SPATIALLY TARGETED ACTIVATION OF A SHAPE MEMORY POLYMER-BASED RECONFIGURABLE SKIN SYSTEM

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DECEMBER 2013
Interim Report

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<table>
<thead>
<tr>
<th>1. REPORT DATE (DD-MM-YY)</th>
<th>December 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. REPORT TYPE</td>
<td>Interim</td>
</tr>
<tr>
<td>3. DATES COVERED (From - To)</td>
<td>01 October 2012 – 30 September 2013</td>
</tr>
</tbody>
</table>

| 4. TITLE AND SUBTITLE     | SPATIALLY TARGETED ACTIVATION OF A SHAPE MEMORY POLYMER-BASED RECONFIGURABLE SKIN SYSTEM |

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| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) | Design and Analysis Branch (AFRL/RQVC)  
|                                                    | Aerospace Vehicles Division  
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| 8. PERFORMING ORGANIZATION REPORT NUMBER | AFRL-RQ-WP-TM-2013-0264 |

| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | Air Force Research Laboratory  
|                                                          | Aerospace Systems Directorate  
|                                                          | Wright-Patterson Air Force Base, OH 45433-7542  
|                                                          | Air Force Materiel Command  
|                                                          | United States Air Force  
|                                                          | AFRL/RQVC |

| 10. SPONSORING/MONITORING AGENCY ACRONYM(S) | AFRL-RQ |
| 11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S) | AFRL-RQ-WP-TM-2013-0264 |

| 12. DISTRIBUTION/AVAILABILITY STATEMENT | Approved for public release; distribution unlimited. |

|                         | This document is comprised wholly of a slide show presentation. |

| 14. ABSTRACT | The objective of the project is to investigate the thermomechanical behavior of engineered shape memory polymer (SMP) materials for use as composite reconfigurable skin systems in morphing aircraft applications. An anisotropic, reconfigurable skin based on selective heating of a cellular SMP material will be designed and investigated to understand its material characteristics. |

| 15. SUBJECT TERMS | |

| 16. SECURITY CLASSIFICATION OF: | |
| a. REPORT | Unclassified |
| b. ABSTRACT | Unclassified |
| c. THIS PAGE | Unclassified |
| 17. LIMITATION OF ABSTRACT: | SAR |
| 18. NUMBER OF PAGES | 40 |
| 19a. NAME OF RESPONSIBLE PERSON (Monitor) | James J. Joo |
| 19b. TELEPHONE NUMBER (Include Area Code) | N/A |
Spatially Targeted Activation of a Shape Memory Polymer Based Reconfigurable Skin System

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Aerospace Systems Directorate
Dr. Richard Beblo
Mr. John Puttmann
UDRI
Outline

- Project Outline
- Project Roadmap
- Magnetic and Thermal Modeling
- Heating Scheme Proof of Concept
- Epoxy SMP Characterization
- Composite Analytic Model
- Composite Characterization
- Composite FEA Model
- System Modeling
- Honeycomb Geometry Optimization
- Heating Pattern Optimization
- Future Work
- Conclusions
Project Outline

**Skin Objectives (via MAS)**
Nominal Panel Size 15” x 20”
Shear from 30° to 75°
No Wrinkling of Skin
Total Skin Weight <0.95 lb/sqft
Aerodynamic Load 400lb/sqft
Max Out-of-Plane Deflection 0.1”

**Heating Patterns**
- 0 degrees
- +45 degrees
- -45 degrees
- 90 degrees
- Diamond
- Large Honeycomb
  - Auxetic
  - Isotropic
- 0 Poisson
- Top/Bottom
- Left/Right

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Project Roadmap

System Concept

Material Characterization

Composite Modeling

Composite Characterization

System Modeling

Validation

System Optimization

Validation

Material Characterization

Composite Characterization

Heating Concept

Magnetic Modeling

Thermal Modeling

Heating Scheme Proof of Concept

Thermal Characterization

Experimentally Validated Design Optimization Tool

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FEA Modeling

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Magnetic Modeling

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Heating Scheme

Proof of Concept

Thermal Characterization

Experimentally Validated Design

Optimization Tool

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Magnetic and Thermal Modeling

Magnetic Field Lines Between Two Magnets

- Nickel: 3-7 µm diameter
- Epoxy SMP
- Neodymium (NdFeB) N42SH magnets

Magnetic Field Lines b/t Ni Particles

- 0.04 T
- 0.13 T
- 0.06 T

Particle Diameter
- 5 µm
- 65 µm
- 125 µm
- 185 µm
- 245 µm

Time to Transition (s)

5 vol% = 2 s

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Velocity of a particle subject to a pulsating fluid

\[ u = \frac{3\rho}{\rho + 2\rho_s} v_\infty \]

- \( u \) particle velocity
- \( \rho \) fluid density
- \( \rho_s \) particle density
- \( v_\infty \) imposed pulsating field


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Heating Scheme Proof of Concept

5 vol% 3-7 µm Nickel particles
Neodymium magnets 40mm separation
350 Hz vibration
212°F for 3 hours
Mold: 10 x 10 x 0.75 cm

$\phi_c = 0.41$ (50 µm diameter, $\delta_c$ 10 nm)
$\phi_{exp} = 0.10$
10 vol%, 10V, random orientation: 60s
Heating Scheme Proof of Concept

Tested several Copper, Steel, and NiChrome mesh electrodes. 100x100 Cu most promising.

