Feasibility Study Final Report

Feasibility Study (FS) Title: Evaluating the potential for in-process eddy-current testing of composites

PI name: Dr Robert Hughes

Research staff/students (*include % of time*): Dr Robert Hughes (50% FTE)

Partners (include support from Industry):

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Executive Summary

The experimental practicality and sensitivity of eddy-current testing (ECT) techniques was explored for the in-line monitoring of carbon fibre reinforced polymer (CFRP) composite materials. The project sought to determine whether; a) eddy-current testing was capable of monitoring critical properties of uncured composite materials i.e. fibre orientation and fibre density, and b) if certain manufacturing conditions, including applied pressure, scanning height, applied temperature and scanning speed, affected the ability to evaluate component quality. Experimental studies were conducted evaluate ECT under these conditions and a lab-bench test platform was developed for further studies.

Although a full suite of studies into all the conditions highlighted above was not possible during the period of the FS, key experimental results were obtained confirming the potential for ECT monitoring of fibre alignment and fibre density (pressure) in uncured composites up to a standoff of 8mm from the surface. However, the FS also demonstrated that ECT measurements struggle to penetrate deeper than one or 2 ply layers in uncured composites, most likely due to the lack of cross-linking between fibres in adjacent ply layers. Important lab capabilities, academic and industrial collaborations were also developed to support continued research through PhDs and other funding opportunities.

Background

Automated manufacturing of carbon fibre composites has increased rates of production from manual manufacturing methods. However, these advances are not supported by effective and quantitative inspection systems to monitor component quality. Currently, machine-laid components are routinely inspected manually (often by eye), undermining the advances made in automated manufacturing and compromises the production rate and reliability of the components produced. It is therefore of utmost strategic importance that suitable automated in-line inspections are developed to support high-rate manufacturing, a key priority of the Hub.

Eddy-current testing (ECT) is a powerful non-contact non-destructive testing (NDT) inspection technique, used regularly in industry for evaluating the quality and integrity of safety-critical metallic components. The technique employs inductive coils with time-varying magnetic fields to induce current flow in electrically conductive materials and monitors any changes in the material properties. Due to the electrical conductivity of carbon fibres themselves, ECT can measure properties of cured carbon-fibre materials including; evaluating fibre orientation and local fibre density, as well as detecting manufacturing flaws, such as inclusions, gaps, overlaps and wrinkles [1]. However, no research has explored ECT techniques for in-line monitoring.

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The main aim of the FS was to evaluate the capability of ECT for monitoring uncured CFRP materials. The key objectives to achieve this aim were to:

1. Determine how variations in automated fibre placement manufacturing conditions (pressure, temperature, height, speed etc),
2. Establish a lab-based experimental rig for testing and evaluating ECT sensors and measurement techniques of uncured CFRP materials,
3. Develop relationships with other academics and industry in composite manufacturing to explore future collaborations.

Results

***Detecting Fibre Orientation in Uncured CFRP* -** The difference between measurements made on cured and uncured IM7/8552 ply layups was examined to determine the feasibility of multi-layered measurements on AFP-laid structures. Preliminary tests using the same mm-scale circular coils used to evaluate cured samples by Hughes et.al. 2018 [2] failed to resolve fibre-orientations in equivalent uncured samples due to surface undulations altering the standoff of the sensor from the surface. A larger anisotropic meander-coil was therefore adopted and a rotating stage used to produce angular eddy-current impedance plots (Figure 1), showing measurements made at 17.2 MHz above uncured and cured samples of identical stacking sequence layups [0/45/90/-45°].

