Advanced micro-CT imaging and microstructure characterization of carbon fiber reinforced 3D printed materials

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Summary: High resolution 3D scans of carbon fibre reinforced materials are obtained using x-ray micro-CT. We use a range of image analysis tools including a new fully convolutional neural network algorithm to quality fine features of the feedstock and 3D printed carbon composites. Our results allow the integration of 3D imaging and image processing into the QC and fabrication process.

1. INTRODUCTION

Carbon fibre reinforced composite (CFRC) materials are characterised by highly desirable physical and chemical properties such as high stiffness and tensile strength, low weight, high chemical resistance and temperature tolerance, excellent durability and design flexibility. Because of their properties these materials are commonly utilised in many structural components in aerospace, civil engineering, military, as well as in competitive sports. A significant impediment to the widespread adoption of CFRCs is our lack of understanding of the structural evolution of carbon-polymer composite when subject to external loading. The mechanical response of carbon composites varies significantly due to the presence of defects and fabrication flows. The problem exacerbates further in dynamic applications where the regions surrounding carbon fibres develop nano fractures that further develops into micro and macro cracks leading towards structural failure [1]. Several image-based approaches to characterize and analyse the distribution of voids and fibres within a composite structure have been proposed. Using optical microscopy (OM) and scanning electron microscopy (SEM) 2D high resolution images of voids and individual fibres can be acquired often in a destructive way. More recently X-ray micro-computed tomography (micro-CT) has gained popularity as a non-destructive inspection technique to investigate in 3D the heterogeneity and architecture of composite materials. In this study advanced 3D micro-CT imaging techniques and image analysis tools have been utilized to acquire and process a series of images for a suite of CFRC materials that are used as feedstock and/or are examples of final products in the 3D printing process of CF composites. There are a number of control parameters that might influence the quality of 3D printed parts and we investigate the effect of these fabrication parameters on the quality of printed parts in terms of identifiable features within their 3D microstructure. Using proprietary (Mango [2]) software and a fully convolutional neural network algorithm, voids and fibres of the samples of the feedstock and printed parts have been processed and segmented into separate phases and their respective amounts quantified, and voids are separated into two different families based on their shape and preferential location.

2. EXPERIMENTAL METHOD

In recent years, new ways of manufacturing CFRCs have been developed including 3D printing of carbon fibre and fiberglass, which improve the durability and structure of 3D-printed products. While the process of 3D printing composite materials is not mainstream yet, many manufacturers have started to experiment with it aiming at creating a reliable and reproducible workflow that will improve the QC. From the materials perspective, there are two main parts in the fabrication of 3D printed CFRCs: 1. the

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feedstock material that is fed into the printing device, 2. the final printed part. Both the feedstock and printed parts contain carbon fibre fragments, however, there are also microstructural features and defects that will affect the quality of final products. These defects are created as a results of fabrication methods. Here we used x-ray computed micro-tomography to acquire volume data and probe the 3D microstructure of both the feedstock and 3D printed composite samples and subsequently we derived relevant sets of structural and geometrical parameters directly from the tomograms. This method is now well established, and it is routinely used for non-destructively 3D imaging of opaque objects. A flat panel detector with 3kx3k pixels resolution and a micro-focus X-ray source of 80 kV were used for imaging. The grayscale projections were processed to reconstruct full 3D digital composites geometry using ANU's Helical Reconstruction software. The scanning resolution (i.e. voxel size) for the various specimen was ~1.1 µm and the acquisition time around 22-23 h per image which warranties for the acquisition of a high signal-to-noise ratio hence high-quality images.

Image processing and analysis

Image processing and quantitative analysis were then performed using Mango the software tool for image enhancement, parallel segmentation and network generation developed at the ANU specifically to work with tomographic data. For selected samples microCT data was then rendered using Drishti [6]. Additionally, we used a convolutional neural network model to identify features and phases within our datasets. Our model is based on a VGG 16 network [3]. Data utilized in our approach contains classifications of a CFRC image into five phases: fibres, matrix, voids, contaminants and background. This data is separated into 80% training and 20% testing data. The datasets are then shuffled, and rotation and blur added and randomly distributed to generalise the process and help prevent overfitting. In addition, 50% dropout is used on the network while training to also help prevent overfitting.

3. RESULTS

Key results from the research program include:

- **High resolution scanning:** we were able to produce high quality and high-resolution scans of composite with voxel size of 1.1 µm See fig 1.a-c
- An automated phase identification workflow that can separate fibre from resin matrix as well as identifying voids based on **Convolutional Neural Network (CNN)** was developed and tested.
- **Void quantification:** We have quantified voids within the 3D structure of feedstock and 3D printed material and we measure 19.9%, 19.1% and 15.9% void within the feedstock, the 3D printed samples 1 &2 respectively.
- A range of fabrication parameters were utilised to investigate their effect on the quality of the produced parts and our results show that the 3D printed sample with "width" fabrication parameter in the range of 400µm (the Reference sample) to 600µm has the least amount of defects/voids.

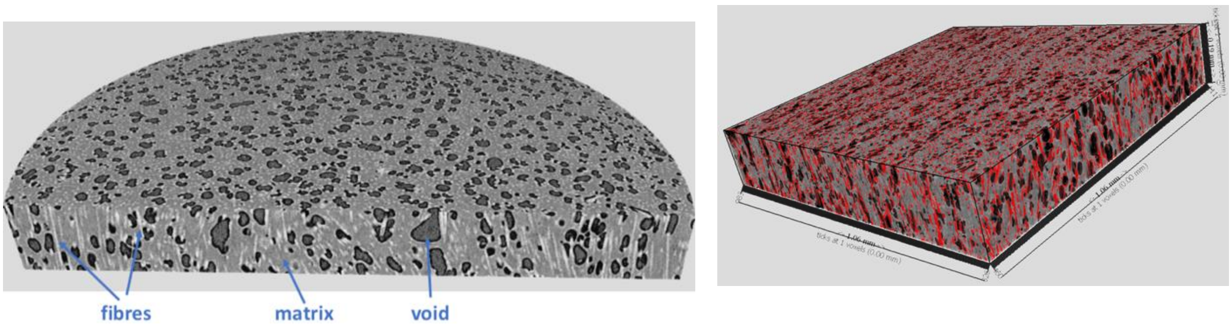

Figure 1: left) a sub-volume of the feedstock used as raw material for 3D printing of CFRC. right) a sub-volume of one of the 3D printed products. Fibres are shown in red.

References

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