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Update on SCC CGR testing of Alloys 52/152 at DMW interfaces and as WOLs

Bogdan Alexandreanu, Yiren Chen, and Ken Natesan

Argonne National Laboratory

NRC Project Manager: Margaret Audrain

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Presentation topics

SCC CGR response of Alloys 52/152 near DMW interfaces

- Alloy 152 butter – reactor head (ANL), two weldments

SCC CGR response of Alloy 52M WOLs

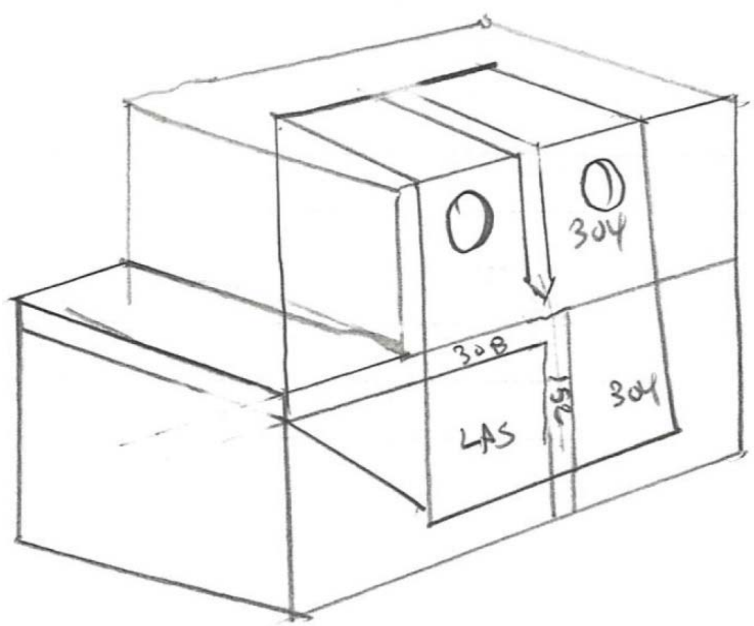
- Alloy 52M WOL-182 by KAPL, two directions (TS and ST)
- Alloy 52M WOL-182 by EWI, one directions (TS)

SCC CGR response of high heat input Alloy 52/152 welds CGR tests on welds:

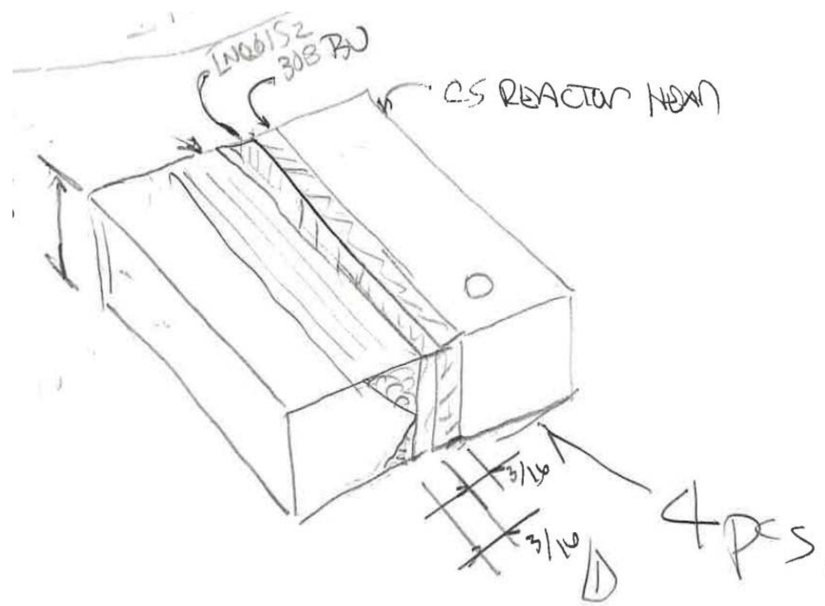
- High heat input Alloy 52M weld (EPRI)
- High heat input Alloy 152 weld (ANL)

Preliminary observations on the aged Alloy 152 weld (focus on Alloy 690)

Weldments produced at ANL for Alloy 152 1st layer testing



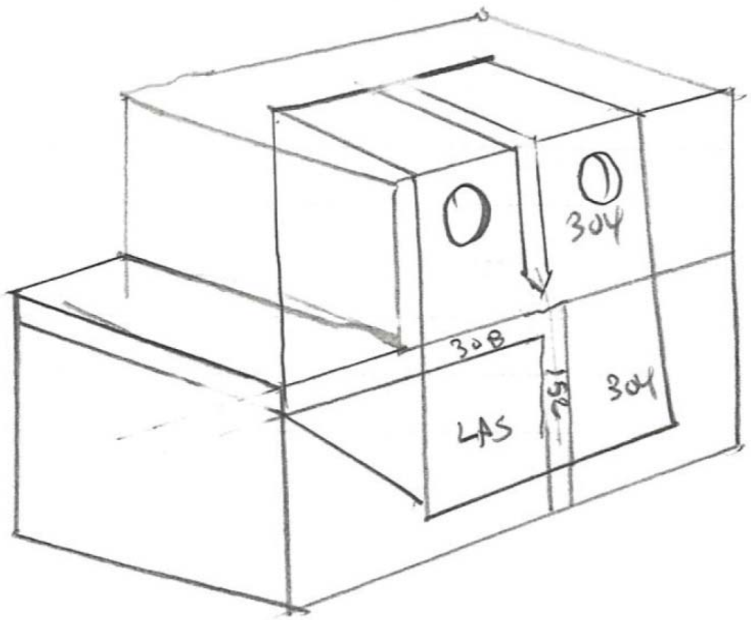
JC152



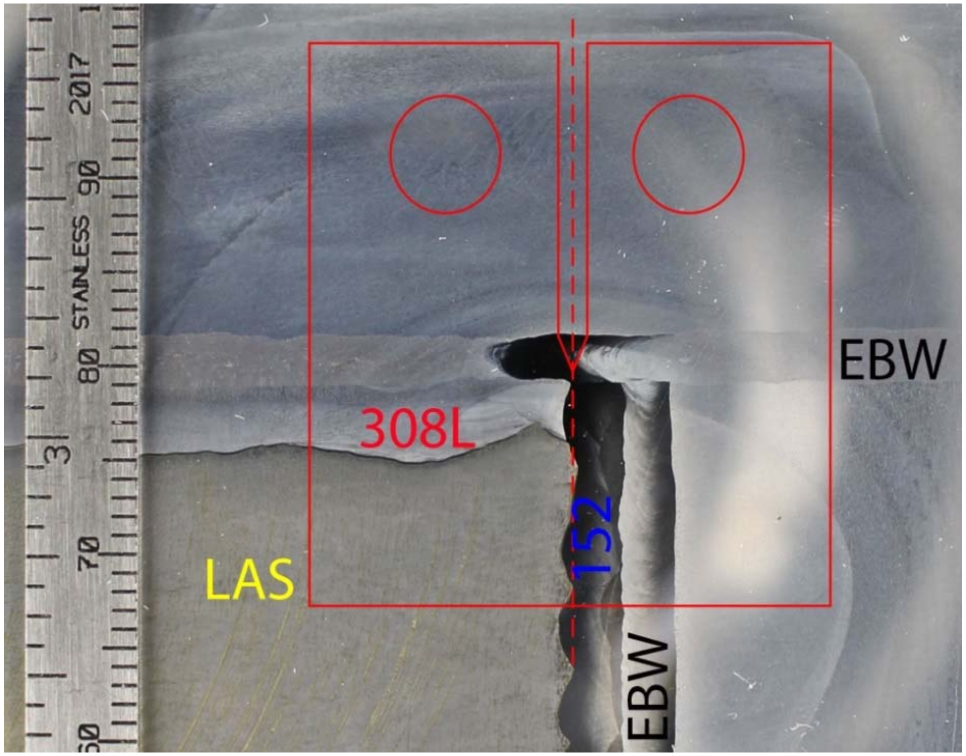
BA152

- Produced using 308L-clad 533-Gr B LAS from Midland lower head, same heat of Alloy 152 (720129, 28.9 wt.% Cr) as was used in the N152-LAS butter
- JC152: propagation in 152 along interfaces with 308L clad and LAS
- BA152: propagation in 152 along 308L clad

Weldments produced at ANL for Alloy 152 1st layer testing: JC152 – reactor head material

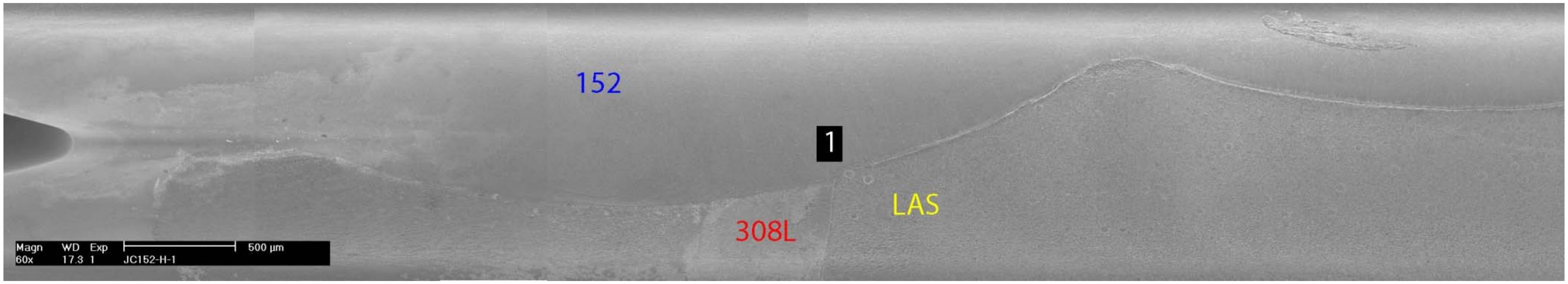


JC152



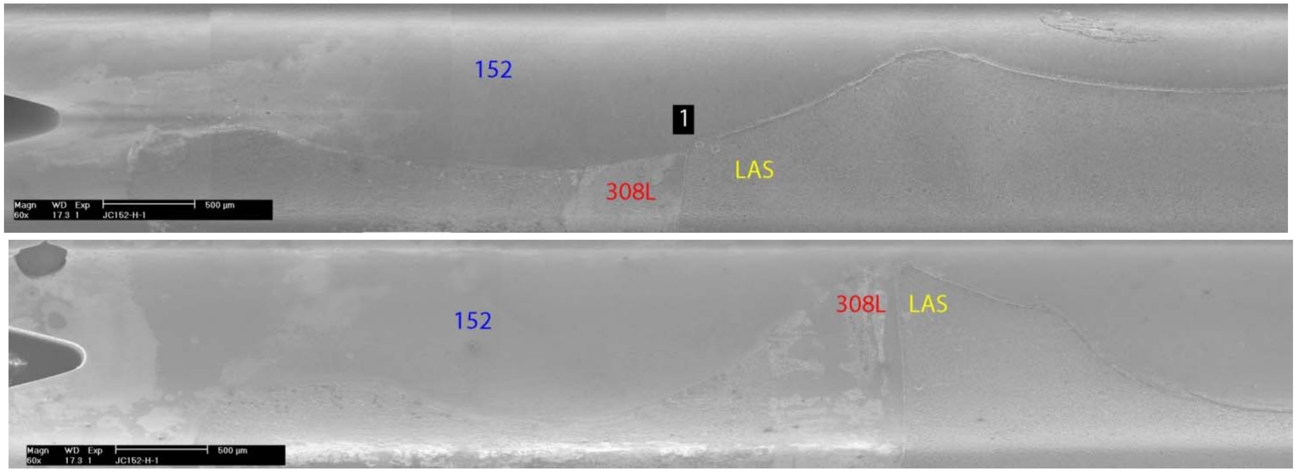
- Produced using Alloy 308L-clad 533-Gr B LAS from Midland lower head; additional pieces EB=welded to accommodate the size of the specimen
- JC152: propagation in 152 along interfaces with 308L clad and LAS

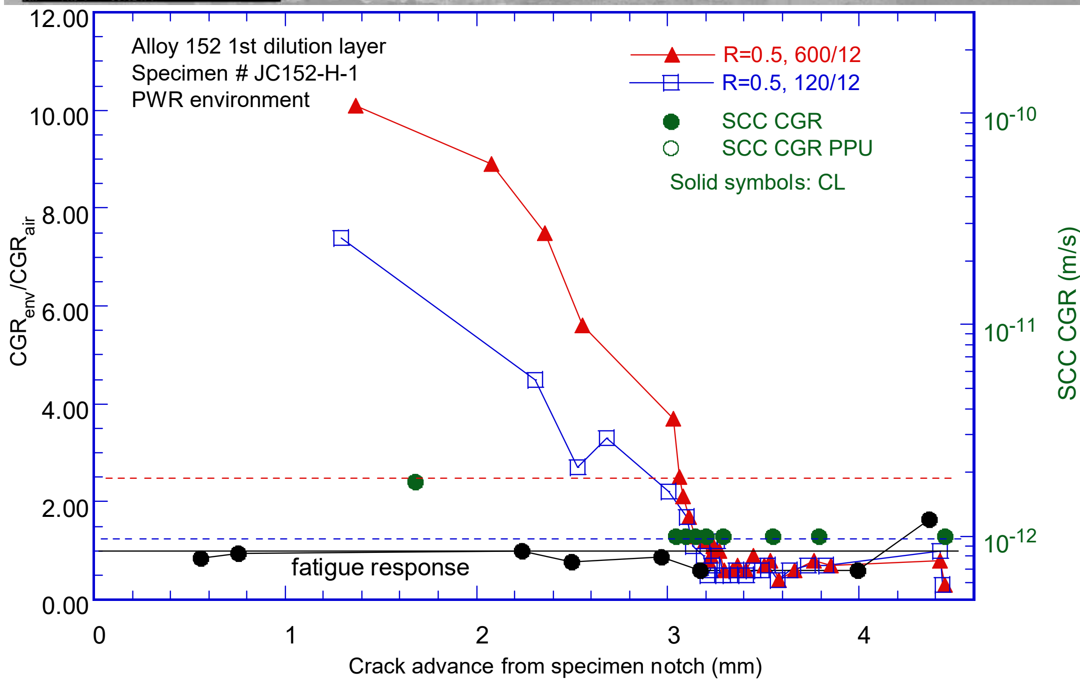
Specimen JC152-H-1



- Orientation chosen close to the steel (despite prior tests that showing that Fe-rich swirls impede SCC propagation, and high SCC CGRs directions were away from the interface)

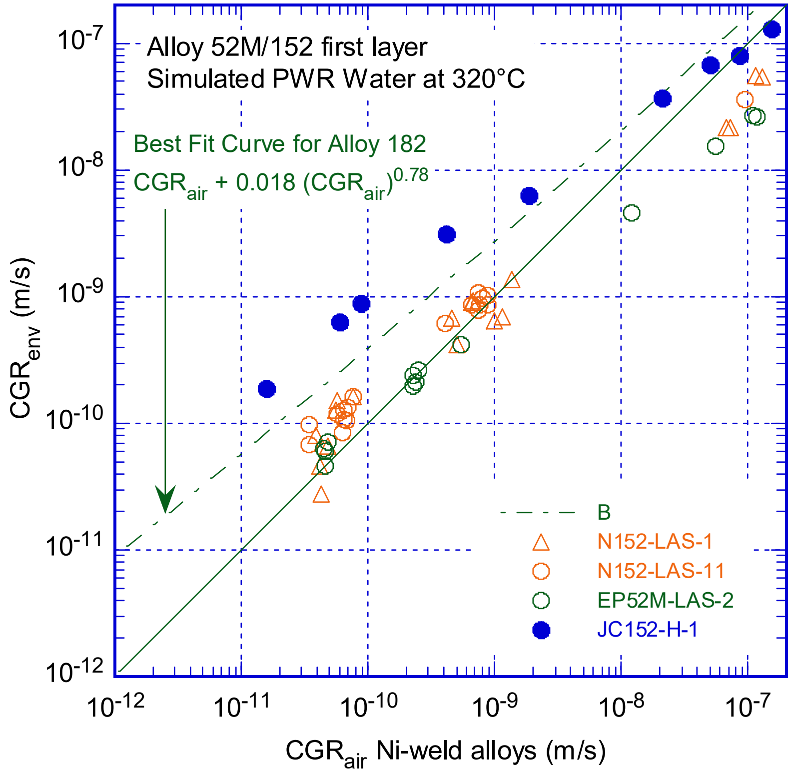
Specimen JC152-H-1

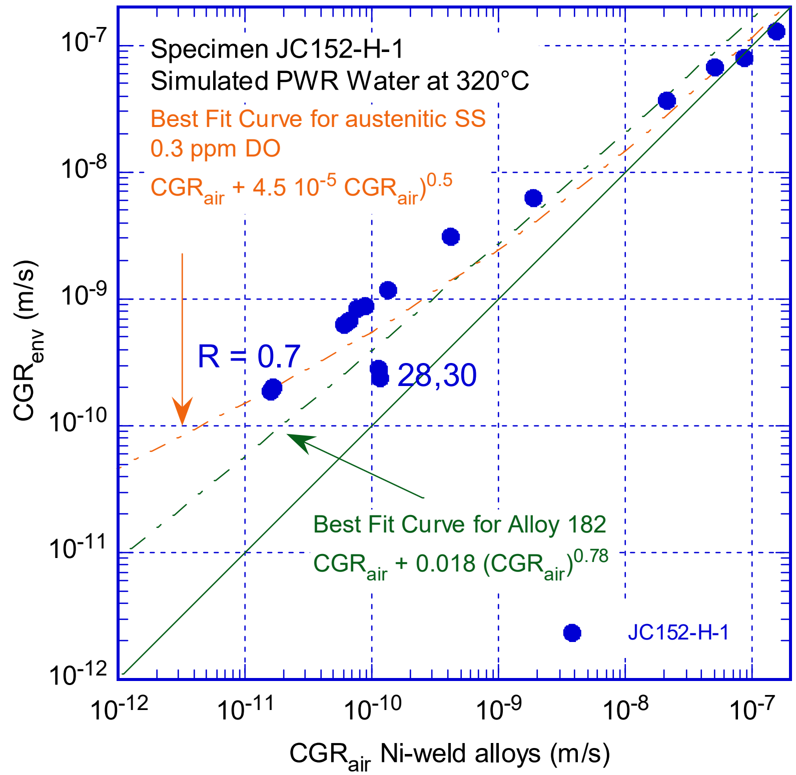




- Three cyclic CGR regions: 10x (expectation is only 2-3x), decreasing, and plausible

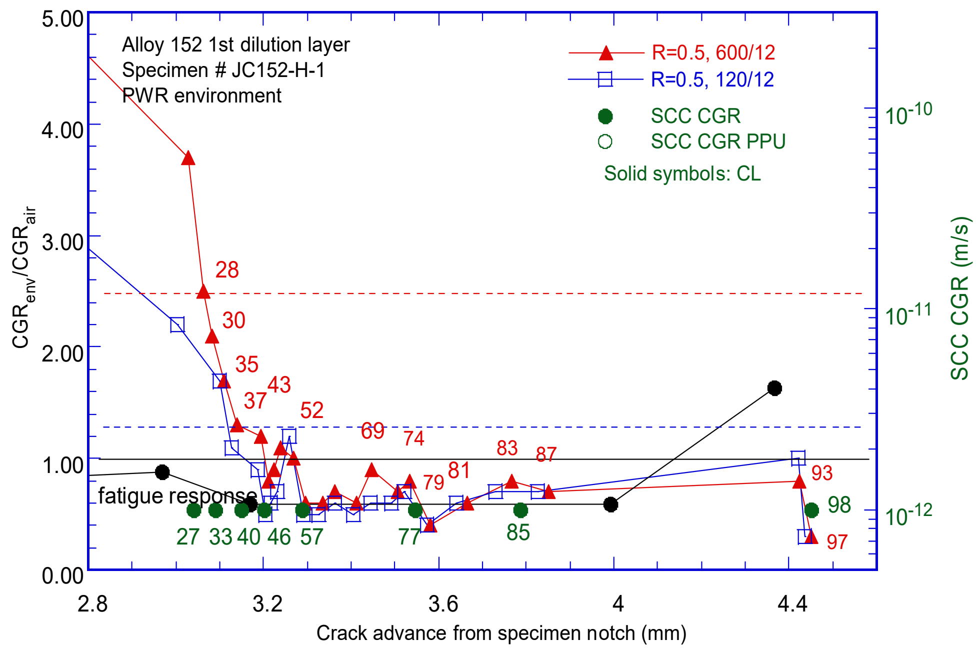
Specimen JC152-H-1

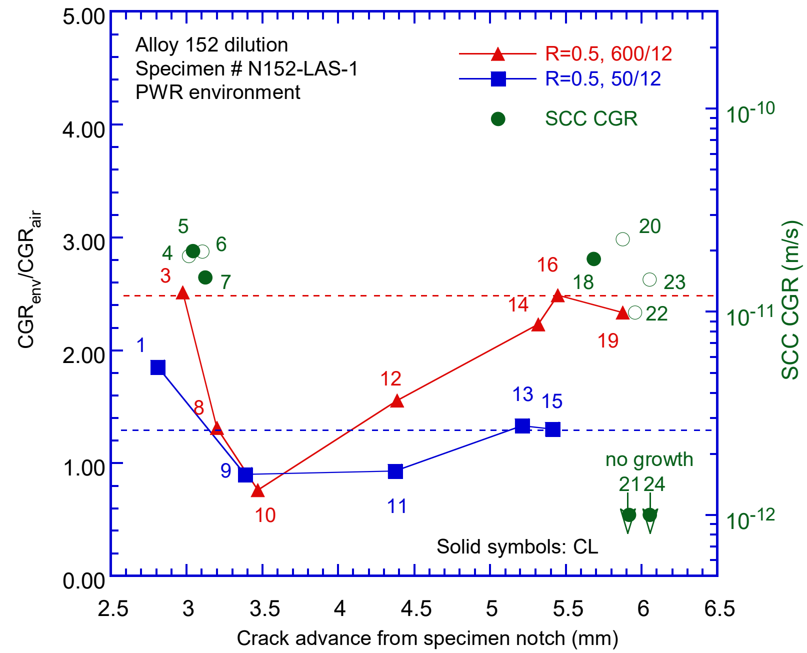




- Cyclic CGR response substantially higher than previous 1st layer Alloy 52/152 tests
- Response consistent with that of SSs

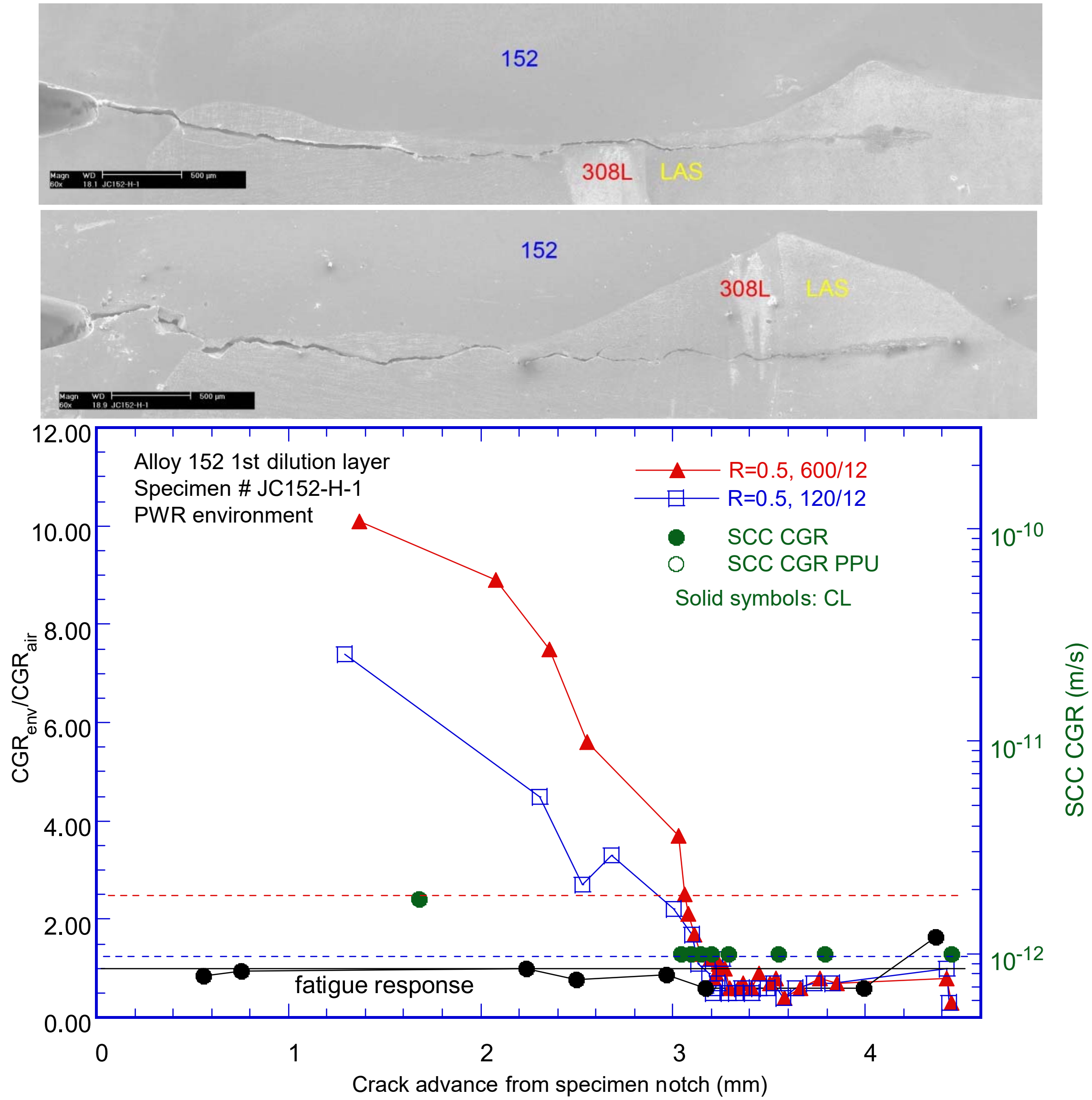
Specimen JC152-H-1 – comparison with previous Alloy 152 butter (ANL) of the same heat





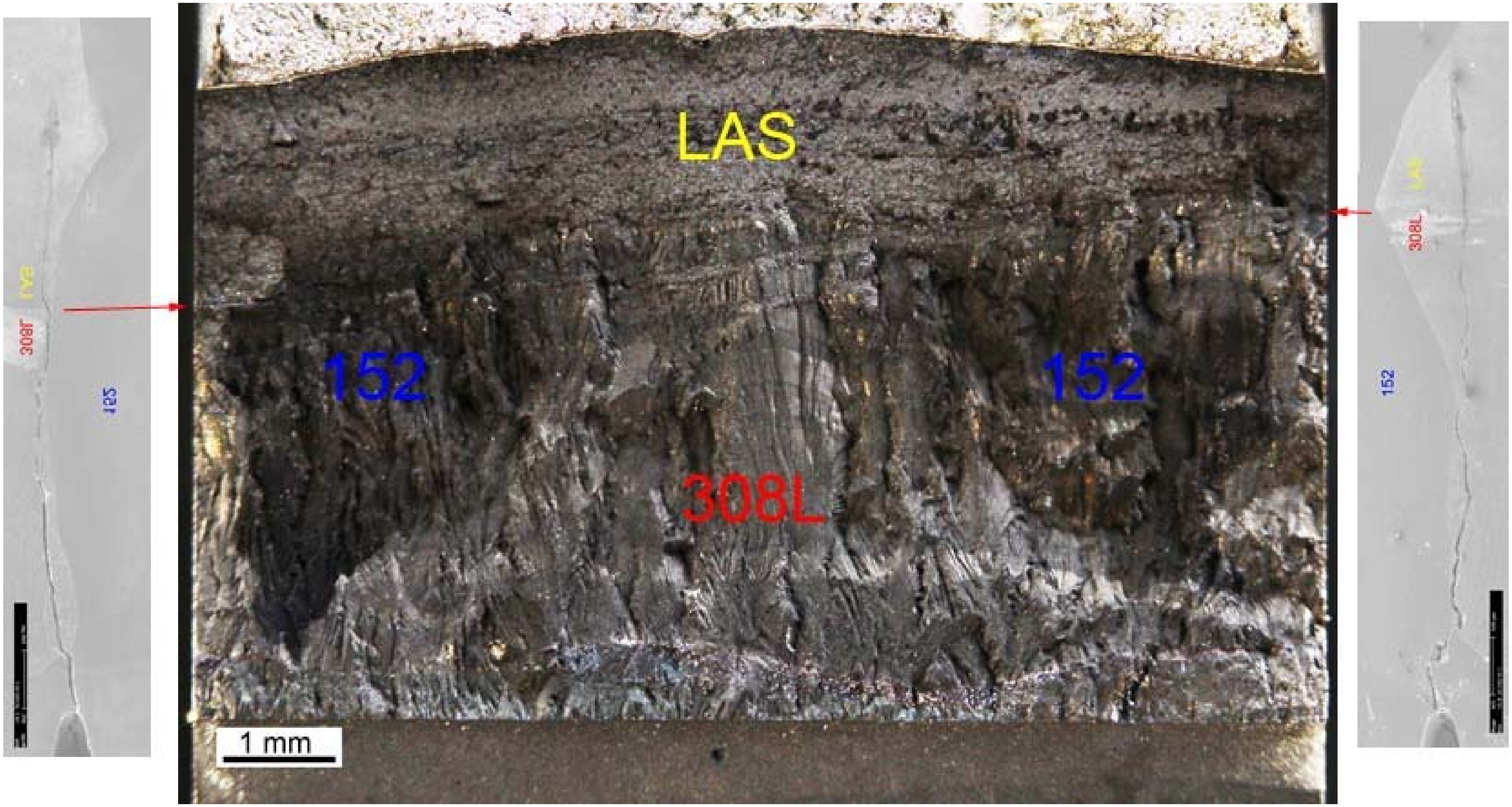
- Not inconsistent with prior response if off-plane cracking is taken into account

Specimen JC152-H-1 – side surfaces



- After side groove removal, side surfaces suggest all propagation took place in steels

Specimen JC152-H-1 – fracture surface



- Fracture surface is complex
- Propagation was close to the interface in several areas, no vulnerability (IG SCC fracture) was detected

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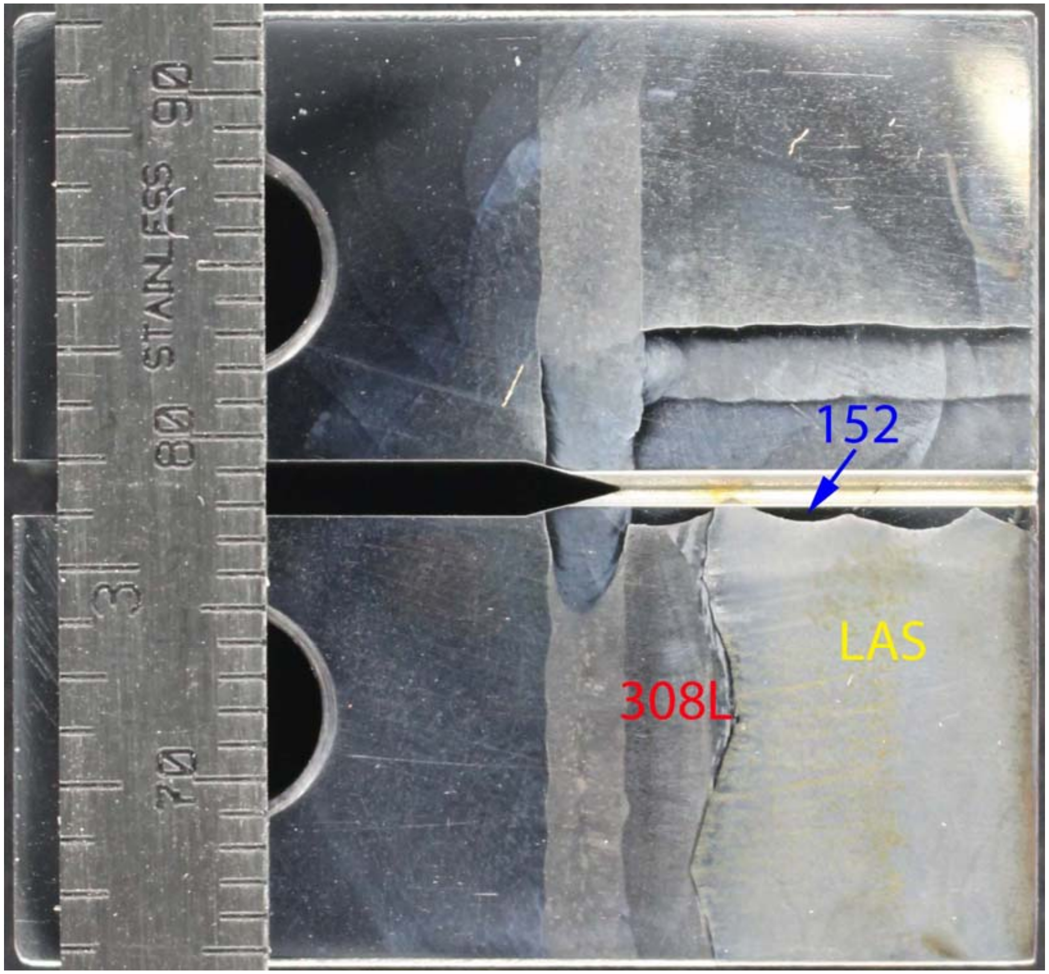
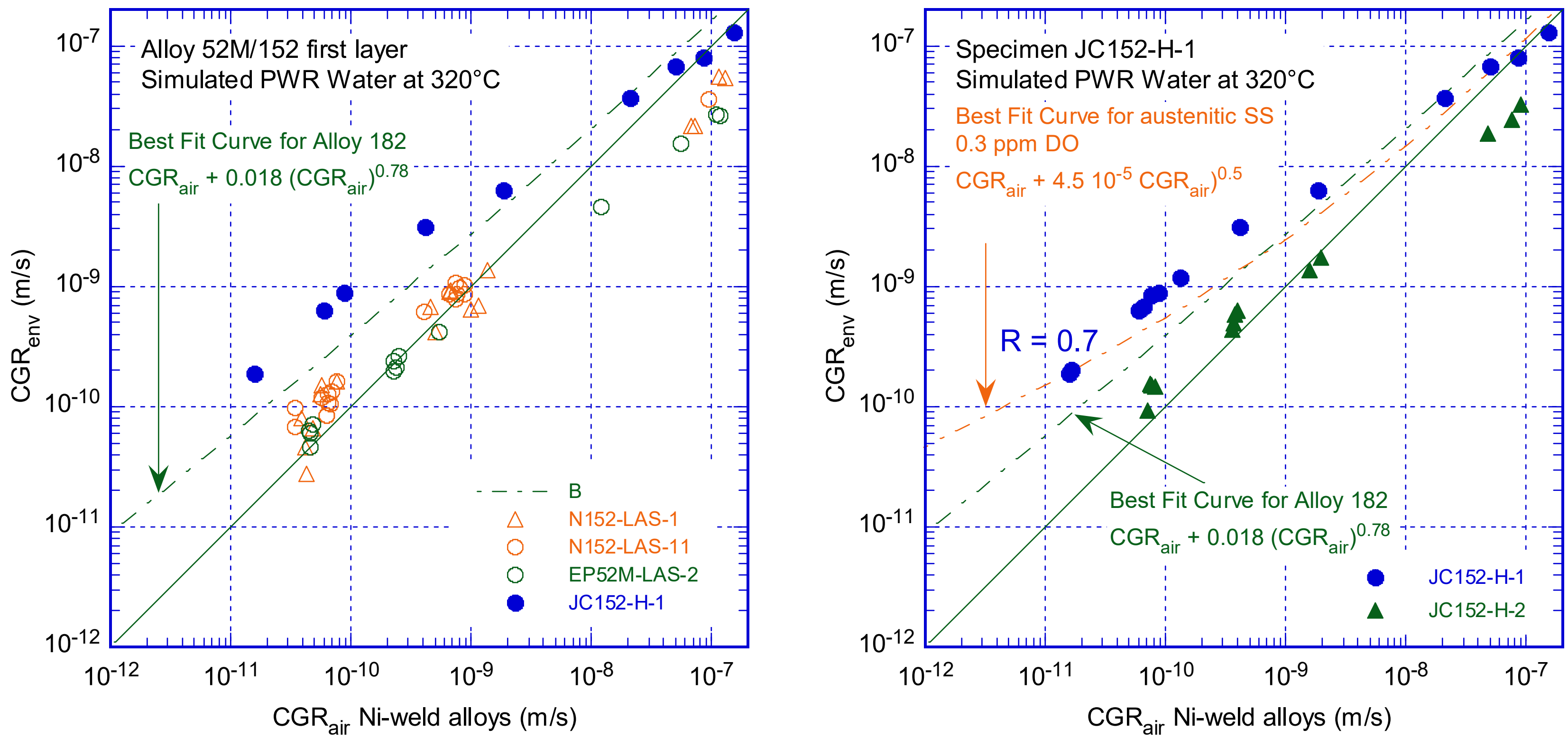
Specimen JC152-H-2 – lessons learned



