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THERMOGRAPHIC ASSESSMENT OF FIBRE REINFORCED 3D PRINTING FILAMENT

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ABSTRACT

This research demonstrates the feasibility of active thermography for online inspection of 3D printing filaments has and its potential to be used to provide quality assurance of short and natural fibre reinforced composites. 3D printing of materials is widely used across a range of industries. Natural fibre composites materials offer sustainable and cost-effective solutions to material challenges. When considering combining natural fibres and 3D printing there are several manufacturing challenges that must be overcome. The focus of this research is to ascertain if active thermography is a suitable tool for online inspection of fibre reinforced filaments used for 3D printing composites. The aim of the inspection is to identify fibre rich and fibre poor regions along the filament, where uniformly distributed fibres along the filament is preferred. Regions with a locally high weight percent of fibres, known as a fibre bunch, can cause problems when used to print a part resulting in a waste of materials and failed print jobs. The paper presents a feasibility study showing the potential of using pulsed thermography to identify fibre bunching. An external heating stimulus is applied to the filament and an infrared detector is used to monitor the thermal decay. The thermal contrast produced by fibre bunches compared to regions of uniformly distributed fibres is used to identify potential problem areas and provide a means of quality control. Investigation includes variation of the heating stimulus, data collection and data processing routines.

1 INTRODUCTION

3D printing of composite materials has the potential to combine the ability to tailor material properties to the application, as provided by composites, with the reduction of waste and ability to manufacture more complex parts, as provided by 3D printing [1]. Short fibre reinforced composites allow a wider range of reinforcements to be used than typical continuous fibre counterparts including use of recycled materials and natural fibres [2]. Thermoplastic composite materials with short fibre reinforcement are typically extruded into a filament form that can then be fed into Fused Filament Fabrication (FFF) or Fused Deposition Modelling (FDM) 3D printers. The ideal filament should be uniform in diameter as well as in reinforcing fibre distribution. Inconsistencies in the filament can cause problems during printing and may be passed on to become flaws in the printed part. Uneven distribution of fibres, or bunching, is of concern as this has the potential to lead to a variation in mechanical properties of the part [3]. Fibre bunching may also lead to nozzle blockages during printing, disrupting print jobs and resulting in material waste and down time [4]. Some of these issues can be addressed by heating the printer nozzle [5]. The present research takes the approach that if we can quality assure the materials going into the printer the part that is produced cannot be impacted by variations in the filament properties.

Various polymer-based composite parts are now successfully produced with 3D printing; these include Carbon/Graphite fibres, fiberglass and natural fibres. Reinforcements in 3D printed parts can be either continuous, long fibre or short fibre. There are more options for short fibre reinforcements than their typical continuous fibre counterparts including the use of recycled materials and natural fibres. For continuous fibre reinforcement spools of separate fibre and matrix material are fed directly

into the printer. For short fibre reinforcement the matrix material is reinforced when the 3D printer filament is manufactured via extrusion. It is this pre-reinforced filament that is then fed into the 3D printer for manufacture of parts. With an increasing demand for biodegradable and durable components, the popularity of natural fibre reinforcements has grown. Recent findings present that Harakeke (New Zealand Flax) reinforced Polylactic acid (PLA), offers strength and stiffness comparable to glass fibre reinforced plastics [6]. Since PLA itself is already a biodegradable thermoplastic, this composite material is therefore even more appealing as a bio-based alternative.

Natural fibre composites (NFCs) have the potential to replace some applications of thermoset (synthetic) matrix composites, however manufacturing factors can significantly affect the mechanical performance of NFCs. Important factors include; fibre orientation and fibre dispersion [2] which lead to fibre bunching. In order to utilize NFCs commercially, these limitations need to be addressed. Part of this problem could be addressed through an improvement of quality assurance of the filament before 3D printing. If the filament material (base material) is quality assured then it is less likely to cause a failed print due to fibre bunching, thus reducing material waste and delays, and is likely to result in a higher quality print.

