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Development of a Distributed Direct Current Sensor System for Intelligent Resin Transfer Molding

by Bruce K. Fink, Roderic C. Don,
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Development of a Distributed Direct Current Sensor System for Intelligent Resin Transfer Molding

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Abstract

Resin transfer molding (RTM) and other liquid molding techniques hold the promise of affordable manufacturing for a variety of critical Army applications including the Composite Armored Vehicle (CAV) and Comanche helicopter. A critical barrier to the development of a quality control system and to our ability to consistently manufacture quality parts using RTM is the availability of an integration-friendly and cost-friendly flow and cure sensing system. SMARTweave is an ARL-patented system for sensing the existence and state of cure of resin in RTM. The process uses a grid of conductive filaments laid within an RTM mold. As resin fills the mold, gaps between transverse filaments at the flow front are bridged by resin, and an electrical circuit is closed providing a signal that the flow front has reached that node. SMARTweave provides researchers and manufacturers with a sensing system that can be placed into an RTM mold and provide low-cost, real-time information about the resin location and state of cure. This information is useful to validate and refine flow and cure models and to study flow and cure for various RTM techniques and materials, providing insight on the role of a complex system of variables that include viscosity, mold temperature, resin inlet temperature, mold design, port and vent locations, pressure, preform architecture and permeability, preform placement techniques, etc.

Acknowledgments

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1. Introduction

Resin transfer molding (RTM) and other liquid molding techniques hold the promise of affordable manufacturing for a variety of critical Army applications including such programs as the composite armored vehicle (CAV) and the Comanche helicopter. Realizing this potential requires an integrated research program that addresses the entire realm of RTM-producible parts from thick (structural) to thin (skin) sections, from large (CAV lower hull) to small (helmets), and with (armor) and without ballistic inserts.

Any control system needs to assess where the state of the process is at any time (e.g., flow, temperature, pressure, cure state) and where the process needs to get to (i.e., flow, cure, residual stress models) and then make intelligent decisions about how to best get there (i.e., control scheme). One of the most critical barriers to the development of a quality control system—and, hence, to our ability to consistently manufacture quality parts using RTM—is the availability of an integration-friendly and low-cost flow and cure sensing system. SMARTweave is a patented system for sensing the existence and state of cure of resin in RTM. SMART is an acronym for Sensors Mounted As Roving Threads. The process uses a grid of conductive filaments laid within an RTM mold. As resin fills the mold, gaps between transverse filaments at the flow front are bridged by resin and an electrical circuit is closed providing a signal that the flow front has reached that node.

The goal of the SMARTweave concept is to provide researchers and manufacturers with a sensing system that can be placed into an RTM mold and provide low-cost, real-time information about the resin location and state of cure within the mold. This information is useful to validate and refine flow and cure models and to study flow and cure for various RTM techniques and materials, providing insight on the role of a complex system of variables that include viscosity, mold temperature, resin inlet temperature, mold design, port and vent locations, pressure, preform architecture and permeability, preform placement techniques, etc. Manufacturers may use such a system for control of the process, such as the opening and closing of ports and vents, the relative temperatures of the mold and resin, the rate of injection, and the optimum times for filling and releasing pressure from the mold. SMARTweave has been adapted to increase the number of sensors for a given number of electrical connections and sensing paths as dictated by acquisition and control equipment. A new wiring and data acquisition methodology was devised, implemented, and tested for the monitoring of flow and cure for several RTM-grade resins. Recently, key experiments have been performed in several industrial environments including DuPont-Hardcore facilities in Delaware and United Defense Limited Partnership facilities in California. These experiments led to significant breakthroughs in our ability to monitor quasi-full-field flow and cure in real time in an industrial environment.

2. Background

2.1 Liquid Molding Research Needs. On-line sensing and control for manufacturing have been shown to be critical to reducing the costs and increasing the reliability of composite materials and components. Sensor and control technologies are required that will enable the practical implementation of viable sensors for composites manufacturing processes that will contribute to the reduction of costs and improvement of the reliability of composite structures for DOD and other applications. This work is essential to the future affordability of composite materials and structures. To reduce the cost of composite structures, it will be essential to determine particular process parameters on line during the manufacturing process as well as during the life-cycle of the structure. Earlier studies have shown that the cost of raw materials is only a small portion of the final cost of a composite structure. Even substantial reductions in the cost of raw materials may lead to only marginal cost savings in the final composite part. Therefore, the most promising path to the affordability of composite structures is the reduction of defective parts and the related efforts required for post-process inspection and repair.

Successful implementation of on-line sensing methods will allow a process to be adapted to normal variations in the materials. By optimizing part quality using on-line sensors in association with appropriate feedback control algorithms, the number and extent of postprocessing inspection steps can be drastically reduced. These on-line control algorithms are based on a fundamental understanding of the processes as described through a variety of process models and are another important cornerstone of successful integration of on-line sensing and process control. In the area of liquid molding, novel on-line sensing techniques are required to nonintrusively obtain such parameters as temperature and pressure profiles. Flow fronts and curing profiles need to be determined throughout preform impregnation in liquid moldings.

Figure 1 shows some of the research or knowledge needs in liquid molding manufacturing. The four topics on the left side of the figure are traditionally performed by manufacturers, while those on the right are traditionally performed at universities and government laboratories and eventually adopted by industry in whole or in part to make better or cheaper parts. Liquid molding is a general term for several related processes including RTM, Seemann's Composites Resin Infusion Molding Process (SCRIMP), and Vacuum-Assisted Resin Infusion (VARI). In RTM, dry reinforcement is precut and assembled into a preform and placed into a closed mold, which is then closed over the preform. A low-viscosity, reactive system is injected into the tool. The advancing resin front within the closed mold cavity displaces the air and forces it through vents located at selected points of the tool. During this infiltration process, the resin "wets out" the reinforcement and is cured. Once the composite develops sufficient strength, it may be removed from the tool and post-cured, if needed. In VARI, resin is pulled through a preform using a vacuum. In contrast to RTM, this process allows the use of one-sided tooling instead of a closed mold. In the SCRIMP process, a permeable layer is used on one side to promote rapid flow of resin in the plane adjacent to the part and a subsequent flow through the part. The process has lower vacuum pressure requirements and the capability for larger parts.

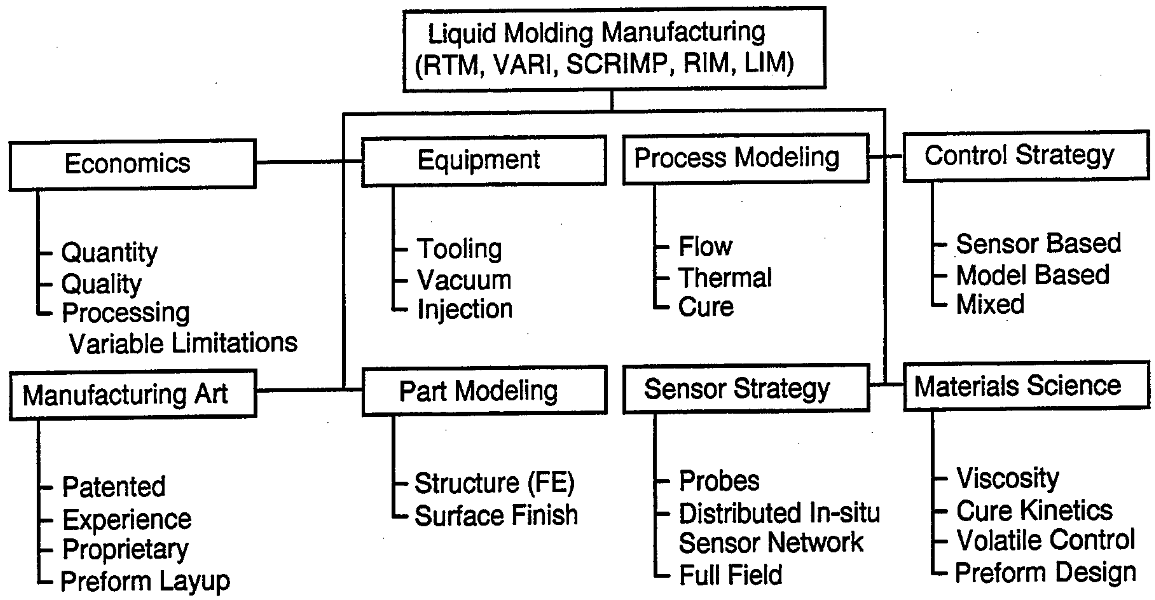


Figure 1. Research Needs in Liquid Molding.

