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Cold Spray Process Details and Nuclear Applications

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Workshop on Advanced Manufacturing Technologies for Nuclear Applications

Solid Phase PROCESSING

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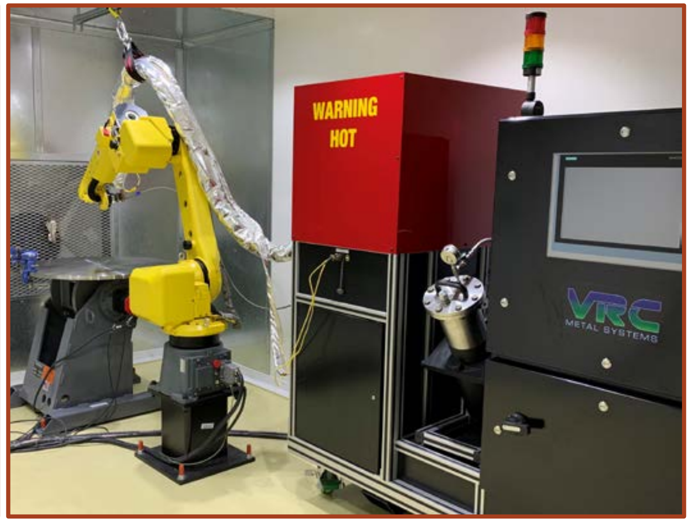
Solid Phase Processing…

Solid Phase
PROCESSING

Involves the application of a high shear strain during metals synthesis or fabrication, to produce high-performance microstructures in alloys, semi-finished products and engineered assemblies, ***without melting the constitutive materials.***

