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Application of Solid Phase Processing for Infrastructure Repair and Life Extension

Solid Phase PROCESSING

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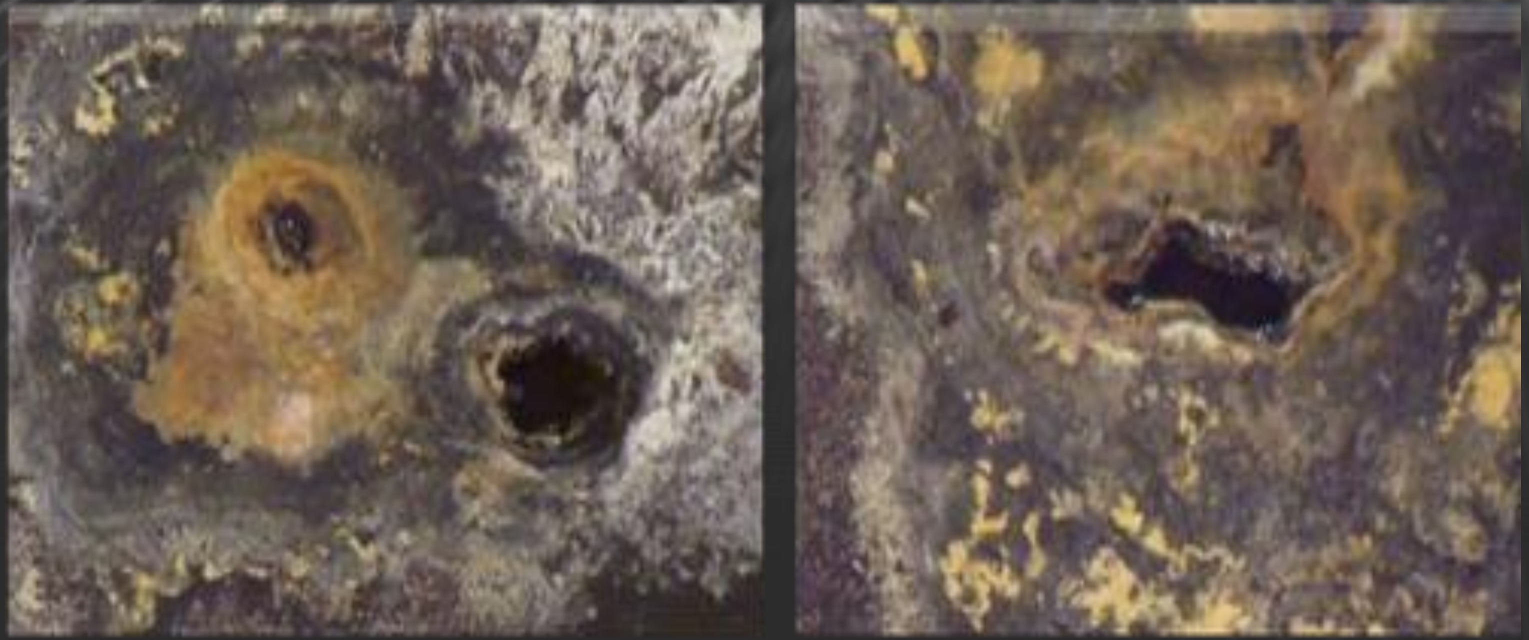

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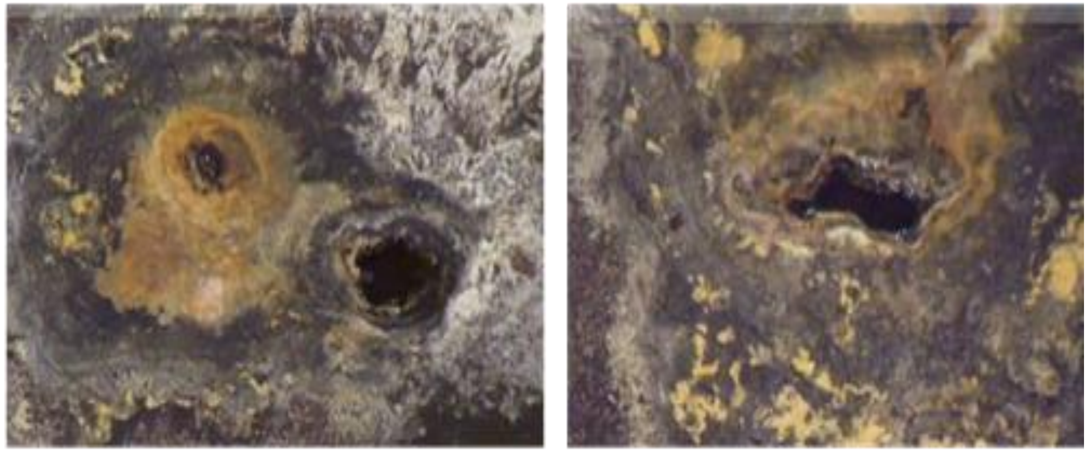
Background/Need

- DOE infrastructure for waste storage and processing (e.g., waste tanks, transfer pipelines, evaporators) in service well beyond original design life
  - Components with 20- to 50-year design lives in service for 55 to 70 years
- Corrosion pitting and wall thinning detected in existing DSTs
  - Corrosion control insufficient (e.g., AY-102)
- Need for repair method(s)
  - Mission life 30 to 50 more years
  - Restore wall thickness and mitigate leaks
  - Extend DST life to avoid new construction
- Develop remote repair system to extend life
  - Use existing commercial equipment/techniques
  - Adapt to limited space environment
    - ✓ < 30 in. to accommodate annulus space of DSTs



Example images of AY-102 primary tank bottom

WRPS Tank Repair Initiative

- WRPS has undertaken an initiative to evaluate tank repair alternatives
  - Developed initial list of technologies based on:
    - ✓ Responses to an Expression of Interest
    - ✓ Unsolicited proposals from vendors
  - Additional technologies identified
  - Preparing a feasibility study for tank repair
    - ✓ Technology writeups
    - ✓ Identify types of repair needed
    - ✓ Evaluation criteria
    - ✓ Recommendations for tank repair technologies
- Report to be released mid-FY 2020
- Based on outcome, WRPS has discussed potential for demonstration in FY 2020

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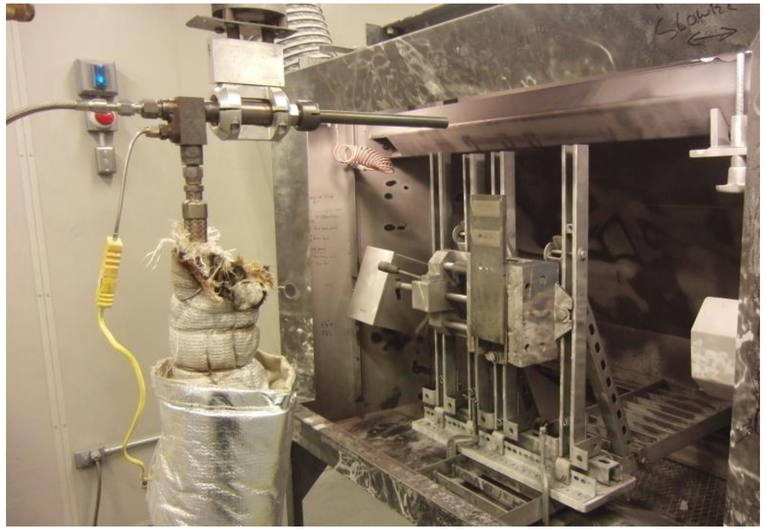
Solid Phase Processing Potential Repair Methods for DOE Infrastructure

- Solid phase processing (SPP) is the application of a high strain during material processing and repair to produce high-performance microstructures in metal materials without melting the constitutive materials
- SPP technologies identified as candidates for life extension of aging infrastructure
- Specific processes and applications
  - Friction stir welding/processing (FSW/FSP)
    - ✓ Stress corrosion cracking (SCC) mitigation and repair
    - ✓ Applications for packaging / dry storage of spent fuel
  - Cold spray
    - ✓ Corrosion repair
    - ✓ Cavitation repair

