Corrosion Resistant Aluminum Components for Improved Cost and Performance of Ultra-Deepwater Offshore Oil Production

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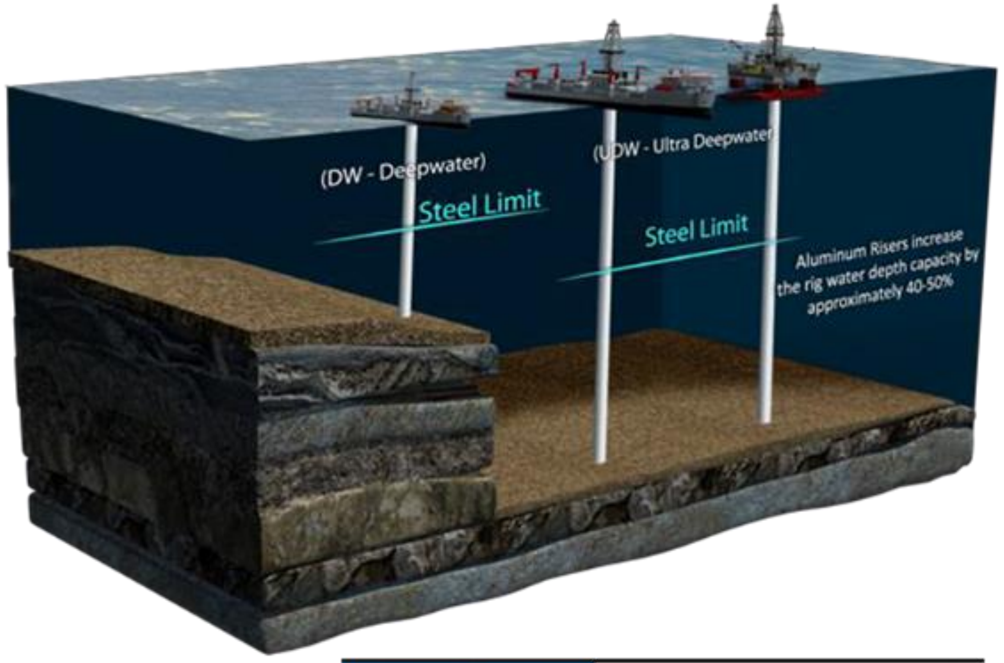
The Opportunity

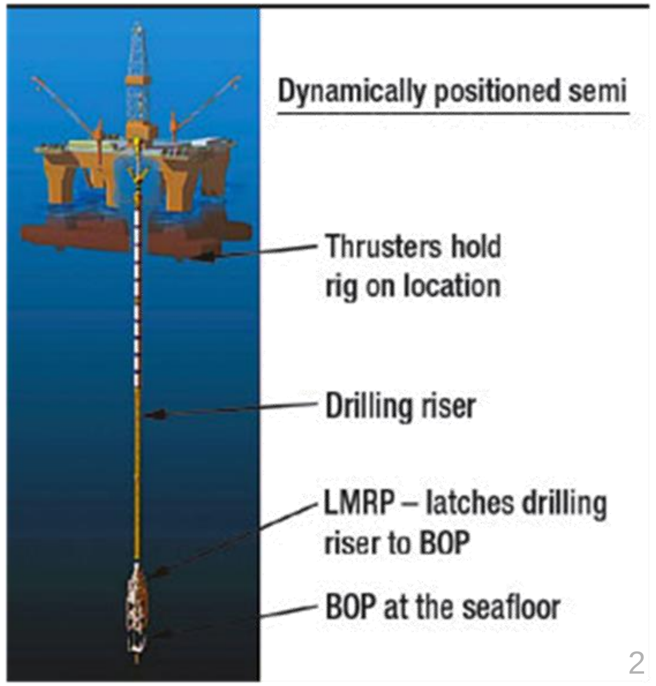
- **A significant barrier for production from ultra-deepwater resources results from the weight of steel riser systems**
- **Replacing steel risers with high-strength aluminum risers would extend offshore drilling depth by >40% without requiring extensive modification to floating rigs.**



Specific Advantages of Aluminum

- 40% lighter than steel riser system
  - Aluminum Slick Riser – 18,000 lbs.
  - Steel Slick Riser – 30,000 lbs
- 1/2 the buoyed weight of steel riser joint
  - 1/3 of joints require buoyancy vs. 95% of steel joints
- 46” versus 54” buoyancy diameter - reduced drag
- For 12,000-foot water depth, aluminum risers could save more than 1,920,000 lbs of deck load

Aluminum risers can increase rig water depth by greater than 40%



Favorable Economics

Steel risers in deep and ultra-deepwater requires that rigs be modified to increase deck load capacity

- Aluminum avoids tensioning system upgrades
- Avoids rotary table and top drive upgrades
- Avoids estimated ~$44M for equipment upgrades
- Easier maintenance - no descaling or painting
- Easier to handle – lighter sections
- Lower marine growth

- In one deep water application analyzed, extending the offshore depth from 4000 feet to 9000 feet would cost an estimated $33M using aluminum risers compared to $200-300M with steel risers

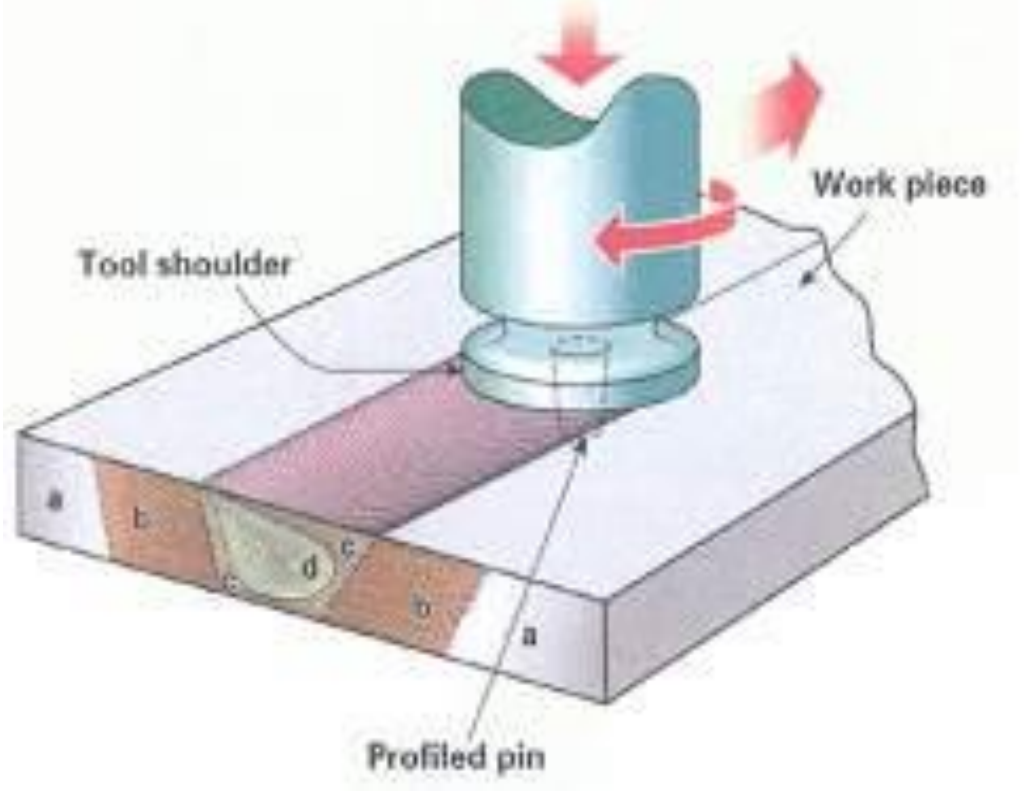
What is the Challenge for Aluminum Risers?