Friction Stir Processes

ShAPE™

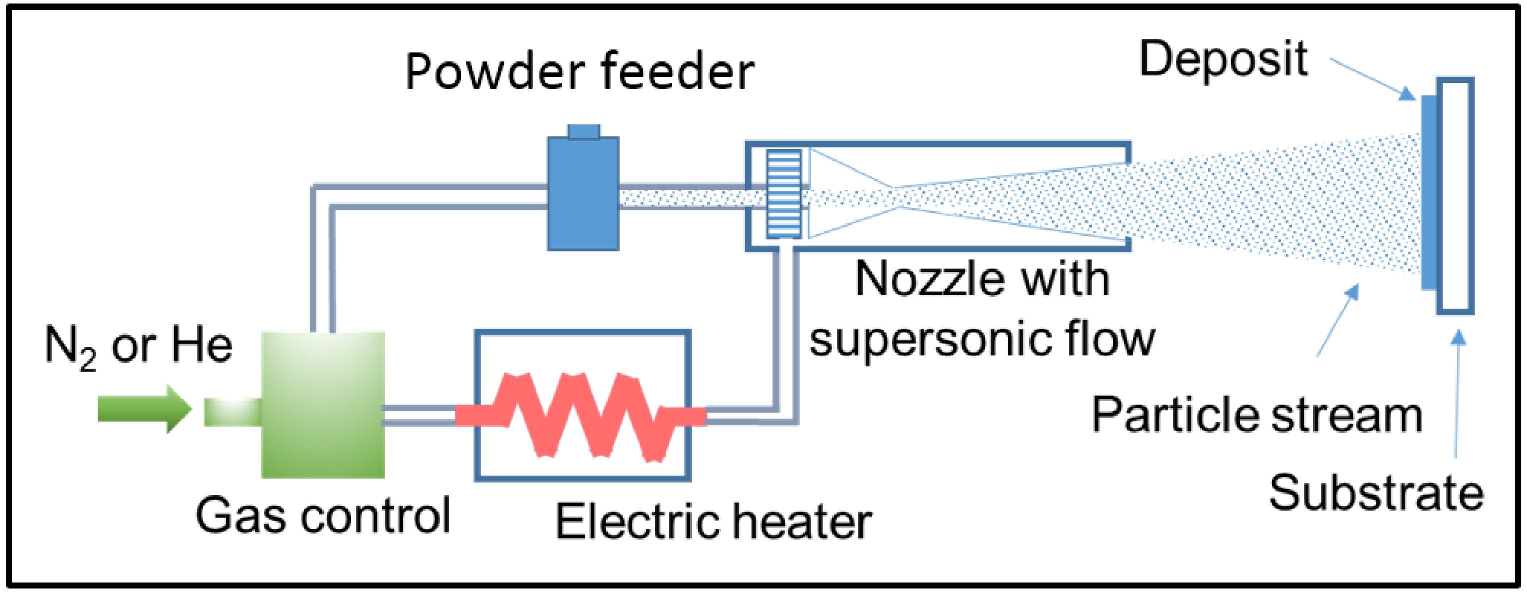


UHV Cold Spray

Solid Phase Processing Capabilities at PNNL

Cold Spray: Description

- <u>**High Pressure/velocity**</u> cold spray
- Solid phase deposition process
- Particles are propelled at Mach 1-4
- Typically particle size is 20 - 50µm
- Carrier gas is typically nitrogen or helium
- Impact energy causes extreme plastic deformation creates grain refinement and metallurgical bonds



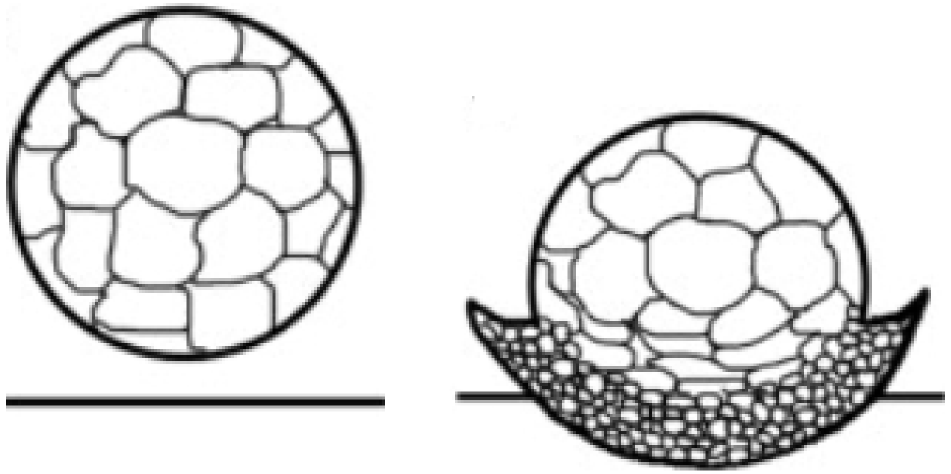
Substrate:	Stainless steel
Powder:	Inconel 625
Carrier Gas:	Helium
Deposition rate:	350g/min
Note:	

Arc welding is .25lbs/min =113.4 g/min

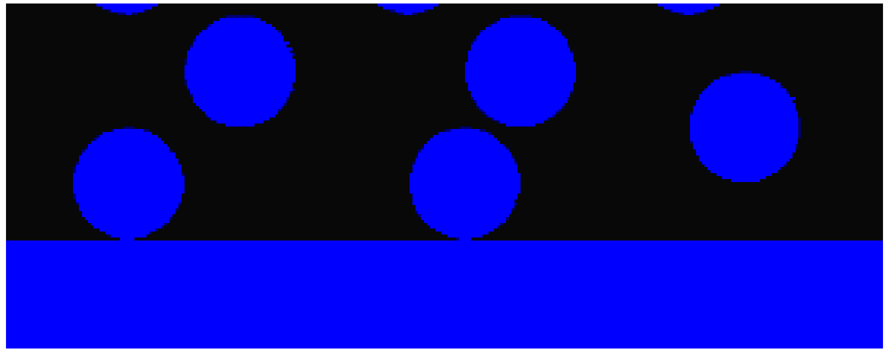
Video courtesy of Plasma Giken

Cold Spray: Process Details

- Extreme plastic deformation when particle impacts substrate
  - produces a highly refined grain structure
  - Energy of a single particle deformation is so low and happens so quickly that detrimental heat affected zones are avoided.
- As particles are deposited a mixtures areas of extreme to low plastic deformation develop



