

NOVEL DIELECTRIC SENSOR SETUP FOR FLOW AND CURE MONITORING IN RESIN TRANSFER MOULDING

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SUMMARY: The development, analysis and experimental validation of a novel dielectric flow and cure sensor for the resin-transfer-moulding of composites are presented. A linear relationship is established between the flow front position and electrical admittance measurements, allowing accurate flow front location. The sensor performance as an indicator of flow front position is evaluated using visual verification of the flow front position. Its efficiency for monitoring of the curing stage is assessed by comparison of the measurements with conventional microdielectrometry data. Experimental results demonstrate that the sensor can locate the flow front accurately. The measurement output is in the form of a complex number; this appears to offer a potential for a qualitative self-assessment. The monitoring of the cure process shows performance similar to that of the established microdielectrometric techniques.

KEYWORDS: dielectric, cure , monitoring, flow, RTM, sensors, impedance

INTRODUCTION

Resin transfer moulding (RTM) is a production method widely considered as the most likely dominant fibre reinforced thermoset composites manufacturing route for the future. The process is performed in three stages. Initially a dry fabric is placed in the rigid mould cavity. Then, forced impregnation by liquid resin occurs. Finally the mould is heated up and the composite cures. Although many problems of the conventional laying-up/autoclaving process connected to prepreg preparation and green composite handling are eliminated, other important matters arise in the RTM process. The impregnation stage becomes critical and is subjected to a far more inflexible design, while the necessity to decouple the infiltration from the curing stage leads to the need for specialised materials and thermal cycles.

In recent years RTM has been extensively studied. Flow models based on Darcy's law have been developed [1-3] and the mechanisms of resin impregnation have been analyzed [4,5] in order to predict filling behaviour. These analyses have given the ability to estimate filling time, evaluate the risk of dry spot formation and examine the effect of various process parameters on them. Cure kinetics [6] and heat transfer phenomena [7,8] have been investigated and modelled, aiming to predict the component behaviour during the cure. Modelling has been utilised combined either with inversion techniques as a design optimisation tool [9] or with measurements as a process control tool [10].

Monitoring complements this general framework of work on RTM. Cure monitoring techniques developed in previous composites manufacturing studies have been adapted for monitoring in RTM

[11,12]. The monitoring of the filling stage has so far focused on visual measurement of the flow front position used in permeability estimation [13-15], subsequently used for flow models input data. Experimental configurations used in these studies involve partially transparent tooling. Therefore they cannot be extended to production or pilot scale moulding. Some studies have been carried out on the implementation of automatic non-visual flow monitoring. Dielectric or electric multiple sensing, comprising usually a grid of sensors, has been used to spot the instant of wetting at a specific location [16-18]. Mathur et al [19] have investigated the application of a flow sensor based on evanescent wave fluorescence, able to locate continuously the flow front.

The present paper describes the development and application of a novel dielectric sensor with a dual monitoring role. During the filling it follows continuously the flow front position and during the cure it monitors macroscopically the progress of the reaction.

DESCRIPTION AND PRINCIPLE OF OPERATION

The geometry of the sensor is given in figure 1. It consists of two parallel flat copper electrodes embedded between two layers of a polymeric film. A very thin layer of adhesive exists between the electrodes and the film and between the two layers of the polymeric film. Some air is trapped in the area between the two electrodes. The bottom of the sensor is guarded so there is no electric field outside its lower side. The electric field is allowed to penetrate the area on top of the sensor where the measurement is performed. This area is divided into the ‘covered by resin’ area and the ‘resin free’ area.

