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TITLE: Re-flow of Epoxy from Semi-cured Laminates into Dry Fabric

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ABSTRACT: Isothermal matched moulded resin infusion has been identified as a potential rate-enabling technology for composite part manufacture. Further process intensification could be enabled through semi-curing smaller elements off-line, before integration into the preform of a larger part. Recent studies of semi-curing have shown that equivalent interlaminar properties, when compared to a conventional infusion of dry fabric, are possible if the semi-cured epoxy is below gelation before subsequent infusions [1]. The strong adhesion reported between the semi-cured and uncured polymers may not only be due to chemical cross-linking. Re-flow of the semi-cured epoxy was observed into the dry reinforcement at elevated temperatures used for hot-infusion of the larger part/tooling.

This study aims to investigate the re-flow mechanisms of semi-cured epoxy from laminate elements into dry preforms before hot-infusion. Key questions are answered around: (i) the proportion of resin re-flow into the interlaminar and intralaminar regions, and (ii) whether the re-flow causes voids in the semi-cured laminate or additional mechanical keying in the dry preform.

Overview of Results

The re-flow is evaluated by X-ray computed tomography (XCT) scanning of partially infused fabrics to quantify the level of impregnation (LoI) of fibrous reinforcements. Carbon fibre reinforced epoxy laminates were made by vacuum infusion and the degree-of-cure (α) advanced to around 0.3-0.4. At this α, the semi-cured laminates are handleable and tack-free at room temperature. The semi-cured laminates were then vacuum bagged with dry fabric layers, and heated to 120°C at a ramp rate of 2°C/min. Examples of ex situ XCT measurements of different samples interrupted at 1, 2, 3, and 4 hours into the dwell are shown in Figure 1. The semi-cured epoxy was observed to flow mostly through the interlaminar regions (i.e. the gaps between the non-crimp fabric tows). Mechanical keying was observed early in the process and after 3 hours, dry fabric tows appear to be fully surrounded by semi-cured epoxy, which may impede filling during the next infusion stage. No voids appear in the semi-cured laminates but the tow gaps become more visible, suggesting that the resin flowing into the dry tows comes from the interlaminar regions.

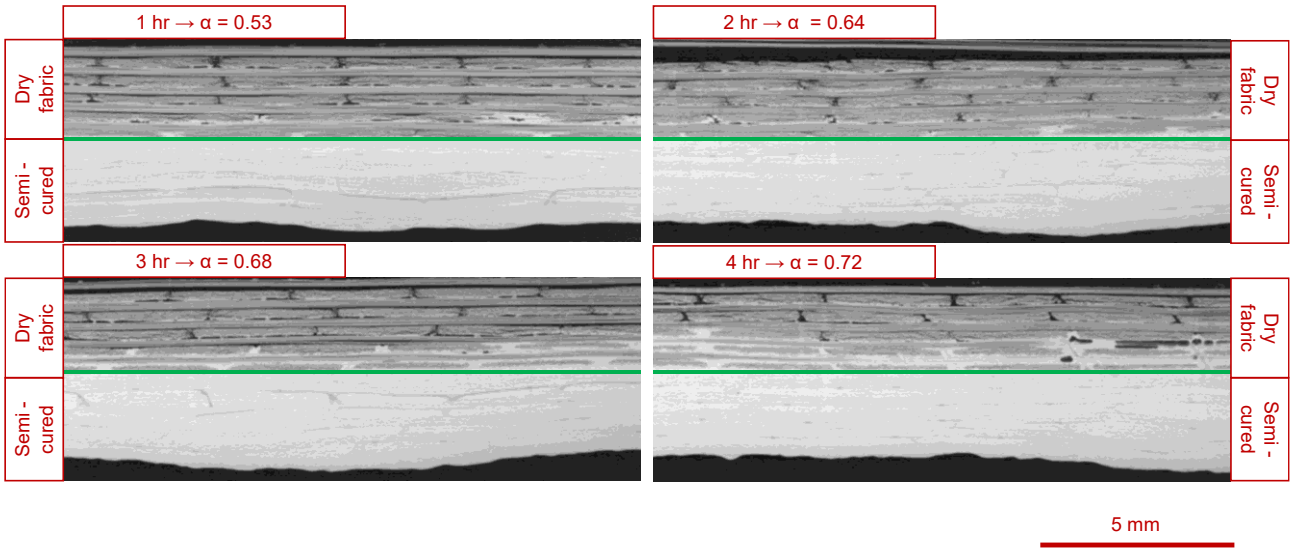

Figure 1. Cross-sections of ex situ XCT measurements showing the progression of epoxy from the semi-cured laminate into the dry preform from four interrupted tests. The green line in each section identifies the interface between the semi-cured laminate and dry preform.

In-order to gain a finer time-resolved understanding of how and when the semi-cured epoxy flows into the interlaminar regions, in situ XCT measurements were performed using a recently developed thermal chamber (i.e. oven) that can be placed inside an XCT scanner [2]. The experimental set-up is shown in Figure 2a and described previously [3]. The oven was heated at 2°C/min to 120°C and held for 1 hour. A 2-minute XCT scan was taken every 3 minutes. The re-flow progression is shown in Figure 2b, alongside the ex situ XCT results. The in situ measurements indicate that the semi-cured epoxy flows during the heating ramp but then stagnated during the dwell. While the in situ XCT results indicate that semi-cured resin is flowing, as it re-flows deeper into the dry fabric, the signal-to-noise ratio of the XCT data obtained from the short in situ scans makes it harder to distinguish the position of the flow front. Since the resin is re-flowing around the tow bundles, the position of the flow front becomes more ambiguous. Cross-sections of the in situ XCT scans are shown in Figure 3. Interestingly, voids appear in the semi-cured laminates processed via the XCT oven.

