Fabrication of High Thermal Conductivity NARloy-Z-Diamond Composite Combustion Chamber Liner for Advanced Rocket Engines

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- NASA-GRC
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- Penn State – Applied Research Laboratory
  - Dr. Jogender Singh – FAST processing
- Momentive Performance Materials
  - Aaron Rape – thermal conductivity
- Global Technology Enterprises
  - Dr. Sion Pickard – coated diamonds
Overview

• Introduction
• Improving thermal conductivity of copper alloys
• Project goals
• Chamber liner fabrication process
• Field Assisted Sintering Technology (FAST)
• Diffusion bonding
• Fabrication challenges
• Results
• Follow on work
Introduction

• NARloy-Z alloy (Cu-3Ag-0.5Zr) is state of the art material for making combustion chamber liner for liquid rocket engines. Thermal conductivity (TC)– 320 W/mK
  • Currently used in RS-25, RS-68

• Improved TC will help to improve the performance of rocket engines
  • Improved turbopump power, thrust to weight ratio, specific impulse

• Prior work on NARloy-Z-Diamond composites showed promise
  • 50% improvement in thermal conductivity relative to copper

• Technology development goals:
  • Fabricate a subscale combustion chamber liner (TRL 4)
  • Fabricate test chamber assembly
  • Hot fire test to demonstrate performance improvements (TRL 5)
Thermal conductivity of Cu-Ag-Zr-D composites

[Graph showing thermal conductivity vs. volume % Diamond for Cu-Ag-Zr-D composites]
Combustion chamber liner, chamber assembly

• Chamber liner (A) – 2.75”OD, 2.5” ID, 8” long
• Chamber assembly (B)

Hot fire test assembly schematic
Chamber liner fabrication steps

1. **NARloy-Z powder**
2. **Diamond powder**
3. **NARloy-Z-D mixture**
4. **Pour into TZM mold**
5. **FAST Sinter at elevated temperature and pressure**
6. **FAST Diffusion bond at elevated temperature and pressure**
7. **Multiple rings stacked in TZM mold**
8. **NARloy-Z-D ring**
9. **Turbula mixer**
10. **Finished liner**
11. **Liner removed from mold**
12. **Finished liner**
Field Assisted Sintering Technology (FAST)

FAST - schematic

FAST system at Penn State - ARL

Sintering at high temperature in FAST apparatus
Diffusion bonding (schematic)

Eight rings stacked inside TZM mold for joining

Translucent model with multi-colors showing the rings

Diffusion bonding by FAST
Fabrication challenges

• Machining of NARloy-Z-D composite
  • Too hard to machine by conventional means
  • EDM and water jet cutting successful

• Near net shape forming
  • Switching from graphite to TZM molds for better strength at elevated temperatures

• Segregation of diamonds in microstructure
  • Diamonds segregate easily – hard to homogenize
  • Metal coatings help to improve mixing – Ti, Cu
  • Cu coating worked better

• Copper coated diamonds – supplied by GTE
  • Coating of MoC for better contact conductance
  • Overcoat of Cu for better mixing and sintering

• Diffusion bonding of NARloy-D rings
  • Interlayer of NARloy-Z for better bonding

• Microscopy and NDE
  • Material is too hard to make metallographic samples
  • Freshly fractured surfaces the best way to examine microstructure in SEM
  • CT scanning to assess segregation and ensure quality
## Tensile properties (preliminary)

