use of infrared thermography and acoustic emission and to determine the efficacy of these, Micro-computerised tomography was conducted.

It was concluded that the combined in-line monitoring method can detect abnormalities in the printing process at the time of print, including uneven material distribution and uneven thermal deposition. 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.

ACKNOWLEDGEMENTS

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] BSI Standards Publication, "Additive Manufacturing - General Principles - Terminology (BS EN ISO/ ASTM 52900:2017)," BSI Standards Limited, 2017.

[2] Y. Fu, A. Downey, L. Yuan, A. Pratt and Y. Balogun, "In situ monitoring for fused filament fabrication process: A review," *Additive Manufacturing,* 2021.

[3] S. Hisham, S. F. Khan and K. Kamarudin, "QUALITY MONITORING FOR FUSED FILAMENT FABRICATION PRODUCT: A REVIEW," *International journal of research and analytical reviews,* vol. IX, no. 2, April 2022.

[4] T. Smith, J. Failla, J. Lindahl, S. Kim, A. A. Hassen, C. Duty, P. Joshi, C. Stevens and V. Kunc, "STRUCTURAL HEALTH MONITORING OF 3D PRINTED STRUCTURES," in *Solid Freeform Fabrication 2018: Proceedings of the 29th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference Reviewed Paper*, 2018.

[5] A. Oleff, B. Küster, M. Stonis and L. Overmeyer, "Process monitoring for material extrusion additive manufacturing: a state-of-the-art review," *Progress in Additive Manufacturing,* pp. 705-730, 2021.

[6] E. Ferraris, J. Zhang and B. Van Hooreweder, "Thermography based in-process monitoring of Fused Filament Fabrication of polymeric parts," *CIRP Annals - Manufacturing Technology,* pp. 213-216, 2019.

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

[8] M. A. Cuiffo, J. Snyder, A. M. Elliott, N. Romero, S. Kannan and G. P. Halada, "Impact of the Fused Deposition (FDM) Printing Process on Polylactic Acid (PLA) Chemistry and Structure," *Applied Sciences*, 2017.

[9] S. N. Vouyiouka and C. D. Papaspyrides, "4.34 - Mechanistic Aspects of Solid-State Polycondensation," in *Polymer Science: A Comprehensive Review*, 2012, pp. 957-874.