

ARMY RESEARCH LABORATORY



Process Control for Resin Transfer Molding (RTM)

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13. ABSTRACT (Maximum 200 words) This document presents the results of the process control for a resin transfer molding (RTM) study. RTM is a composite materials processing method that involves placing a preform of dry reinforcement in a mold, injecting a thermoset resin into the mold, curing the resin, and demolding the finished part. This report describes the equipment and methodology for in-mold resin flow mapping and control. Mold port arrays are used to achieve directional control of in-mold resin flow. A novel flow mapping system based on SMART Weave was implemented and tested. Combining the flow mapping and resin control schemes will lead to closed loop automation of the injection process.				
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TABLE OF CONTENTS

	<u>Page</u>
LIST OF FIGURES	v
1. INTRODUCTION	1
2. EXPERIMENTAL	2
2.1 In-Situ Resin Flow Mapping	2
2.2 In-Situ Flow Control	9
2.2.1 Manipulation of Preform Permeability	10
2.2.2 Control of Viscosity	10
2.2.3 Control of Pressure Gradient	10
2.3 Tool Design	12
3. CONCLUSIONS	19
4. RECOMMENDATIONS	26
5. REFERENCES	29
BIBLIOGRAPHY	31
DISTRIBUTION LIST	33

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LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1. SMART Weave	4
2. SMART Weave sensing gap	4
3. Subscale SMART Weave layup board	8
4. Block diagram of SMART Weave system	8
5. Test mold design	12
6. Test part preform design	14
7. Location of SMART Weave with respect to port array	14
8. Trial 1 node voltages at end of injection	15
9. Trial 1 peak node array voltages during cure	15
10. Trial 1 node array voltages after cure	16
11. Trial 2 node array voltages at end of port B,1 injection	17
12. Trial 2 node array voltages at end of port A,3 injection	17
13. Trial 3 node array voltages at end of port A,1 injection	18
14. Trial 3 node array voltages at end of port C,1 injection	18
15. Trial 3 node array voltages at end of port C,3 injection	19
16. SMART Weave diagram	21
17. Equivalent circuit of a single wetted node	21
18. Equivalent circuit of 3 wetted nodes in series	22
19. SMART Weave diagram with multiple parallel wetted nodes	23
20. Equivalent circuit of unwetted node with multiple parallel wetted nodes	23
21. Equivalent circuit of wetted node with multiple parallel wetted nodes	24
22. SMART Weave diagram of grounded cold cathodes	25

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1. INTRODUCTION

Resin transfer molding (RTM) is a composite materials processing method that involves placing a preform of dry reinforcement in a mold, injecting a thermoset resin into the mold, curing the resin, and demolding the finished part. Good parts are produced only if the resin has completely infiltrated the preform. Failure to achieve complete infiltration results in increased void content and dry or only partially wet-out fiber, leading to weak areas in the part.

Infiltration (fluid saturation of a porous material) of the preform is dependent on a number of factors. Hansen's work on RTM process modeling (Hansen 1990) defines the time required to inject a preform in terms of resin pressure differentials, preform permeability, resin viscosity, and the surface tension between resin and fiber. Preform permeability is determined by fiber type, orientation with respect to resin flow, and volume fraction. While resin viscosity and injection pressure can be adjusted to suit the particular RTM application, preform configuration (fiber type, orientation, and volume fraction) is determined by the part design and its intended end use. Thus the flow of resin in a molded RTM preform is heavily influenced by the size and complexity of the part and its mold. Even in relatively simple part configurations, the permeability of the preform may vary at different points. A large and/or complex part or a multicavity mold may have a wide range of preform permeabilities.

In the production of preforms, even with good quality control, variances exist from one preform to the next. Subtle flaws in preform construction can produce marked changes in preform permeability, particularly in thin cross sections. While the performance of the final part may not be affected, these changes in permeability affect the resin flow path. A local permeability increase due to a preform flaw increases local resin flow rate. Decreased local permeability decreases local flow rate. Either case may result in a failed injection by changing the desired route of resin flow.

During the injection process, the resin will establish flow paths along lines of least resistance in accordance with the conditions described previously. Often this means that the resin will bypass areas of the preform (areas of low permeability) and arrive at the mold vents before infiltrating all areas of the preform. Typically, resin injection is considered complete when resin is detected in the mold vents (either by sight or sensor). Areas of dry fiber or voids are not detected until the part is cured and demolded. While it is possible to alter injection parameters (flow rate or injection pressure) or make modifications to the mold to reduce the incidence of injection flaws, searching for acceptable injection parameters is a

time-consuming trial-and-error process that can generate a large number of scrap parts. Even then, there is no guarantee that the part can be successfully injected or that, in a series of injections, every part is completely infiltrated. Even on well-developed RTM applications, scrap rates due to failed injections can be high.

These difficulties inhibit the use of RTM processing on applications that could benefit from its many advantages. Part configurations that fully exploit the advantages of advanced composites are too often relegated to labor-intensive hand layup of expensive prepegs and consolidation using vacuum bagging and autoclaves because the potential of the RTM process has not been fully realized.

The research described in this report seeks to provide a solution to RTM injection problems by developing techniques to monitor resin infiltration in situ (in the mold) and subsequently control the injection in real time.

The work is divided into three major tasks. The first task involves the design and implementation of an in-situ resin mapping system. The mapping system provides information about the flow of resin through the enmolded preform and renders the information for use in a timely and coherent fashion.

The second task deals with the problem of steering the resin in the enmolded preform. Methods for controlling the flow of resin in a preform are examined, and a working resin steering system is developed and tested.

The final task involves the production of test parts using the equipment and procedures developed in tasks 1 and 2.

2. EXPERIMENTAL

2.1 In-Situ Resin Flow Mapping. Various methods of in-situ detection of resin in the enmolded preform have been proposed and implemented by other researchers, and a number of different sensor designs exist for detecting the presence of resin, resin viscosity, and degree of cure. These different types can be categorized by the physical property they are designed to measure.

One class of sensors works on the principle that thermosetting resins are electrolytic in the uncured or curing condition. Measurements are made of the permittivity and/or conductance of the resin (Kranbuehl, Williamson, and Loos 1991). Measurement methods vary somewhat. Some sensors consist of anodes and cathodes of dissimilar metals and measure the voltage potential generated. Another uses a capacitor to measure the permittivity of the resin. Additional circuitry is incorporated to convert the measurements to a proportional DC voltage output. This output can be conveniently read by a computer data acquisition system or voltage meter channelled to a chart recorder.

Another sensor type measures acoustic attenuation by a wetted laminate stack (Saliba et al. 1992). Ultrasonic pulses are transmitted through the laminate stack to a receiver. Attenuation of the signal by the laminate is measured. Although this method has been used primarily as a means to determine the viscosity and hence the state of cure of sample laminates, it does offer the potential for resin detection in a dry preform.

The original research proposal included a sensor evaluation and selection phase. This work was deleted under the terms of the contract. We were made aware of a sensing methodology known as SMART Weave, which is currently under development at the U.S. Army Research Laboratory (ARL). SMART is an acronym for Sensors Mounted As Roving Threads. SMART Weave is patented by Dr. Shawn Walsh of the ARL Materials Directorate (U.S. Patent 5,210,499) (Walsh 1993). Briefly stated, this novel sensing method uses conductive threads arranged in a nonintersecting grid-like configuration (see Figure 1). The threads form sensing gaps or "nodes" at the apparent intersections (see Figure 2). The ends of the threads are connected to electrical devices that measure or provide electrical signals. With proper conditioning, the electrical properties (resistance, dielectric constant, etc.) of a material can be measured. In the case of SMART Weave, an electrical property measured at a sensing node might indicate the presence or absence of a material (i.e., resin) in the sensing gap.

SMART Weave offers a number of advantages as a system for mapping in-situ resin flows. Mapping resin flow in an enmolded preform requires a number of sensing locations based on the size of the mold and resolution desired. Traditional sensing technologies rely on discrete sensors and require a minimum of two electrical leads per sensing site. For example, if 25 sensing sites in a 5×5 array are required for a specific part configuration, then at least 50 electrical leads are needed. For a similar sensing array using SMART Weave, only 10 electrical leads are needed. The full impact of this advantage is better shown mathematically.

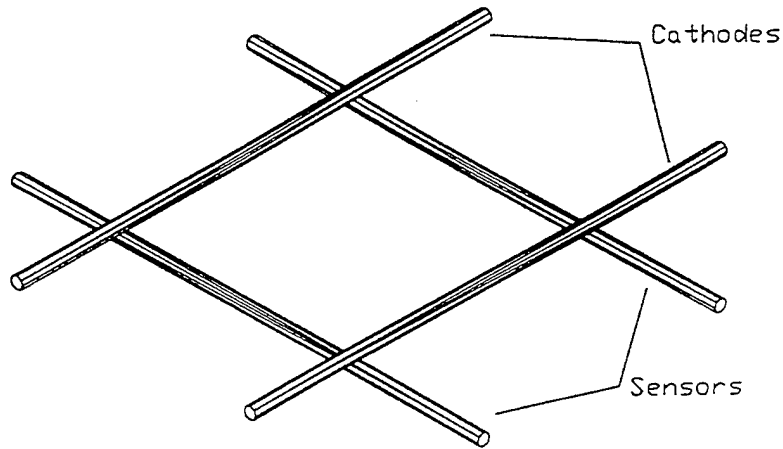


Figure 1. SMART Weave.