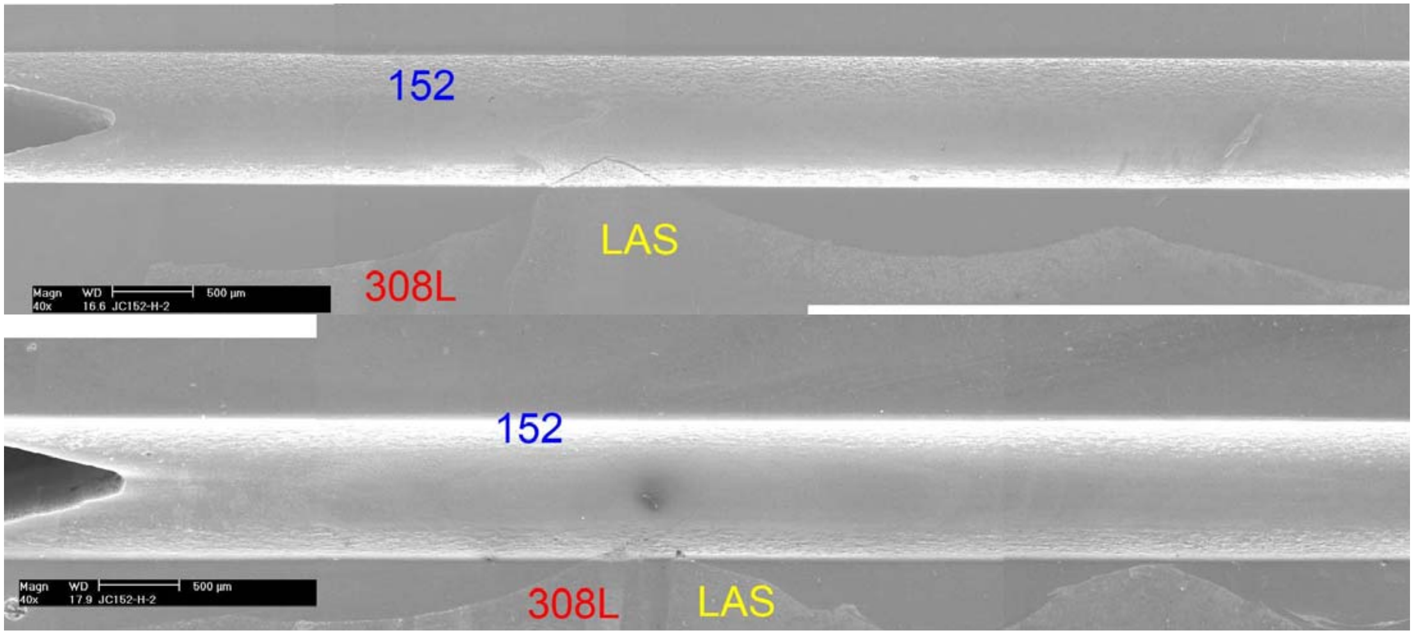
- Crack path clears the steel. Steel impedes/arrests SCC propagation
- In both very high SCC CGR Alloy 152-LAS specimens tested at ANL, the crack propagated away from the interface

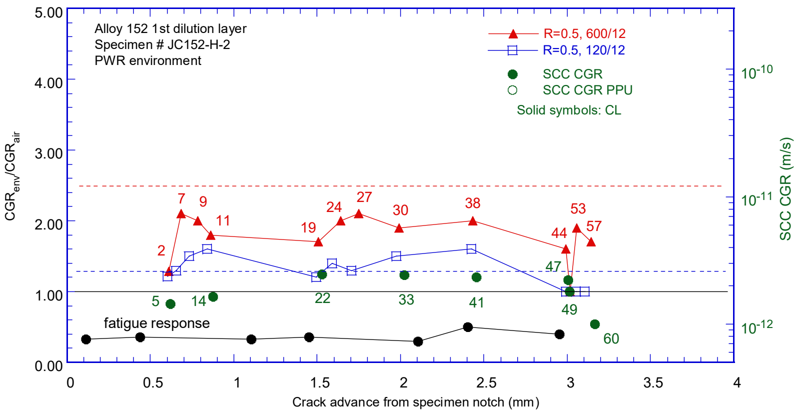
Specimens JC152-H-2 and JC152-H-1



- Cyclic CGR response for the current specimen consistent with that for a 1st layer Alloy 52/152 weld

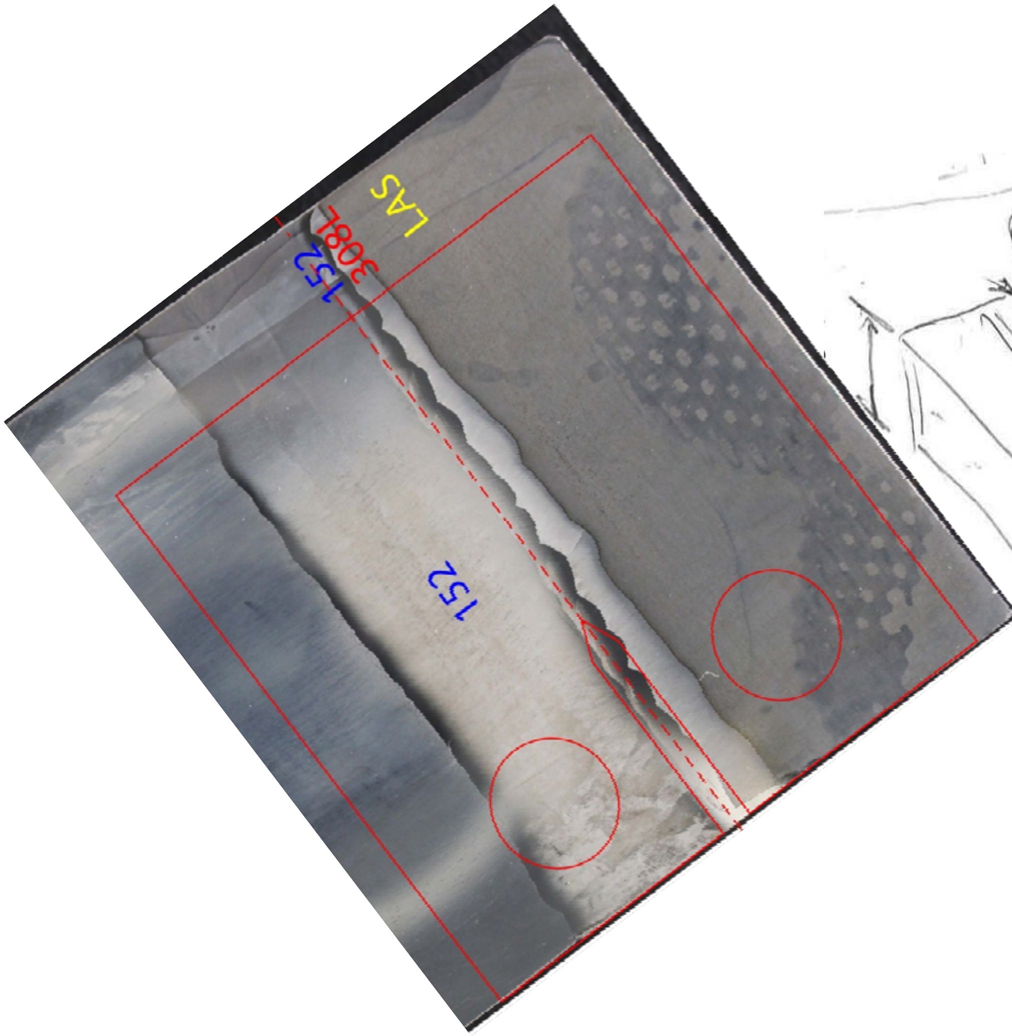
Specimen JC152-H-2 – side surfaces

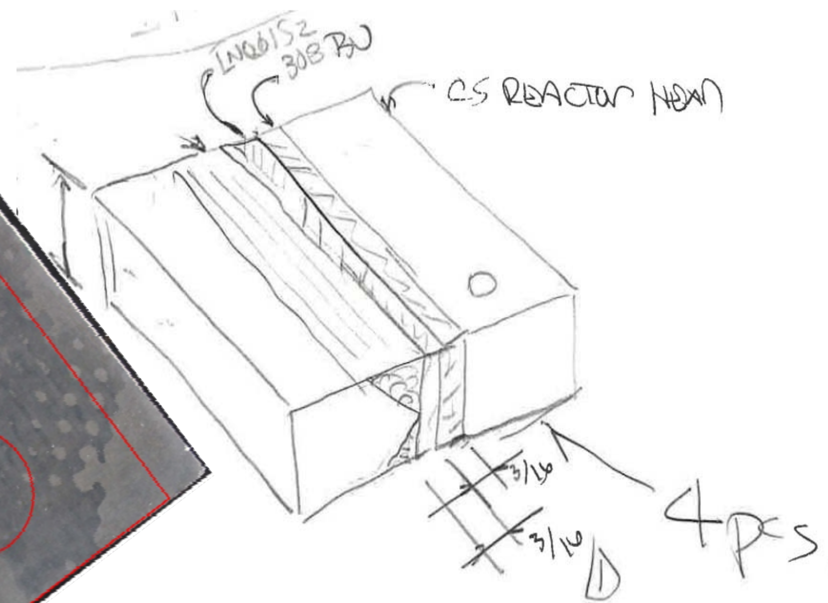




- Test still in progress, to date consistent cyclic CGR response and low SCC CGRs
- Test will continue on the weld side opposite to the LAS

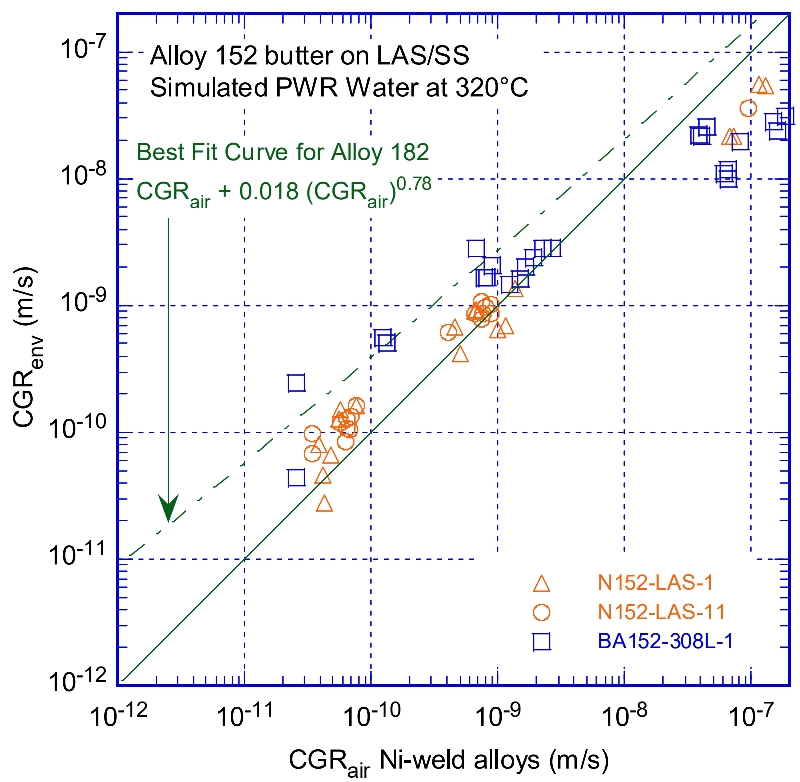
Specimen BA152-308L-1





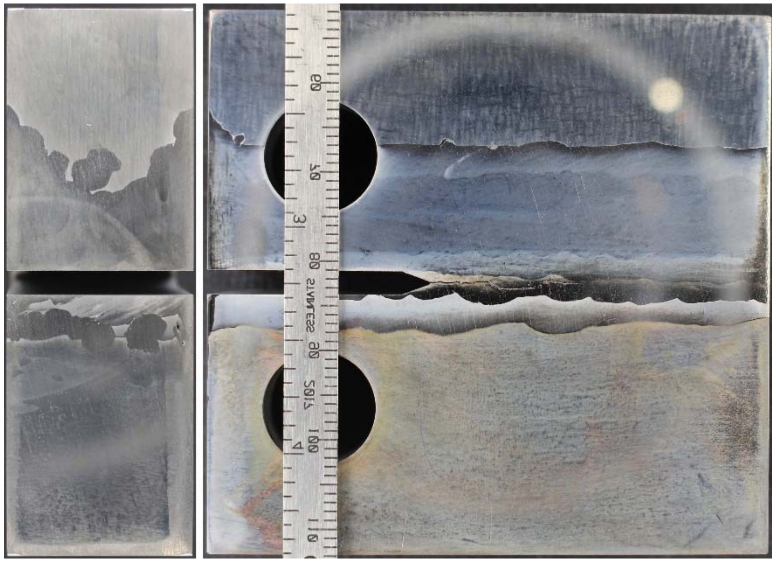
- Propagation is in the Alloy 152 butter deposited on the Alloy 308L clad

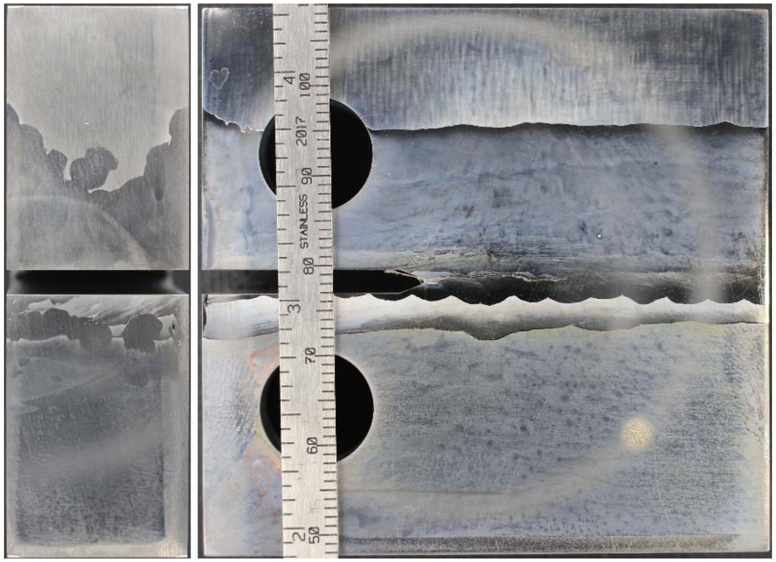
Specimen BA152-308L-1

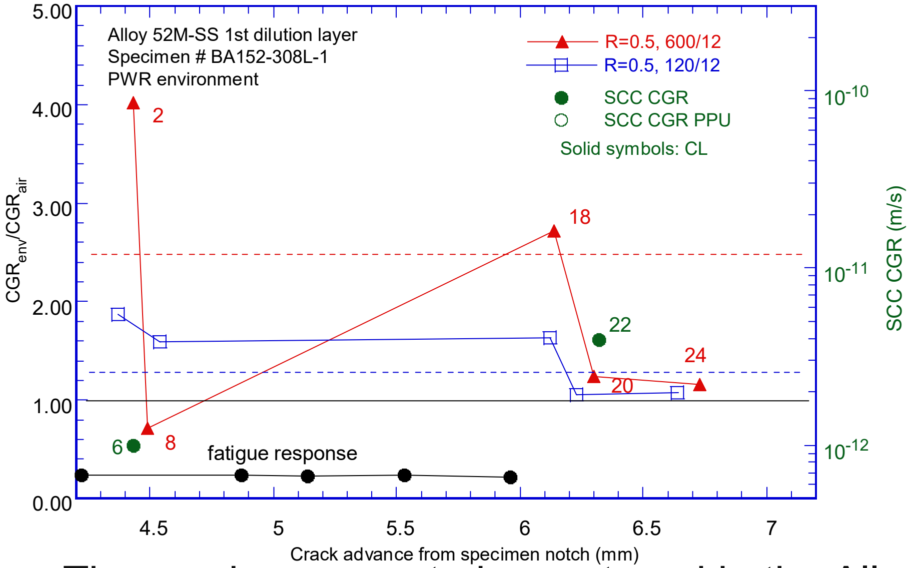


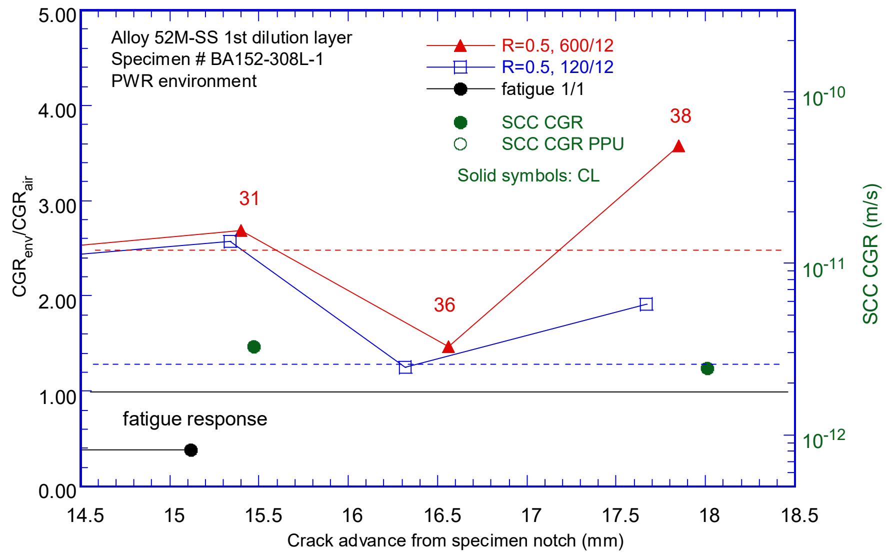
- Cyclic CGR response consistent with that from previous tests on the same heat

Specimen BA152-308L-1







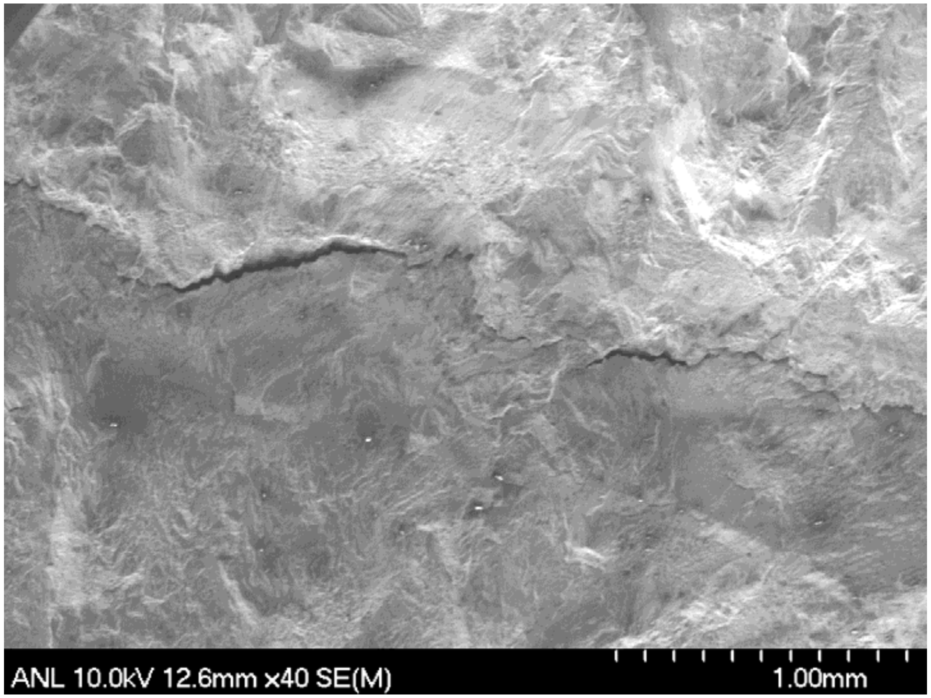


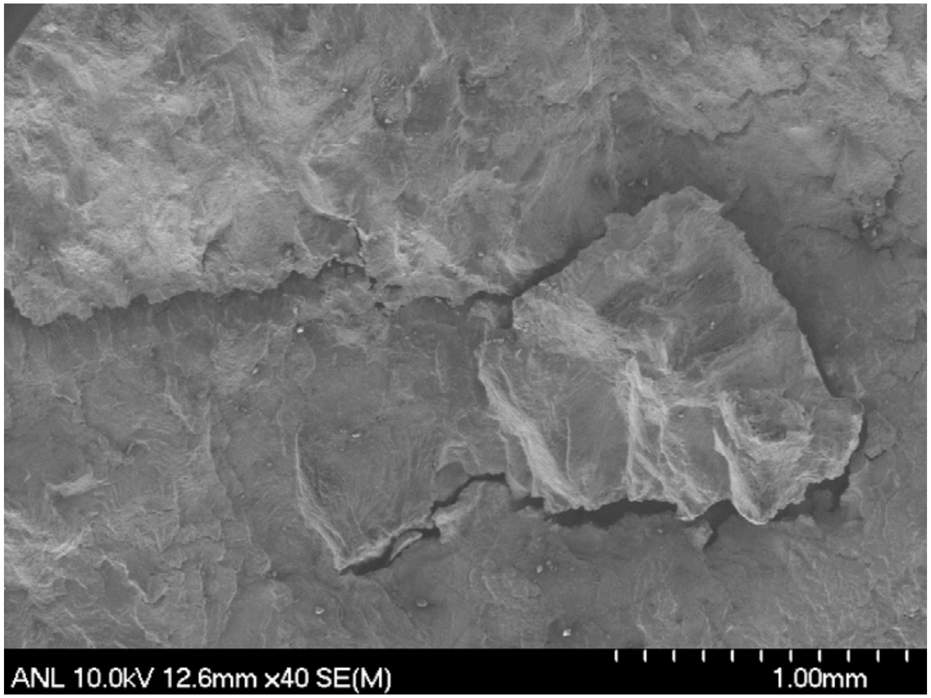
- The crack appears to have stayed in the Alloy 152 butter
- Some possible off-plane cracking, SCC CGR response low

Specimen BA152-308L-1

- Fairly straight front, excellent (7%) agreement with DC potential measurement
- Off-plane cracking, large "flake", lack of IG consistent with the low SCC CGR response low

Specimen BA152-308L-1





- Off-plane cracking, lack of IG consistent with the low SCC CGR response low

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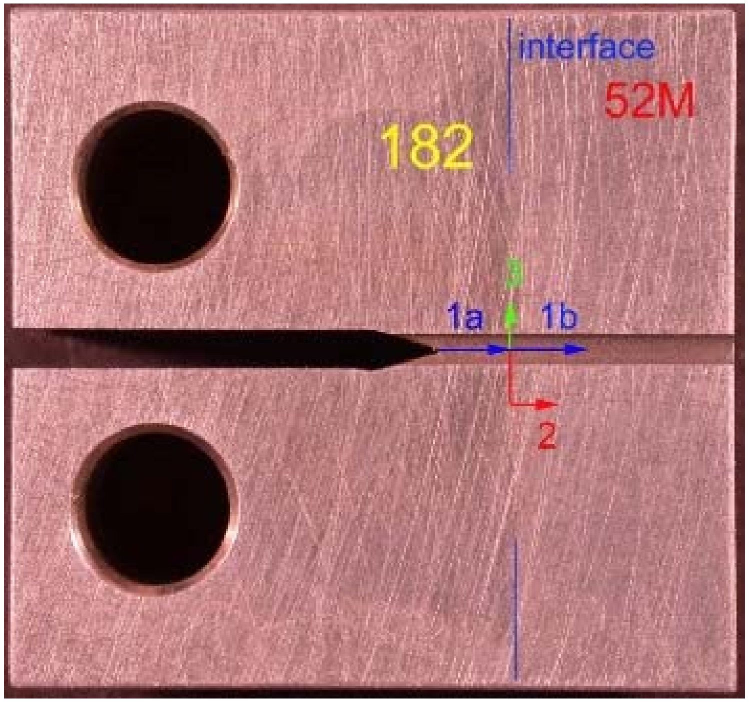
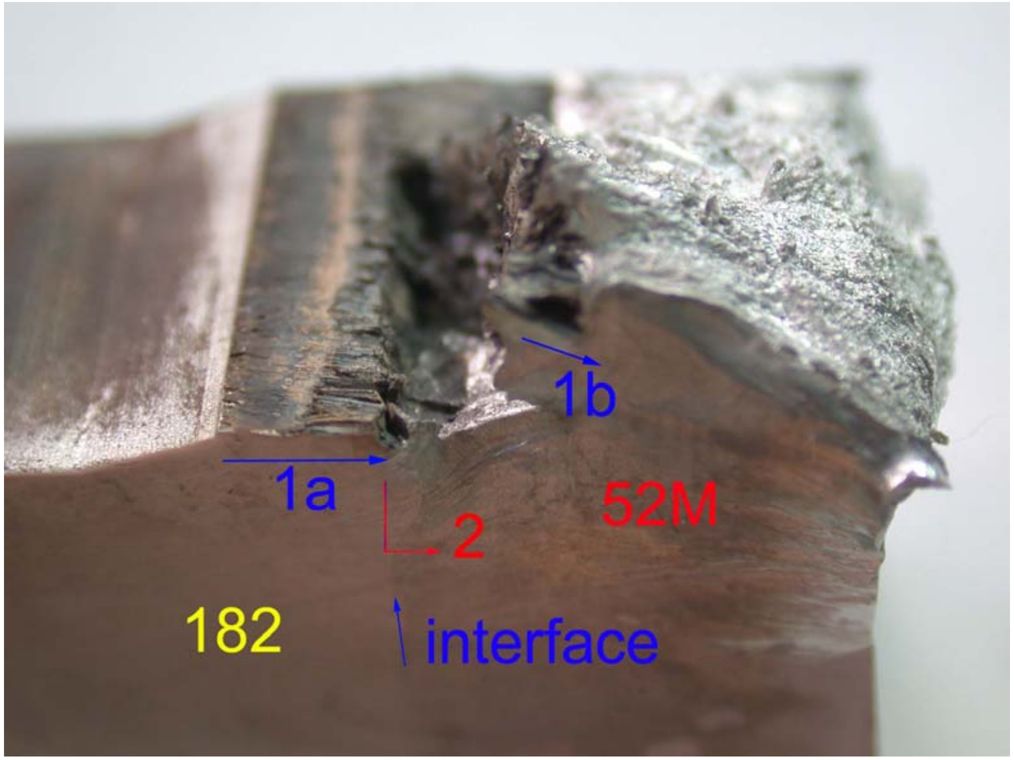
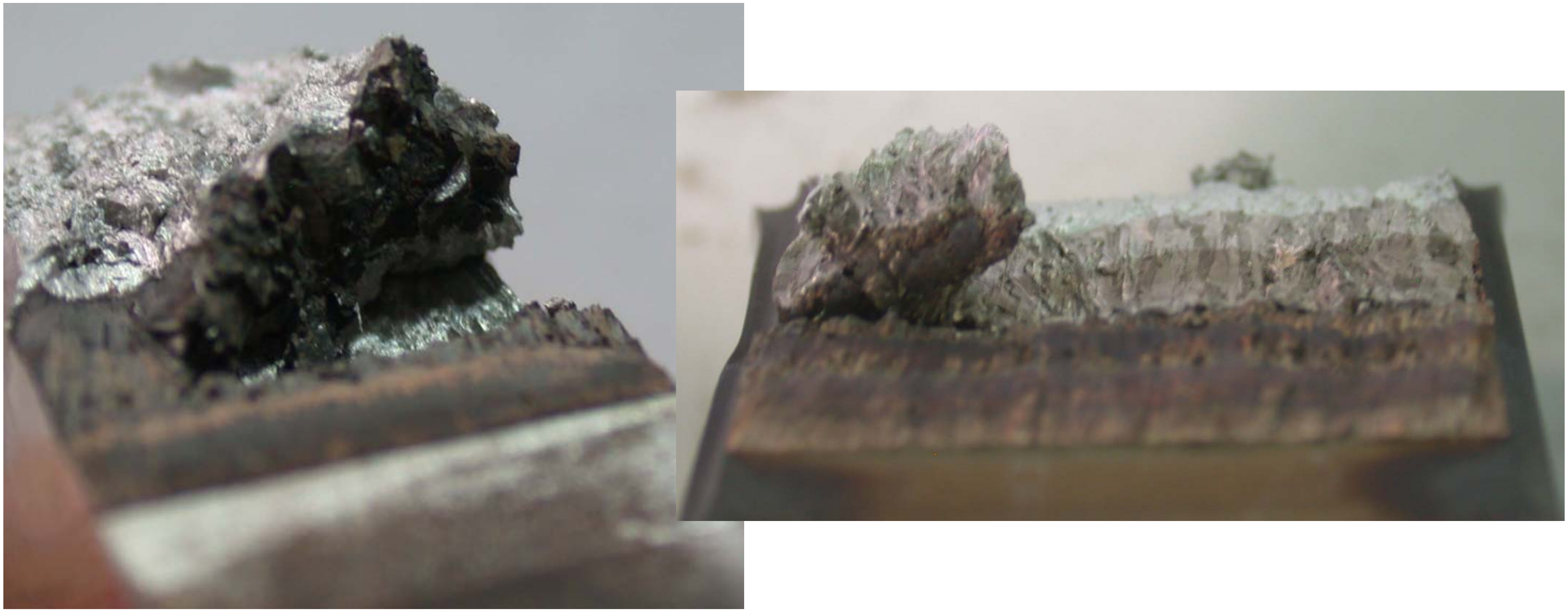
WOL prior testing: ANL Alloy 52M-182 WOL





- Crack deflection at the interface, documented in NUREG/CR-7226
- Consistent with other observations on the susceptible-to-resistant alloy transition [Seifert et al. in the Journal of Nuclear Materials (2008)]

WOL prior testing: ANL Alloy 52M-182 WOL

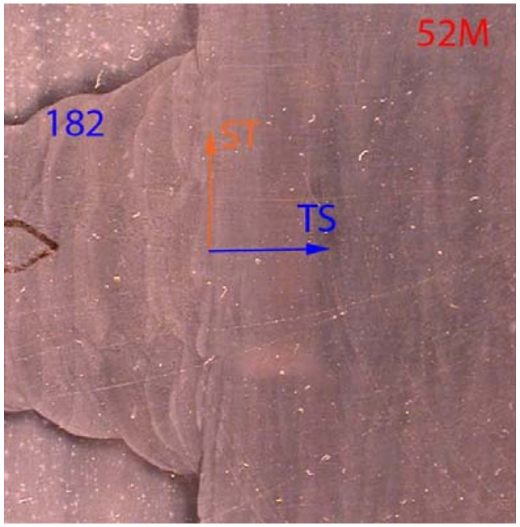


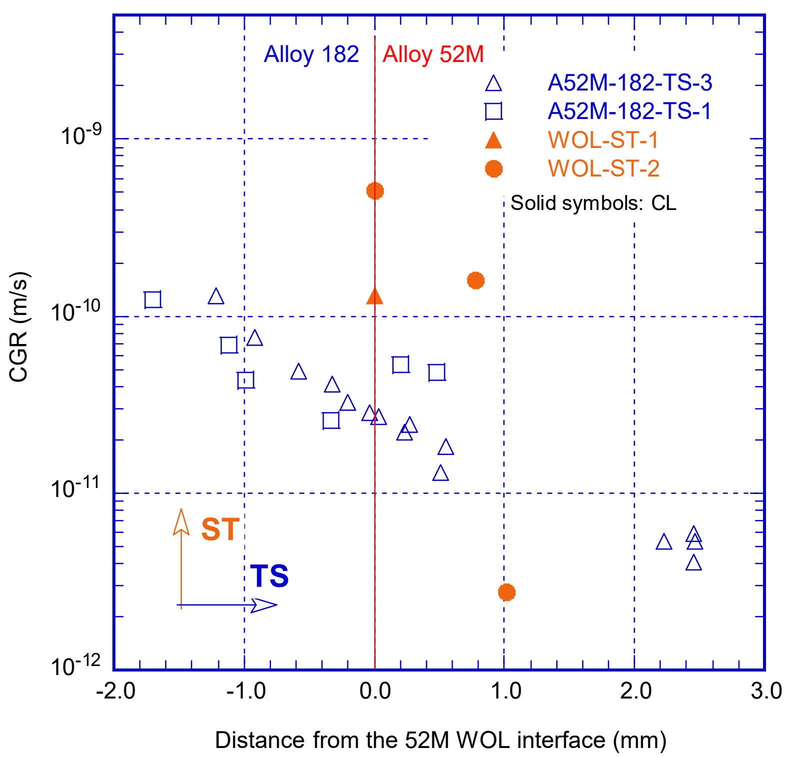
- Crack deflection at the interface was observed on both specimens tested
- Based on measurements, SCC CGR was estimated to be 10^{-10} m/s range
- SCC CGR was measured in a dedicated test to be 10^{-10} m/s range (NUREG/CR-7226)

