Self-Repairing Fatigue Damage in Metallic Structures for Aerospace Vehicles Using Shape Memory Alloy Self-Healing (SMASH) Technology

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Outline

• The innovation: SMASH technology
• Liquid-assisted self-healing approach
  • Impact of the innovation
• Results of the Seedling Phases I and II efforts
  • Distribution/dissemination
  • Next Steps
SMASH Technology Concept

- Liquid-assisted healing:
  - Clamping force from the SMA wires
  - Partial liquefaction of the matrix

- Proof of concept on Sn-Bi alloys

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SMASH Technology

• Proof of concept: healing cm-long cracks with retention of mechanical properties
  – 95% recovery of ultimate tensile strength

Time-lapse video showing actual healing of two overload cracks on a Sn-Bi dogbone specimen. Healing continues when the specimen is held at temperature and partial matrix liquefaction fills in any remaining gaps in the crack faces.
Technical Approach

• Liquid-assisted healing of fatigue cracks
• Thermodynamic design of matrix
  – Binary and Ternary alloy design
  – Optimization of healing parameters
  – Optimization or microstructure and mechanical properties
• Complex specimen fabrication
  – Multi-layer specimens
• Numerical modeling
  – Model validation
  – Reinforcement architecture

Proof of concept material (top) and mechanical properties of cast Al-Si material (bottom)
Impact of Innovation

- Wrought and cast Al alloys used throughout aircraft
  - Fatigue and fatigue crack growth at high cycles is concern.
- Improve damage tolerance and fatigue life of metals at critical structural locations
- Integrated self-repairing approach would improve durability and sustainability of the aerospace material to ensure vehicle safety
Results from Phase I

- Self-repair of Al matrix materials
- Fatigue crack repair
- 90% recovery of UTS after healing
- Multiple healing cycles achieved

Before: Post-Fatigue Testing at KSC

After: Post-Heal at UF

Fatigue crack healed in POC

Adequate Al-Si microstructure for healing treatment

Small-scale multi-ply Al-Cu-Si specimen
Phase I Fatigue Testing Results

- Fatigue testing of matrix material after various healing cycles to study liquid-assisted portion of healing.

![Graph showing crack length vs. cycle count](image)

- Cycle count, N (x 1,000)
- Crack length, a (inches)
- Points represent:
  - Before healing
  - After 1st healing
  - After 2nd healing

![Images showing samples before and after testing and healing](images)

- After first test
- After first heal
- After second test
- After second heal

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Phase II Results: Fabrication Technique

- Improved upon diffusion bonding technique developed during Phase I by consolidating using vacuum hot pressing (VHP)
  - Larger scales
  - Alignment fixtures
  - Multi-step processing
  - Optimized pressures and temperatures
- Allowed for fabrication of more complex test specimens
- Ensured adequate SMA reinforcement by X-ray and computed tomography (CT)
Phase II Results: Fabrication Technique

- VHP samples had a similar microstructure to the cast samples with a decrease in porosity.
- Diffusion bonding interface around wires and between “slices” of matrix material were adequate.
  - Slight bonding line visible, but no contaminants were identified at the interface.
Phase II Results: Healing overload cracks

- Increase in ductility when compared to cast samples from Phase I
  - Resulted in necking of test specimen
  - Healing treatment showed filling of crack

Comparison of cast and healed mechanical properties

\[
\sigma_{0.2\%} = 39.2 \text{ Mpa} \\
\varepsilon_{\text{VHP}} = 9.1 \%
\]

Phase II Results: Driver for treatment optimization

- CT stills showing diffusion front of wire within healed overload composite
Phase II Results: Driver for treatment optimization

- Non-destructive CT vs. destructive metallography showing diffusion of SMA constituents into matrix.
Phase II Results: Driver for treatment optimization

- Sacrificial damage of SMA with original healing treatment
Phase II Results: Healing Treatment Optimization

- Optimization of:
  - Microstructure
  - Mechanical properties
  - Healing treatment
Phase II Results: Healing Treatment Optimization

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VHP specimens after healing treatment for various time periods.
Phase II Results: Healing Treatment Optimization

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VHP specimens after healing treatment for various time periods.
Phase II Results: Healing Treatment Optimization

- Optimization of:
  - Microstructure
  - Mechanical properties
  - Healing treatment
- Grain growth and diffusion vs. mechanical properties

Optimization of healing treatment

VHP specimens after healing treatment for various time periods.

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Phase II Results: Fatigue Crack Growth

- Edgewise single edge notch tension ESE(T) specimens tested by compliance control to grow and heal a small fatigue crack.
  - Surface strain measurements via visual image correlation (VIC-3D)
- FCG specimens were pre-cracked, tested, healed, and re-tested.
  - High-temperature speckle pattern was used to continue strain measurements after healing treatment.
Phase II Results: Fatigue Crack Growth

- Pre-healing treatment CT
Phase II Results: Fatigue Crack Growth

- Strain fields during first fatigue test, after healing, and at the end of the second fatigue test.