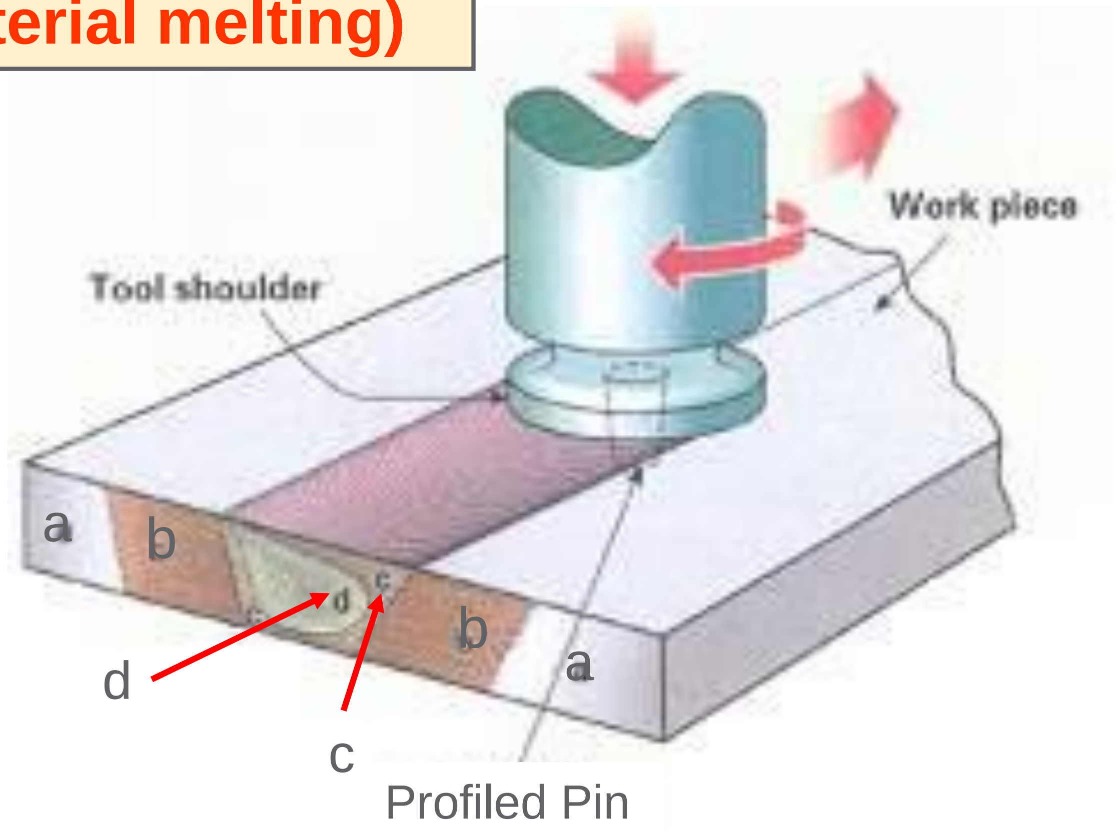


Solid Phase PROCESSING

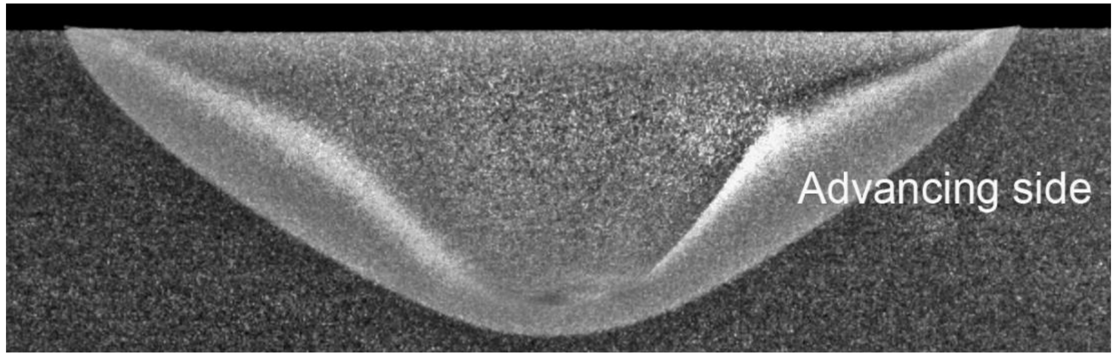
Friction Stir Processing / Friction Stir Welding

Solid-phase joining processes (no material melting)

- Spinning, non-consumable tool is plunged into surface of material
- Friction and plastic work energy heats material sufficiently to lower flow stress
- When material softens, the tool is then translated along the joint line, causing material in front of the pin to be deformed around to the back, and forged into the gap behind the traveling pin
- The resulting joint is characterized by:
  - Fine-grained "nugget" composed of recrystallized grains (d)
  - Surrounded by mechanically deformed region (c) and heat affected zone (HAZ) (b)



FSW was invented and patented by TWI, Ltd. in 1991

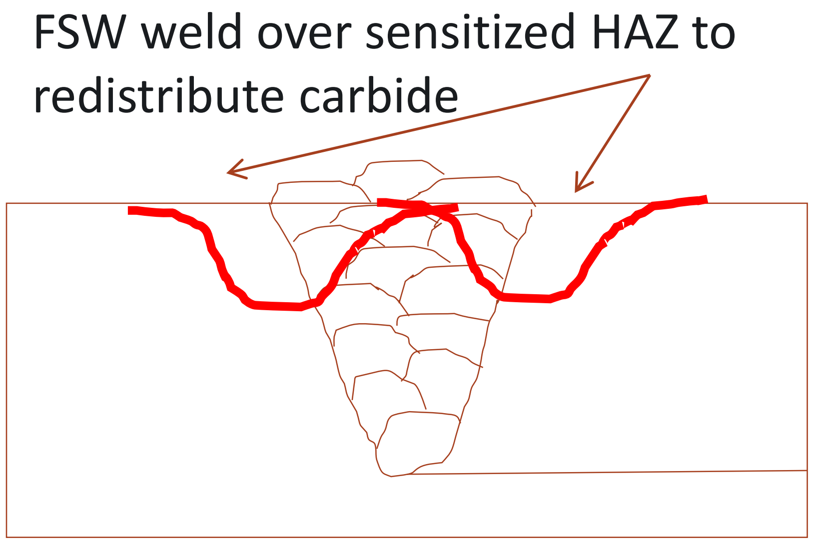


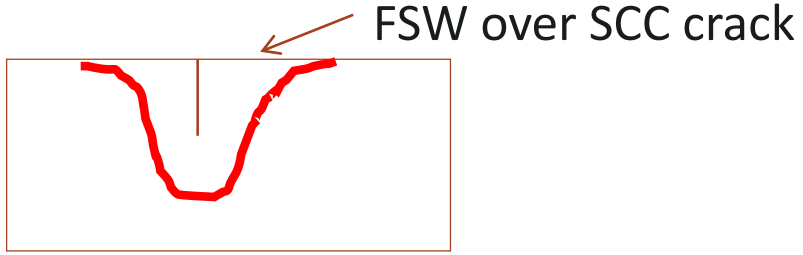
Typical macrostructure of fully consolidated, defect-free steel FSW weld in Gr 91

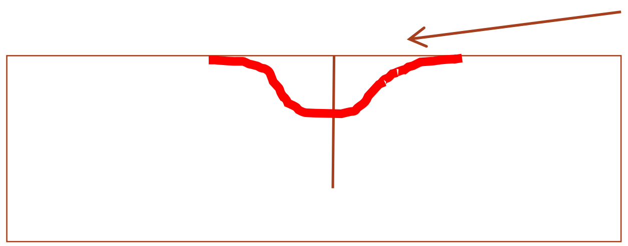
Tools for steels

FSW for Repair and Prevention of SCC Damage

- FSP/FSW used to remediate existing weld degradation
  - FSW can reset sensitized microstructure by FSP over HAZ
  - Redistribute Cr into ultrafine grained material
    - ✓ Restore and possibly improve corrosion resistance relative to base material
  - Produce less-degraded new HAZ
- Process can weld range of materials and alloys
  - Join dissimilar materials
- Tool improvements and process control continue to increase weld thickness
  - For most steels and nickel alloys, commercial tooling can reach thicknesses of 0.35 in. (9 mm) to 0.5 in. (13 mm)
  - Welds up to 1.1 in. (28 mm) single pass in API 5L X70 steels have been demonstrated
- FSW used to affect weld repair or heal SCC identified on surface of in-service canister