It is proposed that thermographic assessment be used to provide information about inconsistencies in the filament. Pulsed thermography uses a pulse heating stimulus and an infrared (IR) detector to assess the thermal decay of the surface after heating [5]. Typically, for defect detection a 'hotspot' is identified on the surface of the component where a subsurface defect hinders heat transfer through the thickness of the part. Defects are detected via their contrasting thermal properties [6]. The present work aims to exploit the thermal contrast created by a fibre bunch compared to uniformly distributed fibres to provide an indication of filament quality. The end goal of the work is to use thermography as a low cost online inspection tool to provide assurance and quality control during short fibre reinforced 3D printing filament manufacture. The work encompasses an investigation into tailoring the heating approach used for filament inspection and providing an efficient means of data collection and processing [7]. Ongoing research assesses the impact of weight percent of fibre on thermal signatures to aid the development of accept/reject criteria for filaments.

2 METHODOLOGY

2.1. Materials

The filament used for analysis is polyactic acid (PLA) matrix that contained 30wt% Harakeke (*Phormium tenax* commonly known as New Zealand flax) reinforcement. The filament has diameter of 3 mm and a total sample length of 300 mm. The filament was manufactured at the University of Waikato via a methodology discussed in [6]. Initial attention has focussed on a single material type for definition of the approach.

2.2. Experimental setup

Two Canon 430EX III photographic camera flashes were used as the heating stimulus for pulsed thermography. The heating stimuli studied to date have included a single flash and a synchronised pair of flashes, doubling the heat deposition. The flash(es) were aligned to heat the section of filament as normal to the surface as possible. They were slightly angled to accommodate for the positioning of the IR detector, as shown in Figure 1. The IR detector used for thermal data collection was an Optris PI 640 microbolometer which has a full frame resolution of 640 x 480 pixels recording at a full frame rate of 32 Hz. Due to the geometry of the samples a sub window was selected and a higher frame rate of 125 Hz was used. The detector and flash(es) were positioned at a standoff distance of 60 mm from the filament. The length of filament contained within this field of view was approximately 20 mm, providing a spatial resolution of 30 μm per pixel. The flash pulse lasted 1/60 seconds and data was recorded for between 10 and 30 seconds, ensuring the full thermal response/ decay was captured. During

inspections the camera, flash(es) and sample were enclosed in a blackout enclosure to prevent influences of external radiation.

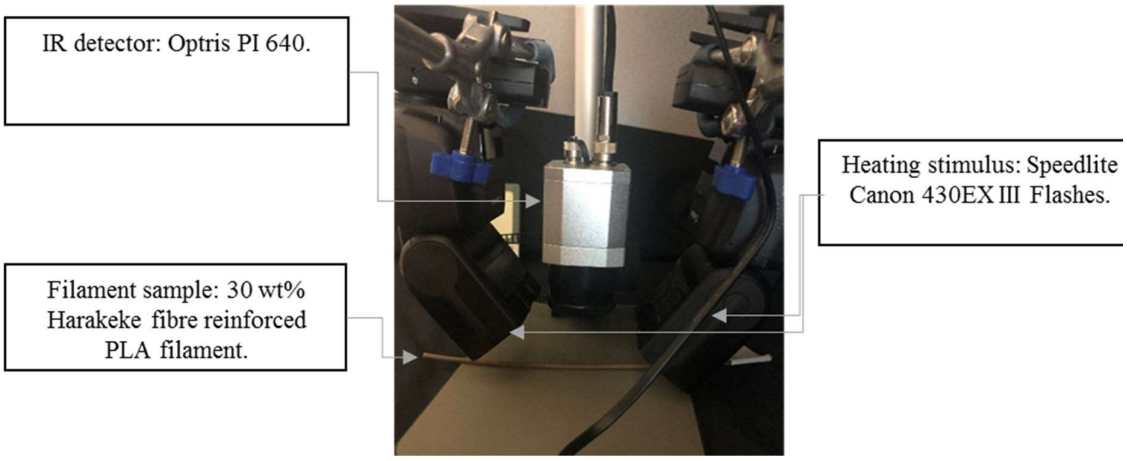

Figure 1: Experimental arrangement for pulsed thermography using the flash pair.