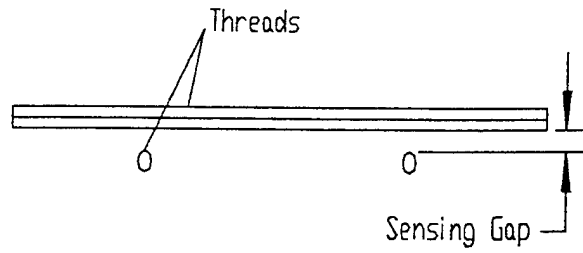


Figure 2. SMART Weave sensing gap.

Let

R = Number of rows of sensors,

C = Number of columns of sensors,

S_{tot} = Total number of sensors = $R \times C$, and

L_{tot} = Total number of sensor leads.

For traditional sensing technologies,

$$L_{\text{tot}} = 2 \times S_{\text{tot}} = 2 \times R \times C.$$

For SMART Weave,

$$L_{\text{tot}} = R + C.$$

This reduction in the number of electrical leads for a given sensor array also has an impact on the complexity of the equipment used to detect the electrical signals as well since the maximum number of channels required to read a given sensor array is directly proportional to the number of electrical leads. Other advantages of SMART Weave are enumerated in Walsh's patent.

Thermoset resins typically have a lower resistance in liquid form relative to their high resistance after curing. In the SMART Weave patent description, Walsh notes a resistance for an uncured resin in the $10^6\text{-}\Omega$ to $10^{11}\text{-}\Omega$ range and $10^{12}\text{-}\Omega$ to $10^{15}\text{-}\Omega$ range after cure. Thus even in liquid form, the resin demonstrates relatively high resistance. Because of this, Walsh uses an electrometer (a device designed specifically to measure very small electrical signals) to measure resistance. Resistance of a material is measured by applying a known voltage, measuring the resulting current or voltage, and calculating the resistance using Ohm's law. In any case, the resistance measurement is made indirectly from current and voltage measurement.

Preliminary to constructing a system for making the requisite electrical measurements, three resin systems were selected from in-house stores for simple resistivity measurement. They are:

- Addax Liquid Formulation (ALF) 215, a Shell Epon 862 Epoxy,
- ALF 238, a Ciba Geigy Araldite PY307/Araldite GY 508 Epoxy blend, and
- ALF 245, a Dow 441-400 Vinyl Ester.

These systems are regularly used at Addax, and their processing characteristics are known. ALFs 238 and 245 have been used extensively for RTM processing. In addition to measuring the resistances of the neat uncured resin, resistance measurements were made with the systems "doped" with a carbon black dispersion in various concentrations. Adding a carbon black dispersion is a method of increasing the conductivity of resin systems. It was felt that it may be difficult to get consistent results if the resistance of the resin systems proved to be too high. With expected resistances in the megaohm range and greater, the signal returned from a SMART Weave sensor node would be in the microvolt or microamp range and

possibly much smaller. In an electrically noisy environment (as might be found in a production setting), such small measurements might be difficult to discriminate from background noise.

Preliminary resistance measurements made using a Fluke 87 multimeter with the test probes spaced 1 cm apart are given in Table 1.

Table 1. Resistances of Uncured Resins at Various Carbon Black Loadings

Resin	Resin Resistance (Ω)					
	0% Carbon Black	1% Carbon Black	2% Carbon Black	3% Carbon Black	4% Carbon Black	5% Carbon Black
ALF 215	>1.0E+8	3.5E+6	2.6E+5	3.0E+5	2.3E+4	1.3E+4
ALF 238	>1.0E+8	6.1E+6	6.5E+6	5.8E+6	4.6E+6	1.6E+5
ALF 245	>1.0E+8	>1.0E+8	>1.0E+8	>1.0E+8	4.5E+3	1.0E+3

Any resistance reading of >1.0E+8 Ω is above the range measurable with the Fluke 87. As can be seen, doping the resins with carbon black is effective in lowering the resistance of the uncured resins. Conductivity increased in the epoxy systems (ALFs 215 & 238) at low concentrations of carbon black while the vinyl ester system remained unaffected until carbon black concentration reached 4% when a precipitous drop in resistance was observed.

As mentioned earlier, Walsh's implementation of SMART Weave utilized an electrometer to detect a decrease in resistance across the node, signaling the arrival of the resin flow front. Since resistance is calculated from current or voltage measurements, it seemed possible to treat the rows of conducting filaments in a SMART Weave as cathodes (that is, apply a known voltage to those filaments) and treat the columns of the weave as sensing elements. In this way, any current leakage across the sensing gap could be measured as an increase in the voltage of the sensing filament. This would allow the use of common data acquisition equipment and forego the need for an electrometer.

The proprietary RTM equipment used at Addax controls both resin injection pressure and volume flow rate in real time. The control system utilizes a PC-compatible computer fitted with an eight-channel, programmable-gain analog-to-digital (A/D) conversion board. Gains are programmable from 0.5 to 1,000.

This board connects to a 16-channel multiplexor board. The A/D board offers 12-bit resolution (4,095 divisions) in ranges from ± 0.005 V to ± 10 V. The computer also has a 24-channel digital input-output (DIO) card and a proprietary motion control card to control the resin pump. Using this system, it is possible to set up a SMART Weave grid in the cathode-voltage sensor mode that is 24 cathodes by 16 sensing channels, yielding 384 total nodes.

A subscale SMART Weave layup board (see Figure 3) was constructed to determine the feasibility of this approach. The base is constructed of nonconductive fiberglass sheet stock. Carbon fiber tows (Grafil 34-700WD), 12k) serve as the conductive filaments and are separated by two layers of 4-mm-thick E-glass cloth, yielding a sensing gap of 8 mm. The interval between adjacent sensor or cathode lines in the SMART Weave is 50 mm. A block diagram of the entire SMART Weave system is shown in Figure 4. The sensor lines are connected to the high side of the differential inputs on the multiplexor board. The low side of the inputs are tied to the system ground. The multiplexor board is in turn connected to the A/D board on the computer. The cathodes are connected to a +5-V power supply via single-pole, single-throw (SPST) solid-state relays (SSRs) that are switched by the DIO board in the computer.

A computer program designated SMRTMOLD (actually SMARTMOLD, but DOS limits file names to eight characters) was written to control the actual implementation of the SMART Weave sensing array. (SMARTMOLD is the designation given to the entire mapping and flow control apparatus as well.) To illustrate the operation of SMRTMOLD, assume that the SMART Weave array consists of two cathode filaments and two sensor filaments (see Figure 4). The cathodes are normally off. The program samples each node in the array by switching on cathode 1 and sampling sensor 1 and then sensor 2. This determines the state of sensor locations (C2, S1) and (C2, S2). Then cathode 2 is switched off, and the cycle repeats. SMRTMOLD is configured to allow the user to easily change the number of switches and sensors, provide a text or graphical display of the resin flow front, and log the data to a disk file.

The mapping system was connected to the layup board shown in Figure 3. The nodes were soaked with the candidate resin systems, and node voltages were captured. The results of these tests are shown in Table 2. The results verify the feasibility of using the cathode-sensor method of detecting resin in the sensing nodes. ALFs 215 and 238 (epoxies) have substantially higher conductivity than ALF 245 (vinyl ester) at all levels of carbon black doping and give acceptable results undoped.

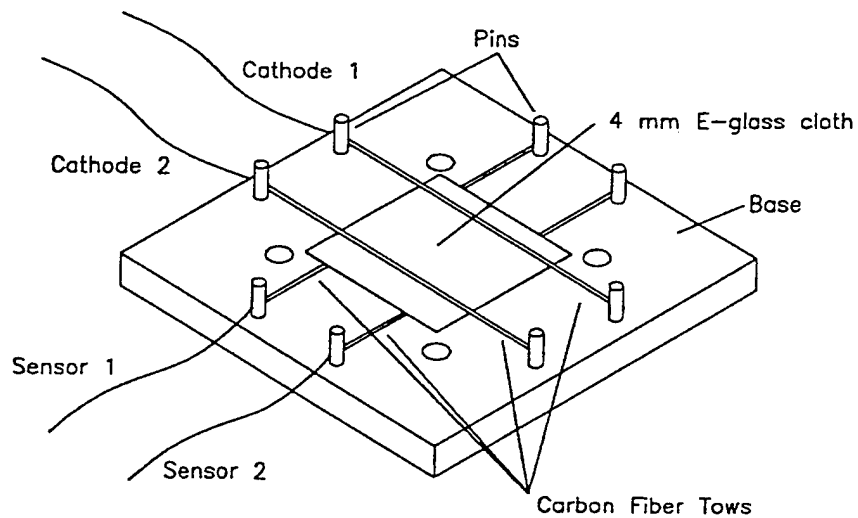


Figure 3. Subscale SMART Weave layup board.

