AN EMBEDDED ULTRASONIC WIRE WAVEGUIDE SENSOR FOR IN-PROCESS CURE AND IN-SERVICE DYNAMIC RESPONSE MONITORING OF LIQUID MOLDED COMPOSITE PARTS

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INTRODUCTION

Over the last decade, liquid molding techniques have become more and more popular for manufacturing of composite parts and structures. These techniques are often selected due to the ease of manufacturing automation and the ability to effectively and inexpensively produce large and complex shaped parts and structures. Resin transfer molding (RTM), vacuum assisted RTM (VARTM) and Seemann's composite resin infusion molding process (SCRIMP) are examples of widely applied liquid molding techniques in the composite industry today.

Resin flow and cure play key roles in the liquid molding techniques. Proper resin flow and cure in these processes are crucial to the quality of the composites and manufacturing consistency, particularly when the thickness of the composite is large. As a result, it is highly desirable to have a sensor system that can obtain flow/cure information and use it to achieve intelligent system control during the composite manufacturing process.

There is also a strong need for in-service monitoring and assessment of the integrity, overall health, and damage on the composite structures resulting from normal use, impact, and battles for military applications. In particular, a smart structure which has the capability to detect damage and degradation can be very valuable for ensuring continued integrity of the composite structures.

SENSOR DESCRIPTION AND NEAT RESIN EXPERIMENT

An acoustical sensor technology has been developed for the liquid molding composite manufacturing techniques. This technology is based on the wave propagation in a thin metallic wire embedded in the composite part[1-4]. Figure 1 is a schematic of the developed wire waveguide (WWG) sensor. The wire is made of stainless steel and has two

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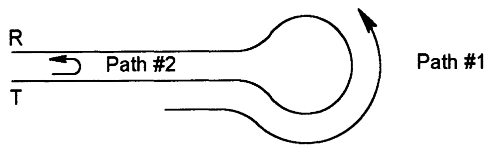


Figure 1. Wire waveguide sensor.

small piezoelectric elements attached to its ends, one is transmitter and the other receiver. The sensor is operated at about 350 kHz and driven with 4 cycles of toneburst.

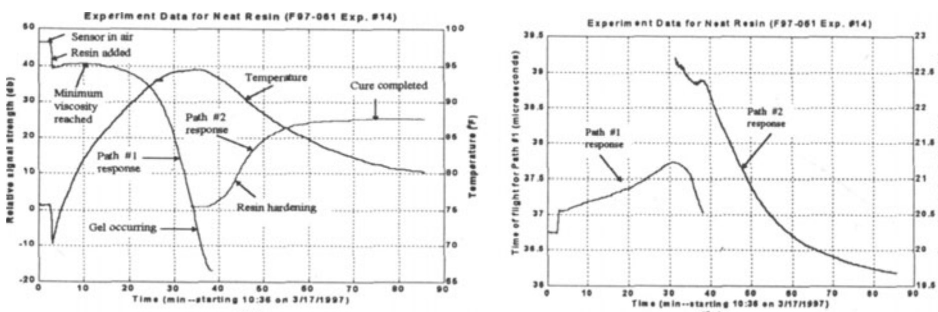
To demonstrate the sensor operation, an experiment was conducted using a small reusable Teflon tray at the room temperature. The resin used was Shell Epon 828 + Epicure 3234 which was selected for availability and popularity. This experiment is representative to many other neat resin experiments we conducted during the course of the sensor development.

Referring to Figure 1, there are two paths for the ultrasonic wave to propagate from transmitting transducer to the receiving transducer. Path #1 is the route followed by the energy propagated through the wire itself. Path #2 is the route followed by energy propagated between the two parallel legs of the wire. These two paths provide the information that describes various stages of a cure process.

The typical ultrasonic amplitude responses from the neat resin experiment are shown in Figure 2a. In addition to the temperature curve obtained from a thermocouple, there are two curves showing the amplitude responses from Paths #1 and #2. Path #1 shows when the resin reached the sensor, the viscosity change and the gelation. Path #2 provides information on the resin hardening through the completion of the cure.

