Laser Glazing Of Cold Sprayed Coatings For The Mitigation Of Stress Corrosion Cracking In Light Water Reactor (LWR) Applications

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Background

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- Nickel-based Alloy 600 and its associated weldments Alloys 82/182 have commonly been utilized as structural material for the light water reactor (LWR) components
- LWR components operate in harsh environment and may be subject to degradation; a major form of degradation is stress corrosion cracking (SCC)
  - Compromises safety and reliability of reactors
  - Reduces operational life
- Different approaches can be taken to mitigate SCC for improved safety, reliability and enhanced operational life of the reactors

a. Replace degraded components as the need arises (expensive)

b. In-situ repair of degraded components and welds

Objectives and Approach

1. Develop and demonstrate the potential of a hybrid process of cold spray (CS) and laser glazing to mitigate stress corrosion cracking of Alloy 600 and associated weldment Alloy 182 material in a simulated pressurized water reactor (PWR) environment
   - Use alloys known to be SCC susceptible, Alloy 600 and Alloy 182 (a weldment prototypic of those used in nuclear industry was produced for this program)
   - Use SCC-resistant Alloy 690 for coating

2. Develop a method to quantify the effect of the hybrid process on SCC growth in Alloy 600 or Alloy 182
   - Use interrupted crack growth rate (CGR) testing in simulated reactor environment to measure SCC CGRs prior and after the application of the hybrid process

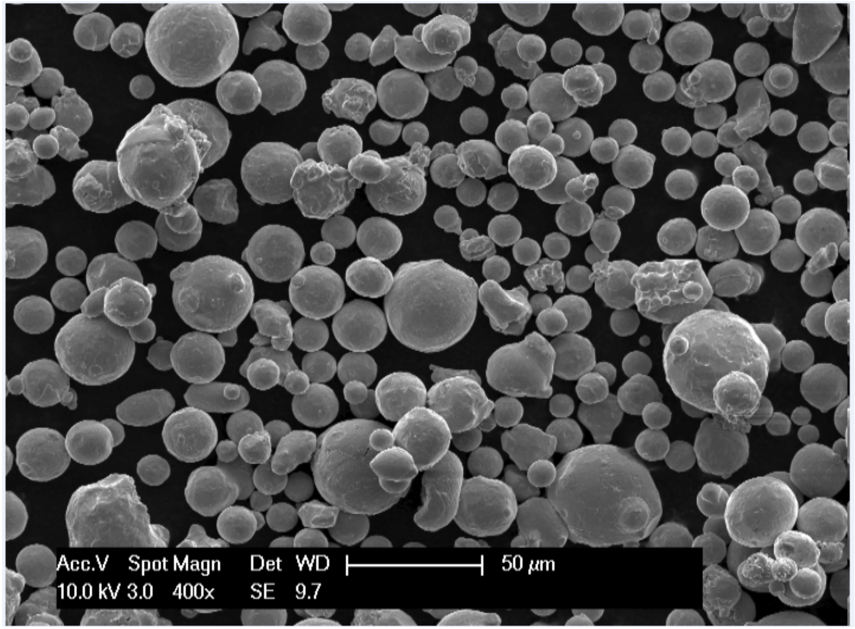
SCC Mitigation – Test Plan

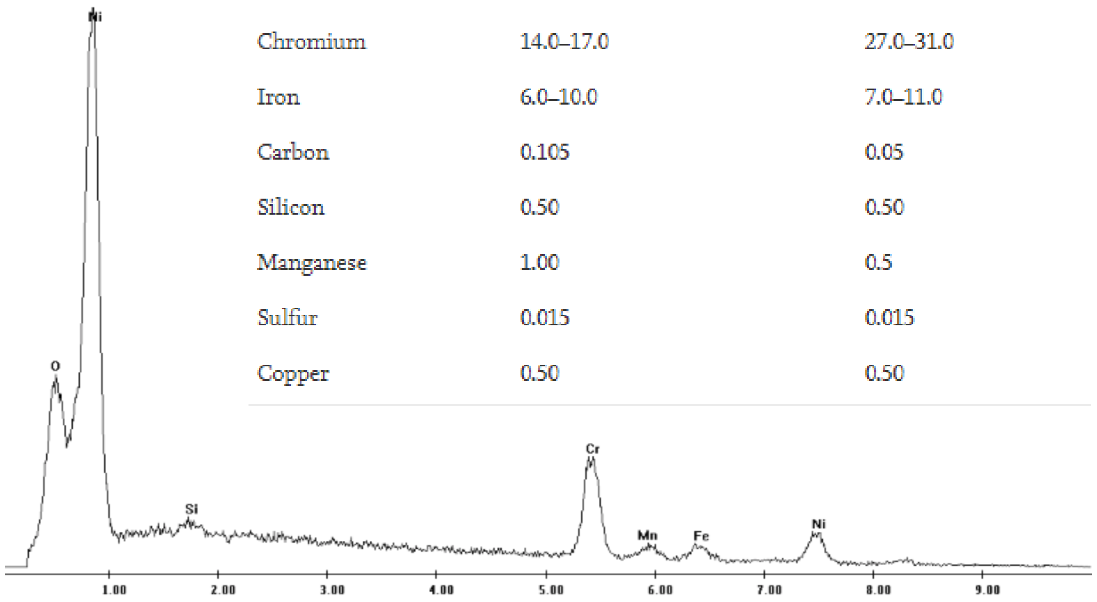
- Coat SCC-prone materials (A600 and A182) with SCC-resistant material (A690) by CS
- Post-treat coating with laser glazing to further densify and smooth out surface
  - Enhanced corrosion protection
  - Repair un-sealed cracks in the substrate beneath the CS coating
- Analyze fusion zone area (depth, width) as a function of laser glazing parameters (power, traverse speed)
- Evaluate effectiveness of the hybrid treatment
  - SCC crack growth rate (CGR) testing using realistic samples and environments

Cold Spray

- Alloy 690 powder (10-45µm), Carpenter Powder Products, Bridgeville, Pa
- CS Equipment: Impact Innovations ISS-5/11

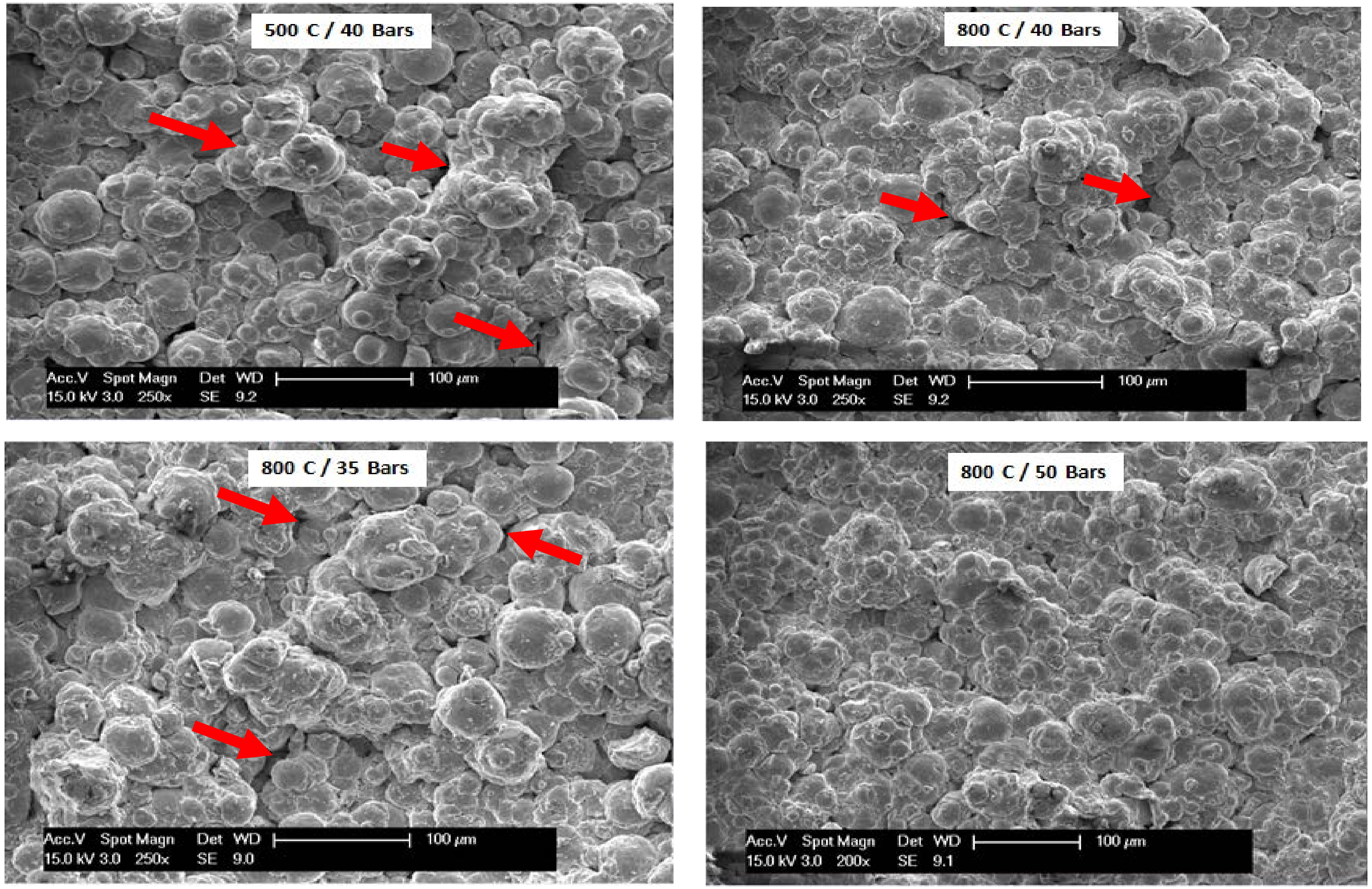
Element	Alloy 600 (wt%)	Alloy 690 (wt%)
Nickel	72.0	56.44
Chromium	14.0–17.0	27.0–31.0
Iron	6.0–10.0	7.0–11.0
Carbon	0.105	0.05
Silicon	0.50	0.50
Manganese	1.00	0.5
Sulfur	0.015	0.015
Copper	0.50	0.50





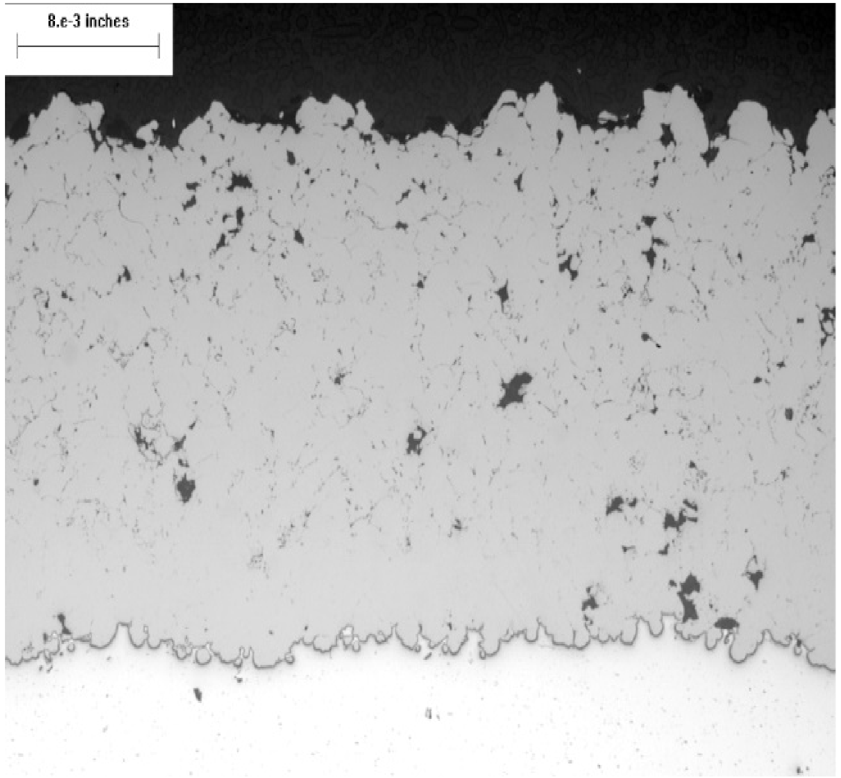
Cold Spray – Parameter Optimization (Microstructure)