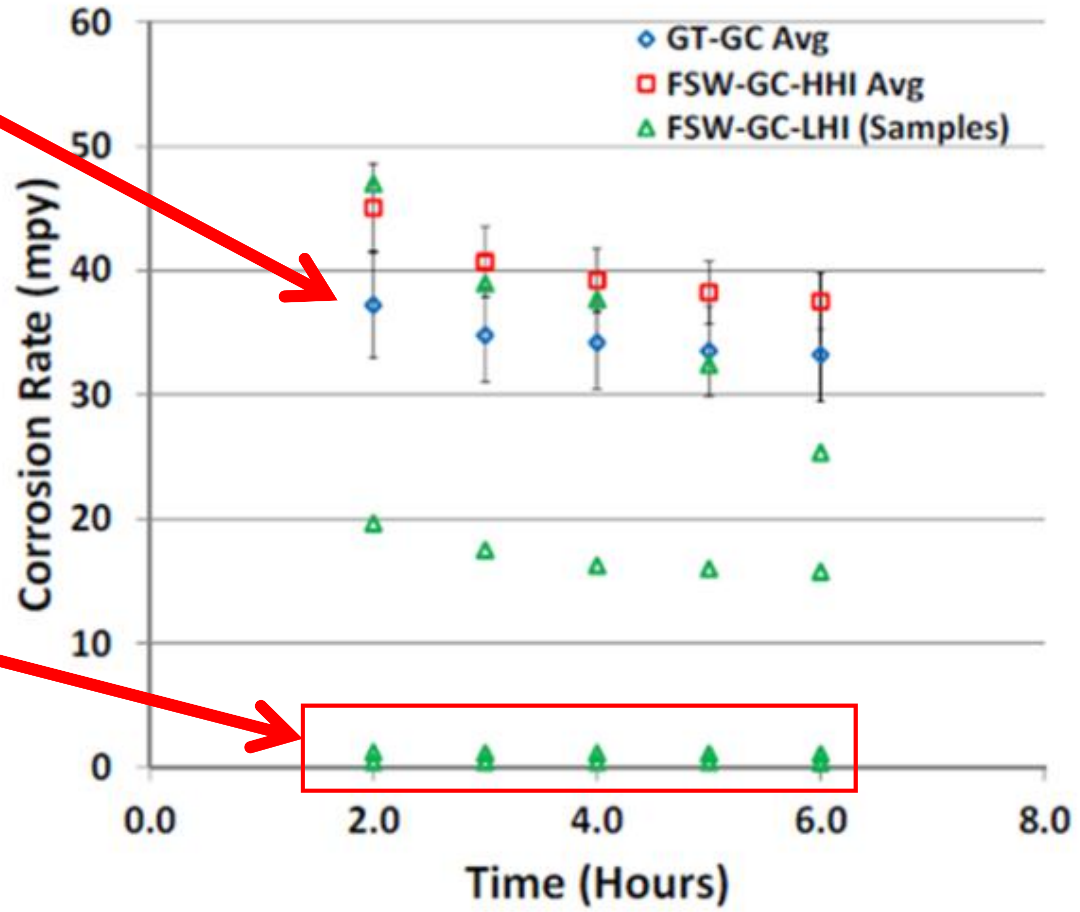




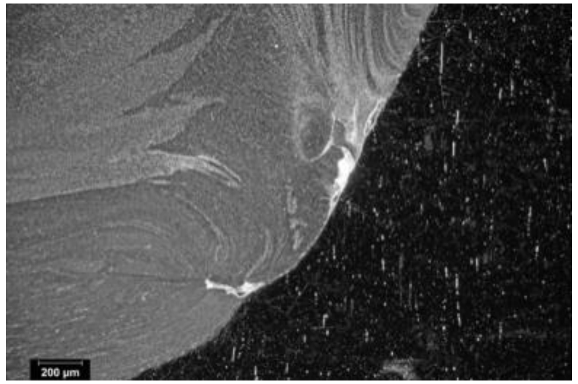
Corrosion Comparison Conducted between Friction Stir Welds and Fusion Welds

Gas tungsten arc weld

Low-temperature FSW weld (<780ºC)



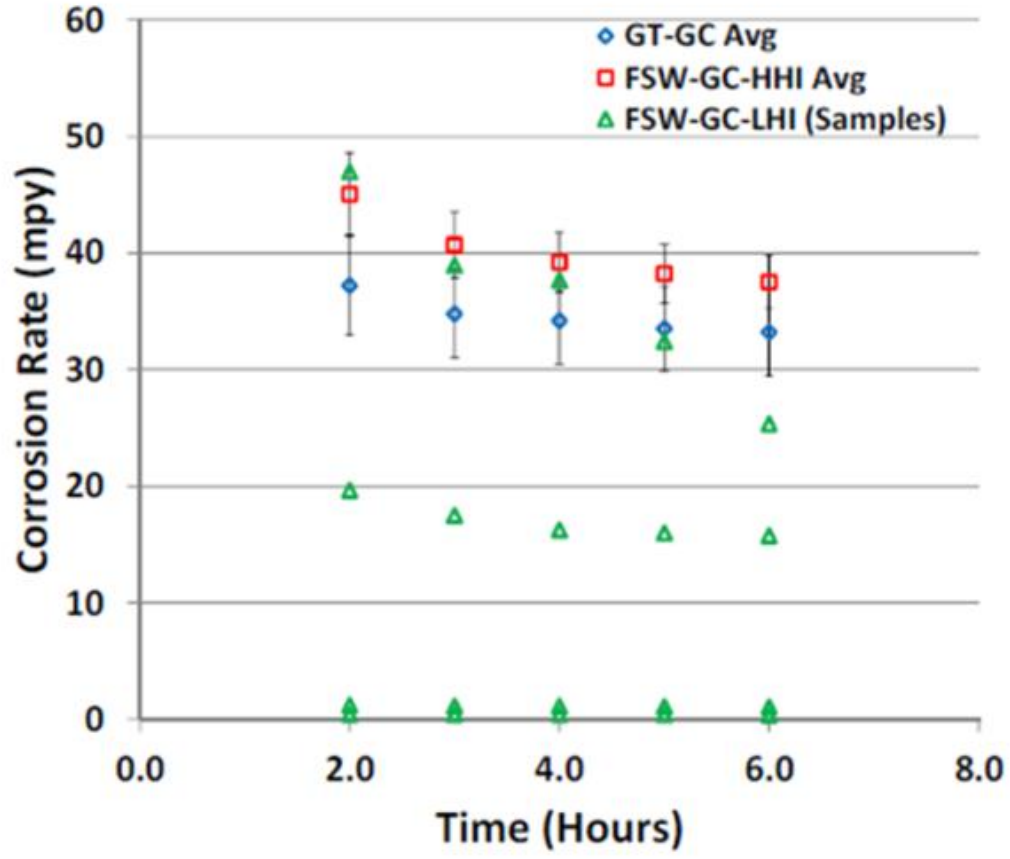
Controlled, low-heat-input welds produce joints with low levels of carbide grain boundary precipitation



Corrosion testing conducted at Savannah River National Laboratory. WM2015 Paper No. 15025, *Demonstration of Friction Stir Welding Technology for Packaging of Used Nuclear Fuel*

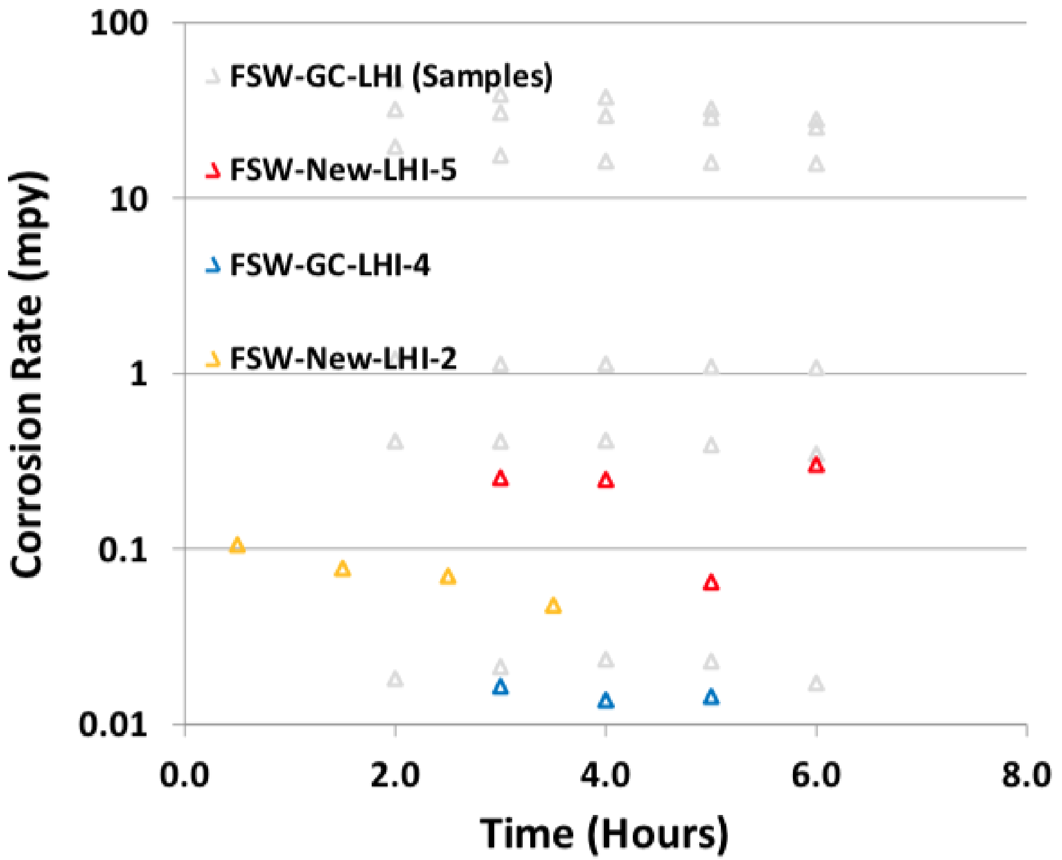
Significant Reduction in Localized Corrosion for Low Heat Input (LHI) Friction Stir Welds

