Introduction to Friction Stir Welding (FSW)

Bob Carter

NASA Glenn Research Center
Advanced Metallics Branch
robert.carter@nasa.gov
216.433.6524
Agenda

- Short History of Aluminum Welding at NASA
- FSW Background and Applications
- “Conventional” FSW
- Self Reacting FSW
- Advantages and Disadvantages
- Microstructure and Avoidable Defects
- Specifications and Non Destructive Evaluation
- Process Variants
- Equipment and Tooling

“A lifetime in rocketry has convinced me that welding is one of the most critical aspects of the whole job!!”

– Dr. Wernher von Braun.
Short History of Aluminum Welding at NASA

♦ Late 1950’s – Early 1970’s (Explorer 1, Mercury, Gemini, Saturn)
  • Welding of aluminum alloys in its infancy
  • Jupiter, Redstone, Saturn I, and Saturn V welded using Gas Metal Arc Welding (GMAW) and Gas Tungsten Arc Welding (GTAW)
  • Horizontal welding of tank structures led to significant welding problems. Porosity and hot cracking key concerns.

♦ Early 1970’s – Mid 1980’s (Shuttle External Tank)
  • GTAW continued to be State of Art
  • Welding position changed to vertical to reduce porosity
  • Defect rate was a continual problem due to the long duration between weld prep and welding

♦ Mid 1980’s – 1990’s
  • Plasma Arc Welding (PAW) and Variable Polarity Plasma Arc Welding (VPPAW) developed to replace GTAW
  • Greatly reduced the number defects

Above: Closeout welding operation of the liquid oxygen tank for the Saturn V SA-501 vehicle for the Apollo 4 mission. 1965

Space Shuttle External Tank major weld area. 1977
Short History of Aluminum Welding at NASA

2000’s - Present

- Aluminum-Lithium alloy 2195 implemented on External Tank
- 2195 has a propensity for hot cracking, particularly in repair welds
- This drove NASA’s participation in the initial group sponsored projects on Friction Stir Welding that were led by The Welding Institute
- First production Friction Stir welds on External Tank were made in 2001
- Friction Stir Welding implemented for assembly of the Space Launch System, and on all elements of NASA’s exploration program

Welding of the Orion capsule at MAF. [2]

Welding of the SLS spacecraft adaptor at MSFC. Nov 2012 [1]

Welding of Space Shuttle External Tank Barrel Sections.
Looking Forward – NASA’s building the Space Launch System (SLS) using FSW

- Will be the most powerful rocket in history
  - 384 ft tall
  - 130 Metric Ton (286,000 lb) payload capacity
  - 9.2 Million lbs of thrust (Saturn V had 7.6 Million lbs)

- At the Michoud Assembly Facility (MAF) the largest FSW system ever is currently being installed to assemble the cryogenic tanks.
Friction Stir Welding is a solid-state process that was patented in 1991 by The Welding Institute (TWI) of Cambridge, England [5]. This patent is now expired.

Since its invention the process has generated significant interests in the R&D community.

- By 2007, 1800 patents had been issued relating to Friction Stir Welding [6]. This number is now ~3060…

The past decade has seen FSW applied in the aerospace, military, naval, rail, auto, and most recently computer industries.

Welding Laboratory at NASA Marshall Space Flight Center

The new iMac [4]
Some (many others not listed) Production Applications

♦ **Marine:**
  - Prefabricated deck panels – Aluminum plate to extrusions
  - Armor plate for various assault vehicles

♦ **Rocket Fuel Tanks – Primarily square butt welds in 2XXX series Aluminum.**
  - Space Shuttle External Tank
  - United Launch Alliance Delta II, Delta IV, and Atlas V
  - Space X Falcon and Falcon 9
  - Japan – JAXA H-IIIB
  - NASA – Space Launch System Core Stage

♦ **Aircraft Primary Structure**
  - Eclipse 550 wing and fuselage – Skin to Stringer
  - Embrarer Legacy 450 and 500

♦ **Automotive**
  - Ford GT center tunnel
  - Lincoln Towncar engine cradle and suspension struts
  - Mazda RX5 – Spot weld aluminum to galvanized steel
  - Mazda RX8 and Toyota Prius trunk lids
  - Wheels
  - Volvo V70 seats

♦ **Pipeline**
  - Field welding of steel pipe
The “Conventional” Friction Stir Welding Process

Operational Description:
1. Rotating tool is plunged into workpiece until the tool shoulder is in contact with the part
2. Tool traverses the weld joint
3. Tool is withdrawn
   • Basic parameters:
     ▪ RPM
     ▪ Travel speed
     ▪ Plunge load or plunge position
     ▪ Tool lead angle
     ▪ Tool design/geometry

Key Points:
• Solid state (no melting)
• Non-consumable Tool
• No filler metal
• Shielding gas not required for Aluminum alloys
• Solid backing anvil
• Thickness and Travel Speed
How does it work?

- Heat is generated by friction between the tool and workpiece material.
- Material adjacent to the tool softens.
- The softened material is mechanically mixed by the tool.
- The softened material is joined using mechanical pressure supplied by the tool shoulder.
FSW Tool Design

- **“Standard” Tool Geometry:**
  - Concave shoulder and threaded pin.
    - Pin tread drives material toward the root during welding. (clockwise rotation with left hand thread)

- **Role of the Shoulder**
  - Provides biggest component of heat generation
  - Plunged below the surface of the material to generate a high pressure forging action
  - Confines the plasticized material

- **Role of the Pin**
  - Establish stirring action

- **Common variants to “standard” tool geometry:**
  - Tapered Pins
  - Fluted Pins
  - Scrolled Shoulders
  - Used to reduce loads, improve material flow, and increase travel speed
Evolutionary Enhancements to FSW

♦ Scrolled Shoulder
  - The development of the scroll-type shoulder geometry eliminated the need for a lead angle
  - Prior to this all welding was performed using a negative lead angle

♦ Retractable Pin Tool
  - NASA Patented [9]
  - A device capable of manipulating the length of the welding pin in real time
  - Allows welding tapered-thickness joints
  - Can be used to eliminate the hole left at the end of the weld.
  - Aids in the avoiding lack of penetration defects
Self Reacting Friction Stir Welding (SR-FSW)

♦ The scrolled shoulder and retractable pin tool technologies enabled development of SR-FSW

♦ Process Description:
  - No anvil required
  - Rotating tool “pinches” the work piece between two shoulders and traverses along the weld joint.