- Resulting microstructure vs. parameters



Cold Spray – Parameter Optimization (Porosity)

- Resulting porosity vs. parameters



500°C/40bars
Avg. Porosity = 2.434±1.404

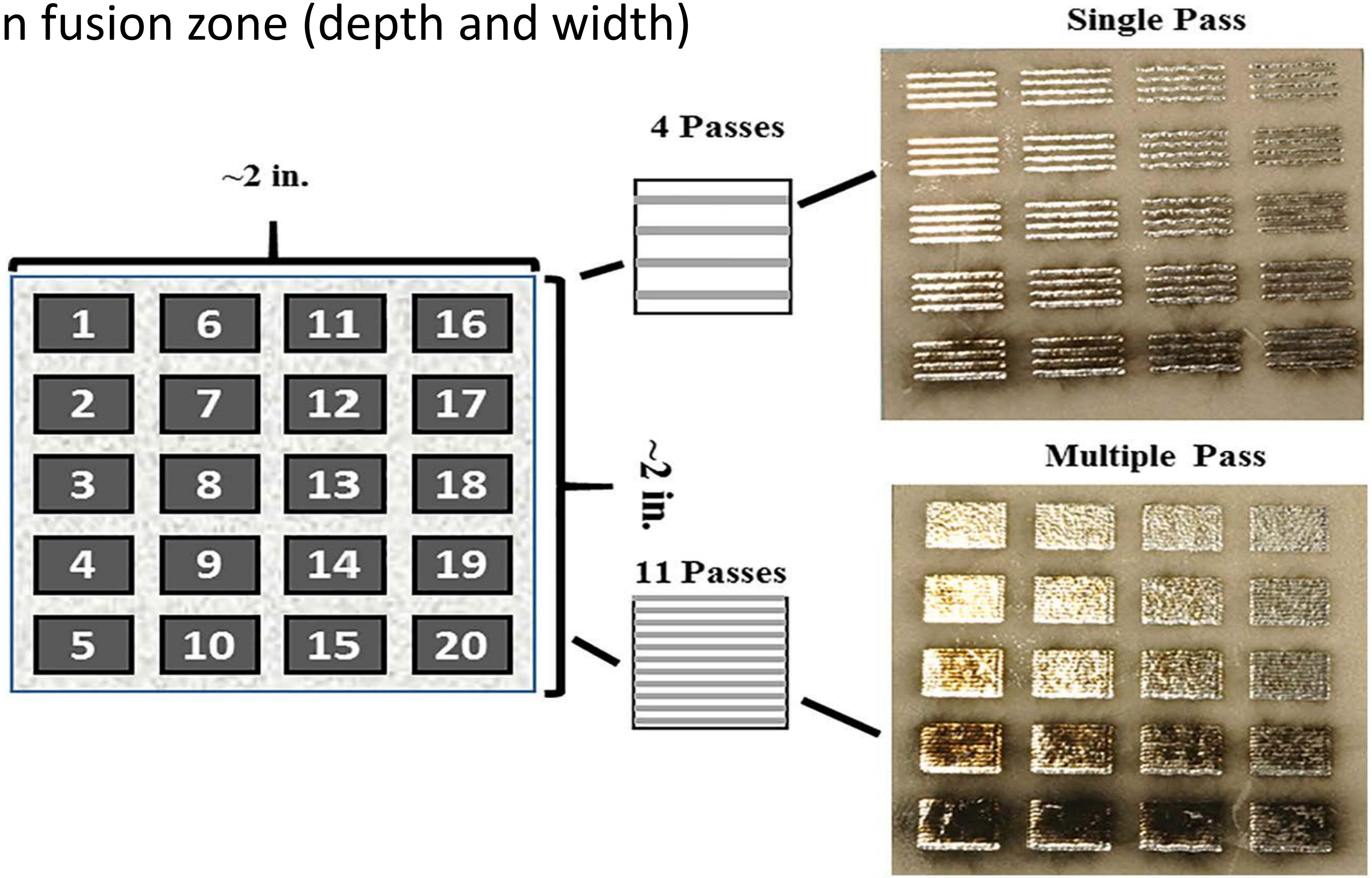
800°C/50bars
Avg. Porosity = 0.116±0.041

Cold Spray – Optimized Parameters

Parameter	Value
Powder	CPP 690/–325 mesh + 10 µm
Gas type and flow rate	Nitrogen/97 m3/Hr
Gas temperature & pressure	**800C/50 bars**
Powder feed rate/vibration	2.0 and 1.5 RPM/60%
carrier gas flow rate	3.0 m3/Hr
Substrate material/dimensions	Alloy 600/2.2” × 12” × 0.25”
Spray distance	25 mm
Coating spec	100, 150 and 200 µm
Blast grit/pressure/distance	46 grit alumina/60 psi/20.0”
Spray direction	Along the 12” direction
Robot speed	1000 mm/s
Step size	1.0 mm

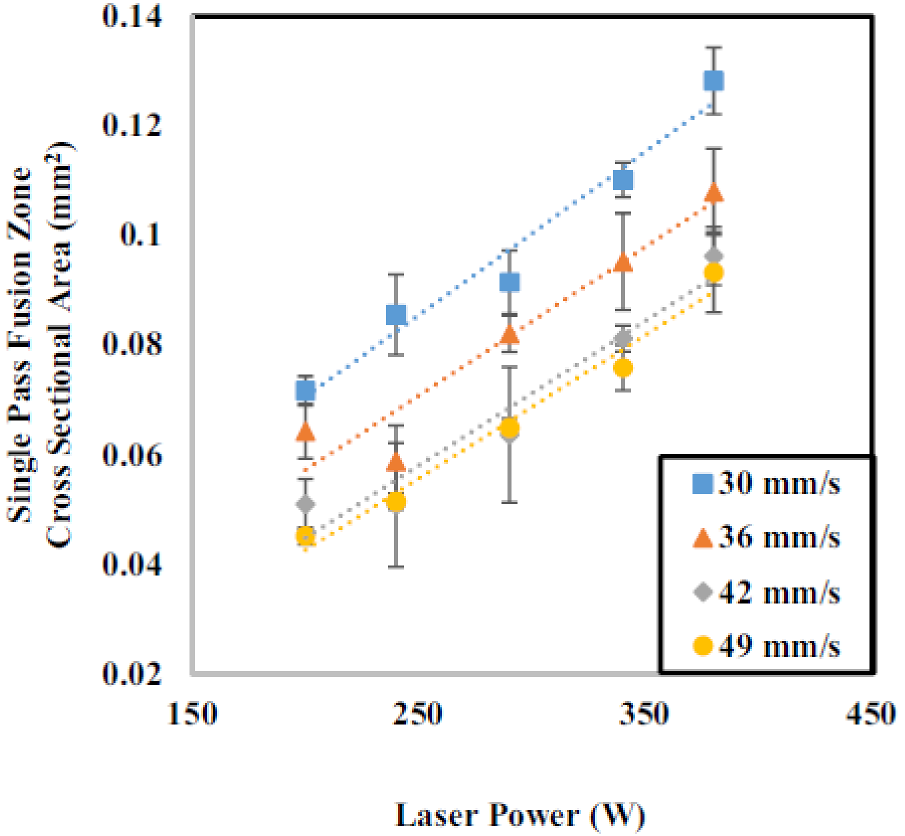
Laser Glazing of CS Coating of A690 on A600

- Single pass verse multi-pass laser trials were compared to see the impact on fusion zone (depth and width)



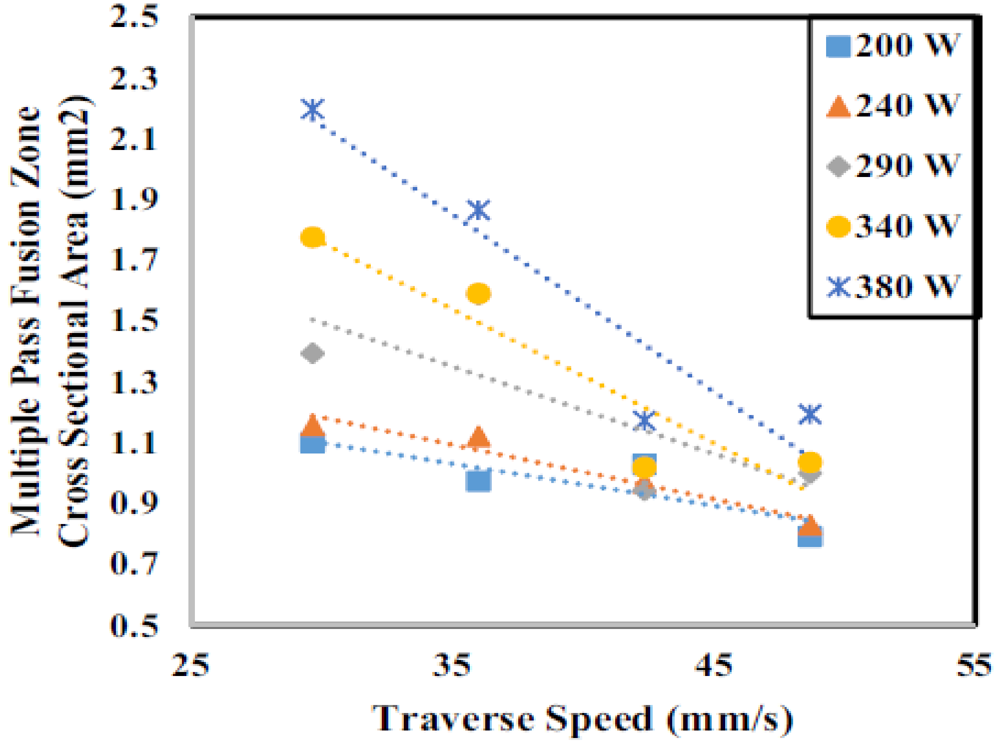
Single Pass Laser Glazing

- Cross sectional fusion zone area increases with increasing laser power
- Cross sectional fusion zone area increases with decreasing traverse velocity



Multiple Pass Laser Glazing

- Cross sectional fusion zone area increases with increasing laser power
- Cross sectional fusion zone area increases with decreasing traverse velocity
- Cross sectional fusion zone area for multiple pass shows on average larger areas relative to single pass



