Thermo-mechanical evaluation of self-healing metallic structures for aerospace vehicles utilizing shape memory alloys

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Outline

• The innovation: SMASH technology
• Liquid-assisted self-healing approach
• Impact of the innovation
• Results of the Seedling Phase I effort
• Distribution/dissemination
• Future work
Shape Memory Alloy Self-Healing (SMASH) Technology

• Designing and testing an aeronautical lightweight structural alloy with self-repairing capabilities
  – Materials system can self-repair cm-long cracks
    • Investigation focused on self-repair of fatigue cracks
  – Aluminum alloy matrix reinforced with high-strength shape memory alloy (SMA) elements
  – Thermodynamic approach to design matrix alloy with pre-determined fraction of low melting eutectic phase

M. Creps et. Al., Incorporating Aluminum Hybrid Materials to Facilitate Life Extension in Legacy Aircraft, Airworthiness 2012 proceedings
Liquid-Based Self-Healing of Metal-Metal Composites

- Clamping force from the SMA wires
- Partial liquefaction of the matrix

Liquid-Based Healing History

- Healing of cm-long cracks has been achieved in a proof-of-concept Sn-Bi matrix reinforced with Ni-Ti SMA wires
  - Healing treatment: 20% liquid in matrix
  - Post heal: 95% strength recovery (UTS)
Knowledge Gap

• POC material showed liquid-assisted self-repair of overload cracks
  – Will self-healing work with a higher strength structural material?
  – Will liquid-assisted self-repair work for repairing fatigue cracks?
  – How is fatigue life affected by this technology?
Aerospace-grade aluminum materials subject to cyclic loading are susceptible to fatigue failure, sometimes catastrophic, at loads well below yield strength.

Wrought and cast Al alloys used throughout aircraft:

**Applications**

- **Upper Wing Skin**
  - Baseline: 7055-T7751, 7050-T7901
  - New Products: 7255-T792, 7255-T7751, Al-Li UW-P2

- **Fuselage Skin/Stringers/Frames**
  - Baseline: Aic: 2524-T3 Skin, Al: 6013-T6 HDT Skin,
  - New Products: Al-Li 2060-T8E36 Skin, 7055-T762

- **Integral Spars/Ribs**
  - Baseline: 7085-T6651, 7050/7010-T7651, 7150-T7751
  - New Products: 2397-T87, 7065-T7451, C9ST-T7X
  - Al-Li TP-1, Al-Li TP-2

- **Lower Wing Skin**
  - Baseline: 2024-T351, 2024-T39
  - New Products: 2024-T351, 2024-T39

- **Forgings for Wing/ Fuselage**
  - Baseline: 7117-T7351, 7050-T7452
  - New Products: 7085-T7452, Al-Li FG-1, Al-Li FG-2

- **Upper Wing Stringers**
  - Baseline: 7055-T7951, 7050-T79511
  - New Products: Al-Li 2060-T8E3, Al-Li 2050-T8E3

- **Fuselage Frames**
  - Baseline: 7055-T7651 HF, 7065-T651, 2024-T351, 7055-T7311
  - New Products: Al-Li 2099-T83, 7055-T74511, Al-Li 2050-T8E3

- **Floor Beams/Seat Tracks**
  - Baseline: 2009-T83, 7065-T765-T7051
  - New Products: 7055-T76511, Al-Li 2065-T8E3

- **Fuselage Stringers**
  - Baseline: 7055-T76511 HF, 7065-T651, 2024-T351, 7055-T7311
  - New Products: Al-Li 2099-T83, 7055-T74511, Al-Li 2050-T8E3

- **Lower Wing Stringers**
  - Current: 2024-T351, 2024-T351
  - New Products: Al-Li 2009-T83, Al-Li 2099-T83

**Green = Commercial**

**Blue = Under Development**
Impact of Innovation

- Improve damage tolerance and fatigue life of metals at critical structural locations
- Alternative to conventional repair techniques of fatigued structures
  - Mechanically fastened, bonded, etc.
- Integrated self-repairing approach would improve durability and sustainability of the aerospace material to ensure vehicle safety

Implications could revolutionize the industry and other NASA programs
Technical Approach

• The principal objectives of Phase I:
  1. Fabricate a high specific strength aluminum-based metal matrix composite that can repair cracks using liquid-assisted self healing
     a. Targeting specific microstructural constituents based on thermodynamics and kinetics of the system.
     b. Testing various fabrication techniques for optimal performance
  2. Characterize the mechanical behavior of the novel aluminum matrix constituent and composite before and after healing
     a. Primarily tensile and fatigue testing
  3. Explore and optimize the reinforcement architecture for composites reinforced in a uniaxial and cross-ply orientation.
Phase I Results