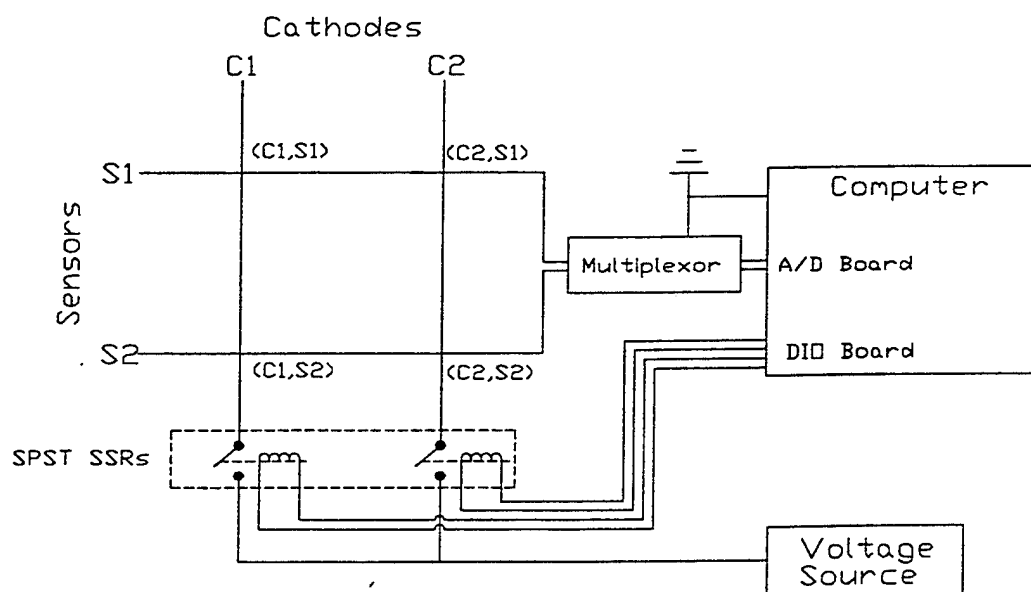


Figure 4. Block diagram of SMART Weave system.

Table 2. Node Voltages of Uncured Resins Obtained From SMARTMOLD

Resin System	Node Voltages (V)			
	0% Carbon	0.25% Carbon	0.5% Carbon	0.6% Carbon
ALF 215	0.010	0.016	0.030	N/A
ALF 238	0.012	0.020	0.037	N/A
ALF 245	0.001	0.001	0.002	0.006

2.2 In-Situ Flow Control. The objective of this task is to find a method for guiding the flow of resin in an enmolded RTM preform and develop the method into a workable system. The system must be effective in the general case and, therefore, must be independent of the preform composition and construction.

Resin flow through reinforcing fibers has been the subject of a great deal of theoretical and experimental research. Researchers (Hansen 1990 and Gauvin, Chibani, and Lafontaine 1986) agree that the flow rate of resin through a mass of fiber is a function of fiber bed permeability, resin viscosity, surface tension between fiber and resin, and the pressure gradient (ΔP) across the control volume. The flow rate of resin through a fiber bed can be characterized with a one-dimensional Darcy's Law as

$$Q = \frac{KA}{\mu} \frac{dP}{dL},$$

where

Q = Volumetric flow rate,

K = Permeability,

A = Cross-sectional area normal to the direction of flow,

μ = Fluid viscosity, and

$\frac{dP}{dL}$ = Pressure drop per unit length of material.

Permeability is a function of fiber type, fiber volume fraction (V_f), and orientation of the fiber with respect to the resin flow direction. The part design will determine most of the permeability parameters for a given preform. Then only the resin viscosity, surface tension, ΔP , and, to some extent, permeability of the fiber bed or preform, are available for manipulation. ΔP and V_f are directly controllable. Based on this and constrained by equation 1, there are three methods for "steering" the resin in situ.

2.2.1 Manipulation of Preform Permeability. The preform permeability is a function of the fiber volume of the preform. V_f can be altered by selectively changing the compaction force exerted on the preform. This concept is utilized in RTM applications where an (intentionally) oversized preform is enclosed in a mold that has a "pinch ring" on one of its parting line faces. The pinch ring compresses the preform and restricts resin flow to the volume it encloses by locally increasing V_f . An example of this technique is found in Becker (1989).

2.2.2 Control of Viscosity. Viscosity and, to a small extent, surface tension of most uncured resins are inversely proportional to temperature. By changing the temperature of the resin, the viscosity can be changed. Boundaries are placed on this method of control by the cure kinetics of the specific resin.

2.2.3 Control of Pressure Gradient. The ΔP across the resin flow is one of the more easily manipulated parameters in the RTM process. Depending on the application, ΔP can be changed by controlling the air pressure ahead of the resin flow front by evacuating the mold, by changing the pressure applied to the resin at the injection point, or by a combination of both. Changing ΔP by evacuation is possible only on sealed molds. Therefore, only net-molded RTM applications are candidates for control of pressure ahead of the flow front. All RTM applications would be candidates for control of resin injection pressure.

Manipulation of preform permeability as a method of flow control could be achieved by selectively altering the compaction of the preform to affect a local change in the fiber volume fraction. Increasing or reducing the force applied to opposing faces of the mold might accomplish this task in response to data from the flow mapping system provided that the mold was sufficiently compliant. This approach might be applicable in elastomeric RTM molds but would be difficult to implement in "hard" tools unless special provisions (perhaps segmenting the mold) were made.

Control of resin viscosity (specifically the selective control of viscosity in the mold) requires that some method be devised for heating or cooling the resin as it infiltrates areas of the enmolded preform. Success of this method is tightly coupled to the cure kinetics of the resin system used. The three candidate resin systems under consideration for this program all demonstrate a directly proportional relationship between resin temperature and viscosity but are sensitive to thermal cycling; raise the temperature of the system too high, and the system might cure before the preform is completely infiltrated.

Using resin pressure for in-situ resin steering requires some method of achieving directional control as well as ΔP control. Recall that the equation for flow rate in a fiber bed relates the flow rate to viscosity, permeability, the fiber bed cross-sectional area normal to the direction of flow, and pressure per unit length. As the length of the fiber bed increases, ΔP must increase to maintain a uniform flow rate. At some fiber bed length, ΔP exceeds a practical range. This limits the size of the part that can be successfully injected using a single injection site and still offers no means of directional control. These limits can be circumvented by adding features in the mold to deliver resin relatively unimpeded to the enmolded reinforcement such as runners or additional injection ports. If an array of injection ports is used, then the resin could be steered by injecting resin at selected ports. The resin would flow through the preform according to its local properties (permeability, area, etc.), but with sufficient port density, good directional control could be achieved.

The local control of permeability mentioned previously requires active, dynamic parts in the mold. This limits the scope of the process and increases its cost and complexity. Viscosity control would require a means of controlling resin temperature in all areas of the mold. This approach presents a number of difficulties. The time interval for creating a small temperature change in a selected area of a mold might be measured in minutes. That sort of response time makes control difficult. There may be application for a viscosity approach, but it and permeability control fail in one important respect. They would work well only on smaller part configurations. Control of permeability or viscosity would work only in proximity to the injection port. As the resin flow front moves out through the preform of a larger part, injection pressure requirements increase rapidly and soon overwhelm any attempt at further infiltration because of drag induced by the resin flowing past more and more reinforcing fiber. Big parts would then require additional ports or runners to deliver the resin unimpeded to remote segments of the mold where the chosen directional control scheme would be implemented.

Since one way to expand the scope of RTM composites processing uses multiple injection sites, it is logical to utilize this same method to implement in-situ resin steering. Incorporating an array of ports into the mold design eliminates the need for additional steering schemes where utilizing some other scheme (viscosity or permeability control) would still require additional injection ports or runners to address larger part configurations. This approach is not without problems. The ports must not affect the integrity of the finished part. Discontinuities in the part structure due to details in the port anatomy have to be considered. Such discontinuities can cause areas of stress concentration and may affect part performance. This problem is minimized in thicker part configurations and may be of no concern provided that the port details do not grossly affect the part. Multiple ports might also affect model cycle time if they are difficult to clean. Despite these drawbacks, the advantages in utilizing this method for in-situ resin steering outweigh the disadvantages.