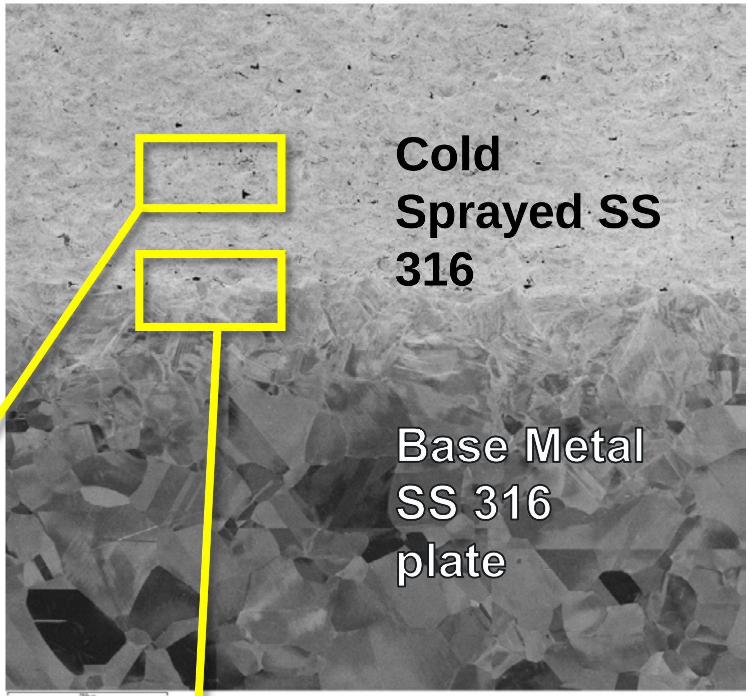
Grain structure of atomized particles prior to and immediately after impact
-courtesy of VRC Metal Systems

