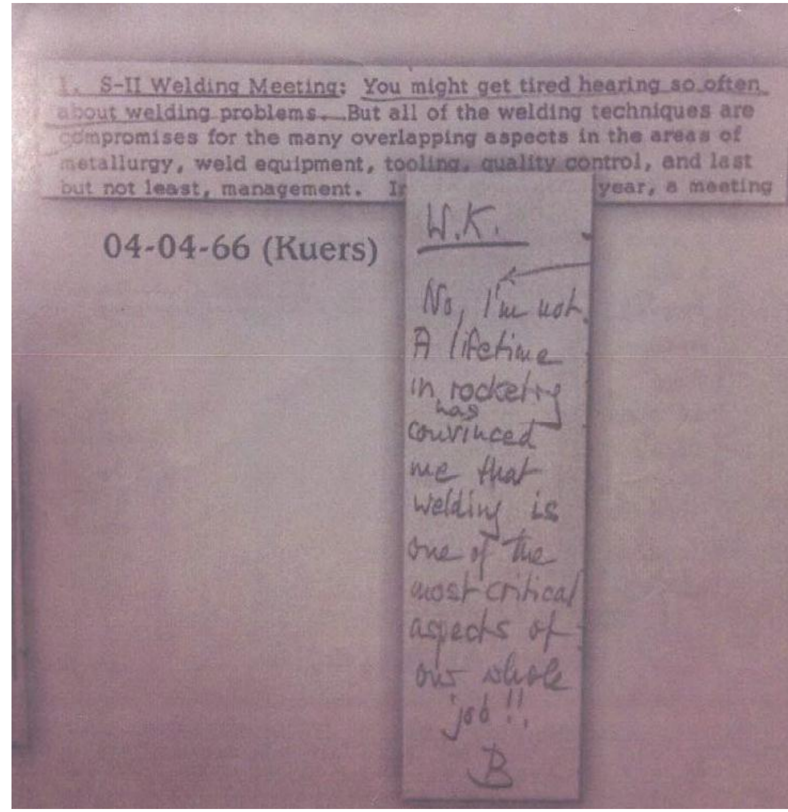
Introduction to Friction Stir Welding (FSW)

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



1. S-II Welding Meeting: You might get tired hearing so often about welding problems. But all of the welding techniques are compromises for the many overlapping aspects in the areas of metallurgy, weld equipment, tooling, quality control, and last but not least, management. In ... year, a meeting

04-04-66 (Kuers)

W.K.

No, I'm not. A lifetime in rocketry has convinced me that welding is one of the most critical aspects of our whole job!!

B

“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.

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

- **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

Space Shuttle External Tank major weld area. 1977

- **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

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 SLS spacecraft adaptor at MSFC. Nov 2012 [1]

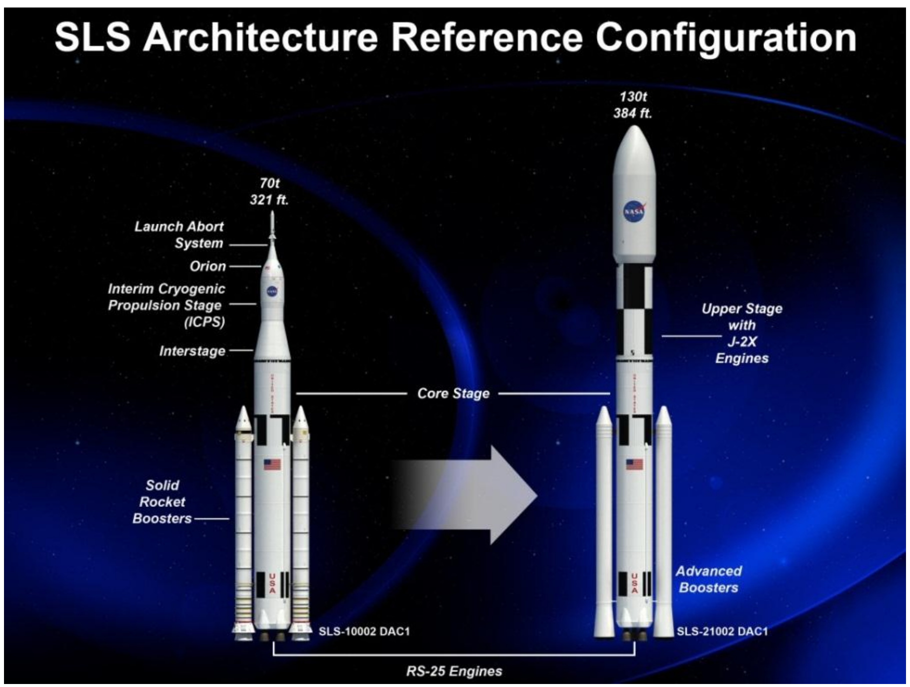
Welding of Space Shuttle External Tank Barrel Sections.

Welding of the Orion capsule at MAF. [2]