These processes can be very complicated because processing and performance issues are integrally coupled. For example, the microstructure must be designed based not only on the expected thermomechanical loading but also on the proposed fiber architecture's influence on permeability and hence on resin flow through the preform. Similarly, the resin injection must reflect the delicate balance among the desire for a short cure cycle, the integrity of the microstructure, the wet-out of the individual fiber bundles, and the removal of entrapped air from the preform. Furthermore, the tool must be designed not only for the particular features of the finished product but also for the specifics of injection, permeability, cure, and demolding. These are just a few examples that demonstrate the challenge of liquid molding—the need to simultaneously consider processing and performance issues in order to ensure a high quality and economical product.

Incorporation of on-line sensors in liquid molding processes can provide feedback to validate cure models and for on-line, intelligent control. Distributed electronic and ultrasonic sensors provide promising techniques for observing the flow front in molds. Output from transducers situated in the mold could be used for real-time control of gates and vents.

Alternatively, portable ultrasonic devices, including laser ultrasonic instrumentation, could be used to validate flow models and monitor resin flow during the development phase of process control for a new design.

2.2 Sensor Development. Sensor development for the RTM, VARI, and SCRIMP processes involves various strategies for process monitoring and control. Depending on production volume and throughput, sensing may be made intrusive and integral to the structure being produced or it may be remote and noninvasive. In the RTM and VARI processes, full-field or distributed sensing for determination of mold fill completion may be required (Figure 2). Consequently, sensing strategies beyond the single-point determination of local properties are required.

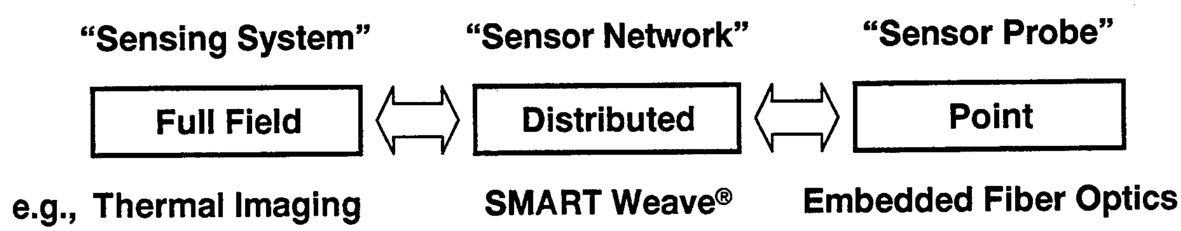


Figure 2. Sensing Strategies.

Sensor development for automated manufacturing systems has focused on moving from post-production evaluation to on-line, in-process monitoring. These technologies employ a range of optical, electromagnetic, thermal, and ultrasonic phenomena for assessment of the manufacturing process (Hunston et al., 1991). The capabilities of sensor techniques range from those that can yield full-field images of in-process parts to those that are best suited to single-point measurement off line. These techniques include time-resolved infrared radiometry, laser ultrasonics, air-coupled ultrasonics, eddy current testing, microwave methods, and optical methods.

The development of sensing strategies for RTM is a critical technology shortcoming. The development and cost-effective integration of a basic sensor system can give needed feedback to validate cure thermokinetics and flow models and provide a framework for on-line intelligent control of the liquid molding processes.

The complexity and variability of liquid molding processes underscore the need for real-time full-field—or, alternatively—distributed sensing and control. As an example, grid-type flow-front sensor systems can provide real-time 3-D flow-front information that is ideal for incorporation into an intelligent process control system. In this system, as resin fills the mold, gaps between transverse filaments at the flow front are bridged by resin, and an electrical circuit is formed, providing a signal that the flow front has reached the node. This information is useful not only to validate and refine flow and cure models and to study the flow and cure of various RTM/VARI techniques and material systems but also to be an integral component of a sensing and control strategy for manufacturers. However, such systems rely upon the electrical properties of the resin material being processed; therefore, further work is needed to (1) quantify these properties—as well as local surface effects—as they relate to sensor design; and (2) establish, through fundamental materials research and applied manufacturing studies, criteria for selection of compatible resin systems and placement of the conductive elements. Once these fundamental issues are resolved and the material-sensor selection and design criteria are established, the concept can be applied to the real-time control of liquid molding processes. It has been shown that embedded sensing grids can be used to monitor the state of cure of the thermoset resin in the mold.

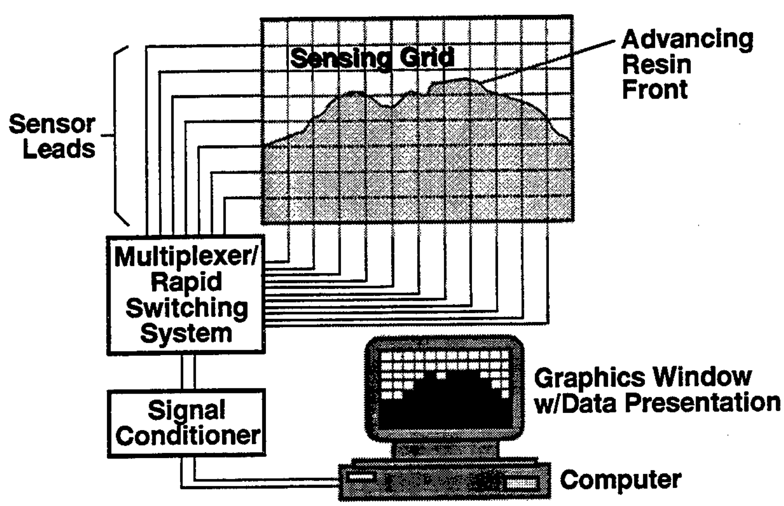


Figure 3. Schematic of the Generic Patented SMARTweave System.

A distributed grid-type sensor system termed SMARTweave has been invented (Walsh, 1990) and patented (Walsh, 1993) by the U.S. Army and utilizes a grid of conductive filaments laid within an RTM/VARI mold/layup (Figure 3). Collaborative work between the U.S. Army Research Laboratory and the University of Delaware's Center for Composite Materials (UD-CCM) has advanced the state of the art in SMARTweave through the development of an improved sensing network scheme and improved data acquisition techniques. These advances have significantly simplified the sensor network placement procedures and greatly enhanced the resolution of the system, allowing accurate detection of flow and cure progress with several RTM-grade resins tested.

2.3 Process Control. Modeling work performed to date has focused on the simulation of mold-flow and cure kinetics. Process engineers have recognized the use of process models and simulation as a tool to guide and select the conditions to produce an acceptable part by RTM. However, the state-of-the-art process development approach has many drawbacks, such as very high dependence on many trial-and-error cycles, process simulations that do not incorporate the physics of all material systems, lack of material system or product information, and inability of process simulations to account for part-to-part variation. These factors contribute to long and expensive composite manufacturing process development cycles. To reduce these development costs, we must move beyond process models that incorporate the appropriate process physics and work on a design model in which the user defines the product and constraints, and the model computes the optimal processing conditions. Secondly, to account for inevitable part-to-part variability, we should be able to make real-time process adjustments. Hence, what is needed is a computational tool that can predict the inverse behavior of a manufacturing process and operate in real time to continuously adjust manufacturing conditions. This control system requires an inexpensive, easy-to-place, and adaptable flow-and-cure sensing system. Finally, an intuitive user interface is required so that the process engineer can focus on process questions and not on simulation operation.

During the RTM process, several critical problems arise that limit throughput: (1) degree of mold fill, (2) void formation within the part, (3) fiber wet-out of reinforcing agents, (4) degree of resin cure, and (5) residual stress formation. From a sensing standpoint, some of the strategies for identifying these problems in-process are identical; however, in closed mold processes, the mold itself precludes many forms of process sensing, as it inhibits visual observation. In light of the sensing requirements, SMARTweave, laser ultrasonics, microwave dielectrometry, and fiber-optic/thermal radiometry are potential RTM monitoring methods. Our approach for SMARTweave has been to determine the circumstances for which this particular sensing system is best suited and the extent to which it can sufficiently monitor the onset of reaction and gelation point of conversion, providing data for use in a process control system. Integral to our work is the development of a full understanding of the relationships among resin conductivity, temperature, and extent of cure. This data can be used for RTM process control through mold filling, energy supply, and demolding decisions. Sensing the onset, development, and completion of the cure reaction through the thickness is possible by either (1) measuring the depletion of species that are consumed as the cure proceeds (extremely difficult); (2) monitoring heat generation and using a thermal model incorporating appropriate boundary conditions and heat generation during cure exotherm to back out degree of cure point by point (possible but difficult); or (3) monitoring the change in state of the resin. Alternative 3 has long been viewed as the candidate with the best probability of success for monitoring the extent of reaction in thermosetting systems. The change in state of the resin can be monitored by detecting changes in ionic mobility (dielectric constant, loss tangent, direct-current [DC] conductivity) or by directly detecting changes in the viscosity (ultrasound).