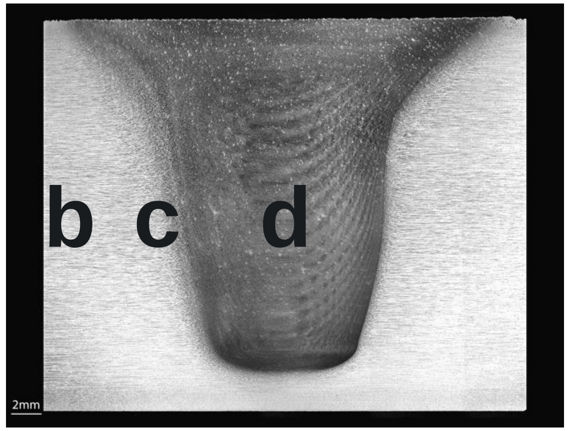
In 12,000-foot water depth an aluminum riser system would need to withstand 3.2 million pounds of tension loading

- 7XXX aluminum alloys are strong enough but…
  - Fusion welds result in poor joint strength
  - Fusion welds are prone to corrosion
- Project will develop solid-phase joining (i.e. no melting) for pipe-to-pipe and flange-to-pipe joints

Friction Stir Welding

- Spinning, non-consumable tool is plunged into the interface between two adjacent plates
- Friction and plastic work heat the material sufficiently to lower the flow stress.
- The plates mix to form a robust joint as the tool translates along the interface
- The resulting joint is characterized by:
  - A “Nugget” composed of recrystallized and transformed grains (d)
  - Surrounded by a mechanically deformed heat affected zone (c) and an un-deformed heat affected zone (b)





FSW of 1" AA7175

Project Overview

- **Objectives**
  - Develop FSW for thick section 7XXX and transfer process to industry
  - Fabricate sub-scale and full-scale risers for testing

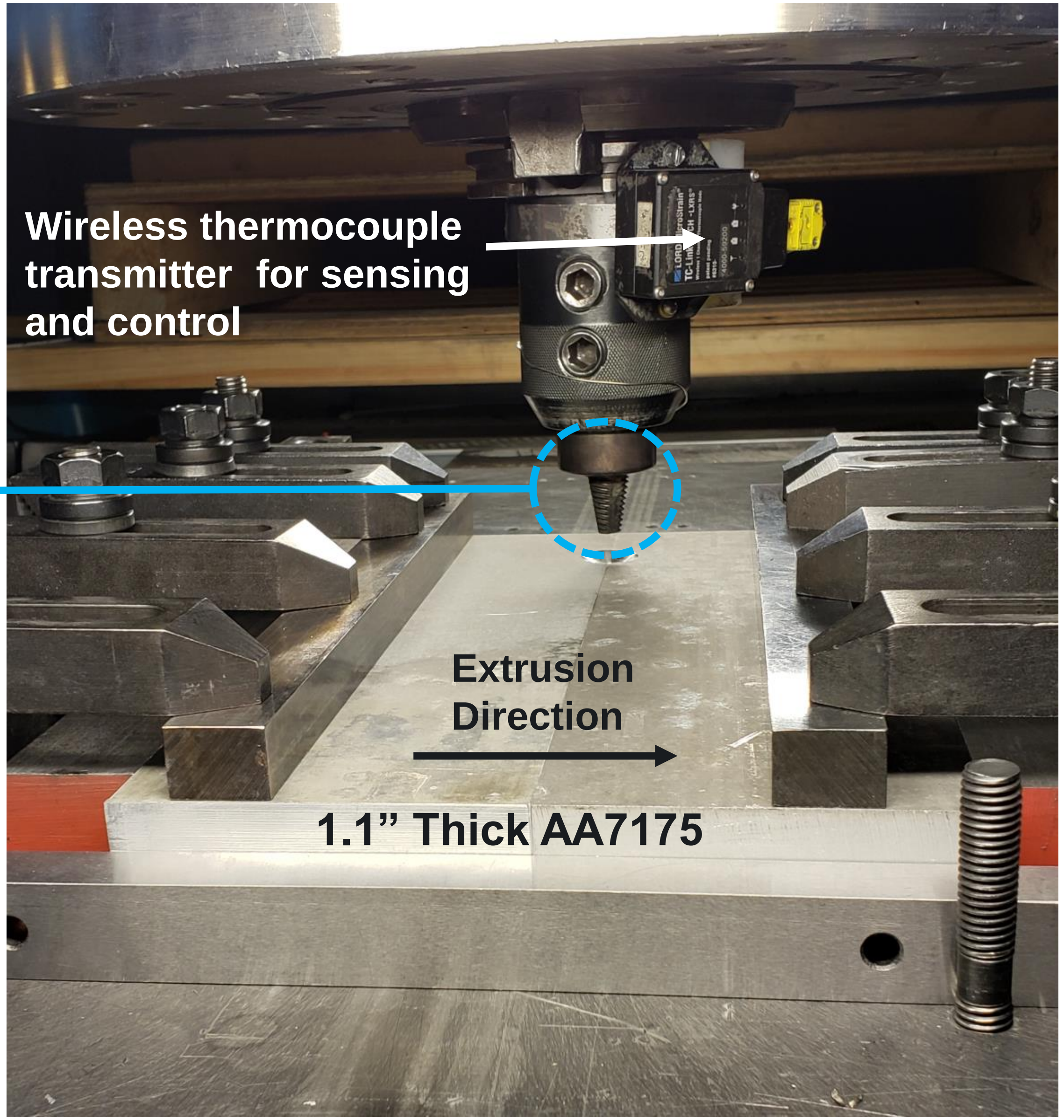
- **Project Duration: FY19-FY22**
- **DOE-FE Share: $1.5M**
- **Industry Share: $4.0M**

- **Approach**
  - Task 1 Develop FSW tooling and process parameters
  - Task 2 Optimize heat treatment and characterize joints
  - Task 3 Explore cold spray as a corrosion mitigation strategy
  - Task 4 Fabricate 7xxx riser assembly for performance evaluation by industry

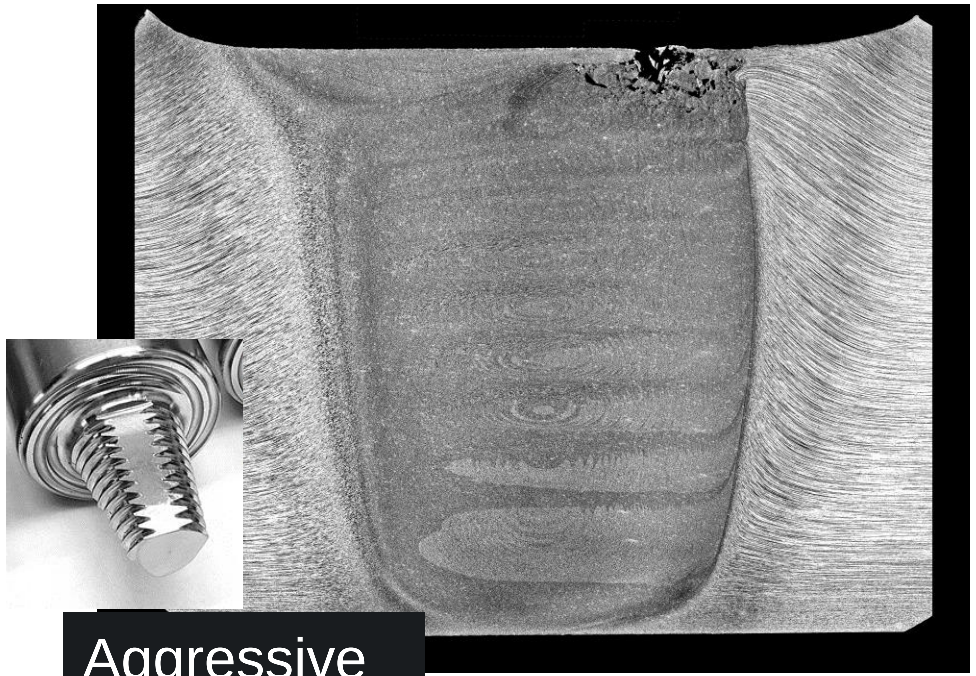
- **Team and Roles**
  - PNNL - Weld process and corrosion barrier development
  - XYMAT Engineering - Full scale aluminum riser fabrication, materials