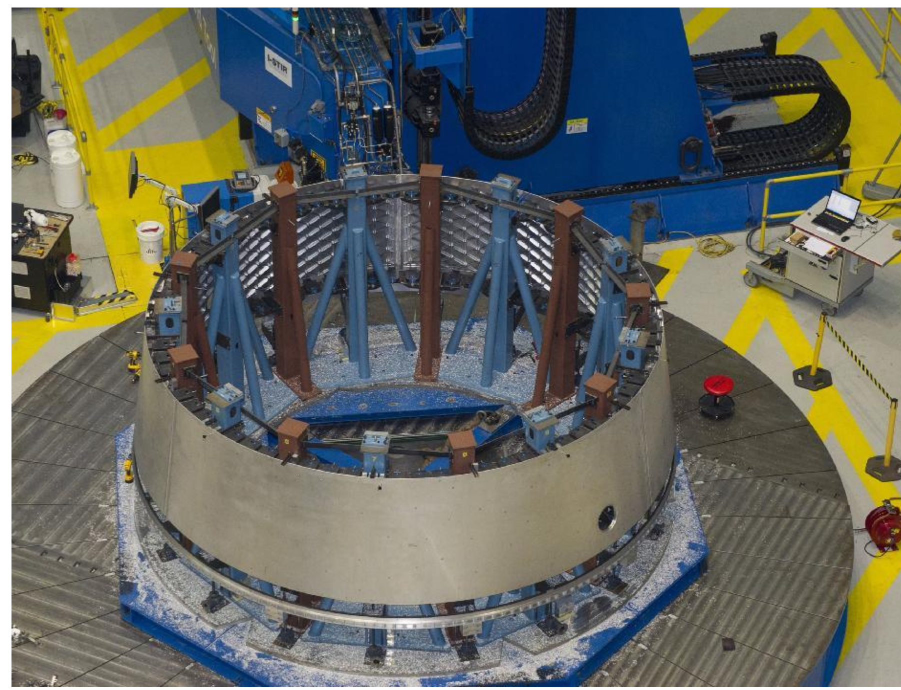
Looking Forward – NASA's building the Space Launch System (SLS) using FSW

- 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.

Reference [3]



Reference [3]



Reference [3]

FSW Background

- **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-IIB
  - 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

Prefabricated Deck Panels [7]

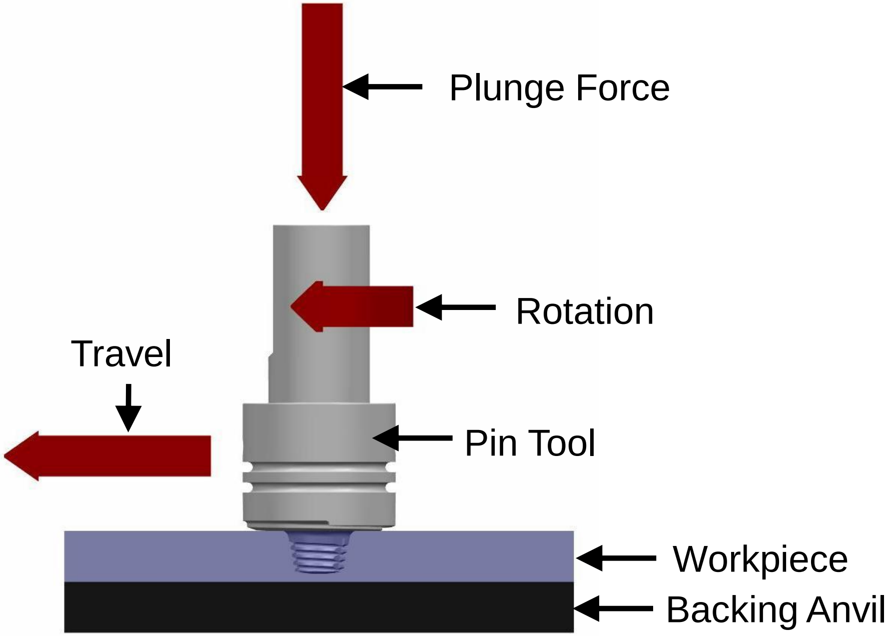
Eclipse 500 [7]

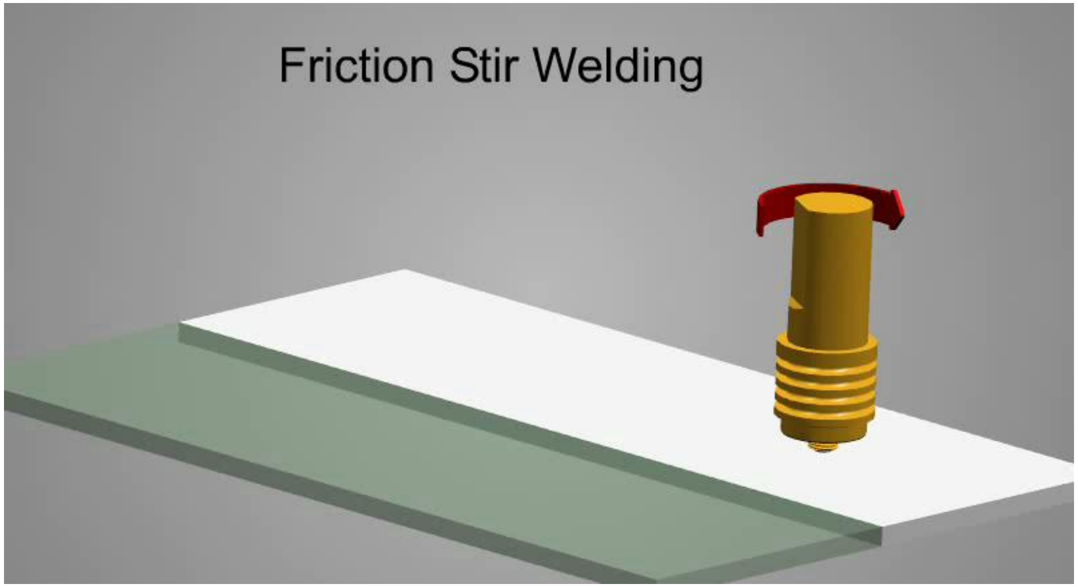
The "Conventional" Friction Stir Welding Process

