SOLID STATE WELDING DEVELOPMENT
AT
MARSHALL SPACE FLIGHT CENTER

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AGENDA

• Introduction
• NASA’s Marshall Space Flight Center
• Solid State Welding Process Development
  • Thermal Stir Welding (TSW)
  • Ultrasonic Stir Welding (USW)
    • Experimentation leading to the USW prototype system
    • First USW welds
• Conclusions
INTRODUCTION

• Engineering Directorate (ED01)
  • Materials & Processes Laboratory (EM01)
    • Metals Engineering Division
      • Metal Joining and Process Branch
        • Welding and Manufacturing Team (EM32)

• B.S. Welding Engineering - The Ohio State University
• M.S. Science – University of Tennessee
• 26 years at NASA’s MSFC
WHAT IS TSW AND USW?

TSW

• U.S Patents – 7,980,449  8,127,977  8,225,984
• A solid state weld process consisting of an induction coil heating source, a stir rod, and non-rotating containment plates
• Independent heating, stirring and forging controls
• Decouples the heating, stirring and forging process elements of FSW.
WHAT IS TSW AND USW?

USW

• U.S Patents – 7,568,608
• A solid state weld process consisting of an induction coil heating source, a stir rod, and a non-rotating containment plate
• Ultrasonic energy integrated into non-rotating containment plate and stir rod
• Independent heating, stirring and forging controls
• Decouples the heating, stirring and forging process elements of FSW.
COMPARISON OF STIR PROCESSES – FSW, TSW, USW

FSW:
Both shoulder and pin rotate together
Material is heated by frictional energy & deformational heating around pin
Cannot decouple heating, stirring, forging

TSW:
Only the pin rotates
Containment plates stationary
Induction coil heats the material
Additional heat is provided by material deformation around the pin
DECOUPLE heating, stirring, forging and Control each independently

USW:
Only the pin rotates
Containment plates stationary
Induction coil heats the material
Additional heat is provided by material deformation around the pin
Ultrasonic energy heats
Ultrasonic energy integrated into stir rod and CP
DECOUPLE heating, stirring, forging and Control each independently
THERMAL STIR WELD SYSTEM AT MSFC

Thermal Stir Weld System

Thermal Stir Weld System Capabilities

- Thermal stir welding (TSW)
- Conventional friction stir welding (C-FSW)
- Self-reacting friction stir welding (SR-FSW)
- Hybrid TSW (H-TSW)
- Hybrid FSW (H-FSW)

May 27, 2011

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RECOGNITION OF TITANIUM TSW SUPPORT AT MSFC

• Solid state joining of alpha and near-alpha titanium alloys conducted at MSFC for Keystone Synergistic Enterprises, Inc. through NASA Space Act Agreement (SAA) process
• In support of Phase I and Phase II Small Business Innovative Research (SBIR) sponsored by Defense Advanced Research Projects Agency (DARPA) and Office of Naval Research (ONR)
• SBIR Phase I and Phase II results are presented
COMMERCIALLY PURE TITANIUM IS TRADITIONALLY DIFFICULT TO WELD

• Reported Methods
  GTAW, GMAW, laser and more recently hybrid versions of these various processes (Lathabai, et al, 2001, Li, et al., 2009, Leary, et al., 2010)
• Allotropic phase transformation (~980°C)
• Non-homogenous microstructure that varies as a function of the cooling rate (Lathabai, et al, 2001, Li, et al., 2009, Leary, et al., 2010)
• Inert gas shielding
• Difficult to maintain adequate inert shielding gases to control the oxidation of the molten pool during fusion welding (Lathabai, et al, 2001, Li, et al., 2009, Leary, et al., 2010)
CONTROL OF FSW TEMPERATURE IS NEEDED TO OBTAIN DESIRED MICROSTRUCTURE

• Cp-Ti can be FSW
  Lee, et al., 2005- 5.6mm thick plate (panel length not reported)
  Zhang, et al., 2008- 3mm thick plate (panel length not reported)

• Final microstructure in the stir zone (SZ) depends of temperature during TSW’ing (avoid β-transus)
  Precise temperature control ensures the α-phase is retained during joining to produce a homogenous microstructure

• Lower temperatures are beneficial to minimize oxidation and distortion
Successful in FSW’ing 3 mm (.250-in ) thick 30.5 cm (12-in) long Ti 6-4. Produced acceptable microstructure, however, sharp grain size gradients degraded mechanical properties (ductility and toughness) and pin tool life considered problematic.
Objective: Demonstrated TSW Process Feasibility

Demonstrated Thermal Stir Joining process is capable of producing 3 mm (.250-in) thick 30.5 cm (12-in) long Ti solid-state welds with in-process controlled microstructure; however, much rework of the heating and mechanical systems on TSW equipment was required.