Task 1: FSW Process Development

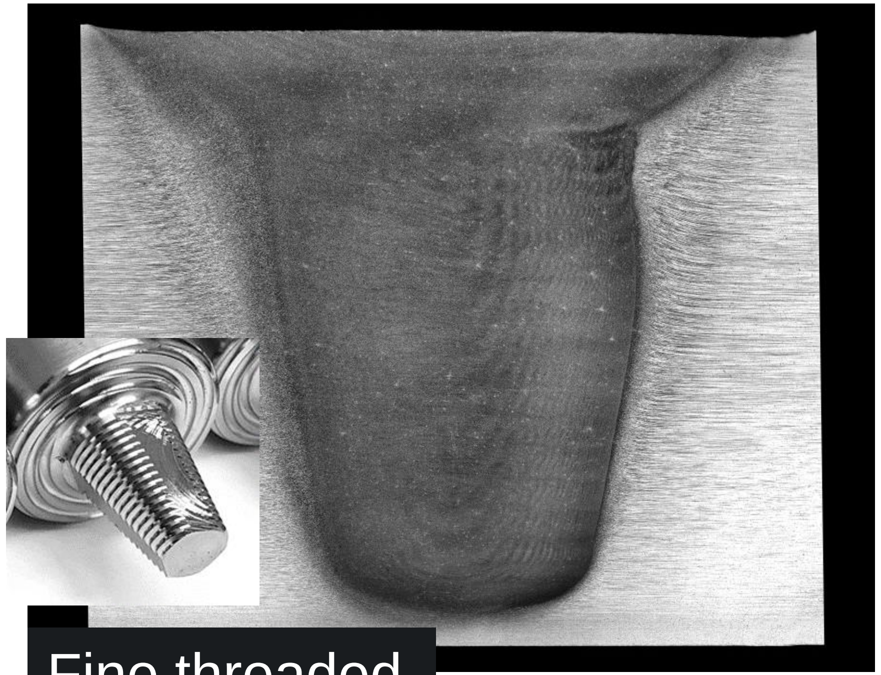
A suite of tools have been investigated to determine the best tool/process combination



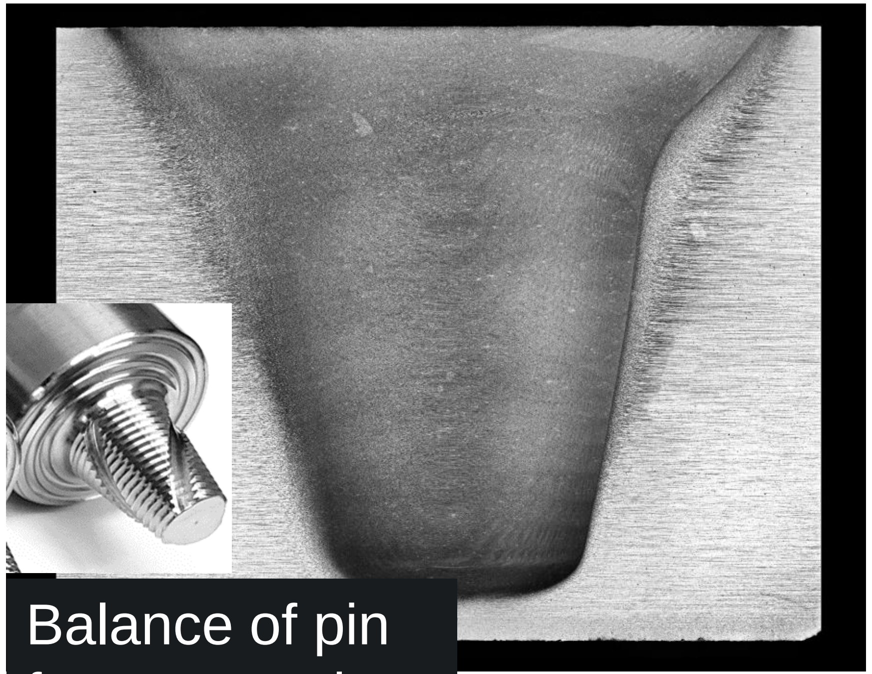
Task 1: FSW Process Development



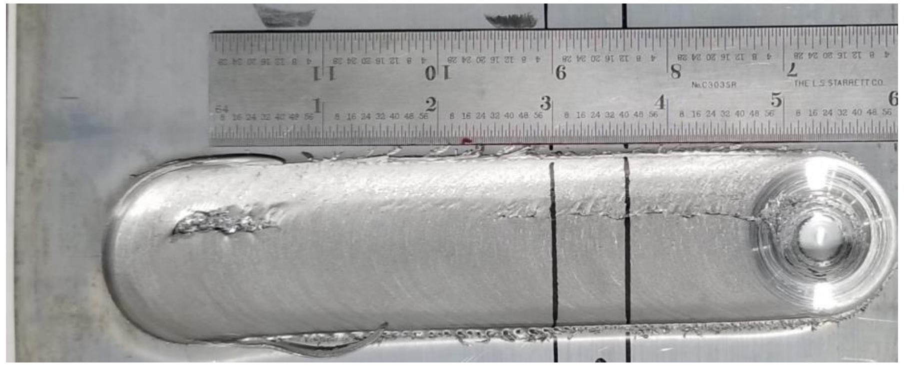
Aggressive pin threads

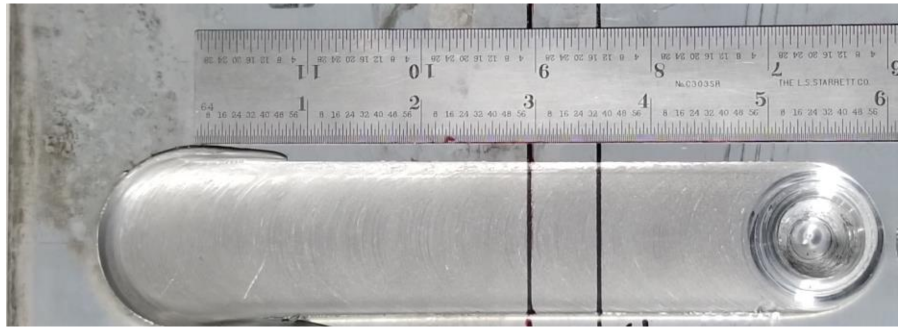


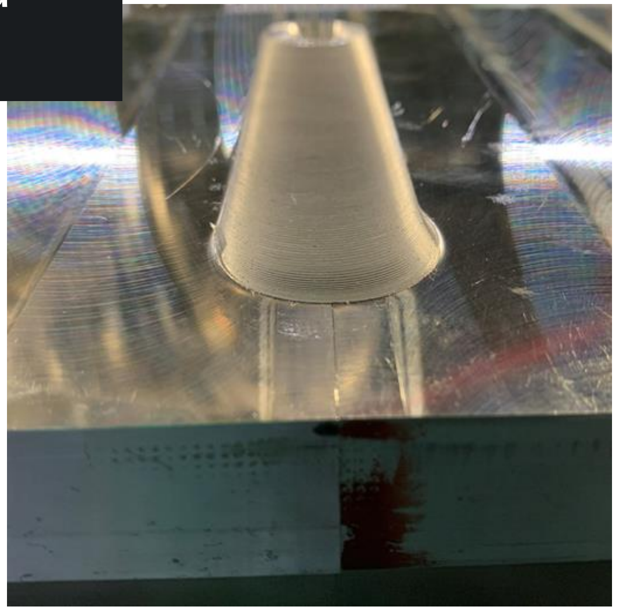
Fine threaded features



Balance of pin features and Parameters







Fracture toughness testing

Fracture toughness tests of the base material in 7175-T79 condition, FSW nugget, and heat affected zone (HAZ) were completed.