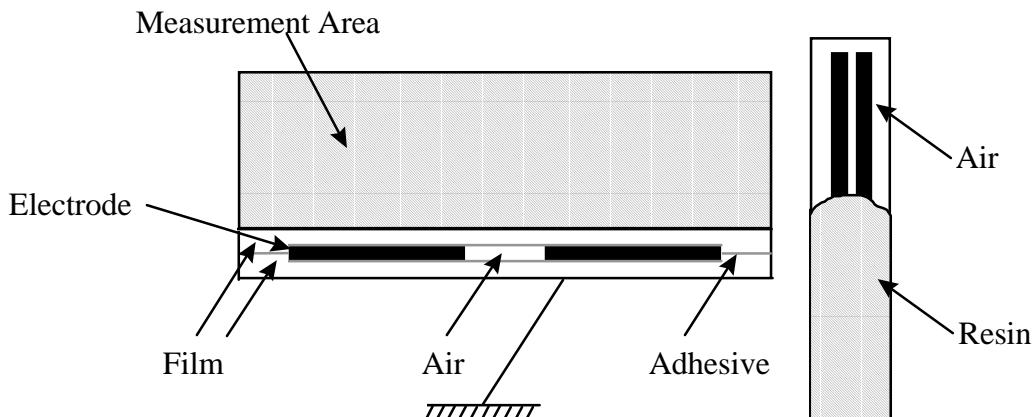


Fig. 1: Geometry of the sensor

The principle of operation of the sensor is illustrated in figure 2. The sensor is aligned parallel to the expected direction of the flow front. The impregnated area of the fabric corresponds to the area of the sensor covered by the resin. As the impregnation progresses the wetted area percentage increases and the dry area percentage decreases. The electrical properties of the liquid resin differ sharply from those of the air. Therefore, monitoring the evolution of the sensor’s dielectric response provides quantitative information about the mould filling process. When the filling is

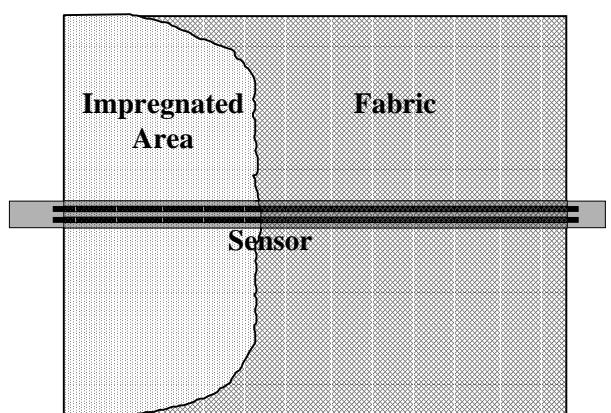


Fig. 2: Principle of operation

completed the sensor performs non-localised dielectric cure monitoring.

ANALYSIS OF THE SENSOR ELECTRIC RESPONSE

Analysis of the electric response can be performed using an electric circuit equivalent to the sensor. Each of the previously described components of the sensor contributes an impedance element to the circuit.

The sensor can be considered as a parallel circuit of the resin-covered and the uncovered regions. Each of these two regions can be analysed further into a series circuit of the support and the corresponding measurement area. According to these the circuit representing the electrical behaviour is as shown in Figure 3.

Solution of the circuit presented leads to the following expression for the sensor admittance:

$$Y_{\text{sensor}} = l_w \left(\frac{z_d - z_w}{z_s^2 + z_s z_d + z_s z_w + z_w z_d} \right) + \left(\frac{l z_s + l z_w}{z_s^2 + z_s z_d + z_s z_w + z_w z_d} \right) \quad (1)$$

where l_w is the ‘covered by resin’ length of the sensor, l is the total sensor length and z_d , z_w , z_s are the impedance values per unit length, of the dry part, of the wetted part and of the support respectively.

It can be observed that according to equation (1), admittance is a linear function of the covered sensor length.

In order to calculate explicitly the position of the flow front from admittance data, it is necessary to know the impedance per unit length for the specific configuration of all the components involved. This task appears to be very difficult especially when the effect of the fabric is considered. Therefore an easy calibration procedure is proposed here : - The two terms in brackets of the linear equation (1) are constant, if the impedance of the materials involved does not change during the filling. The intercept corresponds to the admittance of the dry sensor Y_{dry} . In order to calculate the slope, a measurement of the admittance at some point is required. Moreover, it is observed that the slope is not dependent on the sensor length, so its value is constant for sensors of different lengths in the same moulding. Thus equation (1) becomes:

$$l_w = \frac{Y_{\text{sensor}} - Y_{\text{dry}}}{Y_{\text{cov}} - Y_{\text{dry}}} l_t \quad (2)$$

where Y_{cov} is the admittance of a fully covered sensor of length l_t .

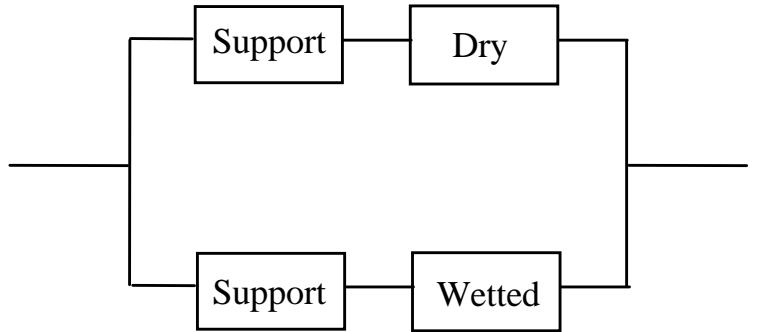


Fig. 3: General equivalent circuit

EXPERIMENTAL DETAILS

Individual sensors were fabricated by embedding two flat copper wires between two layers of a polymeric film. A single electrode width was 1.5 mm and the interelectrode distance was 0.5 mm. The sensor performance was validated during the filling of a glass cavity with silicon oil (Dow Corning 2000) and during the filling and curing of an RTM6/glass NCF reinforced composite in a partially transparent RTM tool.