All RTM resin systems contain mobile ionic species and/or polar groups that react to direct current and/or alternating electric fields. Traditional dielectric probes using alternating fields provide accurate information about the progress of the reaction at a specific point. Alternatively, SMARTweave uses an applied direct current electric field to induce the movement of mobile ions. The movement of the ions, through the measured conductance across the sensor leads (which may be carbon-fiber- or glass-fiber-wrapped ultra-thin metallic wires), is a function of the local temperature of the resin and the viscosity of the fluid.

The goal of the current research program was to validate SMARTweave's ability to accurately and efficiently sense the flow of resin in real time using a variety of standard resins and to validate and define its ability to monitor the degree of cure of these resin systems. Initial work using the equipment defined below proved that the equipment could monitor the existence and provide information about the state of cure in a large variety of standard RTM grade resins. However, these initial studies were performed on a single cell. It was necessary to prove the applicability of SMARTweave to a larger number of sensing points and to show the capability of sensing over a distributed quasi-full-field network. Kikuchi, et al. (1995) first reported the ability to apply SMARTweave to the real time measurement of flow using a standard RTM-grade resin system. Kikuchi, et al. used a novel technique of interrogating the location of the advancing flow front through multiple one-dimensional sensing circuits. Direct current was supplied to a single excitation wire and a voltage was measured across a drop resistor. The calculated resistance is an equivalent resistance of multiple sensor gap resistors in parallel. Therefore, as the resin front moves forward from one end of the excitation lead, the total voltage measured increases in steps that represent the stepwise advancement of the resin front along the linear path of the excitation lead. This method requires that the resin flow front move along a particular path and that only one flow front exists which may impinge upon that linear path. Additionally, with an increasing number of "sensor" locations, n, along the excitation lead, the equivalent resistance decreases as 1/n and, since stepwise changes in the measured voltage are inversely proportional to the equivalent resistance, the step increases in measured voltage become smaller and smaller as flow progresses. The size of the steps could quite easily decrease by two orders of magnitude in large molds. The current work presents a SMARTweave schema that monitors the flow and, possibly, the cure of standard RTM-grade resins with high accuracy for any desired number of sensor locations in the mold by interrogating each sensor node of the SMARTweave network individually using a methodology developed by Fink, et al. (1995).

3. Experimental Setup

3.1 Electronics. The SMARTweave experimental setup is shown in Figure 4. The experimental configuration is comprised of a Zeos Pantera Pentium-90 computer containing a National Instruments AT-MIO-16E-10 ISA-bus data acquisition (DAQ) board, a National Instruments SCXI signal conditioning chassis containing an SCXI-1120 8-channel isolation amplifier module, an SCXI-1161 8-channel power relay module, and an SCXI-1163R 32-channel, optically isolated, solid-state relay (SSR) module. The AT-MIO-16E-10 has programmable gains of 0.5, 1, 2, 5, 10, 20, 50, and 100. The SCXI-1120 has eight differential inputs, each of which has an active, 3-pole RC low pass filter with a jumper selectable 4 Hz or 10 kHz cutoff frequency and jumper selectable gain. An external Tektronix PS280 power supply was used for grid excitation power. The software created in the National Instruments' LabVIEW performs grid control and data acquisition.

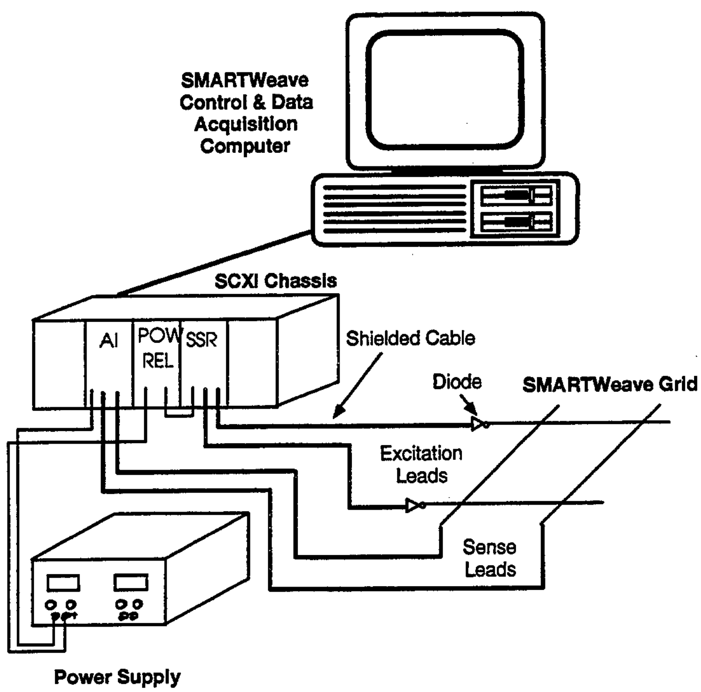


Figure 4. SMARTweave Experimental Setup.

A detailed schematic for the SMARTweave excitation and sensing circuits is shown in Figure 5. The excitation circuit is comprised of the excitation supply, an SPDT (form C) relay, optically isolated SSRs, and diodes. The SSRs are employed because of their high reliability under repetitive cycling. The form C relay actively ensures that the grid will remain unpowered during power up since the SSRs are normally closed when initially powered. The LabVIEW control software forces all SSRs to an open state before closing the form C contact. A diode is incorporated to prevent current flow when the SSR is in the open state.

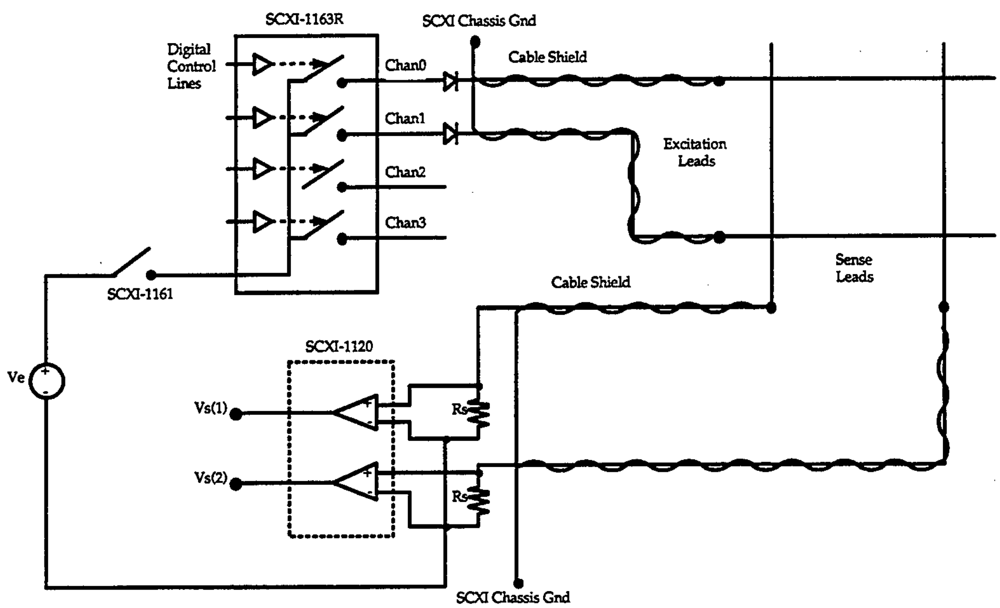


Figure 5. SMARTweave Schematic.

The sensing circuit is essentially a half Wheatstone bridge comprised of a grid junction and a sensing resistor. A fixed voltage of 10 V is applied to the half bridge. The junction and sensing resistor act as a voltage divider. The voltage drop across the sensing resistor indicates the current junction resistance. This voltage drop is measured with an SCXI-1120 differential input. Each differential SCXI-1120 input was set for unity gain and a 4-Hz (-3 dB) cutoff frequency. The sensing resistor was either 100 kΩ, 1 MΩ, or 10 MΩ. The sensing resistance was chosen to limit the active signal amplification. Three factors affect the ability to measure the junction resistance: electrical noise, the sensing resistance, and the DAQ board gain. Several techniques were employed to reduce electrical noise. Shielded cabling was used for both sensing and excitation leads. The shield was tied to the SCXI chassis ground. Shield integrity was maintained up to the connectors attaching the leads to the SMARTweave grid wires. High-frequency noise was reduced with an active analog filter with a 4-Hz cutoff frequency.

