

TDR-LINE SENSORS FOR MULTIFUNCTIONAL PROCESS SENSING

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RELEVANCE

Sensors are needed for processing QA/QC and for health monitoring:

- Flow front detection,
- Cure behavior,
- Defect detection,
- Process strain,
- Service related strain.

In the last decade various research projects have been conducted to develop flow, cure and strain monitoring sensor systems.

ADVANTAGES OF TDR SENSORS

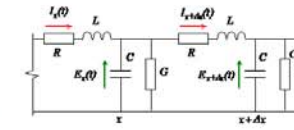
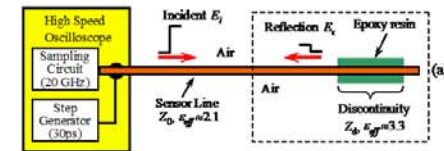
Time Domain Reflectometry (TDR) sensors have the following *advantages* over other sensor types (DC resistance, AC Dielectric, optic fiber, ultrasonic, etc.):

- Low cost,
- Tool-mounted and embedded configurations,
- High accuracy (3mm),
- **Multifunctional sensing**,
 - Resin flow behavior,
 - Cure,
 - In-service strain response,
- Distributed 2D sensing.

TDR sensors completely fulfill the requirements for next-generation sensors!

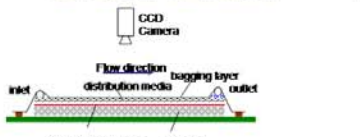
TDR APPROACH

Time domain reflectometry (TDR) is a method of sending high-rise (35ps) voltage step-pulse into a transmission line (TL), and detecting reflections returning from impedance discontinuities within the TL.

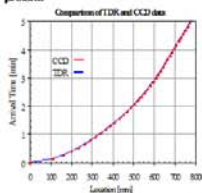


Schematic of the TDR technique (a) and equivalent circuit diagram of the TL (b).

1D FLOW SENSING

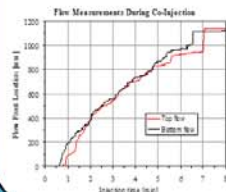


- The accuracy is ± 3 mm.
- Resolution is 2 mm.
- Measurement range of up to 5 m has been proven, but practical limits are much higher.



APPLICATION FOR CO-INJECTION RTM

Flow and cure control in multiple layers of multifunctional composites is essential for process control and QA/QC.



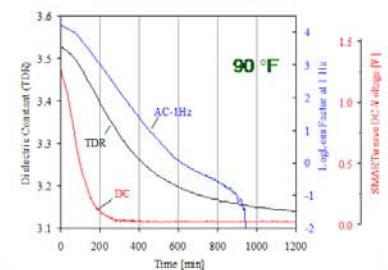
- Such measurements may be used for assessment of barrier layer for leaks.

TDR APPROACH FOR CURE PREDICTION

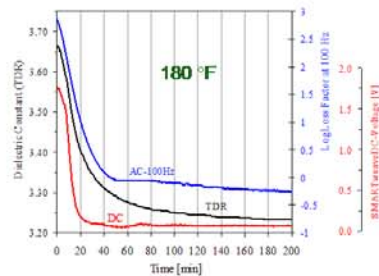


At microwave frequencies, it is possible to capture intrinsic molecular dynamics that change significantly during chemical reaction.

TDR VS LOW FREQUENCY DIELECTRIC AND DC APPROACHES I

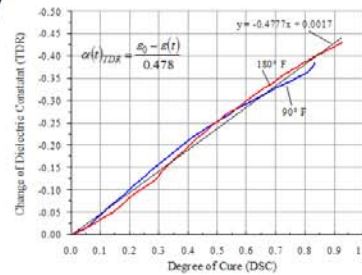


TDR VS LOW FREQUENCY DIELECTRIC AND DC APPROACHES II



- TDR approach is extremely sensitive to curing.
- TDR allows for quantitative cure measurements.
- DC sensors work up to gel point **only**.
- AC sensors respond much longer compared to DC sensor but it can not sense final cure behavior.

CORRELATION



Correlation of the TDR sensor data (90° F and 180° F) VS DSC data.

- TDR approach is extremely sensitive to curing.
- Allows quantitative cure measurements.
- TDR sensor shows good correlation for epoxy-amine based resin systems.
- Microwave dielectric constant is directly related with epoxy-dipole relaxation during cure reaction.
- Simple linear fit can be applied to relate dielectric constant change with degree of cure.
- TDR-Line sensor exhibits improved sensitivity and sensing range over DC and dielectric sensors.

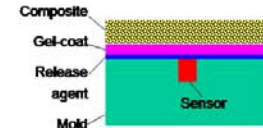
SENSING THROUGH INTERMEDIATE LAYERS

Problem statement:

✓ Typically gel-coats and release agents are used to improve surface quality and part release.

✓ Application of contact sensors are not able to sense through intermediate layers.

✓ Non-contact measurements are required.

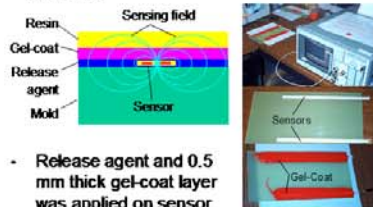


Solution:

✓ Specially designed TDR sensors measure change of dielectric properties in "surrounding" area allowing non-contact applications.

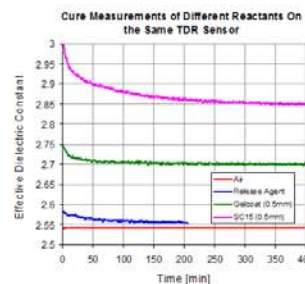
EXPERIMENTAL SETUP I

Flat and thin (150 μm) polyamide cables have been examined as a potential candidate.



- Release agent and 0.5 mm thick gel-coat layer was applied on sensor
- After gel-coat has been cured, 1 mm thick epoxy resin was applied

CURE SENSING OF GEL-COAT AND RESIN I



CURE SENSING OF GEL-COAT AND RESIN II

- Cure monitoring of release agent
- Cure monitoring of gel-coat
- Cure monitoring of epoxy resin through release agent and gel coat

Optimization of the sensor configuration can improve sensing range and sensitivity.

CONCLUSIONS AND FUTURE WORK

Conclusions

- Developed flow sensor for LCM applications
- Developed accurate approach for cure measurements
- Demonstrated sensing through intermediate layer

Future Work

- Develop TDR sensor system for 2D flow sensing
- Investigate cure sensing of different resin systems
- Implement 2D sensing TDR systems for LCM

ACKNOWLEDGEMENTS

This work is supported by the Office of Naval Research through the Advanced Materials Intelligent Processing Center program.