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

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Outline

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- 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

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- 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

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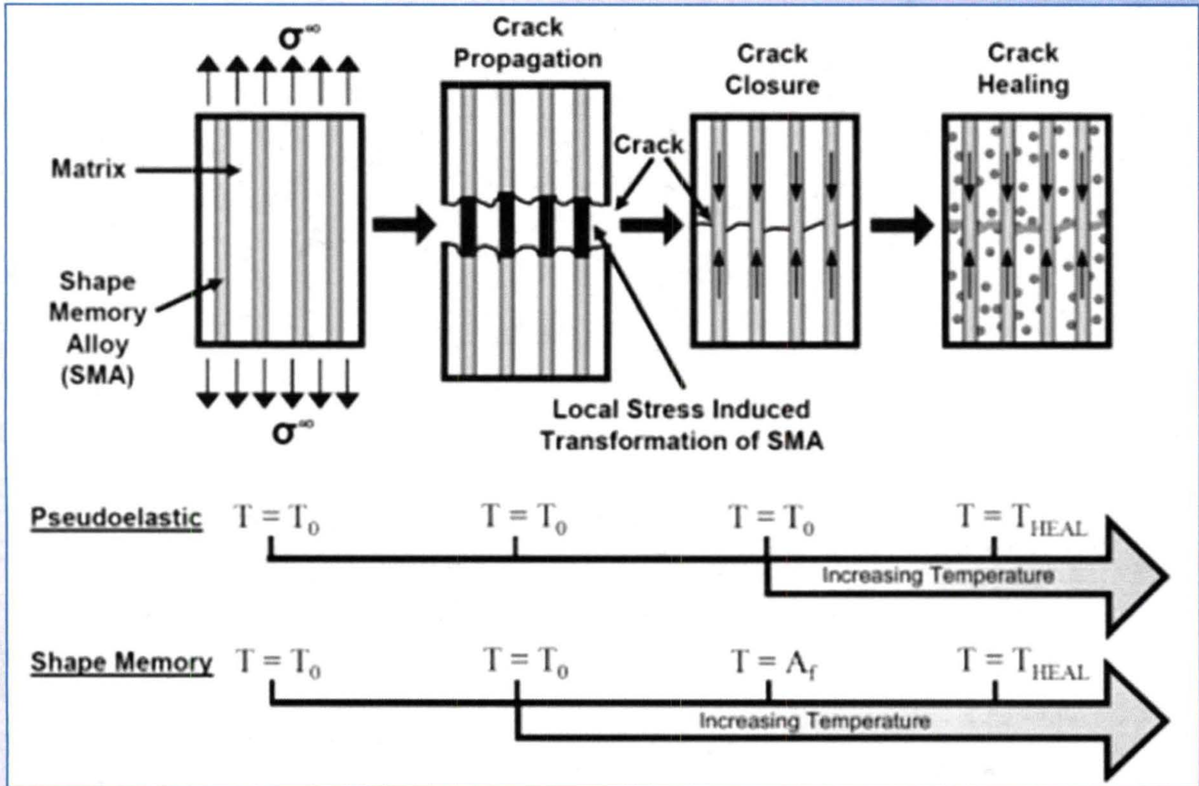
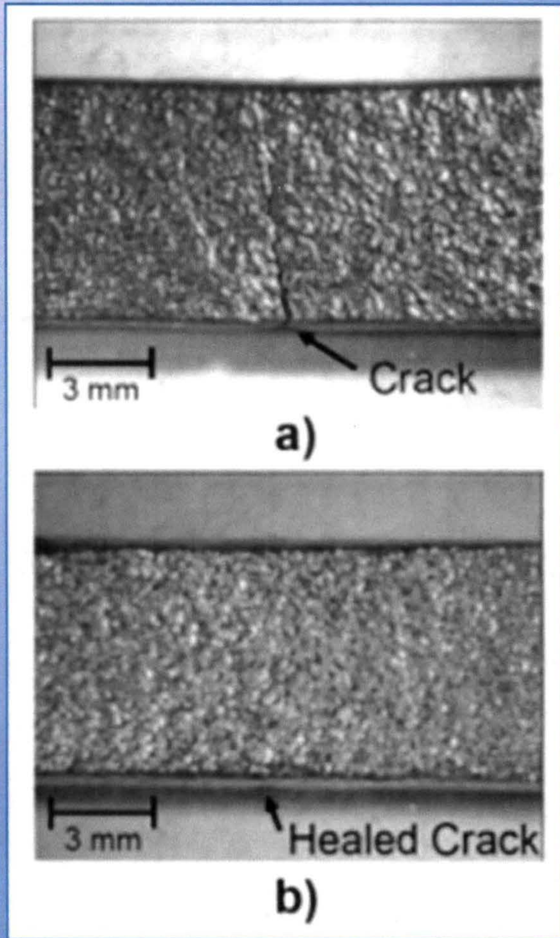
- Clamping force from the SMA wires
- Partial liquefaction of the matrix





Manuel, M.V, Principles of Self-Healing in Metals and Alloys: An Introduction, Chapter in Self-Healing Materials: Fundamentals, Design Strategies and Applications, Ghosh, S. K., Ed. Wiley: 2008; p In Press.

