Experimental Informed Crack Behavior Simulation of Ink-jet Printing Carbon Fiber Composites

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Abstract. A novel method by ink-jet printing of PMMA droplets onto carbon fiber reinforcement (CFRP) prepregs has been proved to increase the interfacial toughness. Experimental informed simulation is carried in this work to both qualitatively and quantitatively track crack propagation. Digital volume correlation (DVC) based on synchrotron in-situ tomography results maps the strain field which then input into finite element to evaluate the crack tip stress intensity factor and J-integral, with the help of phase congruency. The results match double-cantilever beam tests processing by digital image correlation (DIC) that printed samples display higher fracture toughness.

Introduction. Carbon fibre composites are increasingly employed as structural materials in aerospace, automobile and wind power industry because of their high specific stiffness and strength coupled with their low weight appealing. However, composite laminates are susceptible to delamination because of a lack of reinforcement in the through thickness direction, which is considered as the most critical failure mode, developing from micro-cracks during manufacturing or in-service that is hard to detect at early stage. The challenge is to improve the resistance to delamination of laminated composites. Equally, it is important to understand how mechanical damage develops and to implement strategies to prevent it. A novel particle-toughening method using ink-jet printing by PMMA has been proposed to increase delamination resistance of unidirectional CFRP laminates [1], the aim of this work is to figure out the toughening mechanism.

Using synchrotron and laboratory X-ray computed tomography, in-situ traveling wedge fracture propagation tests have been carried out for both printed and non-printed specimens of a unidirectional carbon fibre epoxy resin composite (Fig. 1). Digital Volume Correlation (DVC) utilised the grey scale of the tomographs to retrieve the 3D displacement fields, and a phase congruency method [2] was applied to extract the crack shape and opening displacements in modes I, II and III (Fig. 2 shows an example of mode I opening). These data also provided inputs to an anisotropic linear elastic Finite Element (FE) analysis [3,4] to assess the local stress intensity factors (modes I and II) at the crack tip as a function of crack length. The analysis indicated an increase in mode I fracture toughness of the printed material compared with the non-printed material. Studies were also conducted with double-cantilever beam tests of the same specimen geometry, which were analyzed by digital image correlation to simultaneously measure the change in crack length and the load-line displacements and hence obtain the work of crack propagation. These provided more accurate data for the relative effects of the printing (Table 1), which confirmed the printed materials had higher delamination resistance. Post-test characterization measured the fracture surface topography and investigated the relative contributions of fibre-bridging and surface roughness.

Conclusion. A novel toughening method using ink-jet printing by PMMA, applied to a unidirectional carbon-fibre epoxy composite, increases the work of fracture of delamination. This can be associated with an increase in the fracture surface roughness.

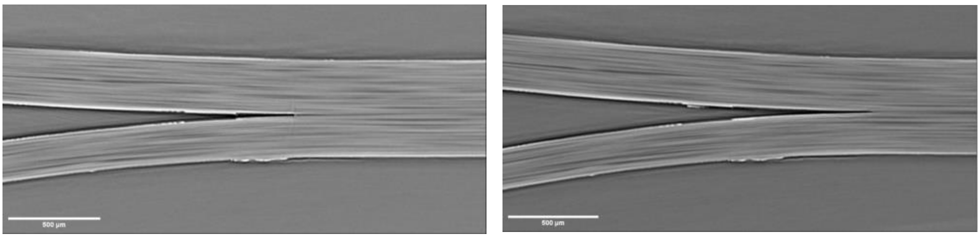

Fig. 1: Successive observations of crack propagation in printed laminate by synchrotron x-ray tomography

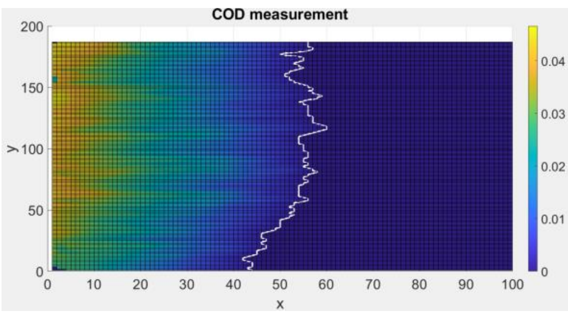

Fig. 2: Example of the measurement of crack opening displacement (in mm) using digital volume correlation. The crack tip, observed by tomography, is marked by the white line. The x and y axes are in (x 10µm).

Sample Type	**G_{1C} /J m^{-2}**
Hexagon Printed	309 ± 5
Parallelogram Printed	315 ± 4
Square Printed	313 ± 5
Non-printed	266 ± 6

Table 1: Mode I Fracture toughness of non-printed and different patterns of printed sample, obtained by double cantilever beam tests.

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