CIMComp
EPSRC
Future Composites
Manufacturing Research Hub

Feasibility Study Final Report

Feasibility Study (FS) Title: COMPrinting: Novel 3D Printing of Curved Continuous Carbon Fibre Reinforced Powder-based Epoxy Composites

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Partners (include support from Industry): FreiLacke GmbH

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Executive Summary

A novel 4-axis rotational printing system together with a customised printer nozzle has been developed. Instead of using thermoplastic filament, thermoset filament was fabricated by coating powder-based epoxy on the continuous carbon fibres through an electrostatic deposition process, which shows minimum voids and high fibre volume fractions up to 50%. Printing of the thermoset filament on the rotational printing system demonstrated excellent fibre alignment for both straight and curved printing paths. To evaluate the concept of performance-driven printing of composites by placing the continuous carbon fibres along the principal stress trajectories, the developed filament and printing system were used to print an open-hole composite which was tested against the composite with a drilled hole. This project addresses the themes of 'high rate deposition and rapid processing technologies' and 'design for manufacture via validated simulation' of CIMComp Hub.

Background

3D printing of continuous carbon fibre-reinforced polymer composites has been gaining rapid momentum across a number of industrial sectors including 3D printer manufacturers, aerospace, automotive, and sporting goods. However, 3D printing of continuous fibre reinforced polymer composites is still facing a few challenges to achieve its full potential, including fibre misalignment, low fibre volume fraction as well as limited print paths. This feasibility study aims to prove the concept of 3D printing carbon fibre reinforced powder-based epoxy filaments on a modified 3D printer to enable fast and low-cost printing of continuous fibres with identified paths to achieve comparable mechanical performance with autoclave processed parts. The technology developed will potentially enable the printing of high performance composites with complex geometries (loading bearing fixtures, tools, moulds, etc.) for applications mainly in aerospace and automotive sectors.

Results/Deliverables/Outcomes

There are four project objectives which are all achieved. Main outcomes and challenges will be discussed below in detail against each objective.

OBJECTIVE (1): Modification of an existing towpregging tapeline for producing low-cost carbon fibre reinforced powder-based epoxy filament (1 to 3k tows, fibre V_f up to 65%) with a low viscosity and high deposition rate for use on FFF 3D printers. This project will increase the versatility of this manufacturing method, to bring forward a faster, more controlled and optimised way to manufacture composites.

The tapeline previously developed by Colin Robert for his Innovation Fellowship was modified. Powder epoxy was coated on the continuous carbon fibre tows through an electrostatic deposition process, followed by melting and cooling. The main change was the replacement of the Joule contact heating by lamp infrared heating which turned out to be more effective to keep a good cylindrical shape of the filament (in particular for 1K fibre tows), see Fig.1.

Produced filaments were firstly printed out for UD lamina using modified Prusa i3 printer with a brass nozzle sourced from Markforged. After consolidation in oven with vacuum bagging, cross-section images of the UD sample in Fig.2 shows the epoxy has very good wettability and interfacial bonding with the carbon fibre with minimum voids. Fibre volume fraction was computed to be 50% on average, and this could be increased (or decreased) by adjusting the powder deposition rate. Uniaxial tensile tests of the printed UD CF/epoxy composite in Fig 3 show significant improvement against the samples printed using Mark Two printer using CF/PA6 filament, i.e., stiffness was increased by 147% and strength was increased by 46%.

