MANUFACTURING OF COMPOSITE PARTS VIA VARTM

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UU

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Examples Of Current Composite Structures Fabricated Via VARTM

Vacuum Assisted Resin Transfer Molding (VARTM)
Vacuum-Assisted Resin Transfer Molding

Schematic And Processing Sequence

Vacuum Bag

Peel Ply

Injection Line
Connected to Resin Bucket

Distribution Media
Breather
Preform
Vent
Connected to Vacuum Port

Processing Steps

PREFORM MANUFACTURING
- Precision Laser Cutter
- Preform Binding Station

IMPREGNATION STEP
- National VARTM Workcell
- Fully Automated Injection Station

CURE STEP
- Induction Heating
- Localized Resistive Heating

QA/QC
- Fiberoptic Health Monitoring
- Modal Analysis
UD-CCM Intelligent VARTM Capabilities I

- Resin Characterization and New Resin Development
- Preforming
  - Laser Cutter
  - 3-D Preforms
    - High-Performance (3TEX)
    - Binder (Solectria)
    - Complex Shape (Bally Ribbon)
  - SMART-Preforms with integrated weaved sensors
- Permeability Station
  - 2-D
  - Fully automated 3-D

Simulation

- 3-D Liquid 1 (LIMS 5.0)
- Analytical Tool for Design Optimization

Sensor

- Flow and Cure

Tool-Mounted (reusable)

Embedded Bag-Mounted
Control and Automation
- Fully Automated Sequential Injection
- Flow Rate Control

Advanced VARTM Processing
- RTM-like Parts
  - Surface Quality
  - Dimensional Tolerances
- Co-Injection Resin Transfer Molding
  - In-Plane
  - Layer by Layer
- FASTRAC
- Elevated Temperature

Tooling
- Rapid Prototyping
- Rapid Water Solvable Tooling
- Reusable Bagging

Multifunctional Materials
- Structural
- Fire
- Ballistic
- Signal
Process Design Tool

MATERIAL DATABASE
- Viscosity
- Permeability
- Infusion Temperature
- Gelation Time

No strong VARTM experience needed to make basic decisions on material and injection scheme.

Database and Design capability can be increased over time.

Flow Behavior
- Infusion Time
- Number of Sequential Injection Lines
- Length of Non-Saturated Flow Region
Automated Permeability Estimation (In-Plane Only)

Online Capturing of Flow-Behavior

- Permeability Estimation (2D) for each preform/distribution media (Offline)
- Future work will incorporate online permeability estimation

Post-Processing of Image Files
- Online/Offline
- Noise Reduction
- Arrival Time Calculation for all Pixels (1024x1024)

Permeability Estimation for Different Distribution Media
Database: Preform Permeability

- **Breather:**
  Airtech Airweave N10
  400g/m²

- **Random mat:**
  Vetrotex Unifilio 816
  450g/m²

- **Non crimp:**
  320g/m²

- **Complex:**
  Vetrotex Stitchment
  2400g/m²

- **Woven:**
  Boeing 300g/m²

- **Woven:**
  Vetrotex 324
  800g/m²
Added Permeability Data to Database of Commercially Available Distribution Media

Database includes now 5 Distribution Media (4 more in progress)
Design tool chooses DM based on lead length and flow times

Data Courtesy of Gaetan Denis
Resin Arrival Times Measured By SMARTWeave

- Increase of non-saturated flow region with number of layers
- Resin arrival times increase linearly with number of layers
- Important VARTM feature ==> Elimination of dry spots during sequential injection with correct opening of injection ports
- Optimization of injection length (sequential injection) is important to reduce cycle times, especially for thick-section and large-scale composite parts
Influence of Sequential Injection Lines

Injection Time Improvement with 20 Sequential Injection Gates

Injection Time Improvement Versus Injection Length
(24oz Woven Fabric, 50% Shading Material, SC-15)

Injection Time Versus Number of Injection Gates

Injection Time Improvement [%]
Injection Time Improvement [s]

Injection Time 100cm Preform Injection
Injection Time 500cm Preform Injection

15min desired Injection Time(100cm) LOWER BOUND
2hr desired Injection Time(500cm) LOWER BOUND
Decisions Required for an Optimal Sequential Injection of Large Parts

1. A minimum number of inlets (lower bound for the number of inlets) are required to assure fill times are less the gel time to ensure complete fill.