2.4.1 Data collection and processing

An interface developed in Matlab was used for detector control and data collection. Recorded digital data was calibrated to thermal data and stored in 3D data sets where data can then be considered both spatially or temporally. Recordings include pre-flash frames (background readings) and flash frames (where the detector is saturated) which can be easily identified and removed. Matlab was used for all visualisation and processing of the data. Thermographic Signal Reconstruction (TSR) [8, 9] was used to reduce the noise of collected digital data. TSR works by applying a logarithmic polynomial fitting of the temperature evolution through time. TSR has the advantage of reducing the noise in the data as well as reducing data sizes. After TSR the pulsed thermography data was then processed into pulse phase thermography (PPT) through application of a fast Fourier transform (FFT) on the thermal response of each pixel through time. Imaginary (Im) and real (Re) components of FFT of thermal data are then used to determine the phase images (phasegrams) using:

$$\varphi(\omega) = tan^{-1}\left(\frac{Im(\omega)}{Re(\omega)}\right) \quad (1)$$

3 RESULTS AND DISCUSSION

3. 1. Single Flash

Initial experiments were based on the use of a single flash. From an implementation point of view this would have provided the most compact set up. The results of single flash experiments found that insufficient energy was delivered as thermal contrast was insufficient to enable fibres and matrix to be distinguished. Therefor a single flash setup was found to be not feasible for the purpose of this research. The remainder of the current paper therefore focuses on the effect of a synchronised flash pair for increased energy deposition.

3.2. Flash pair

Two approaches to data analysis are presented. Firstly a single frame from the raw data has been extracted. This frame is selected as the one directly after the frame in which the flash appears, which is 0.01s after the flash. This frame was selected as it provided a relatively clear image of the near surface

variation in fibre density. The clarity of this frame is caused by the resin material being partially transparent to IR radiation so what is imaged is essentially a reflection of the IR pulse from the near-surface fibres. Although this frame is unable to provide information about deeper subsurface structures directly, if it is possible to estimate through thickness fibre amounts from the fibre distribution on the near surface a process could be established that takes very little time and extremely limited computing power, well suited to online inspections. The second approach is to truncate the recorded data to exclude any pre-flash frames. TSR was then implemented on each pixel throughout the recording to reduce temporal noise. An FFT using a rectangular windowing function was then implemented and phase data found. The post flash frame in digital level (i.e. not calibrated to temperature) is shown in Figure 2 and PPT phase data is presented in Figure 3. The representative results displayed are for a single data capture where the duration of recording was 15 s including pre-flash frames, leaving around 14 s of data to be processed for PPT after pre-flash frame removal.

The edges of the filament as clearly seen at the upper and lower edges of both Figure 2 and Figure 3. The post flash frame in Figure 2 starts to reveal some variations across the sample that are attributed to near surface fibres. Once the data is processed into phase data as in Figure 3 the presence of multiple materials becomes more apparent. The phase data reported was the clearest phase image taken from the 180 frequency bins defined and corresponds to the response at 0.53 Hz.

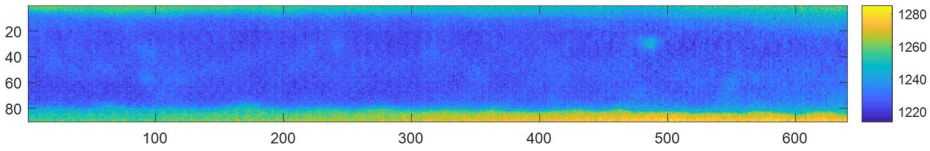

Figure 2: Post flash frame in digital data taken 0.01s after the flash where contrast is created by reflection from near surface fibres.