In the first case the total sensor length was 27.8 cm and the cavity thickness was 8 mm. The filling was performed at ambient temperature. In the second case the sensor length was 73 cm and the mould thickness 3.3 mm. The filling temperature was 100 °C. Admittance data were gathered over a range of frequencies using a Solartron 1260 impedance phase analyser. Visual measurement of the flow front position was carried out simultaneously in both cases. After completion of the filling step the mould temperature was increased to 160 °C to cure the resin. In order to validate the cure monitoring performance of the sensor, the curing of unreinforced RTM6 resin, subjected to an equivalent thermal programme, was monitored using more conventional, embedded, GIA microelectrodes.

RESULTS AND DISCUSSION

Flow monitoring

Equation (2) has been used to calculate the flow front position from the admittance data. It can be observed from equation (2) that the length is a ratio of two complex numbers. In the ideal case these values would be in phase and consequently, the length would be a real number. However, measurement inaccuracies and occurrence of phenomena which alter the impedance of the materials involved, can cause some phase difference resulting in the existence of an imaginary component of the calculated length.

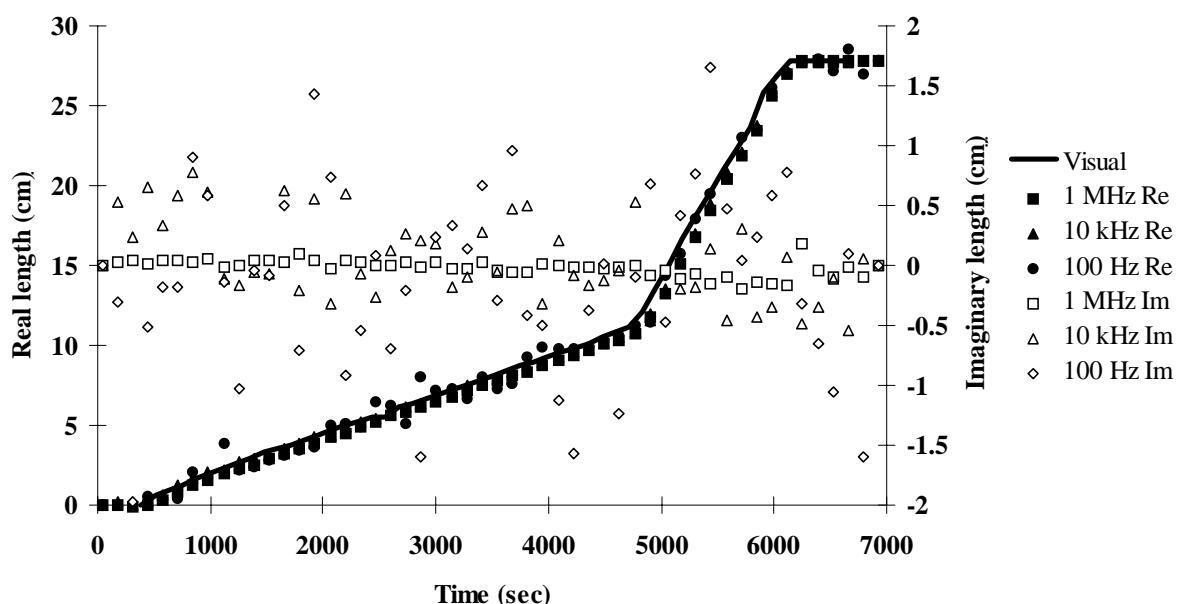


Fig. 4: Silicon oil filling of a glass cavity

The real and the imaginary parts of wetted length, combined with the visual flow front position measurements results, are given for both runs in Figures 4 and 5. It can be observed

that the imaginary part is less than one tenth of the value of the real part. The real length component follows the visual flow front position measurement. The accuracy of the flow front