- Low weld temperatures (tool temps <780°C) were found to produce dramatic **decrease** in generalized and localized (pitting) corrosion rate during electrochemical testing [cyclic potentiodynamic polarization (CPP) and linear polarization resistance (LPR) scans] when compared to fusion welds



Initial comparative corrosion tests with LHI FSW samples having no temperature control

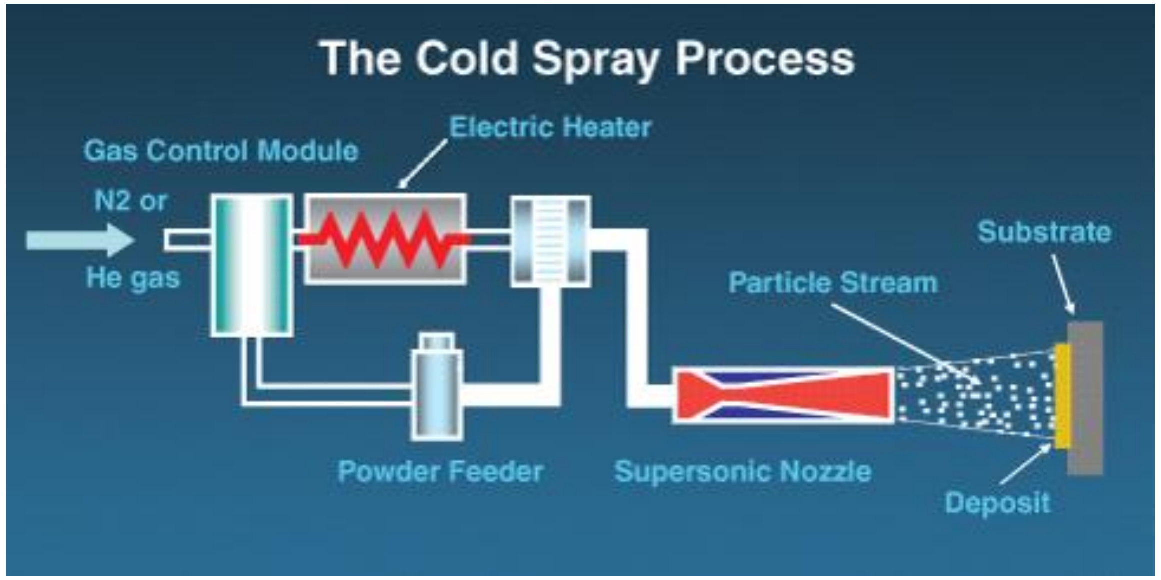
For temp <780ºC FSW achieved corrosion rates 1/640 that of GTAW



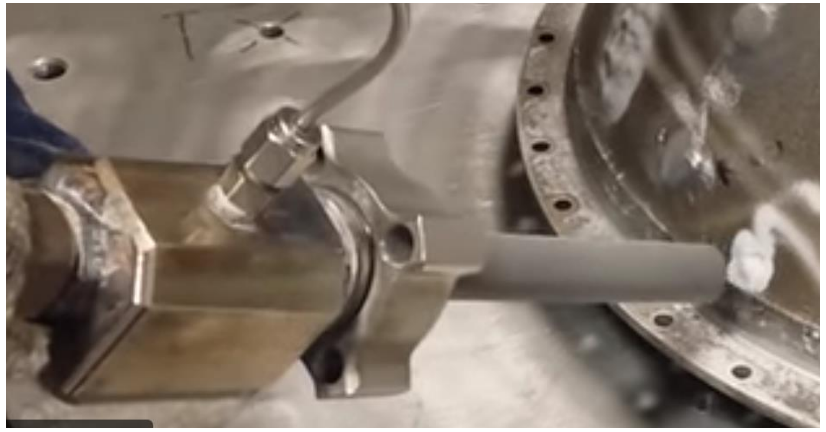
Follow-on corrosion tests with temperature control for LHI FSW samples

Cold Spray Process

- Commercial high-rate metal deposition process where metal powders (~5- to 45-µm particles) are combined with hot gas, accelerated to high velocity (Mach 1-4), and deposited on repair area to build up thickness
  - Fully dense deposit
  - Low thermal input to substrate
    - ✓ No detrimental HAZ
  - No limit on thickness, fully machinable repair
  - Applicable for dissimilar materials
  - Relatively high deposition rate (up to ~350 g/min)
  - Portable – lends itself to remote applications



- High-impact energy
  - Plastic deformation – metallurgical bond
  - Grain refinement (generally enhances material properties)
  - Compressive residual stress in region of deposit
  - Superior bond strength



Courtesy of VRC Systems

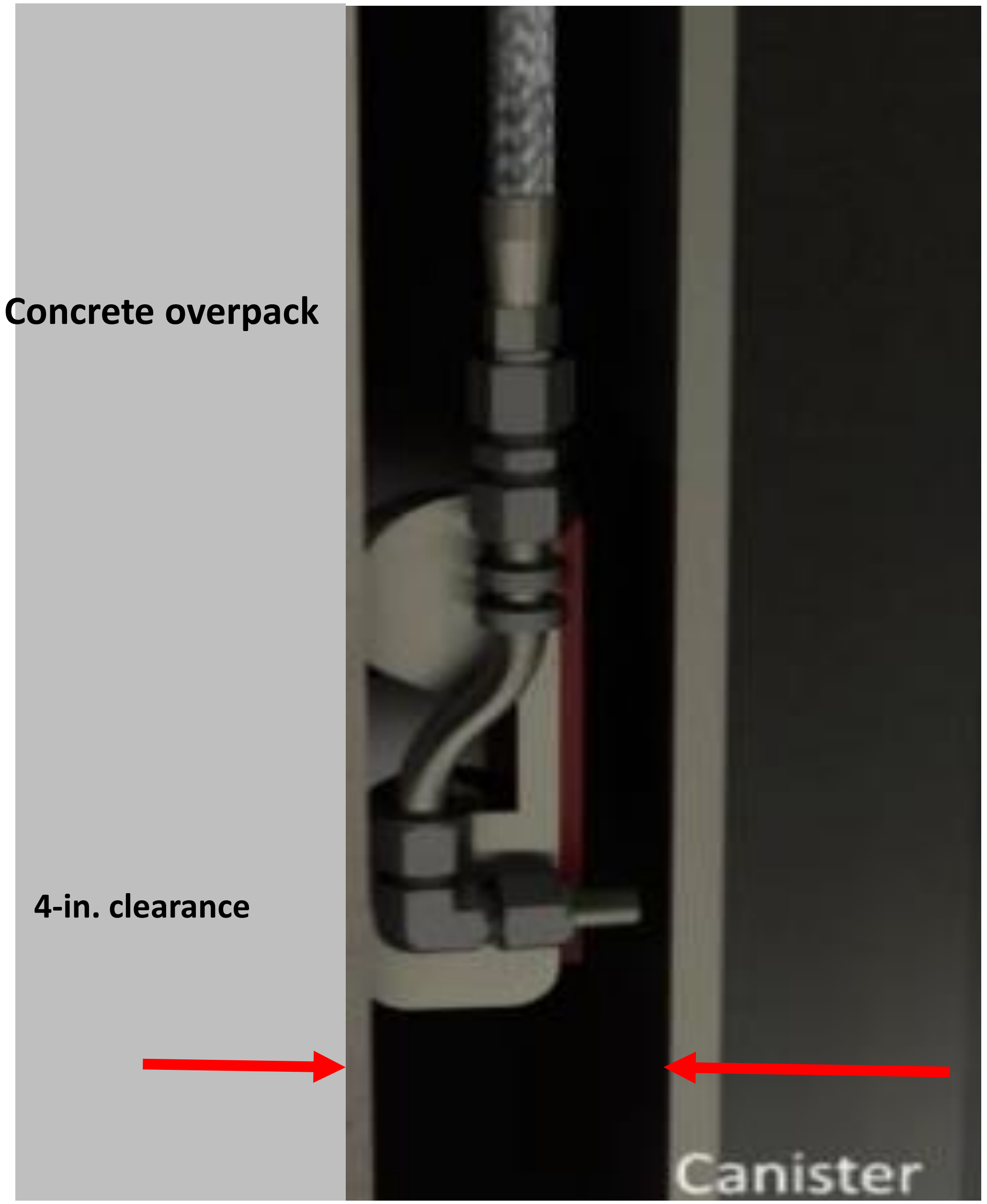
Current State of the Art – Cold Spray Repair