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



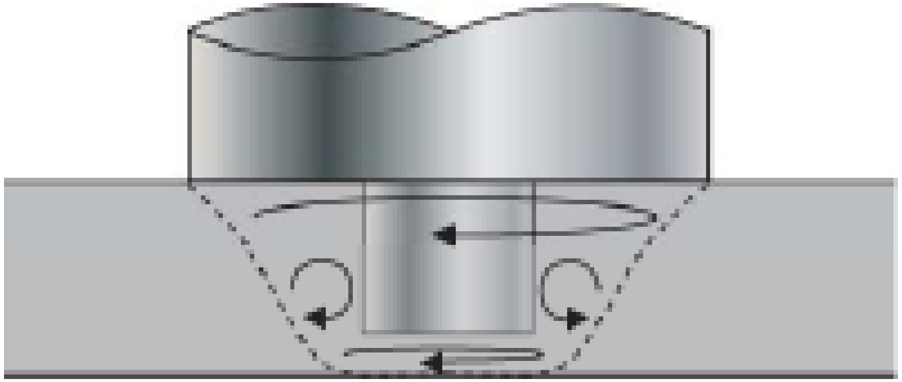


Key Points:

- Solid state (no melting)
- Non-consumable Tool
- No filler metal
- Shielding gas not required for Aluminum alloys
- Solid backing anvil
- Thickness and Travel Speed

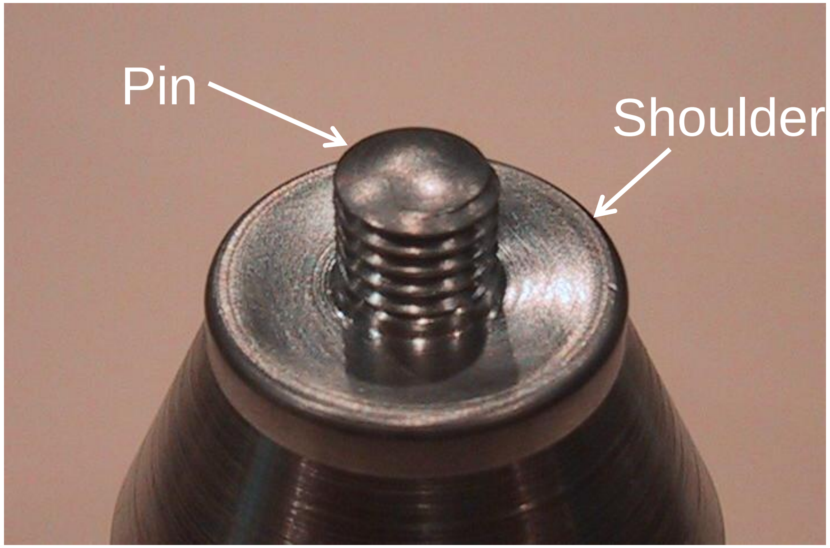
How does it work?

- 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

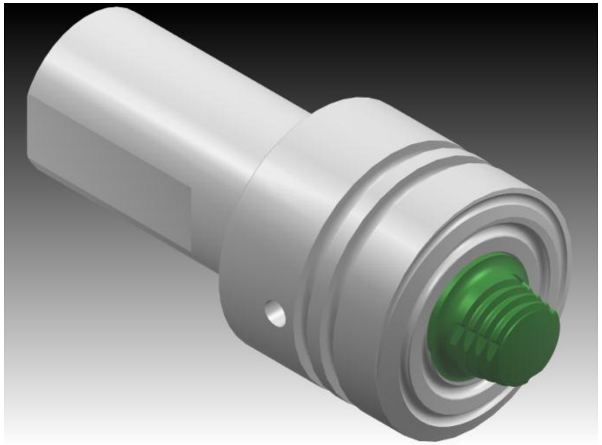


FSW Tool Design

- **"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



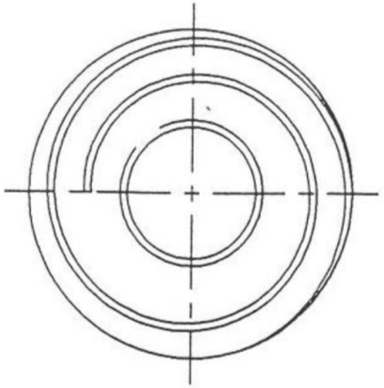
"Standard" Tool Geometry



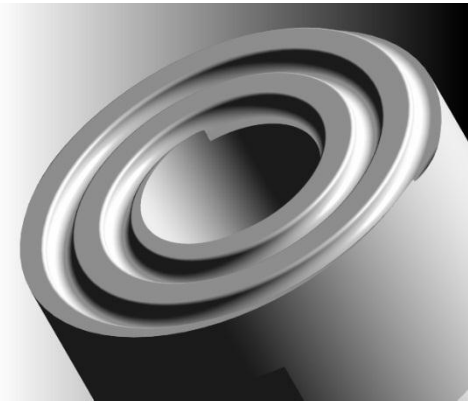
Variant of standard geometry with tapered fluted pin and scrolled shoulder

Evolutionary Enhancements to FSW

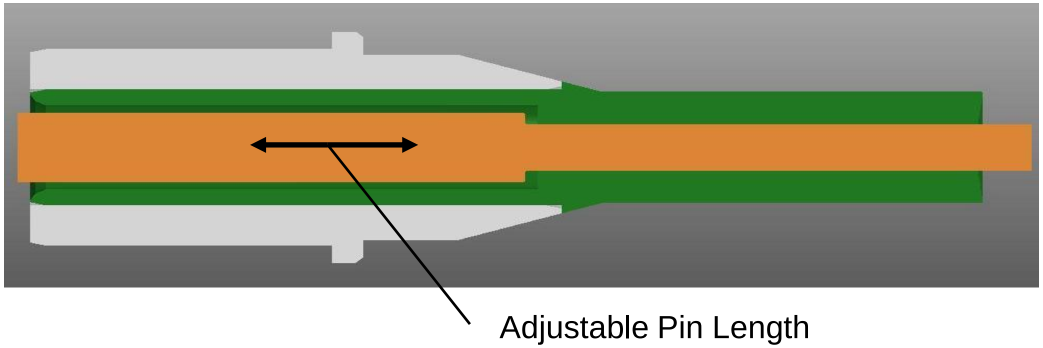
- **Scrolled Shoulder**
  - The development of the scroll-type shoulder geometry eliminated the need for a lead angle
  - Prior to this all welding was performed using a negative lead angle
- **Retractable Pin Tool**
  - NASA Patented [9]
  - A device capable of manipulating the length of the welding 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