*VIC strain field data of ESE(T) FCG specimen pre- and post-healing treatment.*
Phase II Results: Modeling

- Modeled composite using various loading scenarios, SMA compositions, wire placement, continuous vs. discontinuous wire lengths, and wire pre-strain.
  - Evaluated plasticity induced on the matrix and wires from loading, unloading, and heating to healing temperatures.
  - Evaluated ability of SMA wires to force crack closure in the SMASH materials system.
Phase II Results: Validation of Model

- Empirical and model of metal matrix composite 3-point bend tests were in agreement
  - True test data, including material properties at different temperature regimes, was used in the model.
  - Simulation of crack opening displacement (COD) after unloading is in good agreement with the test measurements.
  - Final COD after loading:
    - Model: 0.17 mm
    - Experimental: 0.15 mm

Crack length = 7.6 mm

Crack Opening Displacement (model)

E = 65 GPa for Sn-Bi matrix
Phase II Results: FEA

- FEA showing stress evolution (von-Mises, MPa) upon loading, unloading, and heating.

Step 1: Load

Step 2: Unload

Step 3: Heat

SMA

Matrix
Applying FEA to Fabrication of Complex Specimens

• 3-D model

Matrix  SMA

0°
10°
30°
45°
Applying FEA to Fabrication of Complex Specimens

- FEA was used to model two multi-ply hot pressed specimens:
  - -45/0/+45
  - -30/0/+30
Phase II Results: Using FEA for Extending the Realm of possibilities

- The best wire placement in relation to the crack is perpendicular (0° in figures below)
- Pre-straining reinforcements aids in crack closure
Phase II Results: Using FEA for Extending the Realm of possibilities

- Short vs. Long fibers
  - Continuous vs. discontinuous wire reinforcements were modeled.
  - The best case for crack closure is continuous reinforcements near the crack tip.

Case 1 – discontinuous wires parallel

Case 2: discontinuous wires, offset by 12 mm

Case 3: discontinuous wires, offset by 20 mm
Phase II Results: Matrix Alloy Design

- Al-Cu and Al-Cu-X systems
- Liquid-assisted step in healing:
  - Eliminates work hardening and grain refinement
  - Leaves precipitation hardening and solid solution strengthening
- Candidates:
  - Al-Cu-Mg alloys that can precipitate the high-strength S-phase and its metastable precursors
- Heat treatment:
  - Cast, solution treat, quench, and age to peak strength.
  - Healing treatment performed on diffusion couples
  - Perform heat treatment again.
Distribution/Dissemination

• **Patents:**
  – A provisional patent application titled “*Self-Repairing Metal Alloy Matrix Composites, Methods of Manufacture and Use Thereof*” was filed in June 2014 with the Patent and Trademark Office.

• **NASA Technical Memoranda**
  – Fatigue Resistance of Liquid-Assisted Self-Repairing Aluminum Alloys Reinforced with Shape Memory Alloys
  – Assessment of Fatigue Crack Damage and Mitigation in Self-Repairing Metallic Materials

• **Invited Talks:**
  – TMS 2015 Annual Meeting and Exhibition, March 2015 in Orlando, FL “*Investigating the Fatigue Behavior of Aluminum-Based Shape Memory Alloy Self-Healing (SMASH) Technology*”.

• **Other Conference Talks:**
  – Aerospace Materials (AeroMat) Conference in June 2014 in Orlando, FL. “*Amending Fatigue Damage Using Shape Memory Alloy Self-Healing (SMASH) Technology*”.

• **Media, Articles and Public Relations:**
  – Central Florida Fox 35 News, January 2014
  – NASA video highlight: [http://www.youtube.com/watch?v=VBgGpkesHQo](http://www.youtube.com/watch?v=VBgGpkesHQo)
  – Professor Michele Manuel was deemed as one of three top researchers with groundbreaking research at the University of Florida in part because of the SMASH research, UF Alumni Magazine “*Shaping the Future*”, Spring 2014.
Next Steps

• Currently planning on 7 peer-reviewed journal articles
  – 1 high-level (in work), 2 modeling papers, 2 materials journals, 2 mechanics of materials.

• No-cost extensions granted to universities to complete experimental and modeling work for next 3 to 9 months.
  – Includes testing of multi-ply specimens and precipitation hardened matrix alloys.

• Interest from the Space Technology Mission Directorate to continue work on embedded crack detection and surface or non-contact heating.

• Potential collaboration with JPL to further enhance matrix design.

• Continue to market technology to other NASA Principal Investigators
Summary/Conclusions

• Proved healing of fatigue and overload cracks in proof-of-concept and aluminum matrix composites
• Performed fatigue crack growth tests before and after healing
• Experimentally optimized the processing parameters, healing treatment, matrix heat treatment
• Finite element model optimized the SMA reinforcement geometry, length, and pre-strain conditions
• Validated computer model using experimental data.

THANK YOU ARMD and NARI!