Current activation: 10V, ~60s

End View of Nickel

Side View Nickel

End View of Particle Chains
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Epoxy SMP Characterization

**Epoxy SMP Formulation**
0.02 mol (7.28g) EPON 826
0.01 mol (2.3g) Jeffamine D230
100°C for 1.5hr, 130°C for 1hr

**Experimental Results**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_g$</td>
<td>65 °C</td>
</tr>
<tr>
<td>$E$ (ambient)</td>
<td>1300 MPa</td>
</tr>
<tr>
<td>$E$ (115 °C)</td>
<td>19 MPa</td>
</tr>
</tbody>
</table>

Values consistent over several batches, 0-8 week sample age

T Xie, IA Rousseau, *Facile tailoring of thermal transition temperatures of epoxy shape memory polymers*, Polymer, 2009
\[ \delta_j = \sum_m \left\{ \int_0^{L_m} \frac{N_m^2}{2E_m A_m} \partial_z + \int_0^{L_m} \frac{M_{x,m}^2}{2E_m I_{x,m}} \partial_z \frac{\partial}{\partial F_j} \right\} \]

\[ \delta_0 = \delta_a + 2\delta_{lr} + 2\delta_{ls} \]

\[ E_{c0} = \frac{F_{00}}{\delta_0} \frac{(a + x_0)}{2cy_0} \]
Composite Analytic Model

- Analytic Model

- Empty Honeycomb Young’s Modulus (MPa)

- Hot Composite Young’s Modulus (MPa)

- Cold Composite Young’s Modulus (MPa)
Composite Characterization

<table>
<thead>
<tr>
<th></th>
<th>23 °C</th>
<th>115 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{Epoxy}}$</td>
<td>1.3 GPa</td>
<td>19 MPa</td>
</tr>
<tr>
<td>$E_{\text{HX}}$</td>
<td>62.8 kPa</td>
<td></td>
</tr>
<tr>
<td>$E_{\text{HY}}$</td>
<td>16.6 kPa</td>
<td></td>
</tr>
<tr>
<td>$E_{\text{CX}}$</td>
<td>2.19 GPa</td>
<td>33.9 MPa</td>
</tr>
<tr>
<td>$E_{\text{CY}}$</td>
<td>2.04 GPa</td>
<td>11.8 MPa</td>
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<table>
<thead>
<tr>
<th></th>
<th>23 °C</th>
<th>115 °C</th>
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<tbody>
<tr>
<td>$G_{\text{Epoxy}}$</td>
<td>1.27 GPa</td>
<td>1.06 MPa</td>
</tr>
<tr>
<td>$G_{\text{CXY}}$</td>
<td>1.19 GPa</td>
<td>13.9 MPa</td>
</tr>
<tr>
<td>$G_{\text{CYX}}$</td>
<td>1.13 GPa</td>
<td>13.0 MPa</td>
</tr>
</tbody>
</table>
Composite Characterization

Analytic Model
Experimental Results

Empty Honeycomb Young’s Modulus (MPa)

Hot Composite Young’s Modulus (MPa)

Cold Composite Young’s Modulus (MPa)
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Experimentally Validated Design Optimization Tool

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Composite FEA Model

FEA supports force distribution assumption of analytic model.

X soft tension, axial stress top left beam.

Even stress distribution
-0.2 – -0.3 MPa

Linear stress distribution
0.18 MPa

-0.10 MPa
### Composite FEA Model

<table>
<thead>
<tr>
<th></th>
<th>23 °C</th>
<th>115 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{CX}$</td>
<td>1.40 GPa</td>
<td>52.4 MPa</td>
</tr>
<tr>
<td>$E_{CY}$</td>
<td>1.08 GPa</td>
<td>17.9 MPa</td>
</tr>
<tr>
<td>$G_{CXY}$</td>
<td>0.81 GPa</td>
<td>16.3 MPa</td>
</tr>
<tr>
<td>$G_{CYX}$</td>
<td>0.81 GPa</td>
<td>16.4 MPa</td>
</tr>
</tbody>
</table>

**X hard tension, axial stress top left beam**

### X Hard Von-Mises Stress (MPa)

### XY Hard Von-Mises Stress (MPa)
### Composite FEA Model

<table>
<thead>
<tr>
<th></th>
<th>23 °C</th>
<th>115 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{CX}$</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>$E_{CY}$</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>$G_{CXY}$</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>$G_{CYX}$</td>
<td>TBD</td>
<td>TBD</td>
</tr>
</tbody>
</table>

**X hard tension, axial stress top left beam**

![Graph showing Von-Mises Stress](image)

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Composite FEA Model

Tension (Von-Mises Stress)