WOL prior testing: ANL Alloy 52M-182 WOL

- Some SCC penetration of the WOL (some substantial) was observed

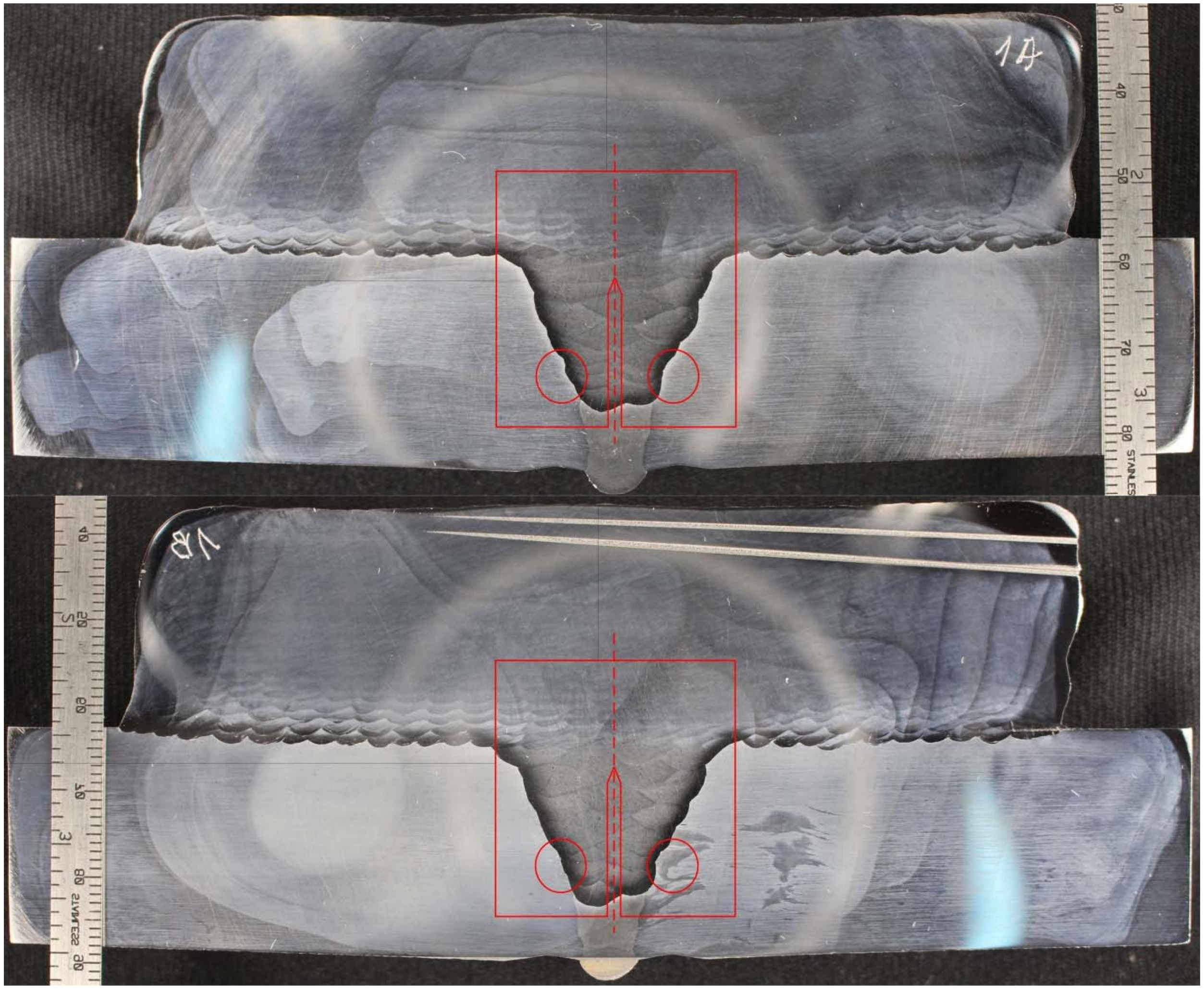
WOL prior testing: ANL Alloy 52M-182 WOL





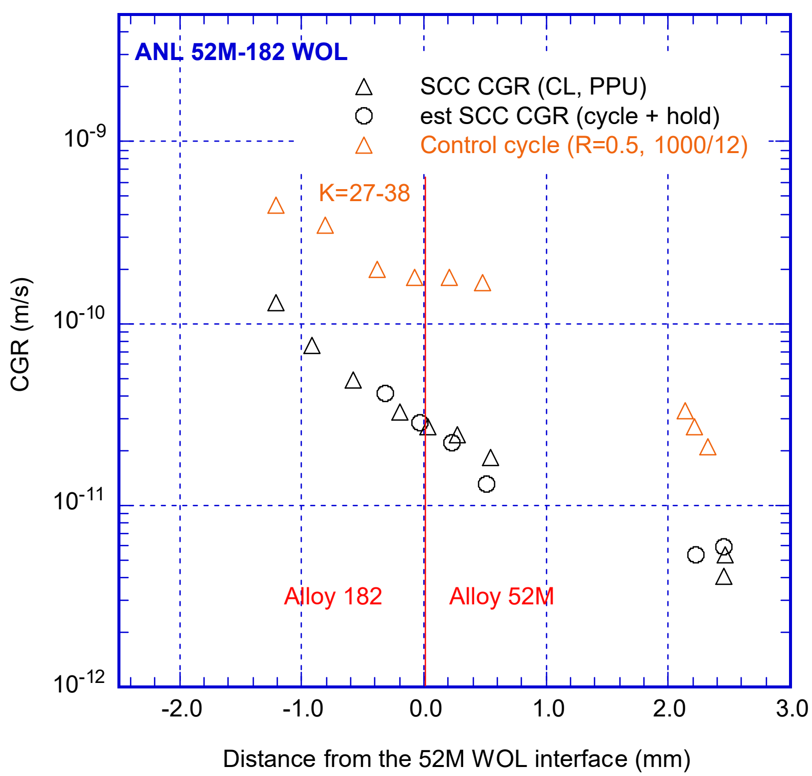
- Factor 10x decrease in SCC CGR in 1 mm ahead of the interface (response reproduced on two specimens)
- Fast (10^{-10} m/s) SCC CGRs in the first layer and along the interface [NUREG/CR-7226]

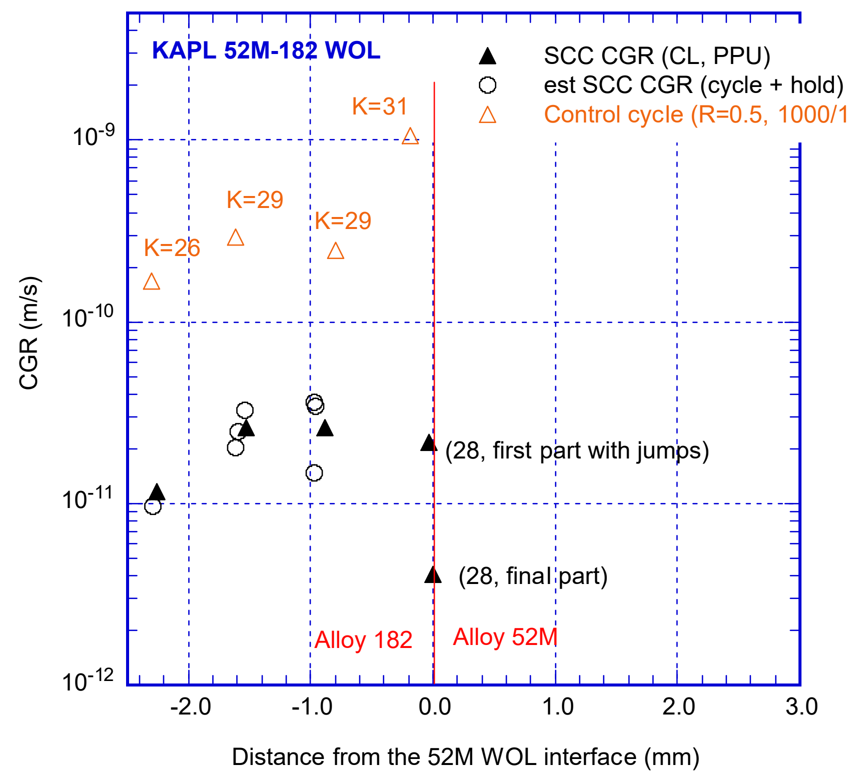
KAPL Alloy 52M-182 WOL: K52M-ST-1



- TS orientation: propagate a crack from Alloy 182 into Alloy 52M WOL

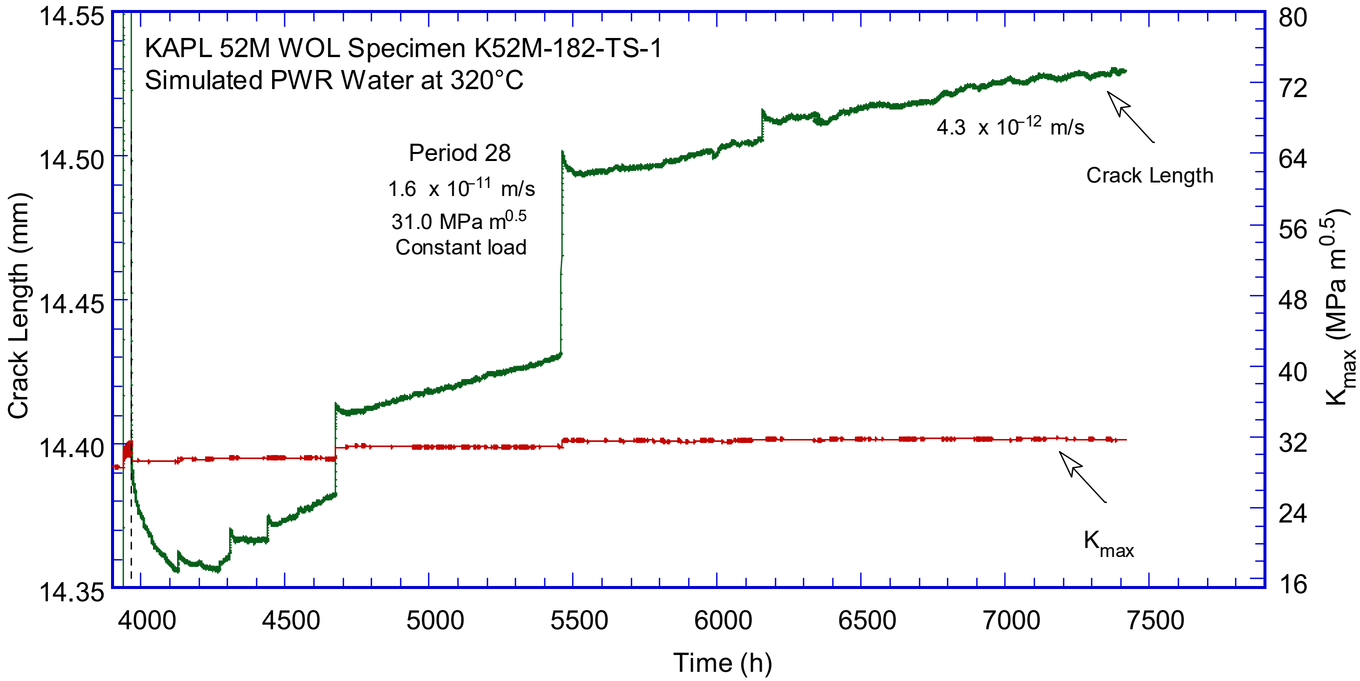
KAPL Alloy 52M-182 WOL: K52M-ST-1





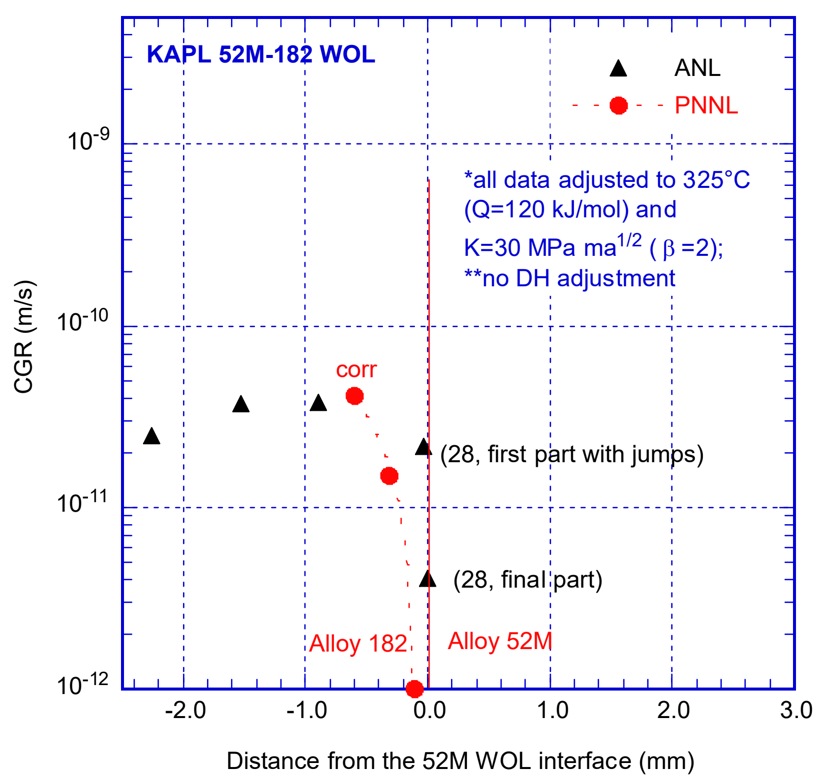
- KAPL WOL uncorrected data

KAPL Alloy 52M-182 WOL: K52M-ST-1



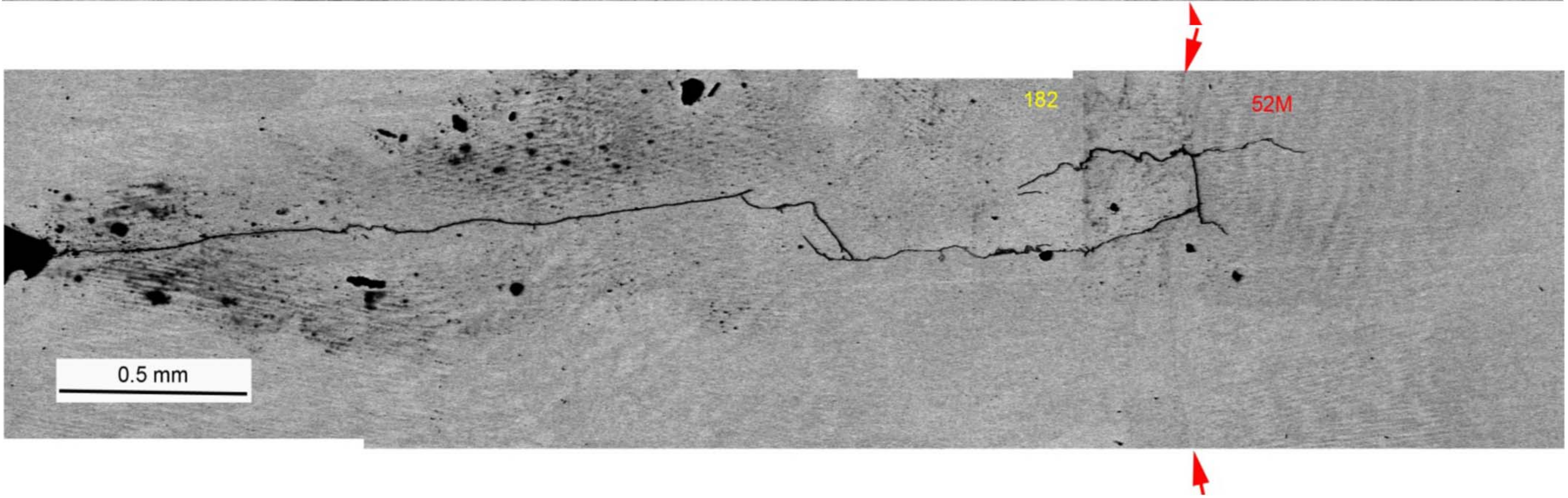
- KAPL WOL uncorrected data
- Set at CL (directly from cycling) for the final test period 0.18 mm from the WOL and only grew that much

KAPL Alloy 52M-182 WOL: K52M-ST-1



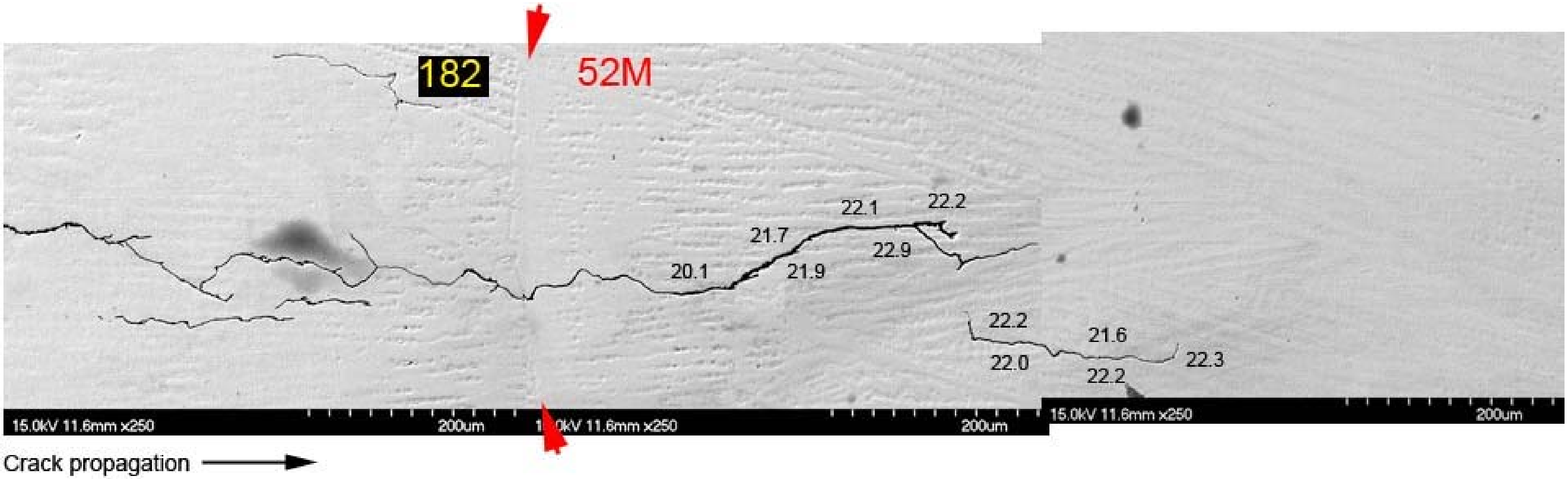
- KAPL WOL uncorrected data
- SCC appears to have been arrested at the WOL

KAPL Alloy 52M-182 WOL: K52M-ST-1 – side surfaces



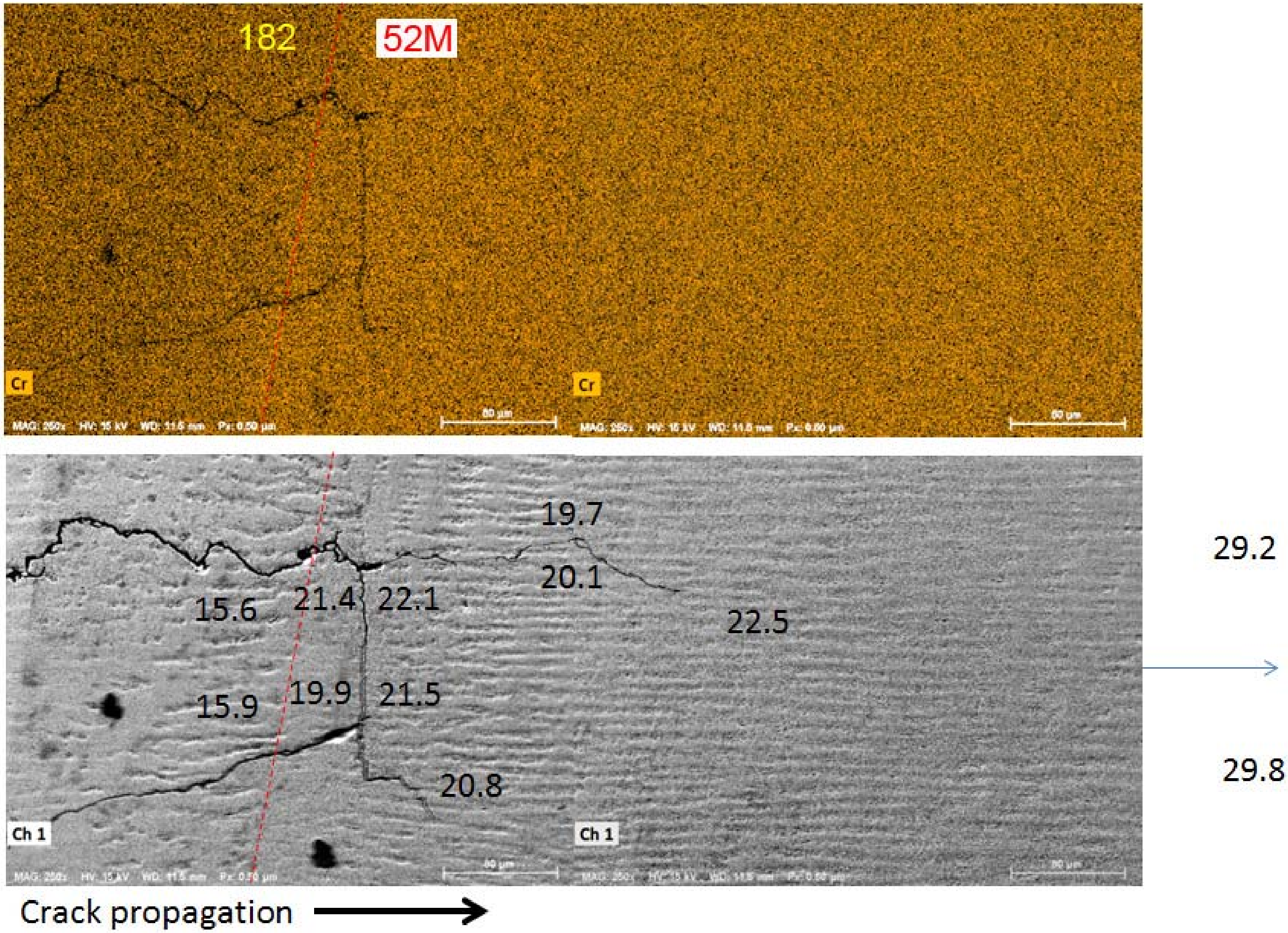
- SCC does not seem to have been arrested at the WOL

KAPL Alloy 52M-182 WOL : K52M-ST-1 – side surface 1



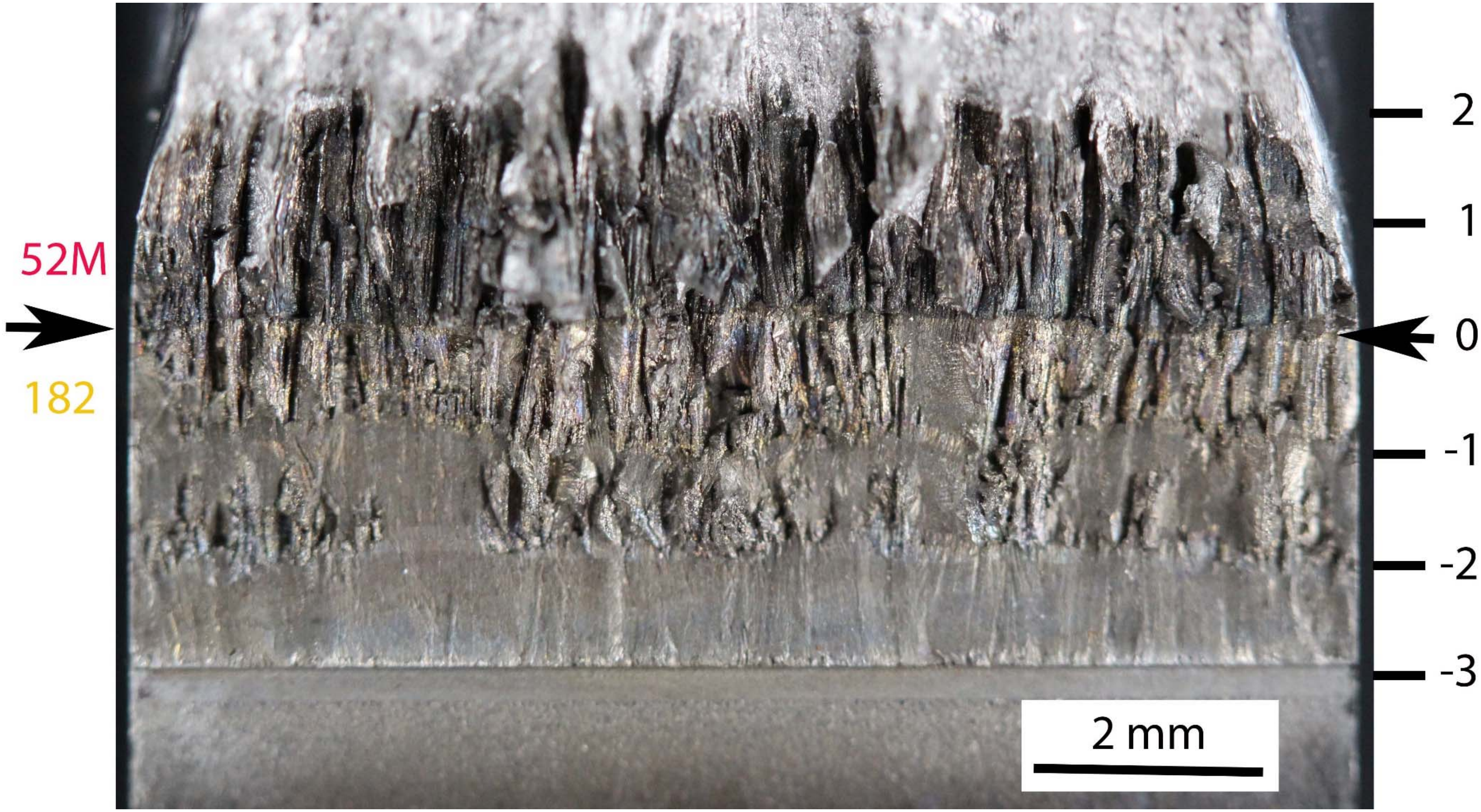
- 1 mm long extension into Cr-depleted region (22 wt.% Cr)

KAPL Alloy 52M-182 WOL : K52M-ST-1 – side surface 2



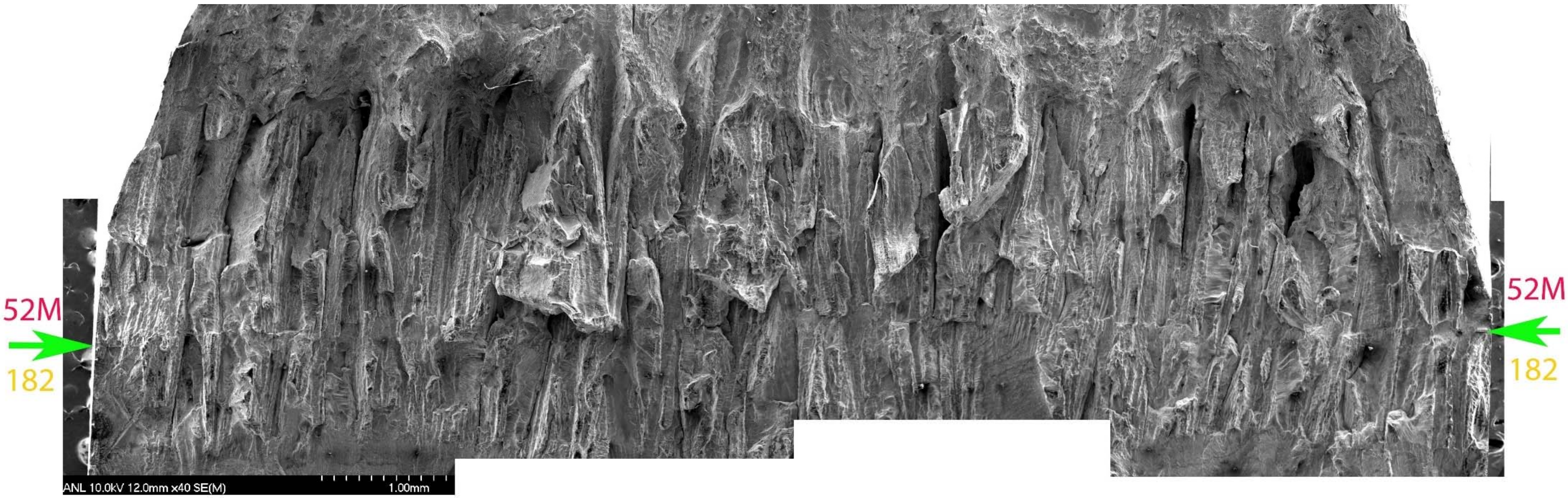
- Off-plane cracking and extension into the WOL

KAPL Alloy 52M-182 WOL : K52M-ST-1 – fracture surface



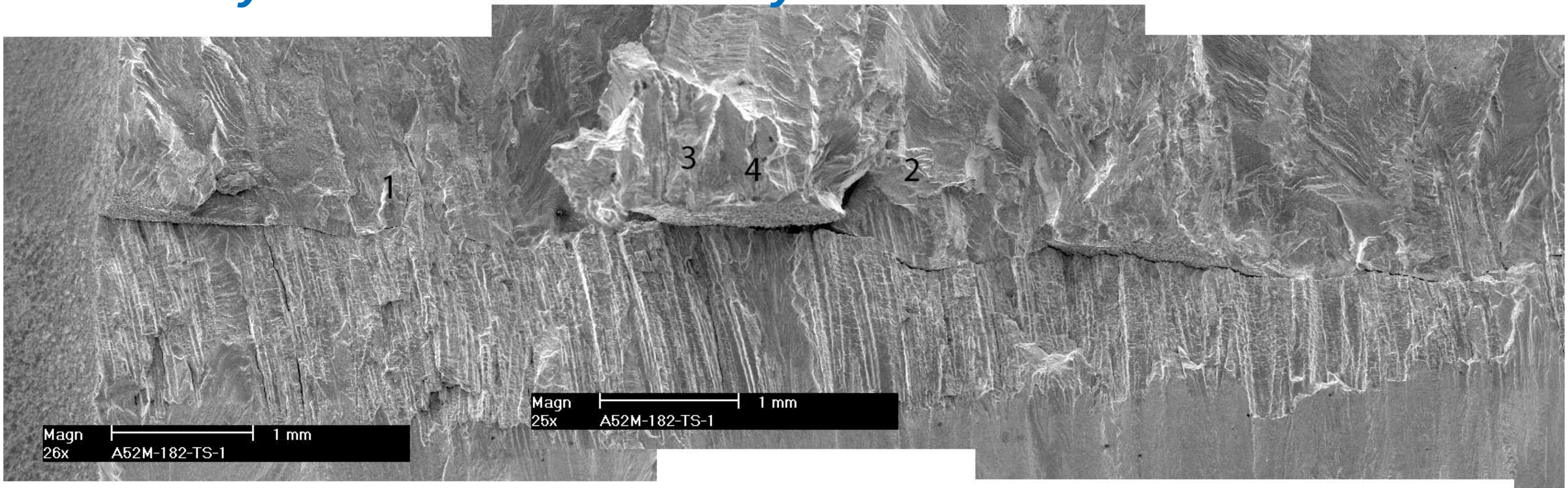
- 1.8 mm extension into the WOL (10x the DCPD measurement) over 4,300 hrs at CL

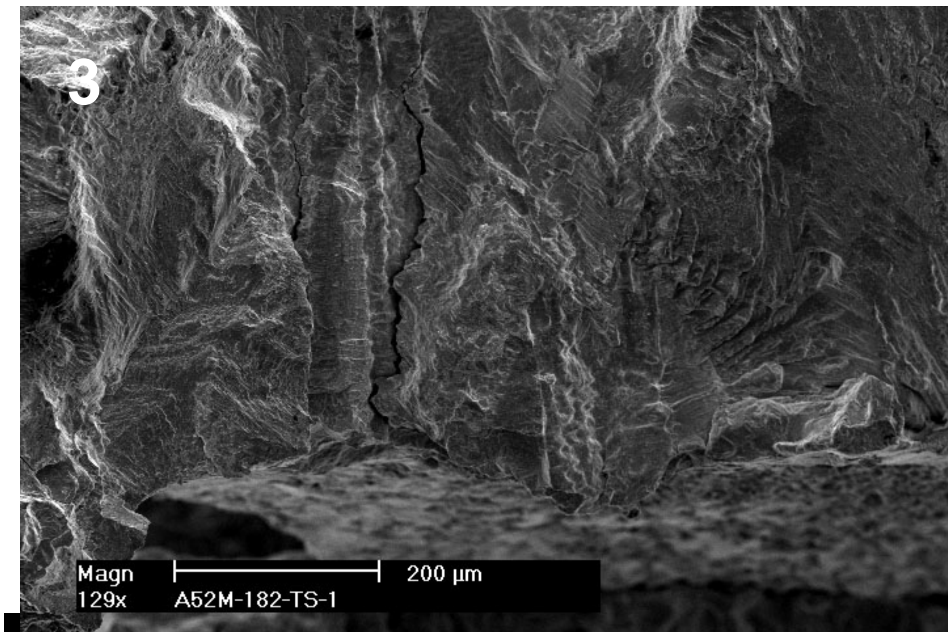
KAPL Alloy 52M-182 WOL – fracture surface