Before the resin was poured into the Teflon tray, ultrasonic energy propagates in the sensor wire. When the resin was poured in, some amount of energy leaked out of the wire, causing a drop in the amplitude. As the curing process progressed, the resin viscosity decreased slightly. This is reflected by the small amount of increase in the transmitted energy in Figure 2a. Before significant gel occurred for the resin, most of the received energy was propagated through Path #1. As the gel progressed, the amount of energy propagated through the wire decreased rapidly. Meanwhile the resin began to harden and provided sufficient support for the ultrasonic energy to propagate via Path #2. Towards the end of cure, the resin reached its viscoelastic asymptote as indicated by the flattening of the amplitude response for Path #2.

Time-of-flight information was also obtained for the experiment and the results are presented in Figure 2b. The response for Path #2 shows an increase in velocity as the resin hardened. Note that the time-of-flight for path #1 reached maximum before the gelation was complete. This seems to be typical in all of the neat resin experiments we conducted in this project. In addition, since Path #2 has a shorter distance, its signal arrives earlier than that of Path #1. In fact, because of our choice of frequency, signals from the two paths can be time-gated to provide separate amplitude responses for the two paths. Typical waveforms for Paths #1 and #2 are shown in Figure 3.



(a) (b)

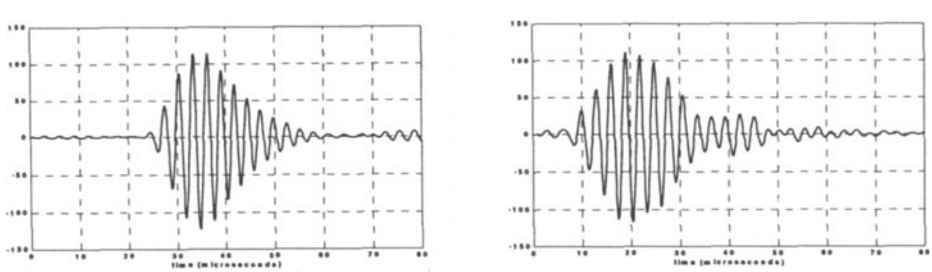
Figure 2. Ultrasonic responses of WWG sensor in a neat resin experiment (a) Amplitude and (b) Time-of-flight.

WWG IN COMPOSITE MANUFACTURING PROCESSES

RTM experiment

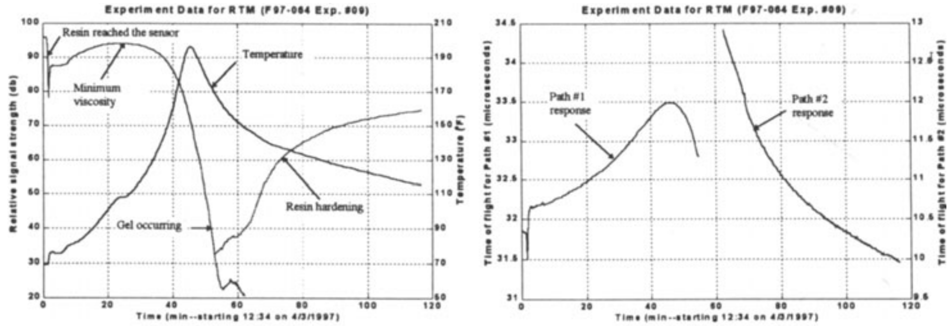
Several experiments were carried out using the WWG sensor for the RTM process. The RTM mold used in these experiments was a ½" thick 8" x 8" aluminum mold. After the layers of glass fabric were placed in the mold and sensors embedded in the middle layer, the mold was tighten by eight C clamps. Resin was then injected into the closed mold with thermocouple and sensor leads coming out from the side. The resin was injected from the bottom of the mold with vent ports on four sides as well as at the top. The resin used was Jeffco 1314A and Jeffco 3109B (4:1 ratio) which has a pot life of 15 minutes at the room temperature. Jeffco resin was selected because it was Shell 828 based and readily available.

