Characterization of Titanium Alloy Friction Stir Butt-Welds TIMET 54M, ATI 425 and BOATI Standard Grain

A. Cantrell, K. Gangwar, and M. Ramulu – University of Washington

Dan Sanders – The Boeing Company

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Outline

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• Friction Stir Welding
• FSW : A brief Review
• Experiments
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  – Hardness
  – Tensile Tests
  – Fatigue
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• Conclusion
Introduction

• Aerospace industry: *Buy to fly* ratio extremely important

• Minimizing material wastage by adopting light-weight materials – *Titanium*

• Near net shapes

• Size Limitation (Titanium Sheets)

• Joining Techniques
  – Diffusion Bonding
  – Friction Stir Welding

• Titanium -High Strength to weight ratio, High Melting point, corrosion resistant, and low density

• Titanium use has been expanded on Boeing 787 to roughly 14 percent of the total airframe [1]

Titanium Alloys

- **TIMETAL 54M** (Ti-5Al-4V-0.6Mo-0.4Fe)
  - New α-β Alloy
  - Superior machinability and strength
  - Produced by Vacuum Arc Remelt (VAR) or Electron Beam Single Melt (EBSM)
  - Take various forms bar, billet, plate and shapes.

- **ATI425** (Ti-4Al-2.5V-1.5Fe-0.25O)
  - Originally developed by ATI for ballistic armor application Aerospace and defense.
  - New α-β Alloy Fe and V as Beta stablizers and Al as alpha stablizers
  - High Strength, high ductility, high corrosion resistance, superplastic formability
  - Developed to improve upon overall production costs of Ti-6Al-4V while providing similar properties.
  - Both Ti-54M and Ti-6Al-4V have similar properties, difference in microstructure to be reason for improved machinability (10-15%)

- Boati (NO INFORMATION GIVEN)
Friction Stir Welding

- Solid state Joining Invented in 1991
- Production of weld: Similar to base metal properties
- No fumes or splatter, less distortion and more energy efficient
- Non-consumable tool imparts severe plastic deformation
- Quality of weld depends on spindle speed, traverse speed, tool geometry
- Have been validated by industry leaders. And production parts in aircraft
- Critical part of certifying the joining process is establishing a high cycle fatigue limit

FSW : A brief Review

Alloy sheet thickness 5 mm

Processing Parameters:
Rotation of the tool (rpm) and Feed rate (mm/min)

Importance of material on the retreating side

Solid state joining incorporated with severe plastic deformation

Commercial application of FSW; spliced with Super Plastic Forming (SPF)
FSW: A brief Review Contd...

FSW Process  FSW Experiment  Ti-Alloy FSW
Friction Stir welding in Ti-Alloys

- **BM** = Base Material (Unaffected by the welding process)
- **HAZ** = Change in the materials properties; due to heat induced by welding
- **TMAZ* = Thermo-mechanical affected zone
- **SZ** = Stir Zone (or Weld Nugget)

* Negligible TMAZ in Ti-alloys due to low conductivity of Titanium

**Weld Profile Macro**
- **TIMET 54M**
- **ATI425**
- **BOATI**

No inclusions or voids in the stir zone; i.e. ‘good’ welding quality
Experiments

Microstructure Analysis

- Each specimen was sectioned, mounted, and polished in accordance with ASTM E3-01.

- Etching: 2% HF etchant per ASTM E407-07.

- The microstructure analysis: Nikon Eclipse LV150 microscope/camera and NIS image analysis software system.
TIMET 54M

- Base material: $\alpha/\beta$ phase*
- HAZ and TMAZ: Transition of primary $\alpha$ with a matrix of $\beta$ into distorted grains with smaller portions of plate like $\alpha$ intermixed.
- WN (or SZ): Refined and distorted grains of $\alpha$ in a matrix of transformed $\beta$ containing acicular $\alpha$
- Microstructure in the welded region in the center is almost same along the weld centerline.

* $\beta$ is dark and $\alpha$ is light as visually observed in optical microscopy
- **ATI 425**

- **Base material**: \(\alpha/\beta\) phase*
- **HAZ and TMAZ**: Transition of primary \(\alpha\) with a matrix of \(\beta\) into distorted grains with smaller portions of plate like \(\alpha\) intermixed.
- **WN (or SZ)**: Refined and distorted grains of \(\alpha\) in a matrix of transformed \(\beta\) containing acicular \(\alpha\)

*\(\beta\) is dark and \(\alpha\) is light as visually observed in optical microscopy
BOATI Standard Grain (SG)

- Base material: \(\alpha/\beta\) phase*
- HAZ and TMAZ: Transition of primary \(\alpha\) with a matrix of \(\beta\) into distorted grains with smaller portions of plate-like \(\alpha\) intermixed.
- WN (or SZ): Refined and distorted grains of \(\alpha\) in a matrix of transformed \(\beta\) containing acicular \(\alpha\)

*\(\beta\) is dark and \(\alpha\) is light as visually observed in optical microscopy
Micro hardness Analysis