<table>
<thead>
<tr>
<th>Sample type</th>
<th>Composition</th>
<th>Test temperature, Environment</th>
<th>YS, ksi</th>
<th>UTS, ksi</th>
<th>Elongation, %</th>
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</thead>
<tbody>
<tr>
<td>NARloy-Z</td>
<td>Base line</td>
<td>75°F, air</td>
<td>18</td>
<td>45</td>
<td>33</td>
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<tr>
<td>NARloy-Z-30D</td>
<td>30 vol% diamond</td>
<td>75°F, air</td>
<td>19</td>
<td>19</td>
<td>&lt;1</td>
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<tr>
<td>NARloy-Z-40D</td>
<td>40 vol% diamond</td>
<td>75°F, air</td>
<td>18-20</td>
<td>18-24</td>
<td>&lt;1</td>
</tr>
<tr>
<td>NARloy-Z-40D</td>
<td>40 vol% diamonds</td>
<td>935°F, GN2</td>
<td>11</td>
<td>11</td>
<td>&lt;1</td>
</tr>
<tr>
<td>NARloy-Z-30(Ti-D)</td>
<td>30 vol% Ti-coated diamond</td>
<td>75°F, air</td>
<td>12</td>
<td>12-13</td>
<td>&lt;1</td>
</tr>
<tr>
<td>NARloy-Z-30 (Cu-MoC-D)</td>
<td>28 vol% diamonds, Cu-MoC coated</td>
<td>70°F, air</td>
<td>18</td>
<td>23</td>
<td>2-3</td>
</tr>
<tr>
<td>NARloy-Z-30 (Cu-MoC-D)</td>
<td>28 vol% diamonds, Cu-MoC coated</td>
<td>1000°F, 250 psi He</td>
<td>5-6</td>
<td>5-7</td>
<td>2-3</td>
</tr>
<tr>
<td>Diffusion bonded NARloy-Z-40D</td>
<td>40 vol.% Diamond; NARloy-Z at bond line</td>
<td>70°F, air</td>
<td>10</td>
<td>11</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>
## Thermal conductivity (preliminary)

<table>
<thead>
<tr>
<th>Sample chemistry (vol%)</th>
<th>Thermal conductivity (W/m-K)</th>
<th>Temperature, °K</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>NARloy-Z</td>
<td>320</td>
<td>300</td>
<td>Base line (Ref. 2)</td>
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<tr>
<td>NARloy-Z-30%D</td>
<td>337</td>
<td>380</td>
<td>Diamond segregation observed (Ref. 3)</td>
</tr>
<tr>
<td>NARloy-Z-40%D</td>
<td>344</td>
<td>380</td>
<td>Diamond segregation observed (Ref. 3)</td>
</tr>
<tr>
<td>NARloy-30%TiD</td>
<td>176</td>
<td>300</td>
<td>Ti lowers TC</td>
</tr>
<tr>
<td>NARloy-Z-28%CuD</td>
<td>462</td>
<td>300</td>
<td>TC acceptable</td>
</tr>
</tbody>
</table>
Microstructure

SEM Micrograph showing diamond segregation (dark area) in NARloy-Z-30%D Composite

SEM fractograph of NARloy-Z-Ti coated diamond composite

SEM fractograph of NARloy-Z-Cu-MoC coated diamond composite
Chamber liner

Chamber liner ring (2.5” ID., 2.75” OD, 1.0” long) made from NARloy-Z- CuD composite

NARloy-Z chamber liner fabricated by FAST - after taking out of the mold

NARloy-Z chamber liner – after cleaning
Follow on work

- Diffusion bond NARloy-Z-CuD composite rings in FAST apparatus
- Machine cooling channels by water jet grinding
- Electroplate with nickel to close out the channels
- Fabricate coolant manifolds and integrate with hot fire test assembly
- Hot fire test in MSFC test stand 115
- Analyze data and assess performance

Hot fire testing at MSFC TS 115
Summary and Conclusions

- Successfully formulated a high thermal conductivity NARloy-Z-CuD composite material that can be processed into shapes.
- Developed processing technique for combustion chamber liner rings by use of Field Assisted Sintering Technology (FAST)
- Developed fabrication technique for chamber liner by diffusion bonding
- This is a break through technology in metal matrix composites, which will help to make our future propulsion systems lighter and higher performance using a high thermal conductivity material for combustion chamber liner.
- Materials and processing technologies can be developed further to optimize properties for specific applications, e.g., heat exchangers and other thermal management systems.