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A novel dielectric sensor for process monitoring of carbon fibre composites manufacturing

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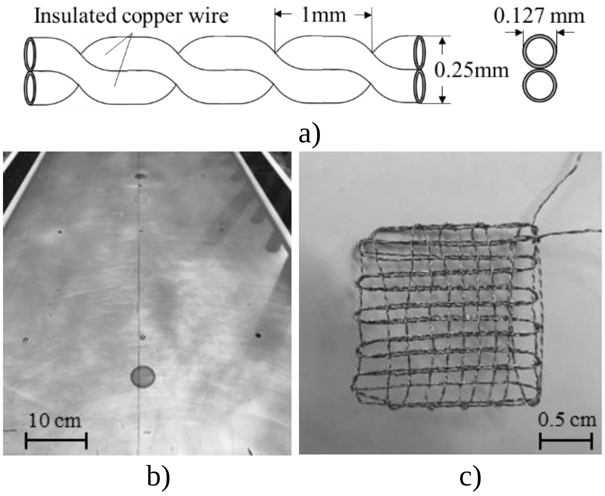
Introduction

Process monitoring techniques have been developed to monitor critical parameters of manufacturing such as flow front position and cure reaction progress and to identify potential defects. The main technologies proposed include dielectric spectroscopy [1], fibre optics [2], time domain reflectometry [3], and pressure transducers [4]. Monitoring based on impedance/dielectric spectroscopy is considered advantageous due to the sensitivity of response to filling state and cure progress, robustness and relatively low cost of the sensors and measuring setup and capability for incorporation on tooling surfaces. Lineal dielectric flow sensors are appropriate for use with non-conductive reinforcement [1] as presence of carbon would disturb the electric field, whilst setups making use of the conductive carbon reinforcement as one of the electrodes of the sensing system [5] involve significant practical complexity as their operation requires electrical insulation of the reinforcement from the tooling assembly. The solution adopted in cure applications for carbon composites is to cover the sensor with a permeable non-conductive material such as glass cloth or a polymer weave [6-8]. This type of solution increases the intrusiveness of the sensing system and generates some differences between the material monitored and the material of the composite.

The present study reports the development of a novel non-intrusive dielectric sensor overcoming the difficulties arising by the conductive properties of carbon reinforcement. The concept is used for the design of two sensor types; a lineal flow front position sensor applied to resin transfer moulding (RTM) and a woven arrangement used to monitor the cure and of a carbon fibre/epoxy composite.

Sensor design

The design of the dielectric sensor is illustrated in Figure 1a. It comprises two uniformly twisted solid copper wires covered by polyurethane enamel coating. The diameter of each wire is equal to 0.127 mm, whilst the twist length is 1 mm. Two different designs based on the same sensor principle were implemented. A lineal sensor is used to monitor the resin flow front position. In this case the sensor is placed on the tooling aligned to the direction of resin flow front, as illustrated in Figure 1b. A woven cure sensor is made by weaving the twisted wire using a miniature loom. The cure sensor shown in Figure 1c is made using 1 m of twisted wire and a nominal weaving distance of 2 mm. The cure sensor is a 20x20 mm square with 0.127 mm thickness. Upon application of voltage an electric field is formed between the wires. The field goes through the insulating coating and gaps between the two wires. The twisting increases the contact length between the wires and the signal strength. The insulating coating prevents contact of the copper wire with the conductive carbon fibre. Although the reinforcement can interfere with the fringing field, it only partially screens the field in gap regions within the twisted double wire. The woven configuration of the cure sensor increases the signal strength further.



a)

b) c)

Figure 1 a) Sensor design; b) lineal sensor placed in RTM cavity; c) woven cure sensor.

