Composites Part B 94 (2016) 389–398

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Investigation of Electrical Time Domain Reflectometry for infusion and cure monitoring in combination with electrically conductive fibers and tooling materials

Christopher Buchmann [a, *], Jürgen Filsinger [b], Elisabeth Ladstätter [c]

[a] Airbus APWorks GmbH, Willy-Messerschmitt-Str. 1, 82024 Taufkirchen, Germany
[b] Airbus Group Innovations, Composites Technologies, 81366 Munich, Germany
[c] Institute for Carbon Composites, Technische Universität München, 85748 Garching, Germany

ARTICLE INFO

Article history:
Received 14 August 2015
Received in revised form
14 January 2016
Accepted 24 February 2016
Available online 3 March 2016

Keywords:
D. Process monitoring
E. Resin transfer moulding (RTM)
E. Resin flow
E. Cure

ABSTRACT

The presented work investigates Differential Electrical Time Domain Reflectometry (D-TDR) as a method to monitor the flow front position and curing degree of resin during manufacturing of composite structures by vacuum infusion technology. The sensor concept is based on the physical principle that a voltage pulse introduced into a transmission line, which serves as a sensor, is reflected at impedance changes, which correlate to changes of the dielectric properties along the line. The method's accuracy under different boundary conditions is investigated by infiltrating glass and carbon fiber preforms on metallic and wooden toolings with epoxy resins. A shielded sensor concept is presented, which eliminates the influence of conductive materials on the signal. For all tested fiber/tooling combinations, the monitoring method shows a good agreement between the flow front position and optically determined flow fronts. Degree of cure measurements at ambient and elevated temperatures show a correlation with Differential Scanning Calorimetry (DSC) and rheology analyses.

1. Introduction

A robust infusion process is vital to the quality of composite parts. Therefore, monitoring of resin flow and cure development in liquid composite molding processes was the subject of extensive research in the past. A variety of sensor concepts based on thermocouples [1], pressure transducers [2], optical fibers [3–6], and electric resistance sensors [7–9] was investigated. An interesting concept is the Electrical Time Domain Reflectometry (E-TDR), which uses changes of dielectric properties. The suitability of dielectric measurements for process monitoring was widely discussed in literature [10–12]. E-TDR was successfully applied to monitor flow fronts as well as the degree of cure [13,14]. The main advantage of the E-TDR technology is the possibility of distributed measurements along the sensor line [15].

The presented work investigates into the applicability of Differential Electrical Time Domain Reflectometry (D-TDR) for flow front and degree of cure monitoring in combination with electrically conductive fiber and tooling materials. These were mentioned to be harmful for precise measurements [15]. However, an in-depth analysis of their effect on the signal quality was not yet given. A not yet investigated field is also the cure at elevated temperatures above 100 °C. As a sensor, a Flexible Flat Cable (FFC) and a sensor with an innovative shielded geometry are analyzed. For the experiments a commercially available, differential TDR reflectometer is used. In combination with a notebook the system is extremely mobile. It requires no additional power supply. Another advantage lies in the possibility of using the sensor system only temporarily (e.g. during the introduction of a new process) and for different parts/toolings.

In preliminary tests the influence of the tooling and fiber material and the sensor position is analyzed. Therefore, samples of reduced size are infiltrated. As tooling materials aluminum and wood and as fiber materials glass fibers and carbon fibers are investigated. For the different fiber/tooling combinations, infusion tests are executed and the detectability of the flow front is compared. The cure of different epoxy resins at ambient and elevated temperatures is investigated for different fiber/tooling combinations as well as for the different sensor geometries. The results are validated by comparison to DSC measurements.

* Corresponding author. Tel.: +49 89 607 29289.
E-mail address: christopher.buchmann@apworks.de (C. Buchmann).

http://dx.doi.org/10.1016/j.compositesb.2016.02.060
1359-8368/

2. Electrical Time Domain Reflectometry – theoretical background

Time Domain Reflectometry (TDR) is based on the physical principle that waves are partially or completely reflected when hitting the interface to a medium with different physical properties. For example, light is reflected at a water surface due to a change of the refractive index [16]. In the field of E-TDR, this wave is a high rise time voltage pulse which is sent into a transmission line. It is reflected at impedance changes along the line. The main application of the technology is the detection of defects in underground or otherwise inaccessible cables. Other applications include moisture detection in soils [17–19] and concrete [20,21] as well as the monitoring of geological phenomena such as landslides [22,23].

In Fig. 1 the setup for single ended E-TDR measurements is schematically displayed. Therein, V_m is the voltage detected by the oscilloscope and V_i the inducted voltage. Fig. 1 also demonstrates the main advantage of E-TDR, which is the detection of distributed flow fronts.