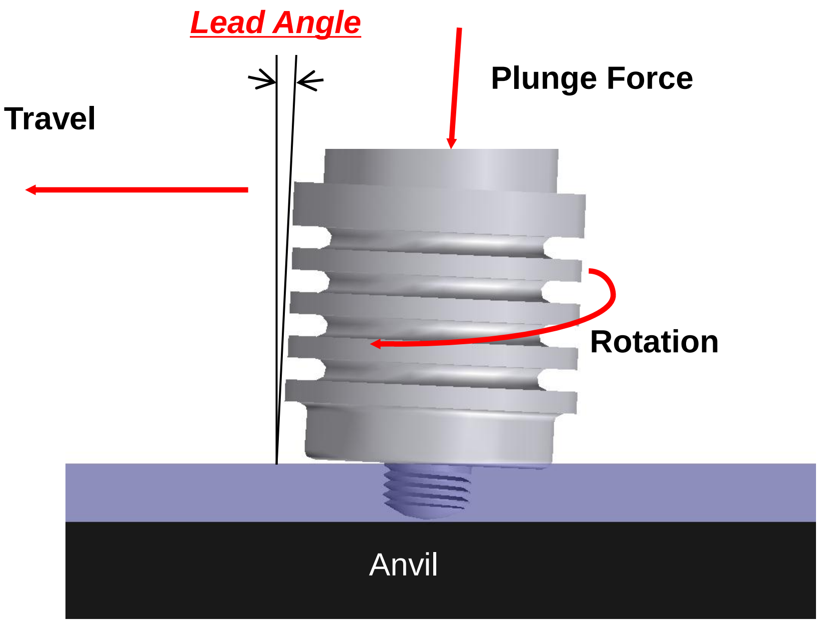
Scrolled Shoulder [8]



Scrolled Shoulder



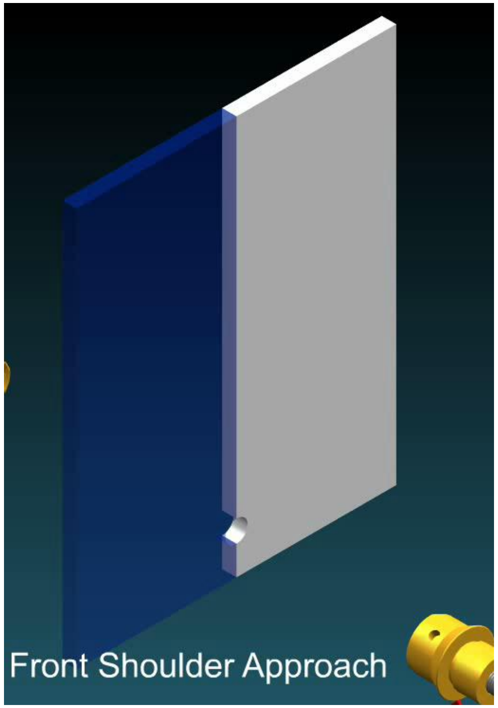
Retractable Pin Tool

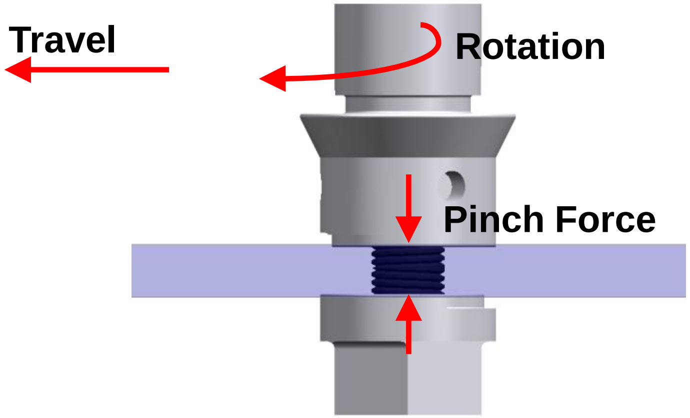


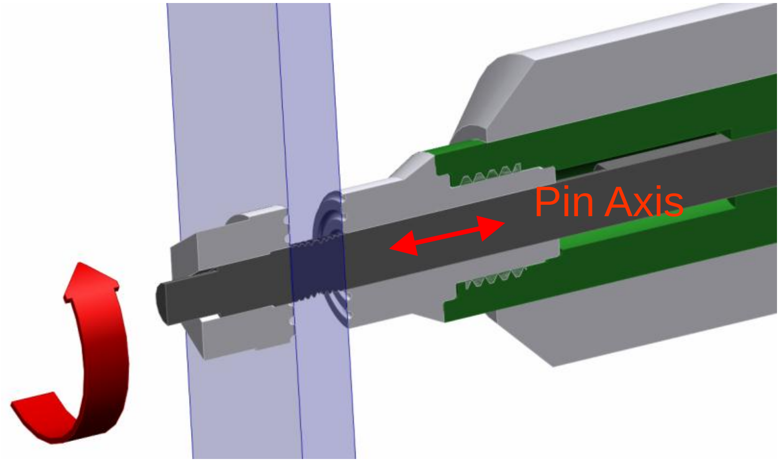
Conventional FSW with a lead angle

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







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Marshall Space Flight Center