Typically the injection was done with a cold or lukewarm mold. After the resin was injected, heat was applied to warm up the mold and speed up the cure process. Figure 4 shows typical amplitude and time-of-flight responses from a RTM experiment . The responses are similar to those shown in Figure 2 for the neat resin. The major differences occurred shortly after the resin reached the sensor. There was a quick increase in the amplitude for Path #1. We speculate this is due to the resin lifting the fabrics from the sensor wire. The rise, however, quickly stabilized at a level lower than before the resin reached the sensor. However, we can not explain why the time-of-flight reduced (velocity increased) when resin just reached the sensor at this time. In spite of this, it is clear that the sensor was able to detect when the resin arrived.



(a) (b)

Figure 3. WWG waveforms (a) path #1 and (b) path #2.



(a) (b)

Figure 4. Ultrasonic responses of WWG sensor in a RTM experiment
(a) Amplitude and (b) Time-of-flight.

<u>VARTM/SCRIMP experiments-small mold</u>

To evaluate the effectiveness and applicability of the sensor in the VARTM/ SCRIMP processes, several experiments were carried out using the lower half of the RTM mold. A slight modification was made to the mold such that the entry port for the resin was relocated to the side for convenience purpose. The vacuum was achieved with bagging materials and a vacuum fitting on the surface of the mold. In addition, a controlled heater blanket was placed under the base of the mold. Figure 5 is a photo of the experiment in progress. The resin used was NanYa 128 (Shell 828 based resin) with EAC100NC (Anhydride) plus EAC catalyst (accelerator/ promoter). The mixing ratio was 100:85:3. This resin system has a long pot life (will remain liquid at the room temperature) and low viscosity (~300 cp). This epoxy system was chosen mainly due to the suitability and availability.

Figure 6 shows typical responses obtained from the VATRM/SCRIMP process. Comparing to those in the RTM, the responses were very similar except minor additions of features due to the vacuum process as annotated on the figures.

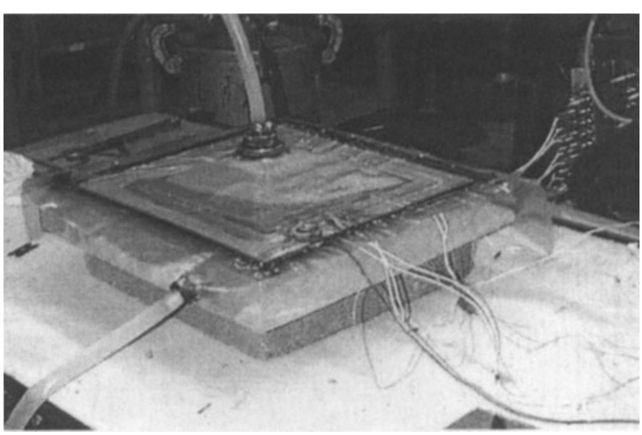
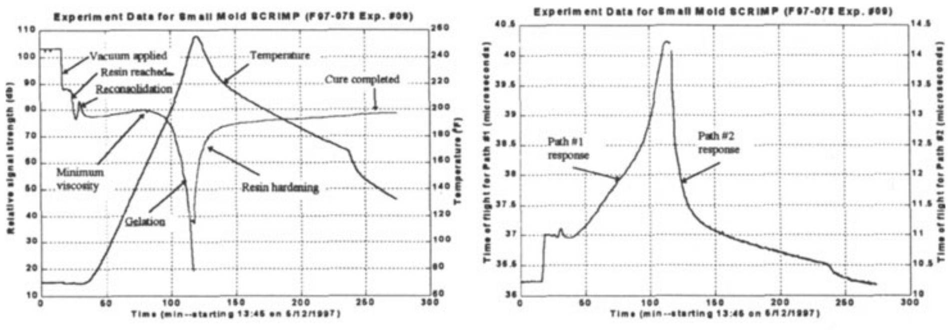


Figure 5. Photo of a small mold VARTM/SCRIMP experiment.



