FRICTION STIR WELDING OF ALUMINUM MMC 6092-17.5%SiC_p

Tracy W. Nelson*, Dick Lederich**
*Brigham Young University
Provo, UT
**The Boeing Company
Phantom Works
St. Louis, MO

Acknowledgments: Work sponsored by the Metals Affordability Initiative

Scott Packer
Advanced Metal Products Inc.
Bountiful, Utah
OUTLINE

- Background
  - MMCs
  - Joining MMCs
- Objectives
- Procedures
- Results
- Summary
Background

Aluminum MMCs offer:

- Advantages:
  - Low density, high specific strength, and high modulus
  - High fatigue strength
  - Better wear resistance

- Disadvantages:
  - Low fracture toughness
  - Fabrication difficulty
  - High cost
Background

Weldability of MMCs is greatly compromised

- reaction between second phase and Al matrix is often detrimental
  - porosity, cracking, aluminum carbides, etc.
- often limited in use because of poor weldability
GTAW in 6061-21%B₄C

- GTAW
  - Hydrogen induced porosity
  - Formation of Al₄C₃
GTAW in 6061-21%B₄C

- Two-pass weld, ER 4043 filler, Ar shielding gas

Shrinkage Porosity

20 μm

Si

1 μm

2 mm
Objectives

- Assess the feasibility of joining 6092-17.5%SiC_p via FSW
  - Compare weld quality, mechanical properties, and second phase distribution
  - Evaluate effects of post weld aging on tensile properties and failure
  - Characterize tool wear
Procedure

- Base Material - alloy 6092-17.5%SiC_p
  - 0.100” (2.54 mm) sheet; 8” X 24” (20cm X 60cm) panels
  - heavily oxidized
    - must remove before welding

- Weld Procedure Development
  - Choose optimal spindle speed, travel speed
  - Tool materials evaluated
    - H13 tool steel
    - Polycrystalline cubic boron nitride (CBN)

- Weldment Characterization
  - Both as-welded and post-weld aged
  - Tensile testing (ASTM E8)
  - Optical and SEM analyses
Weld Parameter Evaluation

- Parameters evaluated for H13 tool
  - RPM – 202, 545 and 815
  - IPM – 6.4, 11, and 26
- Parameters used for further testing – 545 rpm and 11 ipm
Weld Parameter Evaluation

- Welds Made with CBN Tooling
  - No spalling of the surface
  - Less flash
  - Better consolidation
  - Much wider range of parameters possible
Mechanical Properties

- As welded tensile properties for FSW 6092-17.5%SiCp
  - Strengths very similar between H13 and CBN (3% difference)
  - Significant difference in tensile elongation between two tool materials (87% difference)

<table>
<thead>
<tr>
<th>Coupon #</th>
<th>H13 Tool</th>
<th>CBN Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.2% Yield Stress (Ksi)</td>
<td>Ult. Tensile Stress (Ksi)</td>
</tr>
<tr>
<td>1</td>
<td>33700</td>
<td>38020</td>
</tr>
<tr>
<td>2</td>
<td>31526</td>
<td>35070</td>
</tr>
<tr>
<td>3</td>
<td>32500</td>
<td>35398</td>
</tr>
<tr>
<td>4</td>
<td>34284</td>
<td>39446</td>
</tr>
<tr>
<td>5</td>
<td>31847</td>
<td>37302</td>
</tr>
<tr>
<td>6</td>
<td>34000</td>
<td>36643</td>
</tr>
<tr>
<td>7</td>
<td>33000</td>
<td>37365</td>
</tr>
<tr>
<td>8</td>
<td>32800</td>
<td>37382</td>
</tr>
<tr>
<td>Average</td>
<td>32957</td>
<td>37078</td>
</tr>
<tr>
<td>Stand. Dev.</td>
<td>994</td>
<td>1402</td>
</tr>
</tbody>
</table>
Comparison of Tensile Failures

- Tensile Failure locations
  - H13 tool – TMAZ and DXZ
  - CBN tool – HAZ
Effect of Post Weld Aging

- Post weld aging to T6 w/o SHT
  - Initial test age at 325°F for various times
    - Oxide mechanically removed
    - Oxide chemically removed, flash machined after welding