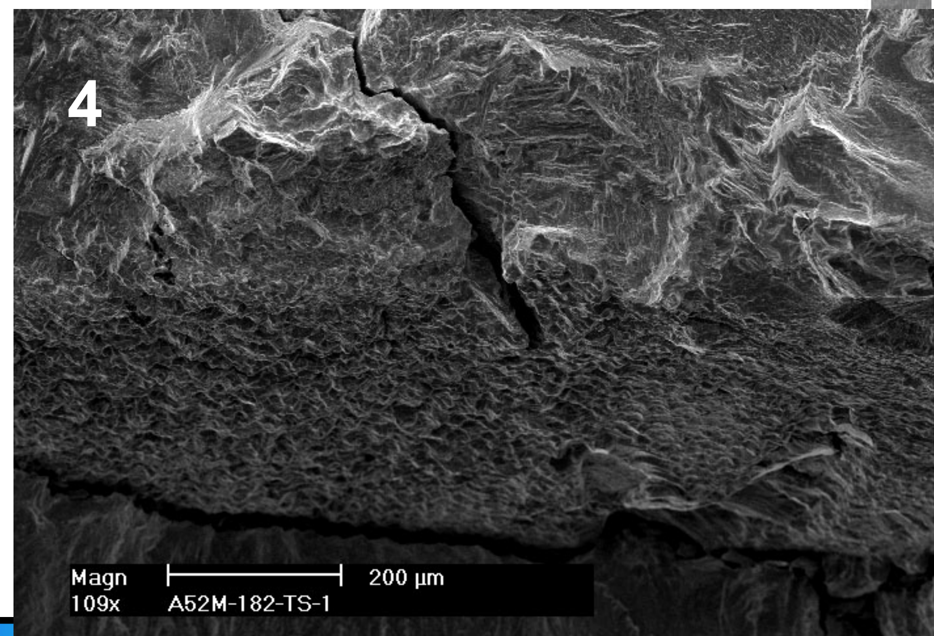


- 1.8 mm IG SCC extension into the WOL
- Not much off-plane cracking (deflection), transitioning from one weld to the other occurred smoothly (implies that this WOL is not very resistant)

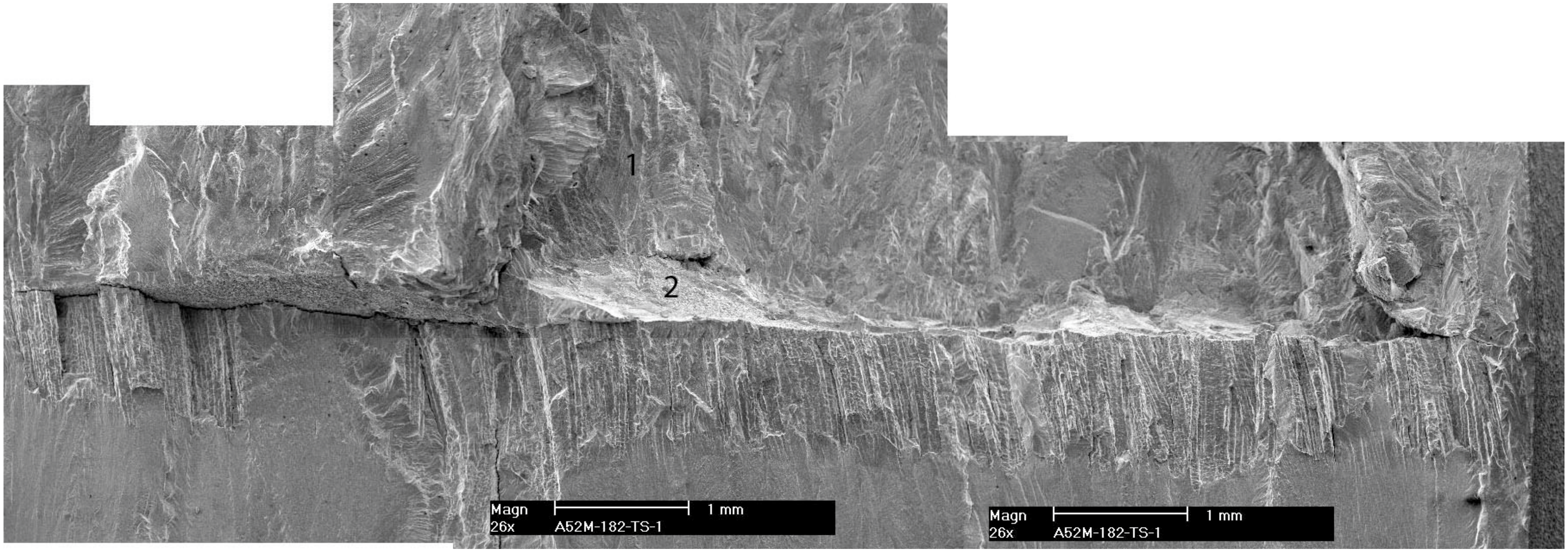
ANL Alloy 52M-182 Weld Overlay – Fracture Surface 1/2

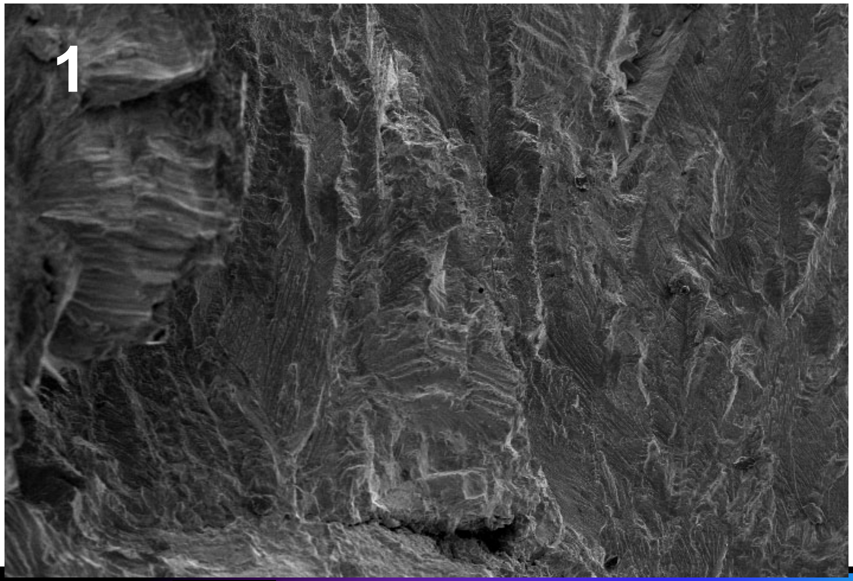


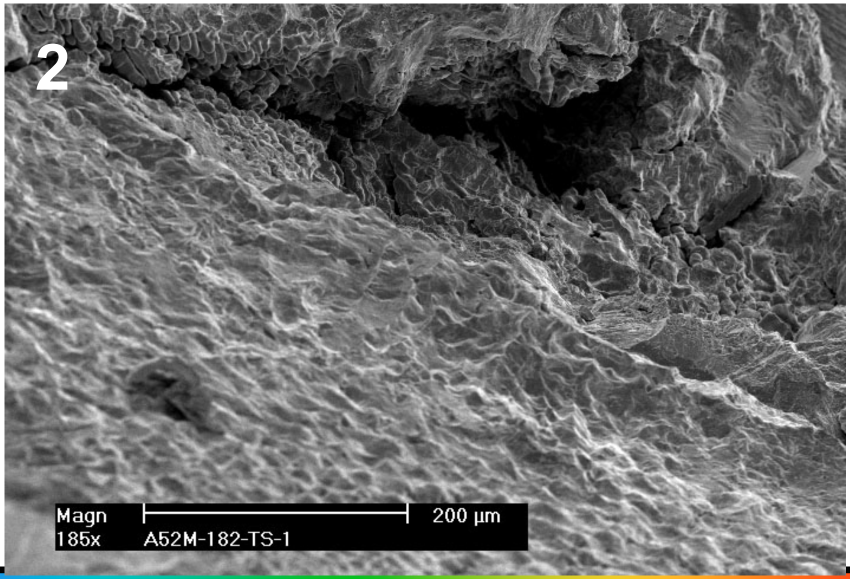




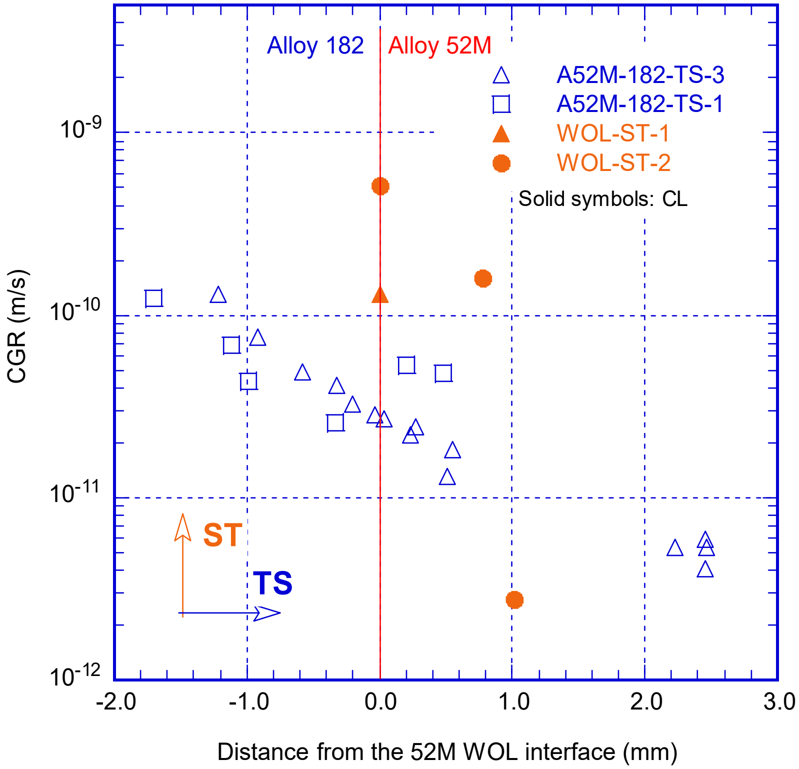
ANL Alloy 52M-182 Weld Overlay – Fracture Surface 2/2

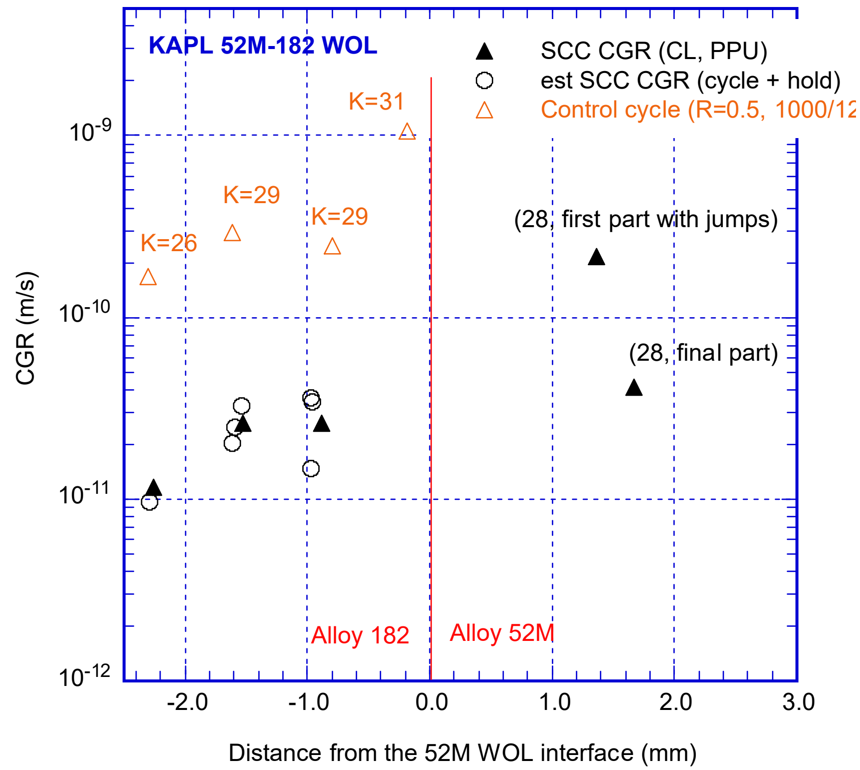






SCC CGR in WOLs

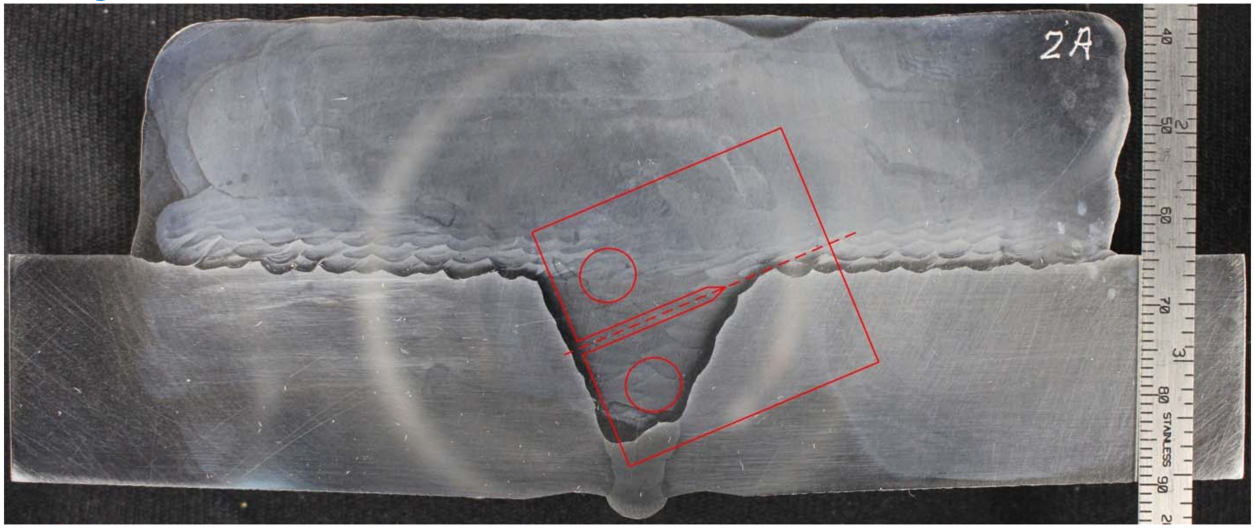


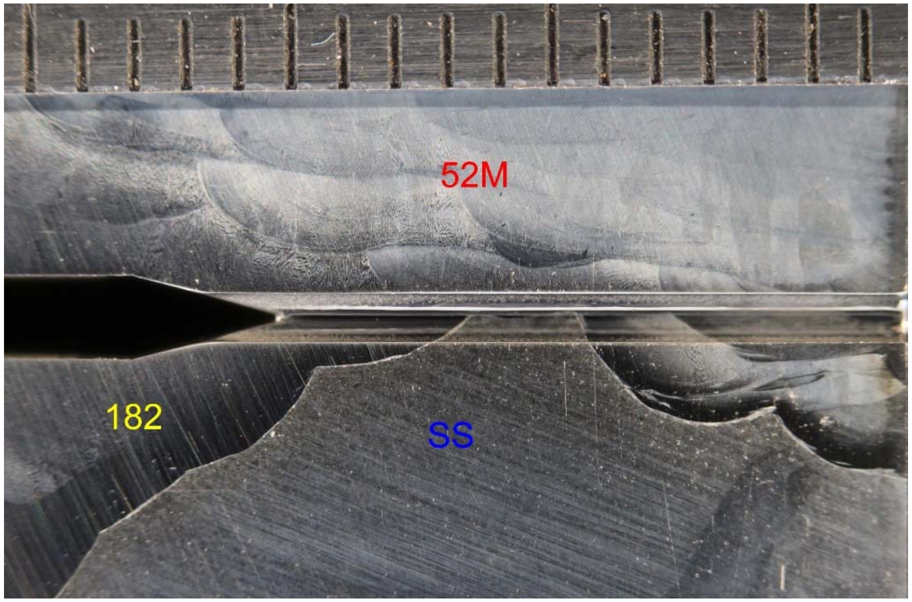


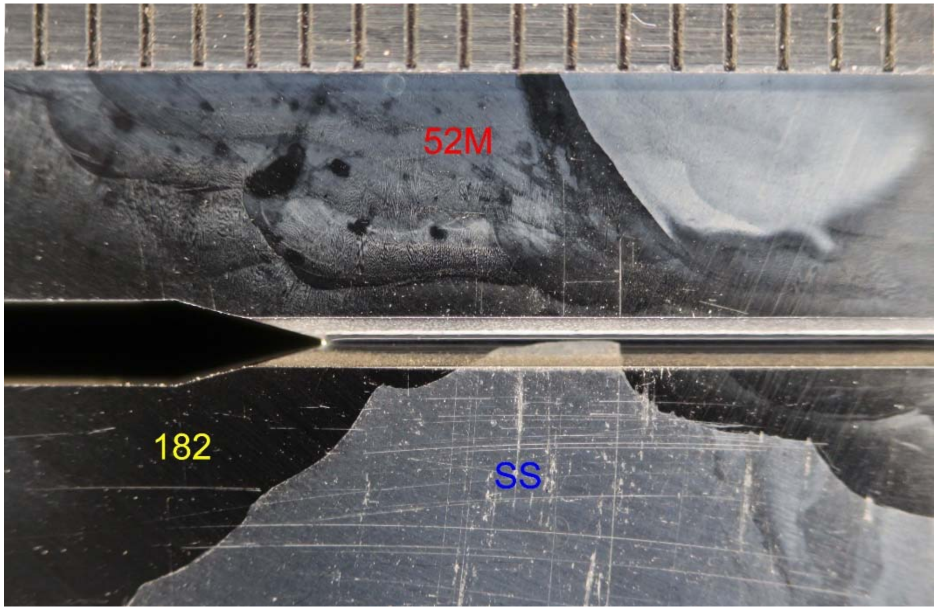
[NUREG/CR-7226]

- Moderate SCC CGRs ahead of the WOL
- Fast (10^{-10} m/s) SCC CGRs in the first layer and along the interface

KAPL Alloy 52M-182 WOL: K52M-ST-2

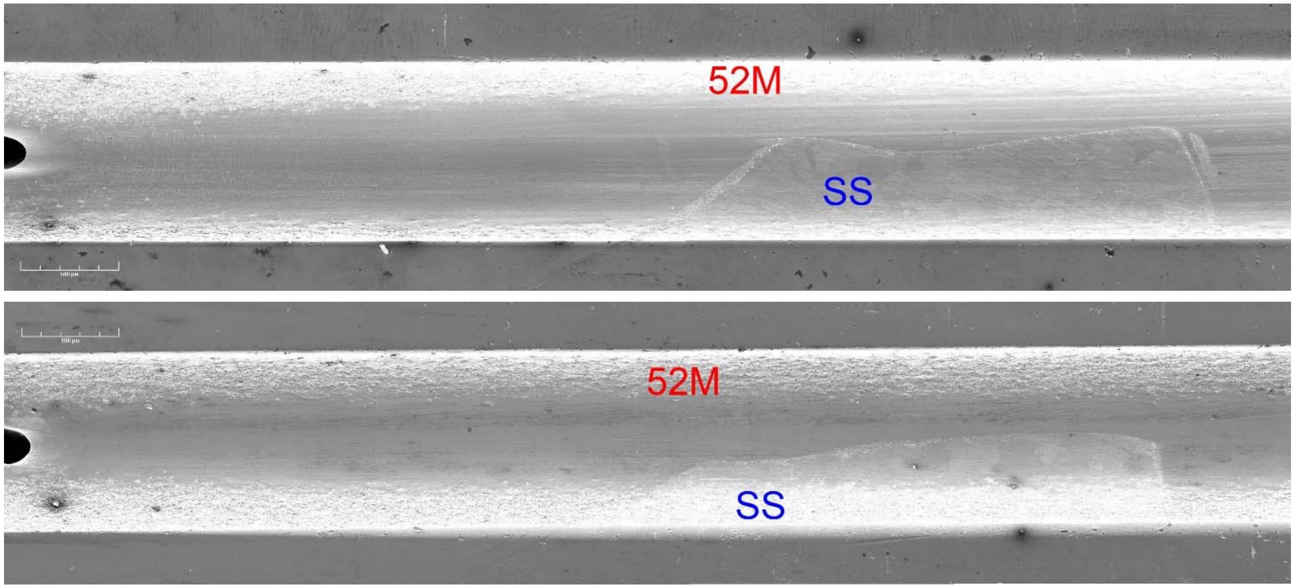




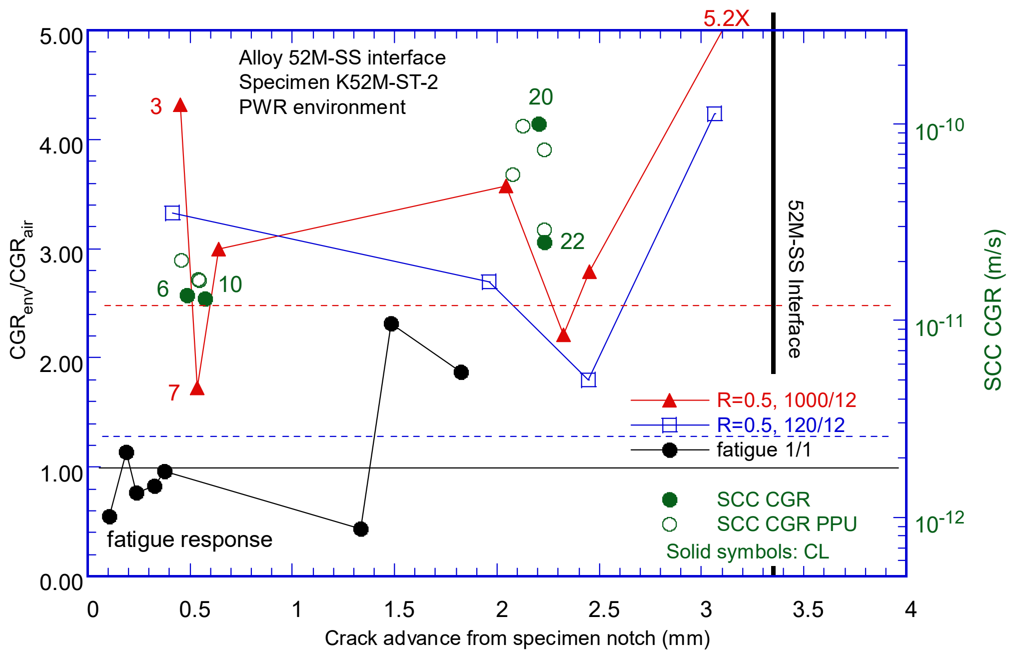


- Approach: generate IG SCC front on Alloy 182-52M interface, transition onto 52M-SS interface

K52M-ST-2

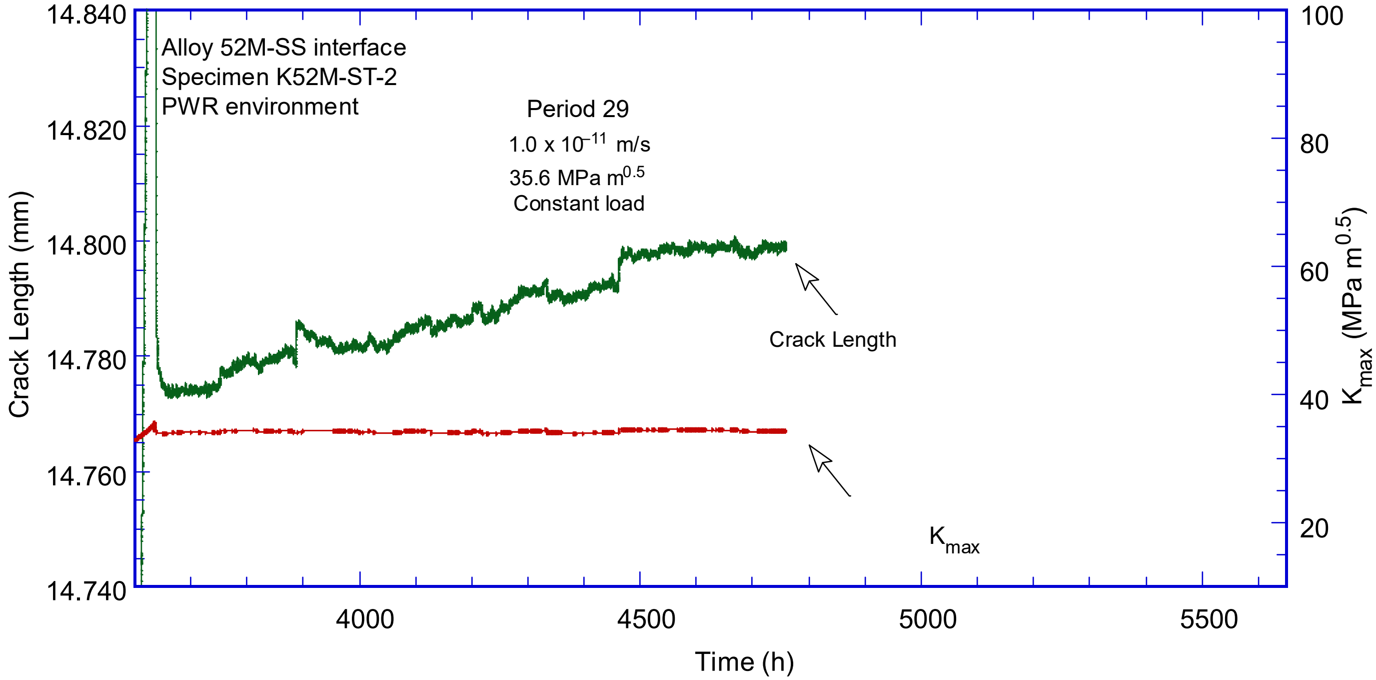


52M
SS
52M
SS



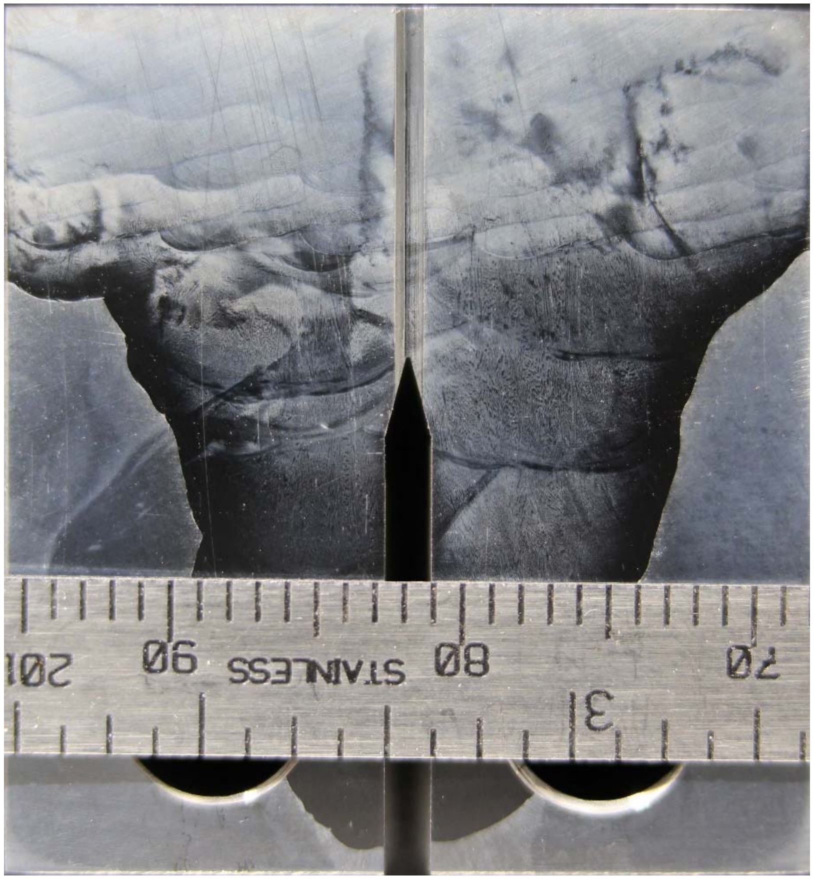
Alloy 52M-SS interface
Specimen K52M-ST-2
PWR environment
5.2X
3
7
6
10
20
22
fatigue response
52M-SS Interface
R=0.5, 1000/12
R=0.5, 120/12
fatigue 1/1
SCC CGR
SCC CGR PPU
Solid symbols: CL
CGR_{env}/CGR_{air}
SCC CGR (m/s)
Crack advance from specimen notch (mm)
0.00
1.00
2.00
3.00
4.00
5.00
0
0.5
1
1.5
2
2.5
3
3.5
4
10^{-10}
10^{-11}
10^{-12}

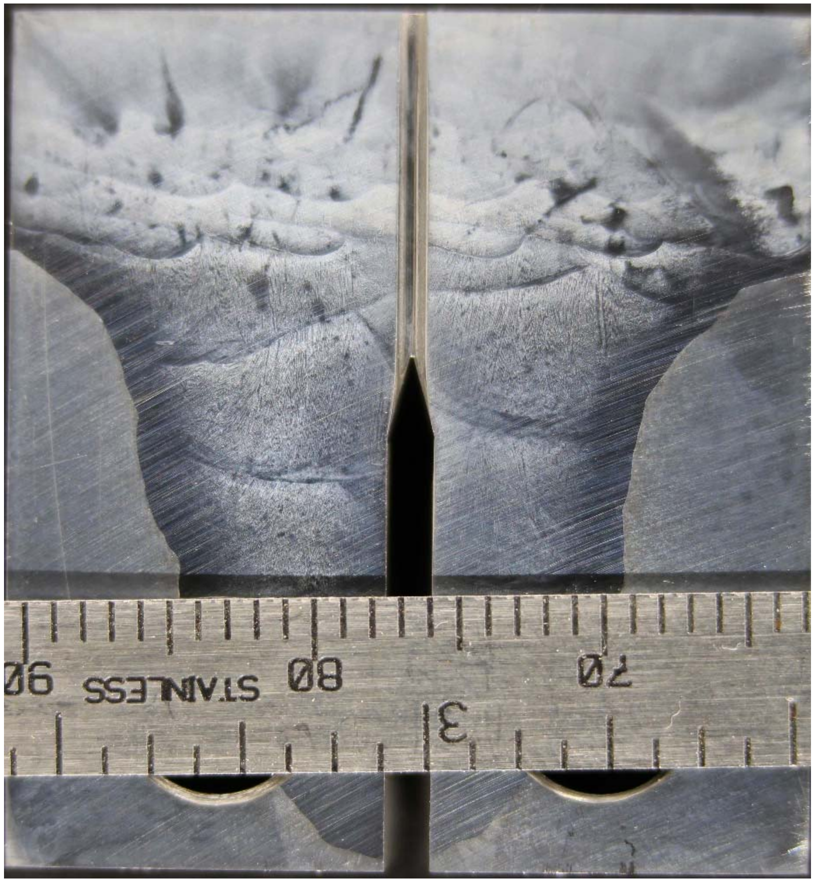
KAPL Alloy 52M-182 WOL: K52M-ST-2



- Set at CL (directly from cycling) 0.2-0.3 mm from the Alloy 52M-SS interface

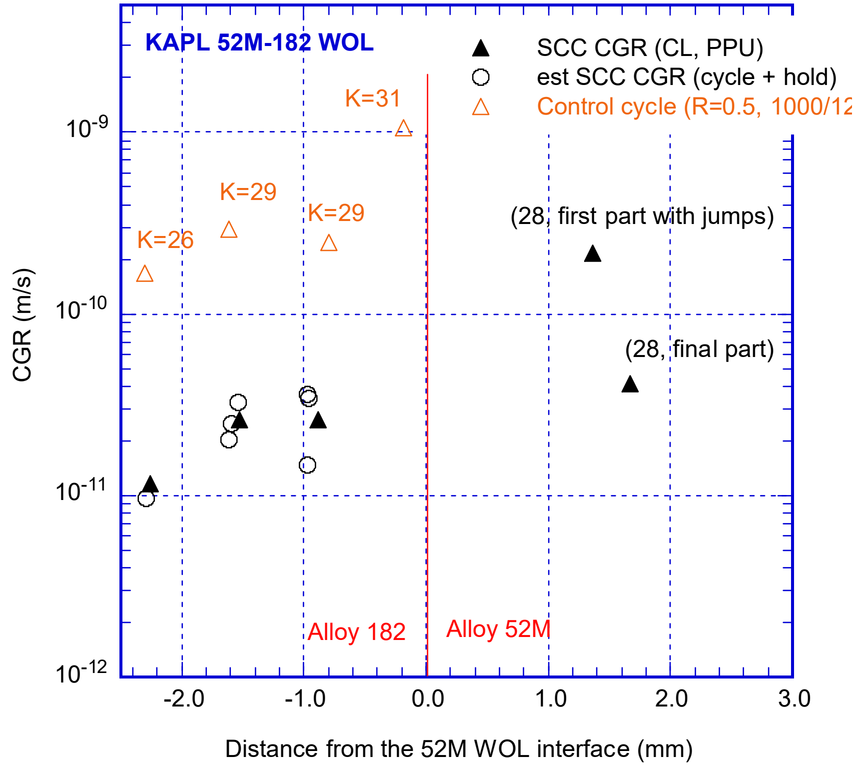
EWI Alloy 52M-182 WOL: E52M-TS-1

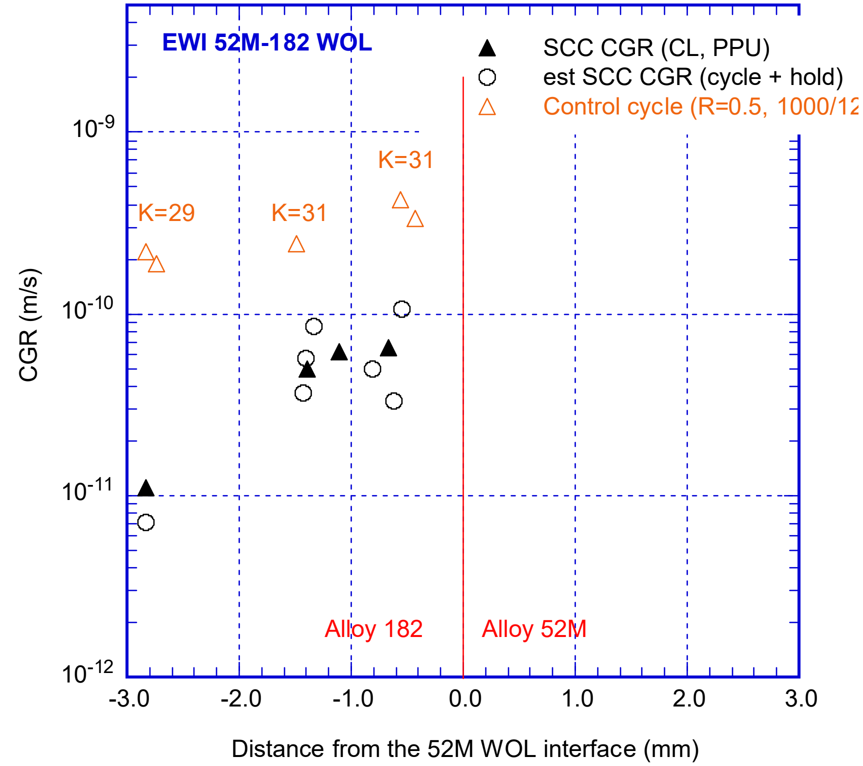




- Notch located 3.85 mm from the interface

EWI Alloy 52M-182 WOL: E52M-TS-1



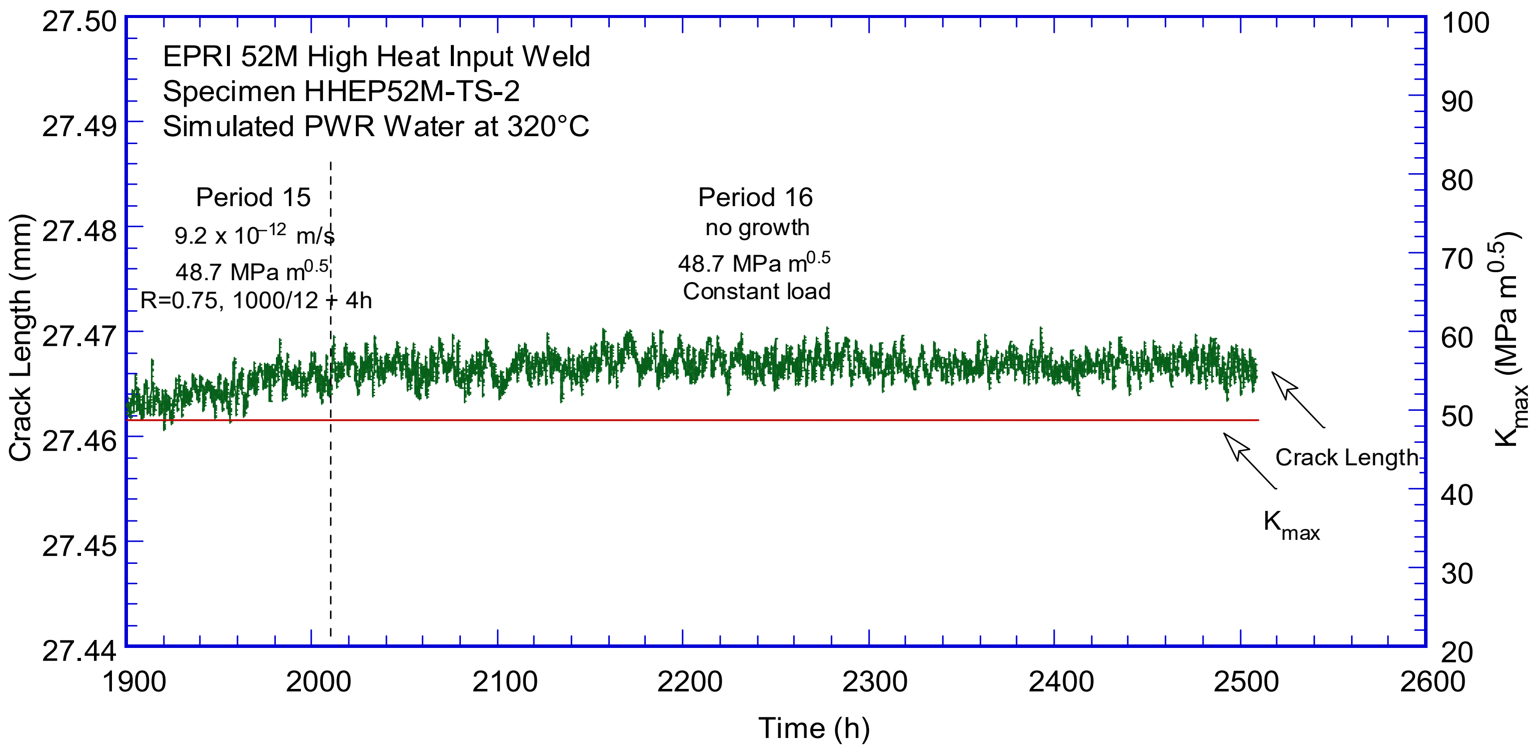


- Similar evolution as the to the KAPL WOL
- Set at CL 0.2 mm from the interface

Alloy 52M with high heat input (produced by EPRI)