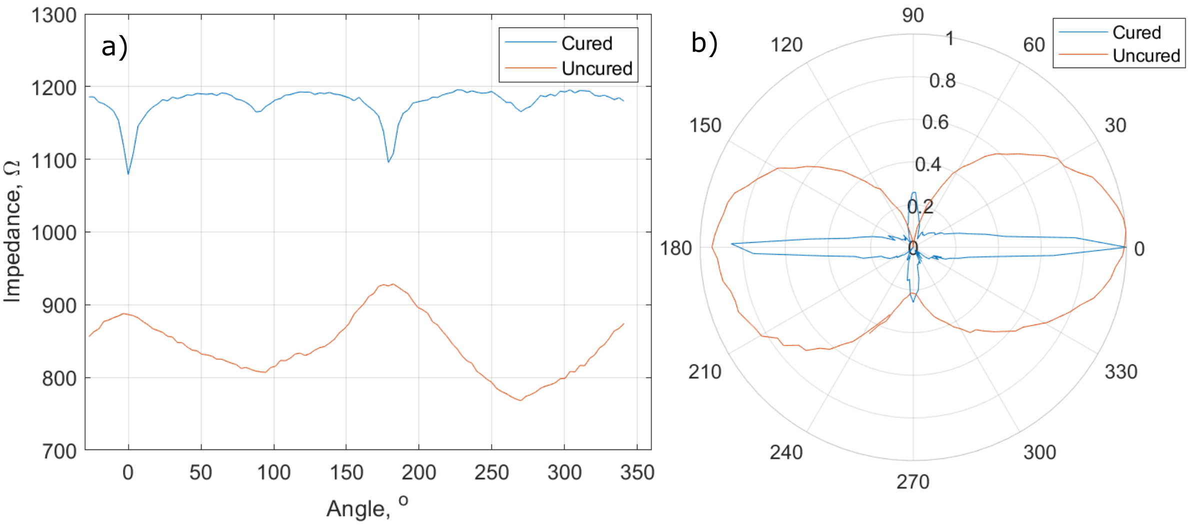

Figure 1 - Fibre orientation comparison between cured and uncured IM7/8552 samples of equal layup structure [0/45/90/-45] showing a) the unprocessed coil impedance data in a linear plot and b) the normalised impedance changes in polar form.

Figure1.a shows the impedance difference between cured and uncured samples demonstrating the difference in effective conductivity, most likely due to different degrees of contact between fibres in different layers[1]. The figure shows the angular variation in both samples with clear indications relating to the top ply orientation (0/180°), while also showing a secondary peak at 90/270° in the cured sample - something not observed in the uncured material. Figure 1.b shows the 2 normalised impedance change as a function of angle, further highlighting the differences between cured & uncured materials. Fig.1b also highlights the spread of the orientation indications in uncured specimens.

<u>Conclusions</u> - Cured samples produce well-defined orientation indications allowing easy, high-resolution evaluation of misalignment in the top ply within ±5° (HWHM), whereas uncured

[1] This is the opposite way round to expected and so will form the basis of further investigation.

samples produce broader orientation indications (mean HWHM 27°), making automatic detection of minor misalignment more challenging.

Determining fibre orientation at standoff - The angular impedance change over a range of standoffs from the surface of the uncured sample was measured. The results in Figure 2.a show the decay in measurement amplitude as the distance between the sensor and the material surface moves form 0-8.0 mm. Figure 2.b shows the normalised results, demonstrating consistent definition in angular indications (mean standard deviation of peak angle = ±4°) over this range.

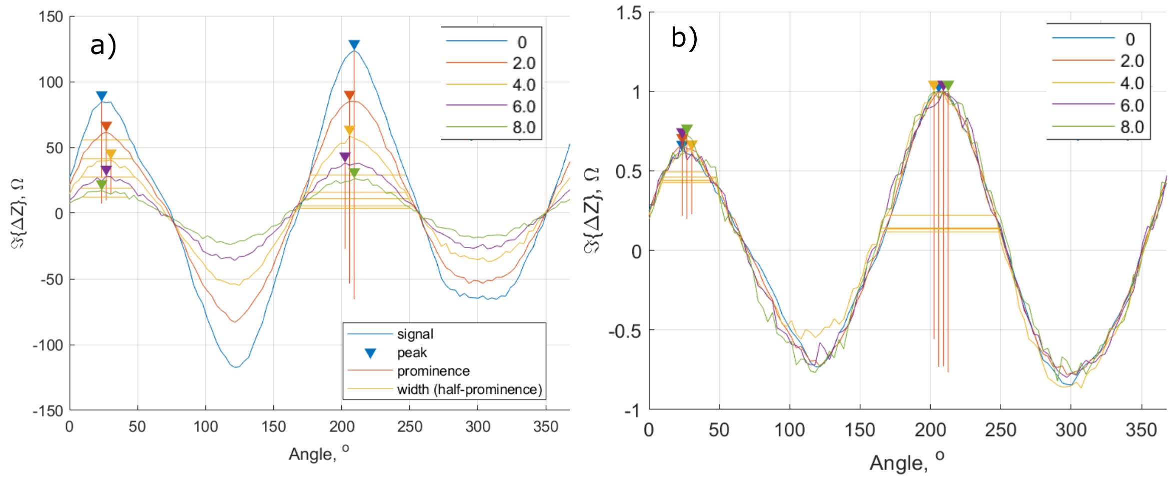

Figure 2 - Evaluating fibre alignment at standoff showing a) the mean subtracted impedance amplitude comparison and b) the normalised angular impedance changes.

Conclusions - *Fibre orientation measurements are achievable up to and beyond 8.0mm from the surface of the sample, with reliable peak-detection with standoff. The sensor could be wired in a differential mode with an identical sensor to counteract the amplitude change with standoff (a common and easy configuration to implement).*

Monitoring Pressure – Eddy-current sensors were fabricated in-house and installed in a pressure rig baseplate to monitor the effect of applied pressure on the measured impedance of uncured IM7/8552 multi-directional layups. The normalised impedance change results are shown in Figure 3 with respect to time and applied pressure to a multi-directional uncured composite sample [0/45/90/-45°].