If we consider a 3 × 3 grid arrangement as shown in Figure 6 and introduce resin into the system, equivalent circuits can be drawn for each unique situation, as exemplified in Figure 7 for the case where resin is at each junction along a single sensing lead and junction 1-A is currently being interrogated through the data-acquisition system.

For resin at any or all junctions, the measured voltage at a single point is discretely measured and is a function only of the junction resistance for a given applied voltage. Similarly, and of great significance, variations in measured voltage between sensor junctions are only a function of variations in junction resistance throughout the mold. Additionally, the sensing resistance effects the system sensitivity defined as the change in grid output over the change in junction resistance:

$$V_s = (V_e - V_d)\left(\frac{R_s}{R_j - R_s}\right) \tag{1}$$

$$\frac{dV_s}{dR_j} = \frac{-(V_e - V_d)R_s}{(R_j - R_s)} \tag{2}$$

If Rs << Rj,

$$\frac{dV_s}{dR_j} \approx \frac{-(V_e - V_d)R_s}{R_j^2}\ , \tag{3}$$

where V_s is the sense voltage, V_e is the excitation voltage, V_d is the forward voltage drop across the diode (approximately 0.6 V), R_s is the sensing resistance, and R_j is the effective

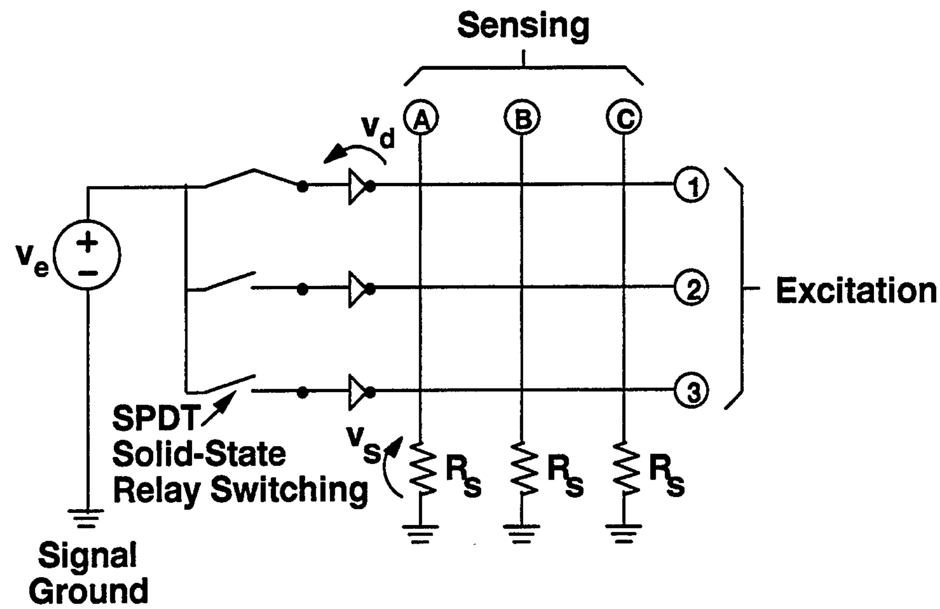
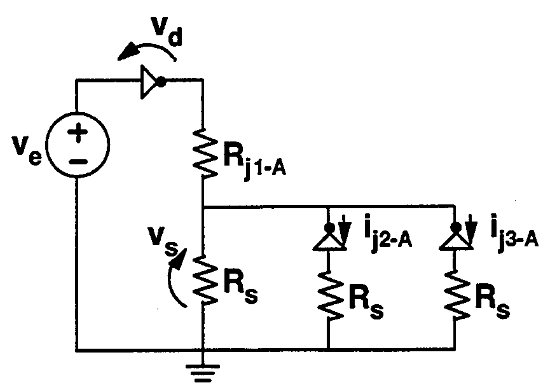


Figure 6. Simplified Schematic of 3 × 3 Sensing Grid With Excitation Leads 1–3 and Sensing Leads A–C.



$$i_{j2\text{-}A} = i_{j3\text{-}A} = \varnothing$$

$$\therefore \; v_s = \frac{R_s}{R_s + R_{j1\text{-}A}} \left(v_e - v_d\right)$$

Figure 7. Sensing of Equivalent Circuit for Resin Connecting Junctions 1–A, 2–A, and 3–A and 1–A.

Note: The measured voltage at 1-A is equivalent to the measured voltage at all other junctions.

junction resistance. The junction resistance is controlled by the spacing between the excitation and sense leads and the resin conductivity. The sensitivity of V_s to changes in the grid decreases with increasing sensing resistance. Hence, the sensing resistance and the DAQ board gain serve to increase the signal amplitude for more accurate analog-to-digital (AD) conversion.

3.2 Flow Experimental Setup. A SMARTweave system was applied to a transparent Lexan mold used for RTM mold filling simulations at the University of Delaware (Advani, 1995). Shown in Figure 8, the mold is an open-bottomed box 5 1/2 in $\times$ 8 in $\times$ 4 in high. This shape requires the fluid to flow around and along corners encouraging the formation of gaps in preform placement, leading to the occurrence of racetracking during the experiments. The transparent mold allows the flow front to be visually tracked. The mold was designed so that a wide variety of experiments could be performed. Figure 9 shows the box mold "unfolded" with the numbers 1 through 5 representing possible injection ports and V1 through V8 representing vent locations. The ports and vents not in use can be closed. The current experiment injected fluid at port 5 and vented at vents V1 and V3. To aid with comparison to numerical solutions and the SMARTweave results, a 1/2-in grid was drawn on the inner side of the female Lexan part. A 13 $\times$ 16 grid of wires was placed in the mold on either side of a single layer of random weave glass fiber preform which was cut to the shape of the flattened box in Figure 9. The separation of the wires in the plane, *s*, was 1 in. The separation through the thickness, *d*, was approximately 1/8 in. For this particular test, the switching of relays on a prototype applied voltage sequencing panel was controlled by a Labview software interface and a National Instruments AT-MIO-16 multifunction I/O board. The AT-MIO-16 was internally set for a floating DC-coupled signal using a 100-kohm resistor. Externally, nonconnected SMARTweave conductors were grounded.

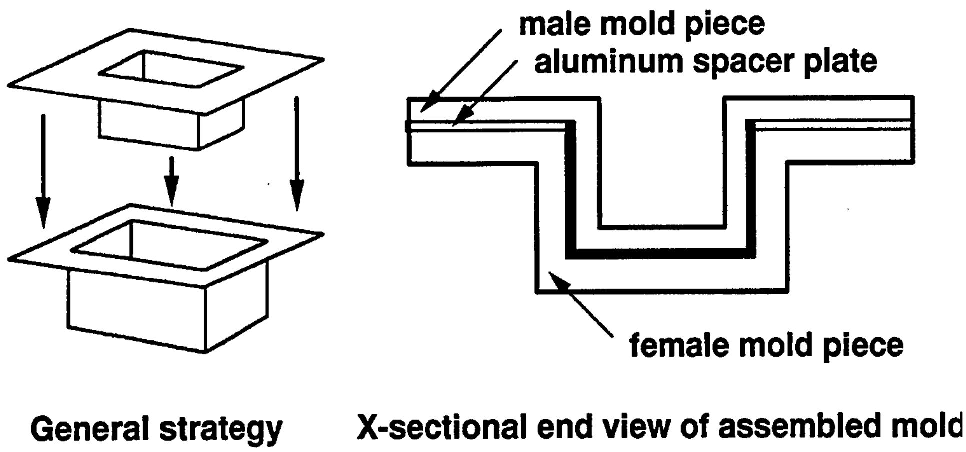


Figure 8. Lexan Box Mold Used in Experimental Verification.

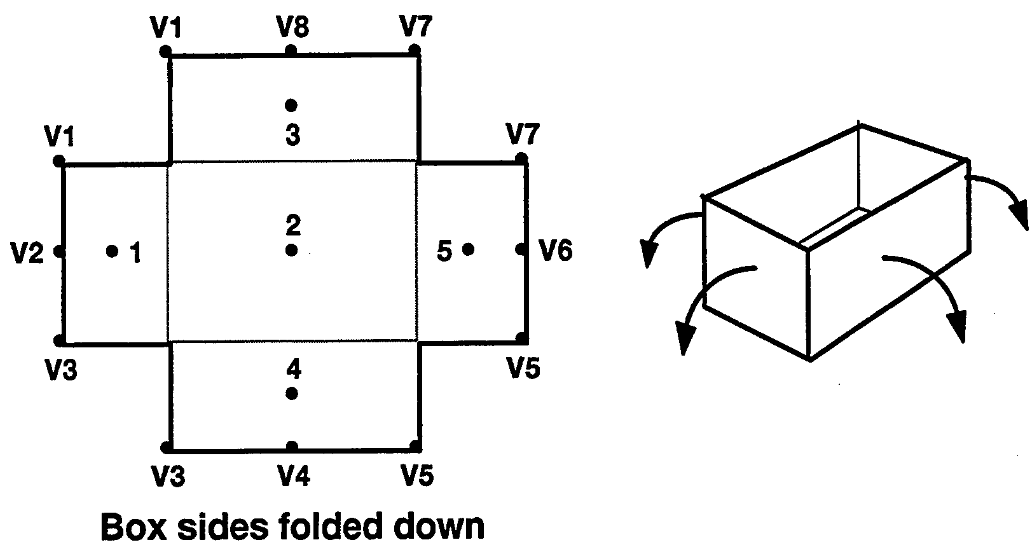


Figure 9. Schematic of Box Mold "Flattened Out" to Show Possible Port Locations (1–5) and Possible Vent Locations (V1–V8).