Repair capabilities of cold spray technology

Cold spray repair has been commercialized in DoD, commercial aircraft, and automotive applications, including corrosion through-hole repair

Image credits to Moog

Cold Spray Applications in Limited Access Spaces



- Magnetic robotic crawlers with cold spray heads have been designed and tested for repair of dry storage containers for commercial spent nuclear fuel
- Small Business Innovation Research (SBIR) Project demonstrated the feasibility of in situ repair on mockup dry storage containers
  - VRC Metal Systems, LLC, under DOE SBIR contract No. DE-SC0017855

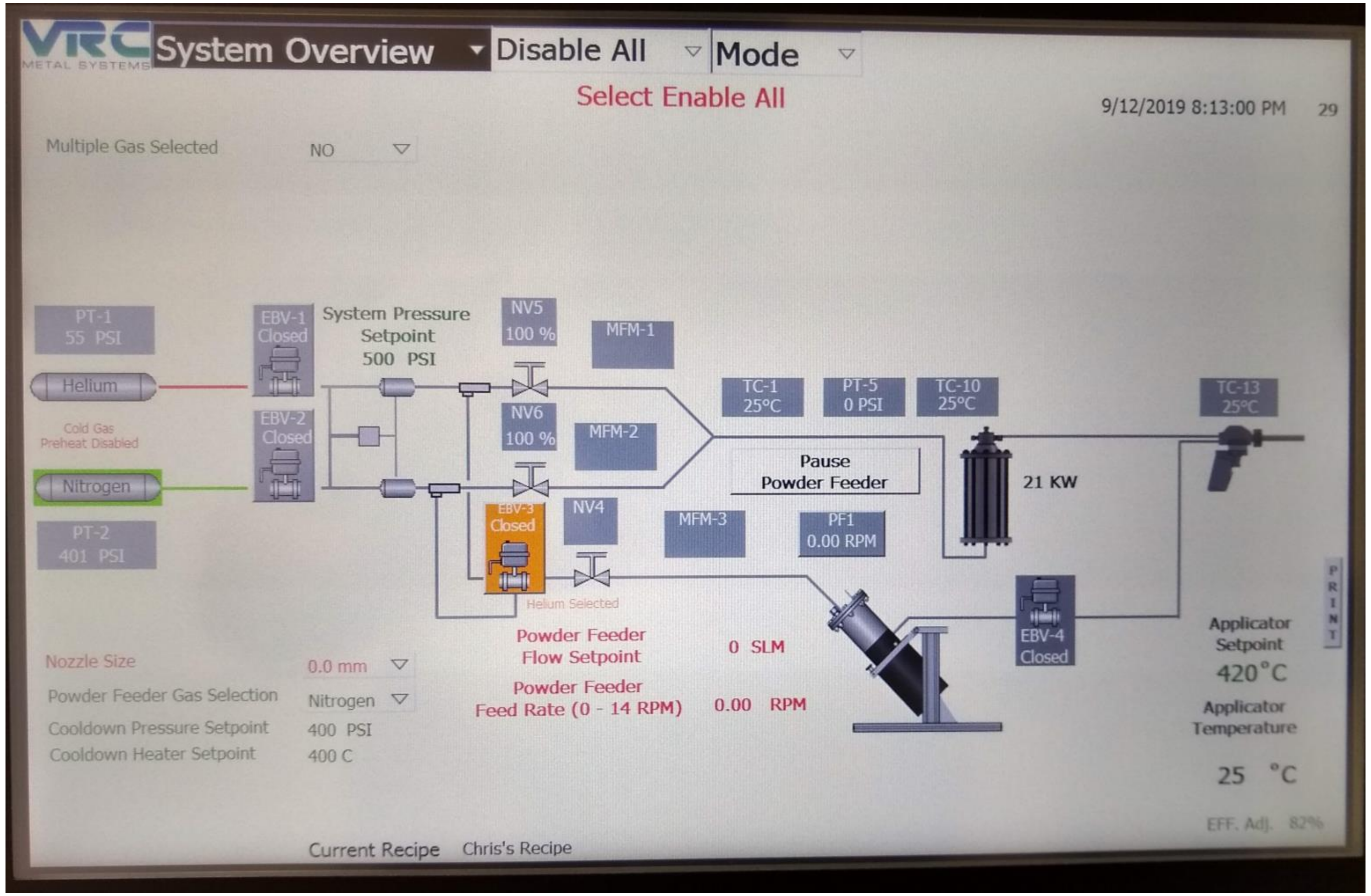
Spray equipment is small enough to deploy through maintenance or service hatches as small as 6 inches

Scope/Objectives for Go/No-Go Assessment of Cold Spray Technology for Tank Repair

- Conduct go/no-go evaluation to:
  - Determine at least one set of operating conditions and parameters for depositing buildup of mild steel on mild-steel substrate, which isn't commercially done
    - ✓ Conservative for corrosion
  - Explore process parameter space based on soundness of metallurgic bonding and minimization of volumetric defects using metrics of material (i.e., deposit) density and consistency from micrograph imaging
    - ✓ Material bonding and deposit density for creating thickened layer – not for structural integrity
    - ✓ Deposit created for corrosion resistance and hermetic seal
  - Demonstrate, in concept, repair by producing dense deposit of mild steel overtop or on backside of small-diameter flaw in 1/2-in. mild-steel plate
    - ✓ For steel plate surface in air environment – not addressing submerged surfaces
- Evaluation of go/no-go process to:
  - Use commercial equipment to form deposits
  - Determine operating conditions for non-commercial process (mild-steel powder on mild-steel substrate) within operating range of commercial equipment
  - Use commercially available mild-steel powder (may require conditioning of powder)

Cold Spray Setup and Process Parameters

- Metal powder
  - Material
  - Density
  - Particle size and shape
  - Particle size distribution
  - Hardness
- Cold spray process input parameters
  - Carrier gas (He or N_2)*
  - Carrier gas temperature at entrance to nozzle*
  - Carrier gas pressure*
  - Powder feeder speed
  - Powder feed gas flow rate*
  - Cold spray gun orientation
  - Nozzle standoff distance