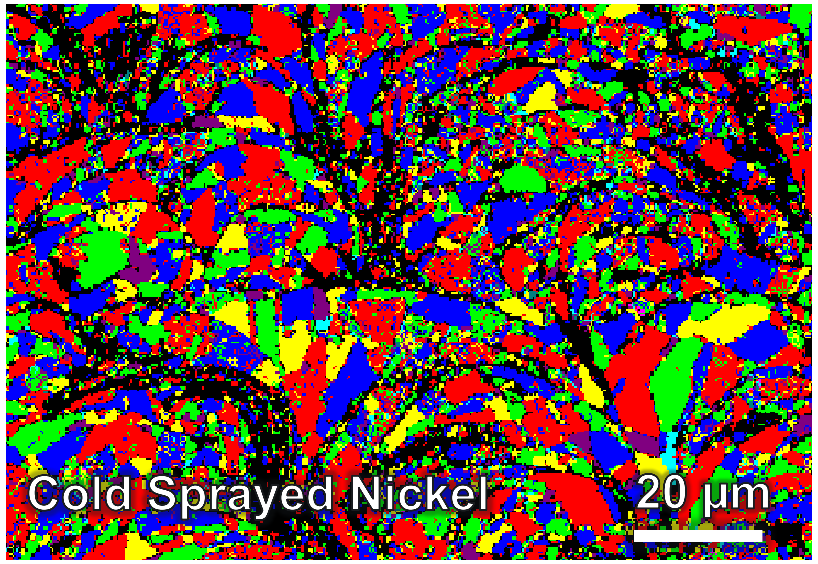


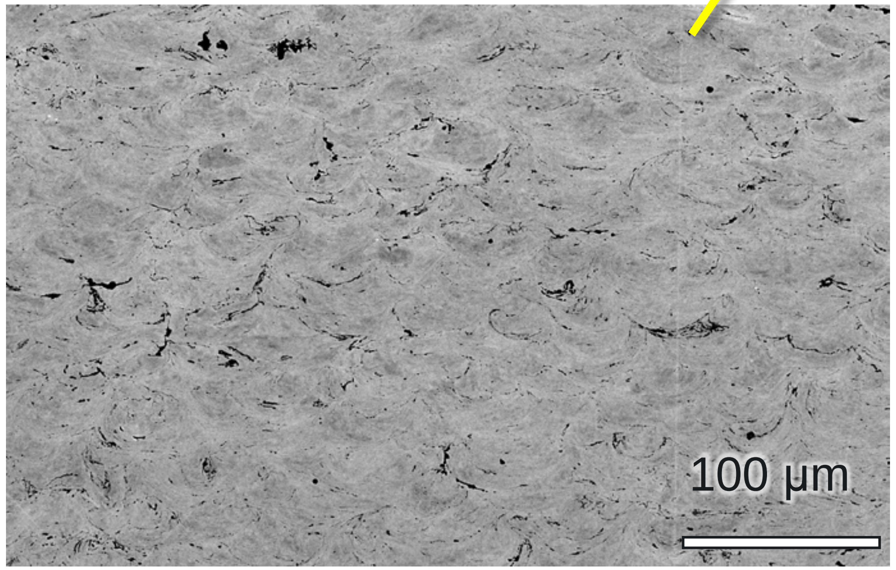
Video: Simulation of particle deformation during high velocity cold spray
-courtesy of VRC Metal Systems

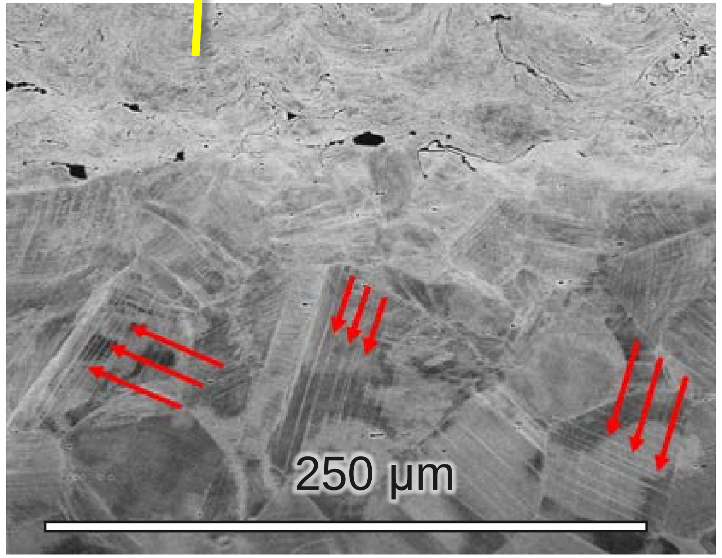
Cold Spray Microscopy

- No heat affected zone!
- Cold sprayed material is highly cold worked
  - Highly deformed with areas of dynamic recrystallization and nano-sized grains at particle interfaces
- Base metal near the cold sprayed interface is severely deformed, extensive slip lines are visible as indicated by arrows below.









