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Smart tooling with integrated time domain reflectometry sensing line for non-invasive flow and cure monitoring during composites manufacturing

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ABSTRACT

An electrical transmission line integrated into composite tooling has been developed to facilitate non-contact multipoint flow and cure monitoring during vacuum assisted resin transfer molding processing. The sensor is made of conductive aramid (Kevlar®) fibers and is an integral part of the glass fiber composite tooling. Electrostatic simulations in COMSOL® have been performed to optimize the wire spacing maximizing the sensitivity of the electric time domain reflectometry measurements. Tooling with integrated wires placed with optimal spacing has been fabricated. TDR flow monitoring experiments with the integrated sensor have been conducted and compared visually using digital image processing. TDR data obtained from the same sensor also enables measurement of the resin cure state. Fast and slow curing resin systems have been studied using the transmission line integrated tooling and differential scanning calorimetry experiments have been performed to validate the cure measurements obtained from TDR. Major benefits of the sensor implementation include elimination of ingress/egress issues associated with standard sensor integration into composite tooling as well as reduced maintenance of the non-contact solution.

1. Introduction

Liquid composite molding (LCM) refers to composites manufacturing processes which involve infusing dry preforms with resin. LCM is a popular manufacturing process to fabricate thermoset composites [1]. Vacuum assisted resin transfer molding (VARTM) is a LCM process variation and is often used to produce low cost, high fiber volume fraction, large-scale composite applications. Optimal resin flow is crucial to manufacture high quality composite parts during resin injection in LCM processes [2,3]. Hence, sensing of flow is important for an online flow control to ensure high quality composite parts without voids. In addition, sensing of the cure state is necessary to ensure full cure of the composite part prior to demolding or debagging.

Some of the reported flow front and cure monitoring sensor systems reported for LCM are: SMARTweave grid sensors [4,5], DC based linear sensors [6,7], dielectric [8], ultrasonic [9], fiber optic [10] and thermocouple based [11]. SMARTweave grid sensors consist of line sensors arranged to form a two dimensional grid which needs to be embedded inside the preform. Multiplexing and measuring voltages through the embedded grid enables the sensing of flow and cure [4,5]. Although SMARTweave sensors enable two dimensional tracking of the flow front, they result in the structural defect in the final part as they require the sensing grid to be embedded in the fiber preform permanently. Also, the sensing grid can change the resin flow pattern by altering the local fabric permeability. DC based linear and dielectric sensors reported in [6–8] suffer from the disadvantage that they need to be calibrated for each resin system and manufacturing setup. To avoid repeated calibration, multiple point sensors can be used but an increase in the number of sensors results in complexity in instrumentation requirements. Ultrasonic and fiber optic sensors [9,10] have the disadvantage of high cost and complexity. Thermocouples are prone to high noise due to environmental temperature changes. Various problems associated with using thermocouples for monitoring of LCM processes are discussed in reference [11].

Electric time domain reflectometry (TDR) refers to a process of sending a high frequency voltage pulse through a transmission line [12,13]. Electrical discontinuities along the transmission line result in reflections and the time difference between the incident and reflected waveforms is used to calculate the position of the discontinuity. During resin flow through a preform, the flow front acts as an electrical discontinuity and hence the reflection from the flow front can be analyzed to calculate the location of the resin. A time

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domain reflectometry based flow sensing has been reported in [14,15]. Using the TDR technique, multi point sensing can be implemented using only a single transmission line and the procedure is suitable for monitoring flow fronts during the fabrication of large composite parts. In addition, the dielectric constant changes as the resin cures resulting in a change in electrical impedance change of the system. Time domain reflectometry can be used to monitor this impedance change and hence can be used to estimate the cure state of the resin. One of the challenges of the TDR sensor implementation is the need to embed the transmission line sensor into the composite part [1]. An embedded TDR sensor provides maximum sensitivity as the resin is in direct contact to the sensor and within the electro-magnetic field. This paper investigates a non-contact sensor implementation where the sensor line is embedded into the tooling and half of the electro-magnetic field above the tool surface interacts with the resin flow and cure. The tool-mounted sensor results in enough sensitivity to measure accurately the flow position and the state of resin cure while providing a non-contact sensor system. This feature provides a permanent integrated solution in the tooling and reduces any maintenance typically associated with tool-mounted sensors.

2. Time domain reflectometry and its application in flow and cure sensing

The basic principle of TDR is illustrated in Fig. 1. A high frequency voltage pulse in the GHz range is generated in the TDR module and travels along a transmission line (a pair of conductors) located in the vicinity of the fabric preform under investigation. Any impedance discontinuities along the transmission line results in a reflection of the TDR input signal. An accurate timing device inside the TDR receiver module acquires the reflected time domain signal. The trace is transferred to a supervisory computer for post-processing and calculation of the resin flow and cure behavior.