An applied voltage of 10 volts was sequenced along each excitation lead with voltage readings taken from along the sensing leads. The computer recorded the voltages at each of the 208 nodes—144 "sensors"—with a sensing cycle time of approximately 1.3 s. The cycle time is controlled mostly by the capability of the relays used. A delay time between relay sequences is controllable from the Labview interface to optimize sensing cycle times. The experimental setup used in this study provided a facility for undertaking the mold filling with constant flow rate injection. Figure 10 shows the setup. Corn syrup was mixed with water and dye to form a "resin" with a viscosity measured as 282 cps. Corn syrup was used since we were only interested in the flow in this test and the corn syrup allows the use of the transparent mold for direct flow comparison. The fluid is placed within the piston and cylinder arrangement and injected at a constant flow rate by varying the flow of oil into the hydraulic cylinder. To record the progression of the flow front in the mold, the experiment is filmed using a video camera placed directly overhead. Mirrors are used to capture the four sides of the mold in the same video frame. The filling of the mold took approximately 110 s obtaining 83 grid data sets (one for each time step).

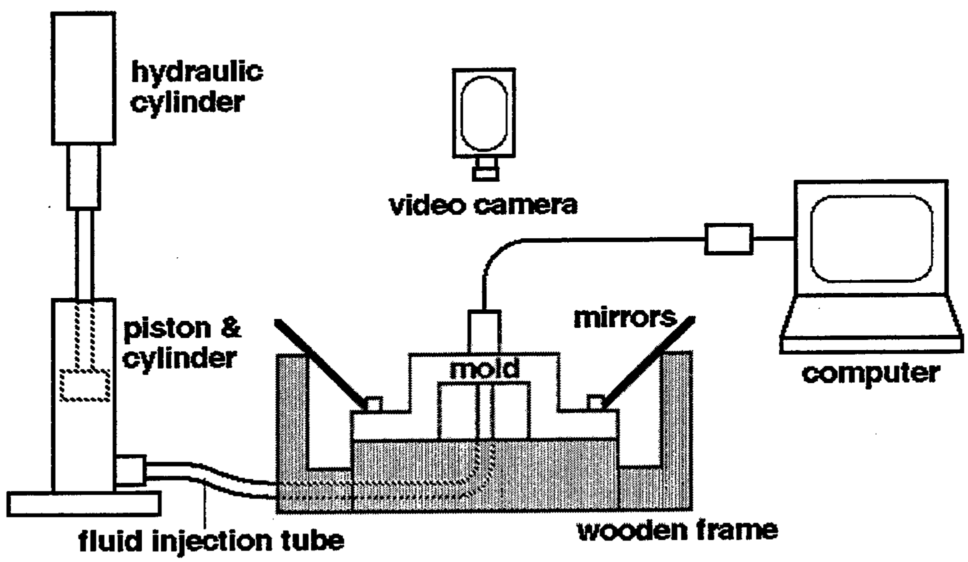


Figure 10. Schematic of Experimental Setup of Box Mold, Mirrors, and Camera.

The National Instruments Labview-based software created for this test was adapted from software designed by DeSchepper and Walsh (1994) and Don (1994). The software can either collect real-time test data or play back previously collected data. In both cases, the voltage matrix obtained at each time step is shown alongside the time-to-threshold plot. Both plots are shown on the computer screen in real time and values are updated every 1.3 s (this cycle time has been improved upon by several orders of magnitude since these tests). The threshold value can be adjusted and represents the minimum voltage value for which a time-to-threshold reading is taken for each sensor. This threshold voltage is set to be just above the electronic noise inherent in the system. The result is a quasi-contour plot of how flow progressed along the mold. For the current test using a transparent mold, the flow could be observed visually along with the flow-front plot on the computer.

3.3 Cure Experimental Setup. The experimental setup for the first cure monitoring study is shown in Figure 11. For this test we desired to have a room temperature cure that was as uniform as possible throughout the specimen. Three layers of random glass matting preform was placed into a 2-in × 2-in × 1/8-in-thick rubber dam and sandwiched between two insulative glass plates. The lack of thermal conductivity in the "mold" and the small thickness assured a uniform cure throughout the specimen. A single excitation lead (5-mil copper wire) was placed between the first and second layers of preform, and two sensor leads were placed between the second and third layers; thus, physically separating the excitation and sensing leads by a single layer of preform. Before the top glass plate was placed, the data acquisition equipment was started and Dow Derakane 411-C50 vinylester resin mixed with 1.77 weight-percent USP-245, 0.12 wt% DMA, and 1.06 wt% Akcros NL-51P accelerator was poured into the preform laden dam.

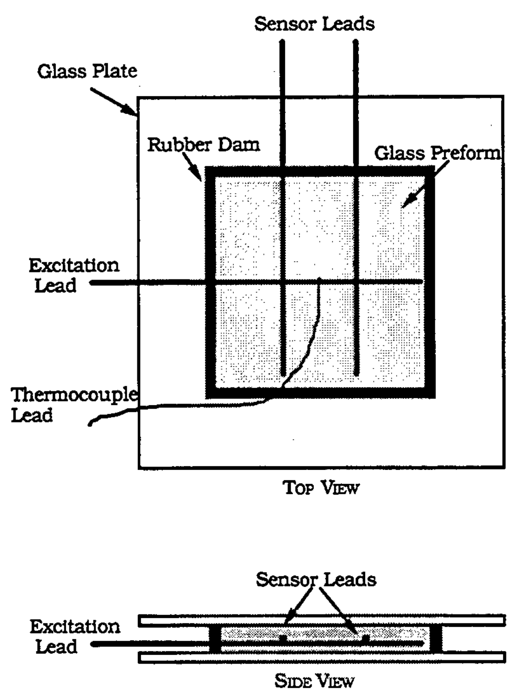


Figure 11. Experimental Setup for Cure Monitoring Study No. 1 Using SMARTweave.

4. Results

4.1 Flow Monitoring Experimental Results. Racetracking is a common phenomenon encountered during the filling of RTM mold cavities and occurs whenever the fluid filling the mold encounters a region of the mold not completely filled with preform material. Due to the lower resistance to flow, the fluid will tend to fill these regions first, significantly altering the form of the flow front. In our flow experiment, the flow rate was set as low as possible without forcing discontinuities in flow rate and the resin was injected into the side port in order to maximize the effect of racetracking and ascertain the ability of the SMARTweave system to detect the effect.

Figures 12 and 13 show the results of the experiment with six time slices showing digitized video stills (Figure 12) and real-time computer screen results of the voltage data (Figure 13). Note the racetracking along the corner lengths, as could be expected. Also note the faster filling of the "bottom" side of the box. This was most likely due to uneven placement of the female mold over the male mold allowing fluid to flow faster on the "bottom" side. Most significantly, note that the data for each time slice appears to indicate the existence of resin along the edges slower than the actual resin front. This is due to the placement of the wires 1/2 in away from the corner edges. The resin actually moves along the corner length ahead of where the wires can sense the flow since it is moving between the adjacent wires. The experimental correction for this is to place the wires directly on the corner edges.

Figure 14 shows a 3D view of the final time plot for a threshold value of 1.0 volt. The x and y axes are spatial showing the 13×16 grid, and the z-axis is time-to-threshold voltage. As viewed, the resin is injected at the right-hand side. The x-y plane is situated similar to that shown in Figure 9. Note that, as shown in the video sequences, the resin slows down considerably in moving transversely across a corner and speeds up in moving along a corner. Also note that the resin front slows down during the time when the front is its widest and speeds up when the front is narrower since the injection flow rate remains constant.