<table>
<thead>
<tr>
<th>Condition</th>
<th>0.2%YS (ksi)</th>
<th>UTS (ksi)</th>
<th>Elong. (%)</th>
<th>Comments – Failure Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Weld</td>
<td>24.8</td>
<td>34.8</td>
<td>2.1</td>
<td>TMAZ (A side)</td>
</tr>
<tr>
<td>325F/2h</td>
<td>30.2</td>
<td>38.4</td>
<td>1.4</td>
<td>TMAZ (A side)</td>
</tr>
<tr>
<td>325F/4h</td>
<td>40.9</td>
<td>48.4</td>
<td>1.2</td>
<td>Flash was machined away (.006”)</td>
</tr>
<tr>
<td>325F/7h</td>
<td>34.6</td>
<td>39.4</td>
<td>0.7</td>
<td>TMAZ (A side)</td>
</tr>
<tr>
<td>As Weld</td>
<td>32.0</td>
<td>45.8</td>
<td>4.5</td>
<td>TMAZ (R side)</td>
</tr>
<tr>
<td>325F/2h</td>
<td>34.4</td>
<td>47.9</td>
<td>3.9</td>
<td>TMAZ (A side)</td>
</tr>
<tr>
<td>325F/4h</td>
<td>37.3</td>
<td>48.1</td>
<td>2.3</td>
<td>TMAZ (A side)</td>
</tr>
<tr>
<td>325F/6h</td>
<td>38.2</td>
<td>48.5</td>
<td>1.8</td>
<td>TMAZ (A side)</td>
</tr>
<tr>
<td>325F/8h</td>
<td>39.4</td>
<td>49.0</td>
<td>1.7</td>
<td>TMAZ (A side)</td>
</tr>
</tbody>
</table>
Effect of SHT and Aging

- SHT at 1030°F for 3 hrs, T6 temper at 325°F for 7-8 hours
  - Rockwell B –77-79, verifying T6

- Results
  - **Failure at root side disbond**
  - **Chemical oxide removal, flash machined after welding**

<table>
<thead>
<tr>
<th>Description of Machining</th>
<th>0.2% YS (ksi)</th>
<th>UTS (ksi)</th>
<th>Elong. (%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>-</td>
<td>30.1</td>
<td>-</td>
<td>Failed at root side disbond</td>
</tr>
<tr>
<td>Flash removed (0.004”)</td>
<td>-</td>
<td>26.4</td>
<td>-</td>
<td>Failed at root side disbond</td>
</tr>
<tr>
<td>Flash removed; 0.020” removed from root</td>
<td>-</td>
<td>23.1</td>
<td>-</td>
<td>Failed at root side disbond</td>
</tr>
<tr>
<td>STA-1</td>
<td>41.2</td>
<td>51.5</td>
<td>1.1</td>
<td>Failed in nugget</td>
</tr>
<tr>
<td>STA-2</td>
<td>-</td>
<td>37.0</td>
<td>0.2</td>
<td>Failed in nugget</td>
</tr>
<tr>
<td>STA-3</td>
<td>40.1</td>
<td>50.3</td>
<td>1.2</td>
<td>Failed in nugget</td>
</tr>
</tbody>
</table>
Root Side Disbond Failures

- Lazy “S” interface
  - Etched dye penetrant and radiograph inspections failed to detect
  - Originally believed to be oxide stringers, but SEM failed to detect oxides (different etch rate)
  - Need to pickle materials
    - mechanical cleaning was insufficient

As welded and Aged  Failed Tensile Sample
Comparison of Particulate Distribution

- SiC particulate distribution
  - Distribution in weld is same as in base metal

Base Metal  Nugget-H13  Nugget - CBN

15 μm
Lack of Bonding at Surface

- Interleaving on top surface of weld in 6092-17.5%SiCp

![H13 Welds](image1)

![CBN Welds](image2)
Tool Wear

- Tool wear after FSW 6092-17.5%SiC$_p$
  - H13 tool after 6 feet of weld
    - Loss on diameter of pin (essentially no threads left)
    - Loss of radius on shoulder
    - Not feasible to produce significant length of weld
  - CBN tool after 20 feet of weld
    - No measurable wear on any features

H13 tool  CBN tool
Effects of Tool Wear

- Degradation of weld quality
  - Surface of weld spalls
  - Pin wear affects penetration and stirring action
Effects of Tool Wear

- Contamination of weld from tool debris

![Image of welds and contaminant analysis]

- Steels

- Effects of Tool Wear

- Contamination of weld from tool debris

![Image of welds and contaminant analysis]

- Steels

- Effects of Tool Wear

- Contamination of weld from tool debris
Super Abrasive FSW Tools

- Cubic Boron Nitride (CBN) and Poly-Crystalline Diamond (PCD) tools
FSW can be used to join this material

- As-welded tensile strengths are considerably lower than parent material. Aging at 250F increases strength 20% at expense of ductility
- STA after welding results in strengths that are marginally higher than direct aging, and 20% lower than parent material
- Distribution and size of reinforcement is unaffected
- Due to severe tool wear, traditional tool steels can only be used for relatively short welds.
- CBN tool materials exhibited no wear in 20’ (3 m) of weld in 6092-17.5%SiC
- CBN tools give better surface finish, wider range of acceptable parameters, no weldment contamination, and better properties.