Adhesion Testing for Selected Cold Sprayed and Laser Glazing Parameters

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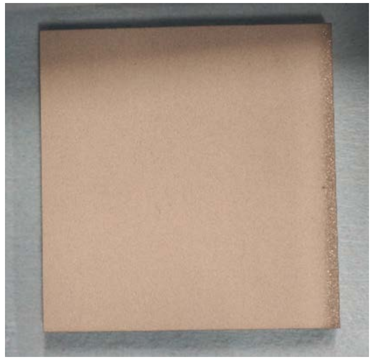
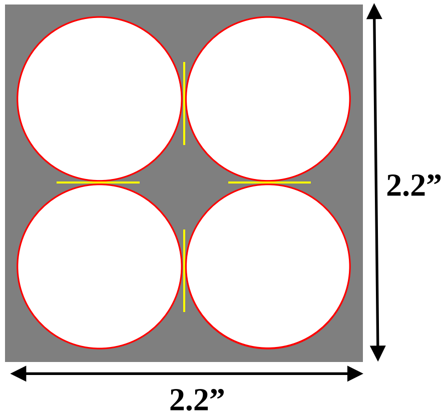
As Cold Sprayed A690

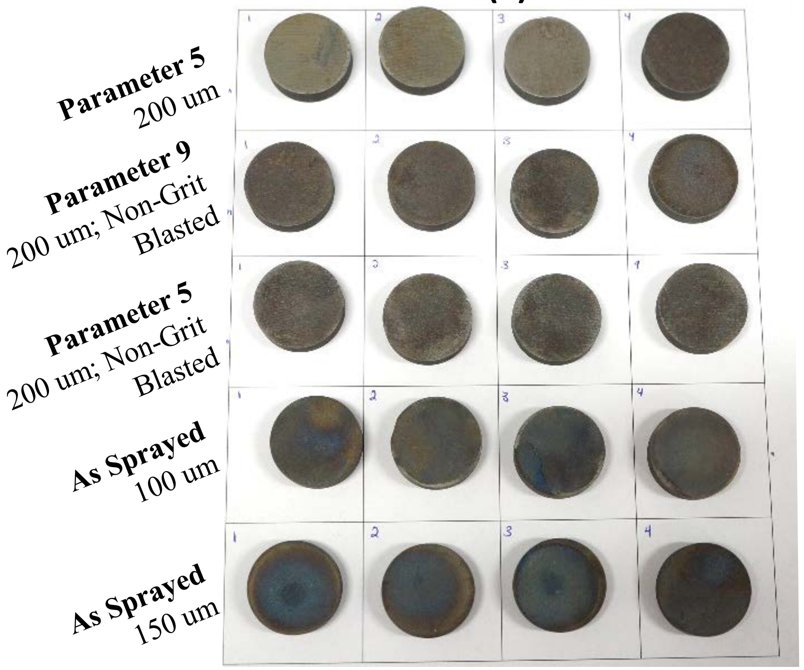


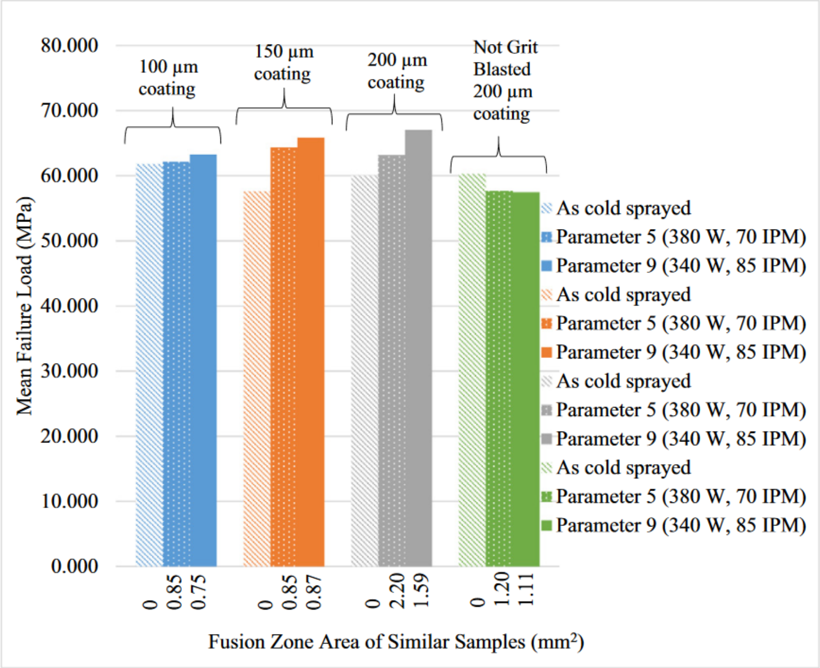
Adhesion Slugs Schematic



- 2.2”x2.2”x0.25”
- Wire EDM four (4), 1.0” buttons from 2.2” square

Example Layout of Adhesion Slugs, Tested in Sets of Four (4)

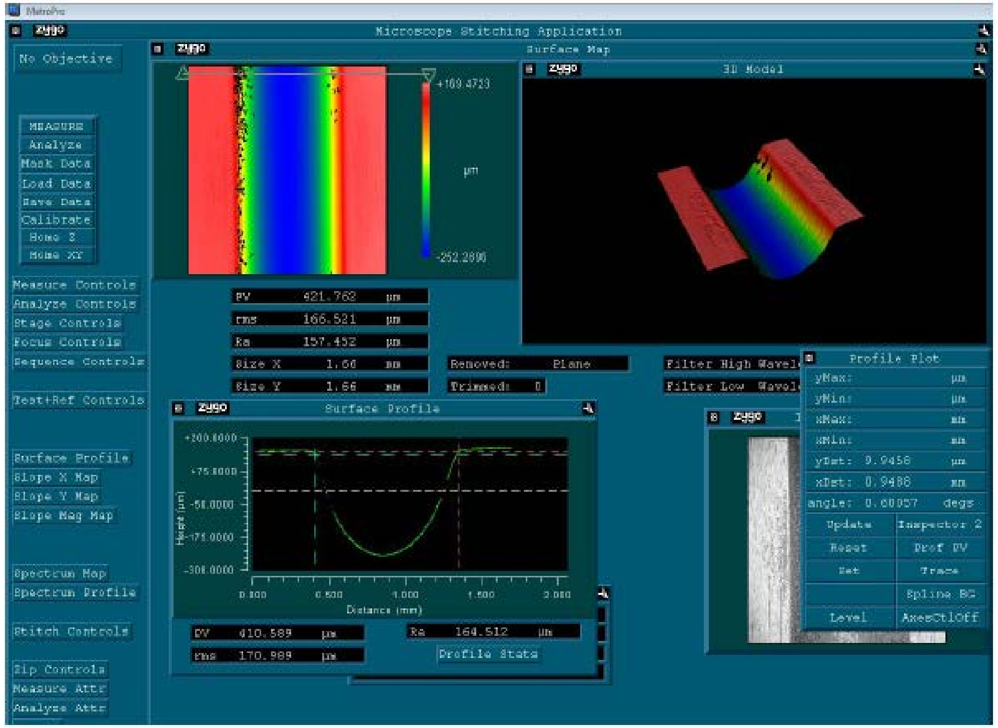


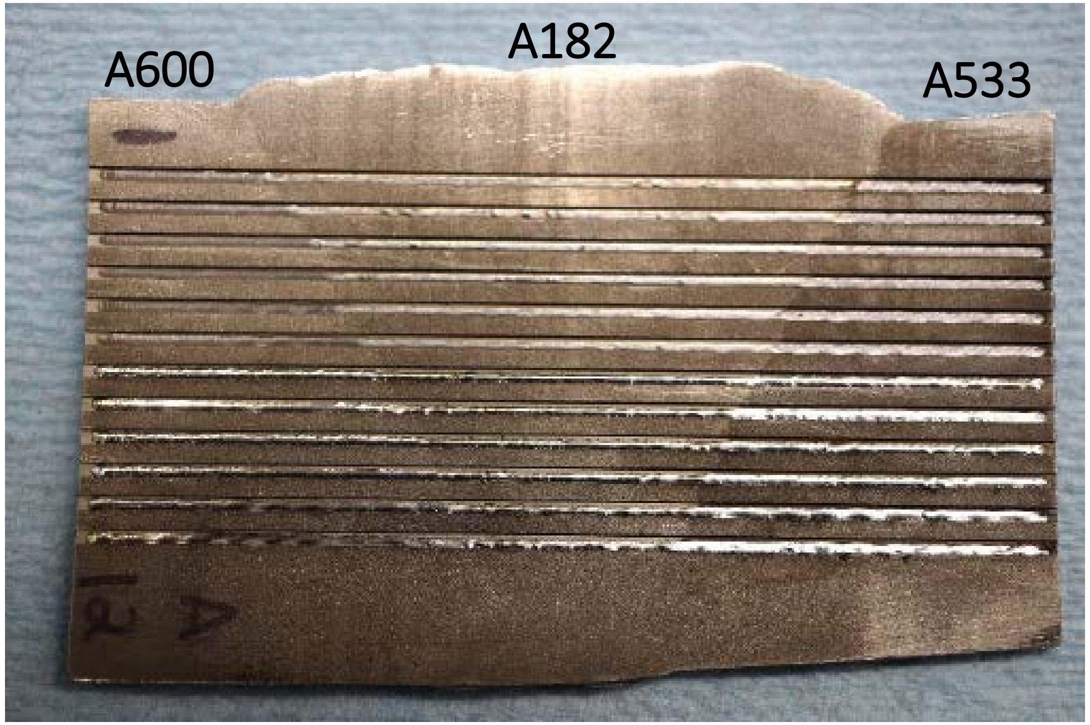


- Adhesion strength was nearly the same regardless of grit blasting the surface prior for non laser glazed samples
- Adhesion did increase in laser glazed samples where the surface was initially grit blasted

Further Evaluation – CT Specimen Geometry

- Practice laser glazing runs were made on machined grooves on a piece spanning three materials: without A690 powder (grooves 1-6) and with A690 (grooves 7-12)
- The machined grooves were matched in terms of depth and width of the CT specimen