2. Increasing number of inlets will reduce cycle time but add cost (additional bagging setup (labor) and hardware requirement, resin waste, etc.). The minimum spacing and thus upper bound for the number of injection lines should be related to the flow front lead length. Analytical studies have shown that the lead length is strongly dependent on the permeability of the distribution media and the preform permeability and thickness.

3. The optimum timing for opening of the sequential injection gate is when no dry-spot can develop under the injection gate. Opening of the injection when the tool surface under the gate is wetted ensures complete wet-out and a minimum penalty on cycle time (optimum opening would be shortly before the tool surface under the gate is wetted out).
Design Tool Demonstration
**Design Example:**
**Hull Section**

**BASELINE:**
Fabric: 42 layers of 24oz. Woven Fabric
Resin: DOW Derakane Momentum 411-100 Resin
Distribution Media: 50% Shading Material

Part Dimension Hull Section
- 12 feet by 8 feet by 1 inch

Infusion time approximately 30 minutes

Center injection scheme will reduce one dimension by a factor of 2
We assume injection along the width of the part
- Problem reduces to an infusion of a 6 feet part
Design Summary

Minimum spacing given by non-saturated lead length ~50cm

- A maximum of six injection should be used

If total infusion time should be below 30 minutes then the optimum number of inlets equals **TWO** (Total of three) !!!
Design Example II: Hull Section

BASELINE:
Fabric: 40 layers of 24oz. Woven Fabric
Resin: Applied Poleramics SC-15 Resin
Distribution Media: 50% Shading Material
Part Dimension Hull Section
✧ 12 feet by 8 feet by 1 inch
Infusion time approximately 90 minutes (3x Derakane 411-100)

Change in resin type results in increase in viscosity but allows longer gelation and infusion time
Change in resin type results in increase in viscosity but allows longer gelation and infusion time.

If total infusion time should be below 90 minutes then the optimum number of inlets equals **THREE** !!!
Design Example III
Hull Section

BASELINE:
Fabric: New fabric with Twice the Permeability
Resin: Applied Poleramics SC-15 Resin
Distribution Media: 50% Shading Material

Part Dimension Hull Section

- 21 feet by 8 feet by 1 inch

Infusion time approximately 90 minutes

Change in fabric type results in increase in permeability decreasing infusion time
Change in fabric type results in increase in permeability allowing faster infusion

If total infusion time should be below 90 minutes then the optimum number of inlets equals **TWO** !!!
SMARTWEAVE and SMARTMolding Sensors

- Low cost sensors measures conductivity of resin
  - SMARTweave (patented by ARL) uses embedded wires, creating nodal measurement points
  - SMARTMolding sensors are tool-mounted
- Resin arrival
- Gelation behavior
Electric Time Domain Reflectometry (E-TDR) Approach

E-TDR is a method of sending a high-speed electrical pulse along a transmission line, and detecting reflections returning from impedance discontinuities within the line. In other words, acquisition speed (50 GHz) is so fast that it is possible to analyze transition even in short (10mm) electromagnetic circuits.

Schematic of the E-TDR technique (a) and equivalent circuit diagram of the transmission line (b).
Surface coplanar transmission line gives very high sensitivity and high signal to noise ratio.

Arrival time of E-TDR sensor during level change in the U-shaped tube.

3mm accuracy has been demonstrated.
TDR Sensor
Detection of Multiple Flow Fronts

Time dependant locations of resin in the preform

Experimental data showing the movement of multiple flow fronts
TDR Cure Monitoring

On-line Cure Sensor Comparison

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

\[ \alpha(t)_{TDR} = \frac{\varepsilon_0 - \varepsilon(t)}{0.478} \]

TDR CURE MONITORING ADVANTAGES

• Accurate on-line cure monitoring comparable to laboratory (FTIR and DSC) test equipment
• Low cost (flexible circuits can be mass-produced)
• Multiple sensor configurations for embedded or tool-mounted (reusable) versions are possible
• Sensing capability through intermediate layers: release agent, gel coat and others
Motivation for an Intelligent VARTM Workcell

Current Industrial Practice

- Prototypes, not production
- Trial and error
- High variability
- No automation, sensing, or control
- Manufacturing base limited to a few companies with know-how
- Costs not competitive with traditional approaches
- No two parts the same

Implementation and Validation of an Intelligent VARTM Workcell

- Design/Modeling of Infusion
- Fundamentals of mixing of reacting systems
- Controlled infusion
  - Sensors
  - Actuators
  - Software
- Preform consolidation mechanics
- QA/QC