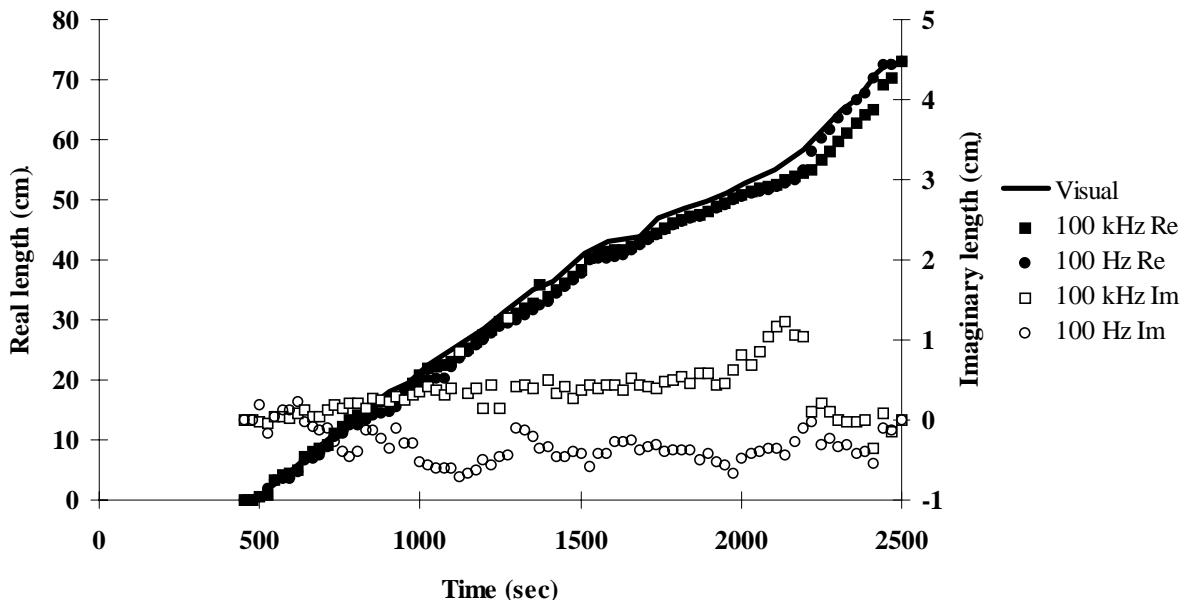


Fig. 5: Filling with RTM6 resin in the RTM tool

position location by impedance measurement increases as the imaginary part decreases. Thus in the silicon oil experiment the flow measurement is best performed at 1 MHz where the imaginary part has its lower values. In the RTM filling the measurement at 100 Hz performs better since its imaginary component values are closer to zero.

Cure Monitoring

The data of impedance amplitude gathered by the flow sensor are given in Figure 6. As observed during the filling stage (500-2500 sec) the impedance decreases due to progressive wetting of the sensor. During the heating up of the mould (3500-5500 sec) the progressing resin reaction seems to counteract the effect of the increase of temperature; the impedance initially remains constant and then increases. The vitrification of the resin is indicated at about 6500 seconds.

Results from microdielectrometry are given in Figure 7. Comparing the time-temperature curves in Figures 6 and 7 it can be seen that the microdielectrometry data correspond to the part of Figure 6 after the completion of the isothermal segment at 100 °C. It is observed that the impedance development measured by the commercial GIA sensors is qualitatively equivalent to that measured by the new flow sensor.