- Each specimen was sectioned, mounted, and polished in accordance with ASTM E3-01.
- All micro hardness indents have spacing of 254 microns.
- All the hardness traverses were conducted with a LECO AMH 43.
- Vickers Hardness (Hv) with a 500g load and dwell time 13s.
- Hardness was conducted in accordance with ASTM E384-06
- Recorded data from Left to right

Magnification: 12.5X

Magnification: 700X

254µm
Micro hardness results

<table>
<thead>
<tr>
<th>Materials</th>
<th>Microhardness Profile</th>
<th>Weld Nugget Center</th>
<th>Parent Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vickers 500 gm load, indent spacing 254 µm</td>
<td>3 indent average off centerline 1200 micrometers</td>
<td>3 indent average from ends of traverses</td>
</tr>
<tr>
<td></td>
<td>Number of indents</td>
<td>Length</td>
<td>Height</td>
</tr>
<tr>
<td>Advance</td>
<td>Retreat</td>
<td>Number of indents</td>
<td>Length</td>
</tr>
<tr>
<td>TIMET 54M</td>
<td></td>
<td>96</td>
<td>22860</td>
</tr>
<tr>
<td>ATI 425</td>
<td></td>
<td>96</td>
<td>22860</td>
</tr>
<tr>
<td>BOATI SG</td>
<td></td>
<td>1859</td>
<td>28194</td>
</tr>
</tbody>
</table>

![Graph showing microhardness results](chart.png)
Micro hardness contours TIMET 54 (ONLY)

Color contour plots were generated using Mathematica 7.0 software package from the hardness measurements of each alloy weld cross-section.

TIMET BFG Hardness Profile

TIMET Hardness profile- Plate 1
In some cases high values of hardness have been observed in the bottom of the weld nugget which could be attributed to the higher penetration depth of the tool.
Tensile tests

- Each specimen was sectioned, mounted, and polished in accordance with ASTM E8M.
- All tensile tests were completed on an Instron/Compression test frame
- The testing was completed in displace extensometer.
- The strain rate ($\dot{\varepsilon}$) was in accordance with AMS-T-9046B until specimen fracture

<table>
<thead>
<tr>
<th>Material</th>
<th>ADV</th>
<th>RET</th>
<th>YS (in ksi)</th>
<th>UTS (in ksi)</th>
<th>Elongation (%)</th>
<th>Fracture Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIMET 54M</td>
<td>136</td>
<td>141</td>
<td>8.2</td>
<td>Parent RET/(or)ADV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATI425</td>
<td>149</td>
<td>156</td>
<td>3.8</td>
<td>Weld</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boati</td>
<td>121</td>
<td>145</td>
<td>8.8</td>
<td>Weld RET</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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- The strain rate ($\dot{\varepsilon}$) was in accordance with AMS-T-9046B until specimen fracture
Tensile tests (TIMET 54, ONLY)
Fatigue tests

\[ y = 1538.5x^{0.069} \]
\[ y = 1538.4x^{0.069} \]
Conclusions

• Each macro specimen evaluated, showed good quality friction stir weld for each material condition of this study.
• No inclusion, or voids are seen in any of the FSWed cross section evaluated.
• A completely penetrated friction-stir butt-welded Titanium plates was verified in each examined case.

<table>
<thead>
<tr>
<th>Base Material</th>
<th>HAZ/TMAZ</th>
<th>WZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIMET 54M</td>
<td>Primary alpha with transformed beta matrix</td>
<td>Refinement of alpha grains in an increasing amount of transformed beta matrix</td>
</tr>
<tr>
<td>ATI 425</td>
<td>Primary alpha with infused intergranular beta</td>
<td>Accicular alpha plates with basket weave morphology</td>
</tr>
<tr>
<td>Boati</td>
<td>Primary alpha with intergranular beta</td>
<td>Refinement of alpha grains in an increasing amount of transformed beta matrix. TMAZ is the termination of large elongated alpha stringers</td>
</tr>
<tr>
<td></td>
<td>Large elongated alpha particles.</td>
<td>Prior beta grains (Basket weave morphology) defined by intergranular alpha plates</td>
</tr>
<tr>
<td></td>
<td>Refinement of alpha grains in an increasing amount of transformed beta matrix. TMAZ is the termination of large elongated alpha stringers</td>
<td>Basket weave morphology with no observed prior beta boundary</td>
</tr>
</tbody>
</table>
Conclusions

- Hardness change of 5-20 has been observed from Base material to weld nugget
- A sudden increase in the hardness of Boati BM is due to weld joint being perpendicular to the original materials rolling direction.
- Hardness slightly increased from top to bottom in all weld due to refinement of weld microstructure.

- TIMET 54M has consistent yield. Most specimens failed in the parent material
- TIMET yield and UTS findings matched with the TIMET corporation data.

- ATI425 failed in the weld region weaker than the base material
- All the properties were lower than the values reported by Allegheny Technologies for parent material

- BAOTI has the largest % elongation.
- BAOTI has the lowest yield strength among the titanium alloys tested
Acknowledgements

• We sincerely thank The Boeing Company for financial support of Titanium Component Manufacturing Research Project at UW.

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THANK YOU!