Technology Transfer
Intelligent Process Control

Intelligent Process Control requires
- Real-Time Process Evaluation
- Real-Time Process Simulation
- Integrated Sensors
- Maximize Automation
- Learning Capability
- Network Capable

IPC system allows
- Repeatability
- Dimensional Control
- Scrap Reduction
- Eliminate Post-Inspection
- Increase Production Rates
- Process Traceability
  - QA/QC of Process
  - SPC
- Reduce Touch-Labor
- Reduce Cost

Advancement of Liquid Composite Mold Filling Processes by Intelligent Processing
- Increase production repeatability
- Reduce trial and error in process design
- Improve quality
- Introduce control

Industrial Hardened Software and Hardware
Schematic of a Fully Automated VARTM Production Cell

OBJECTIVES

• Automated Resin Delivery System
• Smart Tooling
  • Tool-Mounted Sensors
  • Resistive Heaters for Cure Control
• Automated Material Handling of Preforms
• Automated Vacuum Stations
• Reusable Bagging

➔ Intelligent Processing and Control
➔ Automation of all Processing Steps
SMARTMolding
Prototype Cell

1. Manual and Automatic Control and Monitoring
   1. Pinch Valves
   2. Vacuum
   3. Precision Scales
   4. CCD-Camera
   5. Tool-Mounted SMARTMolding Sensors

2. Automation
   1. Sequential Injection Control with feedback from tool-mounted sensors
SMARTMolding
Full Production Cell
Automation, Sensing, & Incoming Material Control Allow Repeat Manufacturing

Vendor certifies incoming material

Material Handling is semi-automated
Material is traced (Witness Photos)

Cure Cycle is fully automated

Infusion is fully automated
Sensor feedback traces repeatability

Resin  Preform  Tiles  Other Consumables

Periodic Checks

Barcode

Heated Tooling
TC for Mold, Surface and Resin
SMARTMolding Features

Automation Features
- Operator Login
- Shell Selection via Barcode
- Automated Tool Selection
- Automated Vacuum Control (Infusion, Dwell) and Leak Check
- Controlled On-Line and Off-Line Mixing
- Supervised Infusion
  - Sensor Feedback from tool-mounted and/or SMARTPad sensors
  - Fully Automated opening/closing of Valves
- Script Files for Sequential Injection
  - Process Variation Easy to Implement
  - Allows Dwell of Last Infusion Lines
- Timed Dwell (Reduction in Pressure to 7Hg) is Automated
- Process and Sensor Information are stored for QA/QC
Two SMARTPad sensors under each injection line was attached to tool
New PC board was developed for simple connectorization
Sensor response indicates
• Arrival time at each sensor
  • SPC
  • Optimization of Infusion Scheme
• Uniformity of fabric permeability
New Tool-Mounted Torlon Sensor
New Embedded or
Surface Mounted Flexible Circuit Sensor

Monitors resin arrival
The degree of cure can be observed up to 50%
Automated On-Line Mixing
CAV-IHS Shell Infusion

Resin Weight During CAV-IHS Infusion
06/21/02

Resin Weight [gr]

0 2000 4000 6000 8000 10000 12000

Injection Scale
Vent Scale

190 Strokes
2 Strokes

TOTAL Automated Infused Weight: 128lb
Sensor Data Review

Timing

Automation enables repeatable processing times from cycle 1

- Individual Time For Each Processing Step Is Recorded
- Witness Photo Of Tool Fill Is Displayed
- Vacuum Loss During Vacuum Check Is Shown
- Request for Operator Comment when Actual Time Step is Larger Than Nominal

Learning Curve
Cycle Time Versus # of Cycles

Average Cycle Time until Cure = 6 hours

Conventional Cycle Time [% of Baseline]
Implementation

**Hardware**

- Pinch Valves
- Vacuum Control and Sensing
  - Leak Check
- Sensors
  - Temperature
  - Flow
  - Cure
  - Scales for Flow rate

**Software**

- Recipes
- QA/QC Database
- Graphical User Interfaces
  - Material Lay-up
  - Infusion
  - Cure Control
SMARTMolding Software Suite

Design Tool
Simple Interface, Limited to simple geometries
Predicts Flow Times, Lead Length
Optimizes # of Seq. Injection Lines
Database with Material Properties

IPC System
Automates the VARTM Process
Records the processing steps
Reporting of collected data
Enables statistical analysis
Guidance Software to define process recipe

