Novel Amalgams for in-Space Parts Fabrication

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Premise

• Replacement parts will likely be necessary during extended deep space missions.
  – Repair parts increase vehicle weight and take up precious cargo space
  – What will break cannot be anticipated
  – Fabricating parts can include complicated procedures
    Handling and pouring of hot liquid metal
    Complicated machining and fluid handling
Amalgam

- Amalgam: An alloy of mercury with at least one other metal.
- Amalgams are based on a peritectic reaction:
  \[(S_1 + L_1 \rightarrow S_2)\]

Dental amalgams are well-understood and have an established application.
Amalgam Considerations

- Room temperature processing
- Corrosion resistant
- Minimum: power consumption, crew interaction, final finishing, and mass/volume consumption
- Moldable
- Net-shape part (no shrinkage or additional machining)
- No fluid handling issues (hot liquid metal)

Amalgams have potential for fabricating parts during deep space missions.
Schematic showing parts fabrication using amalgams during deep space missions.

Solid Freeform Fabricator

Part Mold

Mold + Amalgam

Time + Pressure

Amalgam

Part

Recycle

Liquid Metal

Metal Fibers

Trituration
Amalgam Disadvantages

Mercury, which is toxic, is typically used.

Amalgams have low tensile strengths (~10% of compression)

Cu-Ag-Sn Amalgam Powder Consisting of Atomized Spheres and Lathe-cut Particles
Solutions to Disadvantages

Substitute Ga-In liquid for Hg

Include high-strength steel fibers with commercial Ag-Sn-Cu powder
Research Objective

Can Ga-In liquid substitute for Hg?

Will the inclusion of steel fibers improve the mechanical properties of amalgams?
SEM micrographs of processed samples with and without fibers

Dense fully reacted amalgam with no porosity in both cases.

Color key:
Turquoise = tin,
Indium = green,
Silver = purple,
Gallium = red,
Iron/steel = grey,
Copper = orange
Fracture Surfaces

A typical amalgam (no fibers) fracture surface

A fracture surface of an amalgam with steel fibers

A phase map showing the distribution of steel fibers
Mechanical Testing: Load to Failure

A comparison of the load to failure (crush) strength of amalgams without fibers and those with.

Samples with included steel fibers performed better.
Mechanical Testing:
Diametrical Tensile Strength

Samples with included steel fibers again performed better
Role of Steel Fibers

Micrograph of a broken steel fiber (center) in the amalgam matrix.

Higher magnification showing the dimpled fracture surface of the steel fiber surrounded by reaction products.

Elemental phase map showing the extent of steel (gray color) after necking, ~36% reduction in area.

Mechanical properties increase due to the steel wires inherent strength, its bonding with the matrix, and subsequent plastic deformation prior to failure.
Conclusions

• Sound amalgams can be fabricated by substituting Ga-In liquid for mercury; Cu-coated steel fibers bond well with the amalgam components.
• Inclusion of steel fibers significantly improved mechanical properties.
• An application scenario utilizing amalgams for in-space parts fabrication and repair was suggested.
• Procedure and materials need to be optimized.
Acknowledgments

Appreciation is expressed to Greg Jerman, Ms. Lisa Sharff, Craig Stafford, and Dr. Preston McGill for their timely assistance. Support from the Materials and Processing Laboratory of the Marshall Space Flight Center is also greatly acknowledged.
Backup Slides
Outline

• Introduction
  – Premise

• Amalgams
  – Advantages/Disadvantages/Solutions
  – Scenario applications

• Experiment
  – Objective
  – Process
  – Results: Microstructures, Fracture Surfaces, Mechanical Testing, Modeling

• Future work and Conclusions
Molding

In order to create spare parts, molds can be made by a Fused Deposition Modeling machine and filled with amalgams.

Examples of shapes made by a FDM

Fused Deposition Modeling machine
The Process

- Determine and weigh out amalgam components.
- Place components in plastic capsule and mechanically mix.
- Insert newly reacted amalgam in quartz cylinder between two quartz pistons, compress in clamp, and leave overnight.
- Mechanically test sample using a laboratory press to determine load to failure or diametrical tensile strength.
- Evaluate microstructure.
Amalgam Reactions: Intermetallic Compounds

SEM phase maps and extracted spectrums can be used to predict compounds formed within amalgams.

Phase map showing a reaction product around a Ag-Sn-Cu particle.

Cu-Ga phase diagram

<table>
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<th>Element</th>
<th>Weight %</th>
<th>Std. Dev.</th>
<th>Atomic %</th>
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<tr>
<td>Cu</td>
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<tr>
<td>Ga</td>
<td>61.26</td>
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<td>Ag</td>
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<td>0.68</td>
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<tr>
<td>Sn</td>
<td>4.15</td>
<td>2.46</td>
<td>2.49</td>
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<tr>
<td>Total</td>
<td>100.00</td>
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The rule-of-mixtures was applied to predict optimal tensile strength. The formula is as follows:

$$\delta_{co} = \chi V_f \delta_f + V_m \delta_m$$

Note that $\delta_{co}$, $\delta_f$, and $\delta_m$ are the ultimate strengths of the amalgam, fibers, and matrix (everything but the fibers), respectively. Note that $V_f$ and $V_m$ are the volume fractions of the fiber and matrix and that $\chi$ is a constant which considers fiber orientation and length factors.
Sample Preparation Problems

Good processing with good microstructure resulting in good properties. Well coated fibers.

‘Crumbly’ lack of bonding between fibers and powder, due to insufficient liquid

‘Bunched’ fibers, poor mixing precludes any reaction
Future work

Materials and processing parameters need to be optimized in order to maximize material properties. These include, for example:

- Fiber lengths and volume fractions
- Mixing techniques
- Reaction/setting time (not too fast)

Steps toward preparing larger samples should also be taken.