2.3 Tool Design. A simple mold (shown in Figure 5) was designed to test resin steering via port arrays.

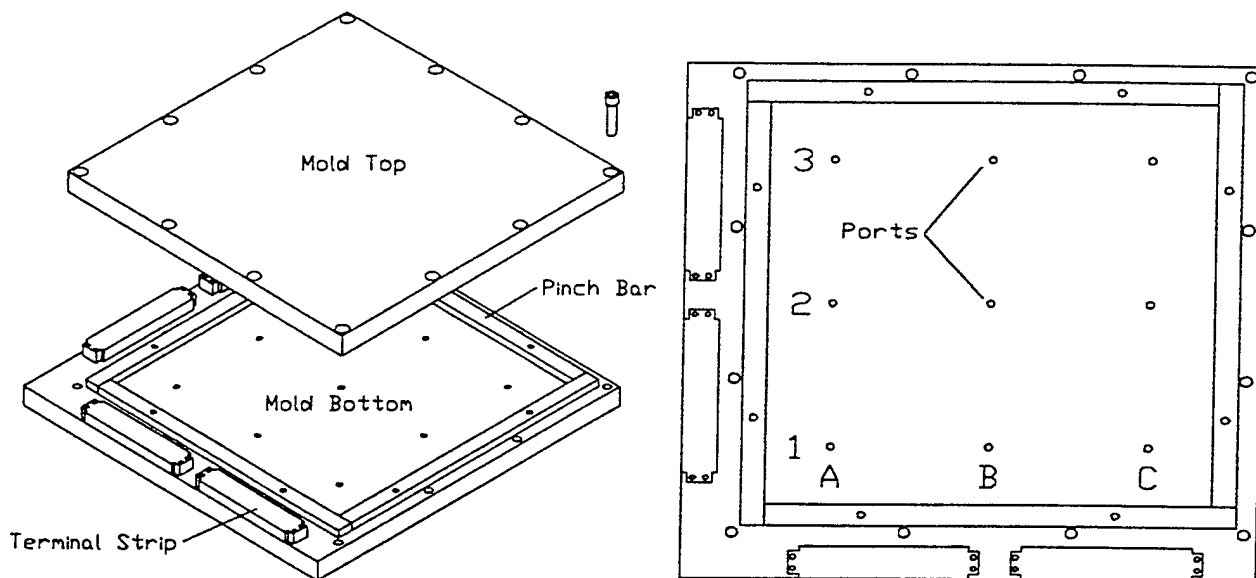


Figure 5. Test mold design.

The mold is of aluminum and steel construction and will make a part approximately 360 mm × 360 mm × 10 mm. The mold has a three-port by three-port array as well as provisions for a seven-

cathode $\times$ seven-sensor SMART Weave array. Ports are identified by column letter and row number with the lower left port (in the mold orientation shown in Figure 5) designated port A,1.

The preform design for the test part is shown in Figure 6. The seven layers of 1-mm-thick E-glass cloth that make up the preform are laid in the cavity made by the pinch bars. SMART Weave is opposite the ported half of the mold and consists of three layers of two plies of 0.1-mm E-glass cloth with the conductive filaments (Grafil 34-700WD, 12k carbon fiber tows) captured between the layers, yielding a sensing gap of 0.2 mm. A sheet of 0.1-mm-thick nylon film is placed between the top layers of glass cloth that make up the SMART Weave array and the mold half to ensure isolation between the charged filaments and the metal components of the mold. Insulating tape is also placed on the pinch bars. As can be seen from Figure 6, the layers of SMART Weave cloth and the filaments extend beyond the pinch bar of the mold, insulating the filaments from mold surfaces. The threads are tied to the terminal strips mounted on two edges of the mold. When the mold is closed, the threads and the insulating glass cloth are captured and compressed between the pinch bars and the mold top, locking them into place and restricting any resin flow outside the pinch bars. The spatial relationship between the SMART Weave array and the injection ports can be seen in Figure 7.

Experimentation to determine the effectiveness of the SMART Weave implementation and the feasibility of using injection port arrays as an in-situ resin steering process consisted of attempts to make parts. ALF 238 was selected as the resin system for initial part-making attempts. It has the highest uncured conductivity (see Table 2) of the three resin systems tested and is used extensively at Addax for RTM applications.

For the first attempt, the resin (ALF 238) was doped with carbon black (0.25% carbon black by weight) to increase its conductivity. On this and all subsequent attempts, cathode potential was +5 V, mold and resin were at ambient temperature (approximately 21° C), and resin was injected at a rate of 20 cm³/min with a peak allowable pressure of 20 psi. (The proprietary Addax injection system monitors the resin injection pressure in real time and reduces the injection rate if the injection pressure exceeds a specified setpoint.) The injection was intentionally stopped before the SMARTMOLD resin mapping system indicated complete infiltration. This was done to verify that the results obtained from the mapping system were truly representative of the actual resin infiltration pattern since the flow of resin through the preform could not be observed. The mold was injected solely through port A,1 (see Figure 5).

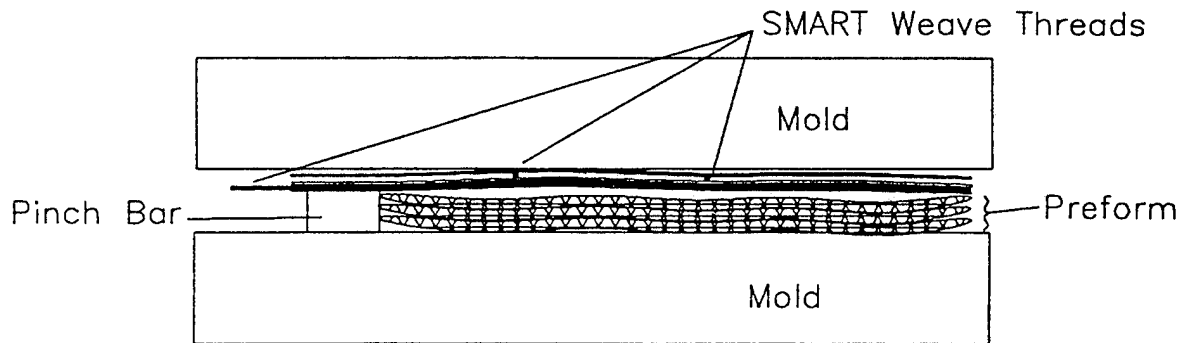


Figure 6. Test part preform design.

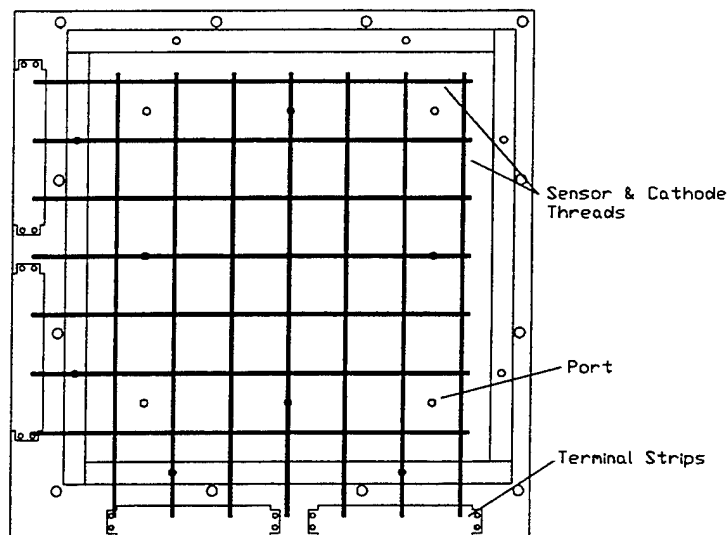


Figure 7. Location of SMART Weave with respect to port array.

During injection, initial wetted node voltages were approximately 50 mV. As the injection proceeded, voltages on those same nodes increased, eventually exceeding 400 mV at the nodes proximal to the injection port. This pattern continued throughout the injection. After the cured part was demolded, a band of unpigmented resin led the entire resin flow front. Figure 8 is a graph of the node array voltages taken immediately at the end of the injection and prior to cure. The higher voltage values were observed in the proximity to injection port A,1 (this corresponds with the left corner of the graph), with the values decreasing as the distance from port A,1 increased. The carbon black dispersion (a very fine particulate with a diameter of approximately 0.001 mm) may have been filtered from the resin as it was forced through the preform, consequently changing the resin conductivity.

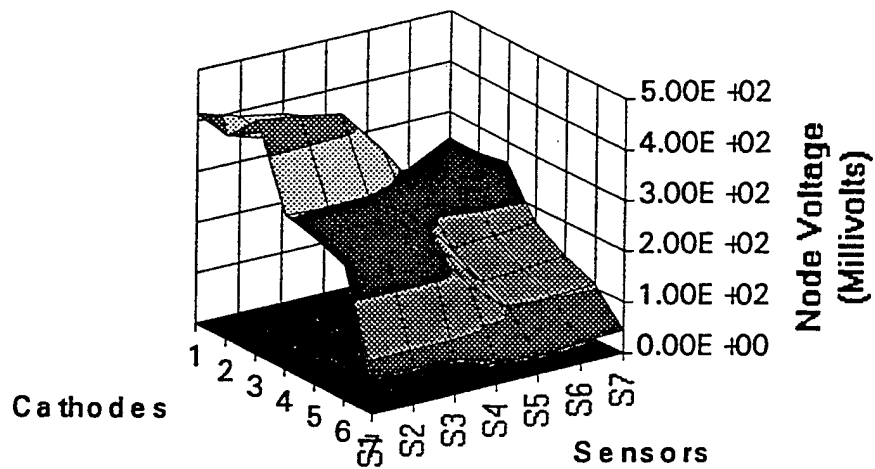


Figure 8. Trial 1 node voltages at end of injection.

