Investigating the effects of pin tool design on friction stir welded Ti-6Al-4V

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Friction stir welding (FSWing), a solid state joining technique, uses a non-consumable rotating pin tool to thermomechanically join materials. Heating of the weldment caused by friction and deformation is a function of the interaction between the pin tool and the work piece. Therefore, the geometry of the pin tool is in part responsible for the resulting microstructure and mechanical properties. In this study microwave sintered tungsten carbide (WC) pin tools with tapers and flats were used to FSW Ti-6Al-4V. Transverse sections of welds were mechanically tested, and the microstructure was characterized using optical microscopy (OM) and scanning election microscopy (SEM). X-ray diffraction (XRD) and electron back-scatter diffraction (EBSD) were used to characterize the texture within the welds produced from the different pin tool designs.
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Overview

- Objective
- Ti-6Al-4V
- Weld Tools and Schedule
- Tensile Strength
- Microstructure
- Summary
Objective

- Investigate the microstructural response of Ti-6Al-4V following FSWing.
  - Response of 2 phase microstructure to deformation.
  - Effect of temperature range and gradients on low conductivity material.
  - Effect of phase transformation during FSWing.
Friction Stir Welding

- Developed at The Welding Institute in 1991
- First used on aluminum alloys
- Solid-state process
Titanium 6Al - 4V

- Alpha- 12% beta alloy
- 6% Aluminum, 4% Vanadium
- Originally developed for the aircraft industry for high strength to weight properties

Micrograph of Ti-6Al-4V

Parent Material Microstructure is biomodal with prior $\beta$ grains containing $\alpha$ colonies

- Bimodal
  - equiaxed $\alpha$ (light regions)
  - colonies of alternating $\alpha+\beta$ laminate
- prior $\beta$ grains: diameter 138 $\mu$m
- $\alpha$ colonies: 17 $\mu$m
- $\alpha$ laths: width 1.4 $\mu$m
- equiaxed $\alpha$: diameter 5 $\mu$m
Expected temperature during FSW is about 60-90% of absolute melting temp

Expected FSW temp for Ti-6Al-4V = 850-1410°C

β transus = 980°C
Variations in Ti-6Al-4V microstructure are a function of thermo-mechanical processing parameters.

- 1065°C
- 980°C = β transus
- 955 °C
- 900 °C
- 645 °C
- All Air cooled

## Weld Schedule

Ti-6Al-4V plates: 6.35 mm thk  
Panels: 7.6 cm x 60.9 cm  
Joint configuration: Butt Joint  
Tool: Microwaved sintered WC  
Weld control: Displacement

<table>
<thead>
<tr>
<th>Weld ID</th>
<th>Taper angle (deg)</th>
<th>Spindle Speed (RPM)</th>
<th>Spindle Travel (cm/min)</th>
<th>Plunge depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>002</td>
<td>45</td>
<td>400</td>
<td>10.2 - 11.4 - 12.7</td>
<td>4.29</td>
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<tr>
<td>003</td>
<td>60</td>
<td>400</td>
<td>9.5 - 11.4 - 13.3</td>
<td>4.29</td>
</tr>
</tbody>
</table>
FSW in Ti-6Al-4V panel with 45° tapered tool

Panel Photo

RS

AS

12.7 cm/min  11.4 cm/min  10.2 cm/min

X-ray Radiograph

RS

AS

Weld direction

Indication of LOP due to 50% penetration of FSW
FSW in Ti-6Al-4V panel with 60° tapered tool

**Panel Photo**

| 13.3 cm/min | 11.4 cm/min | 9.5 cm/min |

**X-ray Radiograph**

Weld direction

*Indication of LOP due to 50% penetration of FSW*
Effect of travel speed on tensile properties

UTS (MPa) vs Travel Speed (cm/min)
45° Pin Tool

UTS (MPa) vs Travel Speed (cm/min)
60° Pin Tool

PM Props
Wormhole defects were present in most welds.
Grain refinement observed in all welds

PM prior $\beta$ grain size = 137 $\mu$m
Largest grains observed in mid-thickness

11-18 µm  11-23 µm  13-17 µm
Small grains near shoulder

(a) 8-15 µm

(b) 11-19 µm
Smallest grains observed at the bottom

Grain size = 4-12 μm
Summary

- Within the range of parameters investigated, both weld tools created similar, refined microstructures within the stir zone.

- Based on the grain morphology, the $\beta$ transus was exceeded in all welds.

- To reduce wormhole defects, a truncated design is recommended to increase the flow of the material around the tip of the pin tool.
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