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

Biliyar N. Bhat
Materials and Processes Laboratory
NASA- Marshall Space Flight Center, Huntsville, Alabama
January 6, 2016

57th AIAA Structures, Structural Dynamics and Materials Conference
San Diego, CA
Materials and Processes Development Team

• NASA-MSFC
  • Biliyar Bhat – Principal Investigator
  • Sandra Greene – Co-Investigator – chamber design and testing
  • Enrique Jackson – thermal conductivity
  • James Coston, Ellen Rabenberg – microscopy
  • Will Tilson/Jacobs – tensile testing
  • Supported by NASA-MSFC Technology Investment Project

• NASA-GRC
  • Dr. David Ellis - consultant

• 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
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. Liner removed from mold
9. Finished liner
10. NARloy-Z-D ring
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>
</tr>
</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>
</tr>
<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>
</tr>
<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</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>
</tr>
<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 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.