During cure, all node voltages increased as the resin heated and then decreased to the original baseline values as the resin gelled. Figure 9 shows peak node voltages of nearly 2 V with node voltages exceeding 500 mV in nearly all areas of the preform.

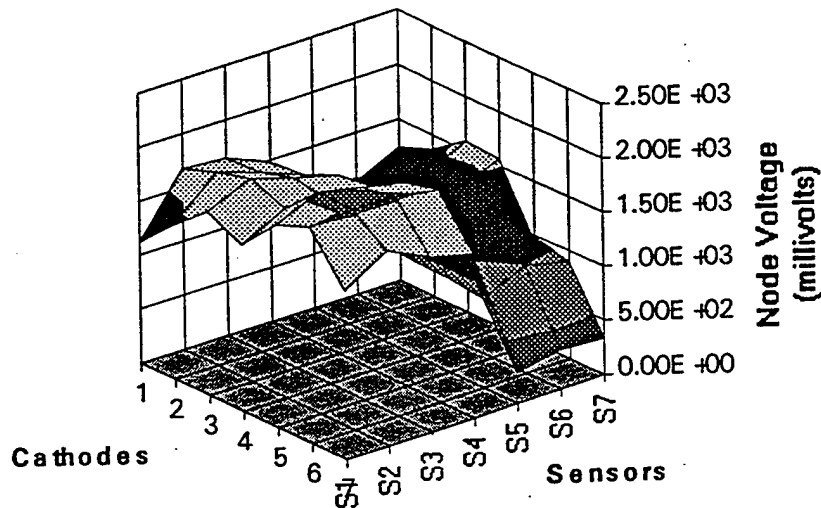


Figure 9. Trial 1 peak node array voltages during cure.

Figure 10 shows the node voltages obtained after the part cured, immediately prior to demolding. All node voltages are under 4 mV after the part is cured.

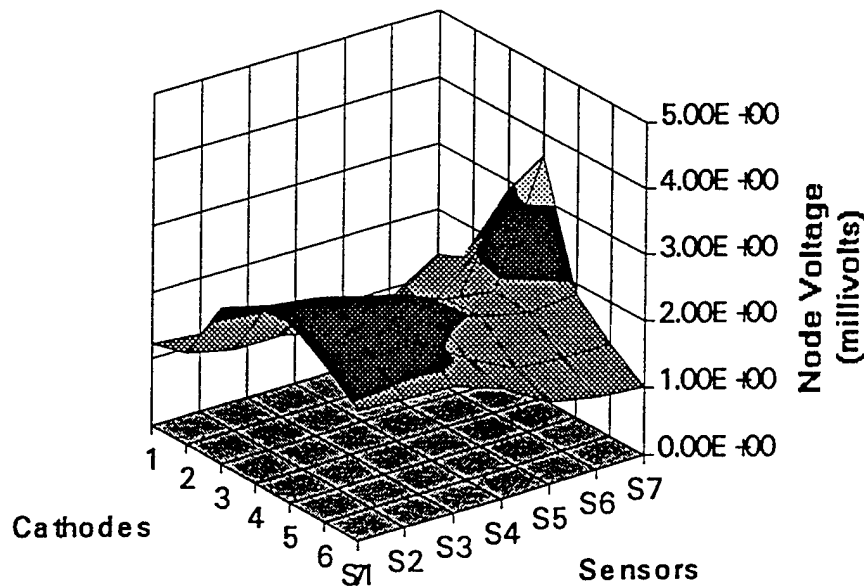


Figure 10. Trial 1 node array voltages after cure.

The next trial injection was designed to test the effect of using undoped resin and to attempt to steer the resin in the mold based on the feedback from the SMRTMOLD mapping system. Other injection conditions remained the same. Port B,1 served as the initial injection port. Figure 11 represents the SMRTMOLD infiltration map at the end of port B,1 injection. Injection was continued at port A,3. Again, injection was halted before SMRTMOLD indicated complete infiltration of the preform. Figure 12 represents the infiltration map at the end of port A,3 injection. Examination of the cured preform verified the injection pattern detected by the SMRTMOLD mapping system.

The final trial proceeded in three stages with injection beginning at port A,1 (Figure 13), continuing at port C,1 (Figure 14), and ending at port C,3 (Figure 15). Injection was stopped when SMRTMOLD mapping indicated complete preform infiltration. Inspection of the part after demolding verified complete infiltration.

In all trials, nodes proximal to the earliest injection sites returned higher voltages (see Figures 8, 12, and 15). It should be noted that in trial 1, when the resin was doped with carbon black, the range of

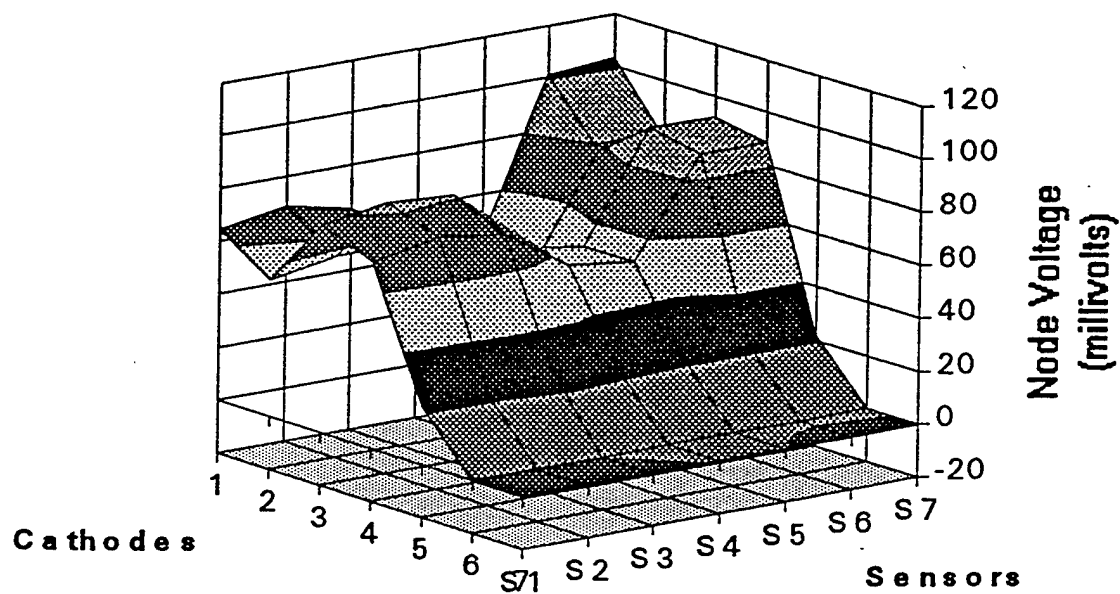


Figure 11. Trial 2 node array voltages at end of port B,1 injection.

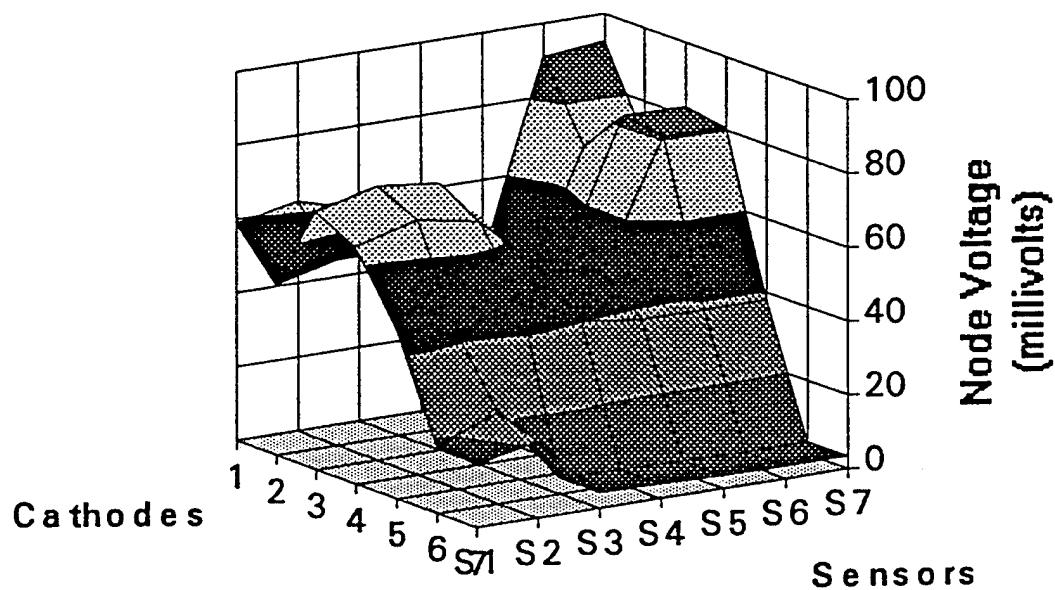


Figure 12. Trial 2 node array voltages at end of port A,3 injection.