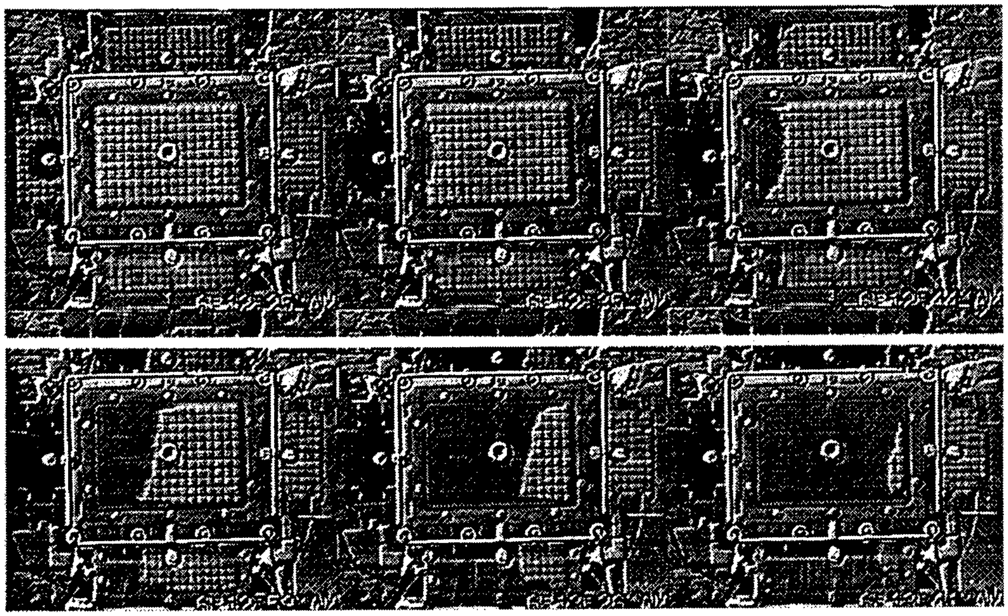


Figure 12. Digitized Video Stills of Experiment at 10.18, 22.82, 32.68, 41.16, 66.64, and 86.35 s Elapsed Time From Top Left to Bottom Right.

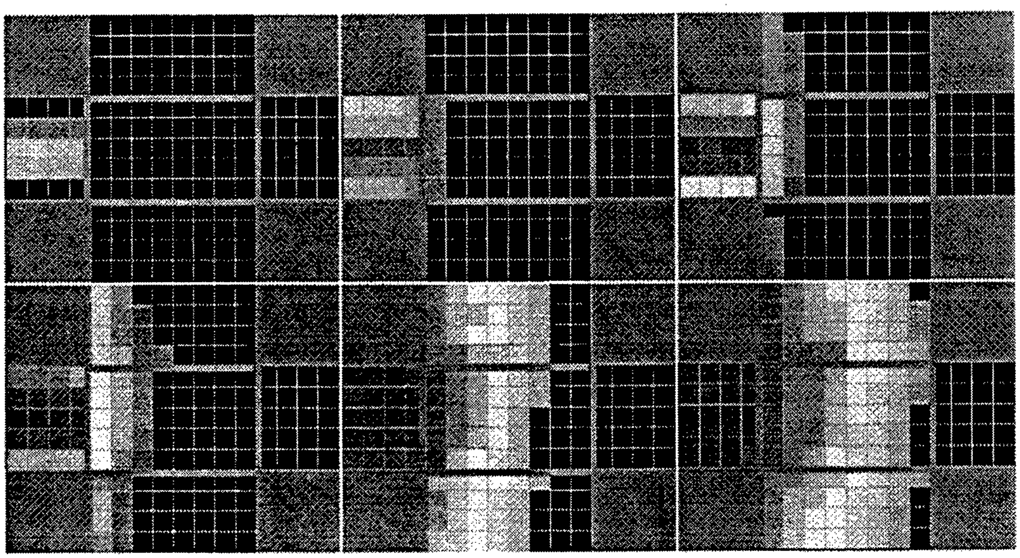


Figure 13. SMARTweave Data-Acquisition Screen Images at Same Time Instances as Figure 12.

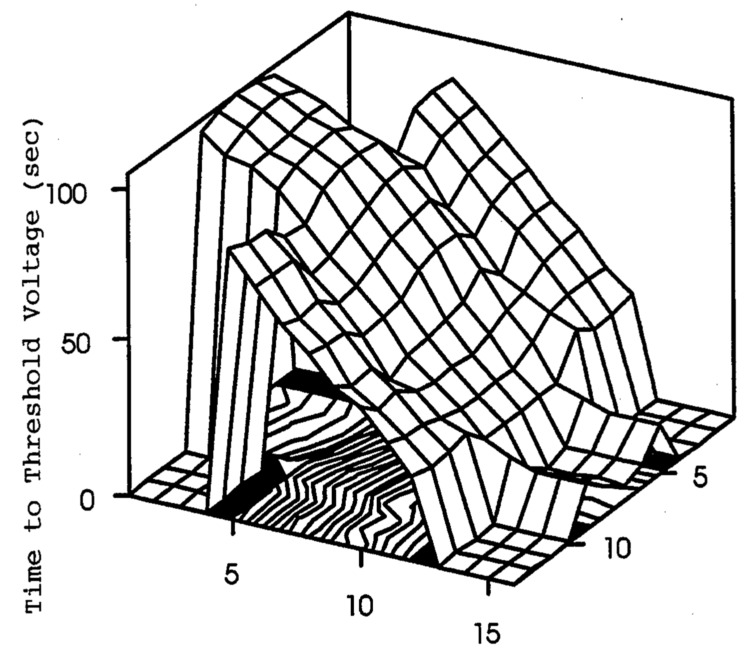


Figure 14. Plot of Time-to-Threshold Voltage vs. Location on Flattened Box Mold of Data for a Threshold Voltage Value of 1.0 Volt.

4.2 Cure Monitoring Experimental Results. Figure 15 shows the results of the first cure monitoring study as indicated in Figure 11. Since the resin cures at room temperature, no external energy is supplied and the temperature remains constant until the reaction exotherms. Note that the voltage readings are null until the resin is poured into the dam. The undulations in voltage readings directly after filling are due to the placement of the top glass plate. The voltage increases when the glass plate is pushed down onto the glass matting causing the excitation and sensor wires to move closer together. Likewise, it decreases when the plates shift and the wires are allowed to move apart. The voltage reading settles to a steady state level once the top glass plate is fixed. We believe the noise in the voltage reading after filling was due to the existence of a standard thermocouple in the system. This exemplifies how little electrical noise is required to upset the system. One of our goals is to understand the sources of noise in a standard industrial situation and learn to control the noise and/or deal with it in the SMARTweave hardware and software.

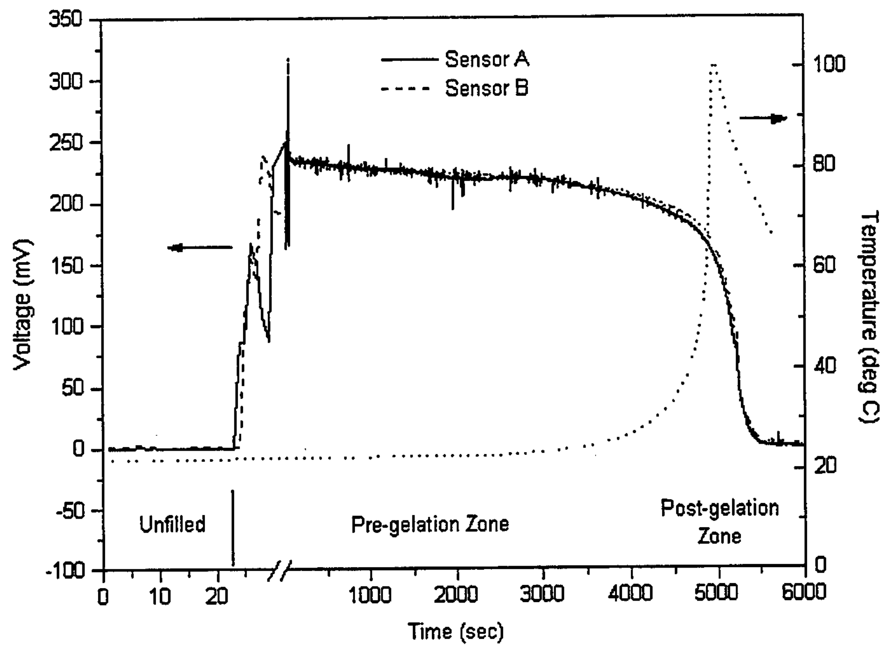


Figure 15. Results From Cure Monitoring Study No. 1 Showing Sensor Voltage and Temperature Data.