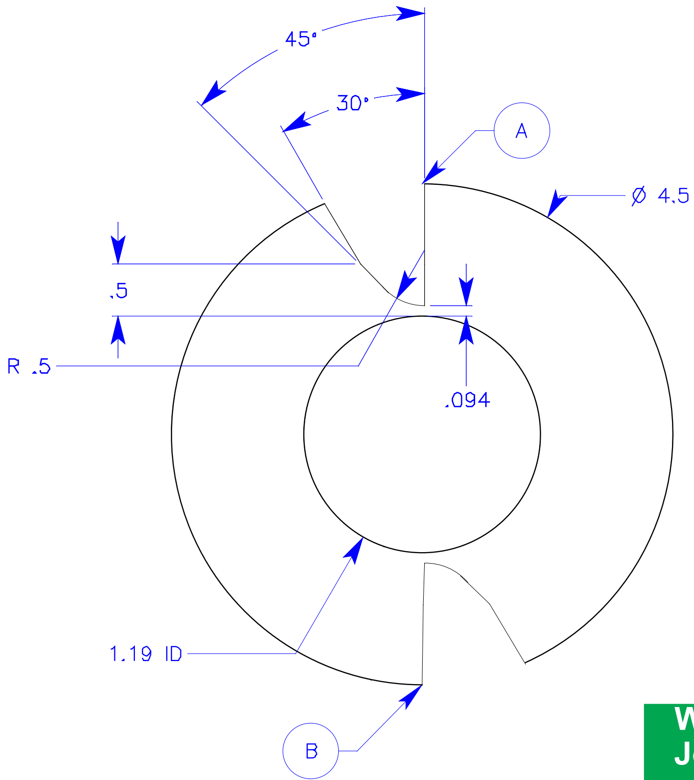
- Heat input approx. 20% higher than industry average
- One test completed, one in progress at high K, weld seems resistant

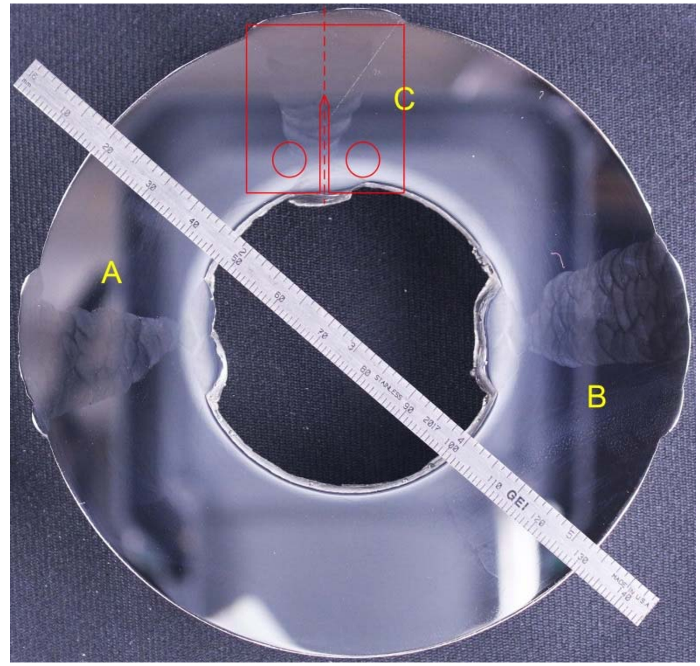
Alloy 52M with high heat input (produced by EPRI)



- Heat input approx. 20% higher than industry average
- One test completed, one in progress at high K, weld seems resistant

Alloy 152 with high heat input (produced by ANL)

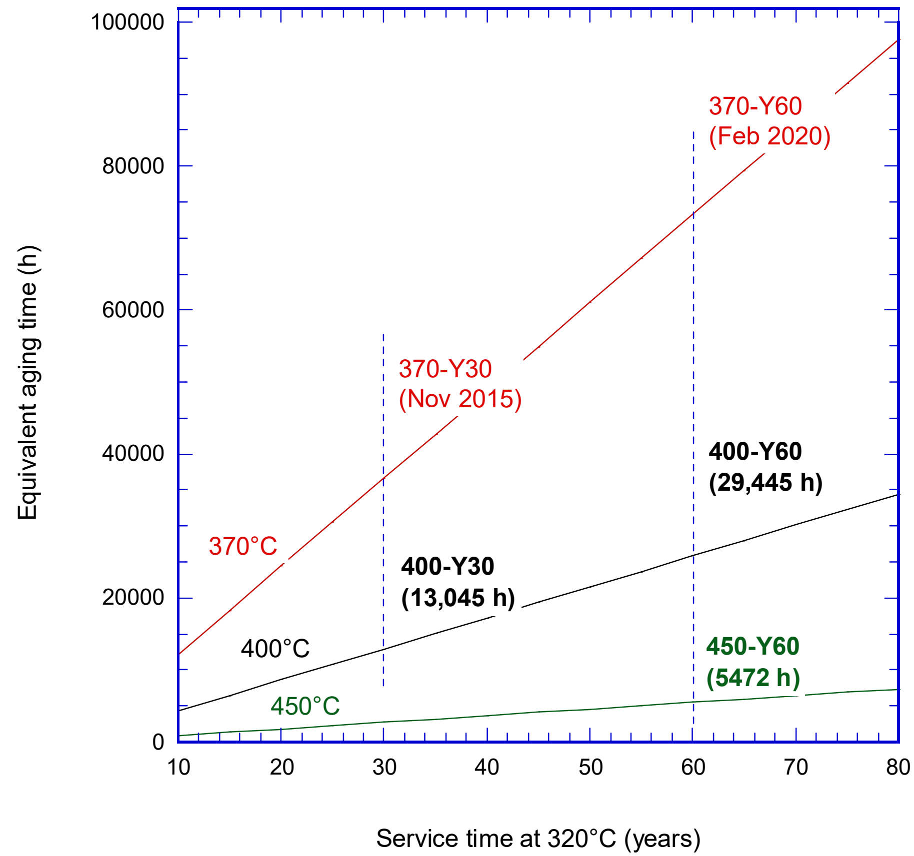




Weld Joint	Approximate Amperage Range	Approximate Voltage Range	Travel Speed (in/m)	Heat Input (kJ/cm)
A	97-102	25-26	3.5-4.5	15.1
B	125-135	29-32	5.5-6.5	15.4
C	134-136	30-32	5.4-5.6	18.0

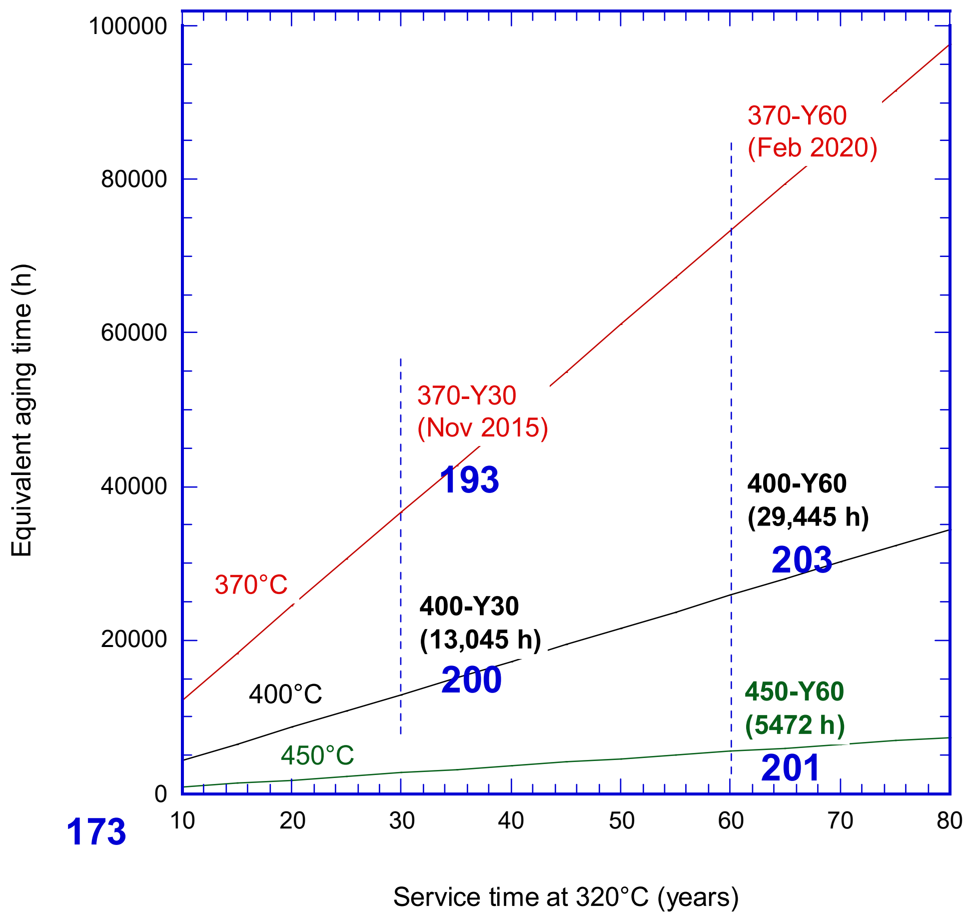
- Weld C: heat input approx. 20% higher than the other two weldments produced with the same filler, in the same geometry on the same CRDM
- Welds A and B were resistant

Aged ANL weld



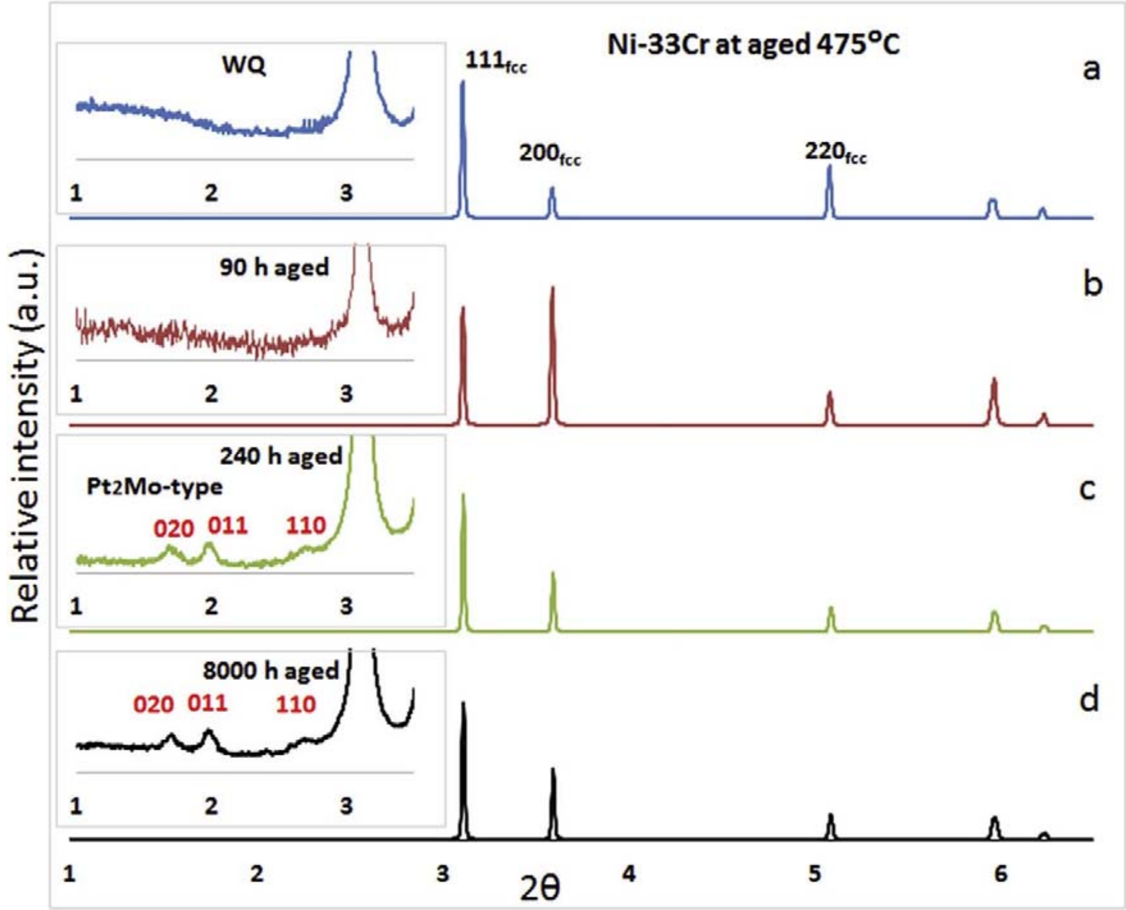
- ANL weld (unaged) was tested extensively: plate, weld, weld butter – LAS, LAS
- Second weldment reproduced “ANL weld”, and was made in 2011 for an I-NERI program
- Focus was on microstructural changes at the Alloy 152 butter – LAS interface, primarily on Cr-depletion
- Specimens aged to 30 yr and 60 yr equivalents (using Q for Cr dilution) at three temps: 370, 400, and 450ºC

Preliminary observations on aged Alloy 690 - hardness



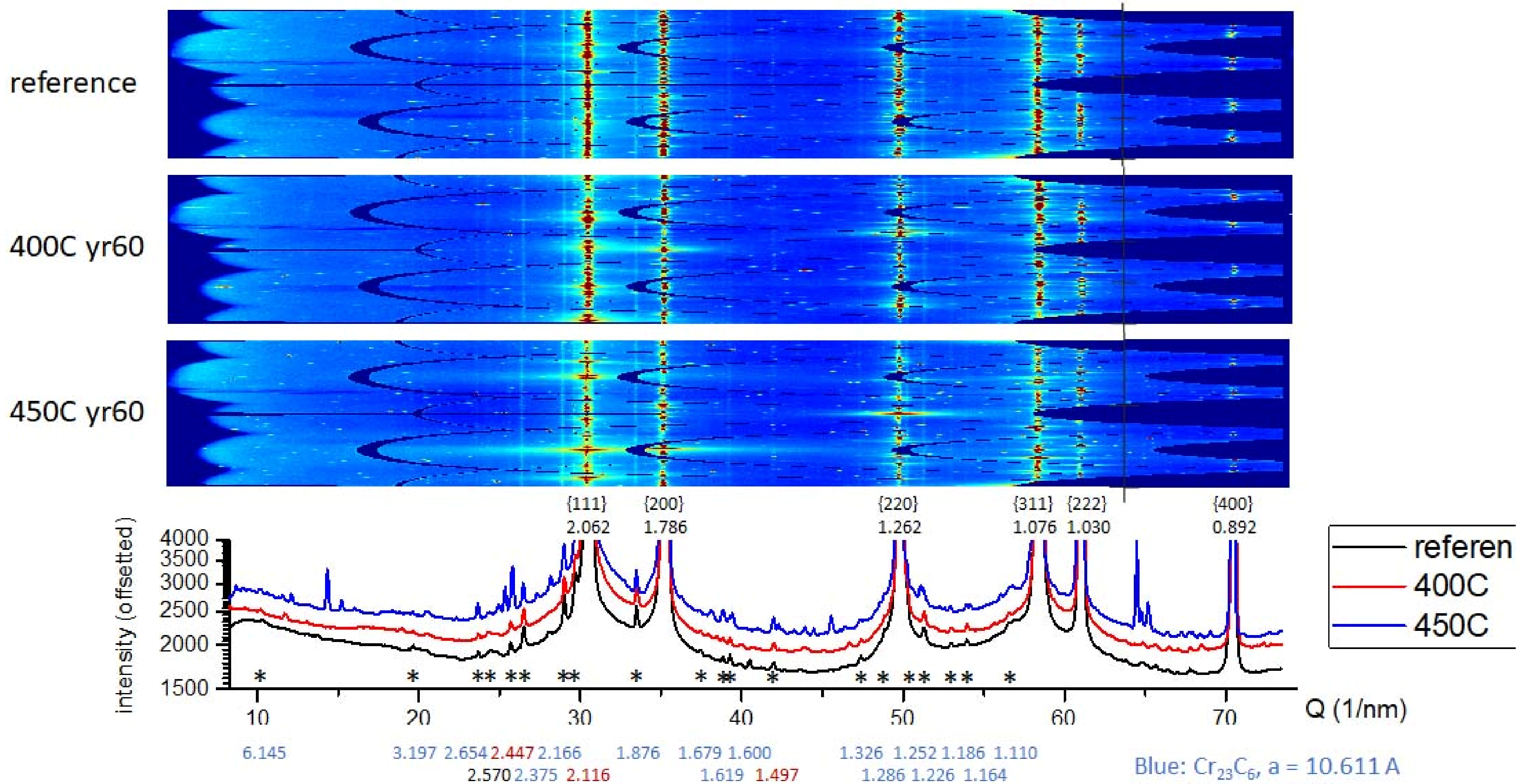
- All aged conditions show some hardening

LRO investigations at ANL APS



- Gwalani et al., Acta Materialia 115 (2016) 372
- Pt_2Mo-type peaks indicate the occurrence of LRO

LRO investigations of ANL plate at ANL APS (X. Zhang)



Note: All d-spacing numbers are in Angstrom.

- No peaks consistent with LRO were found (very preliminary analysis!)
- Appears to be an effective method to scan large areas of material (weld and butter)

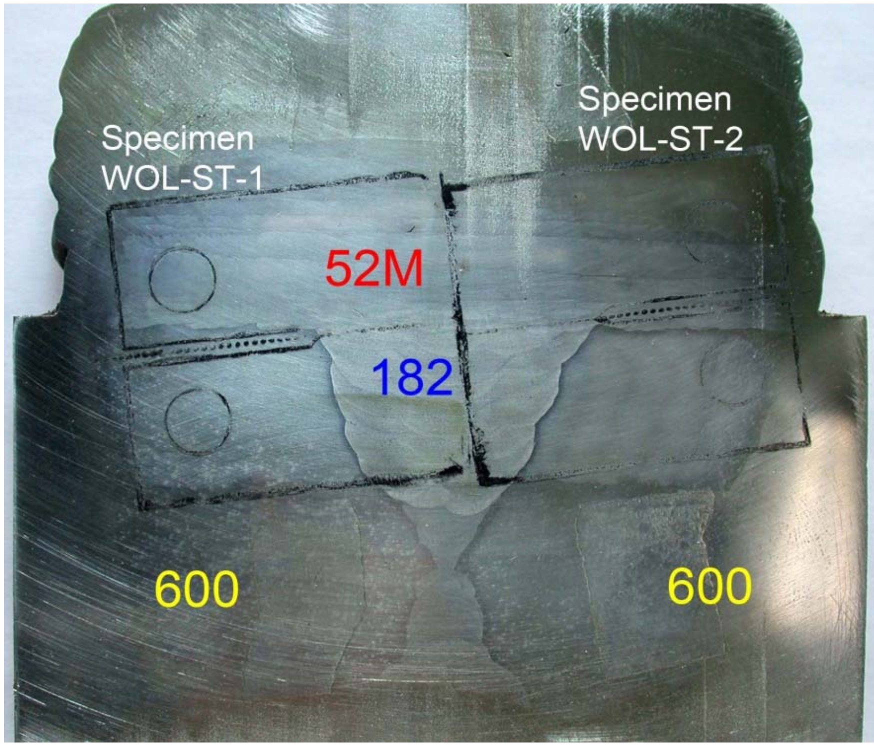
Summary

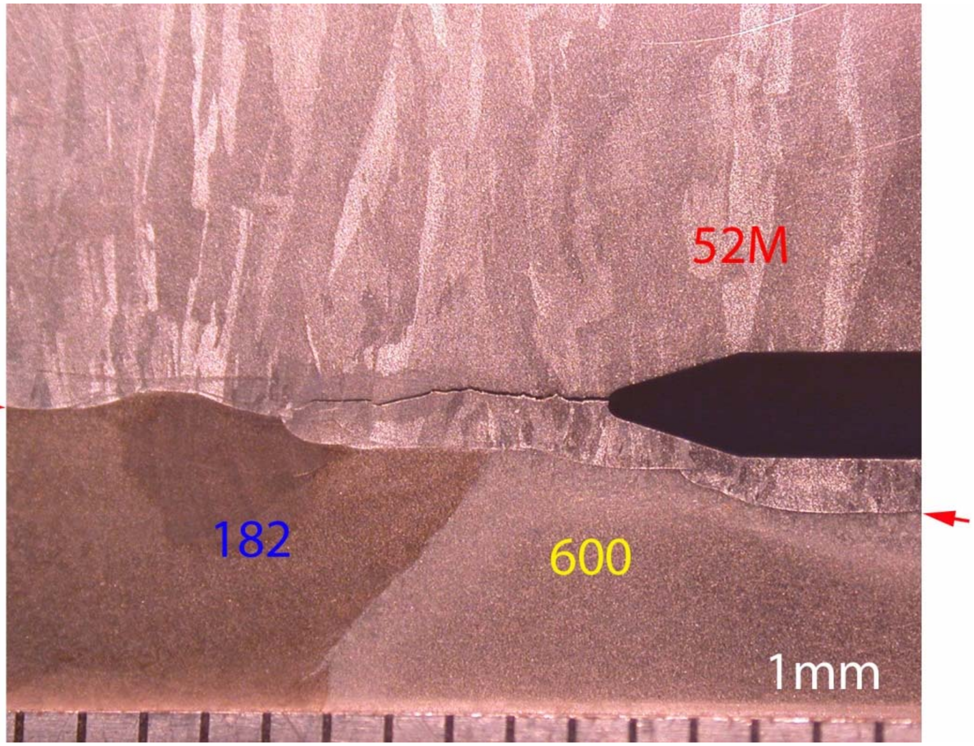
- Alloy 152 butter – reactor head weldments produced by ANL appear to be resistant to SCC (next to the SS). Same weldments (heat and procedure) next to the LAS were found to be very susceptible to SCC (NUREG/CR-7226).

- Alloy 52M WOL-182 by KAPL turned out to be as susceptible as the ANL-produced WOL. In general, crack appear to be deflected at the intersection with a more resistant material, however, in the KAPL-produced WOL, very little deflection was observed.

- High heat input Alloy 52M weld produced by EPRI appears to be resistant, additional testing is in progress on both EPRI and ANL – produced high heat input welds.

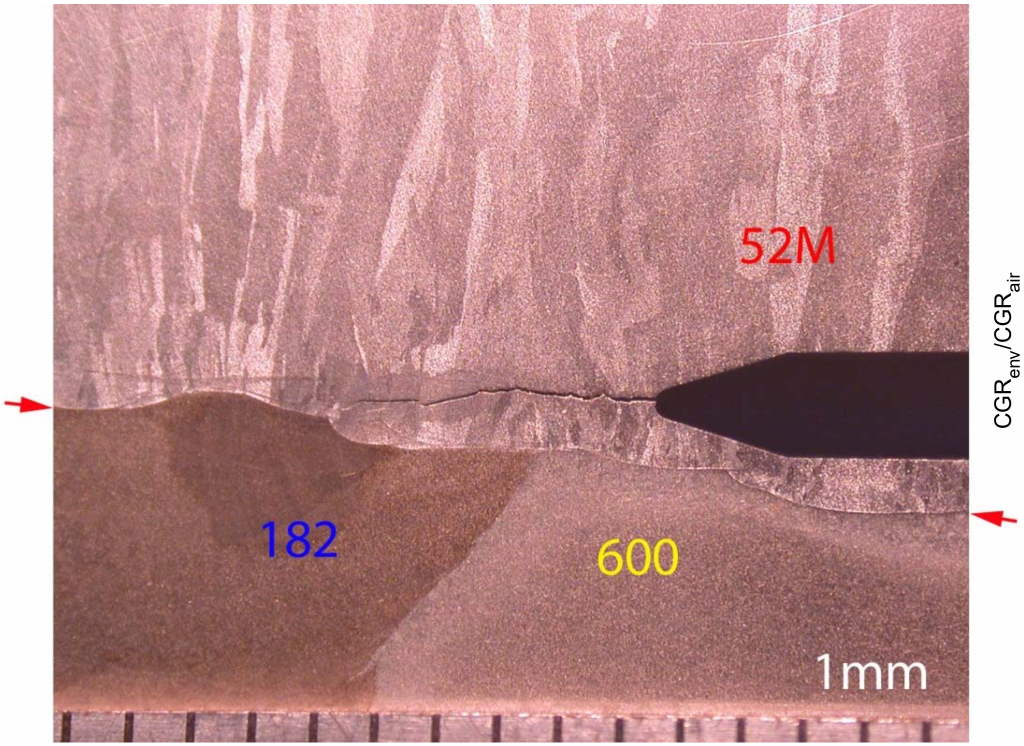
1^{st} Layer weld testing: experimental approach

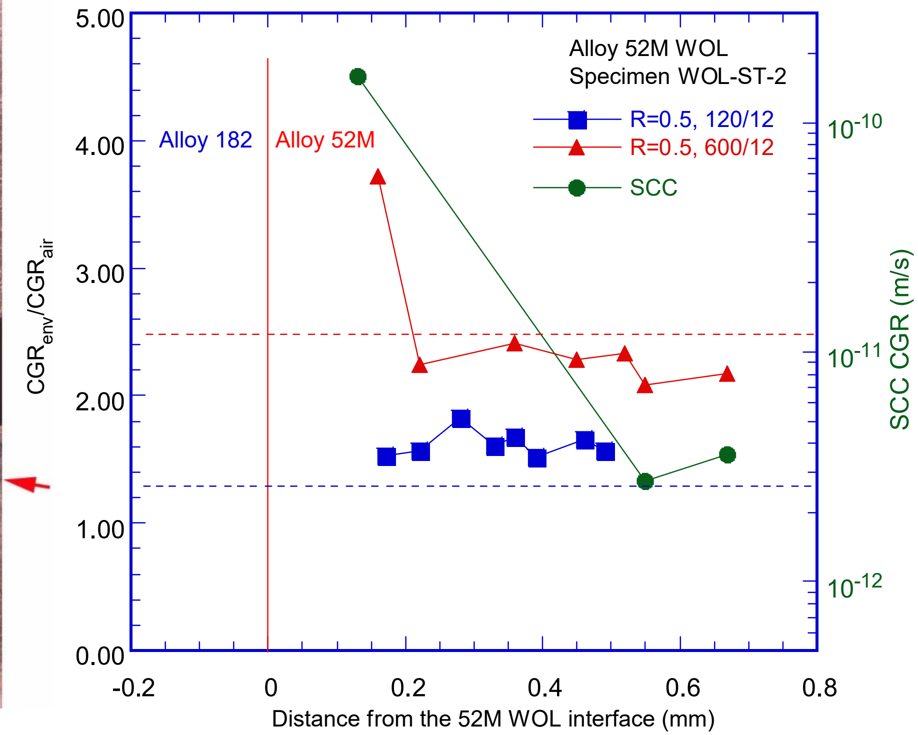




- Example: Alloy 52M 1^{st} layer of Alloy 52M-182 WOL (produced at ANL)
- CGR testing in ST orientation to avoid complications associated with cracking along the interface in TS tests
- Crack propagation normal to the dendritic grains (no type II boundaries)
- CGR response will be used for comparison in many subsequent tests

Experimental approach: test management

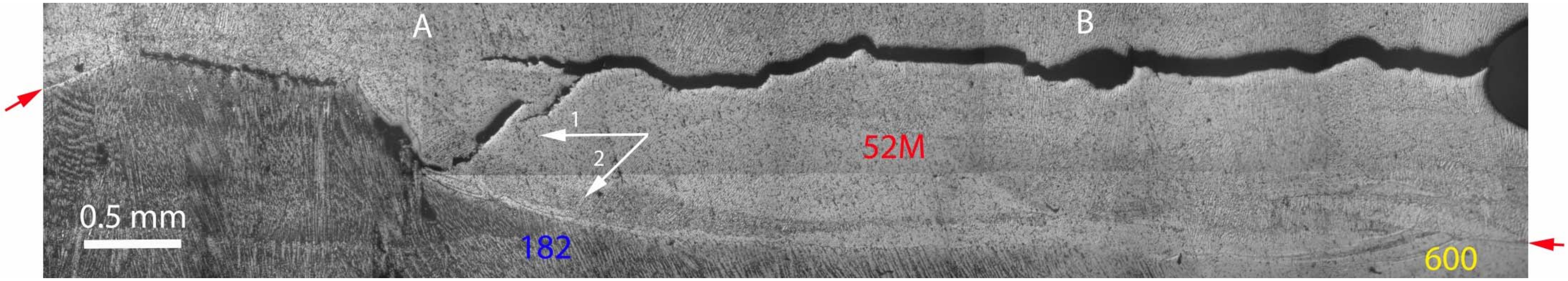


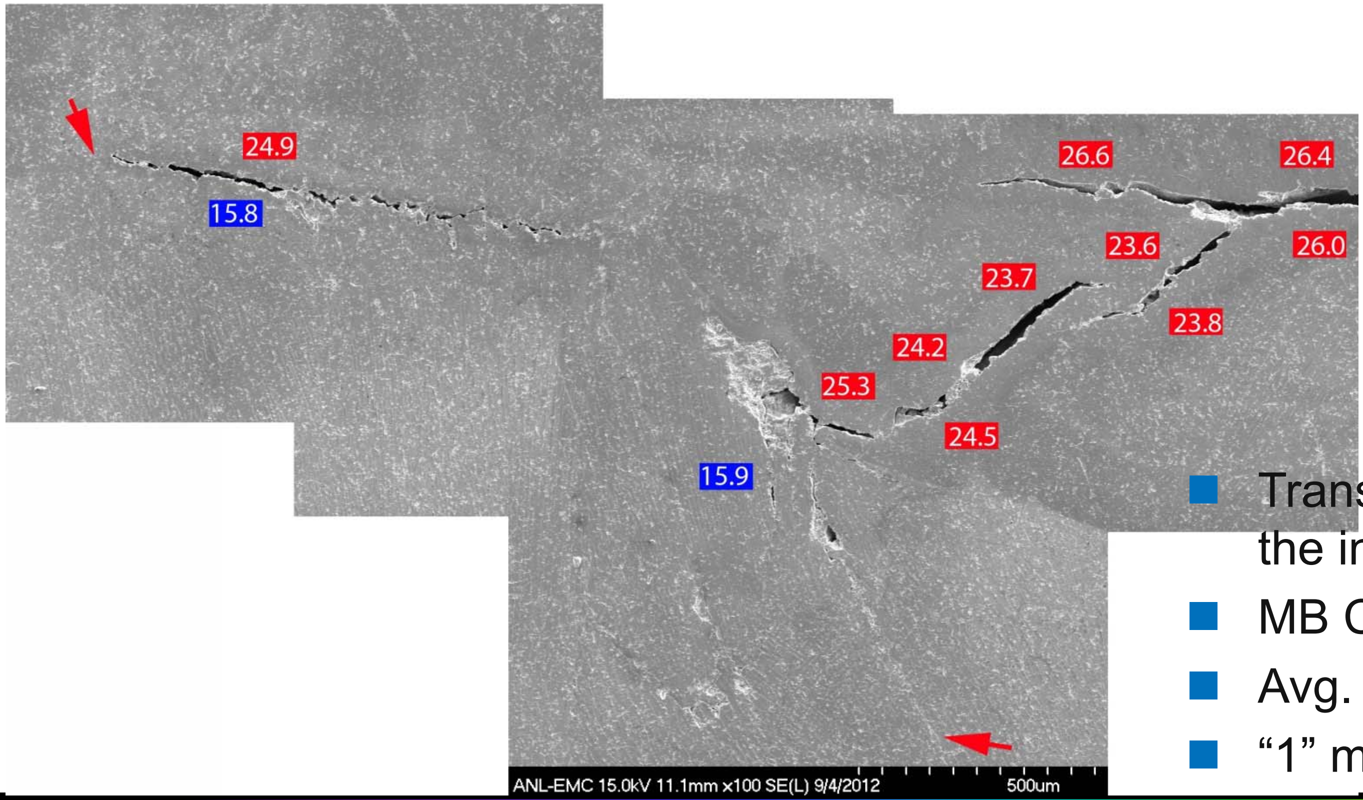


- Test management based entirely on specimen response:

  advance the crack, compare response with known “IG SCC forward propagation”, set at constant load when that comparison is favorable