Liquid-Based Healing History

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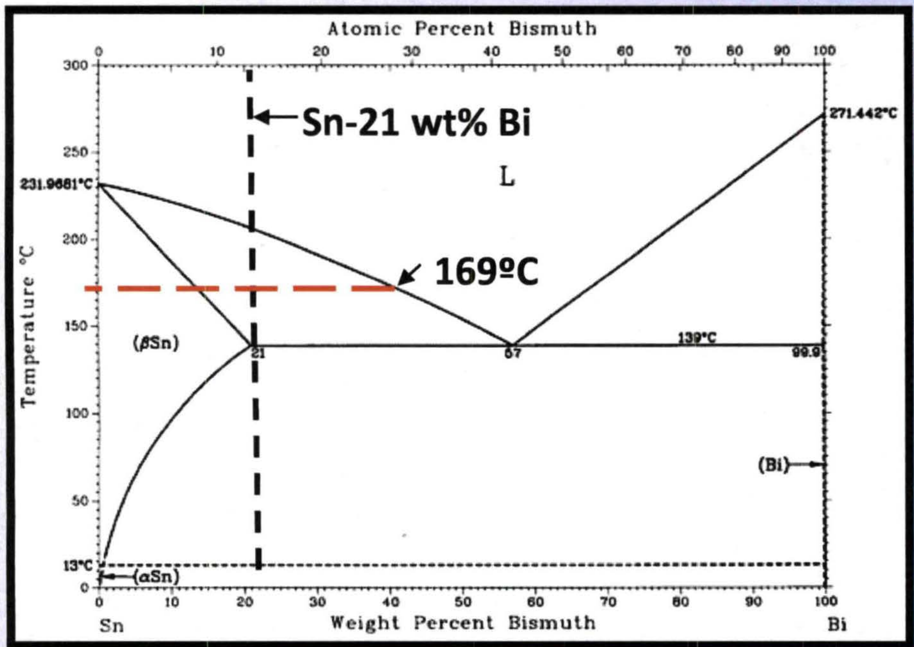
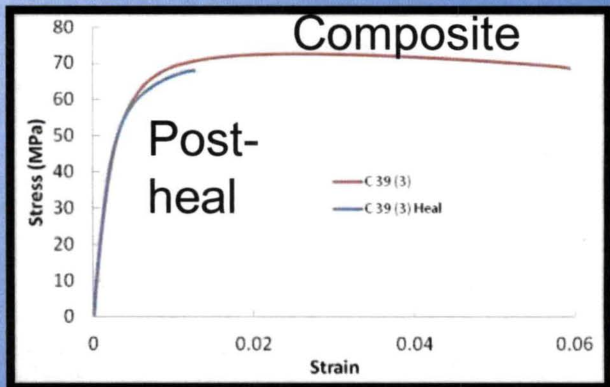
- Healing of cm-long cracks has been achieved in a proof-of-concept Sn-Bi matrix reinforced with Ni-Ti SMA wires
  - Healing treatment: 20% liquid in matrix
  - Post heal: 95% strength recovery (UTS)





Manuel, et al, "Design Considerations for Matrix Compositions in Self-Healing Metal Matrix Composites." 3rd International Conference on Self-Healing Materials; June 27-29, 2011; Bath, England.

Knowledge Gap

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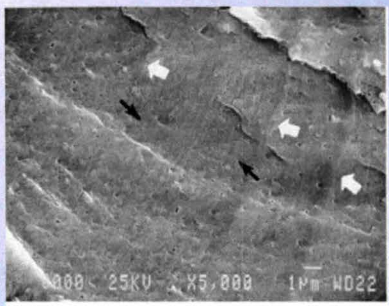
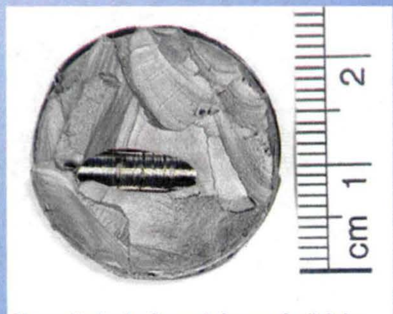
- POC material showed liquid-assisted self-repair of overload cracks
  - Will self-healing work with a higher strength structural material?
  - Will liquid-assisted self-repair work for repairing fatigue cracks?
  - How is fatigue life affected by this technology?



Fatigue striations from the Tail Cone Gap Cover. Scanning Electron Microscope (SEM). Magnification: 5,000X



Macrographic view of confluence point fracture surface displaying extensive fatigue damage.

McDanels et al, NASA KSC
Failure Analysis and Materials Evaluation

Applications

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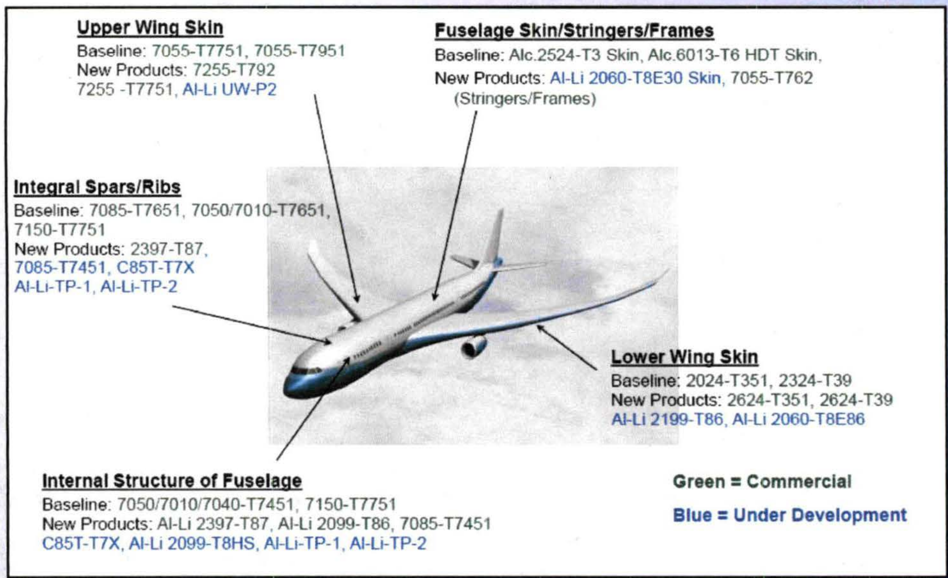
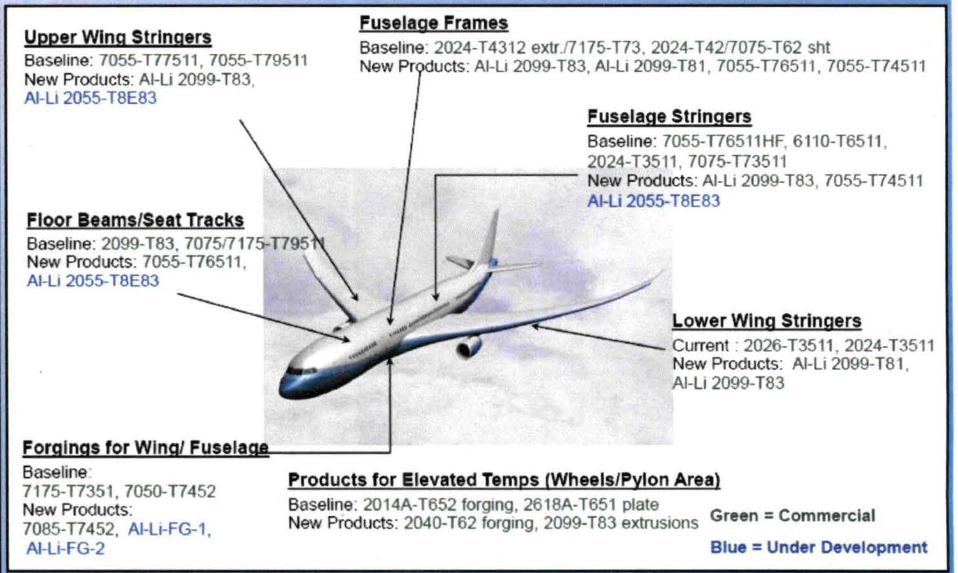
- Aerospace-grade aluminum materials subject to cyclic loading are susceptible to fatigue failure, sometimes catastrophic, at loads well below yield strength.
- Wrought and cast Al alloys used throughout aircraft:





