Effect of Composite Substrates on the Mechanical Behavior of Brazed Joints in Metal-Composite System

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Abstract

Advanced composite components are being considered for a wide variety of demanding applications in aerospace, space exploration, and ground based systems. A number of these applications require robust integration technologies to join dissimilar materials (metal-composites) into complex structural components. In this study, three types of composites (C-C, C-SiC, and SiC-SiC) were vacuum brazed to commercially pure Ti using the active metal braze alloy Cusil-ABA (63Ag-35.3Cu-1.75Ti). Composite substrates with as fabricated and polished surfaces were used for brazing. The microstructure and composition of the joint, examined using scanning electron microscopy (SEM) coupled with energy dispersive spectroscopy (EDS), showed sound metallurgical bonding in all systems. The butt strap tensile (BST) test was performed on bonded specimens at room and elevated temperatures. Effect of substrate composition, interlaminar properties, and surface roughness on the mechanical properties and failure behavior of joints will be discussed.

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Outline

- **Introduction** - Need for Joining and Integration Technologies

- **Challenges in Bonding of Metal-Composite System**
  - Thermal Expansion Mismatch
  - Joint Design and Testing

- **Brazing of Titanium to Composites** (C/C, C/\text{SiC}, \text{SiC}/\text{SiC})
  - Microstructural Analysis
  - Mechanical Behavior
    - Microhardness Behavior
    - Butt Strap Tensile (BST) Tests
  - Effect of Surface Roughness

- **Summary and Conclusions**
Need for Joining and Integration Technologies

• Joining and integration technologies are key to development and utilization of advanced composites in aerospace and ground based applications.

  – Aerospace Systems
    • Aerospace and Space Propulsion Components (Combustor Liners, Exhaust Nozzles, Nozzle Ramps, Turbopump Blisks)
    • Thermal management systems (Radiators, recuperators), optical components, and dimensionally stable space structures

  – Ground Based Systems
    • Nuclear Industries, Land Based Power Generation, Process Industries, Heat Exchangers, Recuperators, Microelectronic Industries (Diffusion Furniture, Boats)

• The development of robust joining and assembly capability will allow the application of advanced composites technology in a timely manner.
Joining and Integration Technologies are Key to Manufacturing of Heat Rejection System

Advanced C/C Composite Radiators

Assembly of Composites with Titanium Tubes
Technical Challenges in Design and Selection of Joints

Typical Joints will have Combination of Stresses Under Operating Conditions

(a) Compression; (b) Tension; (c) Shear; (d) Peel; (e) Cleavage

Different Types of Shear Tests
Various Activities on Bonding of Metals to Ceramics and Composites Using Metallic Interlayers at GRC

**Metallic Systems:**
- Titanium
- Inconel and Other Ni-Base Superalloys
- Kovar
- Stainless Steels

**Ceramics/Composite Systems:**
- SiC, Si3N4
- YSZ, Alumina
- C/C Composites
- C/SiC, SiC/SiC

**Active Metal Brazing**
- Soldering

**Interlayer Systems:**
- Active Metal Brazes (Ag, Cu, and Pd based)
- Metallic Glass Ribbons
- Solders (Zinc based)

**Technical Issues:**
- Melting range / behavior
- Wetting characteristics
- Flux or atmosphere compatibility
- Compositional compatibility
- Cost & availability
Materials and Experimental Details

- **Titanium (CP-2) plates**: TIMET Corp., MO
- **CVI C/C composites** *(P-120 Fibers, 3 HS, large tow size, 1.2 mm thick)*
  - Goodrich Corp., Santa Fe Springs, CA
- **CVI C/SiC Composites** *(T-300 Fibers, 1K tow, PW, 3.2 mm thick)*
  - GE Power Systems Composites, Newark, DE
- **MI SiC/SiC Composites** *(Sylramic Fibers, 800 fiber tow, 5 HS, 2 mm thick)*
  - GE Power Systems Composites, Newark, DE
- **Polished vs unpolished composite surfaces**
- **Microstructural Analysis** *(Optical, SEM, EDS)*
- **Mechanical Testing**:  
  - Microhardness behavior across the joint interface
    - **(Knoop hardness, load: 200 g, loading time: 10 s)**
    - Butt Strap Tension (BST) Shear Tests

**CuSil-ABA braze foil and paste**

<table>
<thead>
<tr>
<th>$T_L$, °C</th>
<th>$T_S$, °C</th>
<th>$E$, GPa</th>
<th>YS, MPa</th>
<th>UTS, MPa</th>
<th>CTE, C⁻¹</th>
<th>% El.</th>
<th>K, W/m.K</th>
</tr>
</thead>
<tbody>
<tr>
<td>815</td>
<td>780</td>
<td>83</td>
<td>271</td>
<td>346</td>
<td>$18.5 \times 10^{-6}$</td>
<td>42</td>
<td>180</td>
</tr>
</tbody>
</table>
Microstructure of Brazed Ti Plates to C-C Composites using CuSil-ABA Paste