What Makes Good Cold Spray

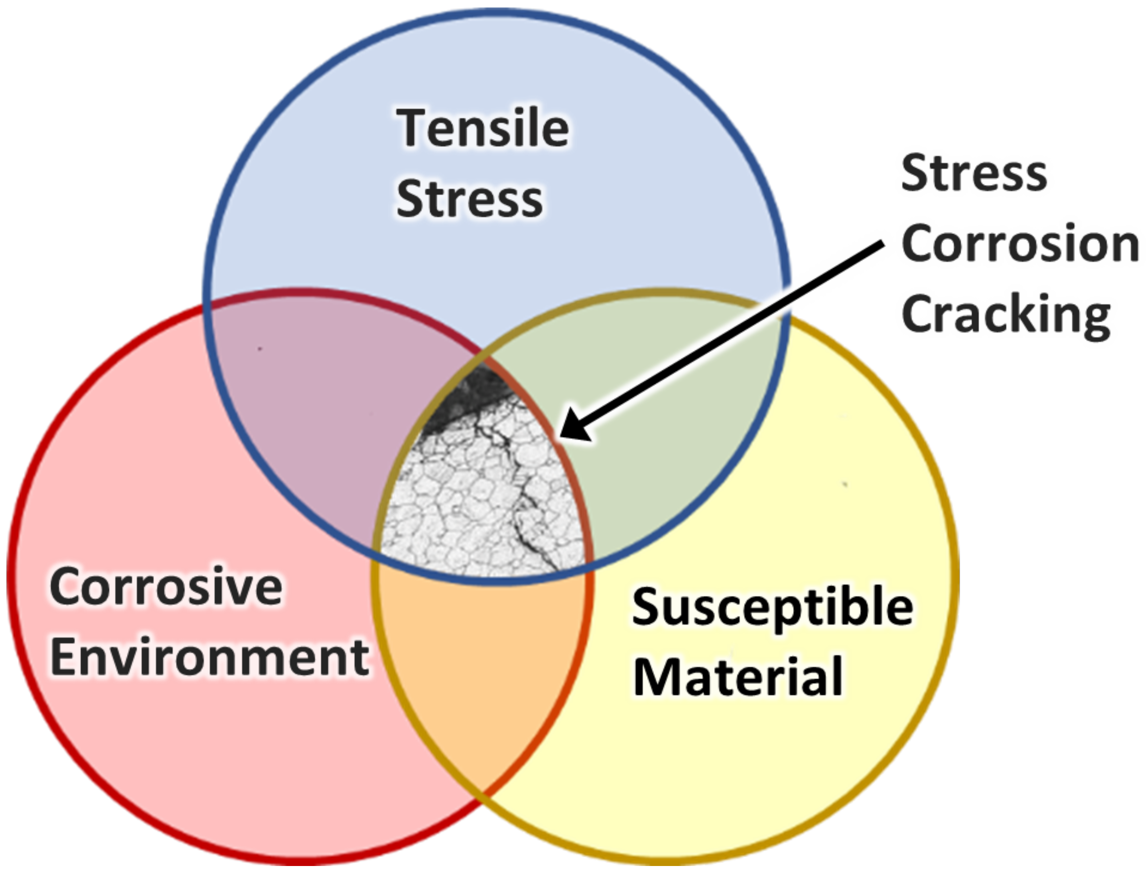
Best properties are typically achieved under the following conditions:

- A high-pressure/velocity cold spray system is used.
  - High pressure systems operate at pressures typically ranging from 300 to 1,000 PSI and typically produce particle velocities ranging from 800 to 1400 m/s
- Helium is used as the carrier gas.
- Surface preparation is done correctly.
- The correct material is selected for the application.
- Powder is processed correctly.
  - Sieving powder to remove fines.
  - Drying powder.

High-pressure cold spray coating of commercially pure nickel sprayed (left side) at PNNL

CISCC Mitigation and Repair

- The US DOE and NRC determined microstructural degradation and residual stresses produced by fusion welds in austenitic DCSS canisters put the fusion weld areas at high risk for CISCC.
- Cold spray provides a corrosion barrier and can produce compressive residual stresses in the coating and directly beneath
  - Removes two of the three conditions required for CISCC
- Applications
  - New canister with factory coatings over welds and HAZ
  - Repair and mitigation using portable cold spray equipment



Hanford Applications

Hanford Tank Farms

- Repairs needed to extend the life of corroding tanks
- PNNL executed an extensive repair process technology evaluation and down selection
- Cold spray scored highest
- PNNL successfully developed and demonstrated feasibility of cold spray as a repair process on laboratory coupons in relevant material system (mild steel)