- Fabricated, tested, and healed overload and fatigue cracks in proof-of-concept tin-bismuth (Sn-Bi) composite.
- Proved self-healing in a cast binary Al-Si matrix alloy with pre-determined eutectic phase and 2 vol% Ni-Ti SMA wires.
- Fatigue tested the self-healing binary Al-Si alloy to create a stress life (S-N) curve.
- Fabricated two Al-Cu alloys with a pre-determined eutectic phase for self-healing: binary Al-Cu & ternary Al-Cu-Si.
- Fabricated multi-ply test samples of Al-Cu-Si alloys by isostatically hot pressing thin slices of the matrix and sandwiching SMA reinforcements at the interface.
Results: POC Material

- Fatigue tested proof-of-concept tin-bismuth (Sn-Bi) material to establish use of technology for cyclically loaded applications.
Healing Fatigue Crack in POC

Proved healing of fatigue crack in POC
Systematic Alloy Design

- Thermodynamic approach used to design binary alloy.
  - Castability
  - Eutectic Temp
  - Strength
- Samples were cast in graphite mold

4th International Conference on Self-Healing Materials, Ghent, Belgium, June 2013
Healing in Al-Si alloy

- Binary Al-3Si cast at 750°C;
  - 2 vol% NiTi SMA wires
  - Microstructural stabilization heat treatment
  - Tensile tested, healing treatment, tensile tested again

Proved self-healing with over 90% UTS recovered
Results: Healing in Al-Si

- Microstructure showed uniform eutectic phase distribution and adequate wire bonding.
  - Eutectic phase distribution ideal for liquid-assisted healing
Results: Al-Si Fatigue Behavior

• Fatigue tested the self-healing binary Al-Si alloy to create a S-N curve.
  – Significant variability in data due to porosity from fabrication technique
  – No effect of fatigue loading on SMA wires

Cast binary alloy fatigue behavior was determined
Results: Al-Si Fatigue Behavior

- Conducted fatigue crack growth tests on middle tension M(T) and single edge notch tension ESE(T) specimens to grow and heal a small fatigue crack.
  - Cracking occurs preferentially through eutectic along grain boundaries both pre- and post- healing.

- Healing of micron-scale fatigue cracks, as well as macro-scale machined notches achieved
- Fatigue crack growth rate decreased after healing; dotted line represents healing treatment

Healed binary Al alloy fatigue crack
Results: Al-Cu alloys

- Fabricated two Al-Cu alloys with a pre-determined eutectic phase for self-healing:
  - Binary Al-Cu & ternary Al-Cu-Si.

- Al-Cu alloys more brittle than the Al-3wt%Si in tension
- Little healing was evident in either Al-Cu or Al-Cu-Si alloys.
- It is theorized that the lack of ductility did not allow for the martensite→austenite transition within the SMA wire, and therefore no closure force was put on the matrix from the SMA wire.
- Without a clamping force to close the fracture faces, healing was unable to occur.
Results: Diffusion Bonding Fabrication

• Fabricated multi-ply test samples of Al-Cu-Si alloys by isostatically hot pressing thin slices of the matrix and sandwiching SMA reinforcements at the interface for diffusion bonding.
  – Eliminates casting defects
  – Potential for improved strength and ductility
  – Composites with more complex wire geometries can be fabricated
Multi-ply Specimens

- Up to four plies with three reinforcement layers at the interfaces were successfully fabricated.

Viable fabrication technique for multi-ply specimens was established.
Distribution/Dissemination

- Team will also continue to present results at relevant technical presentations (MS&T 2013, TMS 2014), write at least one peer-reviewed journal article, and be submitted for inclusion in NASA technical publications such as Tech Briefs.
- The technology will be showcased at KSC’s next innovation day.
Next Steps

• Phase II research will include:
  – Full development and characterization of the fatigue life behavior of the Al-Cu base alloys fabricated with unidirectional, multi-ply SMA reinforcements.
  – Modeling of the multi-ply specimens to determine optimal wire reinforcement and SMA clamping forces for healing using SMA-specific finite element analysis (FEA).
  – Fabrication of multi-ply specimens with optimal wire reinforcement and heat treatment to demonstrate multi-axis crack closure and healing of tensile and fatigue cracks.
Optional Funding

- Design, model, and fabricate a small scale prototype with more complex geometry based on vehicle parts that have shown a history of fatigue cracking in the field.

Team is requesting the additional $75K to create a self-repairing prototype and bring TRL to 4.
Phase II Team

- KSC – project management, fatigue testing, characterization
- LaRC – specimen fabrication, healing
- University of Florida – master alloy creation, fabrication, testing, healing of tested specimens
- Northwestern University – FEA models