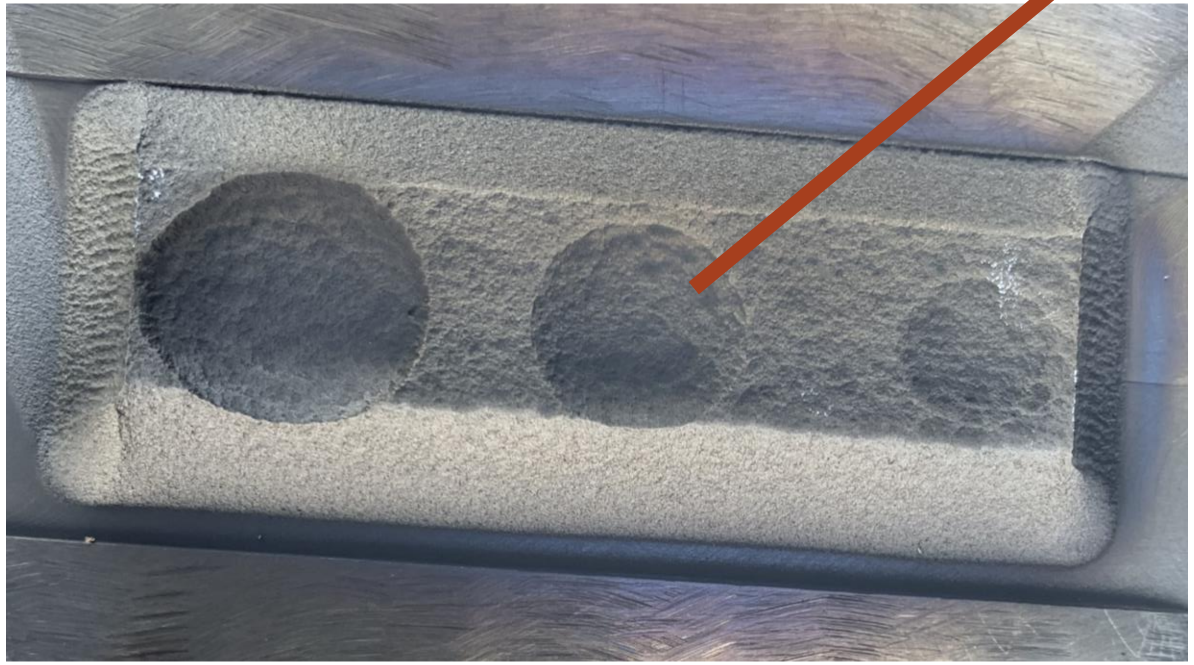


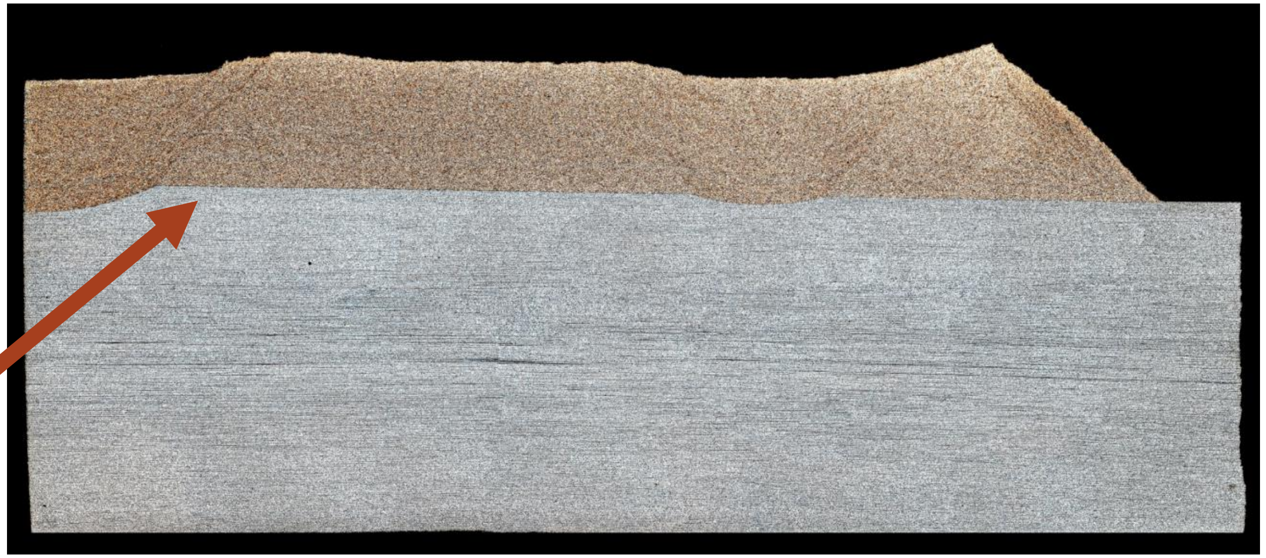
VRC Systems Cold Spray HMI

* Primary variables to be investigated in feasibility stage

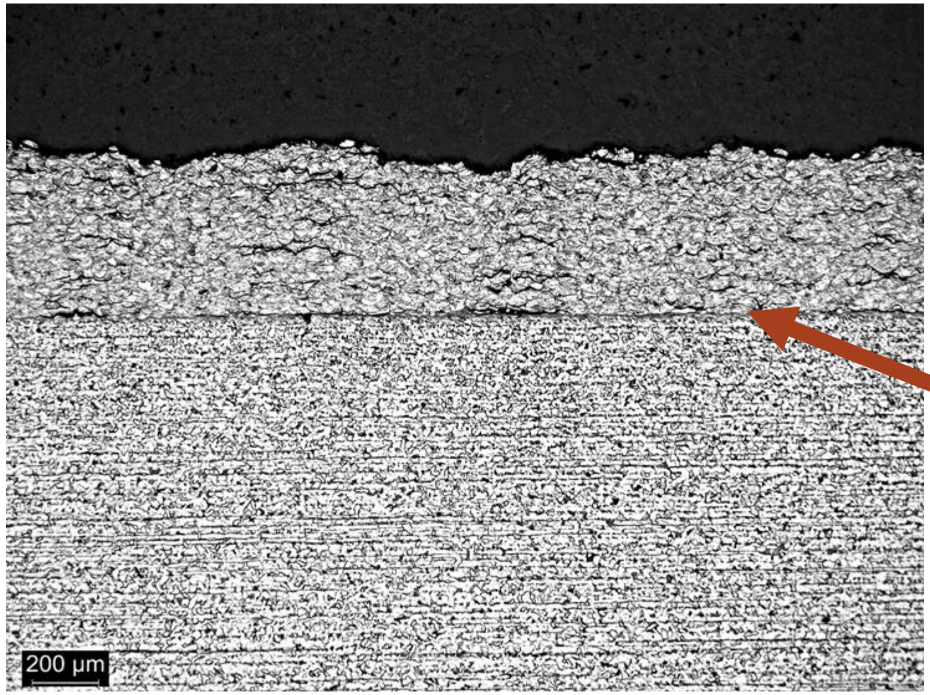
Results – Tank Repair Investigation

- Limit of analysis - surface quality, deposit thickness, porosity, and uniformity a function of operational parameters
  - Repeatability
  - Gas pressure
  - Gas temperature
  - Surface preparation
- Microanalysis of test coupons





Coupon 2.29: 700 psi, 500°C [~ 5-mm buildup]



Interface

Etched micrograph

Estimated Porosity Measurement Method

- Image obtained for mounted and polished (unetched) sectioned samples
- Image processing
  - Removed substrate material from image – bottom of processed image is deposit/substrate interface
  - Removed effects of surface roughness
- ImageJ calculates percentage of pixels below grayscale threshold

Original uncropped image of sample 1.8.3

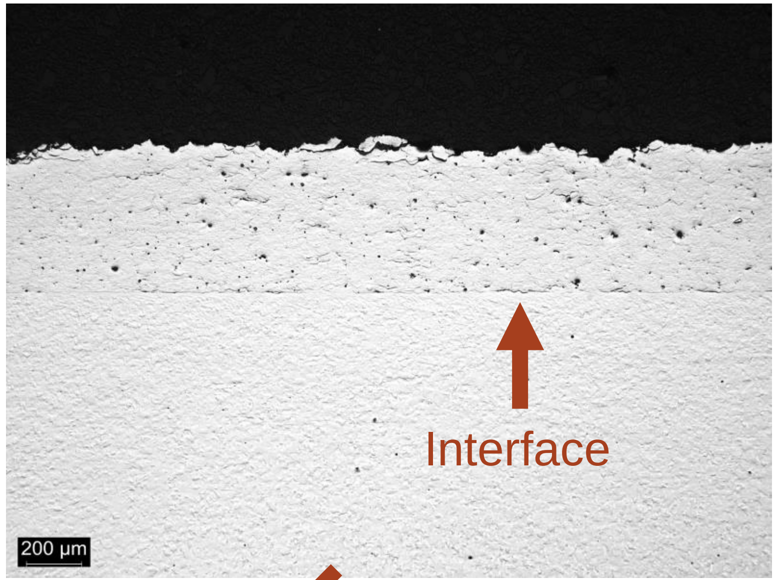
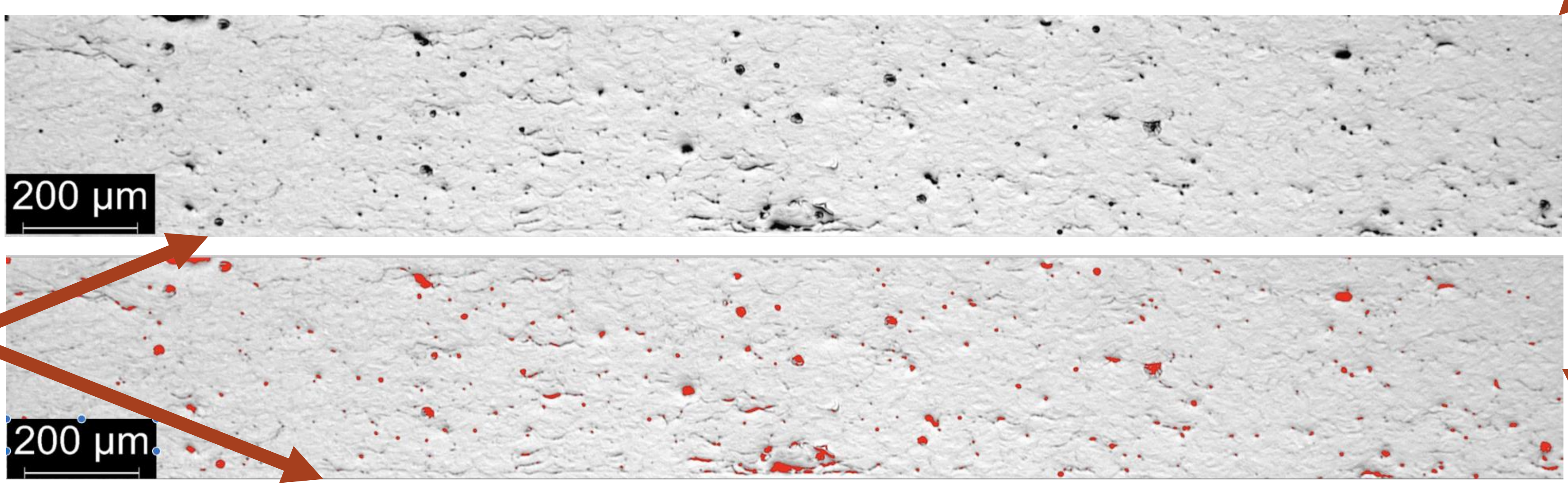