Hanford Cs/Sr Capsules

- Modified Commercial DCSS built by NAC
- 300 year design life
- Cold spray will be applied over all welds during fabrication
  - PNNL proposed this concept to the project stakeholders at CH2M Hill + NAC and continues to provide technical guidance

Common Failure Modes in Nuclear Plant Components

- Over the past 50 years, several failure modes for nuclear plant components have been detected
  - Acid and caustic cracking
  - Fatigue (the primary mechanism addressed in ASME Code)
  - Hydriding and oxidizing fuel rods
  - Crevice corrosion
  - Pitting corrosion
  - Flow assisted corrosion (FAC) and cavitation
  - Mechanical wear
- Several base materials have been affected
  - Carbon steel (pressure vessels and piping)
  - Stainless steel (piping and storage tanks)
  - Ni based alloys (inconel welds and base metal)
  - Zirconium based materials (fuel rods and assembly structures)

Cold Spray Mitigation-Corrosion Resistance

- For corrosion resistance, appropriately selected cold spray coatings provide a barrier between the base metal and corrosive or erosive environment
- Demonstrated powders for corrosion or erosion protection
  - Commercially Pure nickel (CPNi) (corrosion)
  - Stainless steel 316 (corrosion or erosion)
  - Titanium-Titanium Carbide (Crevice corrosion)
  - Inconel 625 (corrosion or erosion)
- Advantages over welding
  - No heat affected zone (HAZ)
  - No tensile residual stresses

Cold Spray Mitigation: FAC

- FAC in part caused by fracturing oxide layers in two phase flow conditions with carbon steel
- Stainless of inconel coatings would eliminate the oxide layer deterioration
- Welding repairs introduces new problems with heat affected zones
- Cold spray of a high alloy coating could prevent FAC
  - Note: This has not been tried to date, but related work on cavitation and flow erosion has demonstrated high potential for this approach