The voltage readings decrease slightly prior to the indication of exotherm. This may be due to either (or both) a piling up of mobile ions on one lead due to the DC excitation or an actual decrease in conductivity of the resin as it cures slightly prior to full exothermic reaction. The real meaning of the voltage data in terms of degree of cure from initiation through gelation to final cure is unknown at this point. In the completed tests, it is apparent that the SMARTweave data give more information than just the point of gelation. However, the definition of gelation with regard to the SMARTweave data need to be defined. In the data from this test, for a room temperature cure, it appears that the point of maximum exotherm coincides with the voltage plot's inflection point. Recall that the ionic mobility is a function of thermal excitation, viscosity, and degree of cure. Of course, these quantities are also dependent upon each other in very complicated ways, making it difficult to sort out the real meaning of the SMARTweave data. At a minimum, we are monitoring a marked indication of the exothermic reaction in a quick reacting system such as the vinylesters.

5. Technology Transfer: Composite Armored Vehicle

Figure 16 shows a section of the composite armored vehicle lower hull which was used to successfully demonstrate the effectiveness of SMARTweave technology to assist in the liquid molding manufacture of a complex part. The part was wired with an 8 × 16 SMARTweave grid in two planes—one on either side of an aluminum honeycomb core. The part was layed up on a metal tool and then vacuum-bagged for subsequent resin infusion using the SCRIMP process. The SMARTweave wires were separated by a single ply and were placed near the honeycomb layer. An innovative technique of splitting the sensing lines enabled us to effectively double the number of sensor "nodes" and obtain information on each side of the honeycomb core.

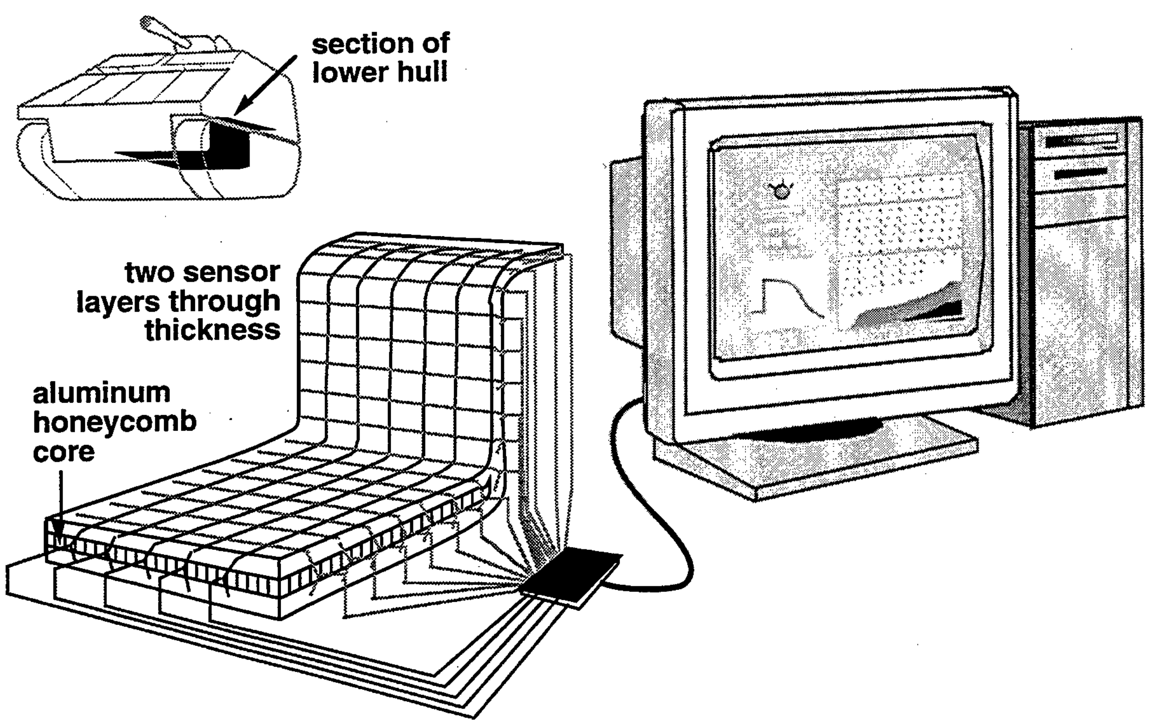


Figure 16. SMARTweave Technology Successfully Implemented in Manufacture of CAV Lower Hull Section at United Defense.

Figure 17 shows SMARTweave data as shown in real time on the computer screen during the filling of the lower section (horizontal section) of the part. "Bag" and "tool" refer to the

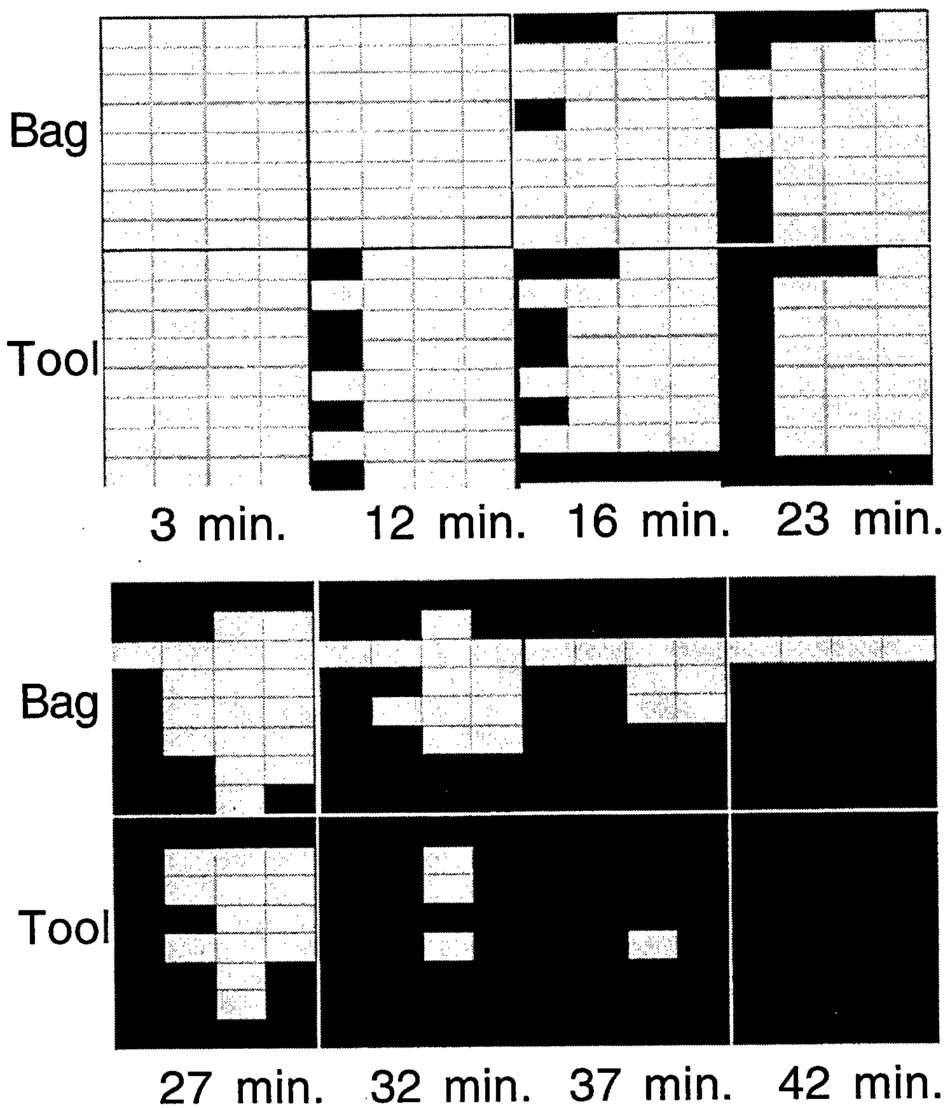


Figure 17. SMARTweave Data From Lower (Horizontal) Section of Part for Varying Time Increments.

top (bag side above the honeycomb layer) and bottom (tool side below the honeycomb layer) of the part, respectively. The fill begins as a line source along the front edge. Recall that while the progress of resin flow can be visually viewed through the vacuum bag on the top of the part, the portion of the part below the honeycomb layer cannot be seen and the progress of resin flow was only "visualized" through the existence of the SMARTweave monitoring system.

As flow progresses to 37 min, note the point on the "tool" side where the resin has enveloped a dry spot. Even though the "sensors" at the 42-min point all indicate complete fill, logic dictates that a dry spot exists at the point of last fill. Therefore, despite a relatively coarse SMARTweave grid (every 6 in), the formation of a dry spot in the process can still be monitored. If a vent had been located in that region of the tool on the lower surface, it could have been opened based upon the information from SMARTweave and the dry spot could have been avoided.