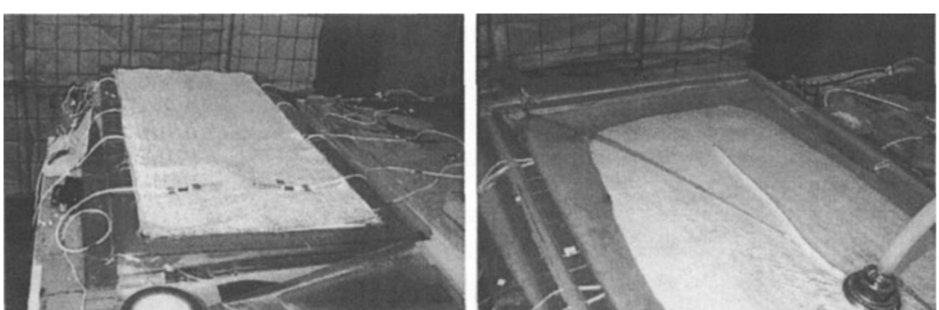
(a) (b)

Figure 6. Ultrasonic responses of WWG sensor in a VATRM/SCRIMP experiment
(a) Amplitude and (b) Time-of-flight.

A large mold VARTM/SCRIMP experiment

After the WWG sensor was developed and validated in the small mold SCRIMP, we proceeded to a demonstration in the large mold. The resin used for this was the same as that for the small mold SCRIMP experiment. There were two resin entry ports located on one side of the large mold. A silicone heater blanket was placed under the base of the mold. To speed up the resin infusion process, special resin distribution tubes were used on the edge of the mold. Sensors and thermocouples were installed in the mid-layer of each of the four sections. The mold was not preheated but the heater was turned on about the time the resin was infused. Figure 7 gives two photos showing the sensor placement and resin infusion process during an experiment.

Again, the WWG sensors worked very well. Figure 8 includes four sensor responses at four different thickness levels. The responses all have similar characteristics and resemble those in Figure 6 except that it appears the viscosity of the resin did not drop before gel occurs. This may be due to a number of factors, such as the heating of the mold before resin was fully infused or that the vacuum pump we used did not have enough capacity to produce quick second consolidation in the part, etc. In spite of this, we can see clearly when resin reached the sensors, when gel occurred, and when the cure was effectively complete.



(a) (b)

Figure 7. Photos of a large mold SCRIMP experiment
(a) Sensor placement and (b) resin infusion.