Further Evaluation – CT Specimen Geometry

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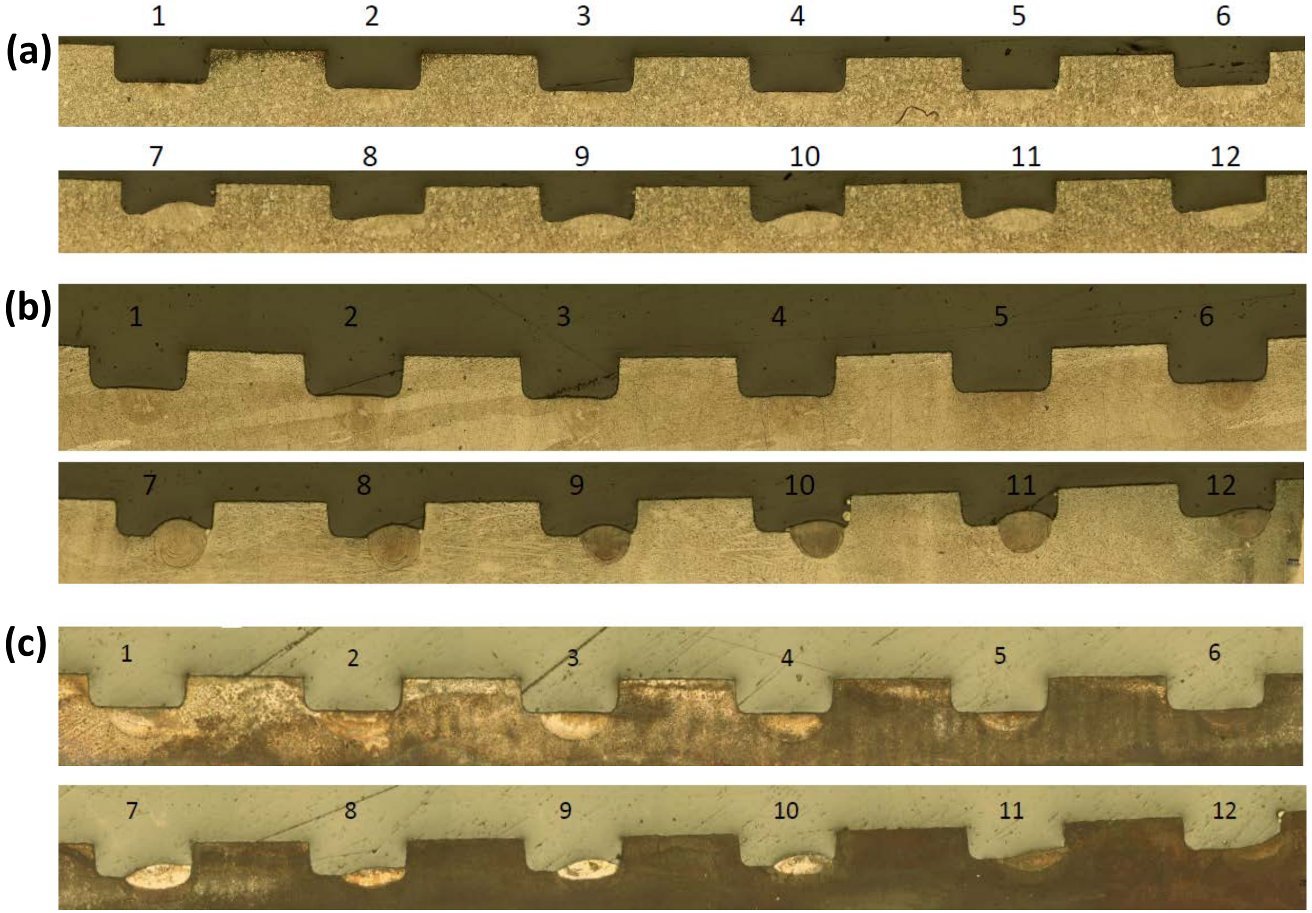
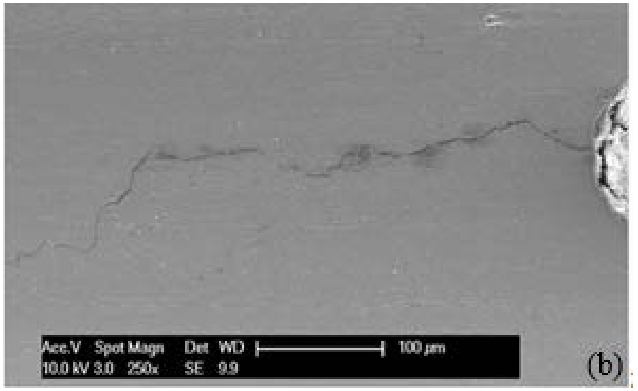
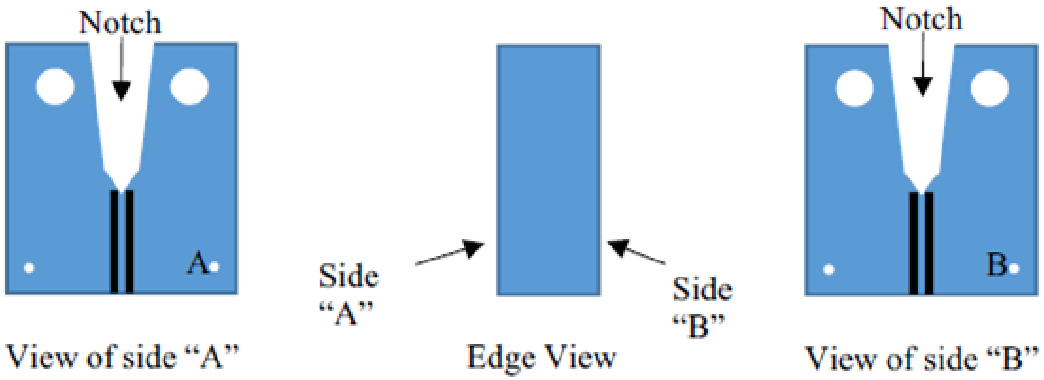
- Treated (a) A600, (b) A182 and (c) A533 to determine depth and width of the fusion zone with and without Alloy 690 powder



Evaluation of Effectiveness of Hybrid Treatment
SCC CGR Testing Sequence

1) SCC growth was first induced in a compact tension (CT) test specimen of Alloy 600 or Alloy 182 exposed to a high temperature water environment, and an initial SCC CGR is measured. Target crack depth was 0.5 mm.
2) Then, the CT specimen is removed from the test to allow for the hybrid treatment to be applied. Due to the notch geometry, we were not able to CS the crack. To demonstrate repair feasibility (fill and seal the crack), powder was laid and laser glazed





Evaluation of Effectiveness of Hybrid Treatment

SCC CGR Testing Sequence

3) The groove on both sides (A and B) and the notch were treated with the hybrid treatment.
4) The specimen is reintroduced into the same environment, and under the same loading, and a new SCC CGR is measured

If the hybrid treatment is effective at mitigating SCC, the SCC crack is sealed, and the SCC CGR measured after the application of the treatment is reduced vs. the CGR measured prior to the treatment

One specimen (A600-ST-1) was destructively examined post-test, whereas two specimens (A600-ST-2 and A182-ST-2) were not destructively examined post-test;   the intent is to conduct fatigue CGR testing to determine whether the response is consistent with Alloy 600, 690, 182 or not – further substantiating the effectiveness of the repair

SCC-CGR Test Before Hybrid Treatment (A600-ST-1)

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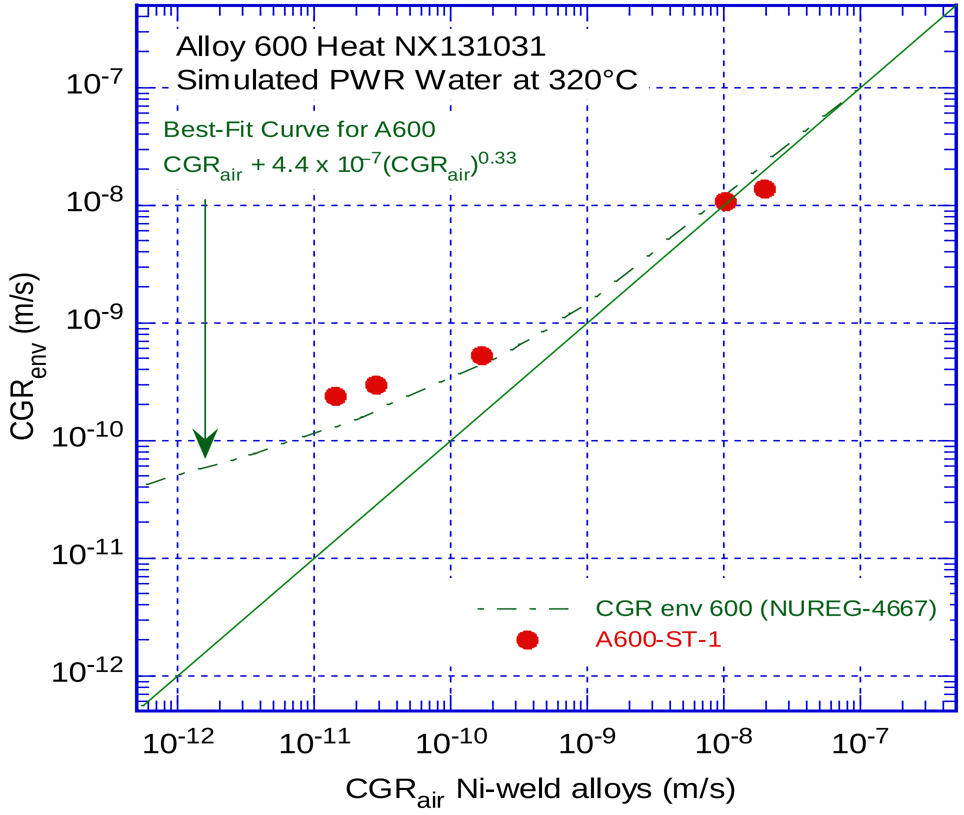
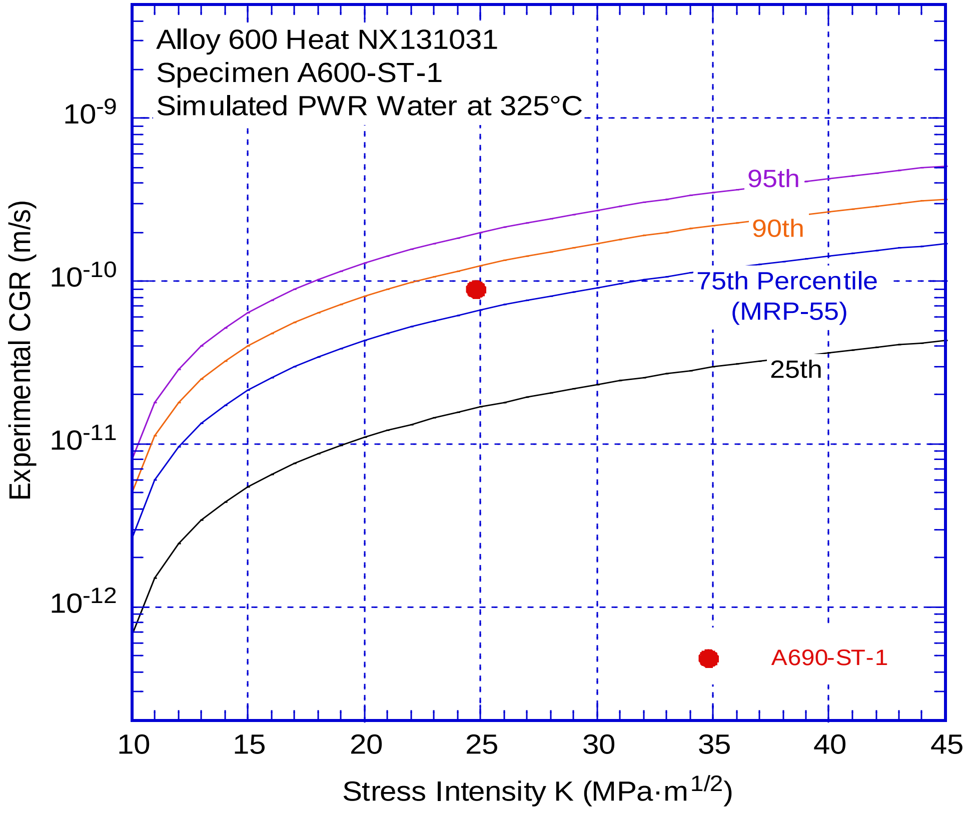
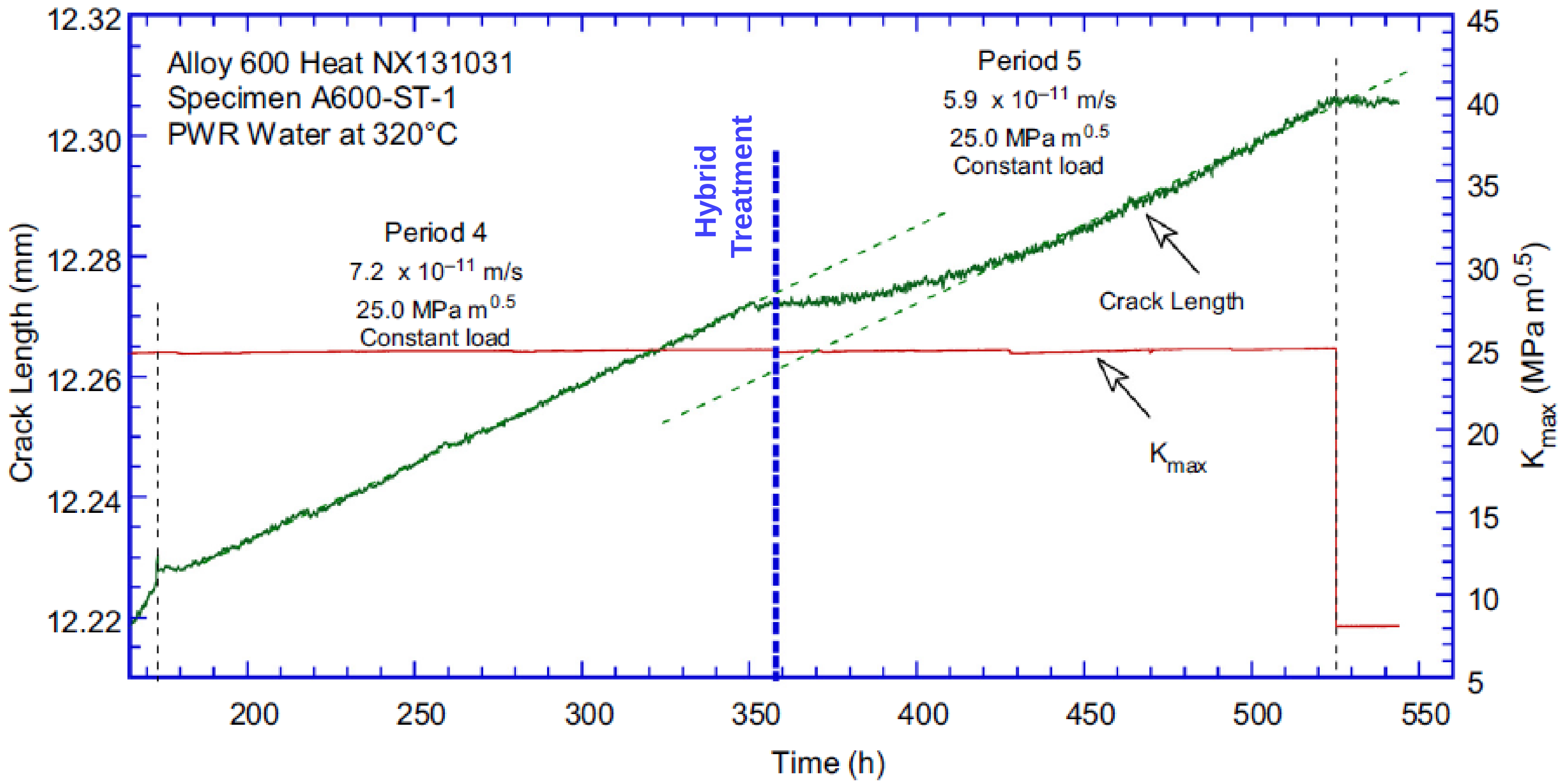
- Test was initiated with fatigue precracking and transitioned to SCC growth in the primary water environment