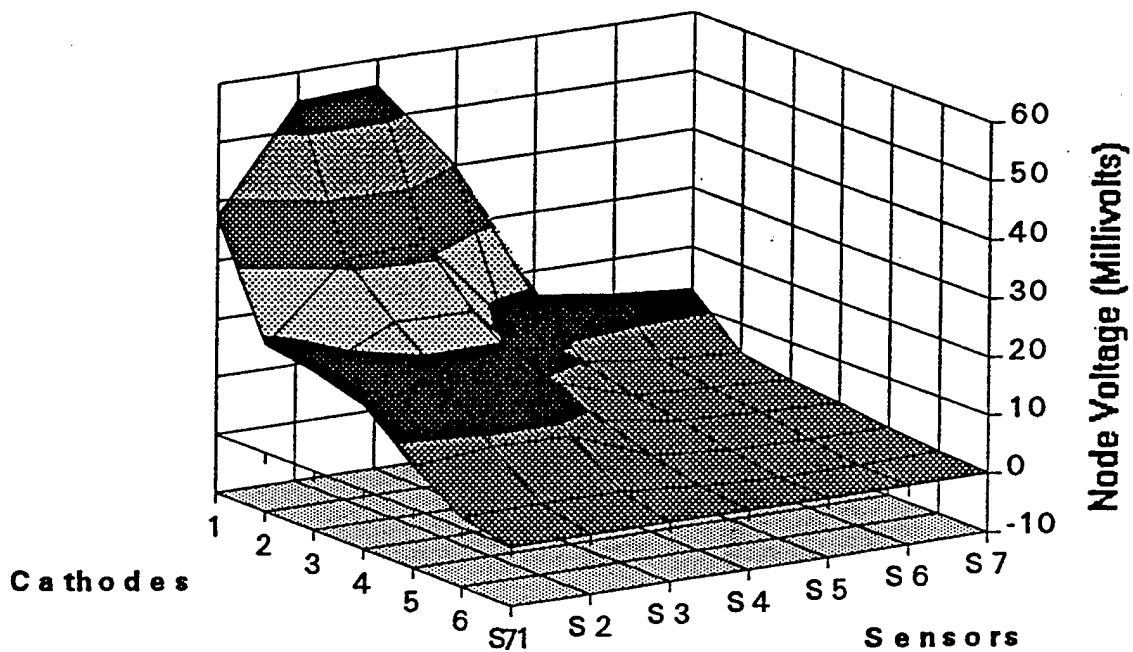


Figure 13. Trial 3 node array voltages at end of port A,1 injection.

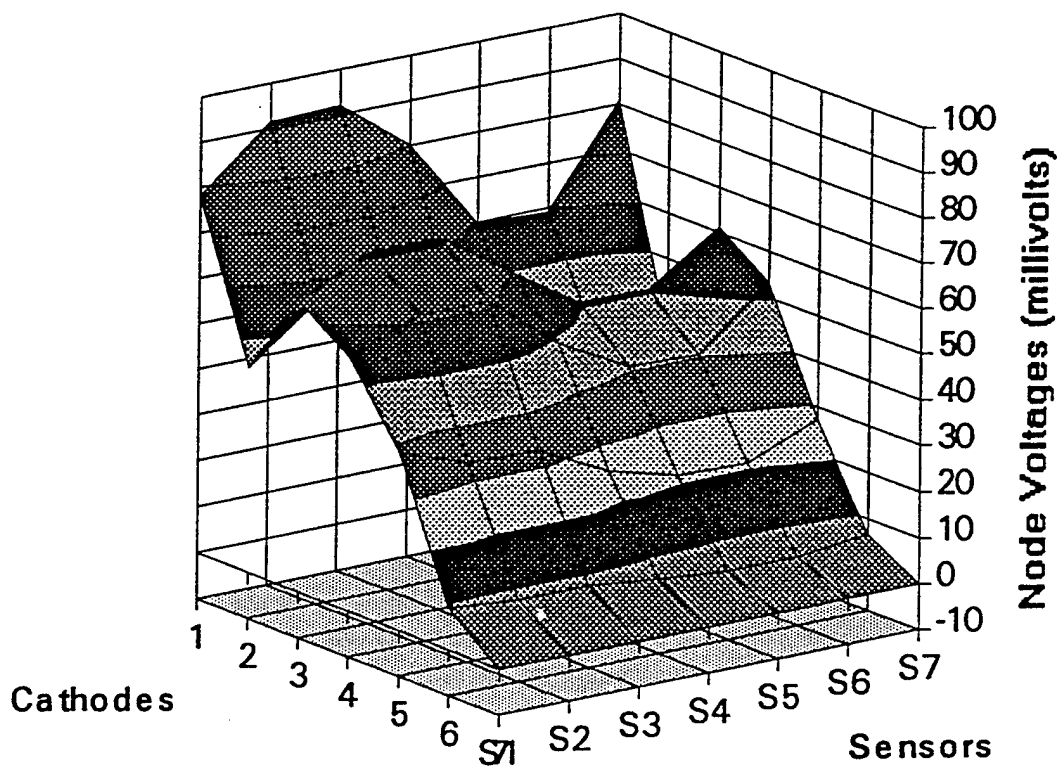


Figure 14. Trial 3 node array voltages at end of port C,1 injection.

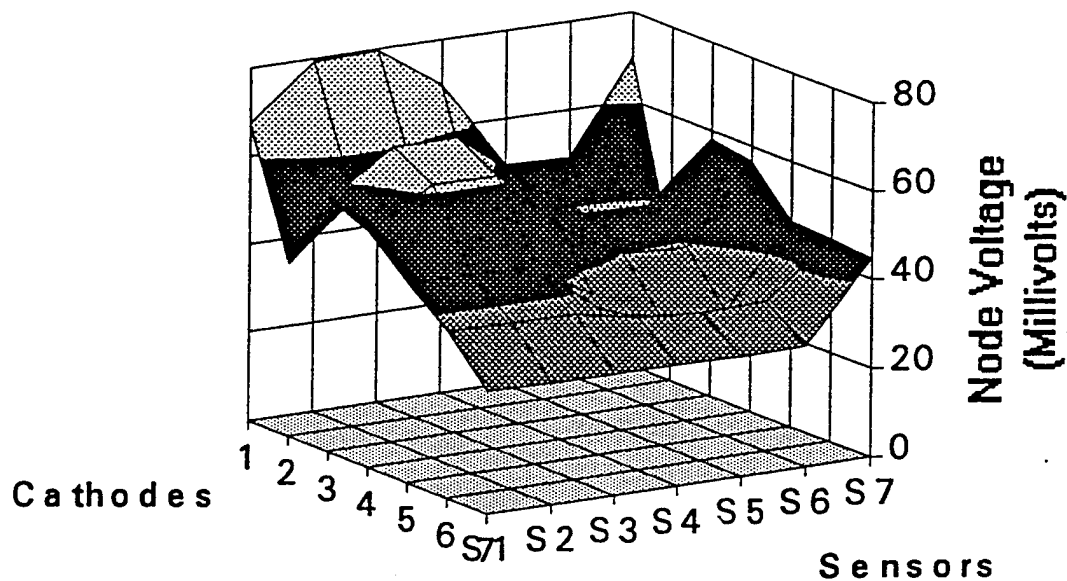


Figure 15. Trial 3 node array voltages at end of port C,3 injection.

wetted node voltages was from 100 to 500 mV (see Figure 8) at the end of injection, while trials 2 and 3 (undoped resins) had wetted node voltage ranges of 20 to 80 mV. The differences in node voltages between trial 1 and the other trials can be explained by the resin conductivity increase resulting from carbon black doping of the resin system used in trial 1. This could also explain the large node voltage range seen in trial 1 if the carbon black were filtered from the resin as it moved through the preform. What cannot be explained at this time is the range of wetted node voltages seen within trials 2 and 3.

3. CONCLUSIONS

Use of carbon black to improve resin conductivity was, by and large, ineffective. Adding the carbon black dispersion to the resin increases its conductivity markedly, but as mentioned earlier in the report, the action of forcing the resin through the preform tends to filter out particulate matter in the resin system, resulting in a progressively less conductive resin flow front that may confuse the mapping system. For at least the epoxy resin system used for these experiments, carbon black doping proved unnecessary. No injections were attempted using the less conductive vinyl ester resins, but tests of conductivity performed using the SMARTMOLD equipment indicate that such resins could be used without trouble.