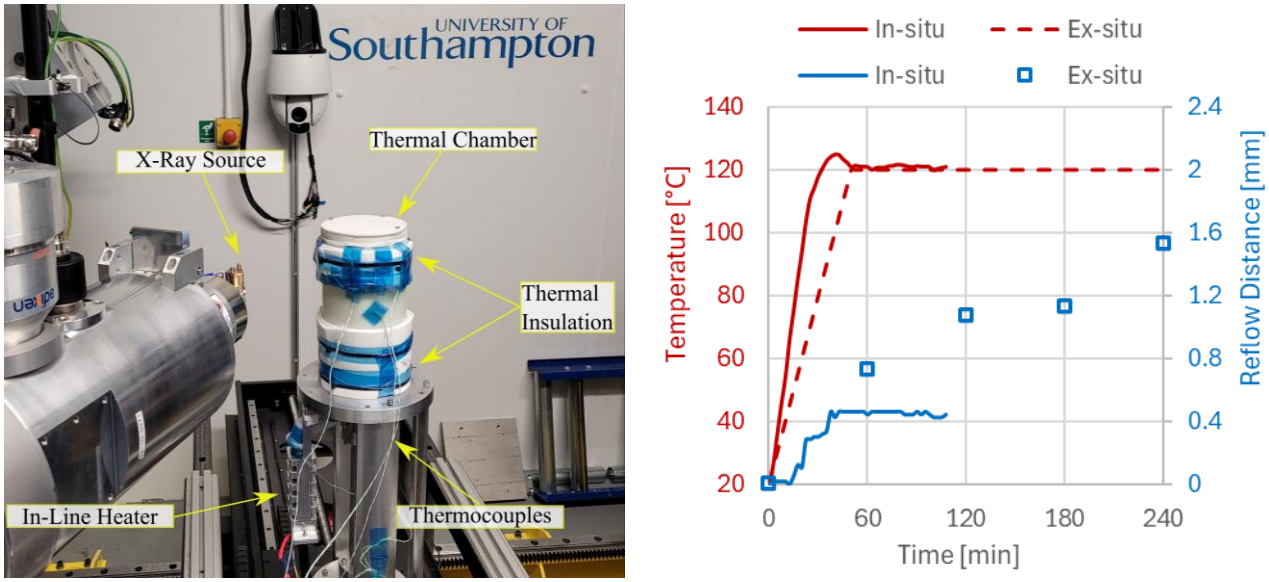

Figure 2. In situ XCT measurements: (a) experimental set-up and (b) re-flow progression of the in situ and ex situ interrupted XCT scans.

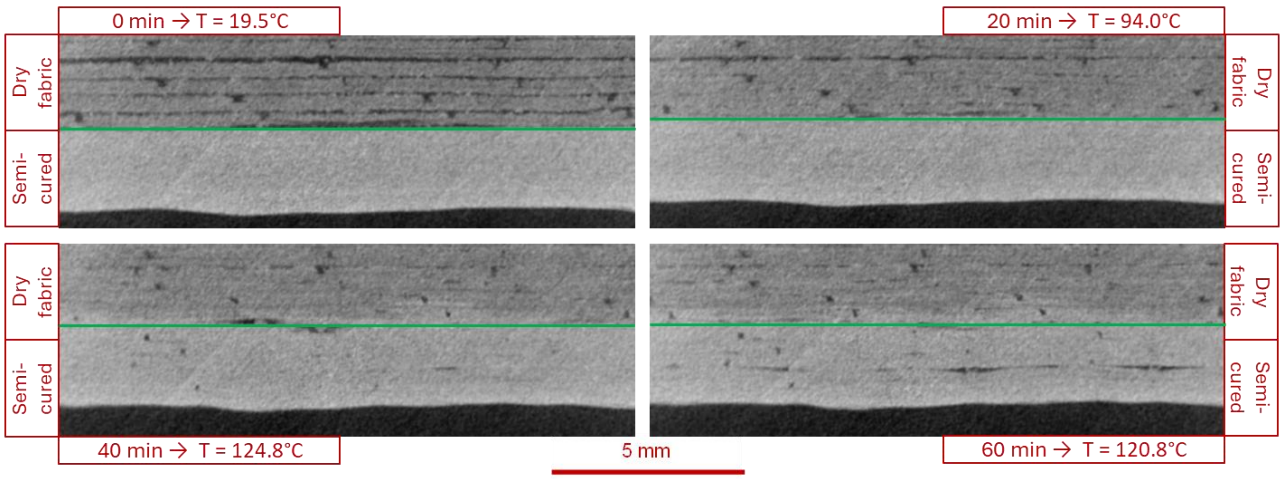

Figure 3. Cross-sections of in situ XCT measurements showing the progression of epoxy from the semi-cured laminate into the dry preform at key points in the heating cycle. The green line in each section identifies the interface between the semi-cured laminate and dry preform.

Conclusions and Future needs

Semi-cured epoxy was observed to re-flow from its parent laminate into the dry fabric of a preform before hot-infusion. The epoxy mainly flows into the interlaminar regions of the dry fabric from the interlaminar regions of the semi-cured laminate. Mechanical keying was observed early in the process and given enough time at elevated temperatures, the resin appears to fully encapsulate tows, leaving dry cores very similar to the microstructure found in prepregs. Voids in the semi-cured laminate were also observed. Whether uncured resin introduced into the preform can saturate the centre of dry tows encapsulated by highly semi-cured resin remains unknown. Re-flow out of interlaminar voids spaces and their re-filling also requires further investigation.

Acknowledgements

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