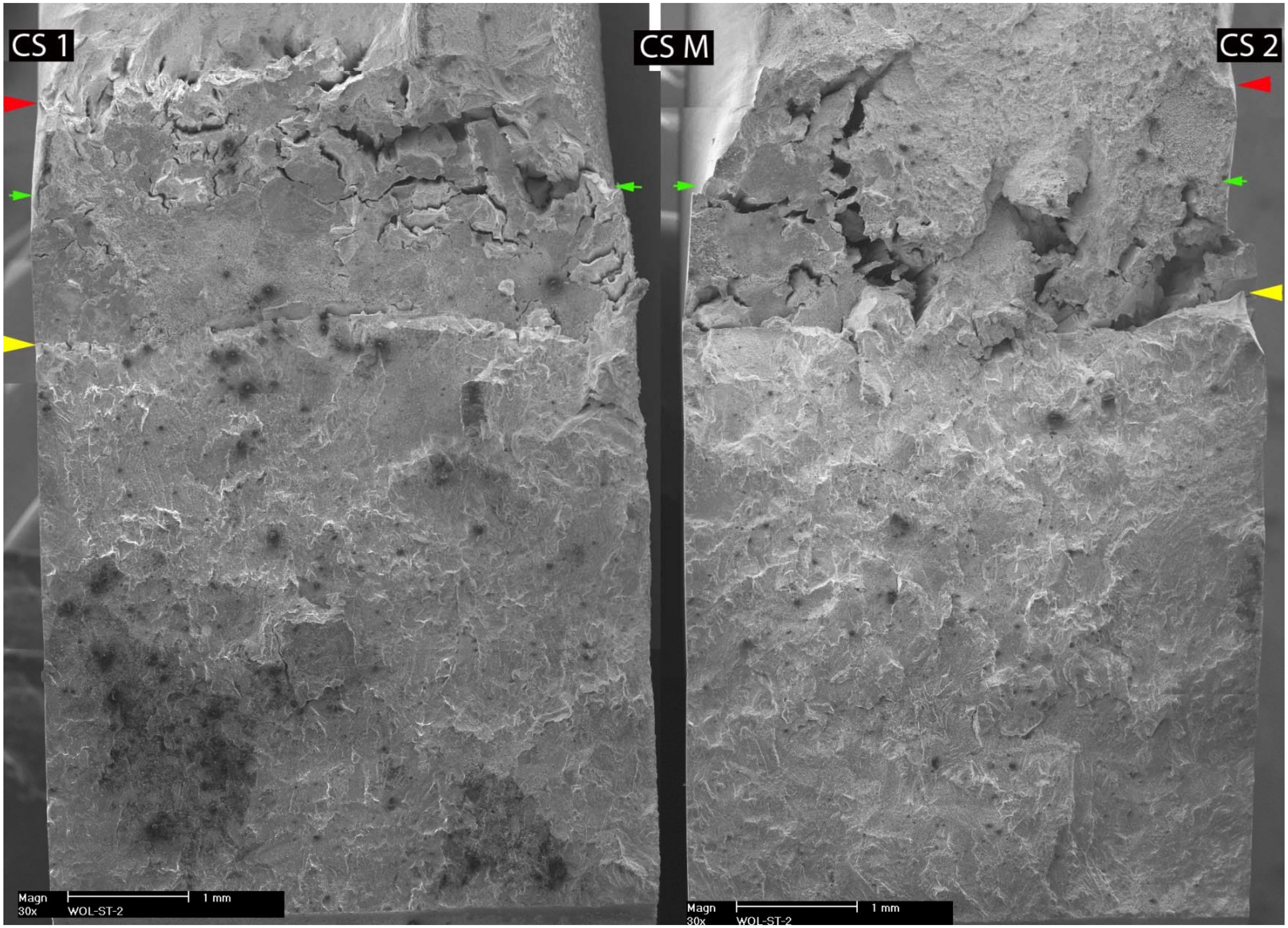
Alloy 52M/182 Weld Overlay Specimen WOL-ST-2 – Middle





- Transitioned 1.0 mm from the interface
- MB Cr: 27.1%
- Avg. MA Cr: 24.2%
- "1" major crack direction

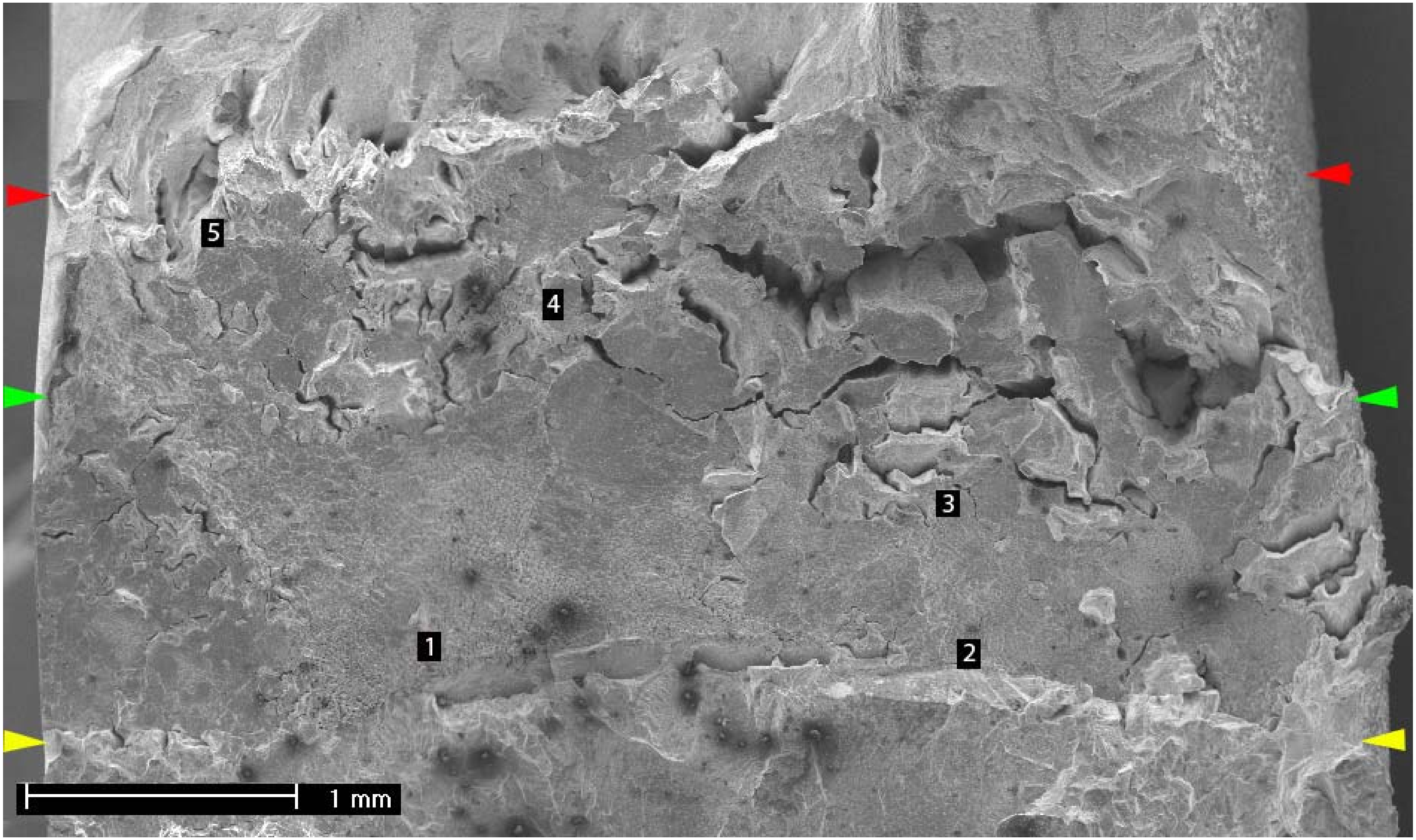
Alloy 52M-182 Weld Overlay Specimen WOL-ST-2 – Fracture



- SCC growth: 1.7 mm (4.2x higher than anticipated)

End precracking/transitioning
182/52M interface
End of test

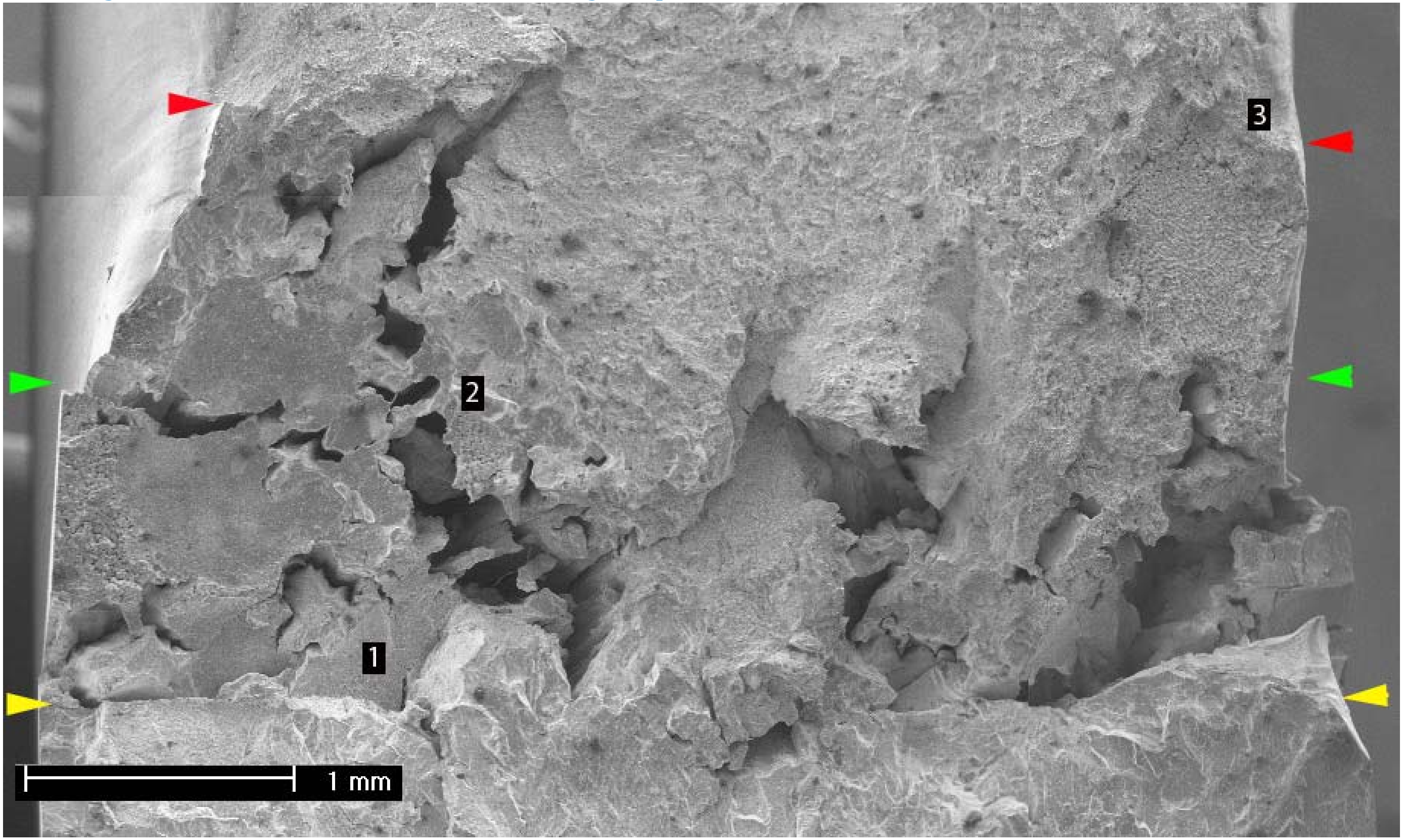
Alloy 52M-182 Weld Overlay Specimen WOL-ST-2 – Fracture A



- SCC growth: 1.7 mm (4.2x higher than anticipated)

End precracking/transitioning
182/52M interface
End of test

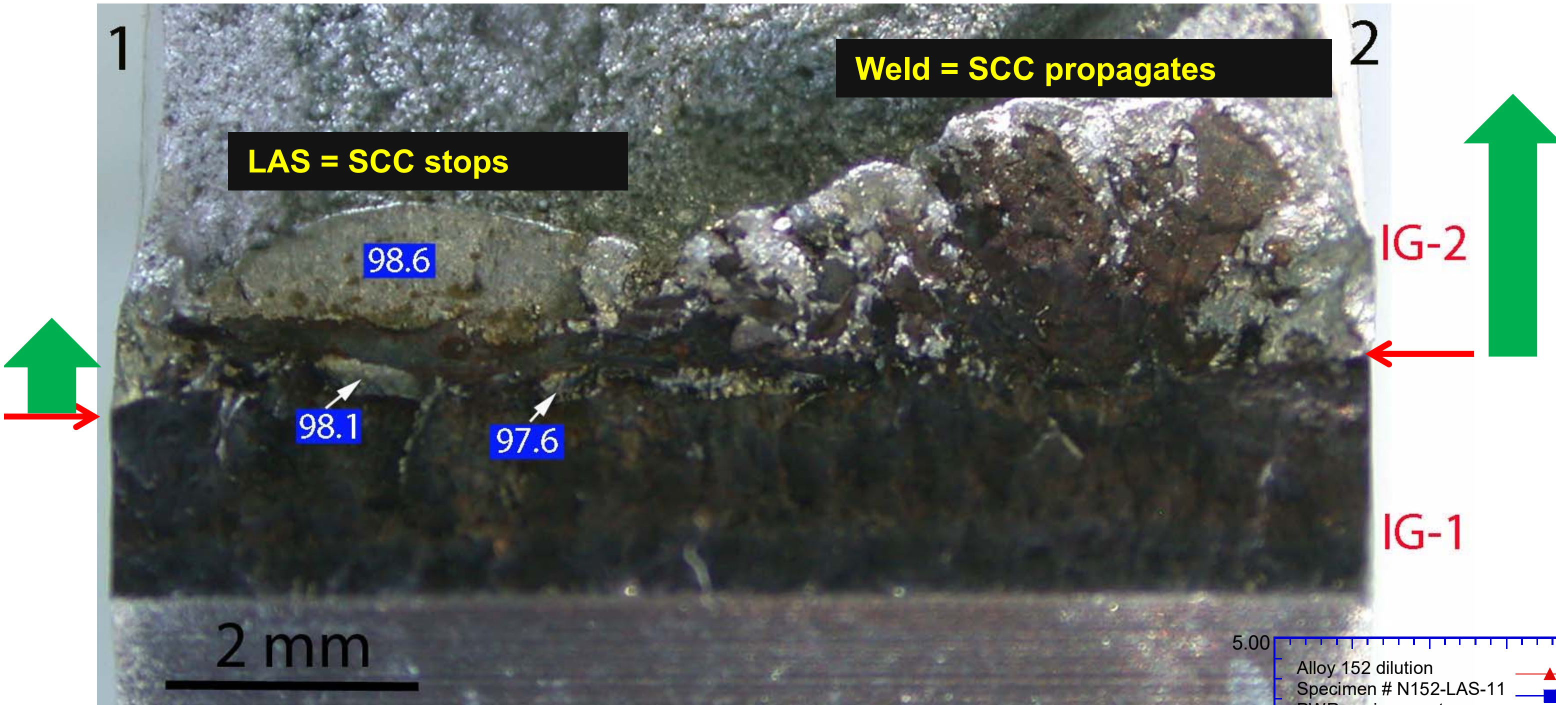
Alloy 52M-182 Weld Overlay Specimen WOL-ST-2 – Fracture B

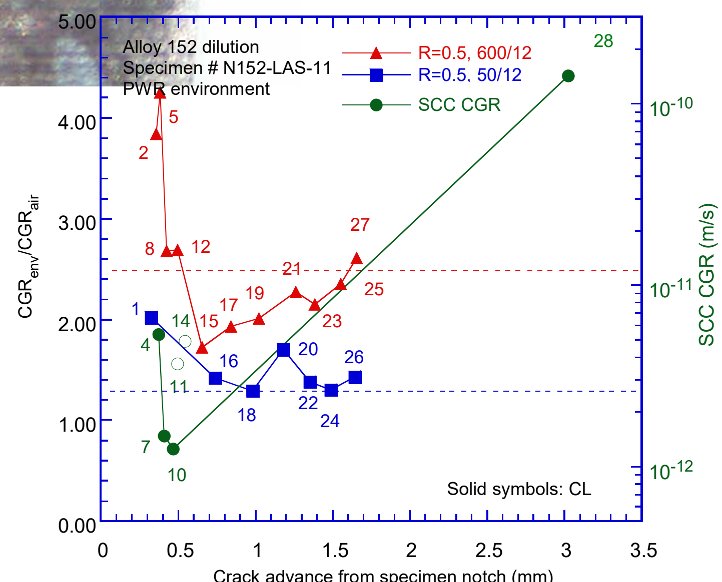


- SCC growth: 1.7 mm (4.2x higher than anticipated)

End precracking/transitioning
182/52M interface
End of test

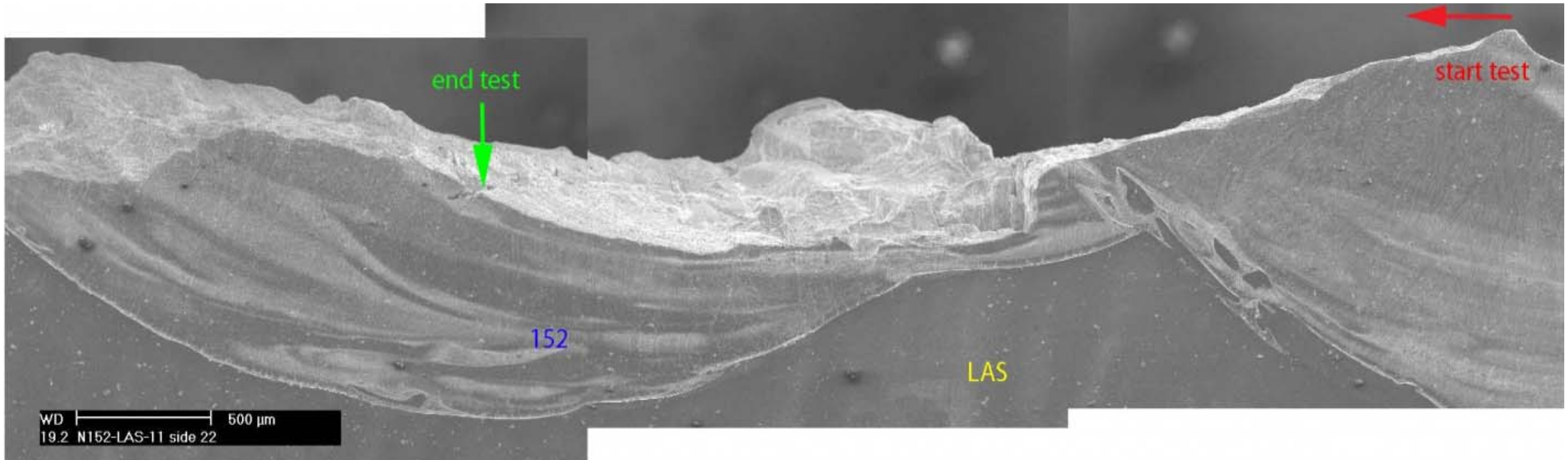
Specimen N152-LAS-11

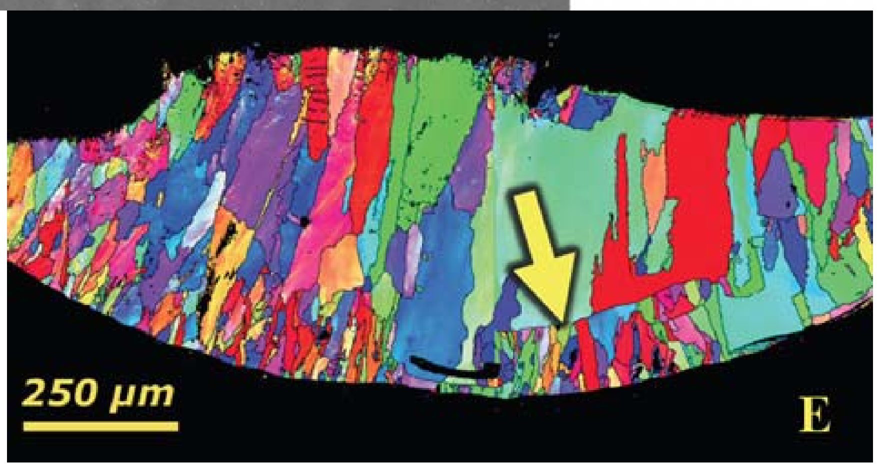




- Red arrows = end of cyclic (sample fully open, reproduced cyclic response), everything above is growth under CL
- Green arrows = growth under constant load (on average 1.4 mm over approx. 3000 hrs
- SCC CGR = 1.4E-10 m/s

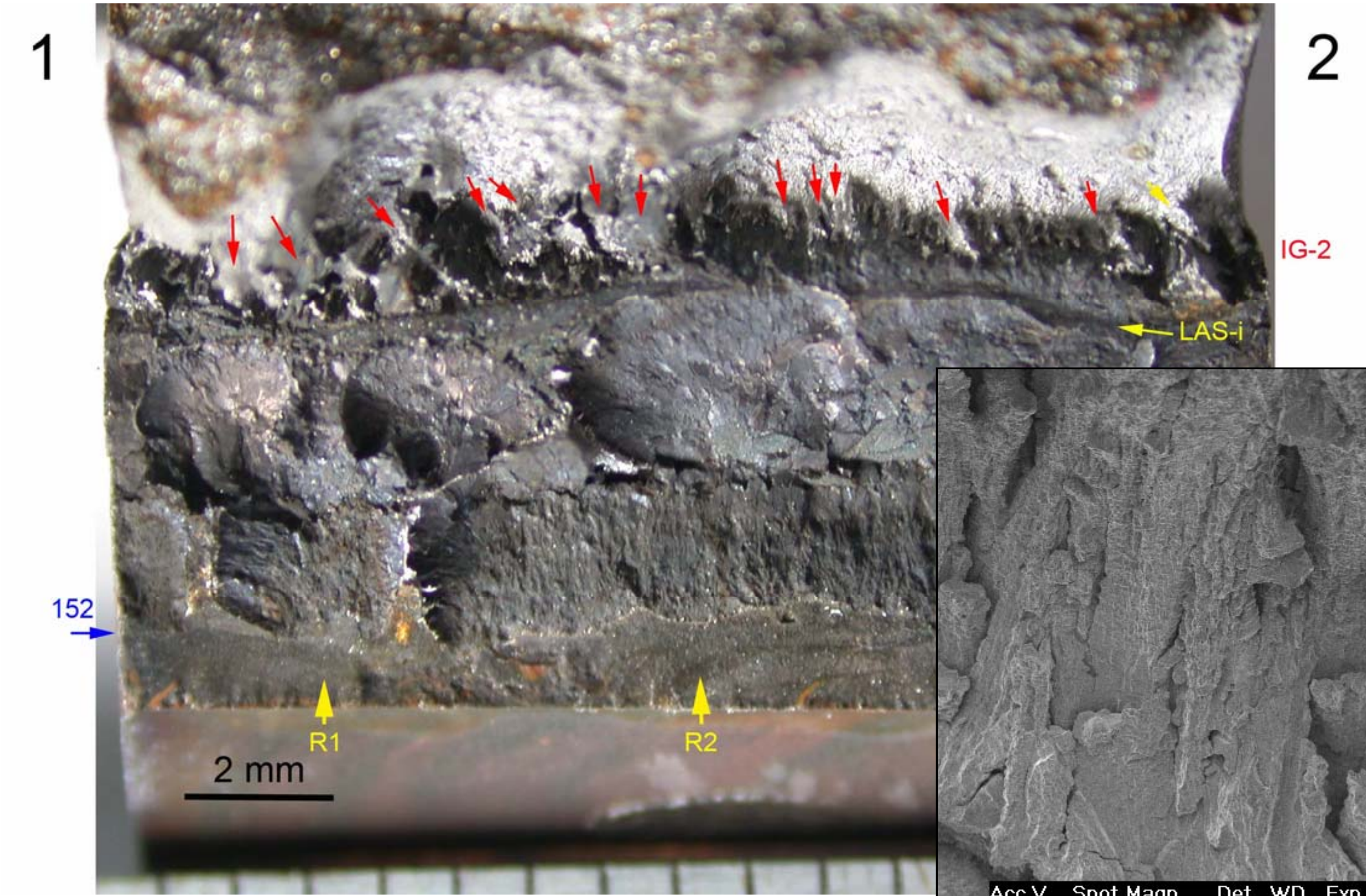
Specimen N152-LAS-11 – Cross section "22"

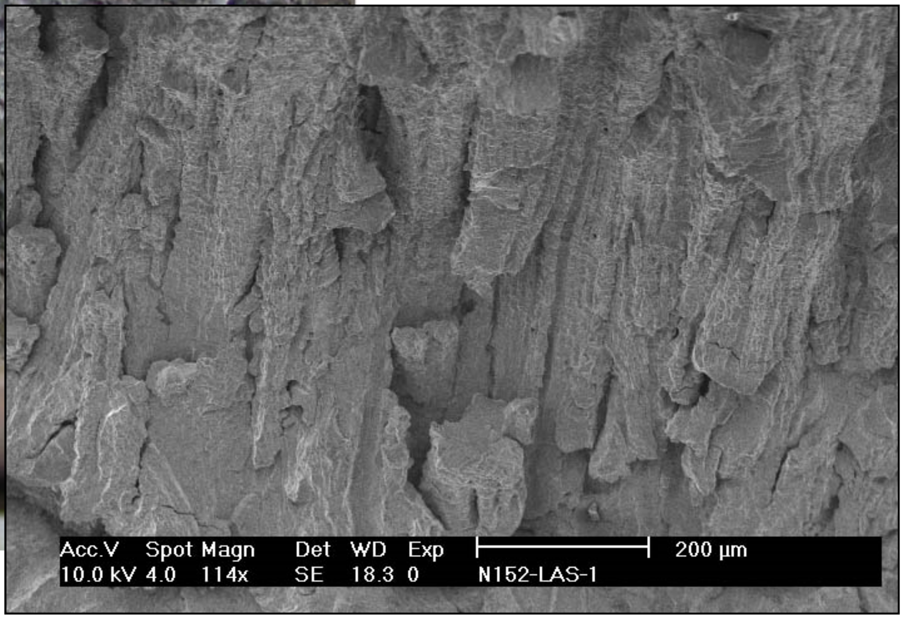




- PNNL: Observed "special" boundaries that could be plausible IG SCC paths

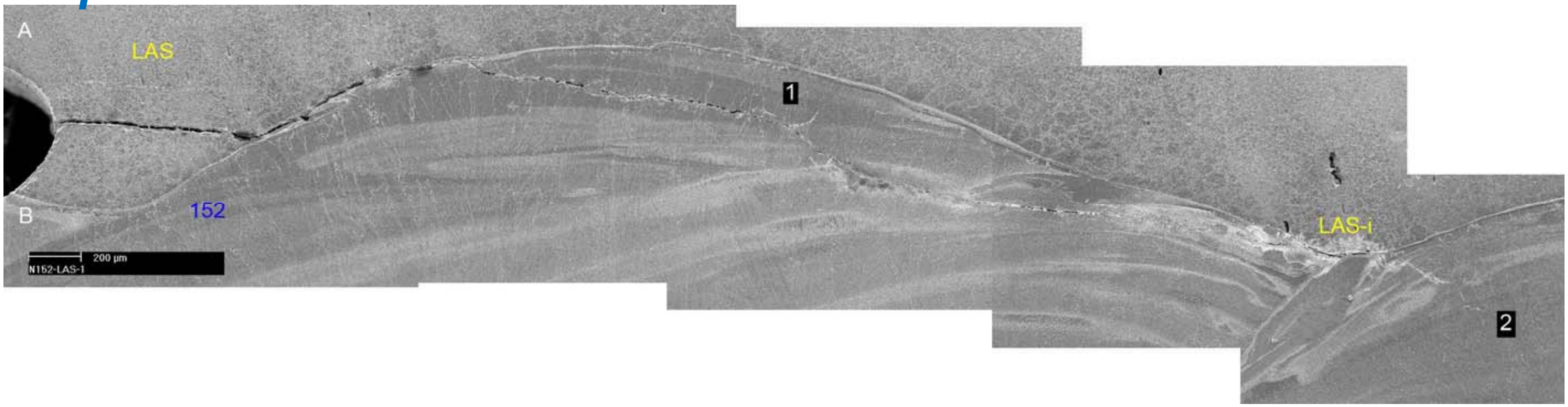
Specimen N152-LAS-1 fracture surface – Side B tilted

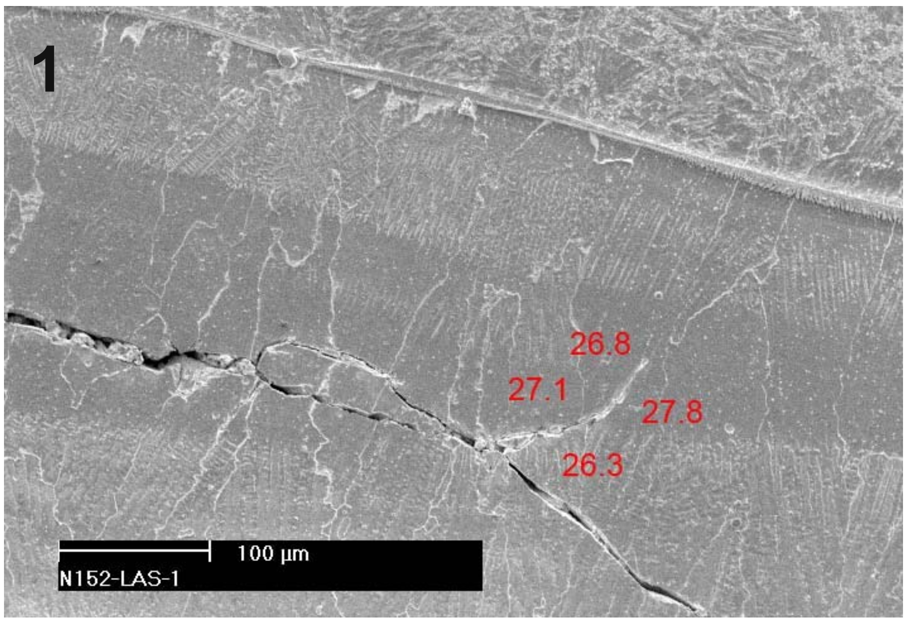


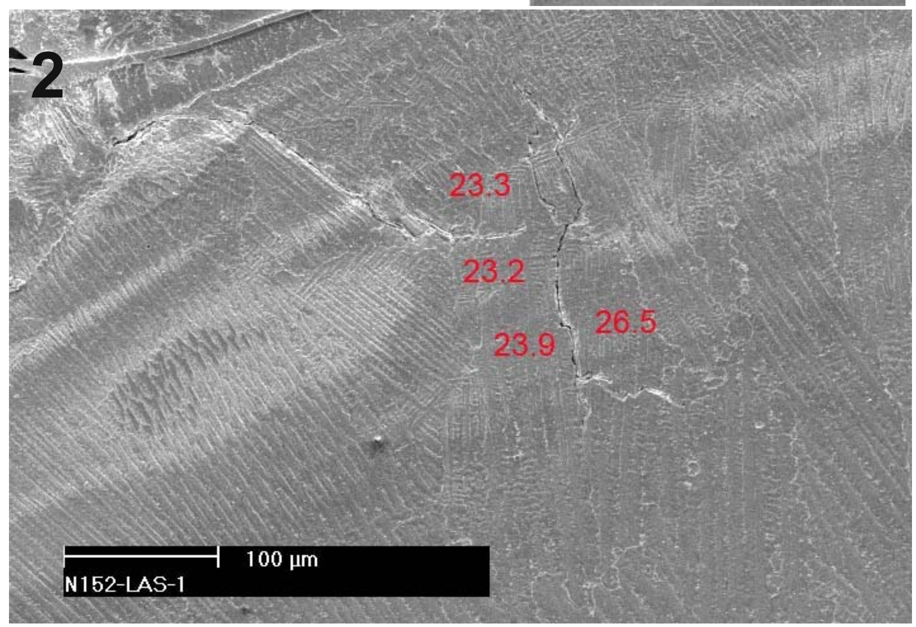


- Off-plane cracking, specimen tilted to show the full extent of IG SCC and identify unbroken ligaments
- IG SCC was parallel to the dendritic grains (as is “typically” observed and expected in welds)

Specimen N152-LAS-1 – Side Surface 1







- Elemental concentration (Cr wt.%) is shown
- Fatigue crack will intersect the LAS, IG SCC will propagate away from the LAS along dendritic grains