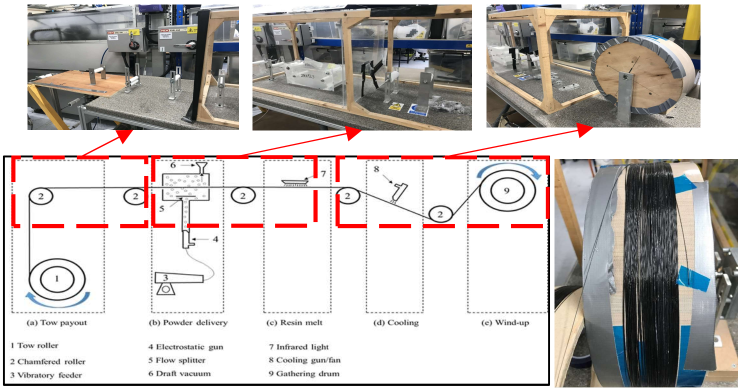

Fig.1 Modified tapeline for fabrication of CF/Epoxy filament

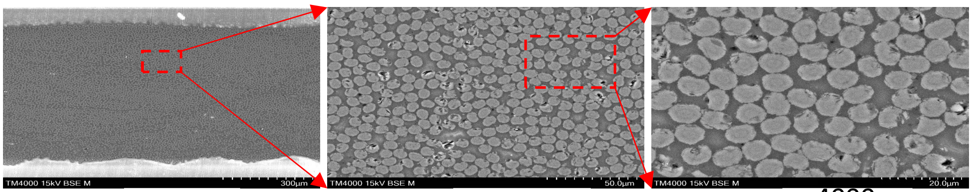

Fig.2 SEM images of printed CF/Epoxy after consolidation

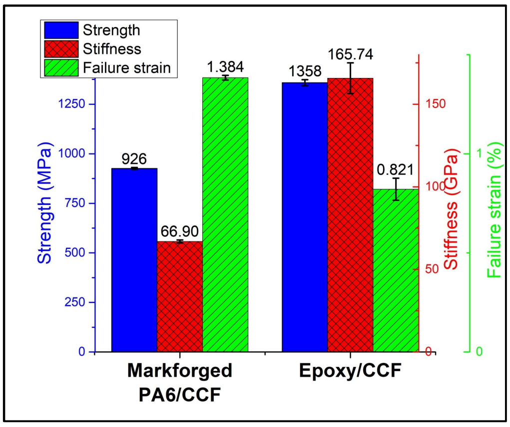

Fig.3 Uniaxial tensile testing results of printed UD CF/epoxy composites

OBJECTIVE (2): Design and manufacturing a novel printer nozzle with a rectangular cross-section at the outlet to enable better compression of fibres and modifying a FFF printer head to enable up to 180° rotation to minimise fibre twisting and misalignment when turning.

A specific printer nozzle was designed and manufactured to improve the fibre alignment during printing. The nozzle has a rectangular outlet (as shown in Fig.4) to have a more even distribution pressure on the printed filament. To accommodate the customised nozzle, an additional rotation was added on the printer head to rotate the nozzle, making sure the nozzle outlet is always perpendicular to the printer direction. Fibre alignment in both straight and curved paths is much improved without noticeable fibre buckling or twisting, as shown in Fig.5.