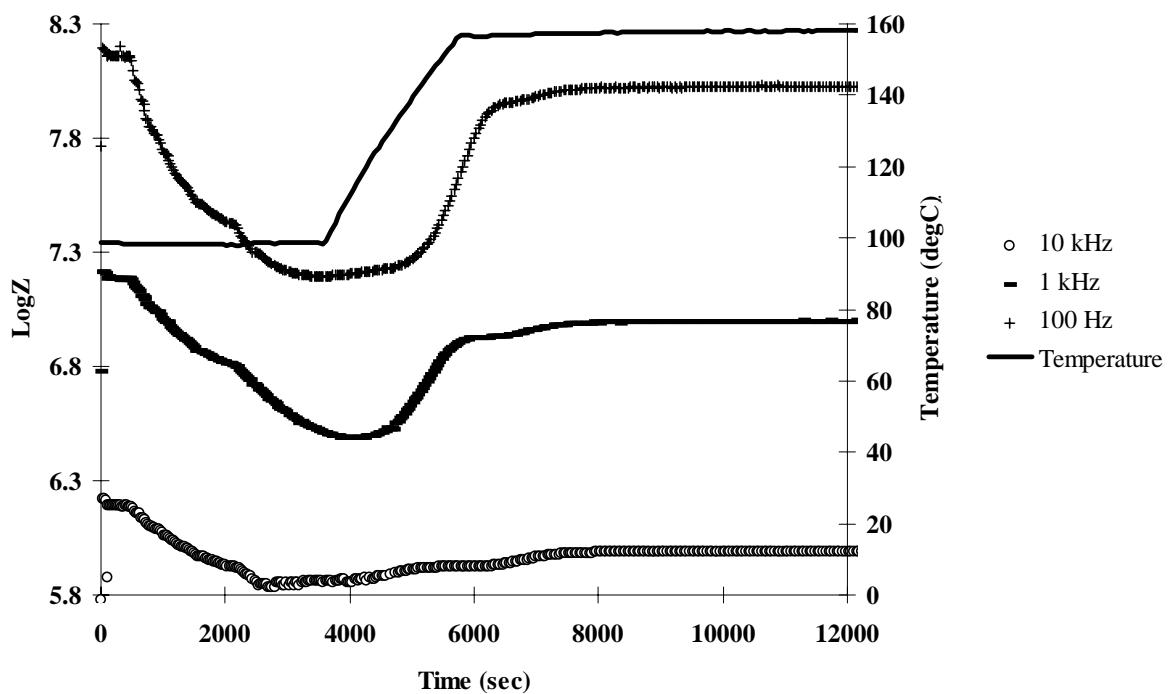


Fig. 6: Impedance amplitude measured by the flow sensor

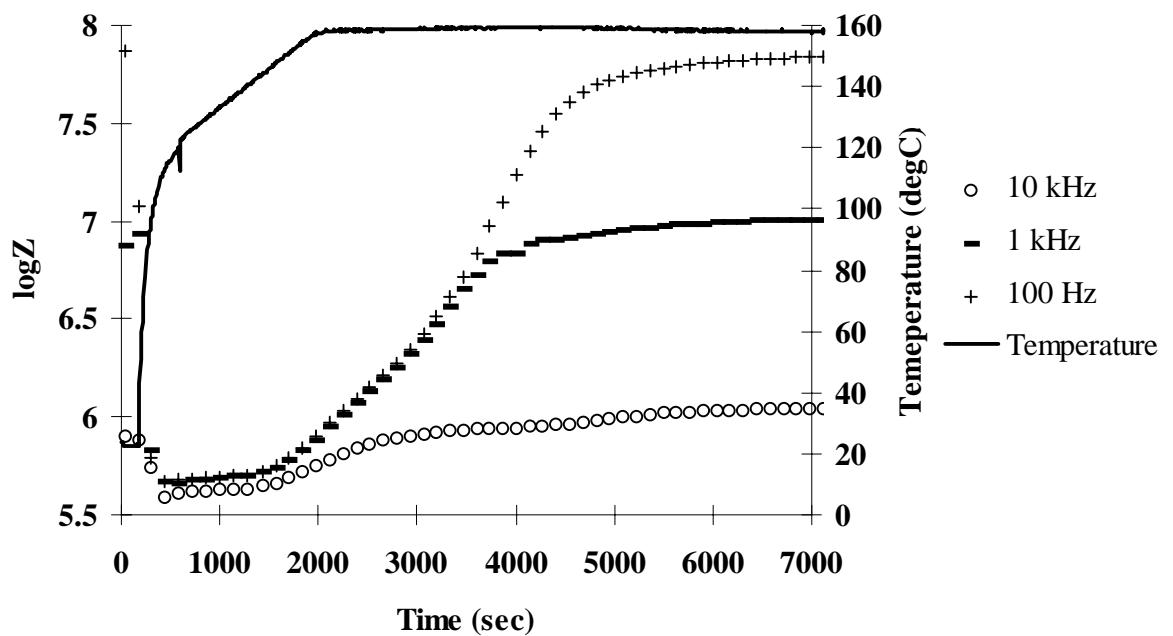


Fig. 7: Impedance amplitude measured by GIA microsensor

CONCLUSIONS

Circuit analysis demonstrated the possibility of monitoring the filling stage of the RTM process through the existence of a linear dependence of the admittance signal, measured by the presented sensor setup, on the flow front position. Experiments confirmed that the flow front position could be located with satisfactory accuracy. In addition, the determination of an imaginary component of the flow front position can be utilized for an assessment of the measurement performance.

The sensor setup also presented the ability to monitor the cure of the resin after the end of the filling stage. Results from this ‘macrodielectric’ cure monitoring performed by the sensor were in fair agreement with results from more conventional microdielectrometry experiments.

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