Sensor evaluation experimental se-up

The evaluation of the lineal sensor was performed during RTM processing of a carbon fibre/epoxy composite panel. The RTM tool is a rectangular cavity with dimensions 900×340×3.3 mm corresponding to length, width and thickness respectively. The reinforcement material was Hexcel G0926 woven carbon fabric with a 5H satin weave pattern and areal density of 375 g/m^2. The resin system was Hexcel RTM6 epoxy. The preform with dimensions 800×340×3.3 mm comprised 9 layers in a [0/90/0/90/0/90/0/90/0] layup resulting in a volume fraction of 56.7%. The filling was carried out at a constant temperature of 120 °C under a pressure of 3 bar with the simultaneous application of vacuum, whilst the curing stage was performed at 160 °C for 2 h. The lineal sensor with length 800 mm was placed in the centre of cavity of the RTM tool and was connected to a Solartron 1260 Impedance Analyser. Impedance data were acquired over seven frequencies swept logarithmically in the 100 Hz - 100 KHz range. The analyser communicates with a computer via an IEEE interface. An in-house code developed in LabVIEW was utilised to drive the measurements and acquire the data. A toughened glass top plate is used in the RTM tool to allow the visual measurement of the flow front for validation purposes using a digital camera.

Two isothermal cure experiments at 150 °C and 160 °C using neat RTM6 resin were carried out to establish the cure monitoring capability of the woven sensor. The experimental set-up used comprises a Eurotherm 2408 controller and a heating mantle mounted on a hollow copper cylinder. The cure sensor connected to the impedance analyser was immersed in a glass tube containing the liquid resin placed in the heated copper cylinder. In addition to the control thermocouple placed in the copper cylinder, a thermocouple was placed in the tube to measure the actual thermal profile the resin follows during cure.

The response of the cure sensor in the presence of carbon reinforcement was assessed in VARTM processing of a carbon fibre/epoxy composite plate. The preform, with in plane dimensions 150×75 mm, comprised six plies of Hexcel G0926 in a $[0/90]_3$ lay-up resulting in a total thickness of 2.2 mm and fibre volume fraction of 57.5%. Infusion with Hexcel RTM6 resin was carried out at 120 °C under vacuum and cure at 160 °C for 2 hours. A thermocouple was placed on the tool of the VARTM process to monitor temperature evolution during the process. Impedance data were acquired over 25 frequencies in the 1 Hz - 1 MHz range. The results of temperature monitoring were used to compute the evolution of the degree of cure based on a non-parametric kinetics model of the cure of the resin system of this study [9].

Results

Lineal sensor

Following the analysis in [1], the length of impregnated area $\mathrm{l_w}$ measured by the lineal sensor can be expressed as a function of admittance measured by the sensor ($\mathrm{Y_{sensor}}$) as follows:

$$\mathrm{l_w} = \frac{\mathrm{Y_{sensor}} - \mathrm{Y_{dry}}}{\mathrm{Y_{cov}} - \mathrm{Y_{dry}}}\mathrm{l_t} \qquad (1)$$