Using the cathode-sensor implementation of SMART Weave proved to be an effective alternative to direct resistance measurement across the sensing gap to detect resin. Either method requires a computer and multiplexing on both axes of the array to obtain the necessary isolation, but the cathode-sensor implementation replaces a relatively expensive electrometer (currently about \$5,000) and two multiplexors with an A/D converter board and DIO board, both of which can be inherently multiplexing (total cost <\$500). Another advantage to the cathode-sensor method is the speed of data acquisition. Resistance sampling rate with an electrometer in the ranges required is approximate 50 Hz. Sampling rates in excess of 3 kHz are available in low-end A/D boards. While sampling rate is not an issue with small sensing arrays, large arrays are another matter, particularly as this technology matures and we begin pushing the envelope in terms of mapping resolution and injection speeds. One aspect of SMART Weave requires further refinement. There is currently no way to completely isolate the nodes when voltage measurements are performed. The causes and effects of this phenomenon are described as follows.

Consider the case of a SMART Weave array like the one shown in Figure 16. Node (C1, S1) is wetted, and all other nodes are dry. Figure 17 shows the equivalent circuit diagram of a single wetted SMARTMOLD sensing node. R_N represents the wetted node resistance (assume $10^8 \Omega$), R_S is the A/D board input impedance ($10^7 \Omega$), and the cathode voltage E is +5 V.

The voltage drop from B to O (V_{B-O}) is the voltage change detected on the sensor 1 and can be easily calculated as

$$V_{B-O} = E - E \times R_N / (R_N + R_S).$$

From the aforementioned values

$$V_{B-O} = 0.455 \text{ V.}$$

Assume that the SMART Weave array in Figure 16 has nodes (C1, S1), (C1, S2), and (C2, S1) wetted and node (C2, S2) unwetted. When SMARTMOLD samples node (C2, S2), cathode 2 is enabled (hot). Electrical current flows from cathode 2 to sensor 2 through wetted nodes (C2, S1), (C1, S1), and (C1, S2).

Then when node (C2, S2) is sampled (with cathode 2 still hot), the electrical current that has traveled through the circuit path described previously causes a voltage change in sensor 2, and SMARTMOLD may falsely interpret that node (C2, S2) is wetted.

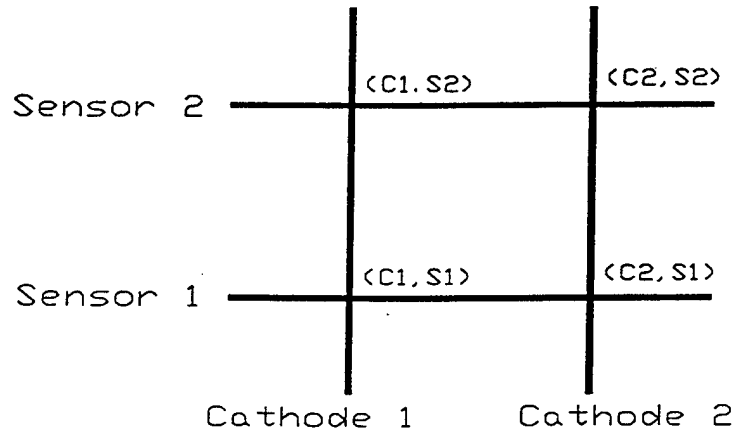


Figure 16. SMART Weave diagram.

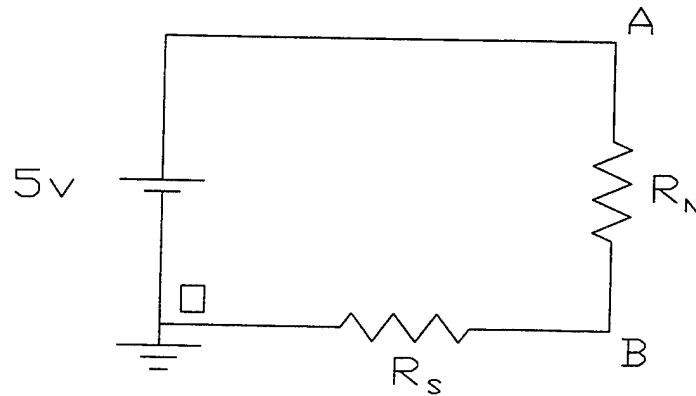


Figure 17. Equivalent circuit of a single wetted node.

The equivalent circuit for node (C2, S2) is shown in Figure 18.

Under the same initial conditions for R_N , R_S , and E , but reading node (C2, S2), the voltage detected on sensor 2 is

$$V_{B-O} = E - E \times (3R_N)/(3R_N + R_S)$$

$$V_{B-O} = 0.161 \text{ V.}$$

Depending on the threshold established for resin detection, SMRTMOLD might still interpret node (C2, S2) as unwetted. However, as more nodes become wetted, the total node resistance is decreased due to the effect of resistors in parallel rather than in series as in the first example.

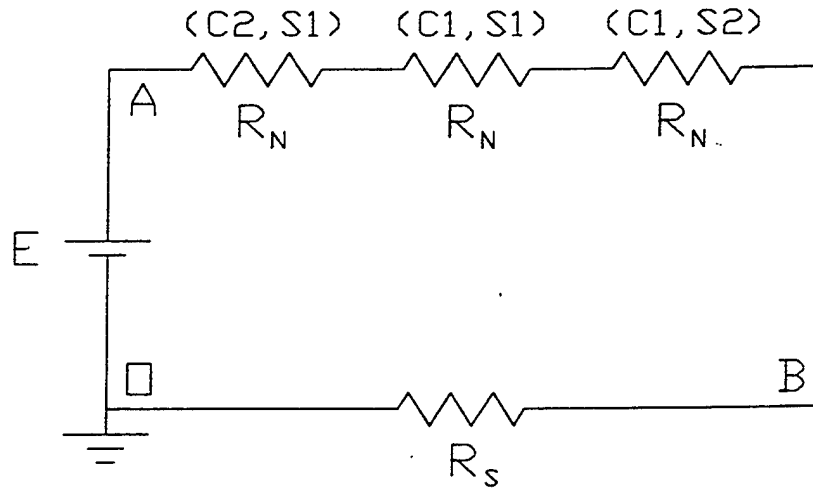


Figure 18. Equivalent circuit of three wetted nodes in series.

Consider Figure 19. All nodes except node (C2, S4) are wetted. The equivalent circuit between cathode 2 and sensor 4 is shown in Figure 20.

When cathode 2 is hot, the total resistance (R_T) between cathode 2 and sensor filament 4 becomes

$$R_T = R_N + 2 \times R_N/3.$$

Under the conditions described previously, the voltage reading V_{B-O} obtained from sensor 4 is then

$$V_{B-O} = 0.283 \text{ V.}$$

As more SMART Weave nodes are wetted and the system becomes more and more parallel (from the standpoint of total node resistance), the circuit path between hot and cold cathodes becomes more conductive, leading to false dry node resistances that approach wetted node resistances. Extrapolating Figure 19 to the seven-by-two array that could be found using the test equipment, R_T would be $4R_N/3$ and V_{B-O} would be 0.349 V, 77% of the wetted node voltage. This phenomenon applies no matter what method is used to detect resin wetting of nodes (direct resistance or cathode sensor).

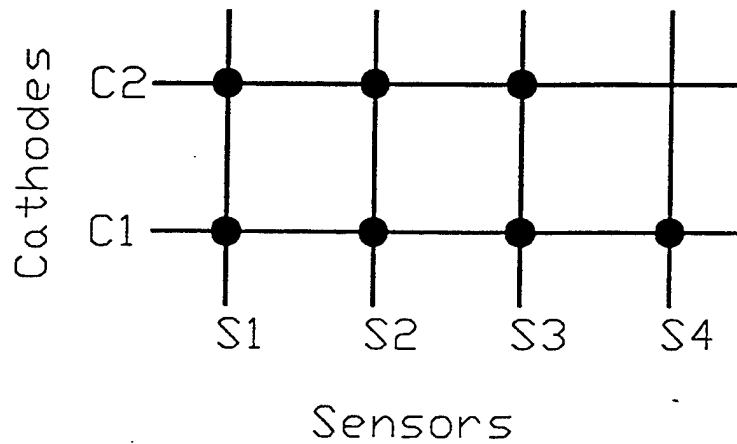


Figure 19. SMART Weave diagram with multiple parallel wetted nodes.

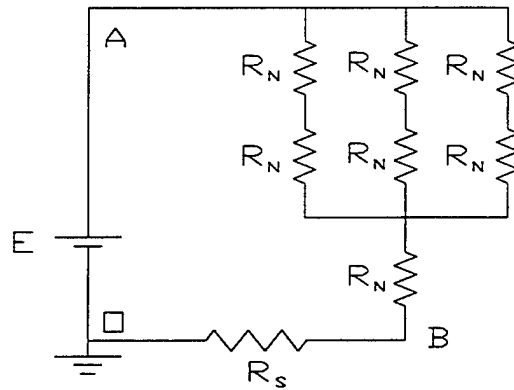


Figure 20. Equivalent circuit of unwetted node with multiple parallel wetted nodes.