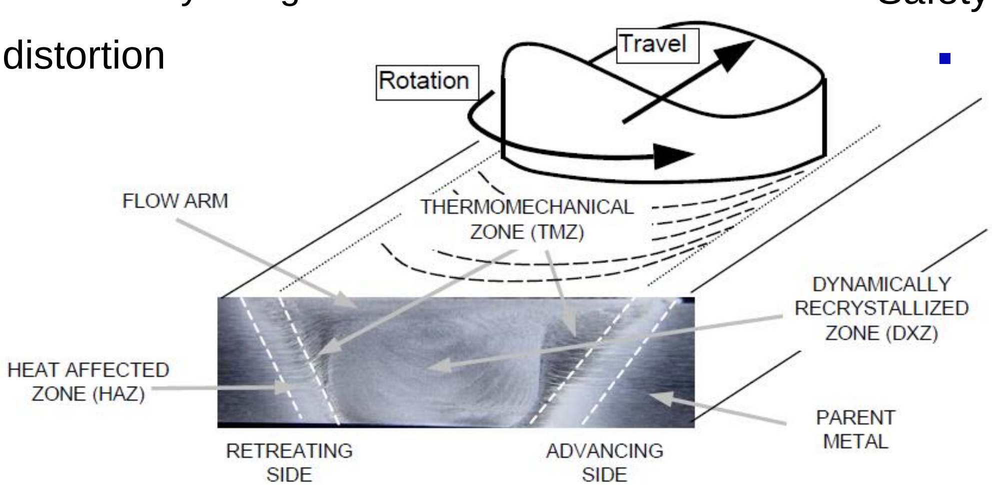
FSW Advantages

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

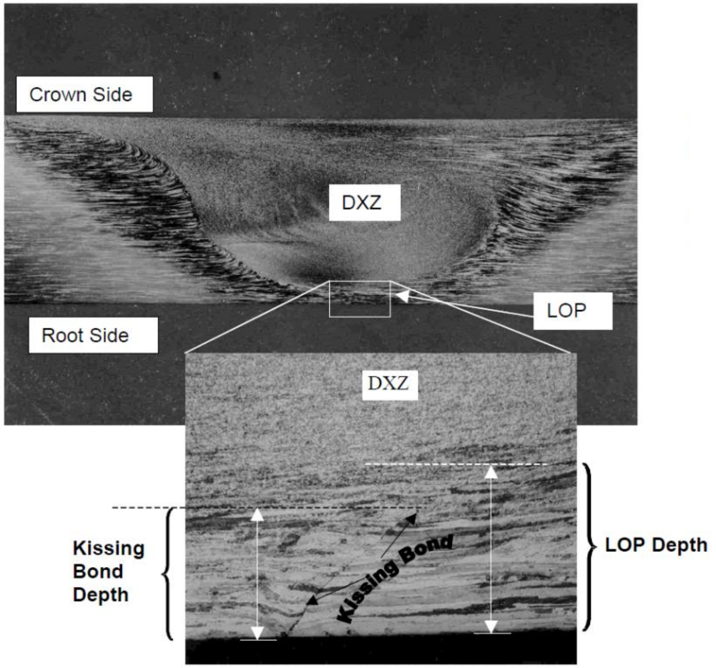


FSW Disadvantages

♦ Disadvantages

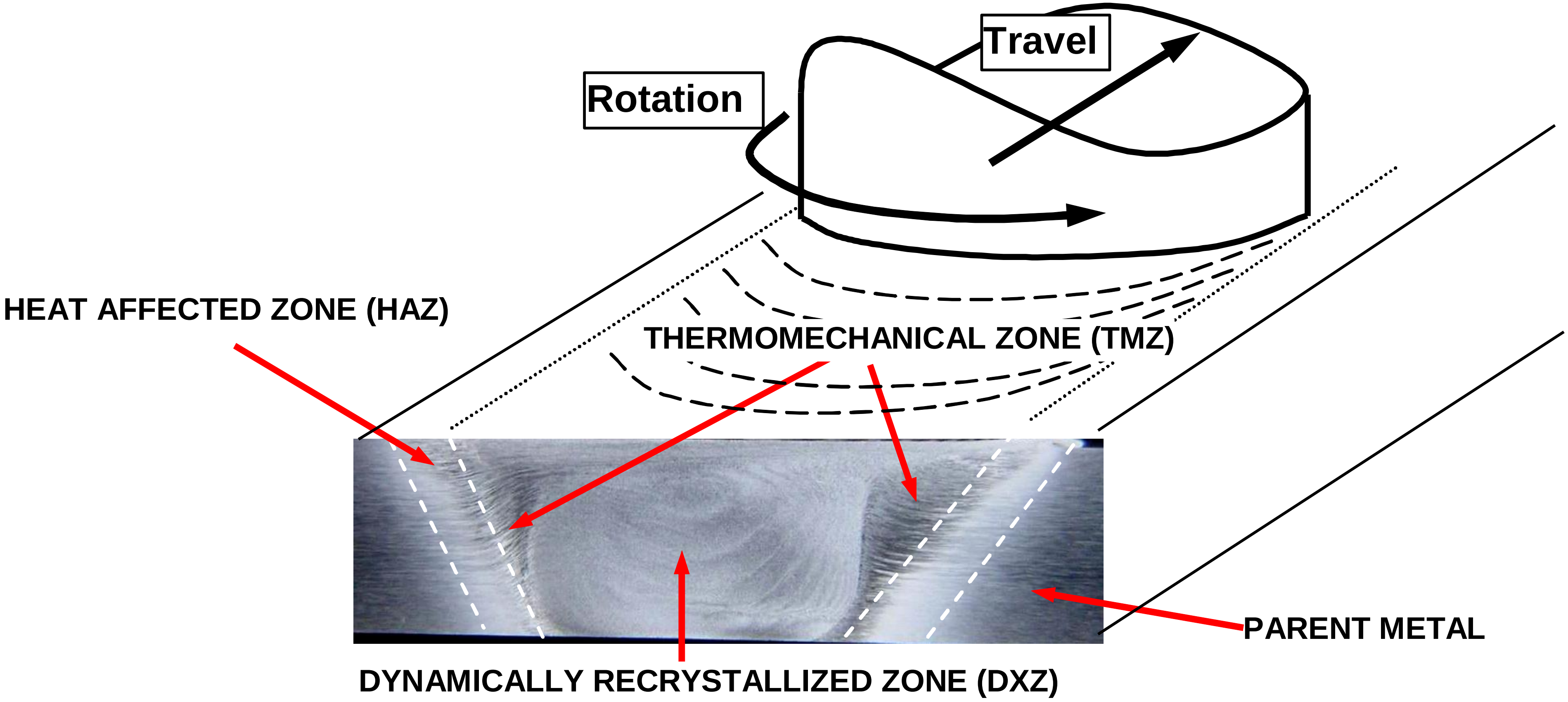
- High initial investment in tooling and equipment
- Sensitive to Joint Tolerances
  - Not forgiving of pre-weld mismatch and gap
  - Mismatch can lead to excessive flash
- Fixed Penetration - Lack of Penetration Defect Concern
  - Lack of full penetration can result in “kissing bonds” that are difficult 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