The reflectometer used for the experiments combines a pulse generator and an oscilloscope. It is connected to a PC where the signal is analyzed. The oscilloscope records the voltage at the traces, V_m, as a function of the time of flight. V_m is the sum of the reflected and incident voltage $V_m = V_r + V_i$. According to eq. (1), the ratio of V_r to the incident voltage V_i, ρ, can be expressed as a function of the base impedance Z_0 of the reflectometer (typically 50Ω) and the load impedance Z_L of the connected object such as a transmission line.

$$\rho = \frac{V_r}{V_i} = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{1}$$

At the open end of a transmission line, the signal is completely reflected. In this case ρ takes the maximum value of 1. In the measured profile an open end leads to a steep increase as seen in Fig. 1. The signal, which the device sends to the PC, is a normalized form of ρ, the so called reflection factor U (eq. (2)). The value of U is recorded as a function of the time of flight, measured in pico seconds. For a precise measurement a significant change of U with changing dielectric properties, e.g. between dry and wet state, is desired.

$$U = (\rho + 1)\cdot 100 = \frac{V_m}{V_i}\cdot 100 \tag{2}$$

The load impedance Z_L is a function of the dielectric properties around the transmission line according to equation (3).

$$Z_L = \sqrt{\frac{L_L}{C_L}} = \frac{1}{\pi}\sqrt{\frac{\mu_0\ \mu_r}{\epsilon_0\ \epsilon'}}\cosh^{-1}(\kappa) \tag{3}$$

Therein, μ_0 is the magnetic permeability vacuum, μ_r the relative magnetic permeability, and ϵ_0 the vacuum permittivity. For a transmission line with two parallel conductors with a rectangular cross section, κ equals the ratio of the pitch p to the width w of the traces. For round conductors the diameter d replaces the width w. Assuming that the relative permeability μ_r and thus the inductance L_L is constant along the transmission line, the equation reduces to a function of the dielectric permittivity ϵ'. The traveling speed of the pulse v_t can be expressed as a function of the speed of light c and the dielectric constant ϵ' according to eq. (4). Using eq. (4), the distance of any point along the profile to the sensor connector can be calculated.

$$v_t = \frac{c}{\sqrt{\epsilon'}} \tag{4}$$

Differential Time Domain Reflectometry (D-TDR), which is discussed in this paper, is a further development of the E-TDR technology. It is used to determine the impedance characteristics of coupled transmission lines, so called differential pairs. It has not yet been investigated as a means to monitor flow fronts and degree of cure in composite manufacturing. A characteristic impedance matrix is obtained by applying a simultaneous signal to both lines. The two modes of signals with the same or opposite polarity are defined as the even and odd mode [24].

In Fig. 2 differential and single ended E-TDR are graphically compared. For a detailed explanation of the technology, the reader is referred to the literature [24,25].

For a symmetrical transmission line the differential impedance Z_{dif} can be calculated according to eq. (5).

$$Z_{dif} = 2\cdot Z_{se}\cdot(1 - k) \tag{5}$$

Therein, Z_{se} is the single ended impedance and k a coupling term. The linear relation between single ended and differential impedance allows the use of similar algorithms as presented in literature [13].

The main advantage of the differential method is the reduced sensitivity of the differential impedance to discontinuities in the return path [24]. This increases the robustness of the measurement and is especially desirable for an industrial environment. A disadvantage is the more complex hardware as two pulse generators with as little as possible skew between the signals are required for precise measurements [24]. However, the use of D-TDR reflectometers, which incorporate the required functionalities, keeps the cost of the hardware at a reasonable level.

3. Experimental

3.1. Materials

The preforms are built out of non crimp fabrics (NCF) with a 0°/90°-orientation. The carbon fiber fabric exhibits an areal weight of

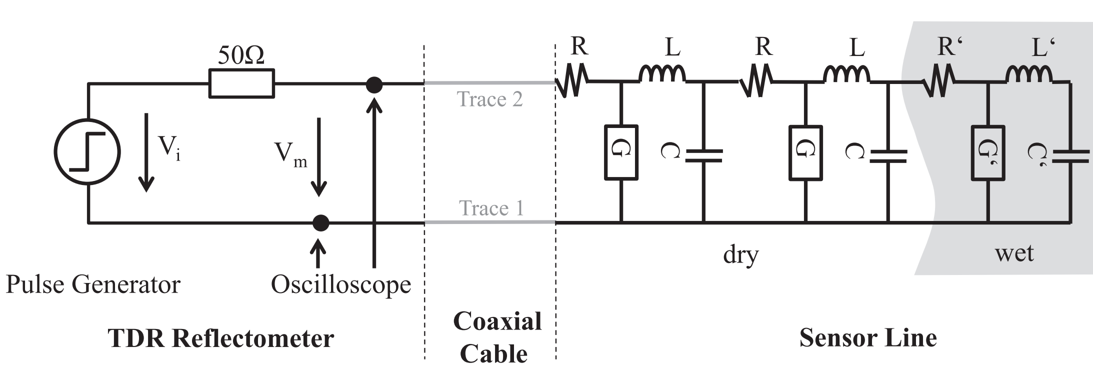

Fig. 1. Schematic E-TDR buildup.