EDS analysis of compositions at marked locations in (b): 1) 100%C, 2) 1%Ti, 3%Cu, 96%Ag, 3) 1%Ti, 95%Cu, 4%Ag, 4) 15%Ti, 80%Cu, 4%Ag, 5) 43%Ti, 54%Cu, 3%Ag, and 6) 99%Ti, 1%Ag.
Microstructure and EDS Analysis of C-SiC/Cusil-ABA/Ti joints from braze paste

<table>
<thead>
<tr>
<th>Location</th>
<th>Si, at%</th>
<th>Ti, at%</th>
<th>Cu, at%</th>
<th>Ag, at%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point 1</td>
<td>93.892</td>
<td>0.282</td>
<td>2.049</td>
<td>3.778</td>
</tr>
<tr>
<td>Point 2</td>
<td>61.302</td>
<td>7.573</td>
<td>14.349</td>
<td>16.776</td>
</tr>
<tr>
<td>Point 3</td>
<td>0.105</td>
<td>45.637</td>
<td>49.164</td>
<td>5.094</td>
</tr>
<tr>
<td>Point 4</td>
<td>0.291</td>
<td>10.060</td>
<td>34.858</td>
<td>54.791</td>
</tr>
<tr>
<td>Point 5</td>
<td>3.249</td>
<td>17.330</td>
<td>4.842</td>
<td>74.578</td>
</tr>
<tr>
<td>Point 6</td>
<td>0.661</td>
<td>1.043</td>
<td>2.846</td>
<td>95.450</td>
</tr>
<tr>
<td>Point 7</td>
<td>0.175</td>
<td>31.059</td>
<td>66.529</td>
<td>2.237</td>
</tr>
<tr>
<td>Point 8</td>
<td>0.442</td>
<td>28.763</td>
<td>68.111</td>
<td>2.684</td>
</tr>
<tr>
<td>Point 9</td>
<td>0.384</td>
<td>60.193</td>
<td>36.909</td>
<td>2.514</td>
</tr>
<tr>
<td>Point 10</td>
<td>0.248</td>
<td>93.601</td>
<td>5.256</td>
<td>0.895</td>
</tr>
<tr>
<td>Point 11</td>
<td>0.045</td>
<td>85.400</td>
<td>13.774</td>
<td>0.781</td>
</tr>
</tbody>
</table>

Braze foil (polished C-SiC)
Microstructure and EDS Analysis of C-SiC/Cusil-ABA/Ti joints from braze paste

<table>
<thead>
<tr>
<th>Location</th>
<th>Si, at%</th>
<th>Ti, at%</th>
<th>Cu, at%</th>
<th>Ag, at%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point 1</td>
<td>91.962</td>
<td>2.614</td>
<td>1.068</td>
<td>4.356</td>
</tr>
<tr>
<td>Point 2</td>
<td>52.058</td>
<td>37.527</td>
<td>5.401</td>
<td>5.014</td>
</tr>
<tr>
<td>Point 3</td>
<td>13.867</td>
<td>68.756</td>
<td>11.784</td>
<td>5.593</td>
</tr>
<tr>
<td>Point 4</td>
<td>11.558</td>
<td>37.308</td>
<td>1.549</td>
<td>49.584</td>
</tr>
<tr>
<td>Point 5</td>
<td>0.994</td>
<td>4.871</td>
<td>1.424</td>
<td>92.712</td>
</tr>
<tr>
<td>Point 6</td>
<td>17.754</td>
<td>51.475</td>
<td>8.891</td>
<td>21.880</td>
</tr>
<tr>
<td>Point 7</td>
<td>2.469</td>
<td>6.935</td>
<td>86.969</td>
<td>3.627</td>
</tr>
</tbody>
</table>

Braze paste (polished C-SiC)
### Microstructure and EDS Analysis of SiC-SiC/Cusil-ABA/Ti joints from braze paste (Ti-Side)