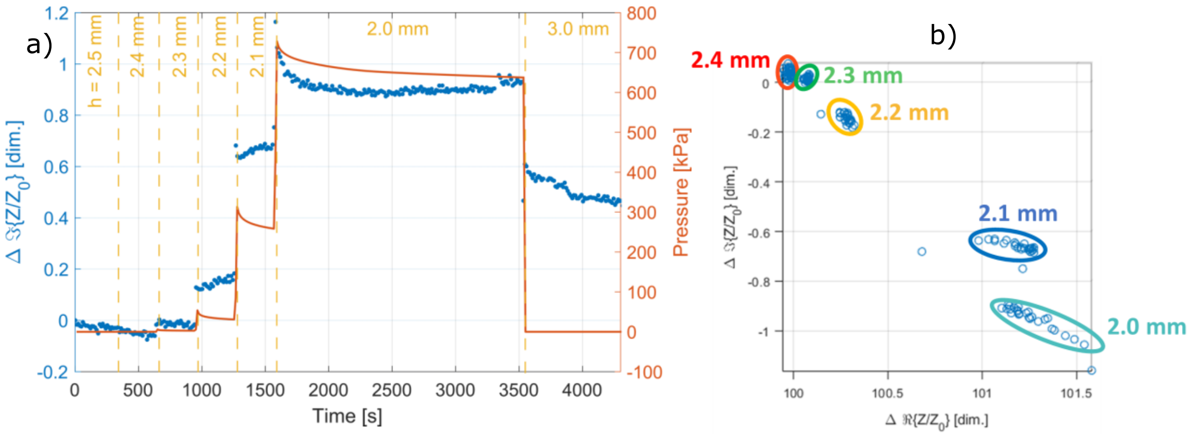

Figure 3 – ECT impedance change with applied pressure to uncured IM7/8552 layup

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The results demonstrate how ECT measurements are dependent on the density of plies which increases as pressure is applied. Characteristic relaxation in pressure is observed at high applied forces (Fig.3.a, 2.0 mm region), and relaxation is also measured through ECT when the pressure is released (Fig.3.a, 3.0 mm region). Figure 3.b shows the normalised complex impedance measurements indicating clearly identifiable regions for each compression stage of the test.

Conclusions - *ECT sensors are sensitive to the applied pressure and as such the fibre density of composite structures could be characterised through ECT techniques. In-line inspection could also be performed to monitor variations in applied pressure of AFP system.*

Temperature & Speed Variations – Preliminary studies were conducted into the effects of temperature on the eddy-current inspection, however the results only served to demonstrate the limitations of the experimental setup. As such a lab-bench experimental testing rig was developed to provide a proof-of-principle platform for these studies. However, due to limitations on researcher time, this platform was not fully operational in time to investigate these effects.

Deliverables: The research summarised above was presented as a paper at the UK's flagship non-destructive testing conference (BINDT) in 2020, however further dissemination at international conferences was not possible due to cancelations caused by COVID-19. A journal paper will be developed to encapsulate the work carried out.

Outcomes: This feasibility study has led to strong collaborative links with composite researchers and industrial partners. A PhD project has begun with support from Rolls-Royce plc. to further explore and characterise the inspection of uncured composite materials for in-line monitoring. A funding proposal is also in development for an EPSRC New Investigator Award (NIA) supported by Rolls-Royce and Airbus.

Future Direction/Impact

Further funding is required to support the full investigation and development of ECT monitoring of uncured composites. There remain many variables and conditions still requiring investigation to successfully develop an in-line monitoring device. I have identified the EPSRC New Investigator Award as a potential source of funding however a Hub Core Project may be the most suitable route for continuing the work.

Realising a working in-line monitoring system using ECT would significantly reduce the time required for inspection and rework thereby improving the production rate of manufacture – a key aim of the future composite manufacturing hub. In the future the technology could provide closed-loop control allowing much higher precision in AFP manufacturing and provide detailed structural information to support simulation of component properties.

Synergy with other Hub projects

I am actively engaged in supporting the CERTEST composite manufacturing project aligned with the Hub's goals. Numerous potential activities have been identified with other projects including Technologies framework for Automated Dry Fibre Placement, and the monitoring of layer-by-layer curing. Links with industrial partners including Rolls-Royce, GKN & Airbus have also been made.

[1] - H. Heuer, et.al., "3 - Non-destructive evaluation (NDE) of composites: eddy current techniques," in Non-Destructive Evaluation (NDE) of Polymer Matrix Composites, Woodhead Publishing, 2013

[2] – R. Hughes, et.al., "Characterisation of carbon fibre-reinforced polymer composites through radon-transform analysis of complex eddy-current data", Composites B, 2018