The resin flow front changes the local capacitance and hence the impedance of the transmission line resulting in a reflection of the TDR input from the flow front. Signal processing software computes the difference between the baseline signal (no resin in preform) and current TDR trace and a threshold algorithm is applied. The delay time to the reflection can be calculated which determines the location of the resin flow, and the voltage difference between the unfilled preform and filled preform (ΔV) determines the sensitivity of the TDR system. The sensitivity can be maximized by optimal design of the transmission line taking fiber and resin properties into account. The optimization procedure is described in Section 3. In order to track the flow front position, the TDR time scale needs to be converted to spatial scale. Let Δt_{FF} and Δx_{FF} denote the location of the flow front on TDR time scale and the actual, spatial location of the flow front, relative to the connector between the coaxial cable and the transmission line. Assuming a constant velocity of electromagnetic wave propagation in the resin free region, the relationship between Δt_{FF} and Δx_{FF} is given by:

$$\Delta x_{FF} = v\Delta t_{FF} \tag{1}$$

$$V = \frac{1}{\sqrt{LC}} \tag{2}$$

In Eq. (2), L and C are the distributed impedance and capacitances of the transmission line. The speed of propagation can be determined by creating a discontinuity at a known distance from the connector end and recording the TDR time corresponding to that discontinuity. Dividing the known distance of the discontinuity with twice the time of flight of the reflected wave (obtained from TDR data), the speed of propagation can be obtained (assuming a uniform impedance and capacitance distribution over the transmission line). In addition to precise flow monitoring, the TDR trace can also be used to determine the degree of cure of composite. Even though traditionally, dielectric properties of polymers are monitored at low frequencies, techniques for measurement of dielectric properties over higher frequencies have been reviewed in [16]. Additionally, [17] report the dielectric cure monitoring of epoxy resins over a wide frequency range (from 1 kHz to 10 MHz) and Hager and Domszy [18] have used broadband dielectric spectroscopy using the TDR technique to monitor the cure behavior of cement. The TDR output is related to the effective impedance of the transmission line, which depends on the dielectric constant of resin. Previous research [19,20] has shown that the dielectric changes in the resin can be used as an estimate of cure state. The characteristic impedance of a transmission line is defined by Eq. (3). R, L, G and C are the distributed resistance, impedance, conductance and capacitance of the transmission line and w is the frequency of the electromagnetic wave. Impedance Z depends on both the material properties and geometrical properties of the transmission line. For example, for a lossless transmission line ($R = 0$ and $G = 0$), impedance is given by Eq. (4). In Eq. (4), K is a constant which depends on the geometry of the transmission line. Neglecting the resistance of the transmission lines ($R = 0$) and the conductance of the resin ($G = 0$), the transmission lines in the present setup can be considered lossless and hence Eq. (4)

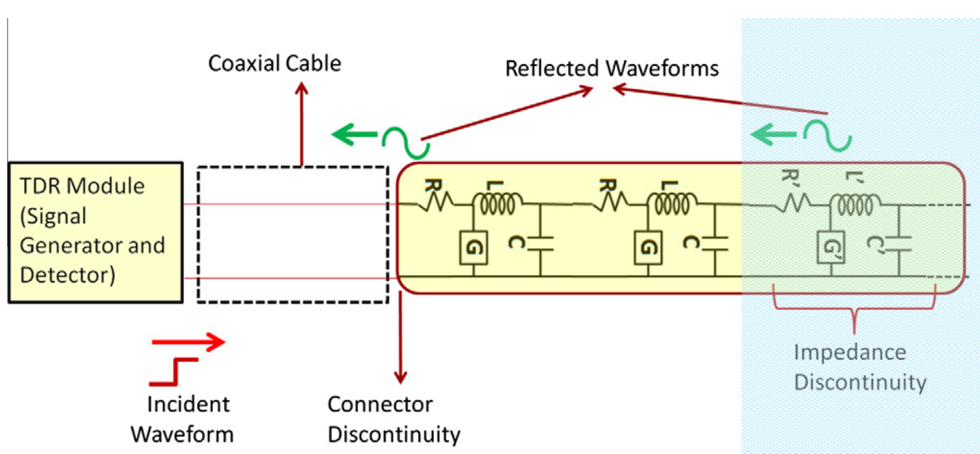

Fig. 1. Principle of flow front measurement using TDR. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)