Data Review
Recipe GUI
Statistical Package

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Database Overview

Configuration Tables

Recipe Tables

QA/QC Tables

Setup (directories, DAQ settings)
Material Info (Resin, Fabric, Core)
Operator Info

Material Sequence
Bag and Tool Selection
Infusion Information
  Max. Leak
  Resin Info (Amount, Type, Ratios)
  Sensor Setup
  Seq. Infusion Script (Valves ↔ Sensors)
Dwell Info (Temperature, Time)

For each part
Sensor Feedback
Cycle Time
Manufacturing Queue

- Allows central administration of VARTM production
- Enables monitoring of production status
Material Lay-up Station

- Login feature
- Automatic part selection
- Recording of cycle time
- On-line help via work instruction
Infusion Station

- Login feature
- Automatic part selection
- Recording of cycle time
- On-line vacuum integrity check (Figure b)
- Allows integration of industrial mixer hardware
- Sequential Injection automation (Figure c)
- Timed room-temperature dwell (Figure d)
- Records sensor feedback
Automated Infusion End

A) Minimum Resin Amount Infused

B) Net gain into Part below 10gr/min

C) All sensors are wetted out

Infusion stops when

\[ A \land B \land C = \text{TRUE} \]
Help Through Work Instructions

- Includes instructions about lay-up, infusion and staging using HTML
  - MSDS
  - Pictures
  - AutoCAD drawings
  - Video

Lay-up

Infusion

WORK INSTRUCTIONS

Lay-Up Step

Part 1. General Instructions

1. General Instructions

2. Drawings

3. Material Requirements

4. Safety Requirements

5. Pictures

6. Videos

7. MSDS

8. AutoCAD drawings

9. Video
**Report**

**Lay-Up Information**

- **Operator:** Hope Driller
- **Start Date/Time:** 1/10/2003 2:26:21 PM
- **End Date/Time:** 1/10/2003 2:40:28 PM

**Sequence and Material Details**

<table>
<thead>
<tr>
<th>Step</th>
<th>Material</th>
<th>Weight [lb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>E-glass 324-2407 Woven Mounding</td>
<td>1906</td>
</tr>
<tr>
<td>2</td>
<td>Perfluor Green</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>50% Reducing (Drying Material)</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>Broadleaf Cloth</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>Tacky Tape (T&lt;250°F)</td>
<td>0</td>
</tr>
</tbody>
</table>

**Cycle Time Information**

- Cycle Time for each processing step
- Arrival Time of Flow Sensors

**Sensor Data**

- Date: 1/10/2003
- Time (Open): 2:34:00 PM
- Time (Close): 2:42:12 PM
- Valve: 7

**Status Information**

- **Operator:** Dirk Holder
- **Start Date/Time:** 1/10/2003 12:12:02 PM
- **End Date/Time:** 1/10/2003 12:12:03 PM

**Calculated Values**

- Calculated Fiber Weight/Volume: 0 [%]
- Final Part Weight: 0 [g]
- Total Production Time: 12:00:00 AM [hh:mm]

**Charts**

- Chart 1: Lay-Up Time History
- Chart 2: Sensor Data

**Basic Information**

- Operator
- Material Sequence during Lay-up with Cycle Time Info
- Opening/Closing of Valves
- Weight and Fiber Volume Info

**Charts**

- Cycle Time for each processing step
- Arrival Time of Flow Sensors
Infusion History Report

- a. Start time
- b. End time
- c. Process time
IPC Demonstration
PEGASUS / CAV IHS

• Wheeled Platform Offer Breakthrough Technologies

• Vehicle Helps Army Meet 2008 FCS Timeline

• Wheeled Vehicle Designed and Built In Less Than 8 Months

SOFTWARE

Vendor certifies incoming material

Material Handling is semi-automated

Material is traced (Witness Photos)

Infusion is fully automated

Sensor feedback traces repeatability

Material Handling is semi-automated

Sensor feedback traces repeatability

Infusion is fully automated

Cure Cycle is fully automated

REPEAT MANUFACTURING

TOTAL Automated
Infused Weight: 128lb

Vehicle Helps Army Meet 2008 FCS Timeline

Wheeled Platform Offer Breakthrough Technologies

Wheeled Vehicle Designed and Built In Less Than 8 Months

Heider ONR Workshop - 46
Fun to Watch!!!
BETA-Site Technology Transition

SMARTMolding

Sensor Development

Sequential Injection

SMARTMolding

Sensor Development

Automation

Design Tool