Heinimann et al, Alcoa, "Advanced Metallic and Hybrid Structural Solutions for Light-Weight, Long-Lived Aerospace Structures Aircraft Airworthiness & Sustainment Conference 2012

Technical Approach

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- 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.

Impact of Innovation

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- 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**

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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

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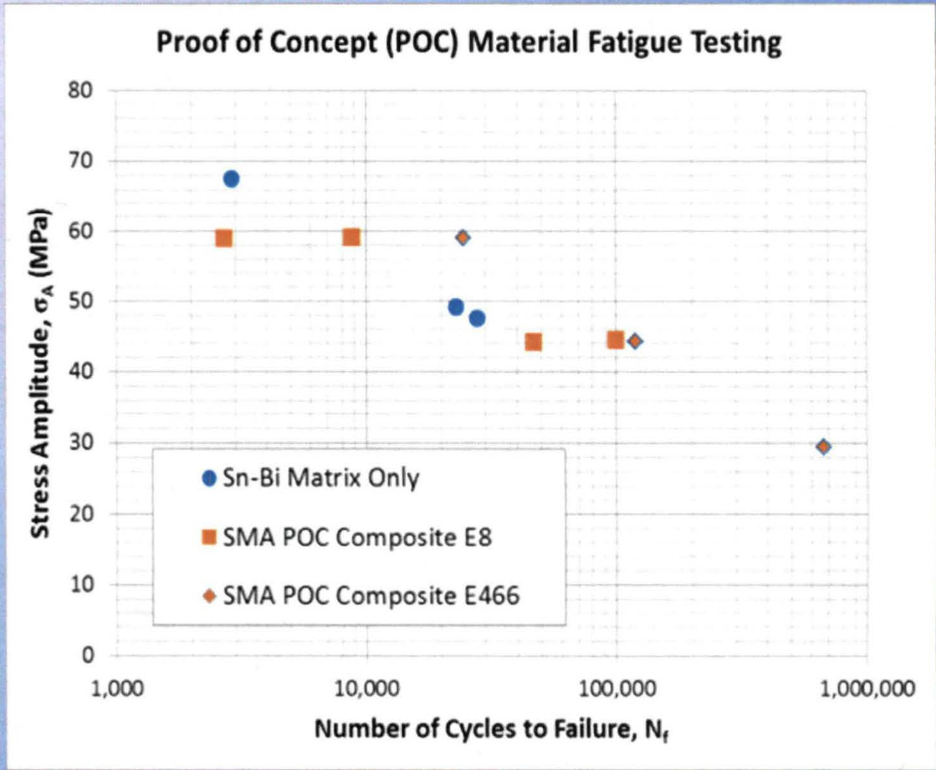
- Fatigue tested proof-of-concept tin-bismuth (Sn-Bi) material to establish use of technology for cyclically loaded applications.