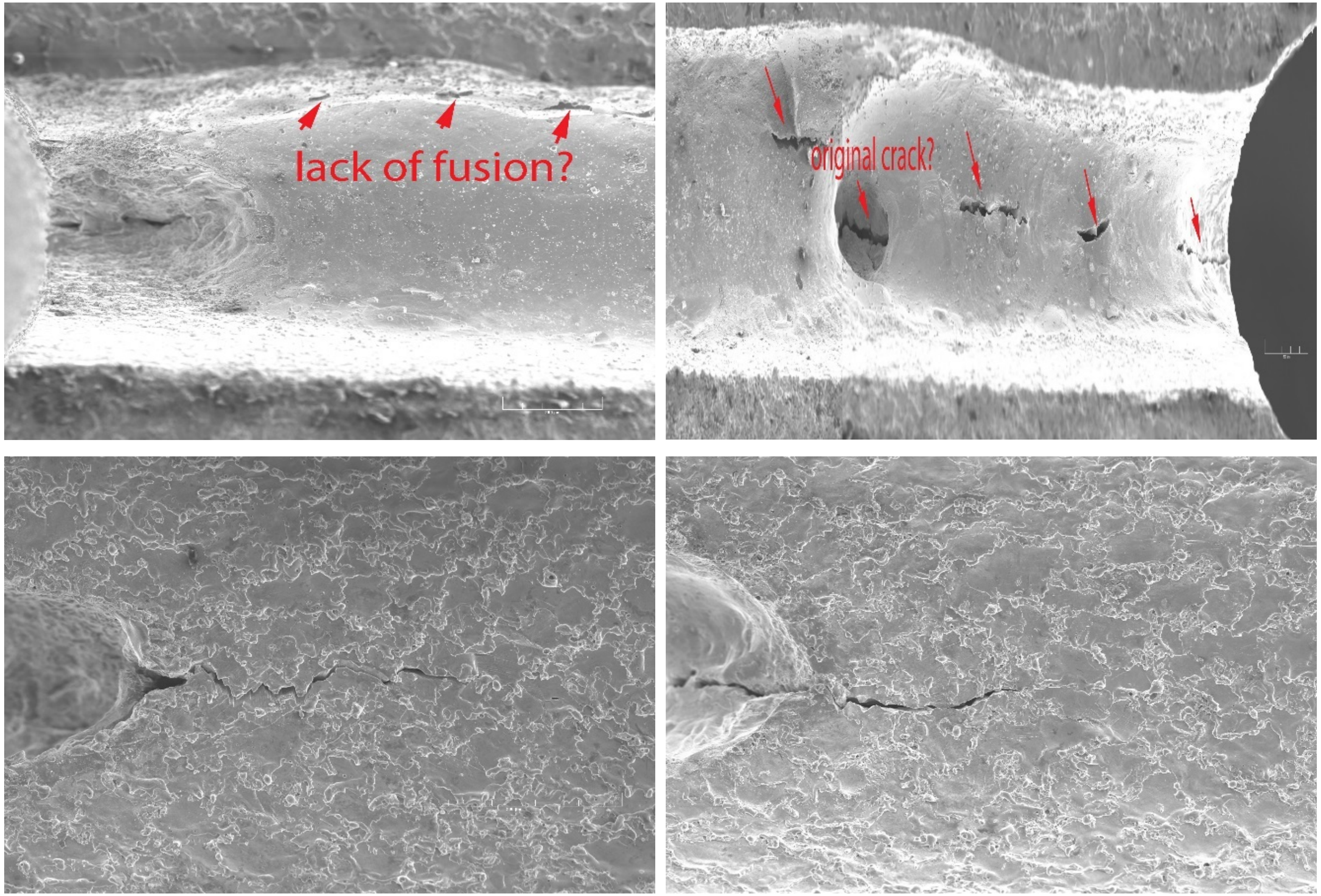
SCC-CGR Test Before And After Hybrid Treatment (A600-ST-1)

- Specimen A600-ST-1 specimen was processed with Alloy 690 powder and laser glazing (200 W, 12.7 mm/s:30IPM)
- Initial SCC CGR resumed shortly after the treatment



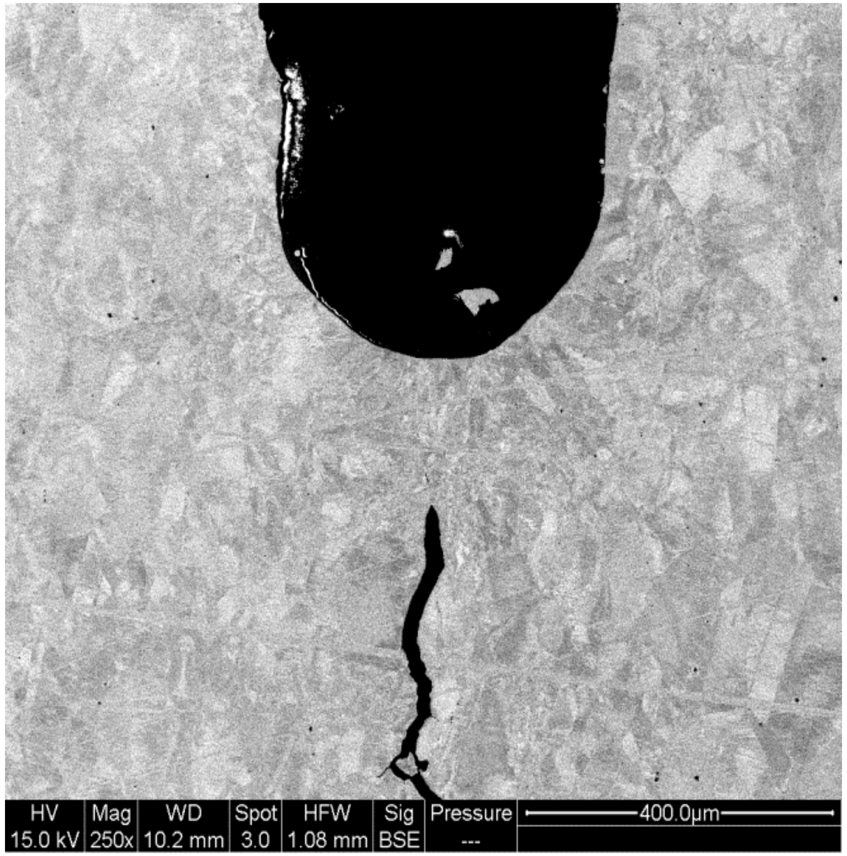
A600-ST-1: Post-test Examination

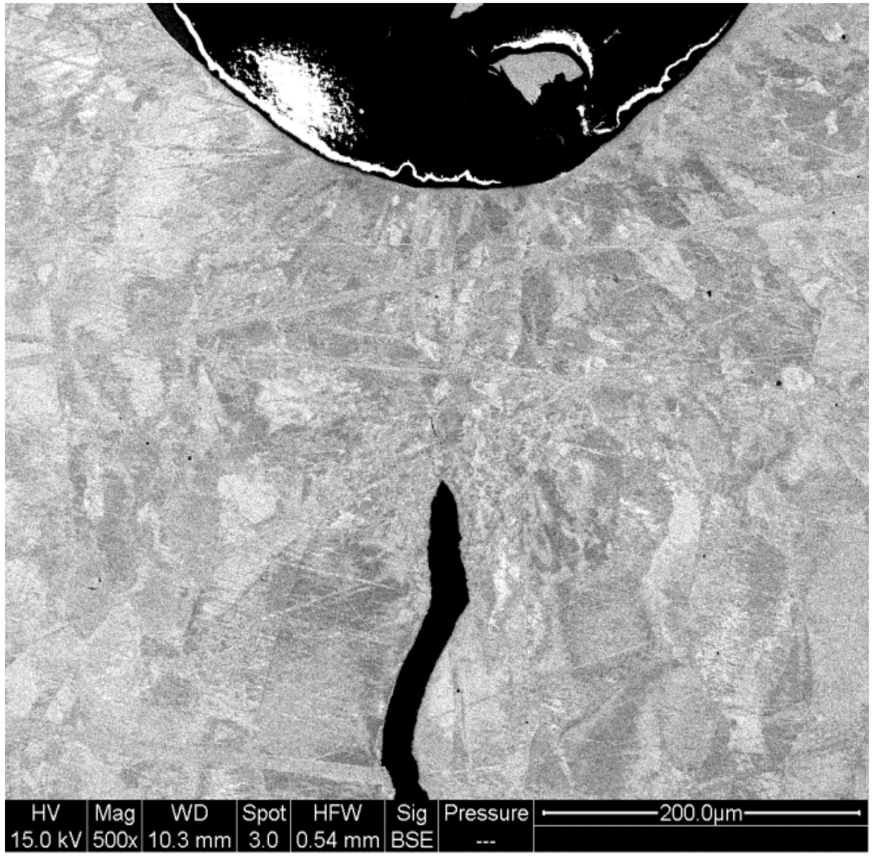
- Post test examination suggests that the crack did not seal – particularly the side grooves of the CT specimen