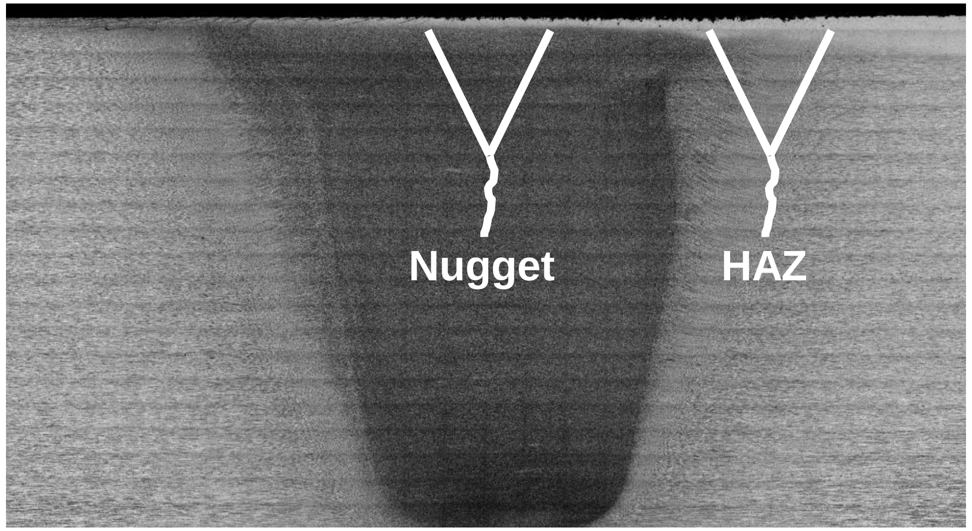
Notch and fatigue crack orientation was same in all the test conditions.

	K_{JIc} MPa $m^{1/2}$
Base material (7175-T79)	49±5.5
Nugget	51.5±2.2
HAZ	74.6±6.0

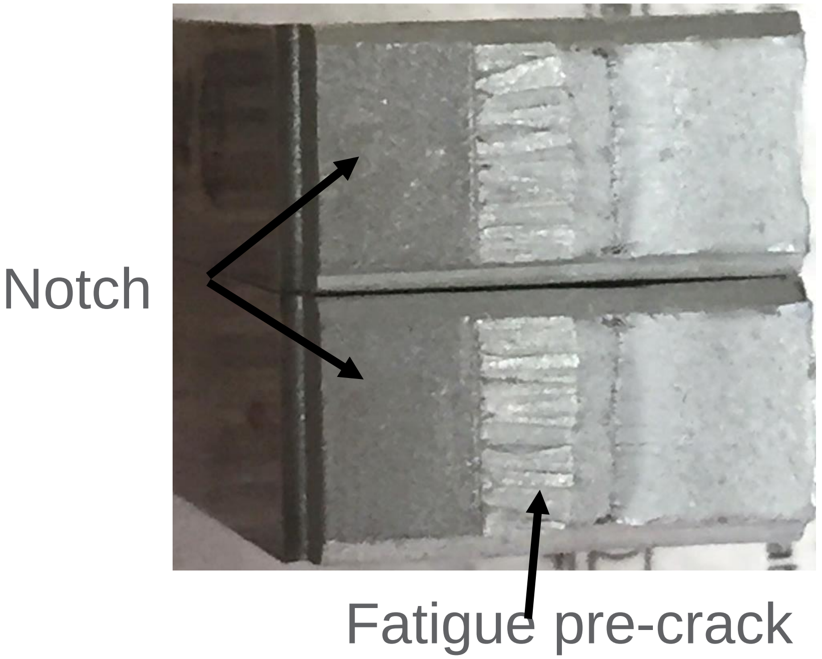
All the tests were valid.

Both nugget and HAZ exhibited increased fracture toughness as compared to the base material

An example of notch locations for nugget and HAZ locations



Fracture surface of the fractured HAZ sample

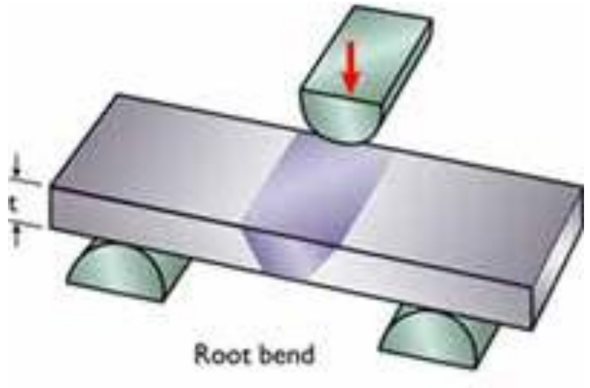


Bend testing of 1" thick 7175 Al alloy in cross-weld configuration

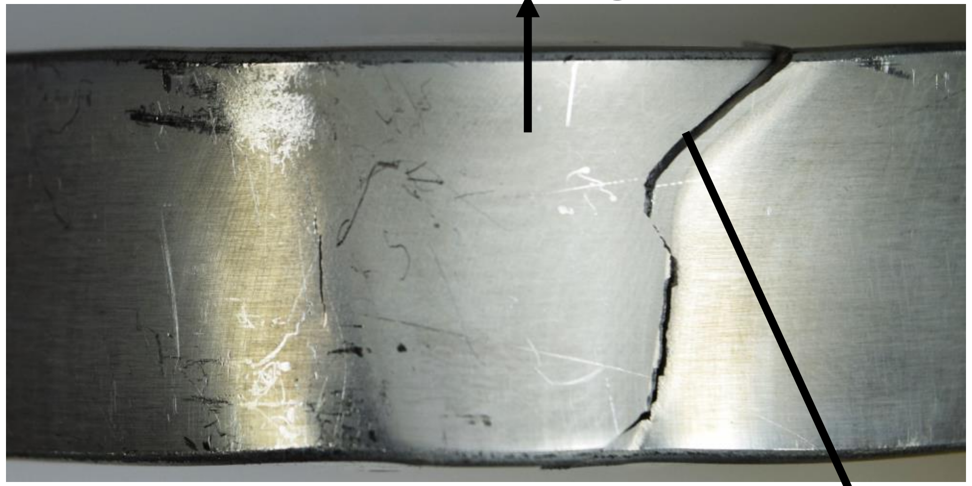
A face, side, and root bend tests of the cross-welded FSW samples were carried out in 2T configuration.

All the samples failed outside the welded nugget region indicating a volumetric defect-free solid-state weld in 1" thick 7175 Al alloy.