Healing Fatigue Crack in POC

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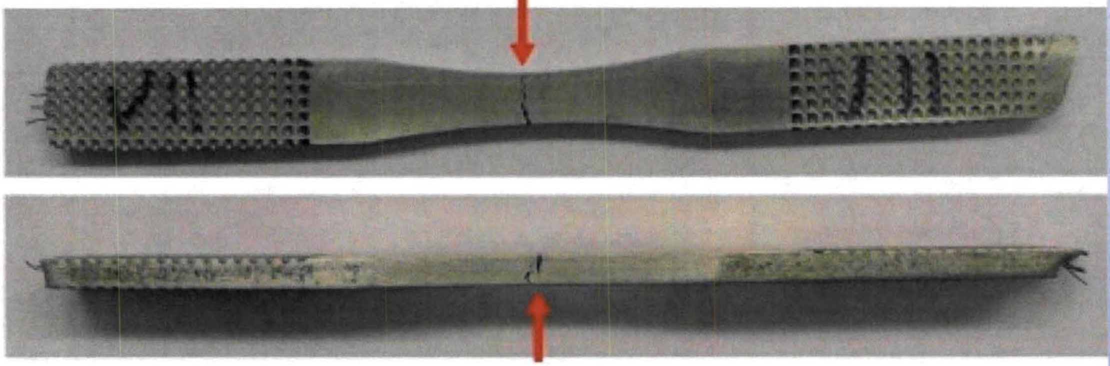
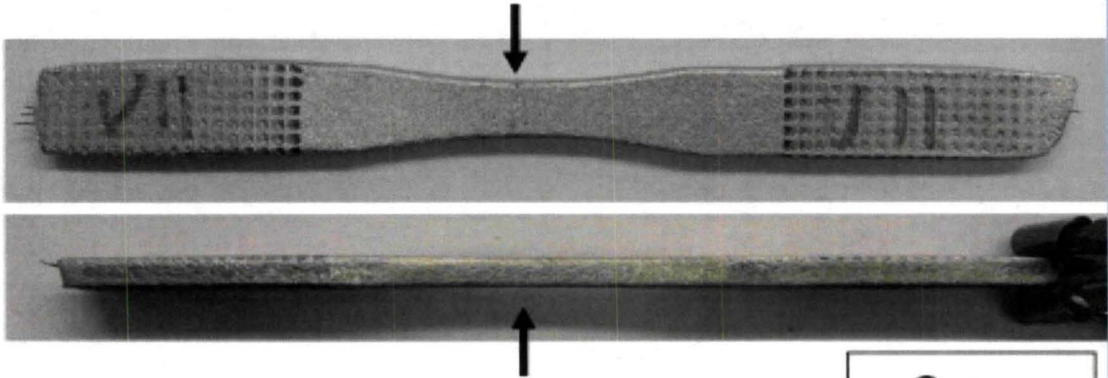
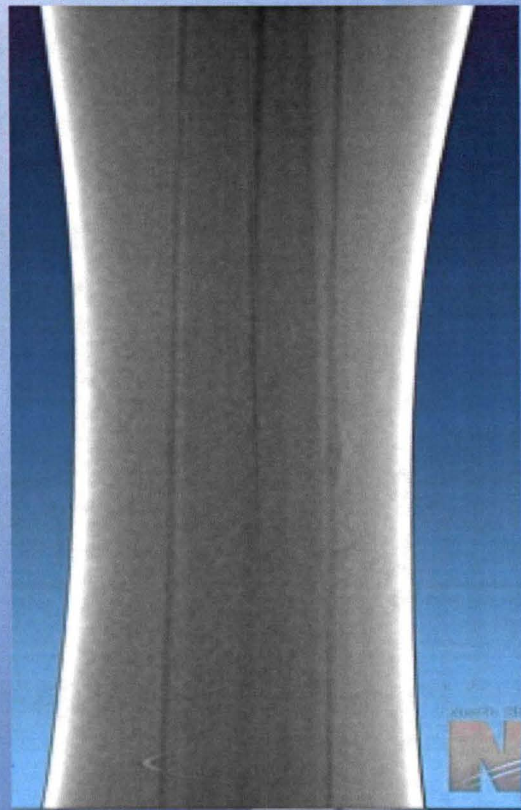
Before: Post-Fatigue Testing at KSC



After: Post-Heal at UF



2 cm



Proved healing of fatigue crack in POC

Systematic Alloy Design

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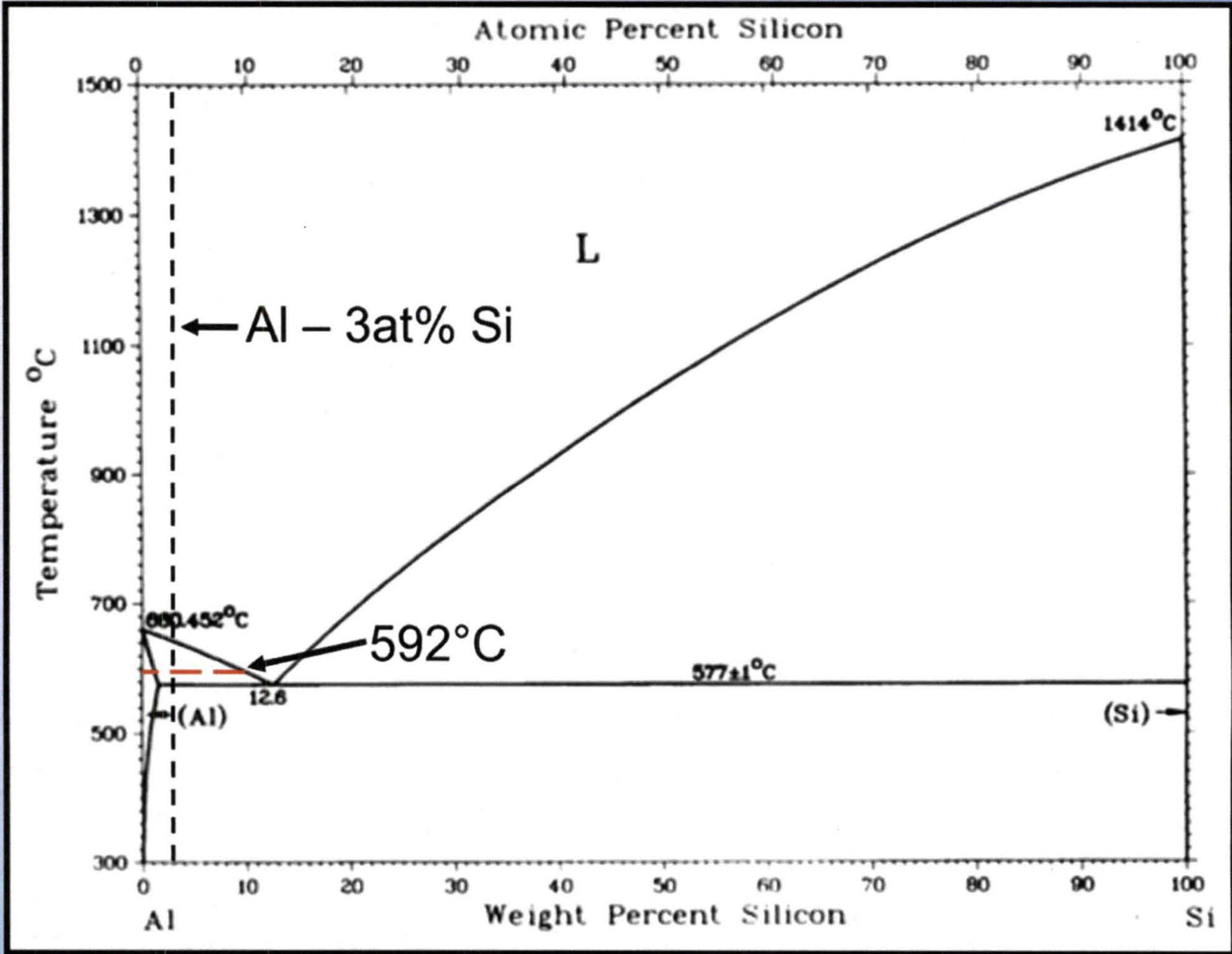
- Thermodynamic approach used to design binary alloy.
  - Castability
  - Eutectic Temp
  - Strength
- Samples were cast in graphite mold