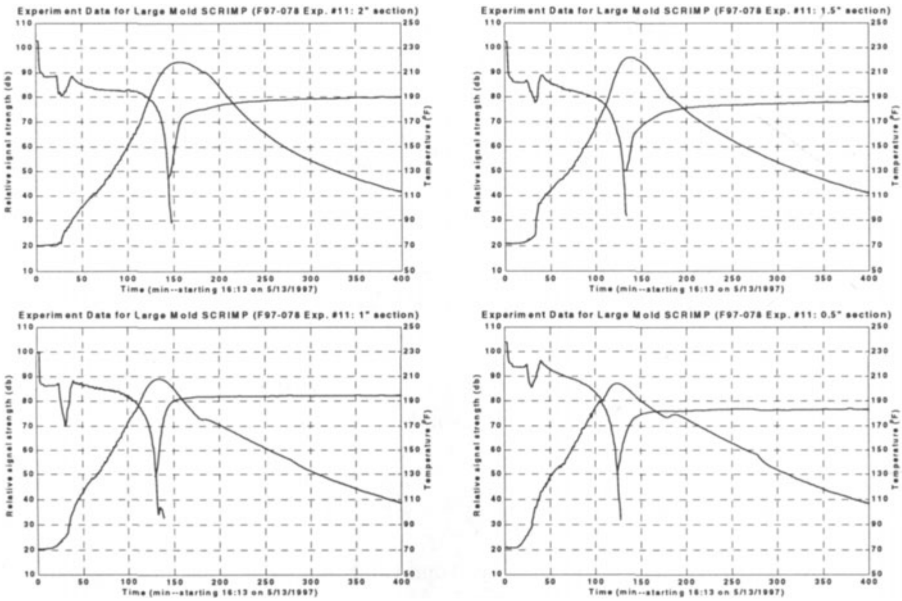
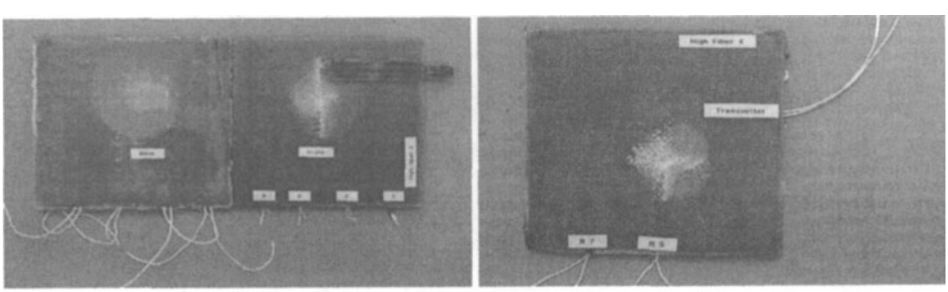


Figure 8. Ultrasonic responses of WWG sensor in a large mold SCRIMP experiment.

IMPACT DAMAGE DETECTION EXPERIMENTS

The objective of these experiments is to show that the WWG sensor for the resin flow/cure monitoring can also be used for the measurement of structure vibrational response. Composite parts fabricated from the small mold VARTM/SCRIMP experiments with embedded WWG sensors were used for the study. Two damage detection methods were used in this study. The first method used a film piezo-actuator as a source of vibration. The second method used one embedded WWG sensor as a transmitter and two other embedded WWG sensors as receivers. Both methods demonstrated the damage detection capability.

In both experiments, measurements were made before impact damage was made to the samples. The impact damage was obtained with a 6' - 28 lbs. impact load per SACMA SRM2 (or Boeing BSS7260) standard. The impact head had a diameter of 1.0", resulting in visible damage. Pictures of impacted parts are shown in Figure 9.



(a) (b)

Figure 9. Photos of impacted composite samples.

In the vibrational damage detection method, a 0.5" x 2" thin film piezo-actuator was attached to the sample with epoxy. It was driven directly by the HP33120A function generator in continuous wave mode through the frequency range of 0.5 to 200 kHz. Amplitude of resonance signals were measured with two embedded WWG sensors. Table I gives the matrix for the vibration measurements along with the corresponding deviations for a sample. The deviation calculation was made in frequency domain using:

$$deviation = \sqrt{\sum (A - A_0)^2} \Big/ \sum |A_0| \tag{1}$$

where A and A_0 are the amplitude values for before and after impact. Figure 10 shows the vibrational responses for before and after the impact of the sample. The embedded sensors were able to pick up the differences in the composite resulted from the impact.

In the ultrasonic damage detection experiment, one sensor was used as the transmitter and another two sensors as receivers. We propagated ultrasonic waves in a composite part at 350 kHz. Ultrasonic measurements were made before and after subjecting the composite sample to the same impact level as described before. The impact was purposely done to the perceived wave propagation path. A photo of the part showing relative positions of the sensors and impact location is in Figure 9b. Table II lists the matrix for the ultrasonic measurement and Figure 11 gives the received signals for this experiment. The deviation calculation was made in time domain using Eq. (1). As can be seen in Figure 11, impact introduced changes in the waveform shapes and arrival times of the signals, proving again that the embedded sensors can detect the damage in the composite part.