♦ Advantages
  - Simplifies Tooling
  - Eliminates Lack of Penetration Defects

♦ Disadvantages
  - Hole left at end of weld
FSW Advantages

♦ Weld Property Advantages

- No melting
  - No solidification defects (porosity, solidification cracking, liquation cracking).
- Improved joint efficiency (strength)
  - Lower processing temperature results in less “damage” in the weld heat affected zone.
  - In precipitation strengthened aluminum alloys we typically see ~20% increase in as-welded ultimate tensile strength relative to fusion welding.
- Improved fracture properties
  - Dynamically recrystallized stir zone with extremely fine grain structure.
- Low distortion

♦ Processing Advantages

- Limited ability to join dissimilar metals
- Full penetration in a single pass
- Low occurrence of defects
- Fully automated and extremely repeatable
- No consumables
  - Shielding gas may be required when welding reactive metals.
- No position/orientation limitations
- Post-weld processing is not typically required
- Safety and Health
  - No arc, fumes, or molten spatter
FSW Disadvantages

Disadvantages

- High initial investment in tooling and equipment
- Sensitive to Joint Tolerances
  - Not forgiving of pre-weld mismatch and gap
  - Mismatch can lead to excessive flash
- Fixed Penetration - Lack of Penetration
  - Lack of full penetration can result in “kissing bonds” that are difficult to detect using non-destructive testing.
  - Avoidance requires precise control of pin position relative to backing anvil.
- Exit hole left at the end of the weld
- Tool material limitations

Example Excessive Flash

Example “kissing bond”
Microstructural Features and Nomenclature

HEAT AFFECTED ZONE (HAZ)

THERMOMECHANICAL ZONE (TMZ)

DYNAMICALLY RECRYSTALLIZED ZONE (DXZ)

PARENT METAL
Uncommon FSW Defects

- All are easily mitigated in Aluminum alloys and are not encountered in production

Reference [11]
Specifications and Verification Methods

- ISO 25239 and AWS D17.3 are standards for FSW of Aluminum

- As built weld properties verified through:
  - Non destructive inspection
    - Dye penetrant crown side surface inspection not practical due to tool marks. Root side of conventional welds with etch to look or lack of penetration.
    - Radiographic volumetric inspection for gross flaws.
    - **Phased Array Ultrasonic Testing (PAUT)** used by most in industry
  - Process control
    - Qualified weld operators
    - Qualified weld procedures
    - Calibrated equipment
    - Post weld geometric inspections
Common Process Variants

♦ Friction Spot Welding

Friction Spot Welding [12]

Mazda Friction Spot Welding [13]

♦ Lap Welding

- Lap joints are common in friction stir welding
- Watch out for “hook” defect – an uplift of surface oxides into the joint.

♦ Friction Stir Processing

- Using Friction Stir Welding technique to modify properties.
  - Homogenization
  - Grain Refinement
  - Elimination of casting defects

Reference [11]
Equipment and Tooling

Key Considerations:

- Torque
- Spindle Speed
- Plunge Load
- Traverse Load
- Side Force
- Clamping Loads

All of the above considerations are closely tied to weldment material type and thickness.

Tooling/Fixtures and Clamping

- Tooling must be designed with process loads in mind.
- Anvil must not deflect under process plunge loads and clamping loads.
- High clamping loads are often required to keep the joint from separating.

Can I weld on a milling machine?

- Yes… But….
- Milling machine spindles are not designed to endure the radial and thrust loads encountered during FSW.
- Milling machines do not offer load control or load monitoring.
- Many researchers start with milling machines

Robotic Weld Tool at NASA MSFC

Articulated FSW Robot [14]
Tool Material Considerations

- For aluminum welding applications tools can be made from tool steels
- For welding materials other than aluminum need to consider:
  - Operating Temperature
  - Chemistry
  - Wear
- Refractory Tools have become common for welding steels and titanium
  - Alloys of Co, Mo, W, and Re
- Polycrystalline Boron Nitride is another popular tool material for high temperature applications

Welding Ti-6-4 using a CP Tungsten tool [15]
Recommended Reading

Friction Stir Welding and Processing
edited by Rajiv S. Mishra, Murray W. Mahoney
Summary

◆ Development and implementation of FSW at NASA driven by the need to reduce defect rate, and improve properties, in Aluminum fuel tanks

◆ FSW has been implemented in multiple industrial applications – not just aerospace

◆ Advantages of FSW include:
  - No melting
  - Improved mechanical properties
  - Reduced defects

◆ Disadvantages include:
  - Initial investment
  - Sensitive to joint tolerances

◆ Industry standards exist and inspection techniques have been established

◆ Key to equipment and tooling design is minimization of deflection induced by process and clamping loads

◆ Tool materials for welding Aluminum are readily available. Tools for welding steel and other high temperature materials exist but have a finite life. Development is still progressing in this area.
Questions
References

12. http://sitemaker.umich.edu/jwo/spot_welding