Manuel et al, "Design Methodology for Liquid-Assisted Self-Healing Materials"
4th International Conference on Self-Healing Materials, Ghent, Belgium, June 2013

Healing in Al-Si alloy

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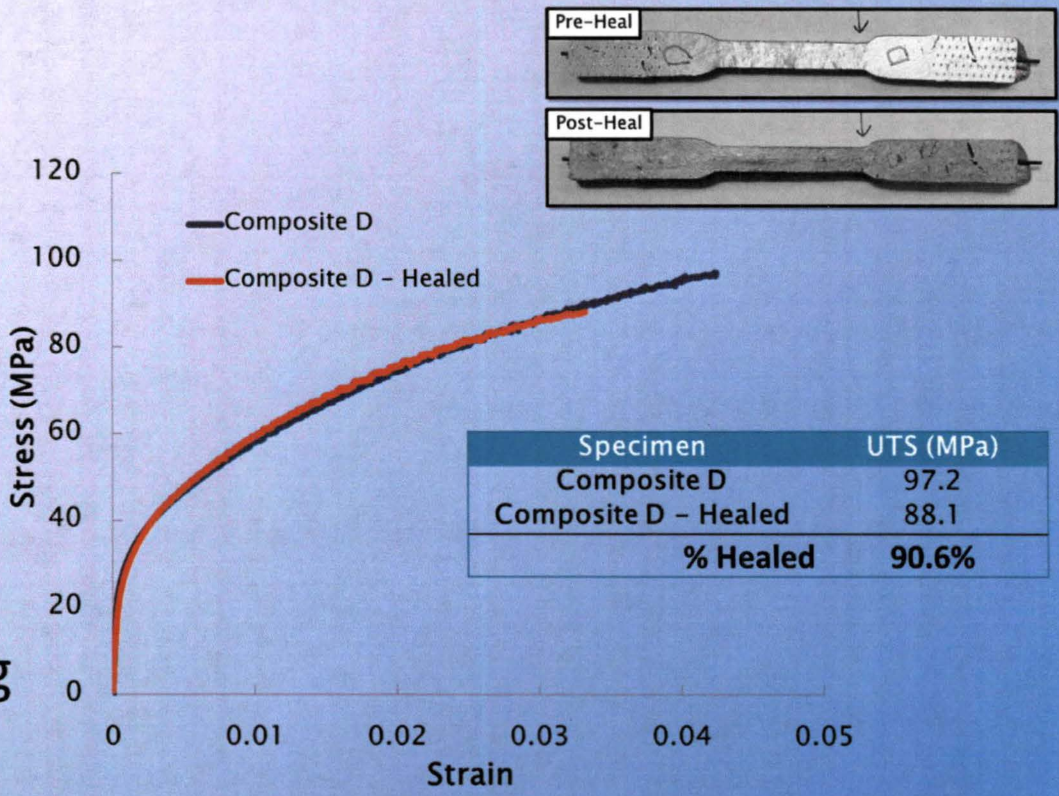
- Binary Al-3Si cast at 750°C;
  - 2 vol% Ni/Ti SMA wires
  - Microstructural stabilization heat treatment at 592°C
  - Tensile tested, healing treatment, tensile tested again