An example of root bending setup is shown below

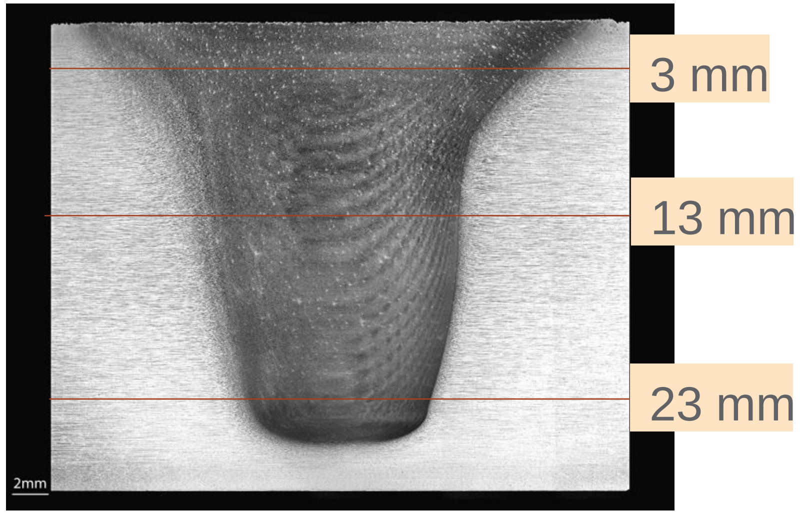


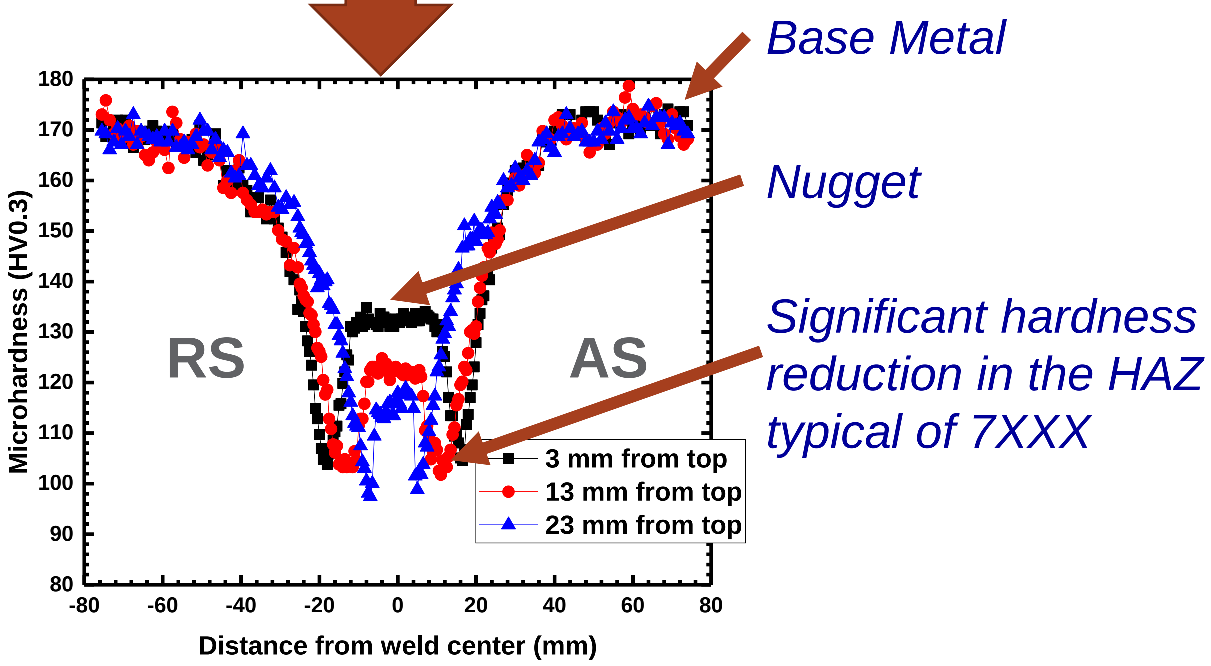
Side bend

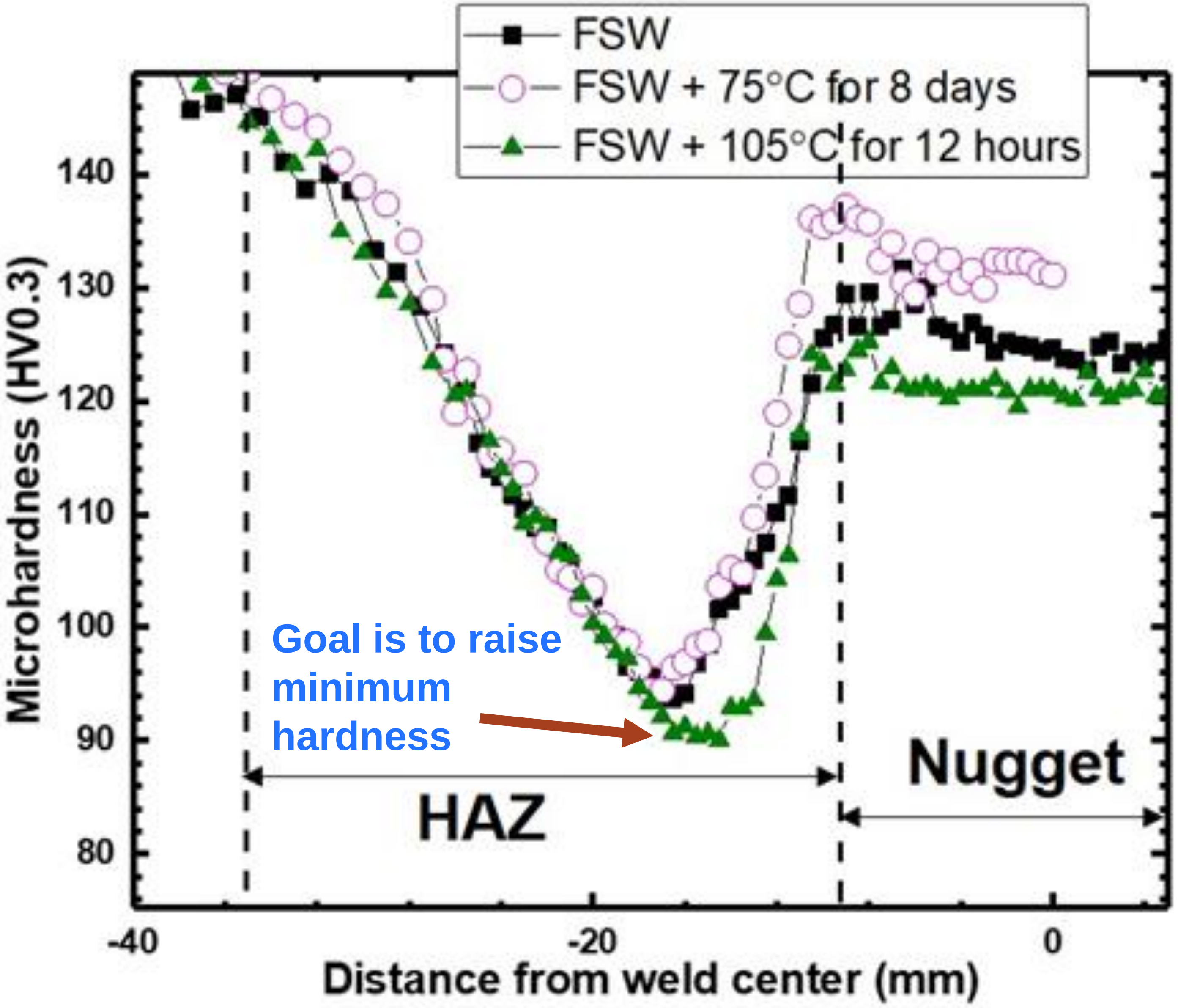


Face bend

The Challenge of the HAZ
Task 2: Optimize Heat Treatment







Reducing degradation in the heat affected zone

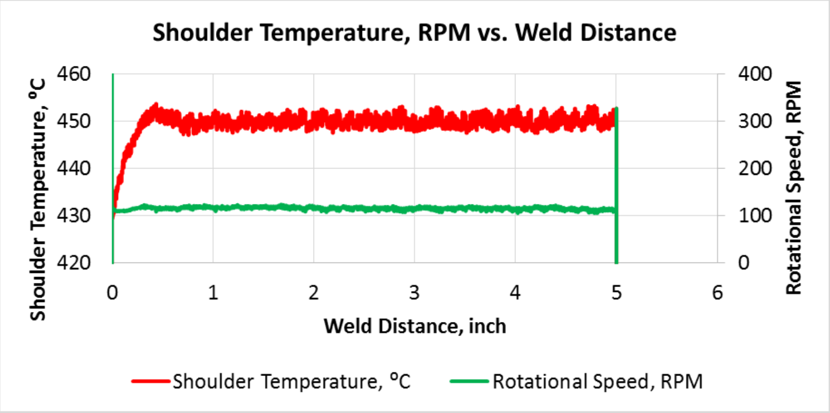
Weld Speed (ipm)	Ultimate Strength (MPa)	0.2% Yield Strength (MPa)
2	381	218
4	418	291
6	437	318

Faster weld speed improves strength due to less heating of the heat affected zone

As weld temp goes up

Temp.	UTS	0.2% YS
ºC	MPa	MPa
450	495 ± 1	338 ± 2
460	494 ± .5	323 ± 10
495	427 ± 7	284 ± 5
500	434 ± 7	309 ± 3