Shear (Von-Mises Stress)

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Composite FEA Model

- Analytic Model
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- FEA Results

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### System Modeling

Low fidelity FEA
Homogenization scheme using effective composite properties
Plane Stress (z direction neglected)
In-plane only
Calculates effective $E_x$, $E_y$, $G_{xy}$, $G_{yx}$
given heating pattern

#### Material Stiffness Matrix

\[
\begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22} \\
\varepsilon_{12} \\
\varepsilon_{21}
\end{bmatrix} =
\begin{bmatrix}
\frac{1}{E_1} & \frac{\nu_{21}}{E_2} & 0 & 0 \\
\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & 0 & 0 \\
0 & 0 & \frac{1}{G_{12}} & \frac{G_{21}}{G_{12}} \\
0 & 0 & \frac{G_{21}}{G_{12}} & \frac{1}{G_{21}}
\end{bmatrix}
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{12} \\
\sigma_{21}
\end{bmatrix}
\]

\[
\mu_{12,21} = \frac{1}{\mu_{21,12}} = \frac{(l^3 + a^3 \cos^2(\theta))(a + x_0)}{2 y_0 a^3 \cos(\theta) \sin(\theta)}
\]

#### Non-zero shear coupling (Chentsov) coefficients

10% Strain X Direction
Stress X (Pa)

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Honeycomb Geometry Optimization

Design Variables

\begin{align*}
0 & \leq l (m) < \infty \\
0.00005 & \leq d (m) < \infty \\
0 & \leq a (m) < \infty \\
0 & \leq \theta \leq \frac{\pi}{2} \\
0 & \leq h_{\text{core}} (m) < \infty \\
0 & \leq t_f (m) < \infty
\end{align*}

Self-Imposed Constraints

\begin{align*}
\varepsilon_{\text{max}} & > 0.1 \\
\varepsilon_{\text{y max}} & > 0.1 \\
\frac{1}{2} & \leq \frac{2y_0}{a + x_0} < 2
\end{align*}

Equation Constraints

Unit Cell Equations

\begin{align*}
\left. \begin{array}{c}
\leq \sin (\theta) \\
\geq \sin (\theta) \cos (\theta) \\
\leq 2 \sin (\theta) - \sin (2\theta) \cos (\theta)
\end{array} \right\} \\
\frac{a}{l} & \geq 0 \\
\sin \left( \frac{3\pi}{2} + 2\theta \right) & \geq \cos (\theta)
\end{align*}

Thin Beam Theory

\begin{align*}
\left. \begin{array}{c}
\leq a \\
\geq \frac{l}{a}
\end{array} \right\} \\
d & \leq \frac{8}{l}
\end{align*}

Sandwich Plate Deflection

\begin{align*}
\delta & \leq (h_{\text{core}} + 2t_f) \\
\delta_{\text{cell}} & \leq t_f
\end{align*}

Material Properties Constraints

\begin{align*}
\frac{C_i w^2 h_{\text{panel}}^2}{t_f h_{\text{core}}} & = \sigma_{\text{max}} \leq \frac{1.0E7 \text{(Pa)}}{2} = \frac{\sigma_f}{\text{FOS}} \\
\varepsilon_{\text{x max}} & \leq \varepsilon_{sf} = \left( \frac{(\beta_x - \cos (\theta))}{a + l \cos (\theta)} \right) \\
\beta_x & = \cos^{-1} \left[ \frac{\varepsilon_{f} a}{l} + \cos (\theta) (\varepsilon_{sf} + 1) \right] \\
\varepsilon_{y max} & \leq \varepsilon_{sf} = \frac{\sin (\beta_y) - \sin (\theta)}{\sin (\theta)} \\
\beta_y & = \cos^{-1} \left[ \sin (\theta) (\varepsilon_{sf} + 1) \right] \\
\varepsilon_{sf} & = 200\%
\end{align*}

Optimized Geometry

\begin{align*}
l & \quad 10 \text{ mm} \\
a & \quad 1.0 \text{ mm} \\
d & \quad 0.05 \text{ mm} \\
\theta & \quad 62^\circ \\
h_{\text{core}} & \quad 172 \text{ mm} \\
t_f & \quad 2.5 \text{ mm}
\end{align*}

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Heating Pattern Optimization

Genetic Algorithm

- 13 full cells
- 12 partial cells
- 7 hot cells
- 18 cold cells

Not included:
Out-of-plane def.
Deformation req.

Minimize $E_{xx}$

Minimize $E_{yy}$

Minimize $E_{xy}$

Minimize $E_{yx}$
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Future Work

Future Work System Scheme
• Heating Pattern Optimization
• System Integration / Fabrication
• System Characteristics Envelope

Future Work Heating Scheme
• Thermal characterization of heating scheme
• Thermal diffusion between cells
• Direct write electrodes (variable patterns)
Conclusions

• Viable Option for Morphing Structures
• 30-40% In-plane Strain Achievable
• Accurate Analytic Model of Filled Honeycomb
• Optimistic High Thickness SMP Heating Scheme