A600-ST-1: Post-test Examination

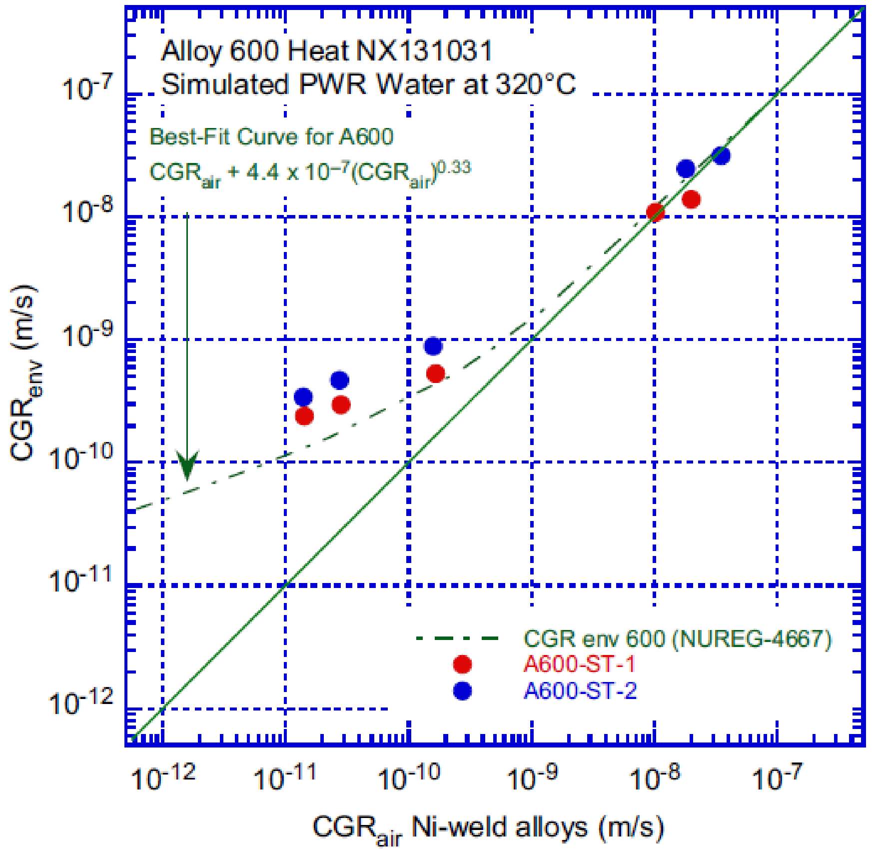
- Post test examination found areas that did seal, however, the side grooves remained open
- Findings informed treatment of the subsequent Specimen A690-TS-2

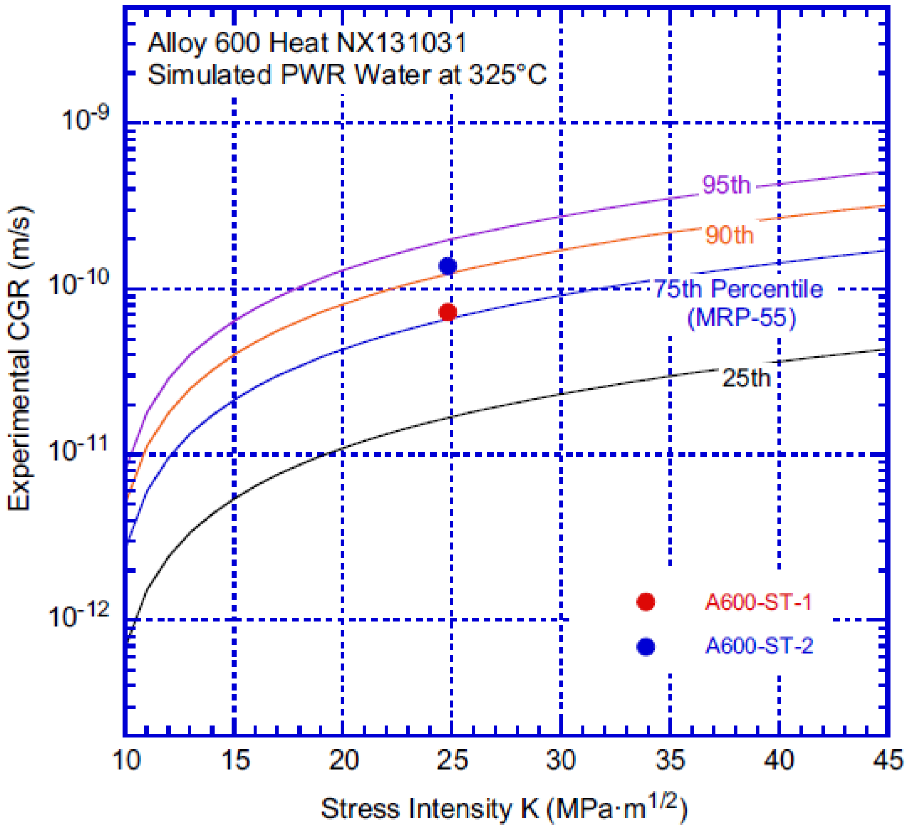




CGR Test Before Hybrid Treatment (A600-ST-2)

- As before, test was initiated with fatigue pre-cracking and transitioned to SCC growth in the primary water environment.
- Identical cyclic and SCC CGR response

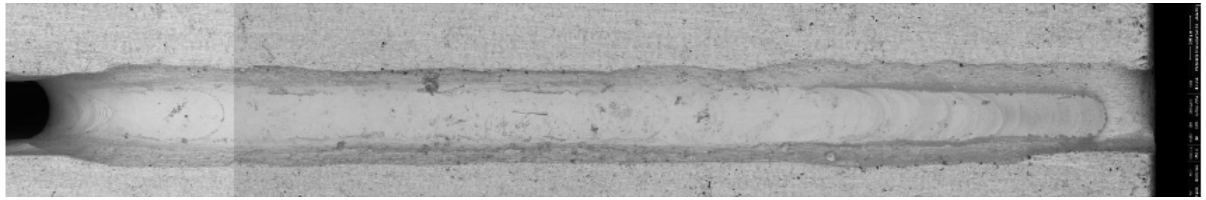




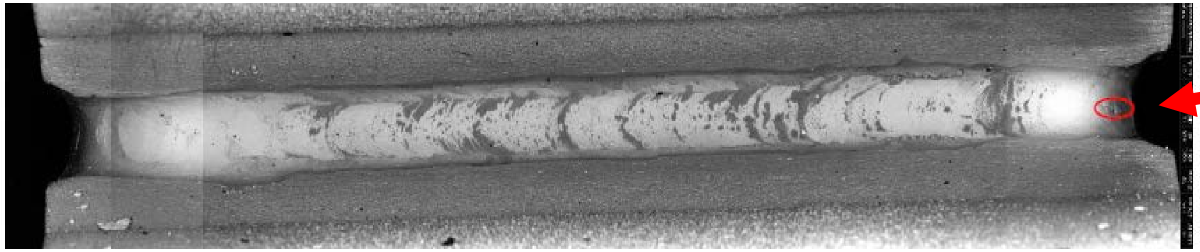
A600-ST-2 – Pre-reinsertion Examination

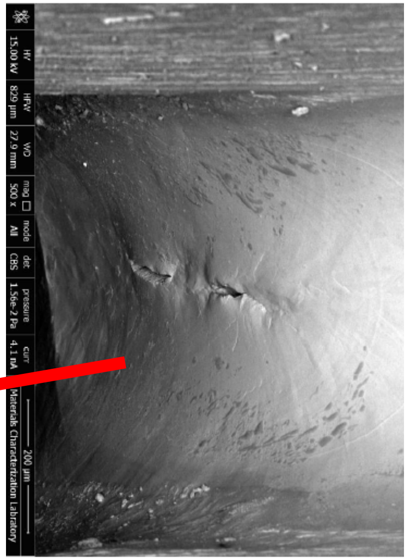
- Pre-reinsertion examination suggests that the crack did seal