Specimen	UTS (MPa)
Composite D	97.2
Composite D - Healed	88.1
% Healed	**90.6%**

Proved self-healing with over 90% UTS recovered

Results: Healing in Al-Si

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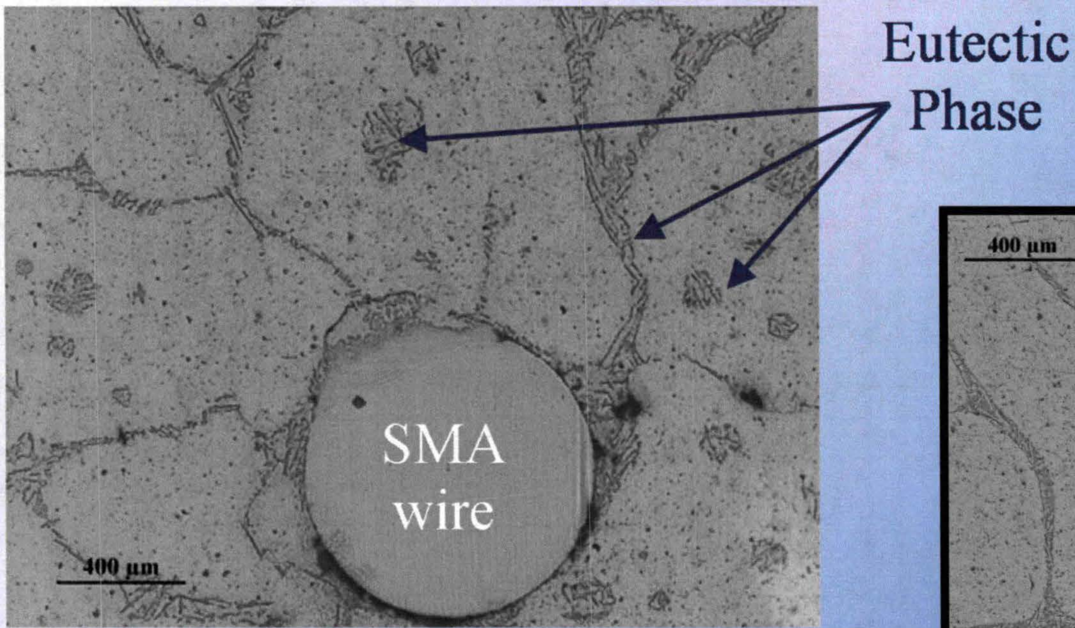
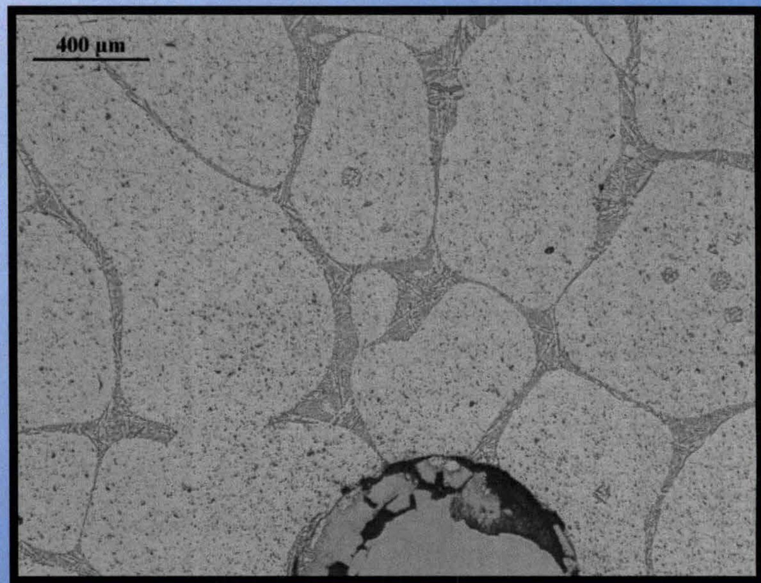
- Microstructure showed uniform eutectic phase distribution and adequate wire bonding.
  - Eutectic phase distribution ideal for liquid-assisted healing





Results: Al-Si Fatigue Behavior

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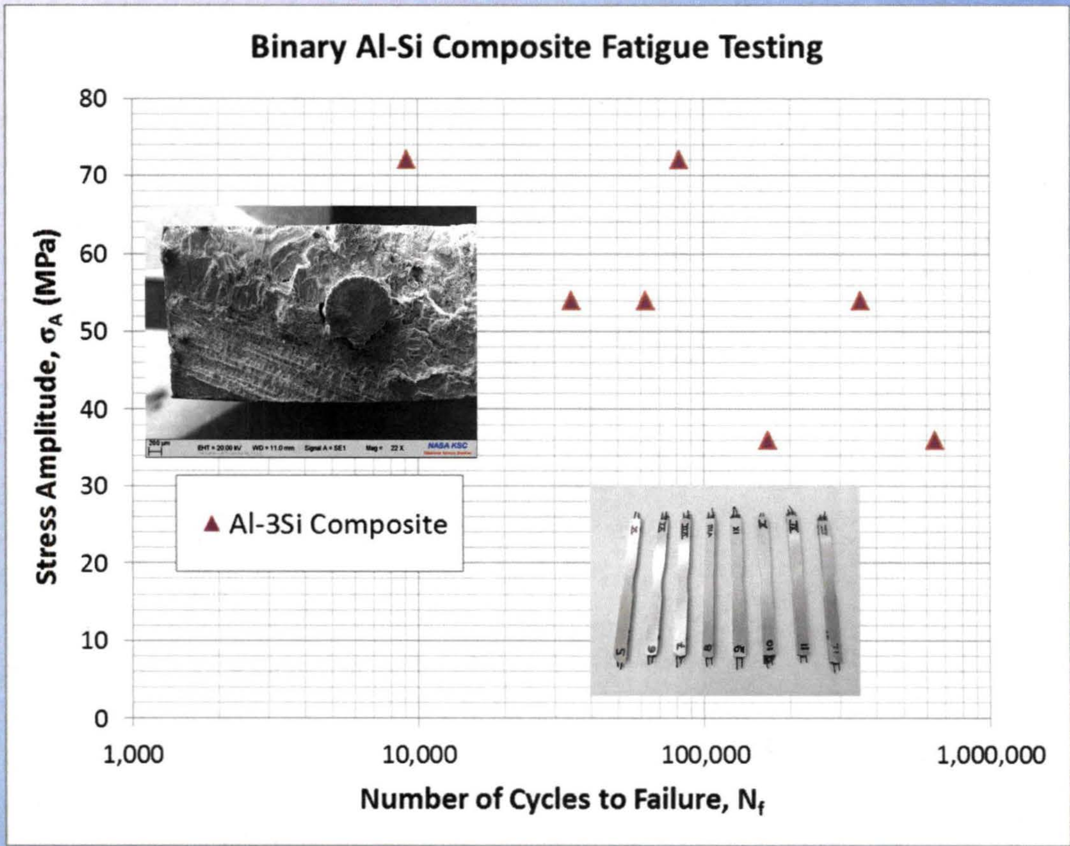
- Fatigue tested the self-healing binary Al-Si alloy to create a S-N curve.
  - Significant variability in data due to porosity from fabrication technique
  - No effect of fatigue loading on SMA wires