Table I. Vibration measurement-- % deviation from the first baseline measurement.

WWG sensor	Baseline	Baseline (repeat)	Impacted	Impacted (repeat)
#5	0	0.78	3.23	3.24
#3	0	0.21	3.53	3.55

Table II. Ultrasonic measurement-- % deviation from the first baseline measurement.

WWG sensor	Baseline	Baseline (repeat)	Impacted	Impacted (repeat)
#7	0	0.83	4.24	4.23
#5	0	0.91	6.67	6.30

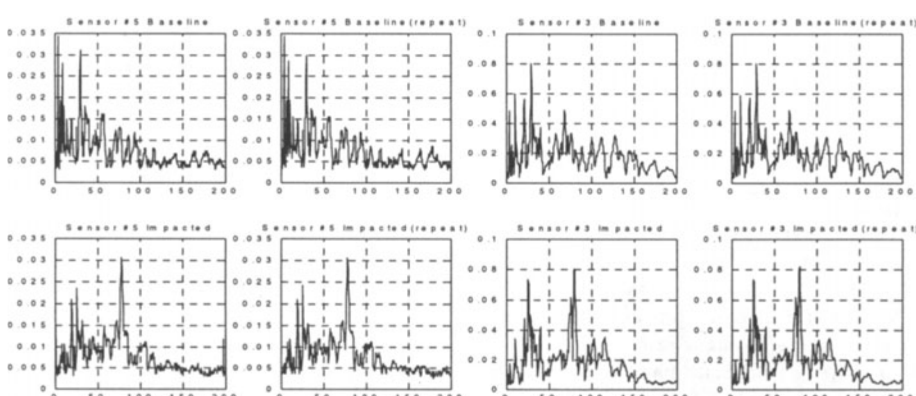


Figure 10. Frequency responses for damage detection – vibration experiment.

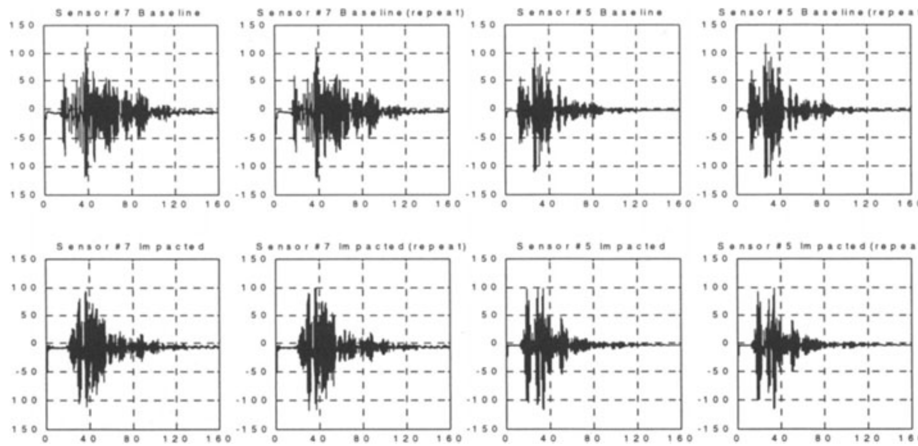


Figure 11. Waveforms for damage detection – ultrasonic experiment.

CONCLUSION

We have developed a novel embedded WWG sensor and measurement technology that can be used for flow/cure/damage measurement of composite parts manufactured by liquid molding techniques such as RTM and VARTM/SCRIMP. The measurement can be performed in real time for in-process flow/cure monitoring during fabrication and the same embedded sensor can also be used for damage detection and dynamic vibrational response monitoring after the parts or structures are placed in-service. Experimental results obtained in this project have clearly established the technical feasibility of this new low-cost, rugged, easy to implement ultrasonic WWG sensor technology.

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