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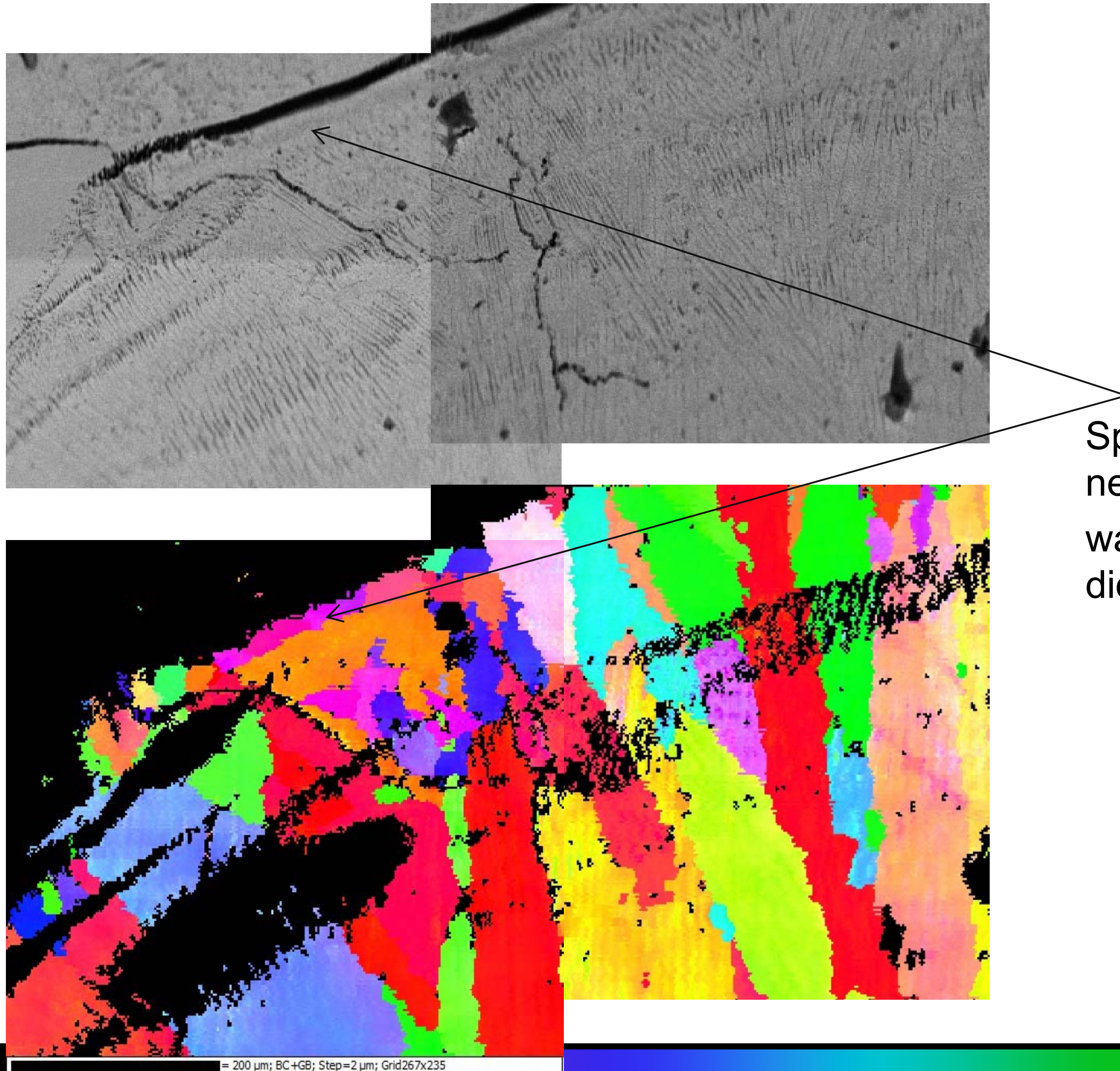
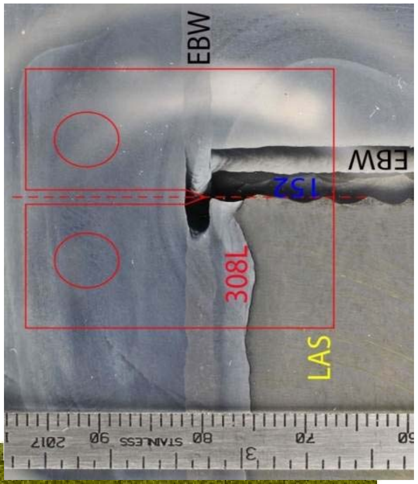
Specimen N152-LAS-1



Special/type II boundary near the interface with LAS was available, but IG SCC did not follow it

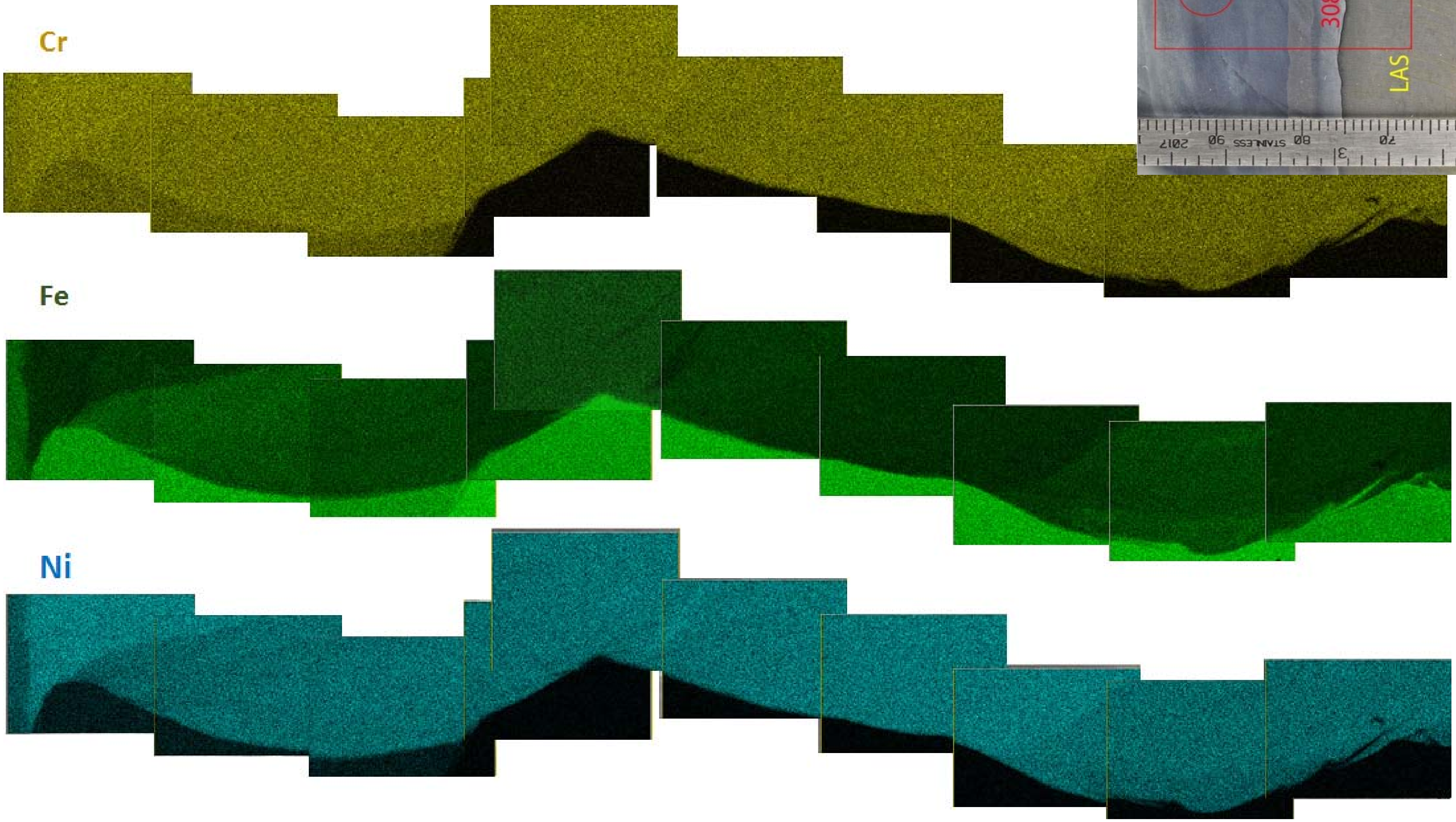
Weldment JC152: Alloy 152 – 308L, LAS



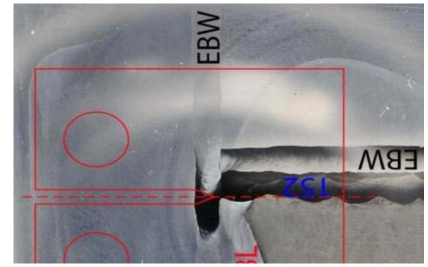
Cr

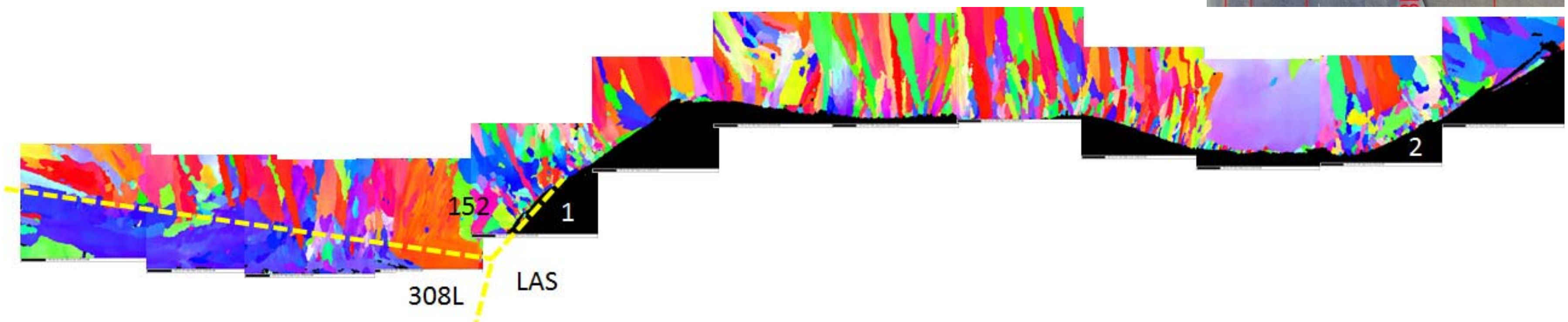
Fe

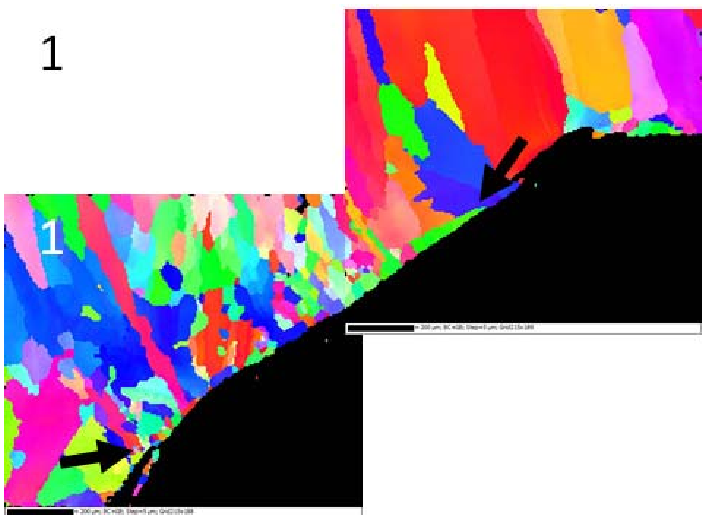
Ni

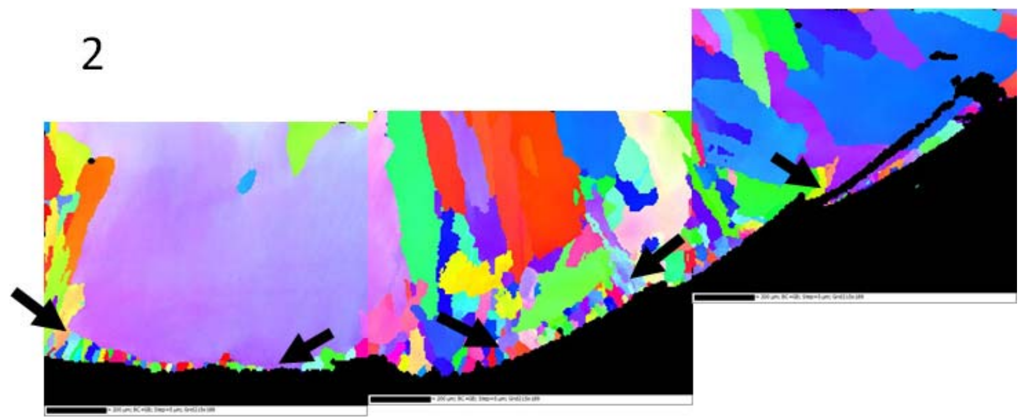


Weldment JC152: Alloy 152 – 308L, LAS



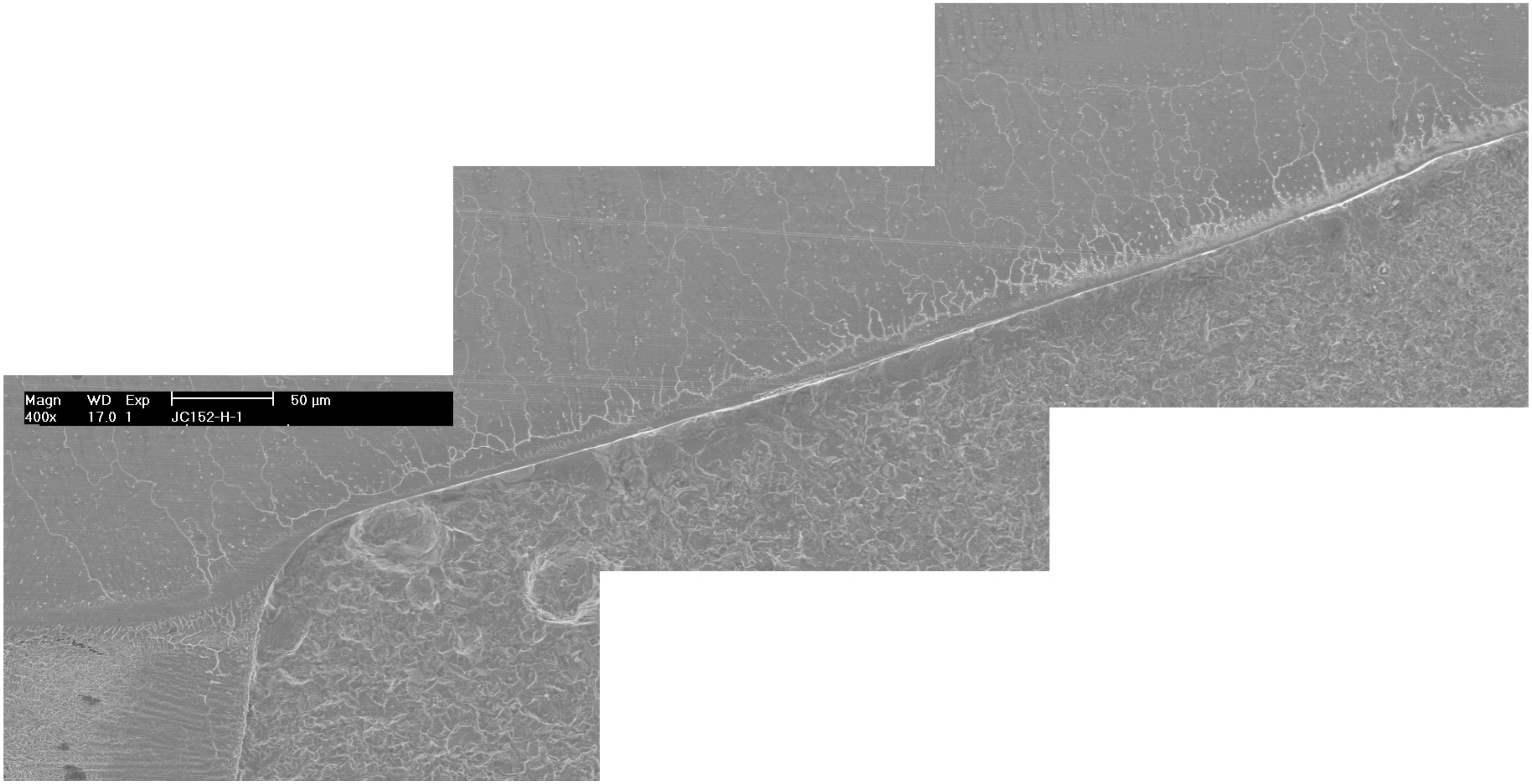






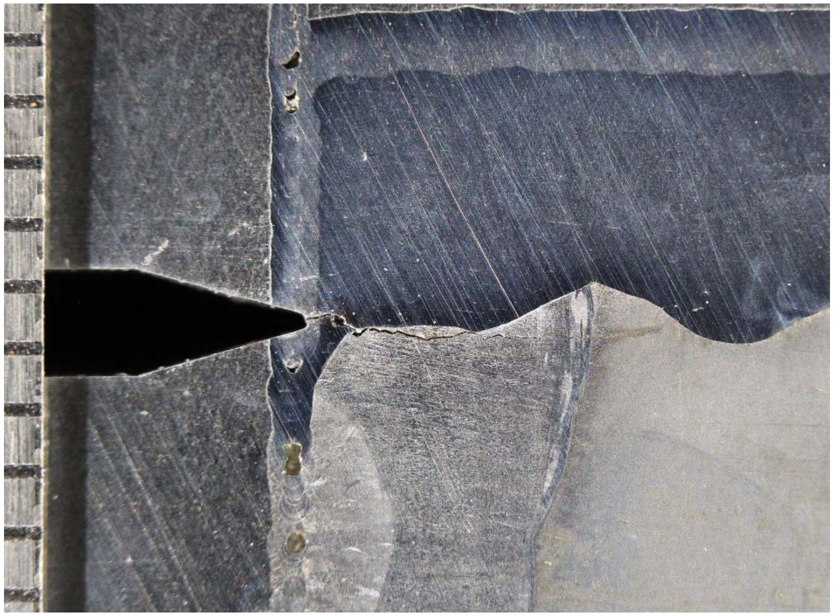
- Favorably-oriented/type II boundaries only along the interface with the LAS (locations 1, 2)

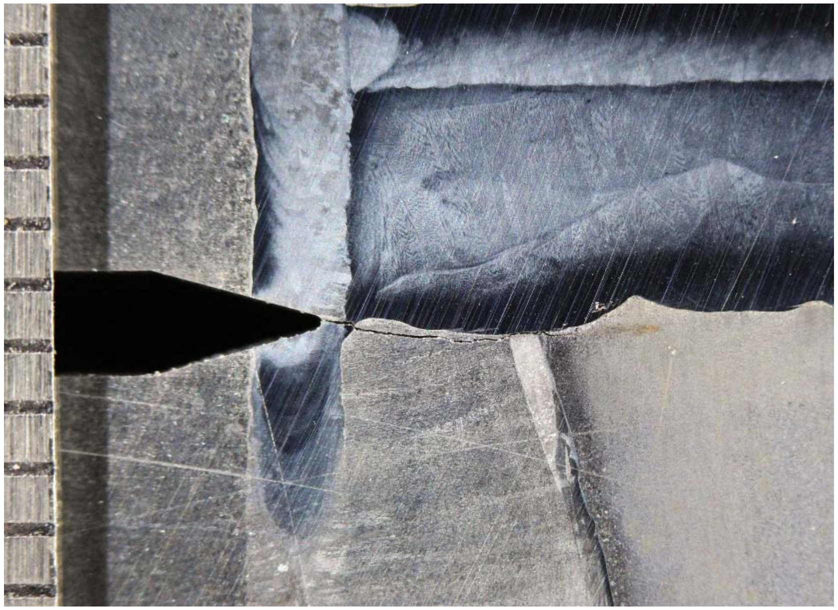
Specimen JC152-H-1 – triple point



- Location 1: Type II and other favorably-oriented collections of boundaries only observed near the LAS

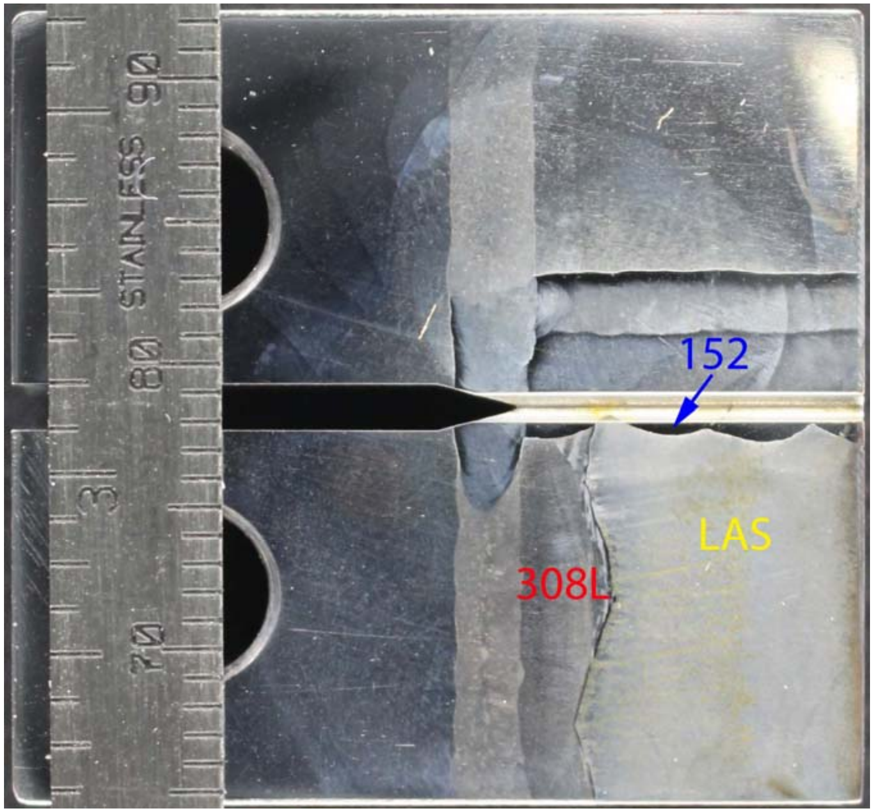
Specimen JC152-H-1 – side surfaces

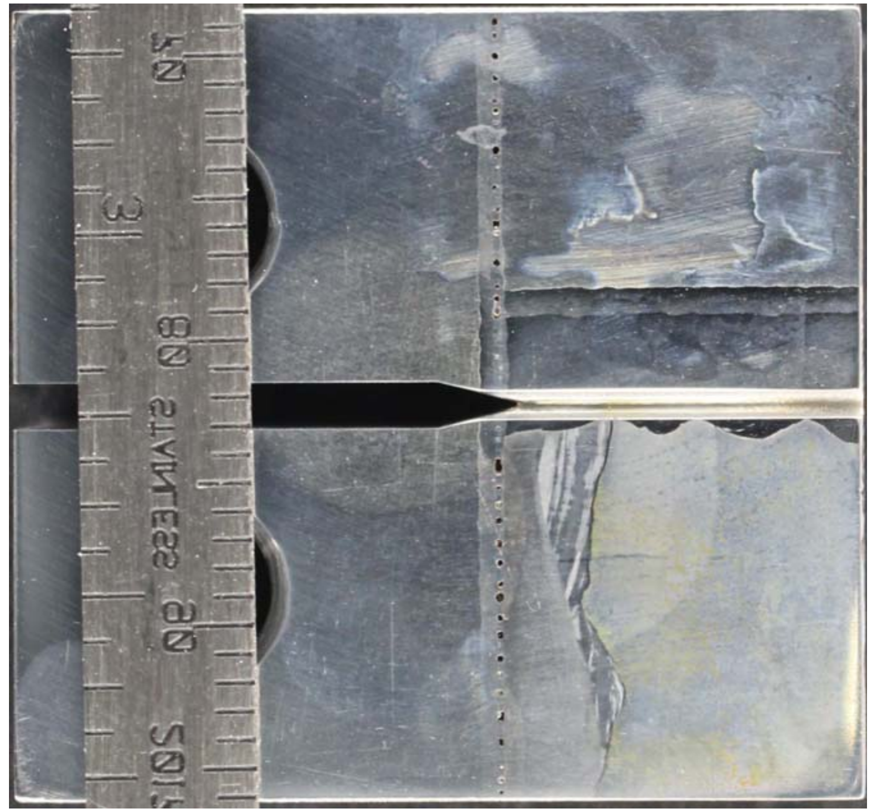




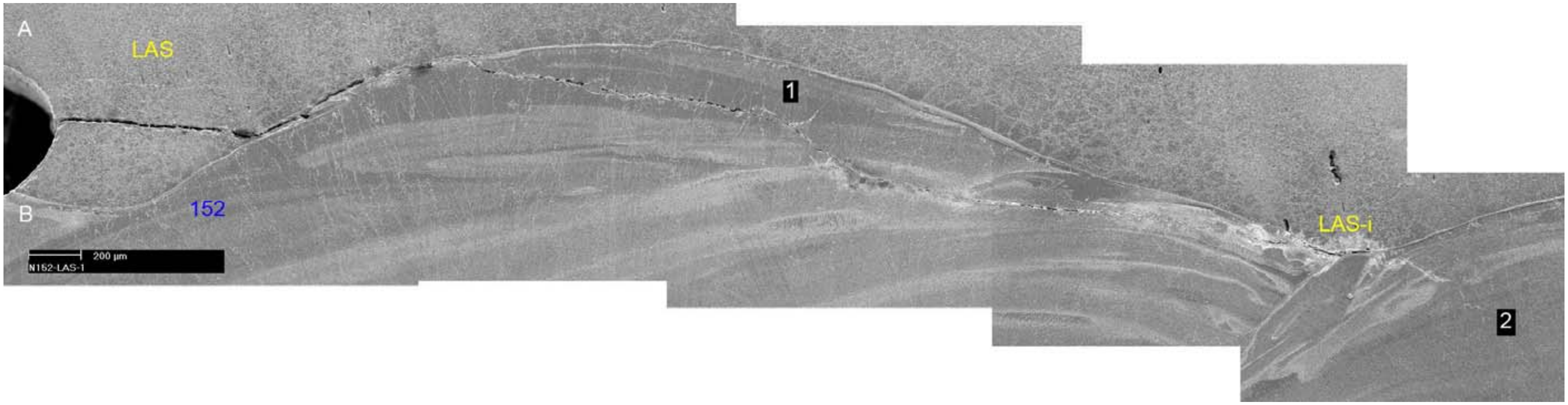
- Used 308L-clad 533-Gr B LAS from Midland lower head
- JC152: propagation in 152 along interfaces with 308L clad and LAS

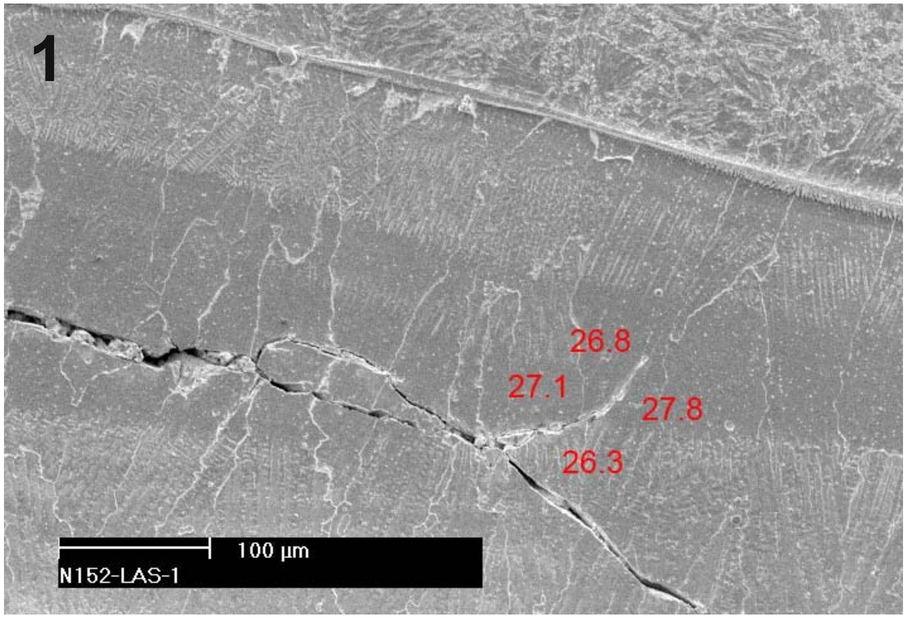
Upcoming test on Specimen JC152-H-2

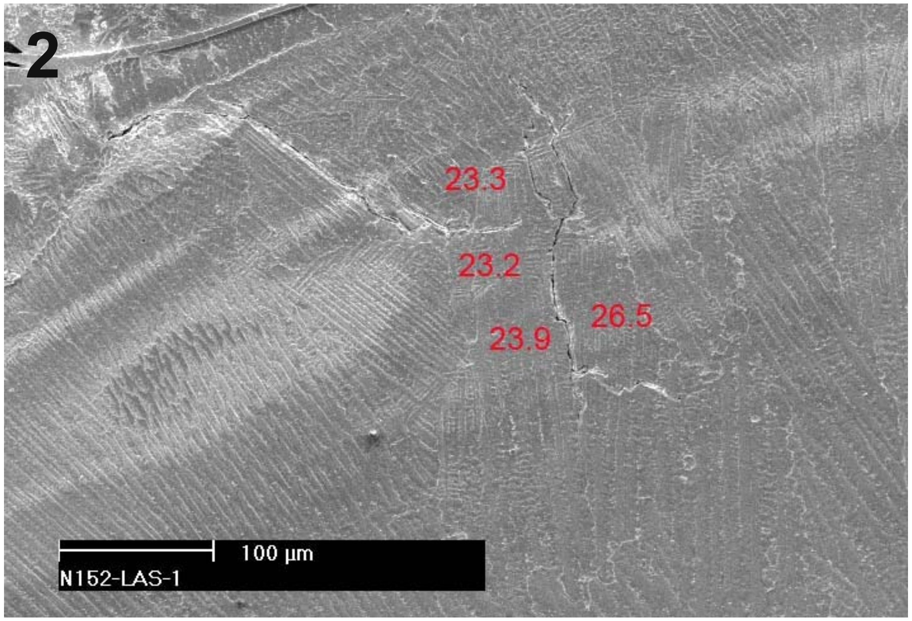




Specimen N152-LAS-1 – Side Surface 1







- A cross section was kept and was available for EBSD

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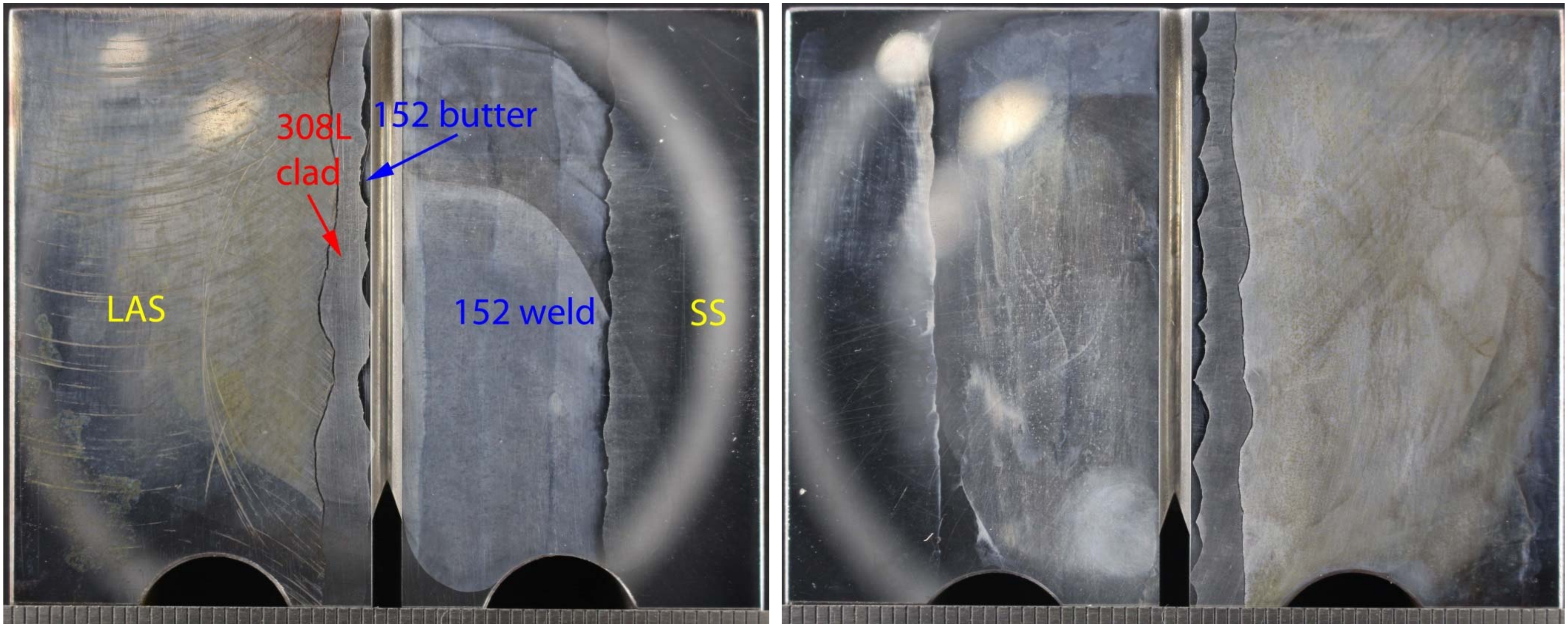
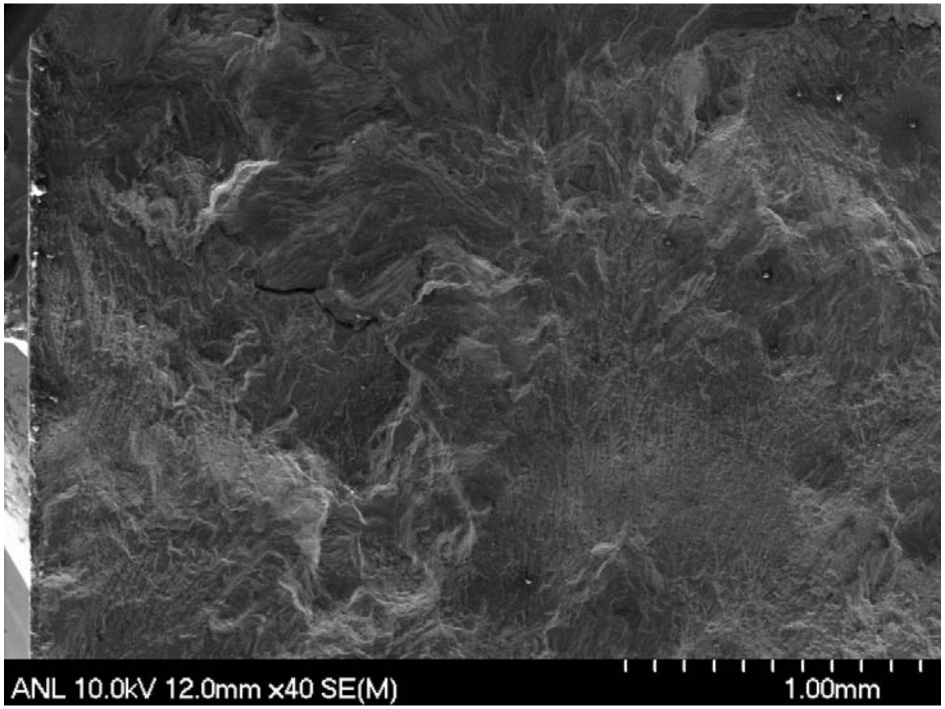
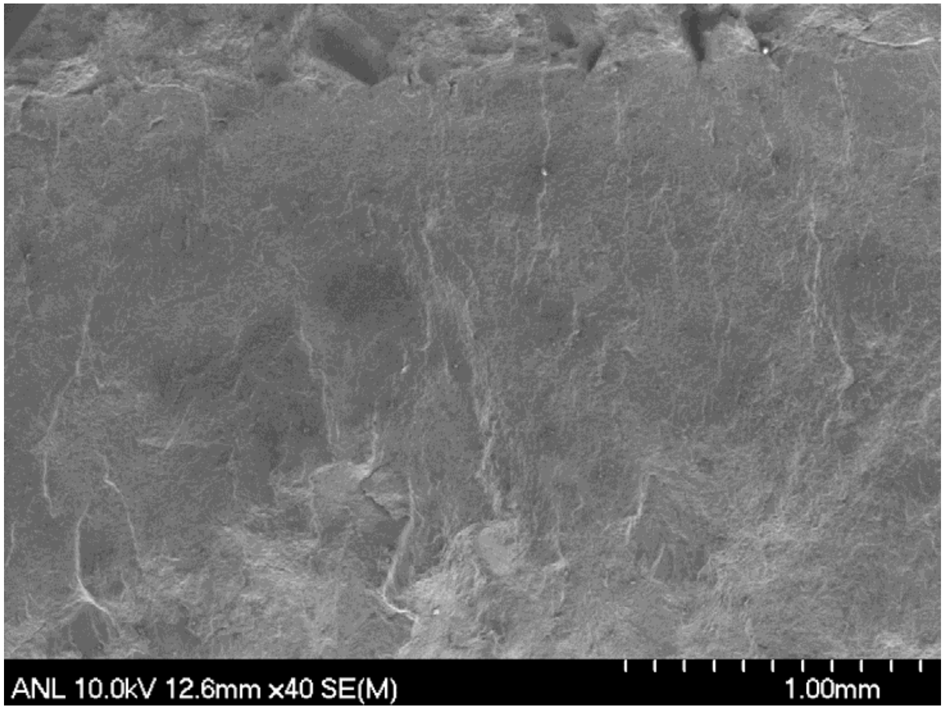
Alloy 152 butter – 308L clad interface
Specimen BA152-308L-1