Cast binary alloy fatigue behavior was determined

Results: Al-Si Fatigue Behavior

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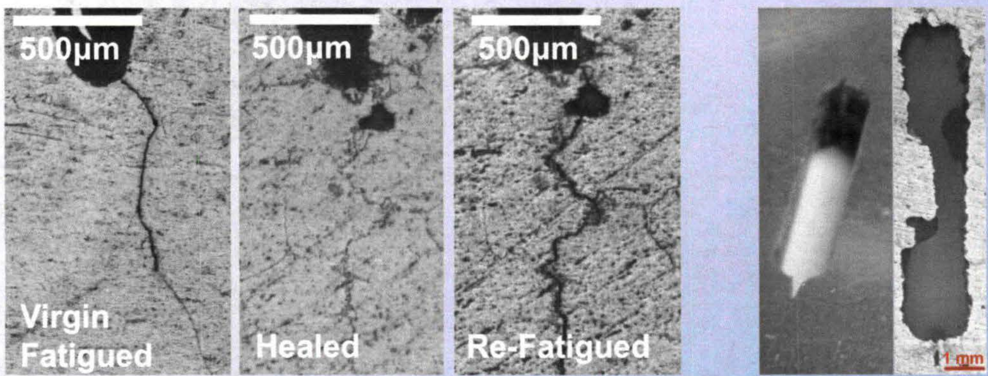
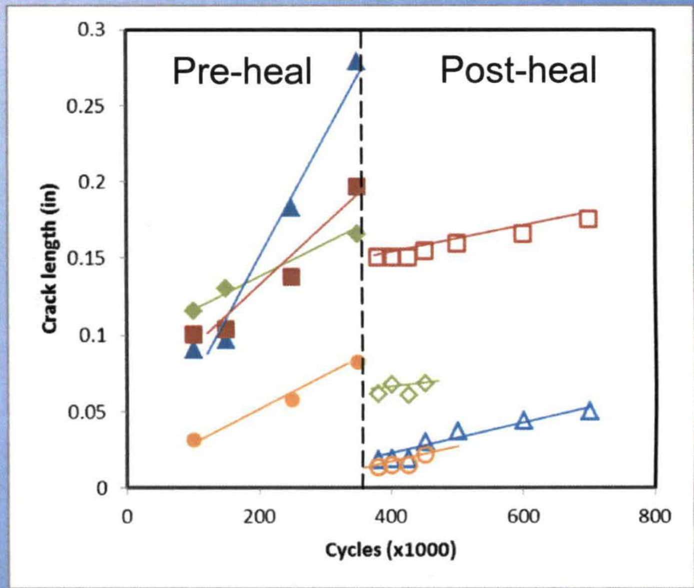
- Conducting fatigue crack growth tests on a middle tension M(T) and single edge notch tension ESE(T) specimens to grow and heal a small fatigue crack.
  - Cracking occurs preferentially through eutectic along grain boundaries both pre and post healing.





- 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

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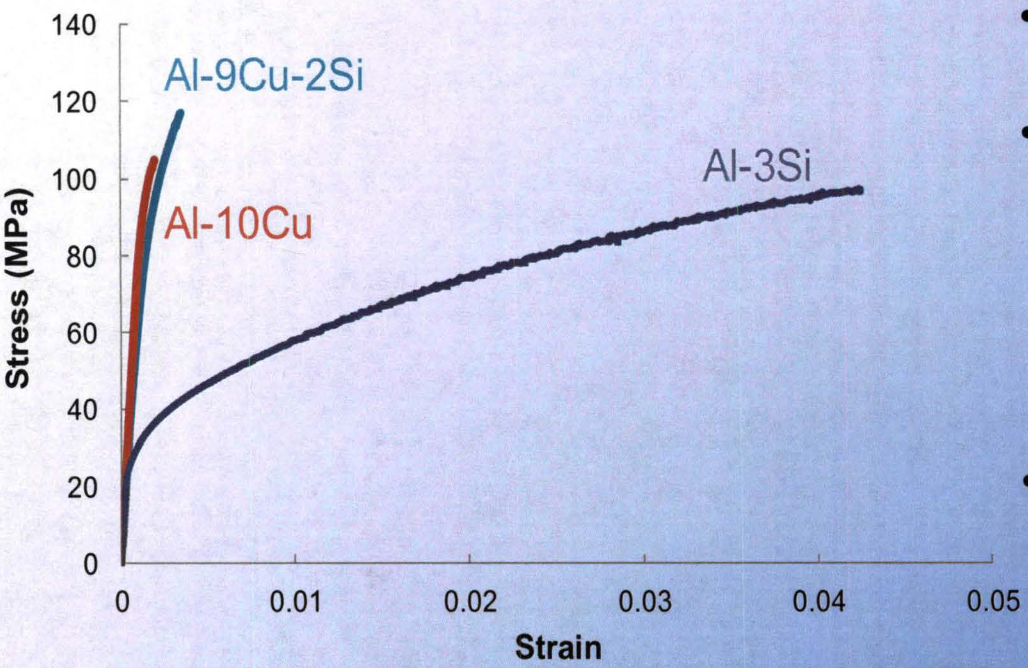
- Fabricated two Al-Cu alloys with a pre-determined eutectic phase for self-healing:
  - Binary Al-Cu & ternary Al-Cu-Si.



- 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

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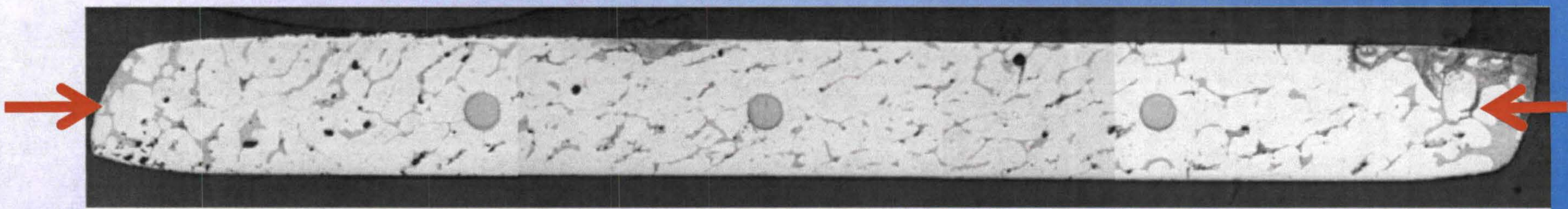
- Fabricated multi-ply test samples of Al-Cu-Si alloys by isostatically hot pressing thin slices of the matrix and sandwiching SMA reinforcements at the interface for diffusion bonding.
  - Eliminates casting defects
  - Potential for improved strength and ductility
  - Composites with more complex wire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



Multi-ply Specimens (cont.)