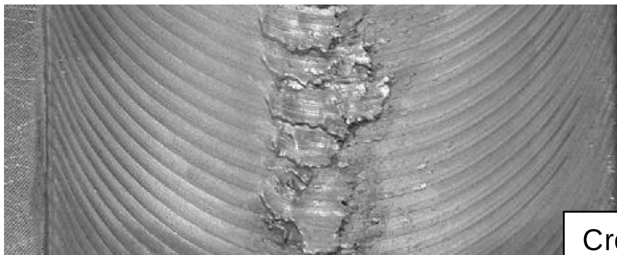
Example “kissing bond”

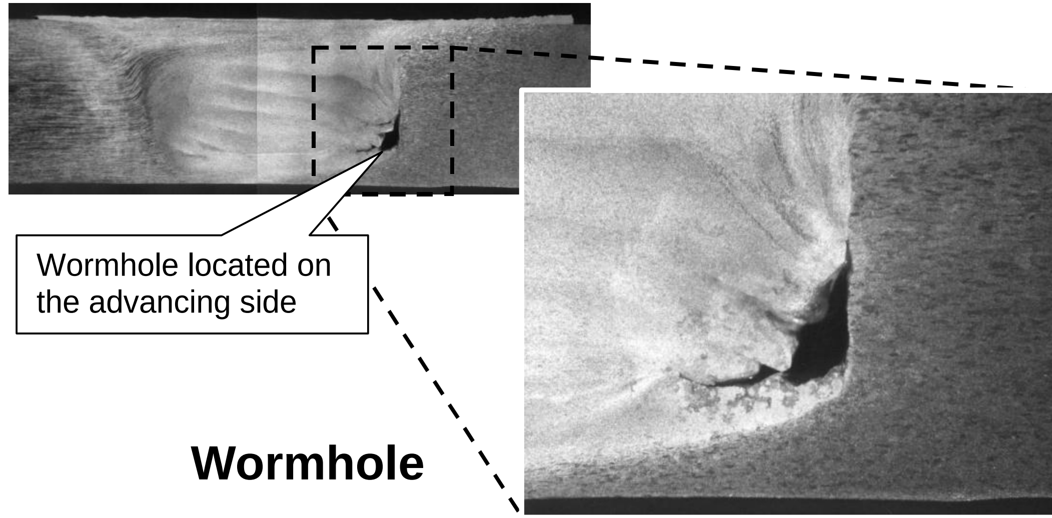
Microstructural Features and Nomenclature



