UNIVERSITY OF DELAWARE
CENTER FOR COMPOSITE MATERIALS
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Time-Domain Reflectometry
Novel Sensors for Process Sensing and Control

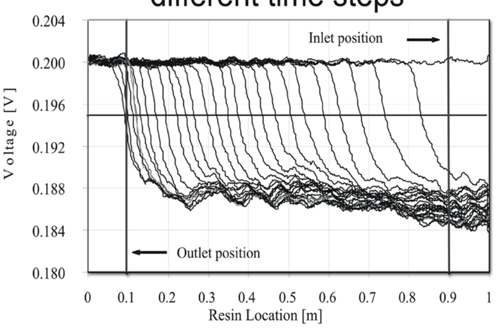
UD-CCM has developed Time Domain Reflectometry (TDR) methods and sensors that allow high resolution distributed sensing along the entire sensor with a single ingress/egress location. TDR is a method of sending a pico-second rise-time voltage step in a Transmission Line (TL) and detecting the voltage reflections resulting from the impedance discontinuities surrounding the TL. This principle has been applied in composite liquid molding processing to measure distributed processing variables, such as the degree of cure and resin flow location with high accuracy.

Benefits of the TDR System

- Distributed resin flow measurement with an accuracy of up to 3mm on a 5m sensor setup has been proven
- Degree of cure measurements comparable to FTIR and DSC
- Fully integrated into composite tooling
- Low-cost hardware and software implementation

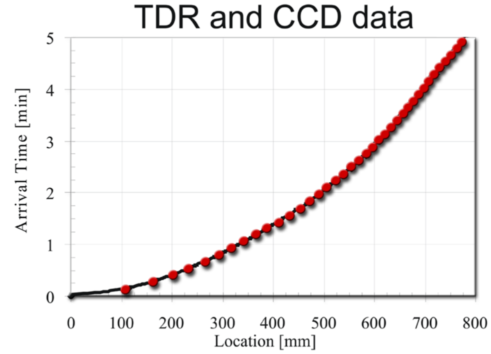
State-of-the-art sensors to monitor the composite manufacturing process are typical point-sensors integrated into the mold or reinforcement and are not capable to accurately measure the spatial distribution of the resin flow or quantitatively measure the degree of cure. Thus, these sensors can not be used for comprehensive quality assurance and quality control (QA/QC). The novel TDR sensor can be integrated into the tool or via conductive fibers into the reinforcement. Distributed flow measurement eliminates the need for multiple point sensors, and accurate quantitative cure sensing comparable to FTIR and DSC methods allows its use for process control.

TDR Raw Data at different time steps



Data Conversion

Comparison of TDR and CCD data



Resin Flow Detection

The TDR approach has been experimentally validated to precisely detect the resin flow front location during the vacuum infusion process (VIP). A TDR sensor was placed on top of a glass fiber preform and a CCD camera recorded the resin flow directly on the sensor. The resin flow results in a dielectric change of the preform surrounding the sensor which is measured by the TDR equipment. The TDR time-domain data is converted online to measure the flow front progression. An accuracy of 3 mm using the TDR approach has been validated and is practically independent of the resin system used. The TDR system has also been used to detect through-thickness flow during thick-section composite processing, flow detection during elevated temperature infusion, as well as multiple flow front detection on a single line sensor. Current research is focused to advance the sensing system to conductive tooling and fiber materials.

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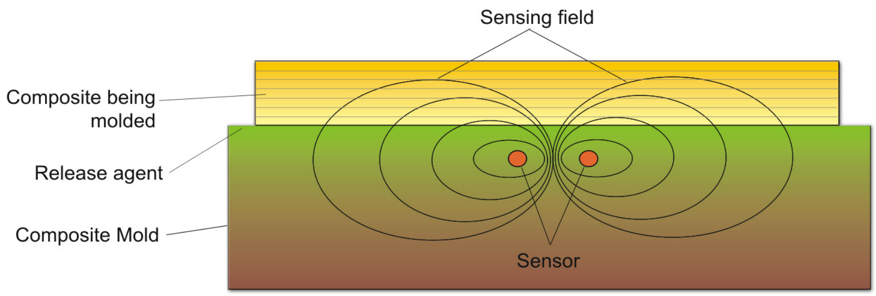
Cure Measurement and Profiling



TDR is a very accurate method to detect dielectric changes inherent in the cure process. TDR captures the intrinsic dynamic properties of the molecular dipoles because of the wide bandwidth of the interrogating electric pulse. The measurements compare very well with DSC and FTIR data and have been validated for various resin systems. For high accuracy measurements the time domain signals are converted to the frequency domain and material parameters such as the frequency dependent permittivity and loss factor can be measured up to the GHz range. The system can be calibrated to be temperature independent to maintain the accurate measurement even during the exothermic reaction.

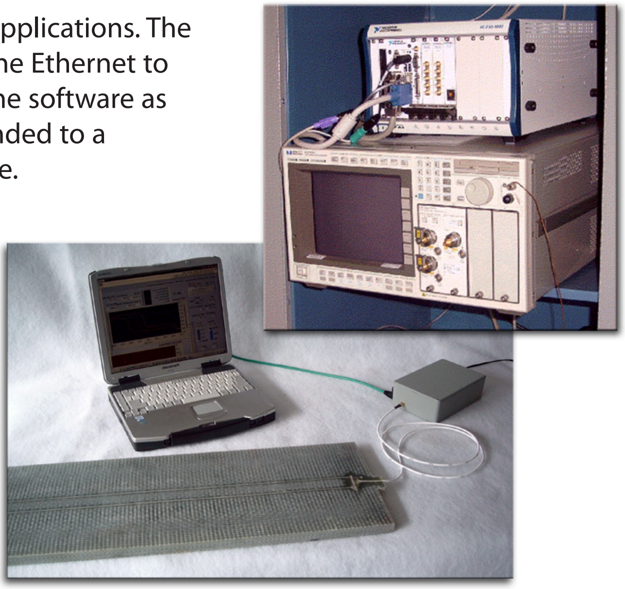
Sensor Configuration

Various sensor configurations have been implemented. For composite molds, the TDR sensor can be integrated via two conductive parallel wires (copper or conductive fibers) in the top-surface ply below the tooling gel coat. The sensing field extends through the tooling surface, release agent and gel coat application into the reinforcement. The sensor is permanently integrated into the tool and does not affect cleaning or maintenance procedures. Similar sensor configurations can be used in a reusable bagging approach. However, the sensor can also be directly integrated into the reinforcement to measure localized flow and cure.

Hardware and Software Implementation

Two TDR measurement systems have been developed. First, a high-resolution system based on a HP54750 TDR unit is capable of operating in the 20GHz range. This allows mm-resolution for distributed flow sensing. The TDR system is connected to a supervisory PC running the data analysis software.

A low cost and robust system has been developed for industrial applications. The TDR hardware is integrated into a single box and connected via the Ethernet to the host computer. The system has cm-accuracy and runs the same software as the high-resolution system. Both hardware methods can be extended to a multi-channel system making sensing of multiple sensors possible.



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