Crossweld tensile strength goes down



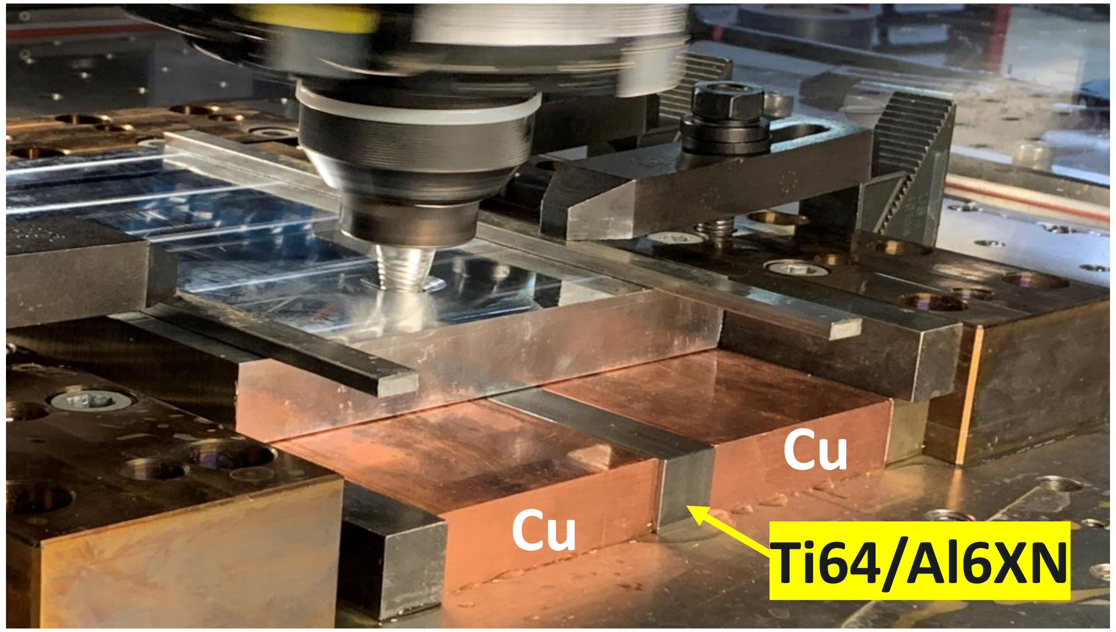
Going cooler:
Go faster, change tool design and materials
Control the boundary conditions

Active cooling

FSW Process Development with Thermal Management

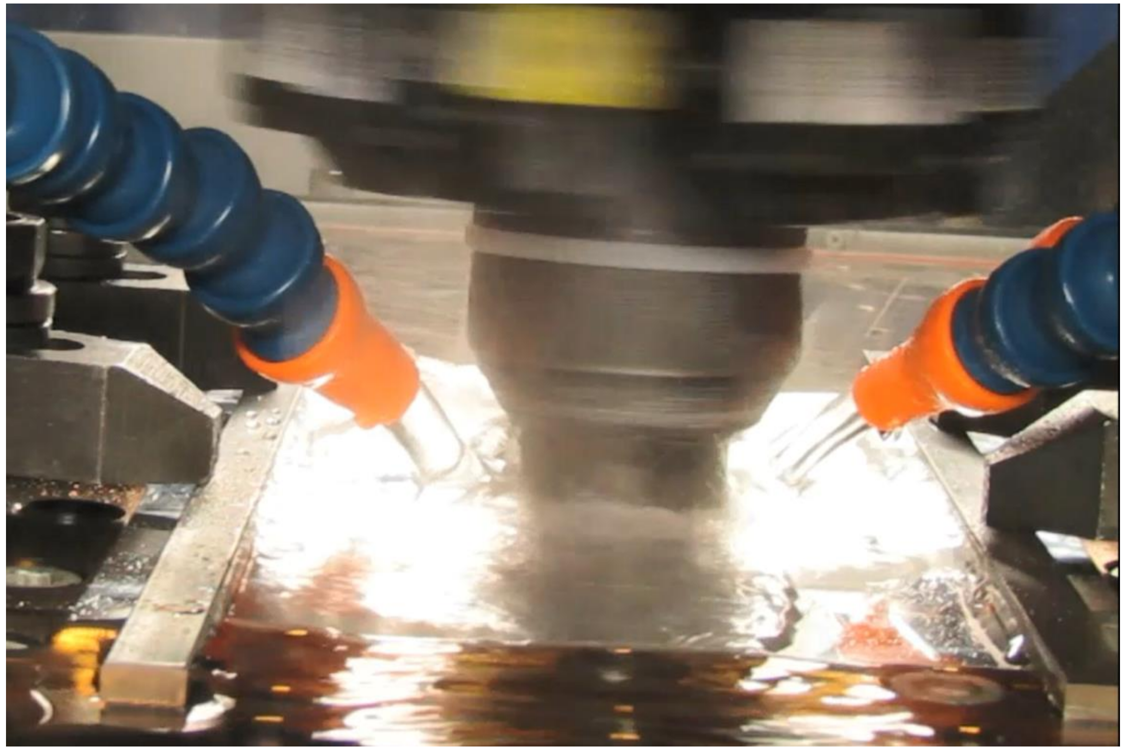
- Joint efficiency was improved by engineered thermal boundary conditions:
  - With composite backing plate
  - With trailing water spray during FSW

Composite backing plate with Ti64/Al6XN (steel) center strip and Cu sides



Benefits: Improved HAZ minimum by extracting heat from HAZ at the same time, providing through thick temperature homogeneity in nugget

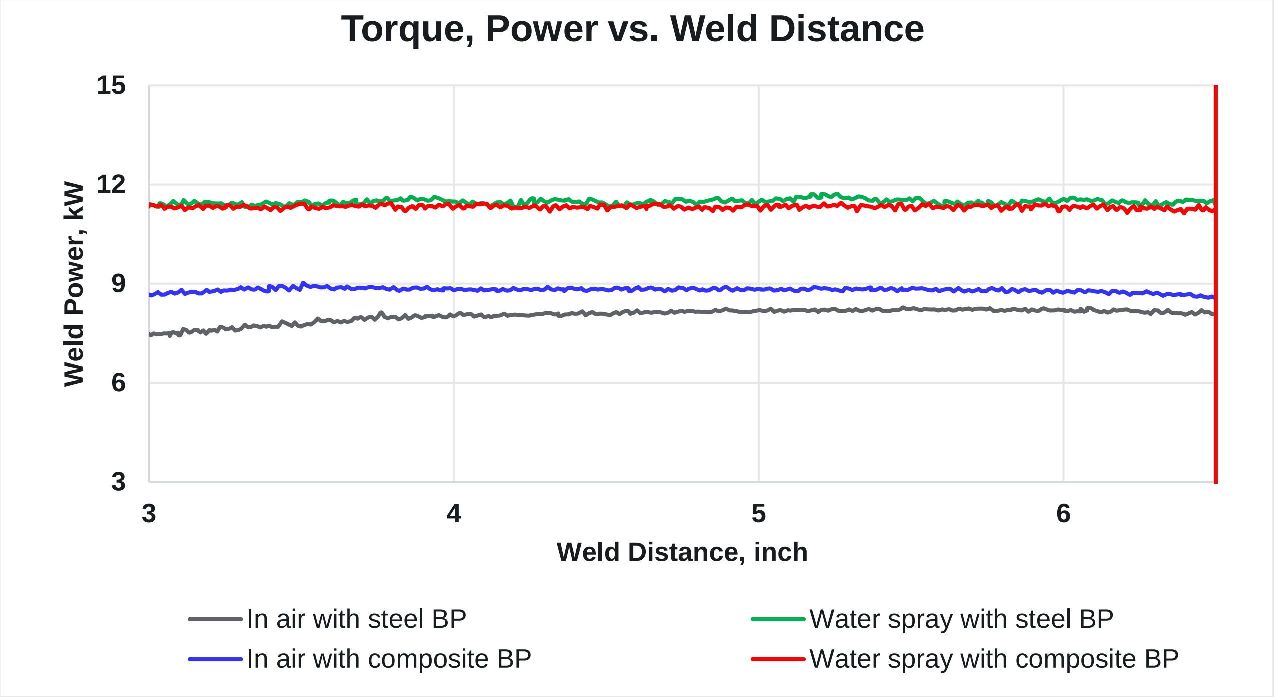
Water spay right behind the tool in HAZ area

