VARTM PROCESS VARIABILITY STUDY

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UD-CCM • 1 July 2003
**VARTM Process Variability Study**

1. **REPORT DATE**
   26 AUG 2004

2. **REPORT TYPE**
   N/A

3. **DATES COVERED**
   -

4. **TITLE AND SUBTITLE**
   VARTM Process Variability Study

5. **PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
   University of Delaware Center for Composite Materials Newark, DE 19716

6. **AUTHOR(S)**
   -

7. **SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
   -

8. **PERFORMING ORGANIZATION REPORT NUMBER**
   -

9. **SUPPORTING/monITORING AGENCY NAME(S) AND ADDRESS(ES)**
   -

10. **SPONSOR/MONITOR’S ACRONYM(S)**
    -

11. **SPONSOR/MONITOR’S REPORT NUMBER(S)**
    -

12. **DISTRIBUTION/AVAILABILITY STATEMENT**
    Approved for public release, distribution unlimited

13. **SUPPLEMENTARY NOTES**
    See also ADM001700, Advanced Materials Intelligent Processing Center: Phase IV., The original document contains color images.

14. **ABSTRACT**
    -

15. **SUBJECT TERMS**
    -

16. **SECURITY CLASSIFICATION OF:**
    | a. REPORT | b. ABSTRACT | c. THIS PAGE |
    | unclassified | unclassified | unclassified |

17. **LIMITATION OF ABSTRACT**
    UU

18. **NUMBER OF PAGES**
    21

19. **NAME OF RESPONSIBLE PERSON**
    -

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*Unclassified data provided.*
Outline

Objectives and Motivation
Approach
Theory
Experimental set-up
  ✦ Materials
  ✦ Process
  ✦ Cycle time
Conclusions
Future work
Objectives

Achieve a repeatable VARTM process by:

- Identifying
- Understanding
- Evaluating
- Controlling

the sources of process variations affecting the final part:

- Quality
- Dimensional tolerances
- Mechanical properties

While maintaining a **low cost** process for composite parts dedicated to high-performance applications:

- Aerospace
- Naval applications
**Motivation**

**VARTM process: +/-**
- Main advantages: low cost, high fiber volume fraction, large scale parts
- Still some limitations
  - High variability compared to autoclave process
  - From part to part
  - In the same part

**Autoclave repeatability difficult to achieve with VARTM**

**Comparison VARTM/Autoclave:**

<table>
<thead>
<tr>
<th></th>
<th>VARTM</th>
<th>Autoclave</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber volume fraction gradient</td>
<td>$\Delta V_f$</td>
<td>$\pm 10%$</td>
</tr>
<tr>
<td>Thickness gradient</td>
<td>$\Delta t_{h_F}$</td>
<td>$\pm 10%$</td>
</tr>
</tbody>
</table>
Following conditions have to be met to make VARTM viable for high-performance applications:

- Process as repeatable as autoclave (reference)
- Slightly lower properties but for a much lower cost
Sources of Variability

Materials as well as the Process have an impact on the repeatability

- **Inputs**
  - Incoming materials
  - Infusion parameters
  - Cure parameters

- **Outputs**
  - Quality of the part
  - Mechanical properties
Manual vs. Automated Set-Up

Current industry practice

- Manual lay-up
- Manual infusion
- Manual control

NO Monitoring

Future industry practice: Variability identified

- Manual lay-up
- Automated infusion
- Automated control
- Automated lay-up (laser cutting)
- Automated infusion
- Automated control

MONITORING – SMARTMolding set-up
Approach

- **Theory**
  - Identification of potential sources of variation → Evaluation of the different degrees of influence

- **Experimental**
  - Manufacture of a large number of panels
  - (Statistical) Analysis of data

- **Synthesis**
  - Model for prediction/optimization of the process variations
  - Actions to control the real sources of variations
Theory