The other difficulty in achieving stable readings from the SMART Weave nodes arises from the same short-circuiting phenomenon described previously. This involves sensor voltages that are artificially elevated due to multiple node pairs being wetted on two sensor filaments. Again referring to Figure 19, assume that all the nodes are wetted and the other conditions (E , R_N , R_S) are identical to the previous cases. Cathode 1 is hot, and sensor 1 is being sampled. Now the equivalent circuit looks like Figure 21.

The R_T between cathode 1 and sensor 1 becomes

$$R_T = 5 \times R_N / 8,$$

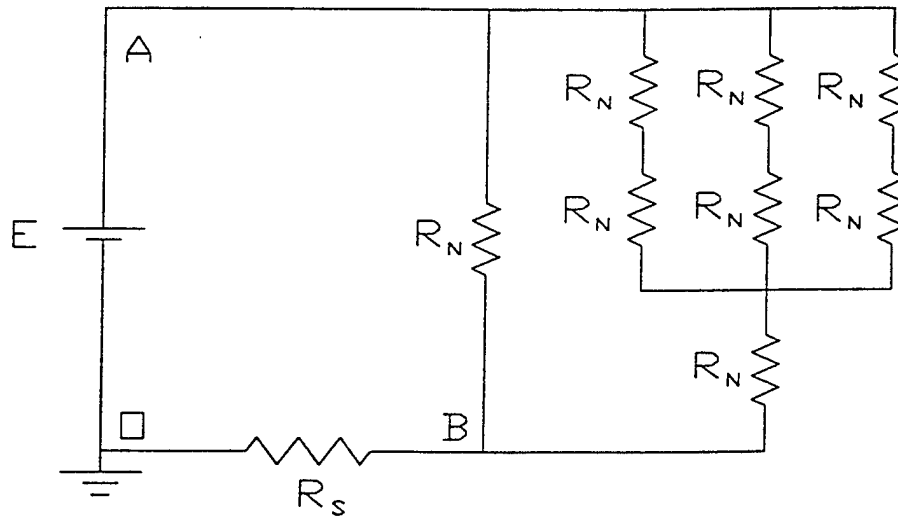


Figure 21. Equivalent circuit of wetted node with multiple parallel wetted nodes.

and the voltage detected on sensor 1 becomes

$$V_{B-O} = 0.690 \text{ V.}$$

Again as more and more nodes become wetted, the voltages detected on already wetted nodes will increase. The aforementioned conditions affect the stability of the SMARTMOLD system and to some extent may account for the range of node voltages seen during the trials.

One potential means of solving this problem involves sinking the cold cathode filaments to system ground and can be accomplished by using an SPDT relay with one pole tied to the voltage source and the other to ground.

Figure 22 shows the proposed improvement to SMART Weave with the SPDT relays in place. During a node sampling run, only one cathode is hot at any time. In the improved method, all the remaining cathodes are sunk to ground (cathode 2 in Figure 22). Current continues to flow from the hot cathode through wetted nodes to the cold cathodes, but the current flow in the cold cathodes is routed to ground, in effect pulling cold cathode potentials to zero and eliminating cold cathodes as a potential current route to a sensor line.

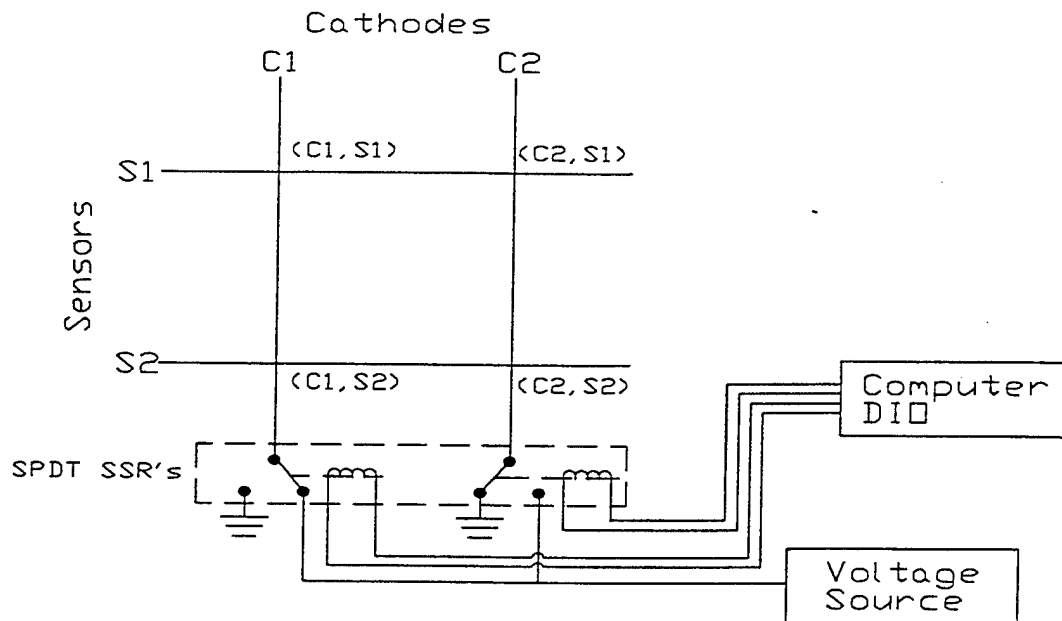


Figure 22. SMART Weave diagram of grounded cold cathodes.

This method causes an increase in current flow from the voltage source and depending on the conductivity of the resin system, may be applicable only on smaller SMART Weave arrays. The stability of larger systems may be affected if current flow to ground via the cold cathodes becomes great enough to alter source voltage.

It may also be possible to condition the SMART Weave data in software to account for the short circuiting effect; however, the solution might well become too cumbersome to apply in real time. Steering the resin through the use of port arrays shows great promise as a general-case solution to RTM injection problems. Although the number of injection trials was limited, it was not difficult to inject the resin to either accomplish incomplete injection in a particular pattern or, if desired, select to completely infiltrate the preform. This method may be used to reduce cycle times as well since multiple sites could be injected concurrently. As mentioned earlier, port design is a consideration for this approach to in-situ resin flow control. In this case, ports were simply 7-mm holes drilled through the 25-mm aluminum plate that served as a mold half. The ports served for either injection or venting the mold and were plugged manually after they had served their purpose. After the cured part was demolded, small resin sprues were attached to the part at the port locations. While these sprues were easily broken off the part, in some applications the resulting appearance may be undesirable. This problem could be addressed in the design of the port. Technology from direct mold injection of thermoplastics might be applied to RTM port design to yield a molded part port detail that is nearly invisible.

In trial 1, resin was injected solely through port A,1, and 90% of the preform was infiltrated. Given more injection time, the preform could have been completely infiltrated from this single port. The array of ports available for injection was never fully exploited in the course of these experiments. Full utilization of the entire port array in a controlled fashion would lead to a marked reduction in infiltration times.

First and foremost, further work needs to be done to SMART Weave before it can fulfill its potential as a resin-flow mapping system.

Full automation of the injection process is the next logical step in closing the RTM loop. Using arrays of ports to inject parts will facilitate the process. Mating an injection head to a computerized motion control device (gantry or robot) would allow the system to address a wide variety of mold configurations. Programming of the injection sequence could be done "off-line." Injection would proceed from the initial site until feedback from the flow mapping system signals completion and the injection head is moved to the next site. The sequence continues until the injection is complete. The positioning accuracy and repeatability of current motion control equipment is more than sufficient for this application. An improved port design could include features to facilitate the interface with the injection head.

One could envision a number of schemes in a production setting. For instance, a conveyor system could feed a diverse mix of loaded RTM molds to a robotic injection cell. An operator initiates the injection by plugging the control system into mold-mounted SMART Weave connectors and selecting the proper injection sequence. The injection is carried out flawlessly in response to the feedback available from the sensor array. The mold is disconnected and shuttled to the curing station. The mold sensor array is again utilized to control the cure. The part is demolded, and the mold prepped and reloaded with a preform and queued for injection.

An injection system such as the one described previously would truly be a general-case solution to RTM injection.

4. RECOMMENDATIONS

The project successfully demonstrated that the SMART Weave concept can be combined with readily available instrumentation to create a practical resin sensing-and-control system suitable for use in RTM

of complex components. Addax recommends that a demonstration program be conducted that will prove the feasibility of the SMART Weave-controlled RTM manufacturing cell with general-purpose capabilities.

This program would incorporate:

- A refined sensing system.
- A large RTM mold incorporating SMART Weave sensing and multiport steerable injection, including porting and valving for the mold.
- A computer control system to detect resin flow sensed through SMART Weave and to create the commands to operate the multiport injection system. Control of injection would be in real time on a large part.
- Resin mixing and injection equipment tailored to the multiport system requirements and the requirements of the resin system. The motion of this equipment would be computer-controlled to transport the injection nozzle(s) (Gantry or robot).

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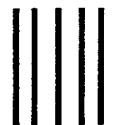
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