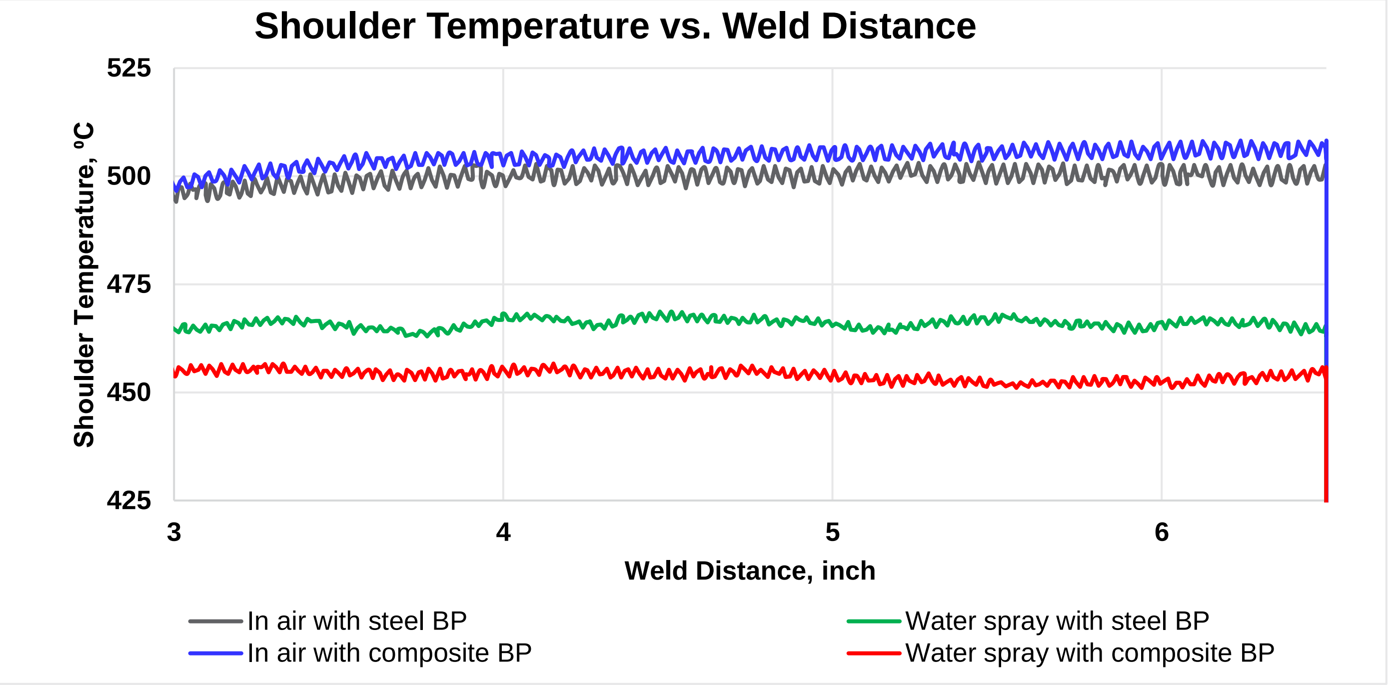


Effectively extract heat from HAZ near weld surface and prevent overheating weld crown

Trailing water spray during FSW

FSW Process Data Comparison: Weld Power and Temperature





Trend in weld power

- Weld power is higher for trail water spray weld than in air weld since torque in tool is higher in order to stir colder material

Trend in tool temperature

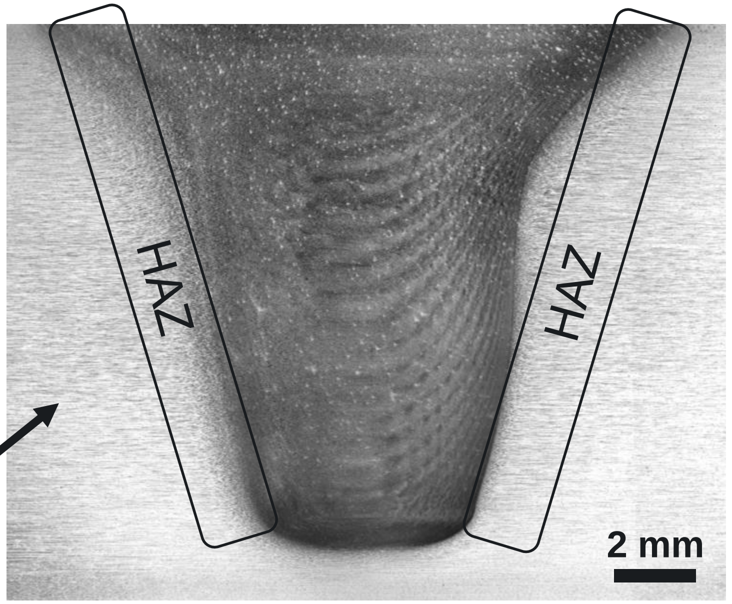
- Trail water spray drastically reduces the tool shoulder temperature

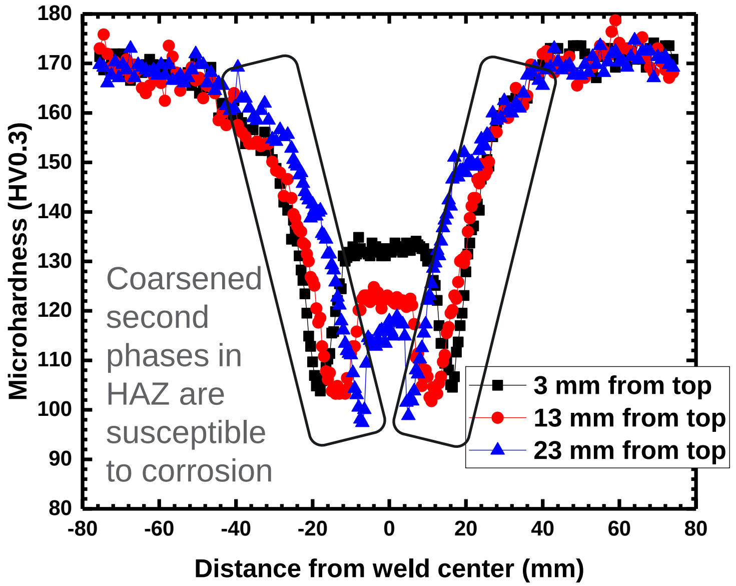
Task 1: FSW Process Development- Joint Strength

Thermal Boundary Condtion	Temp.	UTS	0.2% YS
Welding speed: 6 inches per minute	ºC	MPa	MPa
In air welding with steel backing plate	495	427 ± 7	284 ± 5
Trail water Spray with steel backing plate	460	494 ± .5	323 ± 10
In air welding with Composite backing plate	500	434 ± 7	309 ± 3
Trail water spray with Composite backing plate	450	495 ± 1	338 ± 2

- Both 0.2% YS (13-19%) and UTS (13-18%) was significantly improved with trail water spray welding
- Composite backing vs steel plate improve the YS (9%), however have minimum effect on UTS

HAZ is Susceptible to Corrosion in Seawater





Simulated seawater corrosion testing per ASTM G31-12a and D1141-98

Cold Spray Barrier for Improved Corrosion Resistance

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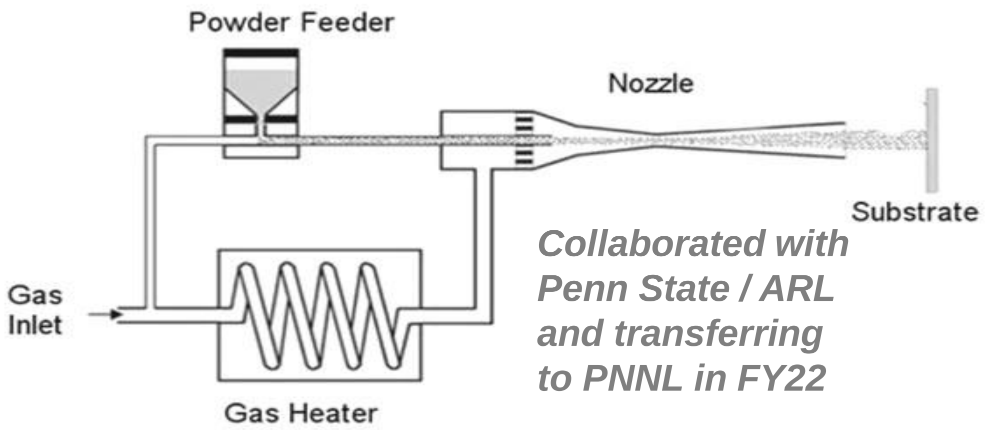
Solid Phase PROCESSING