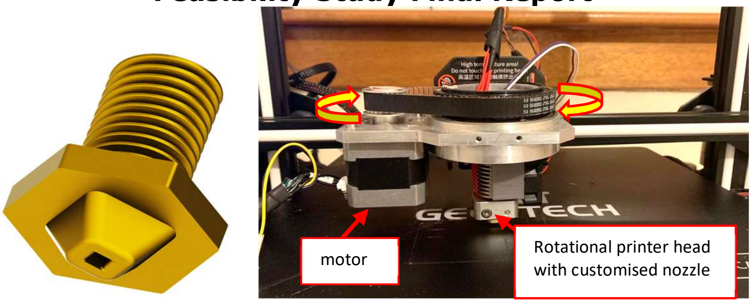

Fig. 4 Customised printer nozzle and 4-axis rotational printer

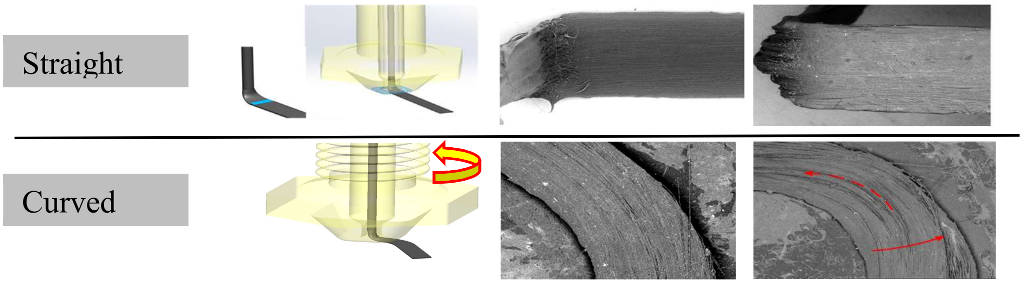

Fig.5 Rotational printing of single path with customised nozzle

OBJECTIVE (3): 3D printing powder-based epoxy composites with identified performance-driven curved continuous fibre paths that are demonstrated in our previous numerical study, followed by vacuum bagging and curing in oven.

A composite plate with an open hole under uniaxial tension was chosen as a case study to demonstrate the developed printing system, see Fig.6. Finite element analysis was first carried out to identify the maximum principal stress trajectories in the neat polymer under this specific loading condition. The trajectories were processed in Matlab and connected using G-code for the later printing. The rotation of the printer head was synchronised with the printing path direction, ensuring a good fibre alignment at every position in each print path. A substrate was printed separately using short fibre reinforced PA6 to avoid the use of extra metal mould for the subsequent curing.

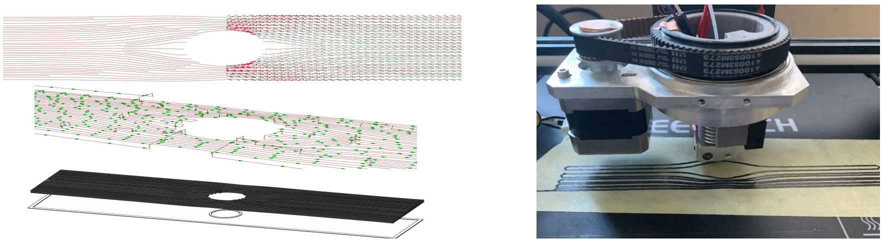

Fig.6 3D printing of continuous carbon fibre along identified stress trajectories

OBJECTIVE (4): Testing and characterisation of the printed composites using digital image correlation (DIC), SEM as well as X-Ray µCT to evaluate the printing quality and elucidate the failure mechanisms of the printed composites with identified curved continuous carbon fibres.

Uniaxial tensile tests of the printed open-hole composites were carried out with the assistance of DIC. Results of failure patterns and strain distributions are shown in Fig. 7. It was demonstrated that the printed composite with identified fibre paths has much uniform distribution of strain around the hole. As expected, the drilled composite (printed with straight fibre paths) has strain concentration on both left and right edges of the hole. Markforged Mark Two printed composite has a quasi-isotropic lay-up with additional fibres placed around the hole, and the principal strain is concentrated on the +/- 45 degrees leading to a shear failure. One challenge was the unavailable access to high-resolution X-ray micro-CT due to COVID19, therefore the failure mechanisms and 3D imaging of fibre alignment has not been fully understood yet. We have planned to do this as soon as we gain the access.