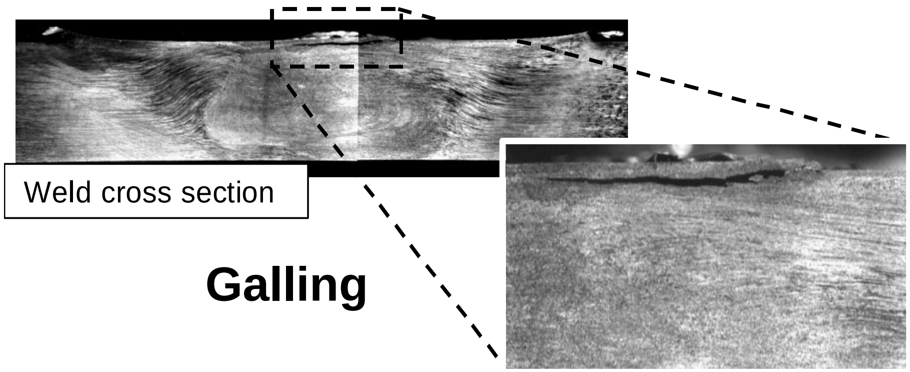
Uncommon FSW Defects

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



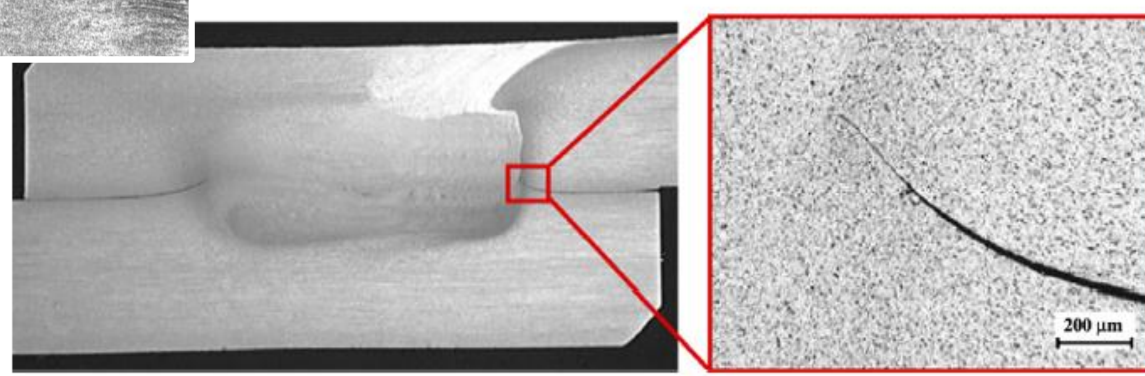


Wormhole



Galling

Hook Defect in Lap Welds



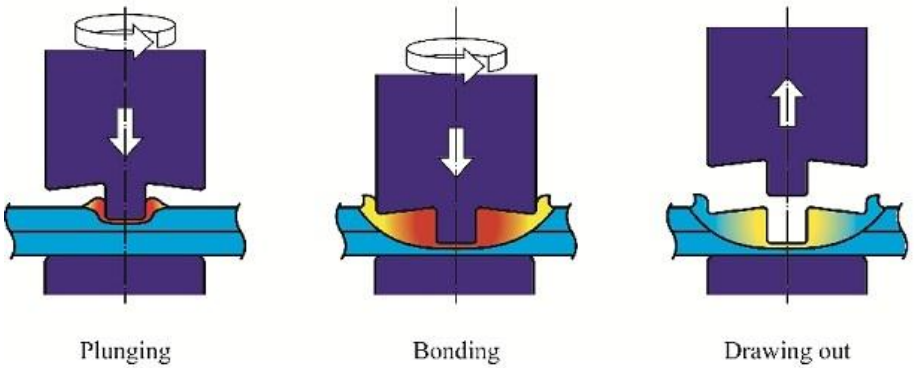
Reference [11]

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]

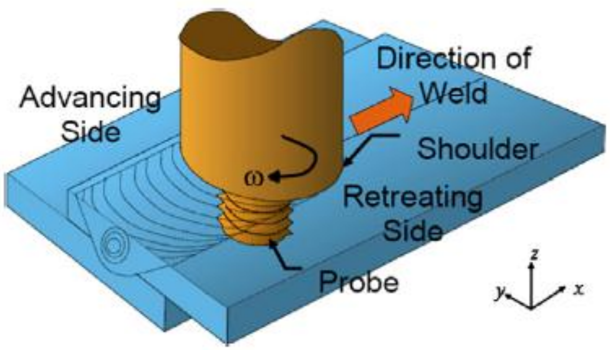
Mazda Friction Spot Welding [13]

♦ 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

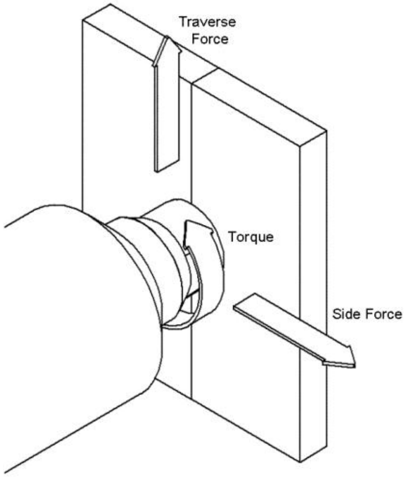
- Using Friction Stir Welding technique to modify properties.
  - Homogenization
  - Grain Refinement
  - Elimination of casting defects



Reference [11]

Equipment and Tooling

- **Key Considerations:**
  - Torque
  - Spindle Speed
  - Plunge Load
  - Traverse Load
  - Side Force
  - Clamping Loads



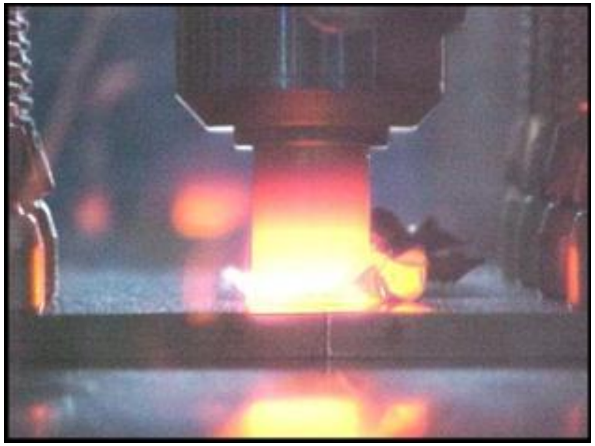
- **All of the above considerations are closely tied to weldment material type and thickness.**
- **Tooling/Fixtures and Clamping**
  - Tooling must be designed with process loads in mind.
  - Anvil must not deflect under process plunge loads and clamping loads.
  - High clamping loads are often required 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]