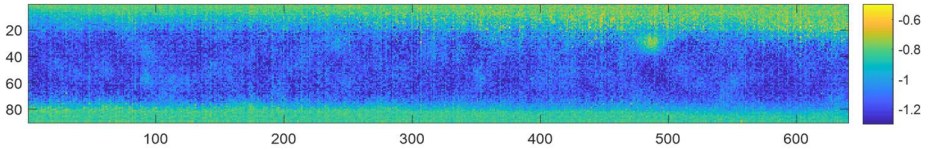

Figure 3: PPT phase data at 0.53 Hz after TSR.

4 CONCLUSIONS

An identifiable thermal contrast between the fibre and matrix has been displayed in the Harakeke/PLA filament. Thermal contrast was better achieved with double flash in comparison to single flash. These initial results are encouraging that thermography may be used to identify fibre bunches in such short fibre reinforced filaments as underlying structures are revealed. Contrast between different structures are found to be clearer in the phase data provided however there is significant further analysis to be done. Future work can be divided into two aspects, firstly the hypothesis that near-surface distributions of fibres are likely to be representative of through thickness distributions must be proven. If this is proven to be true attention should turn to near surface inspections. This would be vastly advantageous as inspection times, due to only needing the first frame after the flash and the processing time and computational expense would be greatly reduced. This would be extremely well suited to an inline inspection process. Should the hypothesis be found to be negative and a deeper subsurface inspection be required then processing into phase data has shown promise. The second aspect of further work would include investigation of processing parameters such as the windowing function used, where the importance of windowing function selection is discussed in [9]. Aspects such aliasing, truncation and leakage [10] should all be explored. In either case further work will assess different processing routines for clearer identification of contrasting regions. Thermographic inspection data will then be

compared to cross sectioned filaments to correlate the thermographic response to measured fibre weight percent. The end goal is to define a probabilistic approach to non-destructively quantify the fibre weight percentages of the Harakeke/PLA filaments.

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REFERENCES

[1] Wang, X., et al., 3D printing of polymer matrix composites: A review and prospective. Composites Part B: Engineering, 2017. 110: p. 442-458.

[2] Pickering, K.L., M.G.A. Efendy, and T.M. Le, A review of recent developments in natural fibre composites and their mechanical performance. Composites Part A: Applied Science and Manufacturing, 2015. 83: p. 98-112.

[3] Sezer, H.K. and O. Eren, FDM 3D printing of MWCNT re-inforced ABS nano-composite parts with enhanced mechanical and electrical properties. Journal of Manufacturing Processes, 2019. 37: p. 339-347.

[4] Parandoush, P. and D. Lin, A Review on Additive Manufacturing of Polymer-Fiber Composites. Composite Structures, 2017. 182: p. 36-53.

[5] Matsuzaki, R., et al., Three-dimensional printing of continuous-fiber composites by in-nozzle impregnation. Scientific Reports, 2016. 6: p. 23058.

[6] Stoof, D. and K. Pickering, Sustainable composite fused deposition modelling filament using recycled pre-consumer polypropylene. Composites Part B: Engineering $V 135, 2018: p. 110-118.

[7] Wagner, H.D. and L.W. Steenbakkers, Mechanical Breakdown of Single Fibres and Microcomposites, in Integration of Fundamental Polymer Science and Technology—3, P.J. Lemstra and L.A. Kleintjens, Editors. 1989, Springer Netherlands: Dordrecht. p. 250-256.

[8] Oswald-Tranta, B., Time and frequency behaviour in TSR and PPT evaluation for flash thermography. Quantitative InfraRed Thermography Journal, 2017. 14(2): p. 164-184.

[9] Olafsson, G., Tighe, R.C. and Dulieu-Barton, J.M., Improving the probing depth of thermographic inspections of polymer composite materials. Measurement Science and Technology, 2018. 30(2): 15pp.

[10] Ibarra-Castanedo, C. and X. Maldague, Pulsed phase thermography reviewed. Quantitative InfraRed Thermography Journal, 2004. 1(1): p. 47-70.