1) Gather parameters influencing VARTM variations
   Literature review

2) Screen the parameters
   For each critical parameter
   (Example: fiber volume fraction, $V_f$)
   1) Identify contributing parameters
      ✤ Areal density of the fabric
      ✤ Density of the fibers
      ✤ Final thickness of the part
      \[ V_f = \frac{n \times \rho_A}{th_f \times \rho_f} \]
   2) Evaluate their variations
   3) Rank parameter contributions

3) Example:
   Rank 3: \[ \frac{\Delta V_f}{V_f} \bigg|_{\Delta \rho_f} = -2.5\% \]
   Rank 2: \[ \frac{\Delta V_f}{V_f} \bigg|_{\Delta \rho} = 3.34\% \]
   Rank 1: \[ \frac{\Delta V_f}{V_f} \bigg|_{\Delta th_f} = -5\% \]
Experimental Set-Up

**System**

24 oz. Woven fabric E-glass  
Dow Derakane Momentum 411-100

**Materials**

- **Fabric**: Weight, Size, Areal density, Permeability, Porosity  
- **Resin**: Viscosity, Mix-ratio  
- **Consumables**: Weight

**SMARTMolding processing**

- **Operator**: Accuracy, Cycle time  
- **Processing variability**: Vacuum leak, Infusion time, Gel time

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**Diagram:**

- Injection lines
- Vent gate
- Preform layer
- Layer for permeability study
- Ref layer
- 48”
- 12”
- 6”
- 12”

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1 Jul 2003
Materials: Fabric Weight
(source of variation: preform)

Manual cutting
Fabric weight = \(2426 \, g \pm 1.4\%\)

Future work:
Measurement of
- Areal weight, Porosity (affect directly \(V_f\))
- Permeability

Contributing parameters: Operator

Areal density
Process: Arrival Time  
(source of variation: infusion)

Infusion – Focus on the 1st part of the injection:

The variations are almost constant with flow distance.

<table>
<thead>
<tr>
<th>Sensor number</th>
<th>Variability of the time (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensors 1</td>
<td>18.8</td>
</tr>
<tr>
<td>Sensors 2</td>
<td>17.1</td>
</tr>
<tr>
<td>Sensors 3</td>
<td>14.8</td>
</tr>
<tr>
<td>Sensors 4</td>
<td>14.4</td>
</tr>
<tr>
<td>Sensors 5</td>
<td>14.6</td>
</tr>
</tbody>
</table>

Contributing parameters:  
Viscosity  
Permeability  
Porosity

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Materials: Resin Viscosity
(source of variation: infusion)

Viscosity = 129.4 cP ± 11.5%

Fill time at 60cm = 375s ± 14.9%
(modelisation)

\[
\ln(\mu) = 146.69 \times \frac{1}{T} + 2.9531
\]

Contributing parameters:
- Temperature
- Mix-ratio
Process: Resin Volume
(source of variation: infusion)

Injected resin vs. Sensor distance

⇒ Variability is distance sensitive
⇒ Fiber volume fraction: $V_f = f(\text{part size})$
⇒ Other factors can include permeability (flow shape) of DM and preform
Process: Cure

Gel time: 1st approximation \( \Rightarrow \) half-peak time

Gel time = 1:46 ± 21.7%

Future work will include:

- K. M. England & M. B. Dorairaj prediction of gel time
- Monitor and control of mix-ratios

Contributing parameters:

- Ambient temperature
- Exothermic reaction
- Mix-ratios

NB: Infusion time \( \approx 1500 \) s
Process: Final Part

Weight (final part) = 3320 g ± 1.7%
Fiber weight fraction = 73% ± 0.55%

Contributing parameters:
- Initial fabric weight
- Final thickness

Future work: Quality of the part (Void content, Fiber volume fraction), Mechanical properties.
Cycle Time Variability

**VARIATIONS**
- Mold prep + lay-up: 0:46:02 ± 97%
- Bagging: 0:42:35 ± 120%
- Vacuum check: 0:09:30 ± 57%

**SOLUTIONS**
- "Kitting of material is key"
- "Reusable bagging"

<table>
<thead>
<tr>
<th>Operator</th>
<th>Average</th>
<th>41</th>
<th>42</th>
<th>43</th>
<th>44</th>
<th>45</th>
<th>46</th>
<th>47</th>
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<tr>
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<td></td>
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<tr>
<td>Gel time</td>
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</tr>
</tbody>
</table>