Figure 18 shows transient voltage data for two randomly chosen "sensor" nodes. Note the time lag of approximately 30 min between the existence of resin at the node on the horizontal section (where filling began) and the existence of resin at the node on the vertical section. Also note the upward shift in voltage at approximately 190 min. It was at this point that a new vacuum bag was fitted, sealed, and pressurized. The increase in consolidation pressure most likely caused the part to compress and the distance between sensing and excitation wires to decrease, resulting in a lower nodal resistance and a higher voltage across the drop resistor. The periodic jumps in voltage value are due to ambient electromagnetic noise.

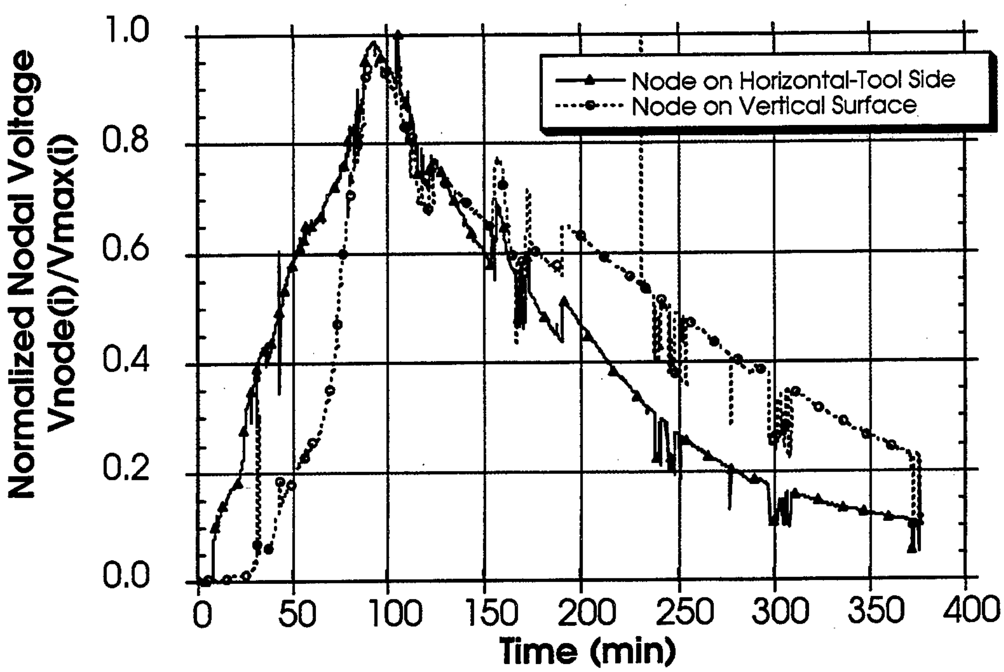


Figure 18. Transient Voltage Data for Two Randomly Chosen Sensor Nodes.

Several lessons were learned concerning the implementation of the SMARTweave sensor system in an industrial environment including the following:

- It is essential to electrically isolate the metallic tool, preform, and ground tool.
- Resin conductivity can vary significantly from batch to batch; it needs to be measured in situ.
- A robust mechanism is needed to pinpoint "bad" sensor leads during filling

Some improvements in the hardware and software are being incorporated as a result of these findings, including the following:

- Increased size of measurement grid to 64×64.
- Improved system robustness to static shock.
- Incorporated solid-state excitation switches.
- Added low-pass filter to remove 60-Hz noise.
- Added capability to change sense resistor via software on line.
- Implemented a lead/connection check feature.
- Established ability to determine voltage threshold based on in-situ-measured resin resistivity on line.
- Incorporated automatic on-line threshold and software filters.
- Improved real-time visualization of flow and cure data.
- Added RTDs for thermal measurement to reduce noise.
- Scanned full 4096 sensor population in less than 5 s.

Other areas currently being investigated include the following:

- Improvement of multiple plane capability for sensing in thick section parts.
- Optimization of data collection for flow simulation verification.
- Optimization of data collection for full-field flow sensing.
- Combined thermochemical and electrical characterization of resin systems for more complete understanding of relationship between direct current measurements and state of cure.

6. Conclusions

For liquid molding manufacturing processes, a sensor has been developed that

- is easy to place,
- is inexpensive,
- is quasi-full-field (in three dimensions for any size mold), and
- provides information about resin location, thermal gradients, and state of cure in real time.

The experiments discussed in this report used uncoated thin metal wires as excitation and sensing leads. While these wires work fine for glass fiber systems in a process such as SCRIMP, where they can easily be electrically insulated from the conductive components of the mold, adaptations to the conductive excitation and sensing leads have been devised for carbon fiber-based systems and for incorporation into closed metal molds. The choice of conductive leads has no effect on the SMARTweave system employed. Another consideration is the spacing in the plane, s, and through the thickness, h, of the conductive leads. Essentially, there is no practical limitation on the spacing in either direction as long as the through-thickness separation distance, h, is at least an order of magnitude greater than the in-plane separation distance, s, ($h >> s$), which is an acceptable assumption.

Further research is required to establish the meaning of the DC voltage data in terms of the cure and to validate SMARTweave in a manufacturing environment. Future work focuses on the transformation of the SMARTweave sensing system into a robust experimental system for detection of mold filling and resin degree of cure. The program will incorporate efforts to enhance the system measurement capabilities and an experimental program to correlate system measurements with process parameters. Industry feedback from ventures applying the SCRIMP, VARI, and RTM processes will guide system development and focus fundamental research.

7. References

Advani, S. G. "High Performance Computing and Modeling of Composite Manufacturing Processes Such as Resin Transfer Molding." Final Technical Report, Research Agreement No. DAAH04-93-G-0087, Center for Composite Materials, University of Delaware, 1995.

DeSchepper, D. C., and S. M. Walsh. "SMARTweave: A Sensor System for Resin Transfer Molding." *Proceedings of the 41st Sagamore Conference on Intelligent Processing*, Plymouth, MA, GPO, 1 September 1994.

Don, R. C. Personal communication, 1994.

Fink, B. K., S. M. Walsh, D. C. DeSchepper, J. Kleinmeyer, S. Bickerton, and R. C. Don. "Development of a Two-Sided Wiring Scheme for Resin Transfer Molding Flow Monitoring Using SMARTweave Sensors." Report No. 95-08, Center for Composite Materials, 1995.

Hunston, D., W. McDonough, B. Fanconi, F. Mopsik, F. Wang, F. Phelan, and M. Chiang. "Process Monitoring Sensors for Polymer Composites." NISTIR 4514, National Institute of Standards and Technology, Gaithersburg, MD, 1991.

Kikuchi, A., E. Higuerey, and J. Coulter. *ASME Journal of Engineering Materials and Technology*. Vol. 117, pp. 86–93, 1995.

Walsh, S. M. "Artificial Intelligence: Its Application to Composite Processing." *35th International Society for the Advancement of Materials and Process Engineering Symposium*, J. Janicki, V. I. Bailey, and H. Schjelderup, eds., The Society for the Advancement of Materials and Process Engineering, Covina, CA, pp. 1280–191, 1990.

Walsh, S. M. "In-Situ Sensor Method and Device." *U.S. Patent No. 5,210,499*, 11 May 1993.

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12a. DISTRIBUTION/AVAILABILITY STATEMENT
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13. ABSTRACT *(Maximum 200 words)*

Resin transfer molding (RTM) and other liquid molding techniques hold the promise of affordable manufacturing for a variety of critical Army applications including the Composite Armored Vehicle (CAV) and Comanche helicopter. A critical barrier to the development of a quality control system and to our ability to consistently manufacture quality parts using RTM is the availability of an integration-friendly and cost-friendly flow and cure sensing system. SMARTweave is an ARL-patented system for sensing the existence and state of cure of resin in RTM. The process uses a grid of conductive filaments laid within an RTM mold. As resin fills the mold, gaps between transverse filaments at the flow front are bridged by resin, and an electrical circuit is closed providing a signal that the flow front has reached that node. SMARTweave provides researchers and manufacturers with a sensing system that can be placed into an RTM mold and provide low-cost, real-time information about the resin location and state of cure. This information is useful to validate and refine flow and cure models and to study flow and cure for various RTM techniques and materials, providing insight on the role of a complex system of variables that include viscosity, mold temperature, resin inlet temperature, mold design, port and vent locations, pressure, preform architecture and permeability, preform placement techniques, etc.

14. SUBJECT TERMS
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