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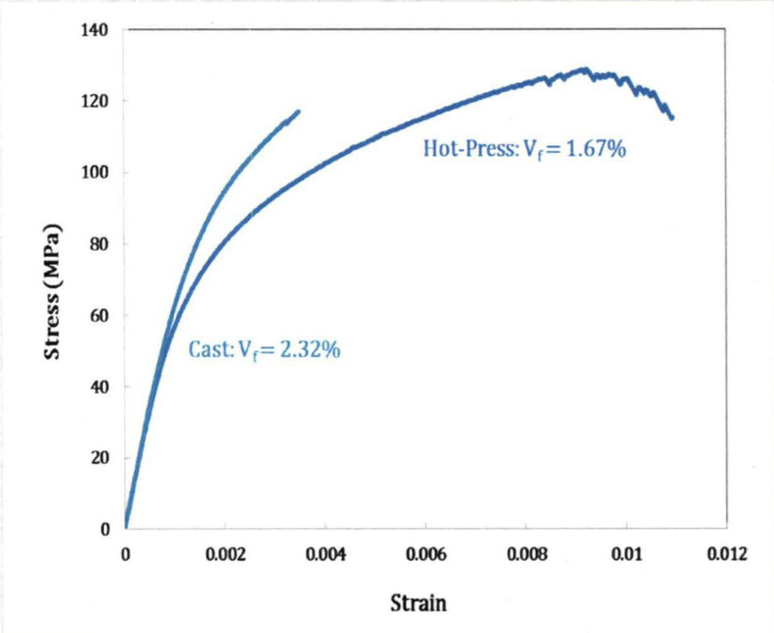
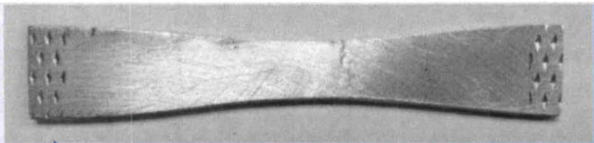
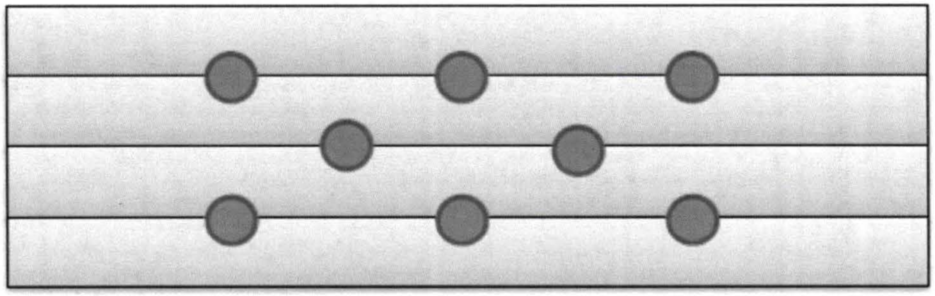
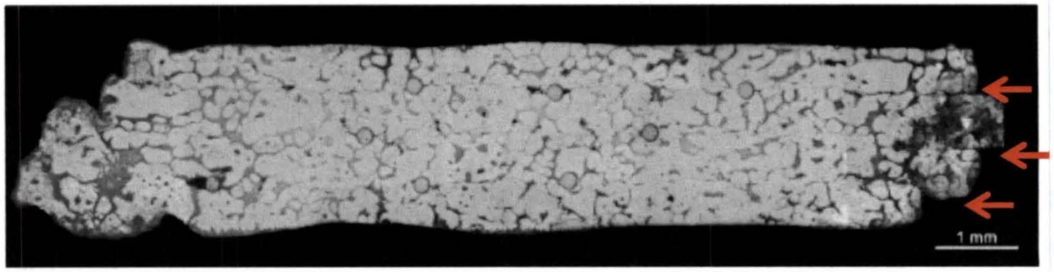
- Up to four plies with three reinforcement layers at the interfaces were successfully fabricated.









Viable fabrication technique for multi-ply specimens was established

Distribution/Dissemination

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- Submitted for NASA New Technology Report for future patent application.
- International Conference of Self Healing Materials, Ghent, June 2013, *Design Methodology for Liquid-Assisted Self-Healing Metals*.
- 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

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- Phase II research will include:
  - Full development and characterization of the fatigue life behavior of the Al-Cu-Si fabricated with unidirectional, multi-ply SMA reinforcements.
  - Modeling of the multi-ply specimens to determine optimal wire reinforcement (including long/short fibers) 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

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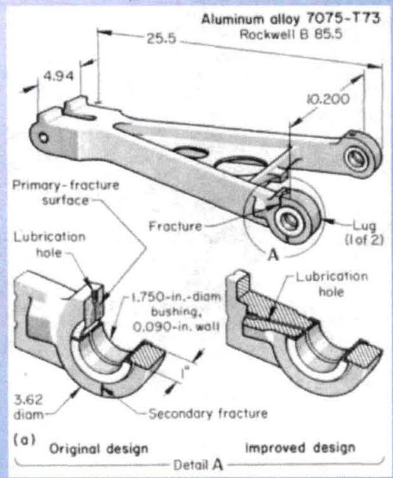
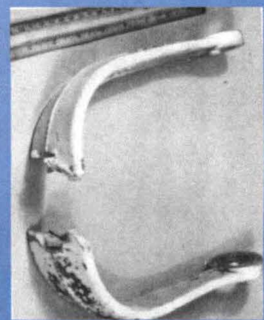
- Design, model, and fabricate a small scale prototype based on aerostructural or non-structural vehicle parts that have shown a history of fatigue cracking in the field.

ASM Failure Analysis Center, Case Histories in Failure Analysis, 2024-T3



Aluminum alloy 7075-T73 landing-gear torque-arm assembly that was redesigned to eliminate fatigue fracture at a lubrication hole.



Nose wheel fork failed when plane was in service.

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

Phase II Team

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