<table>
<thead>
<tr>
<th>Location</th>
<th>Si, at%</th>
<th>Ti, at%</th>
<th>Cu, at%</th>
<th>Ag, at%</th>
<th>Si, at%</th>
<th>Ti, at%</th>
<th>Cu, at%</th>
<th>Ag, at%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point 1</td>
<td>18.029</td>
<td>60.288</td>
<td>2.361</td>
<td>19.323</td>
<td>18.029</td>
<td>60.288</td>
<td>2.361</td>
<td>19.323</td>
</tr>
<tr>
<td>Point 2</td>
<td>0.843</td>
<td>3.229</td>
<td>2.038</td>
<td>93.891</td>
<td>0.843</td>
<td>3.229</td>
<td>2.038</td>
<td>93.891</td>
</tr>
<tr>
<td>Point 3</td>
<td>1.112</td>
<td>16.114</td>
<td>70.797</td>
<td>11.977</td>
<td>1.112</td>
<td>16.114</td>
<td>70.797</td>
<td>11.977</td>
</tr>
<tr>
<td>Point 4</td>
<td>0.277</td>
<td>35.785</td>
<td>59.986</td>
<td>3.952</td>
<td>0.277</td>
<td>35.785</td>
<td>59.986</td>
<td>3.952</td>
</tr>
<tr>
<td>Point 5</td>
<td>0.421</td>
<td>63.491</td>
<td>33.433</td>
<td>2.656</td>
<td>0.421</td>
<td>63.491</td>
<td>33.433</td>
<td>2.656</td>
</tr>
<tr>
<td>Point 6</td>
<td>0.185</td>
<td>97.555</td>
<td>1.422</td>
<td>0.838</td>
<td>0.185</td>
<td>97.555</td>
<td>1.422</td>
<td>0.838</td>
</tr>
<tr>
<td>Point 7</td>
<td>0.382</td>
<td>98.170</td>
<td>1.035</td>
<td>0.413</td>
<td>0.382</td>
<td>98.170</td>
<td>1.035</td>
<td>0.413</td>
</tr>
</tbody>
</table>

**Paste, polished SiC-SiC**
Microhardness Profiles across the Joint Region in Brazed C-SiC/Ti System
(Knoop indenter, 200 g load, 10 s loading time)

- Braze/Ti interface was diffuse and its location shown is approximate.
- Braze region shows significant variation in KHN than Ti region.
- Joints made from unpolished composites show marginally higher peak KHN values than polished samples.
Microhardness Profiles across the Joint Region in Brazed SiC-SiC/Ti System

(Knoop indenter, 200 g load, 10 s loading time)

- Braze/Ti interface was diffuse and its location shown is approximate.
- Braze region shows significant variation in KHN than Ti region.
- Joints made from unpolished composites show marginally higher peak KHN values than polished samples.
Mechanical Testing of Brazed Joints

**Tube Tensile Test**

**Butt Strap Tensile Test**


Factors to consider:
- Substrate composition, Processing variables
- Bonded area, Location of failure
- Architecture effects
### BST Shear Strength of Brazed Ti-Composite Joints at Room Temperatures

<table>
<thead>
<tr>
<th>Composite</th>
<th>Surface Condition</th>
<th>Number of Specimens</th>
<th>Shear Strength, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-C As-processed</td>
<td></td>
<td>6</td>
<td>1.51 ± 0.76</td>
</tr>
<tr>
<td>C-SiC As-processed</td>
<td></td>
<td>2</td>
<td>1.78 ± 0.09</td>
</tr>
<tr>
<td>C-SiC Ground</td>
<td></td>
<td>6</td>
<td>1.46 ± 0.56</td>
</tr>
<tr>
<td>SiC-SiC As-processed</td>
<td></td>
<td>4</td>
<td>5.30 ± 1.62</td>
</tr>
<tr>
<td>SiC-SiC Ground</td>
<td></td>
<td>3</td>
<td>9.05 ± 0.55</td>
</tr>
</tbody>
</table>

Typical literature values for interlaminar shear strength (ILS) of composites: C/C: 12-15 MPa; CVI C/SiC: 18-22 MPa; MI SiC/SiC: 40-45 MPa
Thermally-Induced Cracking in Composite Controls
Shear Strength of Brazed Joints

- Ti-C/C Composite
- Ti-C/SiC Composite
- Ti-SiC/SiC Composite

Crack in outer ply of C/SiC
Crack in outer ply of SiC/SiC

ΔT induced crack

150µm
BST Shear Strengths of Brazed Joints in Ti- C/C Composites (woven) with P120 and K1100 Fibers

- High temperature testing of joints with C/ SiC and SiC/ SiC composite substrates in progress.
Summary and Conclusions

• Cusil-ABA foil and paste can be used to vacuum braze C-C, C-SiC, and SiC-SiC composites to Ti.
• Joint interfaces were defect free and exhibited sound metallurgical bonding in all the systems.
• EDS analysis of the joints in all composites show interfaces enriched in Si and Ti.
• The room-temperature BST tests revealed a higher shear strength in Ti/SiC-SiC joints made using polished composite specimens than as-fabricated specimens.
• Knoop hardness in the braze region was greater than in Ti and showed variation with distance due to residual stresses. The peak hardness in the joint region was marginally higher in unpolished samples.