Dynamic, in-process control of μ-structure shown feasible with Thermal Stir Joining.

Elimination of sharp grain size gradients.

Decoupling heating and metal stirring considered enabling for in-process microstructural process control.
FIRST THERMAL STIR WELD OF Ti 6-4

Ti 6-4 bead on plate.

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SBIR PHASE II OBJECTIVES AND DELIVERABLES

• Transition to 12.1 mm (.500-in) thick CP Ti Grade 2 using both FSW and TSW processes
  • Deliver 274.32 cm (9 foot) long welds – CP & Ti 6-4 ELI
  • Deliver complex geometry (angular) welds
• FSW’ing completed at Michoud Assembly Facility (MAF), New Orleans, LA.
  • After 41.14 m (135 ft) weld and 25 pin tool design changes – still generating wormholes.
• Keystone abandoned FSW portion of project
• Focused on TSW at MSFC
CLOSE UP OF SURFACE FINISH

CHRIS KOLB HOLDING 1ST SUCCESSFUL 8 FOOT LONG CP Ti WELD 12.1 MM THICK

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No reduction in strength of TSW’d CP-Ti compared to parent material

<table>
<thead>
<tr>
<th></th>
<th>Ref. Prop.*</th>
<th>PM (RD)</th>
<th>RS SZ (Trans.)</th>
<th>SZ (RD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength (MPa)</td>
<td>344</td>
<td>333 $\pm$ 6</td>
<td>353 $\pm$ 10</td>
<td>371 $\pm$ 4</td>
</tr>
<tr>
<td>Ultimate tensile strength (MPa)</td>
<td>275 to 410</td>
<td>449 $\pm$ 4</td>
<td>433 $\pm$ 6</td>
<td>464 $\pm$ 1</td>
</tr>
</tbody>
</table>

UTS and yield strength increase agrees with results reported in the literature for FSW CP-Ti


* www.matweb.com
MICROSTRUCTURE CP TITANIUM

Weld Start Hole

Advancing Side Fusion Line 100x

Weld Nugget Center 100x

Advancing Side Fusion Line 100x
Angled weld tooling
SBIR PHASE II RESULTS (cont.)

CP Ti .500-in thick angled weld - outside

CP Ti .500-in thick angled weld - inside
Close-up macro photograph of etched angular Stir weld sample (4-22-10 End) showing approximate field of view for higher mag imagery at right. Note that microphotographs are horizontally inverted.

*TOP RIGHT:* 50X microphotograph of weld metal region (FOV D).
*BOTTOM RIGHT:* 200X microphotograph of weld metal region (FOV D).

May 27, 2011
In support of Keystone Synergistic Enterprise’s Small Business Innovation Research (SBIR) contract N0014-06-C-5200
Sponsored by Defense advanced Research Projects Agency (DARPA) and Office of Naval Research (ONR)

Fabricated from Ti 6Al-4V Extra Low Interstitial alloy

HEXAGON TURET WITH ANGLULAR WELDS
Defect free cross-sections containing equiaxed grains were obtained

- Minimal HAZ around the weld nugget
- No tool debris in stir zone
ULTRASONIC STIR WELDING WILL BE PRESENTED
FIRST HIGH POWER ULTRASONICS (HPU) DATA GENERATED AT MSFC IN 2008

• Leased a Bridgeport machine from Edison Weld Institute (EWI), Columbus, Ohio
  • Integrated with HPU for twist drill applications
  • Used for experimentation
    • Ultrasonic heating
    • Twist drill plunge force reduction
    • Friction reduction between rubbing metallic surfaces
Characterization of Thermal Process

Experiment Design

- Steel rod
- Thermal couples
- Load cell
- Drill machine table
- Workpiece
- Workpiece legs

Viewed from Bottom of Workpiece:

Thermal couples distribution, total of ten (two overlaps in this view)
CHARACTERIZATION OF HPU ASSISTED HEATING

Objective

To investigate the effects of ultrasonic energy on the drilling process (force, torque, temperature, etc.), which will benefit the design of portable tools for remotely-deployable applications.
CHARACTERIZATION OF HPU TECHNOLOGY