Groove A

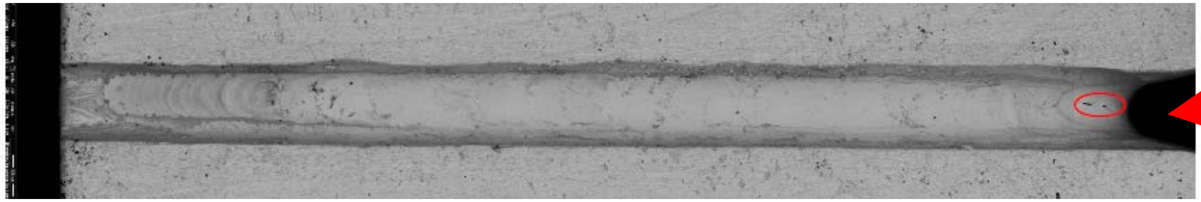


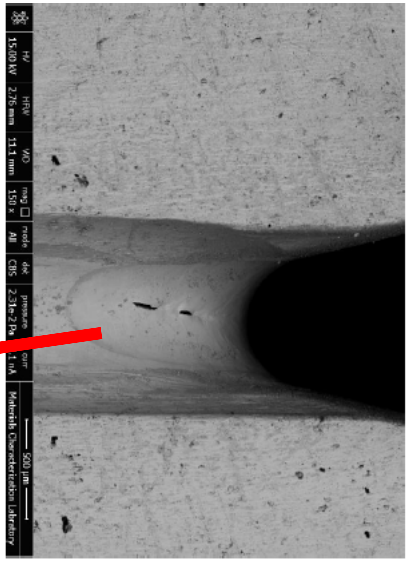
Notch





Groove B





A600-ST-2: SCC CGR Response Before and After the Hybrid Process

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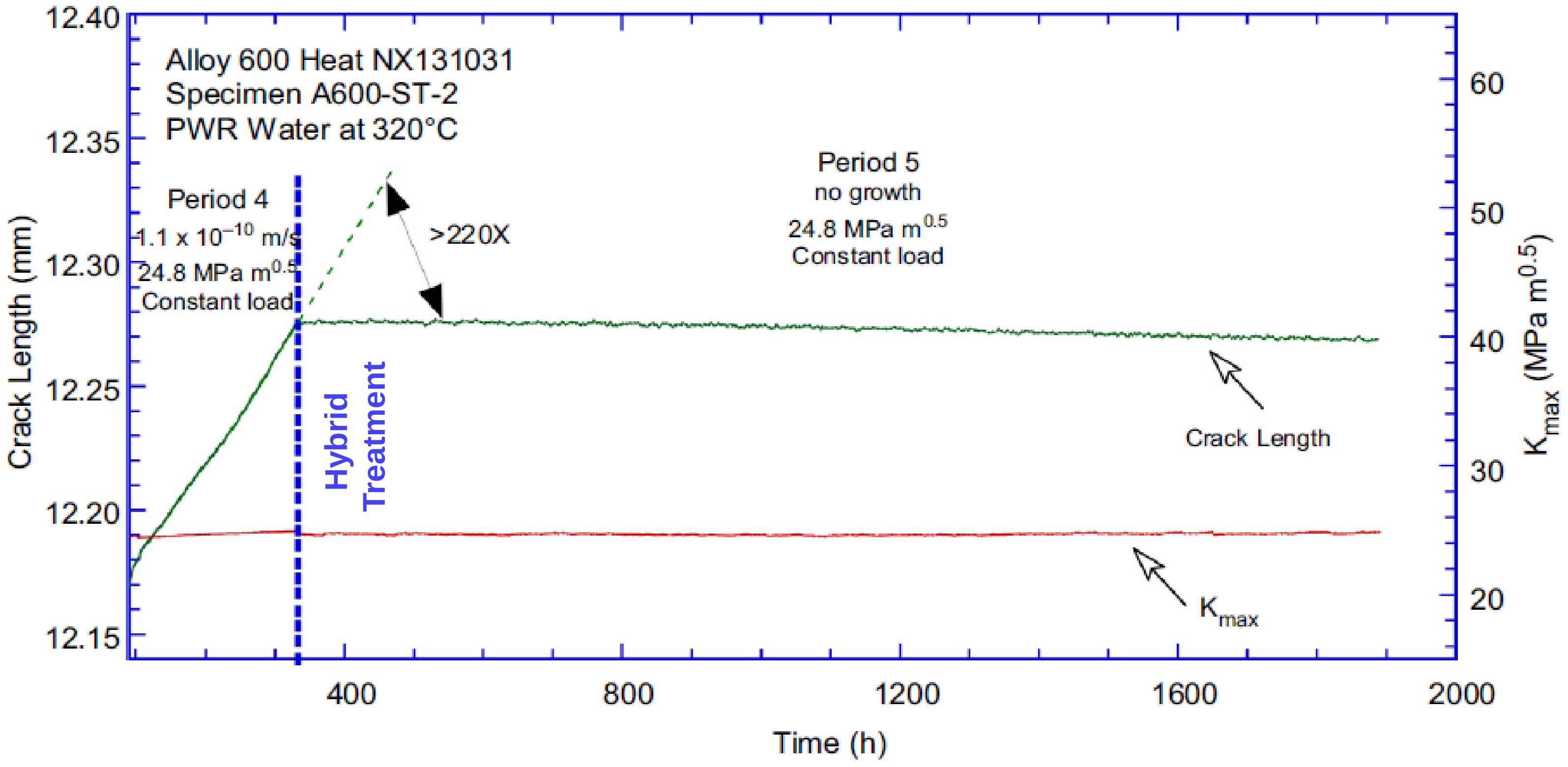
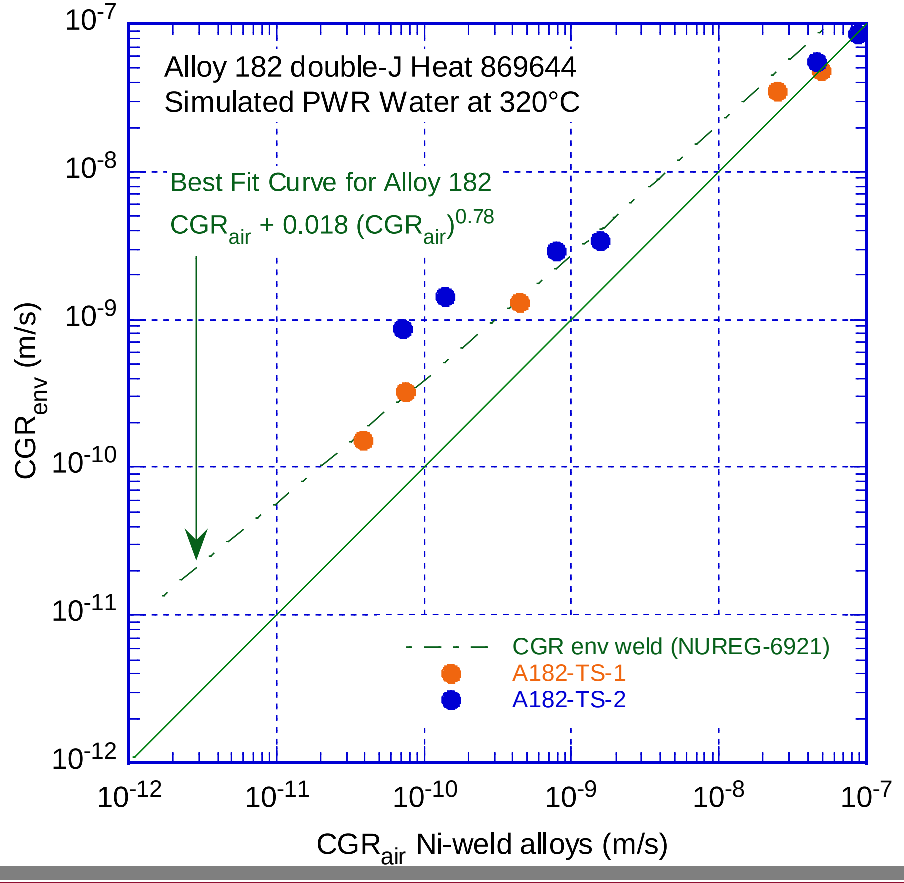
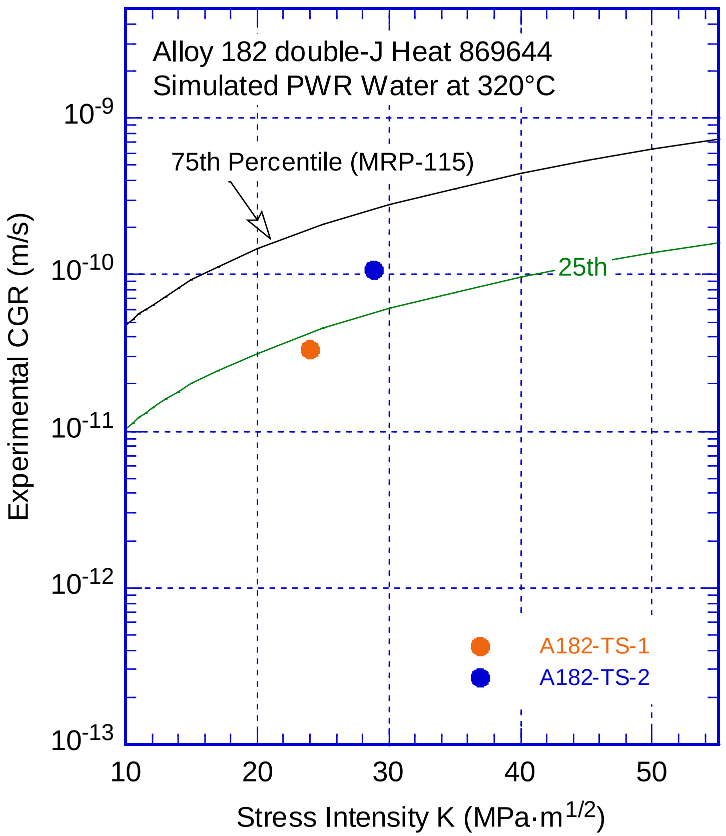
- Specimen A600-ST-2 was processed using two laser glazing steps:
  - 500 W at 25.4 mm/s followed by 300 W at 25.4 mm/s
- Growth did not re-initiate cracking in 1200 h (FOI > 220 assuming detection limit 5 x 10^{-13} m/s)



Alloy 182 SCC CGR Testing

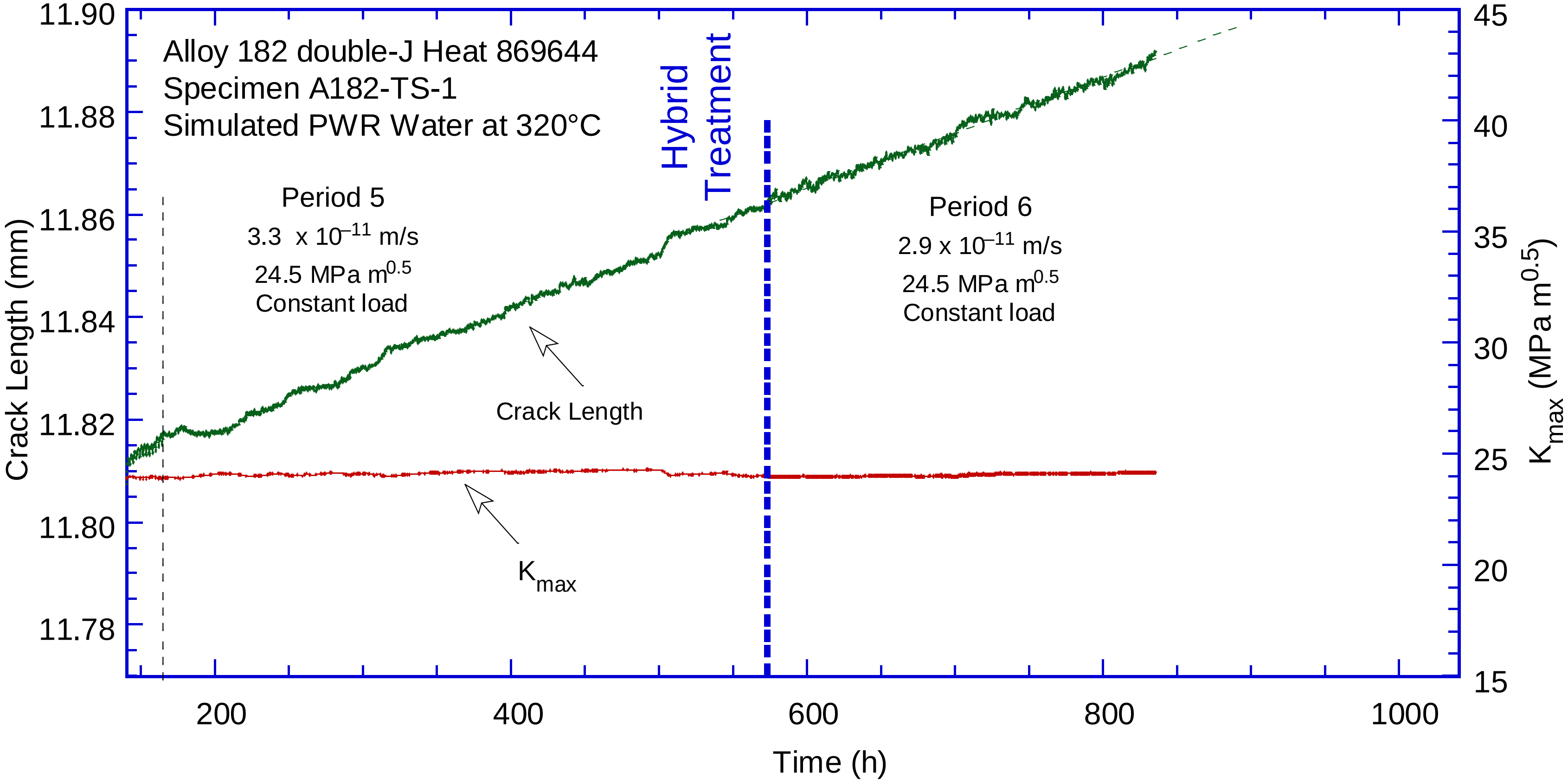
- Two SCC CGR tests were conducted on Alloy 182 (Specimens A182-TS-1 and A600-TS-2)
- Both tests were initiated with fatigue pre-cracking and transitioned to SCC growth in the primary water environment.