Examples of Stainless Steel Corrosion

- Chloride cracking

- Crevice Corrosion

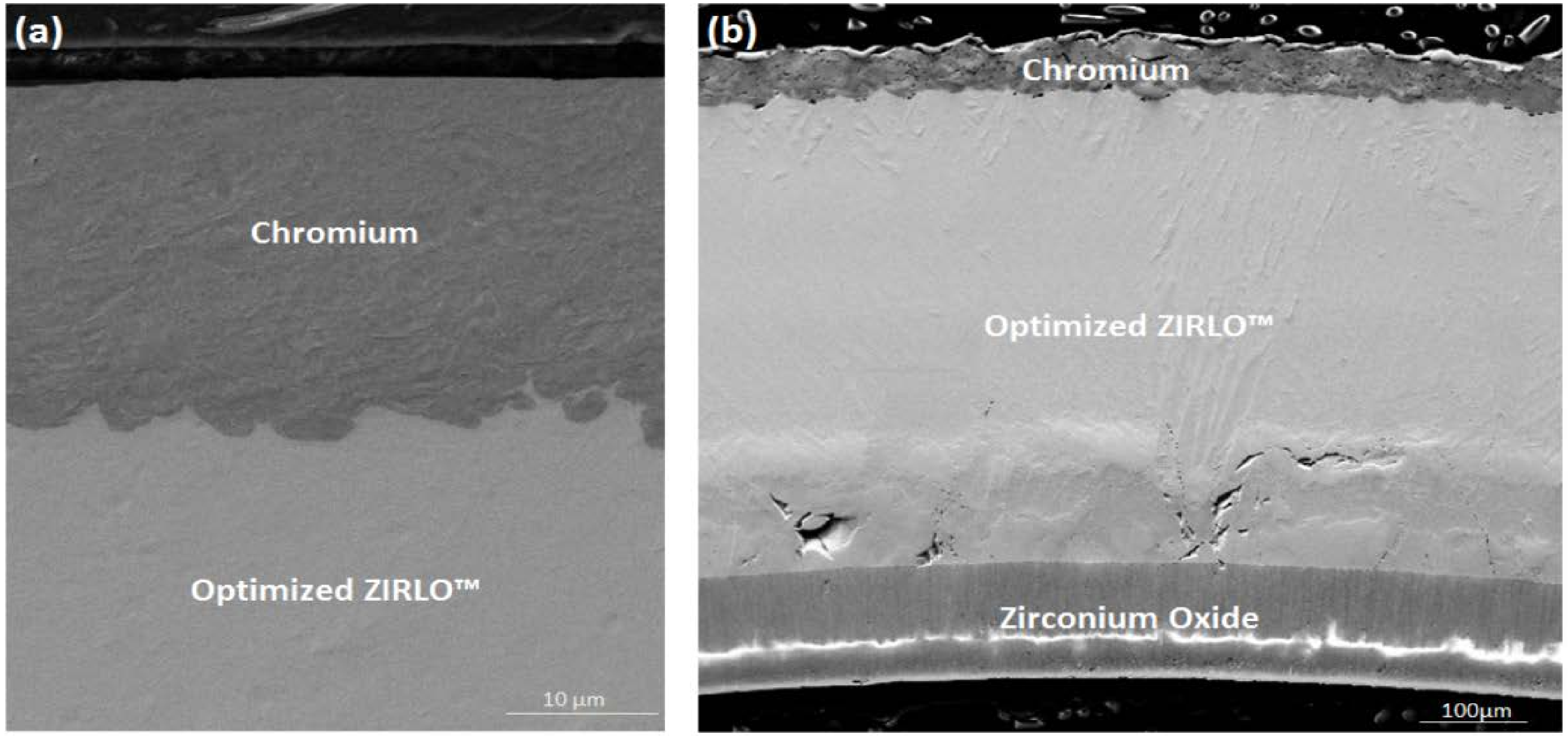
Examples of Carbon Steel Degradation

- Flow Assisted Corrosion

- Boric Acid Corrosion of Carbon Steel

Westinghouse LWR Fuel Cladding

- Cold sprayed Chromium on Optimized ZIRLO
- Irradiation testing Byron Unit 2 Cycle 22
- Improved
  - Economics
  - Safety
  - Reliability