BRIDGEPORT MACHINE – HEATING EXPERIMENT
Characterization of Thermal Process

Test 5: steel plate, 250 lbs pressure load, 40% sonic power
Characterization of Thermal Process

**Results**

Test 7: AL2195, 100 lbs pressure load, 40% sonic amplitude

- TC0
- TC1
- TC2
- TC3
- TC4
- TC5
- TC6
- TC7

Temperature (F) vs Elapsed Time (sec)
Characterization of Thermal Process

Results

Test 8: AL2195, 400 lbs pressure load, 40% sonic amplitude

Temperature (°F) vs Elapsed Time (sec)

- TC0
- TC1
- TC2
- TC3
- TC4
- TC5
- TC6
- TC7
CHARACTERIZATION OF HPU ASSISTED DRILLING

Objective

To investigate the effects of ultrasonic energy on the drilling process (force, torque, temperature, etc.), which will benefit the design of portable tools for remotely-deployable applications.
Characterization of Drilling Process

Load Measurement
Characterization of Drilling Process

Results

Sonic-Assisted Drilling vs. Conventional Drilling
(Vertical Drilling Force)

![Graphs showing force vs. time for different drilling conditions.
- 400 RPM, 1 IPM, 40% Sonic Power
- 400 RPM, 2 IPM, 40% Sonic Power
- 500 RPM, 3 IPM, 40% Sonic Power
- 400 RPM, 1 IPM, No Sonic Power
- 400 RPM, 2 IPM, No Sonic Power
- 500 RPM, 2.5 IPM, No Sonic Power
]
Characterization of Drilling Process

Results

Sonic-Assisted Drilling vs. Conventional Drilling

(Drilling Torque)

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FRICTION REDUCTION SET-UP

FRICTION REDUCTION
FRICTION REDUCTION SET-UP
FRICITION REDUCTION RESULTS

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[Graph showing friction force over time with and without sonic power]
ULTRASONIC FRICTION REDUCTION
TEST BED SET UP
ULTRASONIC FRICTION REDUCTION RESULTS

Clamping – 400-lbs., 40% amplitude
ULTRASONIC FRICTION REDUCTION RESULTS

Clamping – 1,000-lbs., 40% amplitude
CURRENT USW DEVELOPMENT
CURRENT USW DEVELOPMENT
CURRENT USW DEVELOPMENT

• Weld 11-2 shows the difference in HPU being turned off during a weld
• Weld 12-2 shows stirring while HPU is on
• Weld 13-2 shows stirred weld joint
• The microstructures indicate that HPU energy assists in the heating of the weld nugget during the weld process.
USW SUMMARY

• With HPU power constantly “ON”, the stir pin “stirred” the plasticized weld nugget
• HPU assisted with the heating of the weld nugget
• Advancing side of the weld nugget did not “stir” into the parent material
• Retreating side “stirred” into the parent material
USW SUMMARY - UPGRADES

System capabilities will include:

• Ability to “pulse” ultrasonic energy on and off
• Ability to adjust parameters real-time (travel speed, spindle RPM, US amplitude)
• Increase travel speed from 10 ipm to 20 ipm.
• Means to measure draw force.
USW SUMMARY – UPGRADES (cont.)

• Ability to record US power versus time
• Integrate a more powerful power supply
• Increase stiffness of Z axis drive and reduce head deflection
• Add linear encoder to better control tool penetration setting.
• Modify containment plate to eliminate gouging, increase vibration uniformity.
The mechanical property results portray a material that possesses high plasticity and good damage tolerance behavior with weld properties very similar to the PM in two orientations.

Based on survivability of the tool after 201 cm of weld and lack of tool debris, TSW’ing appears to be a viable method for producing long welds without detrimental tool wear.

Further microscopy is needed to determine the overall temperature the material was subjected to during the TSW’ing process.
FUTURE TSW SYSTEM UPGRADERS

- Incorporate closed loop temperature control
- Select nominal “real time” welding temperature
- Select optimal travel rate, RPM, IC power
- Push “START”
- If nominal temperature increases
  - Increase travel and/or decrease RPM and/or decrease induction coil power
- If nominal temperature decreases
  - Decrease travel and/or increase RPM and/or increase induction coil power
TSW AND USW PROCESSES (AS WELL AS OTHER NASA OWNED TECHNOLOGIES) ARE AVAILABLE FOR LICENSING FROM NASA.

CONTACT SAMMY NABORS
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