SCC-CGR Test Before And After Hybrid Process (A182-TS-1)

- Initial test on Alloy 182 (Specimen A182-TS-1). Processed with 2 laser glazing steps that were successful for Alloy 690 (500 W at 25.4 mm/s followed by 300 W at 25.4 mm/s)
- As with A690-TS-2 previously, decision was made to further adjust laser parameters



Optimized Laser Glazing Parameters in Alloy 182 Weld (A182-TS-2)

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- As before, optimized laser glazing parameters for Alloy 182 (Specimen A182-TS-2), notch and both side grooves were included
- Three laser glazing steps were used (IG interdendritic morphology in the weld may not be as uniform as that of the base metal)

Laser Power Setting (watts)	Travel Speed (IPM)	Shielding Gas (L/min)	Focus Head Standoff (mm)	Spot Size (mm)	Comments
500	60	25	18.62	1	preheat to 400 C side A, A690 powder added
500	60	25	18.62	1	preheat to 400 C side B, A690 powder added
500	60	25	18.87	1	preheat to 400 C side Notch, A690 powder added

A182-TS-2 – Pre-reinsertion Examination

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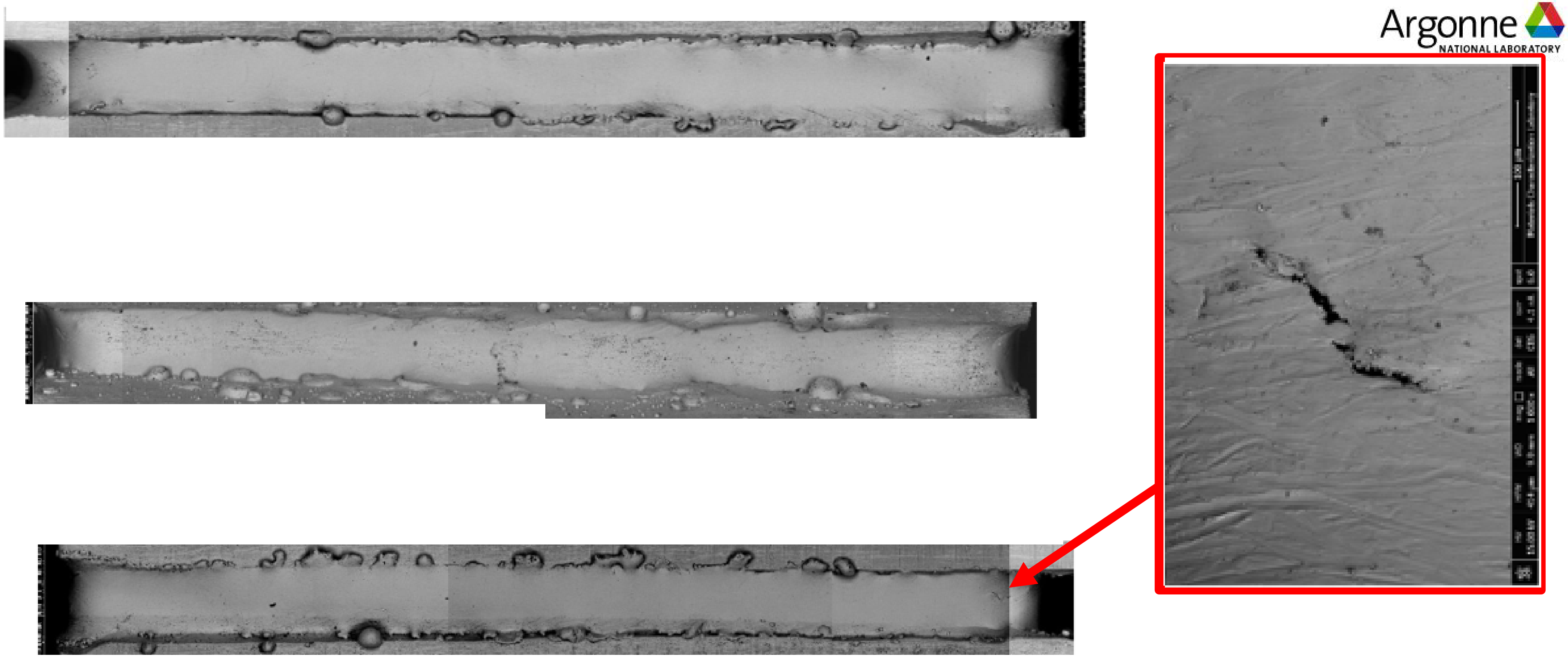
- Pre-test examination suggests that the crack did seal

Groove A

Notch

Groove B



SCC-CGR Test Before And After Hybrid Process (A182-TS-2)

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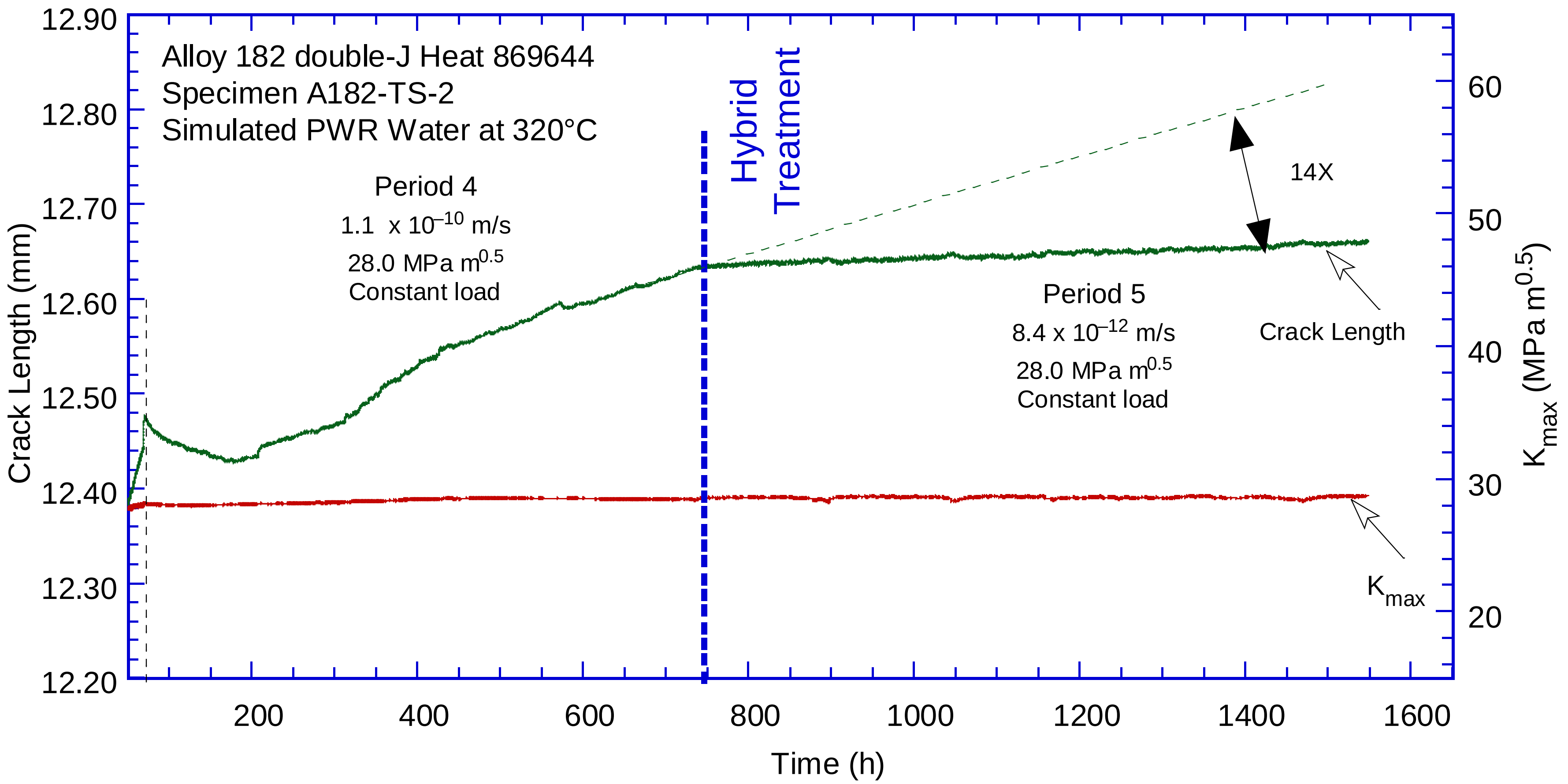
- Optimized, three laser glazing parameters were used on Alloy 182 Specimen A182-TS-2 (FOI = 14, not as high as the one for the base metal, suggests crack morphology plays a role)



Summary

1. Alloys 600 and 182 weld were selected as the SCC-prone substrate materials. Alloy 690, an alloy with superior resistance to SCC was selected as the repair material.
2. CS processing parameters were optimized to fabricate denser and highly adherent coatings of Alloy 690 powders. The adhesion strength of the coating with the substrate was determined and found to be very high (>8140PSI).
3. Several laser processing tests were conducted on uncoated and CS-coated alloy substrates to determine optimal conditions for the repair (sealing) of underlying cracks at a given depth/dimension.
4. Using the optimized laser and CS parameters, hybrid treatments were further adapted and optimized for the compact tension (CT) specimen geometry used in SCC CGR testing and sharp cracks
5. A method to quantify the effectiveness of the hybrid process to seal the cracks, thus mitigating SCC growth in Alloys 600/182 was developed: interrupted crack growth rate (CGR) testing to measure SCC CGRs prior and after the application of the treatment
6. SCC CGR testing have shown that under optimal conditions, the hybrid treatment sealed the crack, and substantial reductions in CGR of **220x** in Alloy 600 and **14x** in Alloy 182 were achieved for test durations of ~1000 hours demonstrating the feasibility of the laser-cold spray hybrid process to mitigate SCC.

Future Work

1. Utilize repaired A600-ST-2 and A182-TS-2 specimens to conduct fatigue CGR testing to determine whether the response is consistent with Alloy 600, 690, 182 or not – further substantiating the effectiveness of the repair.

2. Utilize cold spray and/or hybrid treatment to develop coatings for corrosion resistance and/or tritium permeation in molten salt environment of advanced high temperature reactors (AHTRs)