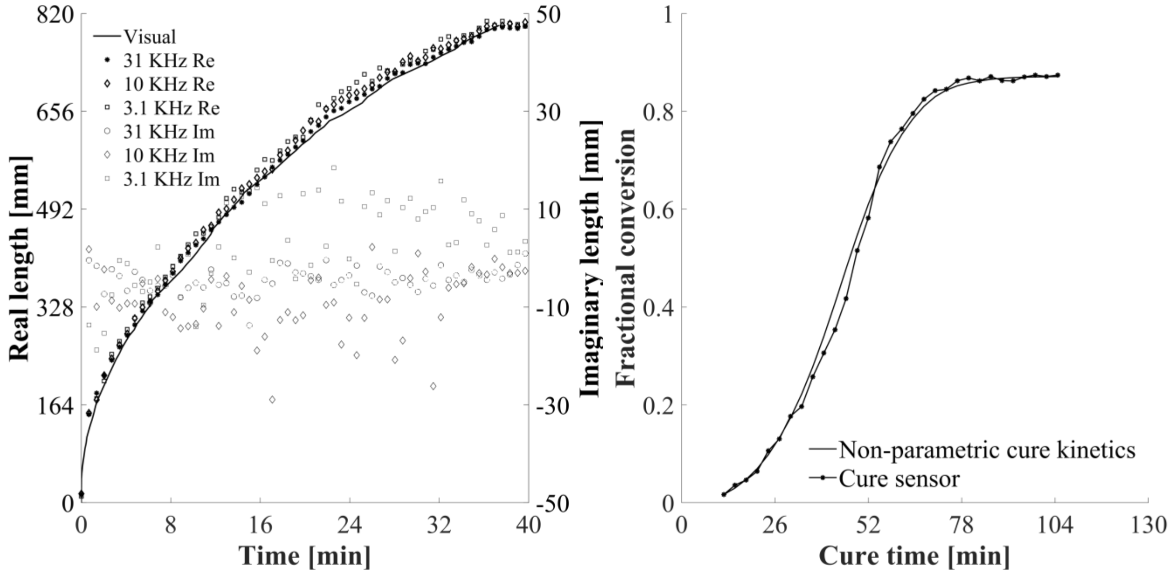
where $\mathrm{Y_{dry}}$ is the initial admittance of the sensor when the preform is dry, $\mathrm{Y_{cov}}$ is the admittance when the preform with full length of $\mathrm{l_t}$ is impregnated by the resin. Figure 2a illustrates the sensor response for a range of frequencies alongside the visual measurements and the corresponding imaginary part of the length, which can act as an estimate of the corresponding error. The results show that the sensor response follows closely the behaviour of the flow front position during the whole duration of the impregnation stage. The average error never exceeds 9 mm which is negligible in comparison to the order of magnitude of the overall length allowing the use of sensor in real time applications.

Cure sensor

In order to uncover the quantitative characteristics of the resin reaction during cure it is necessary to translate the dielectric/impedance signal to information related to resin reaction state. The behaviour of a thermoset under an alternative current electric excitation is dominated by three phenomena: a) dipolar relaxation b) migrating charges and c) electrode polarisation. The imaginary impedance of a simplified equivalent circuit expressing this behaviour can be expressed as follows [10]:

$$\mathrm{Z''} = \frac{\omega \mathrm{C}{\mathrm{R_i}}^2}{1 + \omega^2\mathrm{C}^2{\mathrm{R_i}}^2} + \frac{2}{(\mathrm{A_e}\omega)^{\mathrm{n}}} \qquad (2)$$

Here, the first term corresponds to migration charges and dipolar relaxation phenomena where C denotes the corresponding capacitance of induced and static dipoles and $\mathrm{R_i}$ the resistance due to migration charges mobility. The second term of Eq. (2) corresponds to the impedance of a constant phase element (CPE) formed at the interface between the electrodes and the material, where $\mathrm{A_e}$ and n are the parameters of the CPE. The imaginary impedance spectrum maximum after subtracting the electrode polarisation term depends only on $\mathrm{R_i}$. The migration charges term can provide an accurate estimation of the reaction progress under isothermal conditions since the value of $\mathrm{R_i}$ is directly dependent on mobility. Coefficients $\mathrm{A_e}$ and n were computed using the low frequency part of the imaginary impedance spectrum. Subtracting the CPE term allowed estimation of the imaginary impedance maximum and its evolution during the cure. The dielectric fractional conversion can be calculated by normalising the imaginary impedance maximum value of the spectrum after subtraction of the CPE term. Figure 2b illustrates the degree of cure evolution during curing stage as calculated from impedance signals and compares it to that obtained using a cure kinetics model for the resin system of this study based of differential scanning calorimetry [9] and the thermal profile followed by the material during the experiment. The results highlight the capability of the cure sensor in monitoring the cure in the presence of carbon reinforcement.



a) b)

Figure 2 a) Validation of lineal sensor response against visual monitoring data b) Validation of cure sensor against non-parametric cure kinetics results [9].

Acknowledgments

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