Image cropped



Interface

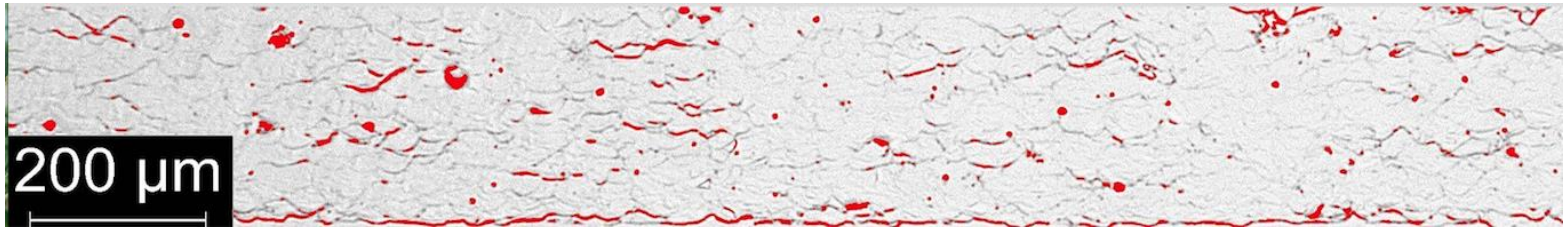
Image processing with ImageJ to color voids based on grayscale threshold and obtain estimated porosity

Sample 1.8.3, estimated porosity = 1.24%

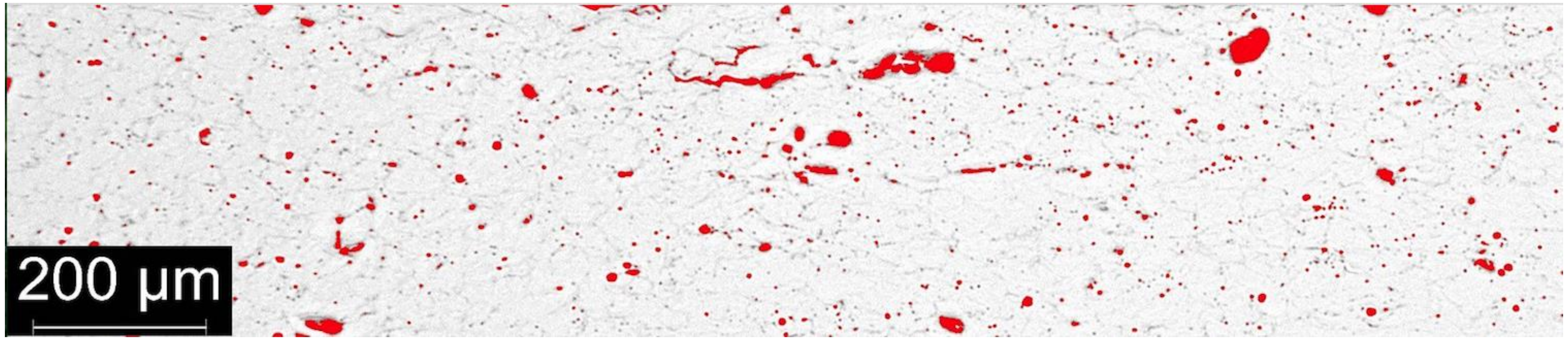
Impact of Surface Prep on Porosity

Change in surface prep in bold print Note: Sample images have been cropped for presentation

- Surface preparation impact initially observed in micrographs of coupons with machined flaws
  - Improved bonding appeared to exist at bottom of flaws compared to manually ground substrate surface



Sample 1.6.3: He, 500°C 435 psig, **Baseline manual grinding**, Est. porosity = 3.37%, Avg.= 3.14%

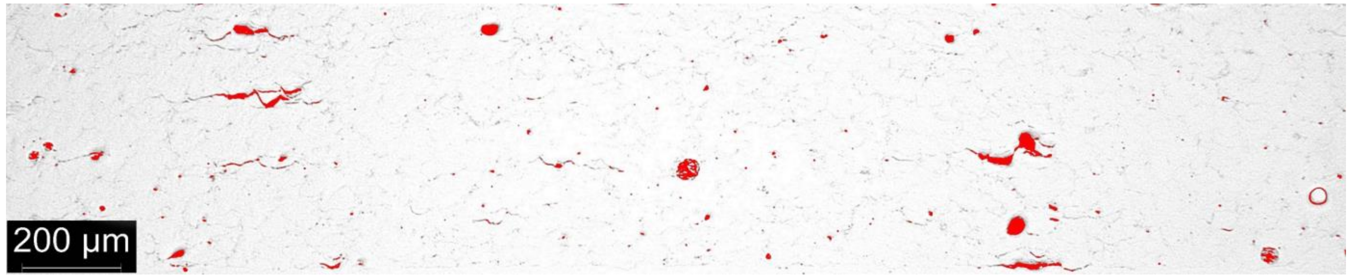


Sample 2.20.3: He, 500°C 435 psig, **Machined surface**, Est. porosity = 2.15%, Avg.= 2.28%

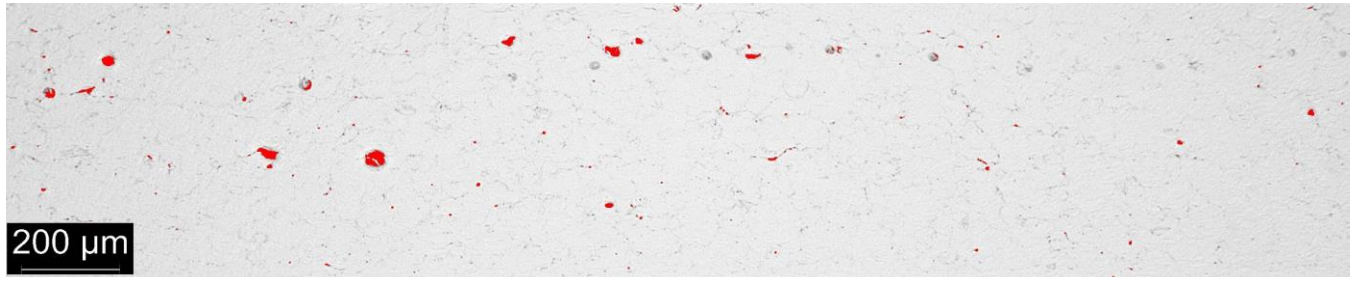
- Improvement with machined surface observed in porosity and bonding at interface for carrier gas pressures of 435 and 700 psig
- Machined surface applied only as test condition – not expected for deployed application
- Surface prep may be performed using sprayed powder at conditions not conducive to bonding