![Bar chart showing cycle time variability for different parts](chart.png)
Conclusions

- Initiation of the first set in characterizing VARTM variations, Part-to-part only.
- Development of an experimental set-up to study incoming materials
- Identification of a first set of variations
  - Among the inputs
    - Materials
      - Fabric (weight)
      - Resin (viscosity)
    - Process’ parameters
      - Injection (time to reach the sensors, amount of injected resin)
      - Cure cycle (gel time)
Current and Future Work (1/2)

- Include:
  - Distribution media contribution to the variability of the process
  - Determine the variations of:
    - Permeability
    - Porosity
    - Areal density

- Measure:
  - Void content
  - Fiber volume fraction
  - Mechanical properties

- Create larger experimental data set for meaningful statistical results
- Variability increases with complexity of the part
  - Manufacture of panels with more complicated shapes (stiffener, 3D)
- Measure "in-part" variations
- Show benefits of automation
Current and Future Work (2/2)

Long term objectives

- Create interaction between the quality of the part and the variations of the inputs

Other materials

- Carbon fibers
- High-temperature resins

Modeling (prediction)

For given allowables, the variation of contributing parameters can be calculated
## Description of the Parameters

### Exhaustive list

<table>
<thead>
<tr>
<th>Preform</th>
<th>Resin</th>
<th>Infusion</th>
<th>Resulting part</th>
</tr>
</thead>
<tbody>
<tr>
<td>df</td>
<td>$\mu_R$</td>
<td>$K_{DM}$</td>
<td>$V_f$</td>
</tr>
<tr>
<td>$\rho_f$</td>
<td>$E_r$</td>
<td>$V$</td>
<td>$V_{f_F}$</td>
</tr>
<tr>
<td>$R_{tow}$</td>
<td>$\theta$</td>
<td>$Q$</td>
<td>$V_{f_F}$</td>
</tr>
<tr>
<td>$S_{tow}$</td>
<td>$P_{deg}$</td>
<td>$t_{infusion}$</td>
<td>$V_{f_F}$</td>
</tr>
<tr>
<td>$V_{f_{tow}}$</td>
<td>$t_{deg}$</td>
<td>$t_{gel}$</td>
<td>$t_{deg}$</td>
</tr>
<tr>
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<td>$T_g$</td>
<td>$T_{gel}$</td>
<td>$t_{gel}$</td>
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<tr>
<td>$\rho_A$</td>
<td>Cure kinetics</td>
<td>$xv,yv$</td>
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<td>$\phi$</td>
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<tr>
<td>$K$</td>
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<td>$n_{debulk}$</td>
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<tr>
<td>$C_p$</td>
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<td>$C$</td>
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<tr>
<td>Binder</td>
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<td>$\sigma_{fsF}$</td>
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<td></td>
<td></td>
<td>$K_c$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$E_F$</td>
</tr>
</tbody>
</table>

- Diameter of the fibers
- Density of the fibers
- Radius of the tows
- Saturation of the tows
- Fiber volume fraction of the fiber tows
- Permeability of the fiber tows
- Areal density of the fabric
- Porosity of the fabric
- Permeability
- Compressibility
- Compaction
- Thickness of the final preform
- Fiber volume fraction - Wet fibers
- Fiber volume fraction - Dry fibers
- Number of debulking cycles
- Pression of the debulking cycles
- Presence of binder
- Viscosity of the resin
- Young's modulus of the resin
- Contact angle
- Degassing pressure
- Degassing time
- Glass transition temperature
- Cure kinetics
- Permeability of the DM
- Vacuum pressure
- Flow rate
- Infusion time
- Gel time
- Gel temperature
- Vent location
- Final fiber volume fraction
- Final void content
- Final thickness
- Tensile strength
- Compression strength
- Open hole compression strength
- Flexural strength
- Interlaminar shear strength
- Toughness
- Young's modulus