FSW Tool Material Considerations

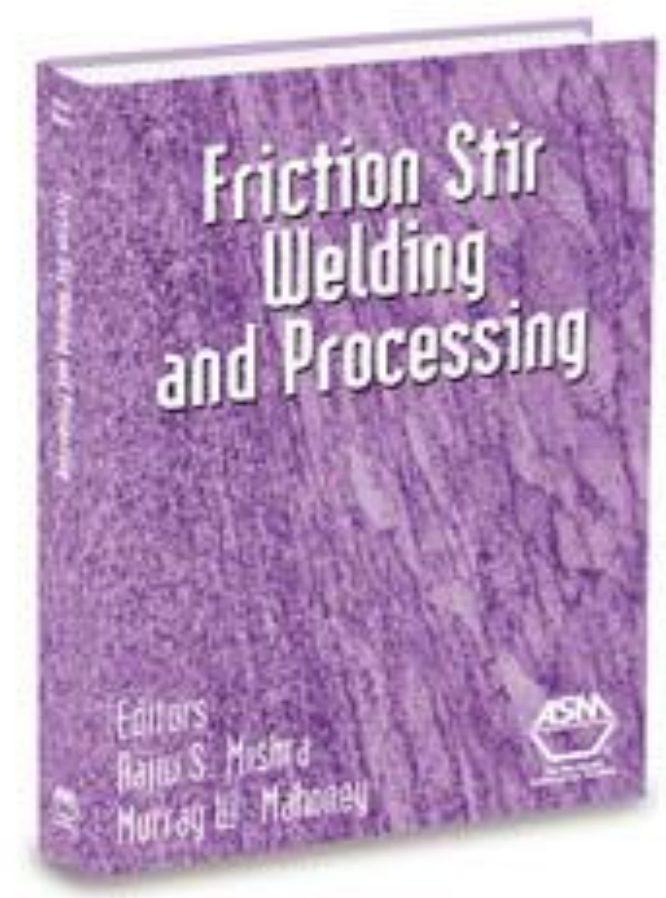
- **Tool Material Considerations**
  - For aluminum welding applications tools can be made from tool steels
  - For welding materials other than aluminum need to consider:
    - Operating Temperature
    - Chemistry
    - Wear
  - Refractory Tools have become common for welding steels and titanium
    - 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

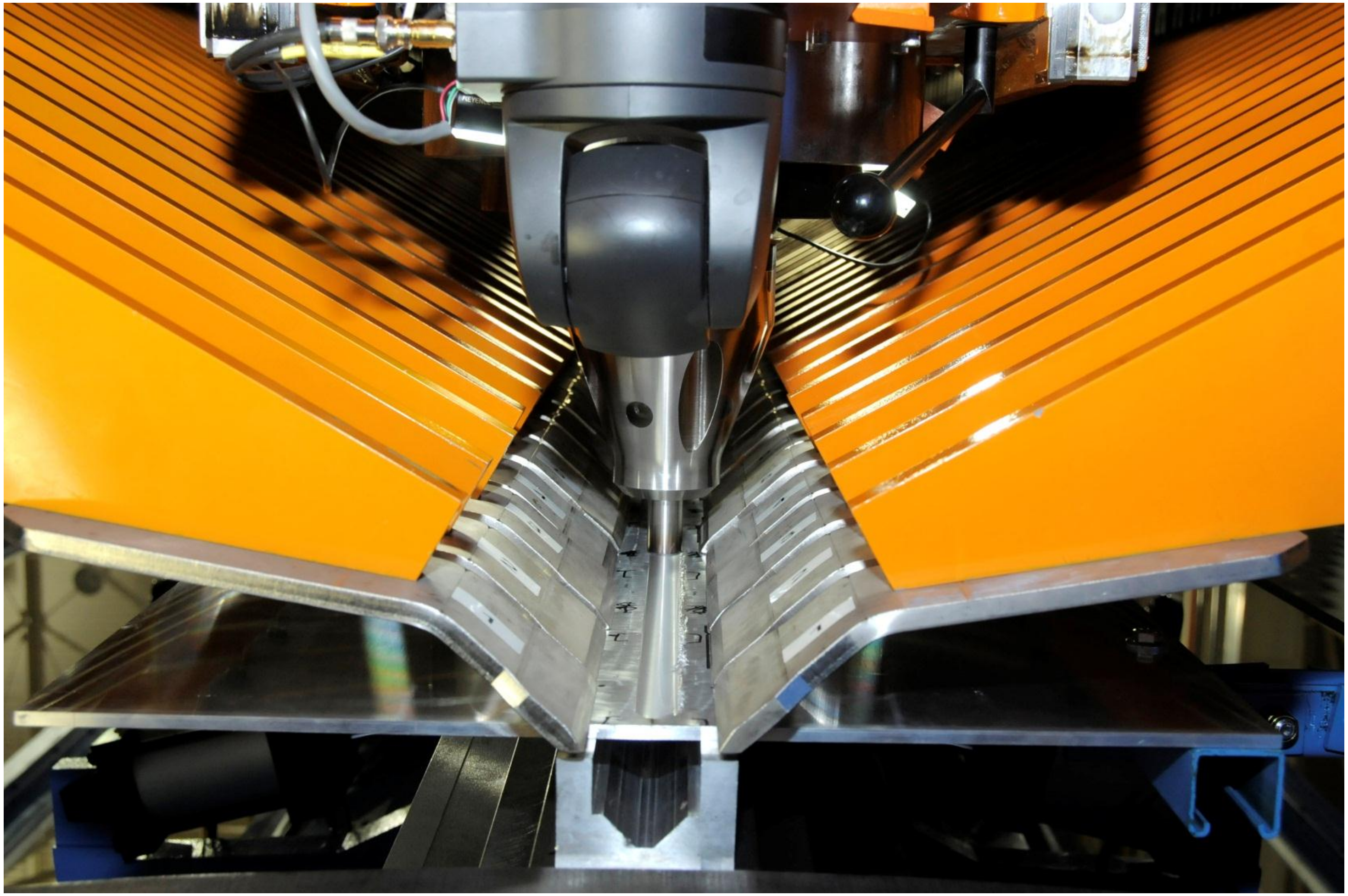
Friction Stir Welding and Processing
edited by Rajiv S. Mishra, Murray W. Mahoney



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



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