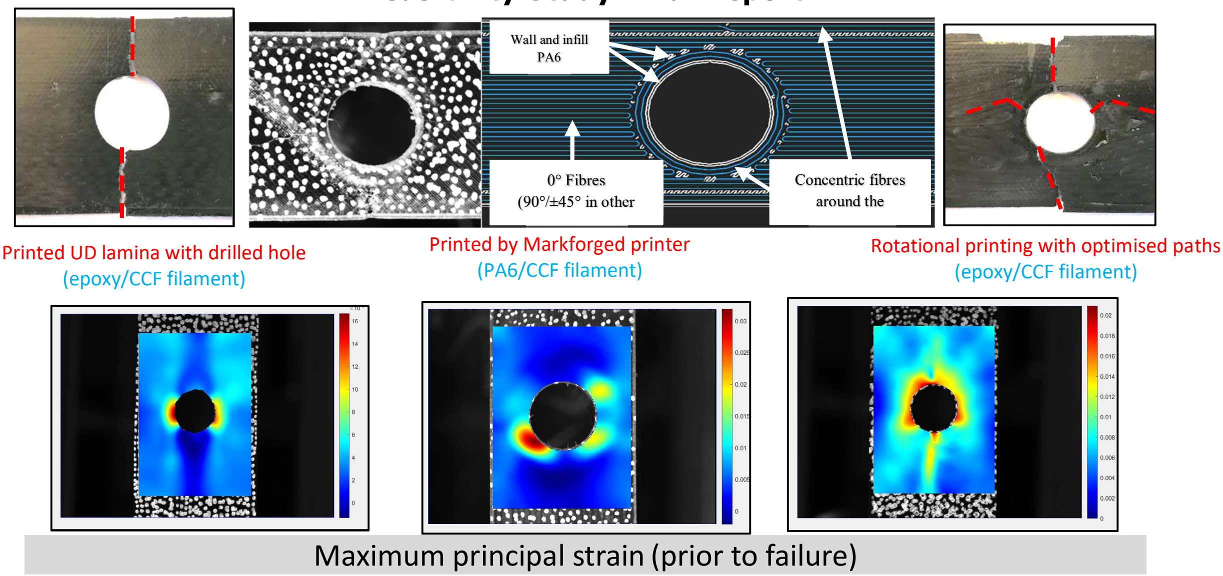

Fig. 7 Uniaxial tensile test of printed hole-in-plate composites (failure path & DIC imaging)

Fig.8 shows that the load bearing capacity is improved by 58% (on average) compared to the drilled composites. Very consistent stiffness is achieved as a result of the identified fibre paths. Loading strain Eyy is improved by 26% (on average), and Maxi-principal strain is improved by 120% (on average) around the hole just before the failure. The Markforged Mark Two printed composites have a much low failure strength and stiffness, although more ductile failure behaviour is found due to the PA6 thermoplastic.

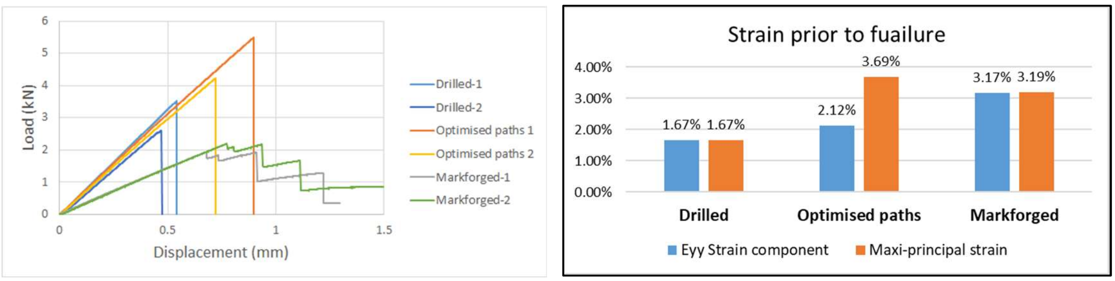

Fig. 8 Uniaxial tensile test of printed hole-in-plate composites
(Loading curve & maximum strain around the hole just before failure)

Future Direction/Impact

It would be ideal to continue this research if there is an opportunity to work on a Hub core project. If not, we will plan to go for an EPSRC standard grant application. The next step is to develop a more robust dual-polymer (or multiple-polymer) printing system where two (or more) printer nozzles can be used for different regions of a composite part in a single step printing process. A robotic arm has been purchased using PI's other funding and it would be nice to scale up this technology using collaborative robotic arms. This would complement the current AFP/ATP technology and enable the manufacturing of composites with ultra-lightweight, more highly complex shapes and smart multi-functions by using smaller fibre tows and multiple material deposition.

Synergy with other Hub projects

The project was linked with an Edinburgh-Ulster synergy grant to inject short fibre thermoplastic into the 3D printed composite preforms so as to stabilise the curved fibres and keep them in the identified loading paths. There has also been a new collaboration between the PI and the HiPerDif team in Bristol composites group. PI has agreed to trial the rotational printing system to print Bristol's discontinuous long fibres and improve the fibre alignment.