Impact of Surface Prep on Porosity

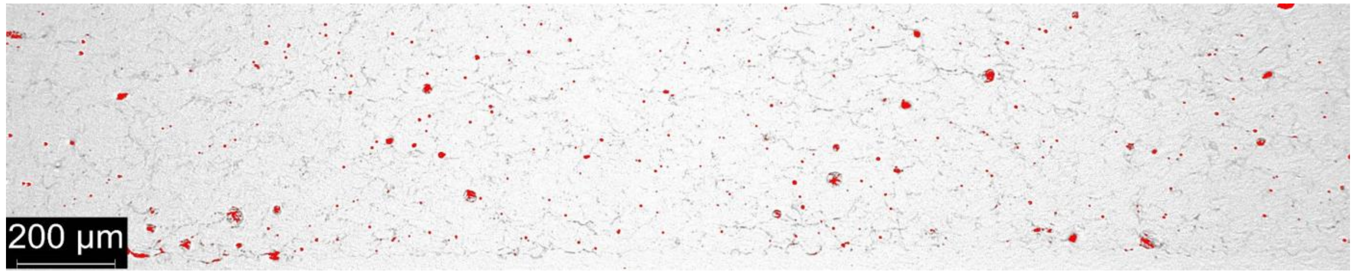
Change in surface prep in bold print



Sample 2.10.1: **Baseline manual grinding**, Est. porosity = 0.83%, Avg.= 0.94%

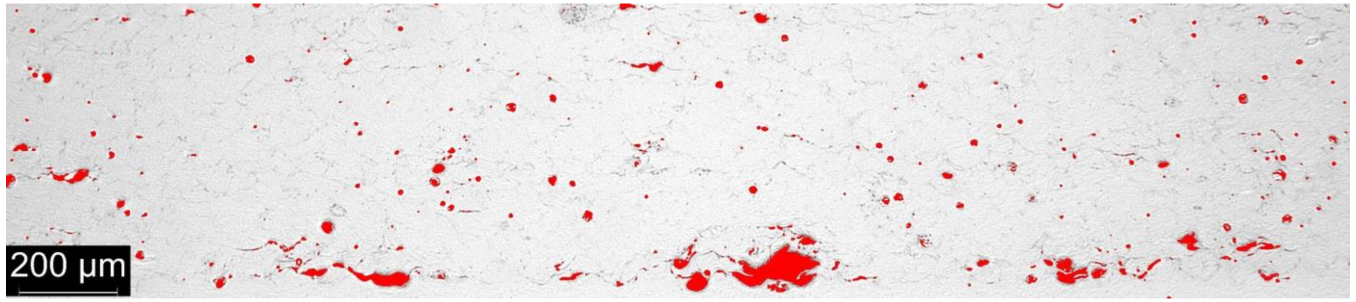


Sample 2.18.1: **Machined surface**, Est. porosity = 0.35%, Avg.= 0.34%



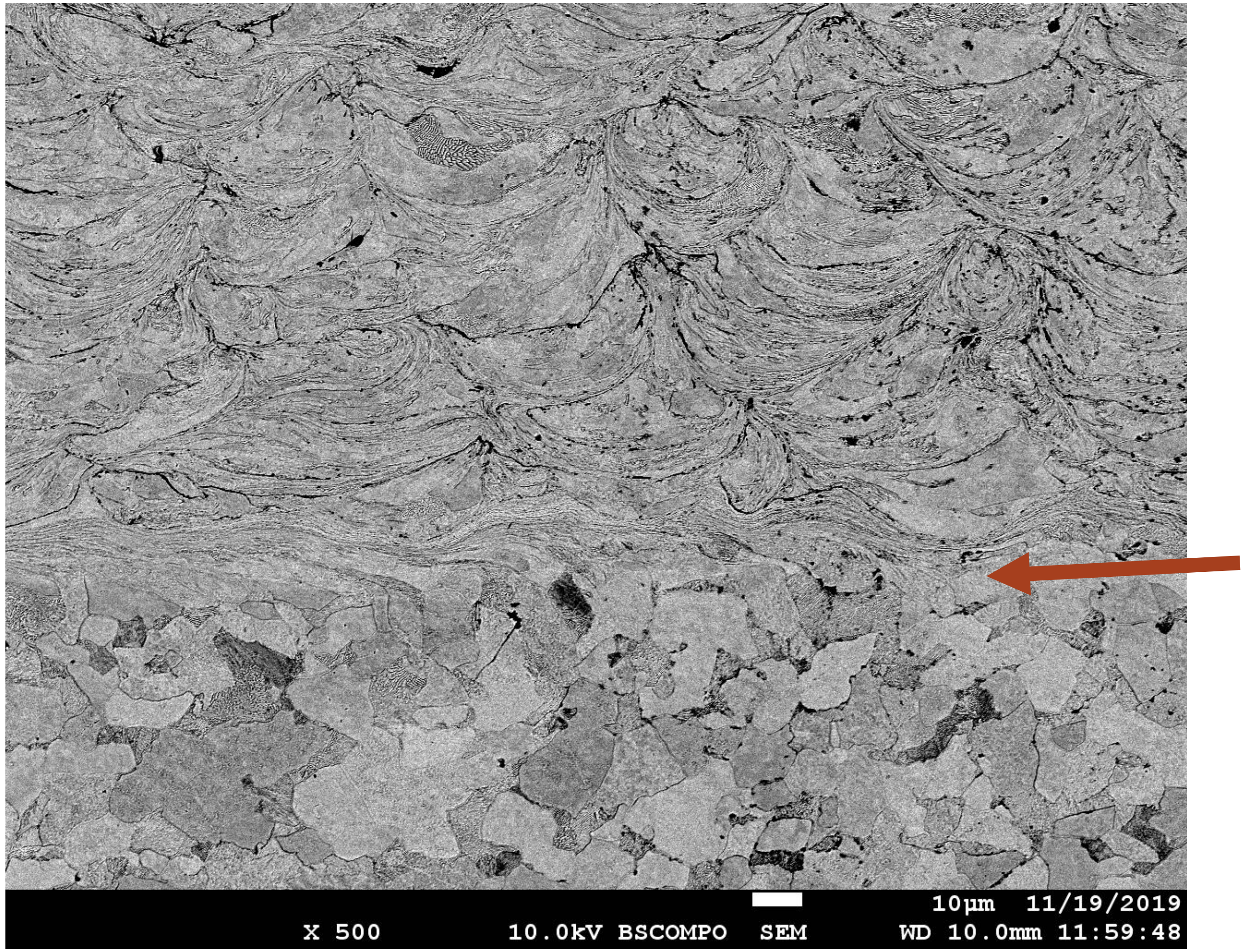
Sample 2.28.1: **Nitrogen/powder spray at 500ºC, 650 psig, nozzle 90º w/ substrate**, 2 passes, Est. porosity = 0.62%, Avg.= 0.64%

- He carrier gas at 500°C, 700 psig
- Results indicate surface prep important for best adhesion
- Machined surface yielded best performance based on interface with substrate and porosity
  - Marginal improvement over manual grinding (may be timing)
- Pre-cleaning with metal particle spray (process powder) can be benefit or detriment
  - N prep yields performance comparable to machined surface
  - He prep may contaminate surface with poorly bonded particles



Sample 2.26.1: **He/powder spray at 500ºC, 700 psig, nozzle 45º w/ substrate**, 2 passes, Est. porosity = 2.33%, Avg.= 3.05%

Scanning Electron Microscopy Analysis at Substrate/Deposit Interface



Sample 2.17: He, 700 psig, 500°C, Baseline surface prep

- Evidence of bonding
  - Substrate surface deformation observed
  - Substrate/deposit interface wavy in nature
- Cold spray splats (individual particles) rounded and moon shaped, as expected
- Microscopy shows features typical of high-quality deposits:
  - High plastic deformation
  - Low porosity
  - Dynamic recrystallization at inter-particle boundaries - good interparticle bonding

Summary of Cold Spray Go/No-Go Assessment

- Bonding of mild-steel powder to mild-steel substrate achieved
  - Best results achieved with He gas, temp = 500°C, and pressures of ~700 psig
    - ✓ Within range of existing commercial equipment
  - Flaw repair / material buildup demonstrated to ~5 mm (0.20 in.)
  - High-density (> 99%) / low-porosity (< 1%) deposits achieved uniform deposition without defects extending through deposits
- Surface preparation affects density and bonding/adhesion
  - Cold spray process equipment provides potential means for surface prep
- Corrosion work for FSP/FSW indicates low heat input and reduced grain structure can have significant reduction in corrosion potential
- Additional cold spray work indicates corrosion potential for bonded dissimilar materials with superior corrosion resistance significantly reduced for SPP applications
- Recommend corrosion testing be conducted for all potential candidate repair methods so results can provide guidance in determining process conditions for tank repair

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Questions