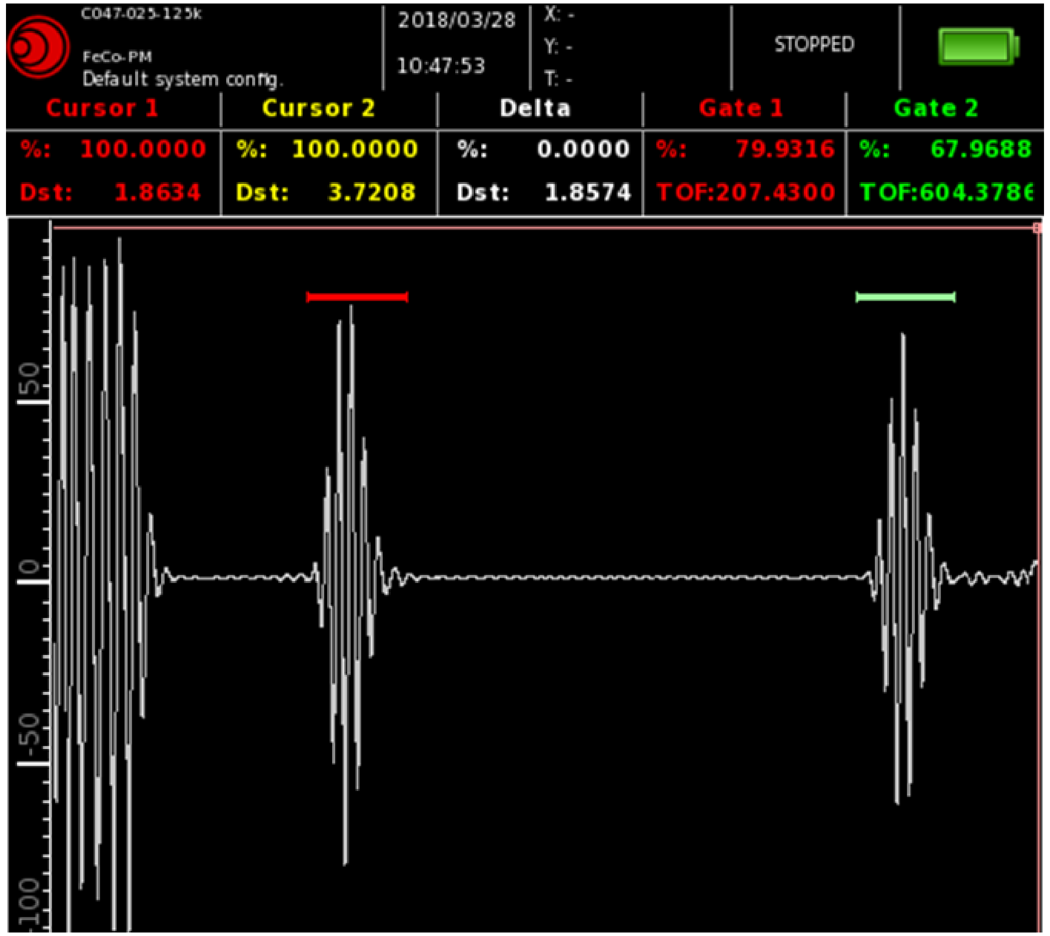
As-fabricated microstructure of cold spray chromium coating on Optimized ZIRLO cladding (a). Microstructure of cladding tube following oxidation in steam at 1200°C for 20 minutes
https://www.euronuclear.org/archiv/topfuel2018/fullpapers/TopFuel2018-A0145-fullpaper.pdf

CP Ni Ultrasonic Transducer

- Cold Spray for online monitoring

- Ni cold spray coatings are magnetostrictive
- Can be used as a permanently installed electromagnetic acoustic transducer (EMAT)
  - Austenitic stainless steel is not suitable by itself for EMATs
- On-line ultrasonic monitoring of pre-existing cracks is possible

- EMAT reflections form 6 mm reflectors



ASME Code Aspects

- Anticipated nuclear applications of cold spray are non-structural in nature
  - Anticipated coating thicknesses are on the order of 1-2% of component thickness (no fatigue credit)
  - Corrosion resistant layers and hard-facing are allowed

- This avoids the large hurdles of Code acceptance
  - Section II specifies material properties to be used for structural evaluation
  - Section III specifies design criteria for pressure retaining structures
  - Section XI specifies inspection and repair
    - ✓ Cold spray is a mitigation technique rather than a defect repair
    - ✓ Inspectability must be maintained
    - ✓ Code relief would be required for inspection interval or technique changes
    - ✓ Mitigation techniques have been addressed in Code Cases, as required

Regulatory Aspects

- NRC regulatory requirements are diverse, but manageable
- Anticipated cold spray applications may fall under 10CFR50.59 requirements
  - 10CFR50.59 allows plants to make engineering judgement to approve many applications
  - NUREG 1927 discusses the use of corrosion resistant coatings to extend component life for spent fuel storage canisters
- Technical justification reports would be required for many applications
  - ✓ Demonstrate the process works to correct issue
  - ✓ Has no adverse unintended consequences
  - ✓ Does not affect other Code requirements (inspection, dimensional fit up, surface finish)

Technical Justifications

- Application specific technical reports could be used to document efficacy of cold spray
- Several ASTM standards and military standards are available for guidance
- Required coating characteristics should be addressed
  - Porosity
  - Adhesion
  - Corrosion and/or erosion resistance
  - Surface finish
  - Radionuclide activation considerations
  - Thermal and mechanical constraints
  - Other application specific attributes

Acknowledgments

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Thank you