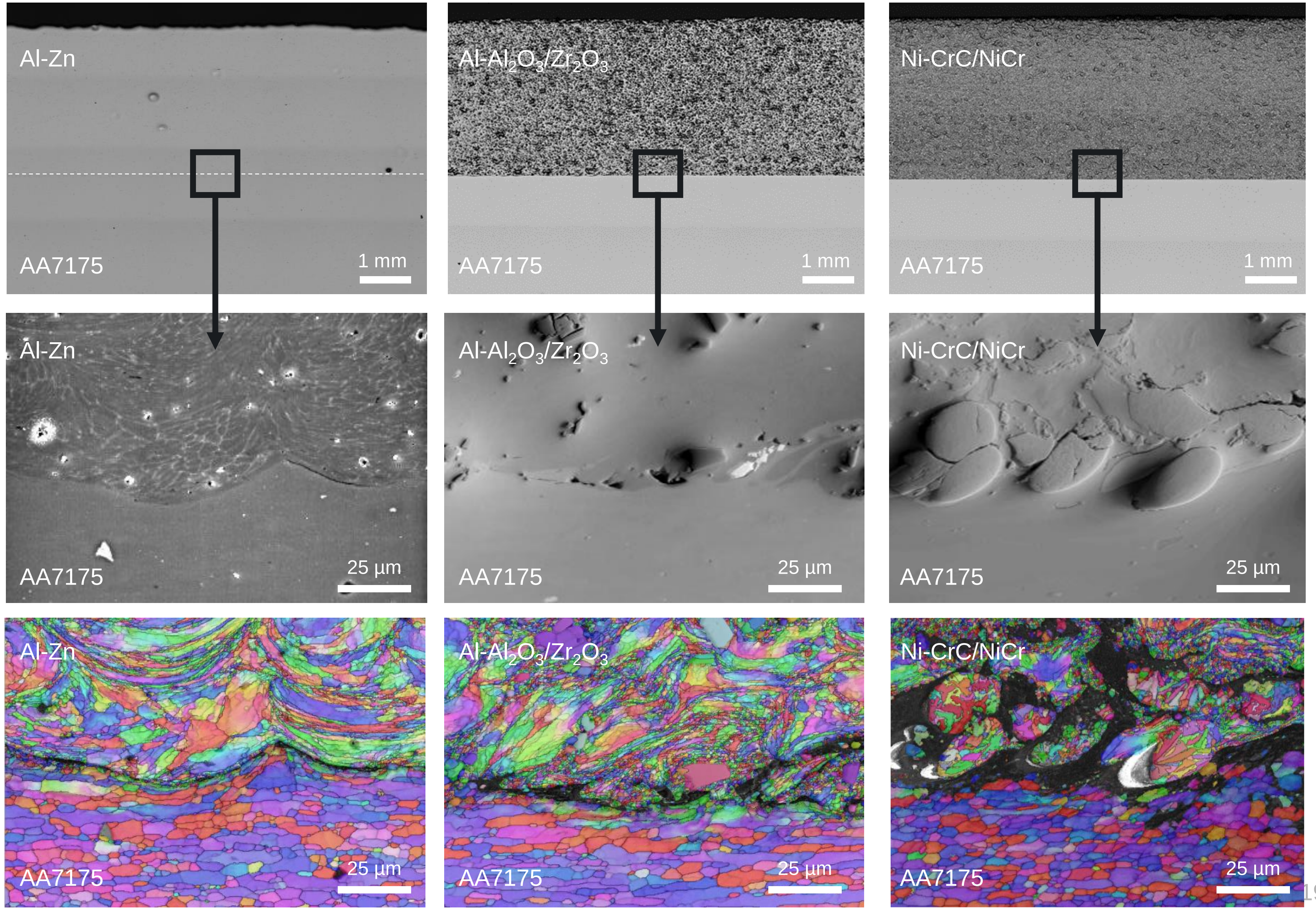
Cold spray over surface of friction stir weld



Collaborated with Penn State / ARL and transferring to PNNL in FY22

- Commercial process
- Coat weld region
- Augment anodic protection
- Performance evaluation
  - Corrosion
  - Adhesion
  - Wear

Al-Zn	$Al\text{-}Al_2O_3/Zr_2O_3$	Ni-CrC/NiCr



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Cold Spray Barrier for Improved Corrosion Resistance

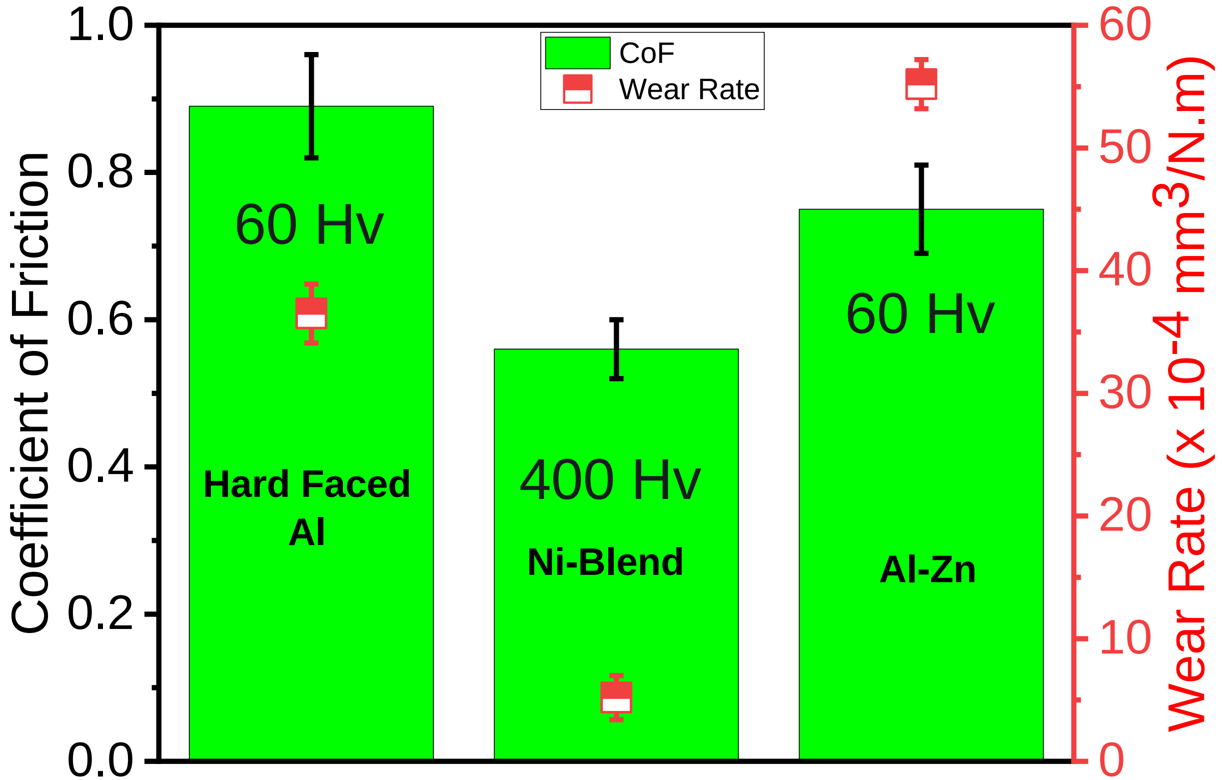
Solid Phase PROCESSING

Al-Zn is anodic to 7175

$Al\text{-}Al_2O_3/Zr_2O_3$ is cathodic to 7175

Ni-CrC/NiCr is cathodic to 7175

Oscillating sliding wear tests



Ni-CrC/NiCr had lowest wear rate by far

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Task 4: Fabricate Full Size Riser Sections

Solid Phase PROCESSING

First unit on display at OTC in May 2019

Second unit shipped to PNNL Apr 2020

Xymat Engineering is engaged with industry to identify opportunities for field demonstration

Conclusion

- Moving to better and better mechanical performance (WSRF) through development of tool designs, process and now, thermal boundary control

- Trailing water spray and composite material anvils can improve tensile properties by almost 20%

- Cold Spray coatings are being developed to produce robust, metallic coatings to protect the weld zone from galvanic attack in the marine environment and mechanical damage during installation and operations

- Application space is being broadened through discussion with industrial stakeholders

  - Potential other applications for ultra high-strength aluminum
    - Marine structural members, lightweighting offshore platforms in general (H_2 production, offshore wind)
    - High strength aluminum pipeline systems for high H_2-natural gas transmission or H_2 transmission and distribution (Embrittlement resistant)

Thank you

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