- Used 308L-clad 533-Gr B LAS from Midland lower head
- BA152: propagation in 152 along 308L clad

Specimen BA152-308L-1

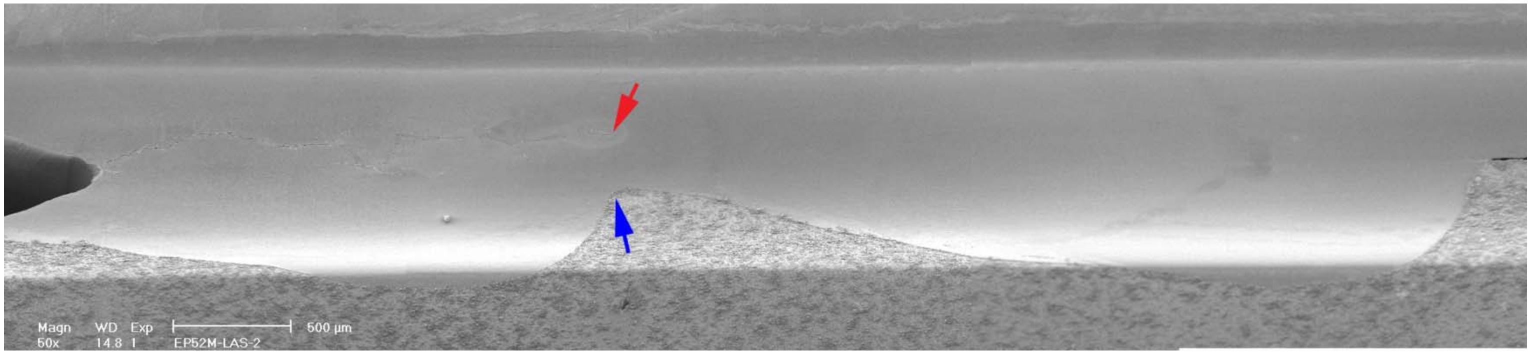




- Flake: limited, not unambiguous IG
- End of test: TG

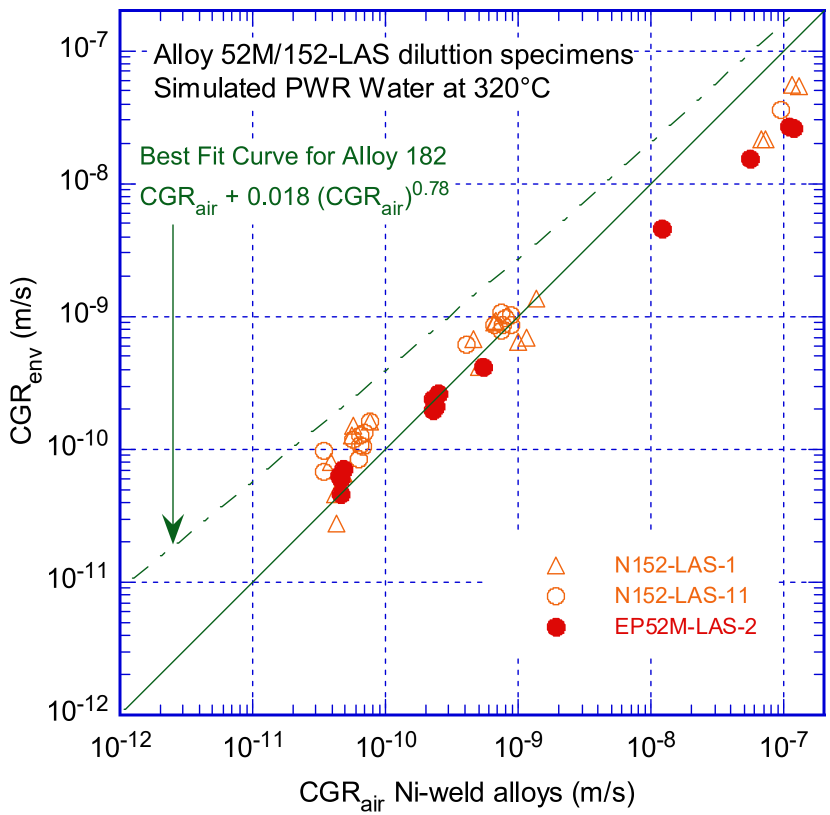
EPRI Alloy 52M-LAS repair weld

EPRI Alloy 52M-LAS Specimen EP52M-LAS-2



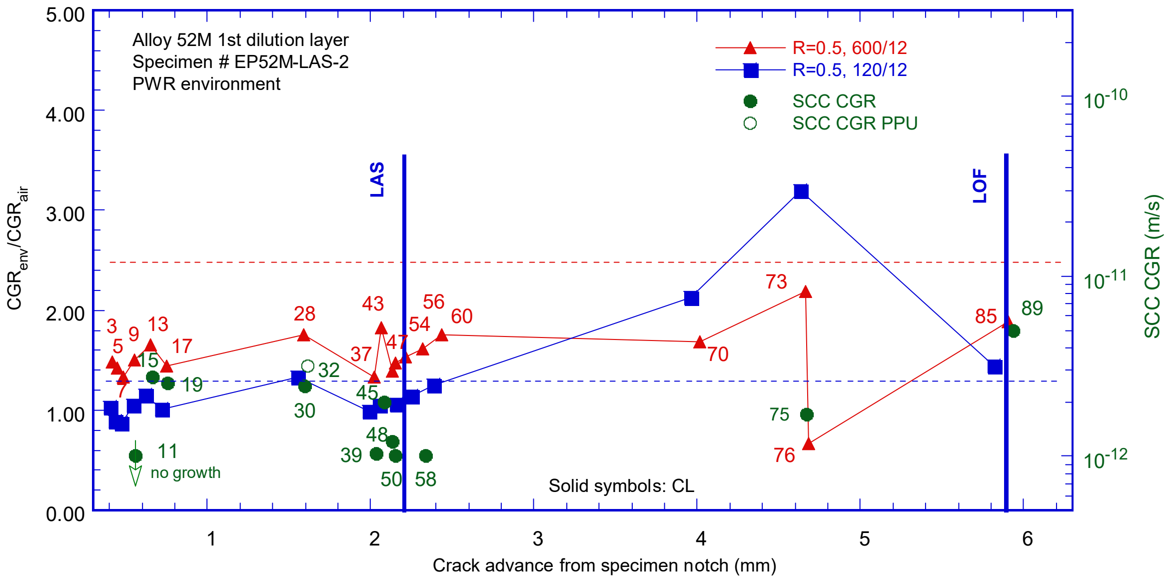
- Stopped midway to confirm location: crack (red)
- Next objective: reach the lack of fusion (LOF) defect

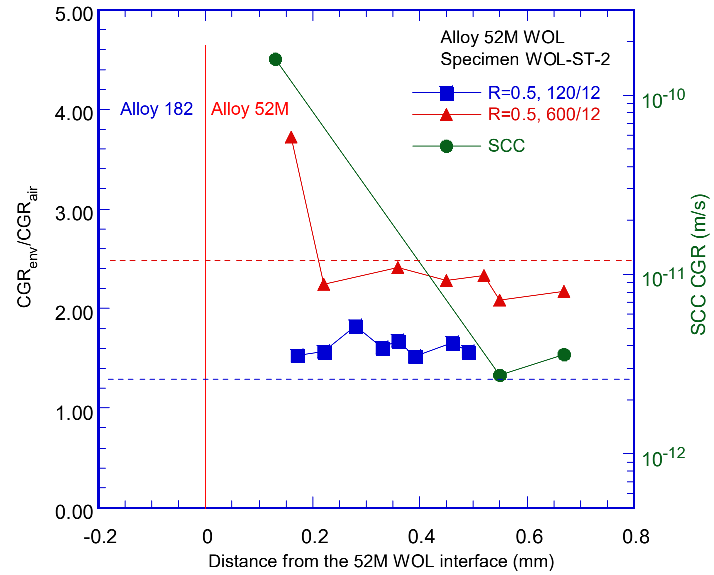
EPRI Alloy 52M-LAS Cyclic CGRs



- Fatigue response is lower than expected for a Ni-base alloy weld
- Observation is consistent with ANL Alloy 152-LAS 1st layer welds

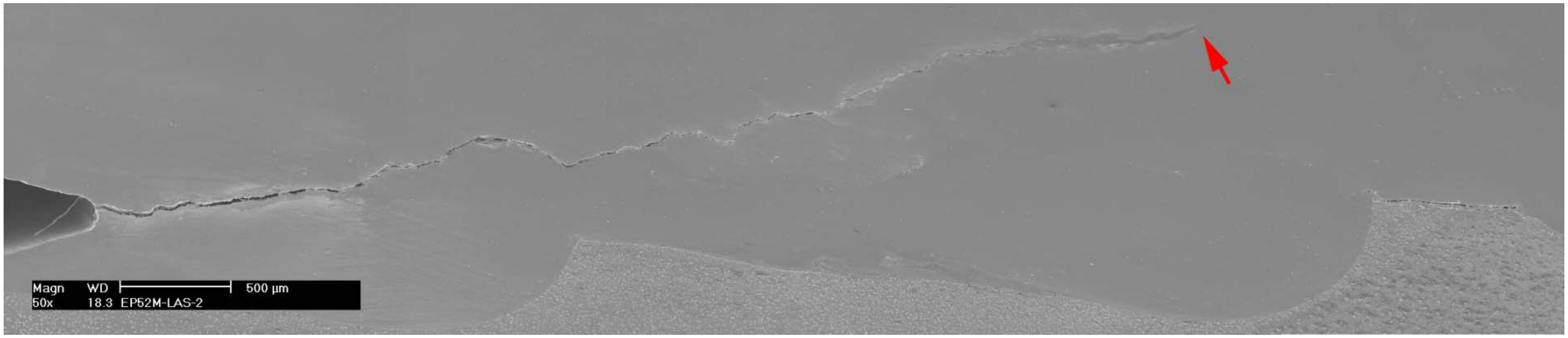
EPRI Alloy 52M-LAS vs. ANL 52M WOL





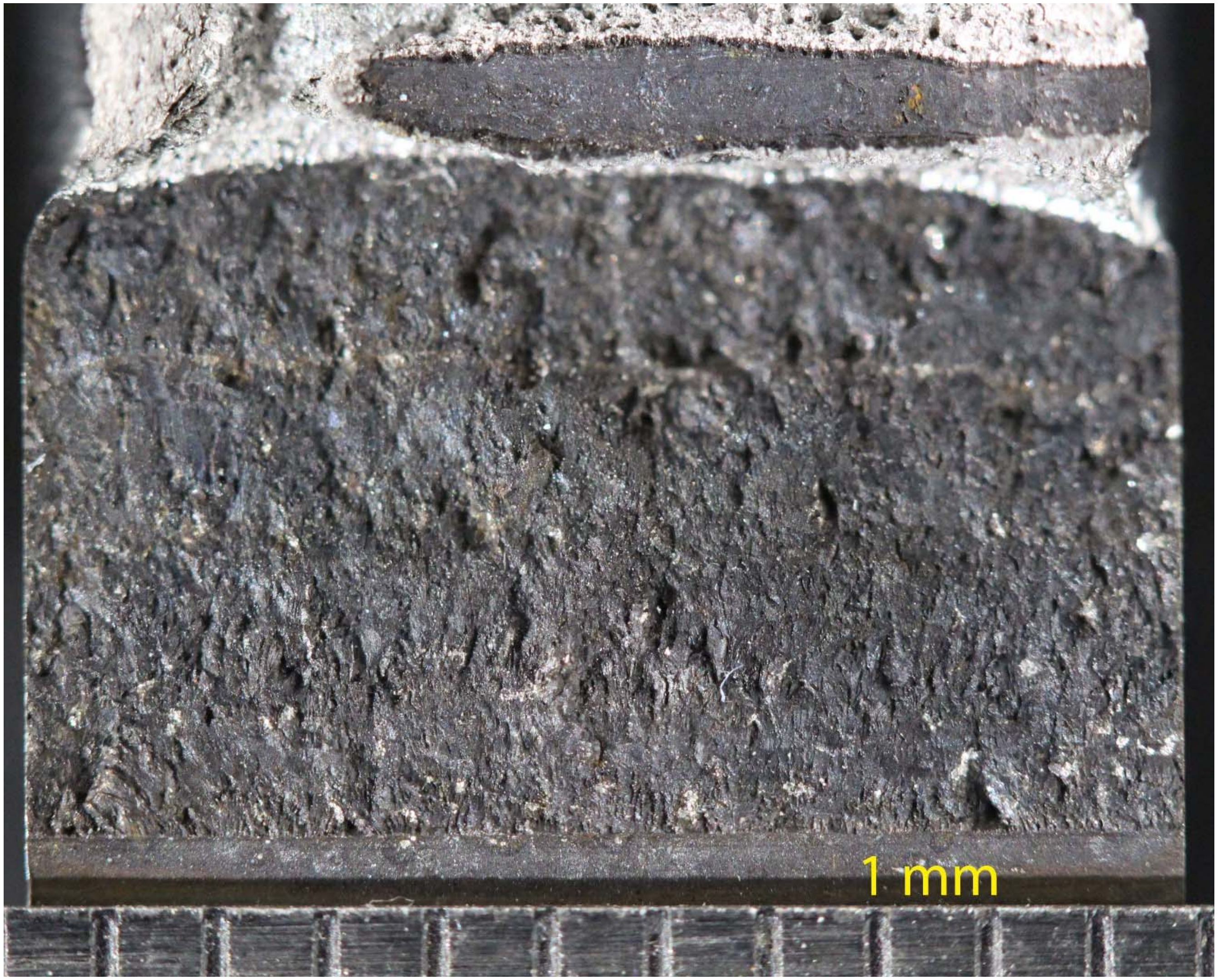
- Overall, the EPRI Alloy 52M weld (on LAS) has a lower cyclic than the ANL 52M WOL (on Alloy 182)
- Does the LAS substrate play a role? Fe-rich “swirls” were found to impede crack propagation; highest response obtained when crack was furthest away from the LAS
- Overall, SCC CGR response in the EPRI Alloy 52M-LAS is low

EPRI Alloy 52M-LAS Specimen EP52M-LAS-2



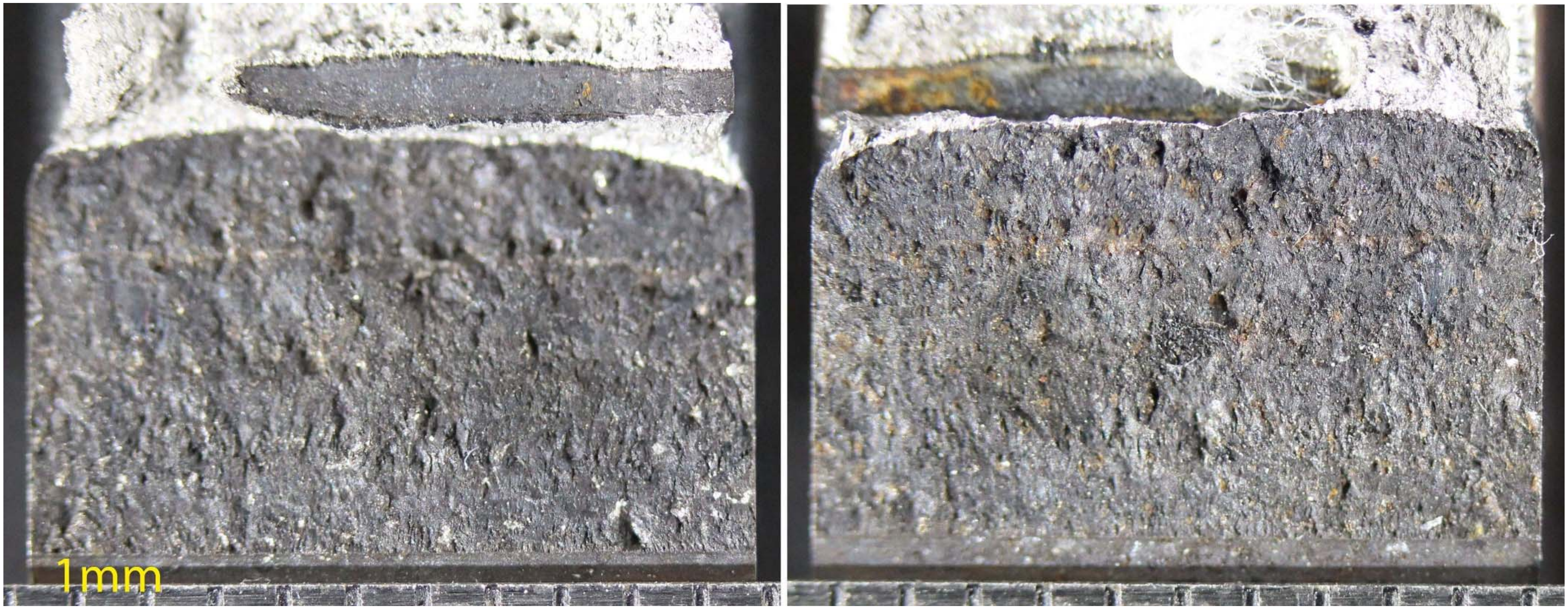
- After the removal of the side grooves, the LOF is visible on only one side
- Missed the LOF by at least 0.5 mm

EPRI Alloy 52M-LAS Specimen EP52M-LAS-2



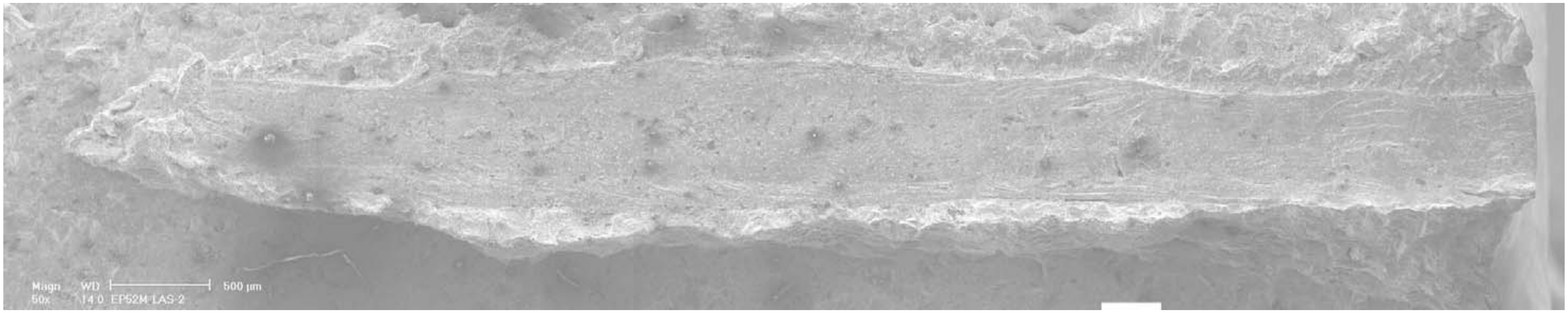
- Fracture surface as expected, except for the LOF

EPRI Alloy 52M-LAS Specimen EP52M-LAS-2



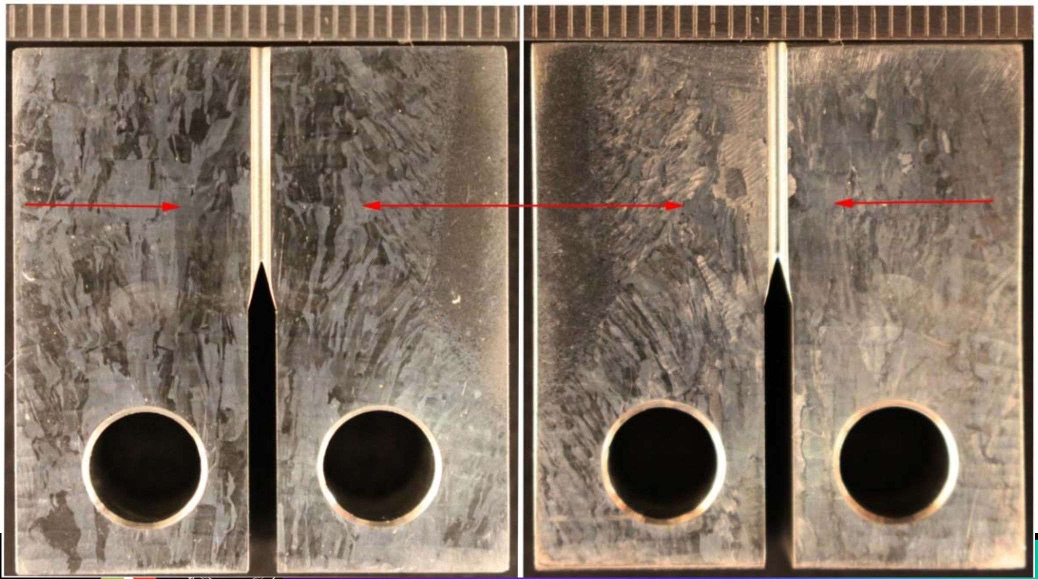
- Fracture surface as expected, except for the LOF
- The connection between the “test” and the LOF is unclear
- No/low IG fracture (as expected for low/no SCC growth)

EPRI Alloy 52M-LAS Specimen EP52M-LAS-2



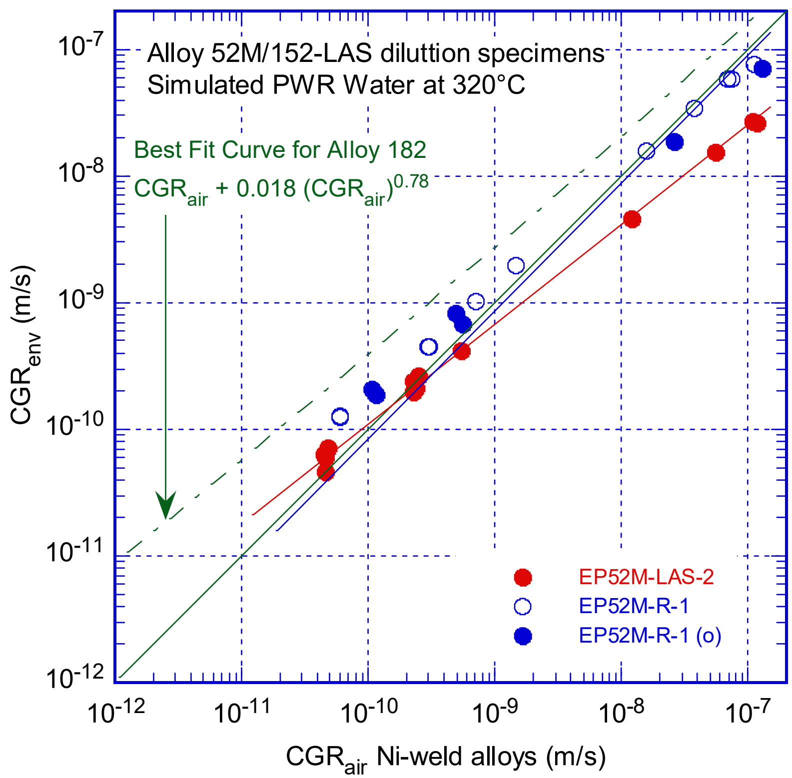
- The connection between the “test” and LOF unclear
- No IG SCC fracture at/near the LOF

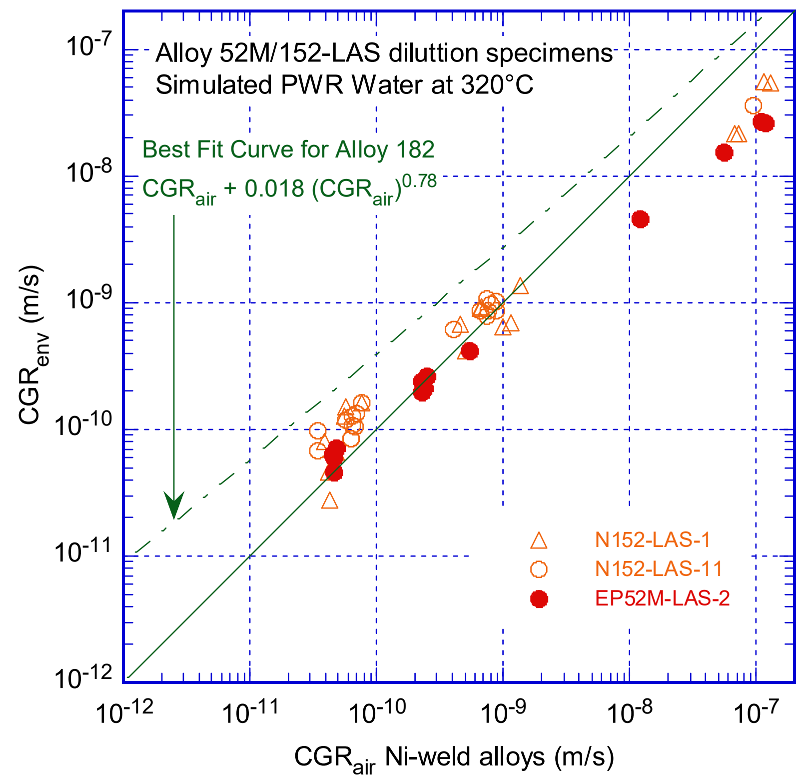
EPRI Alloy 52M repair weld Specimen EP52M-R-1



- Interface between the original and repair welds is approx. 3.4 mm form the CT specimen notch

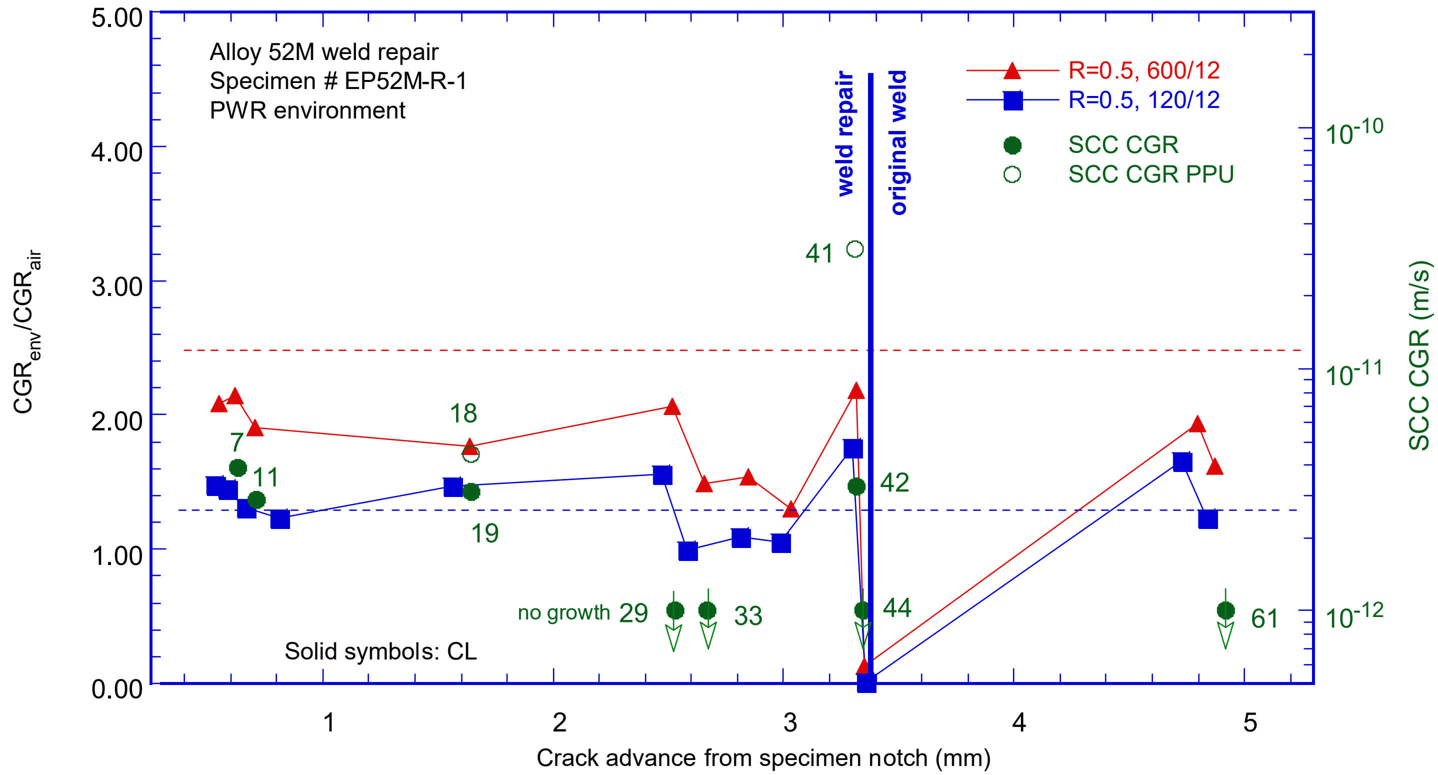
EPRI Alloy 52M-LAS vs. EPRI 52M repair





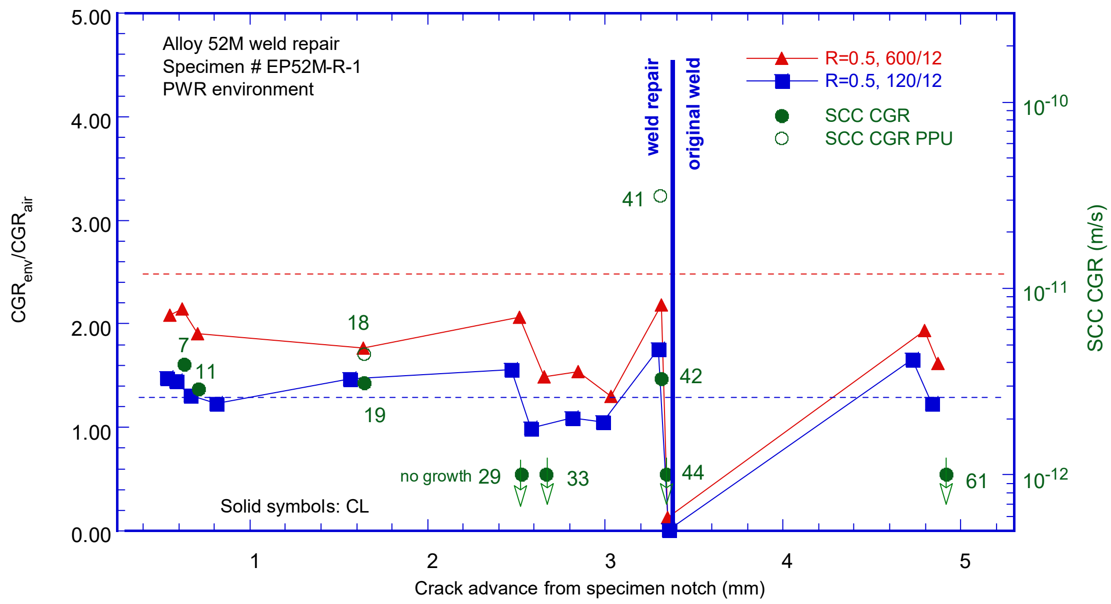
- While the 1st layer was resistant to fatigue (consistent with other 1st layer welds),
- The fatigue response of the repair (and original) welds are as expected
- No difference in fatigue response between the repair and the original

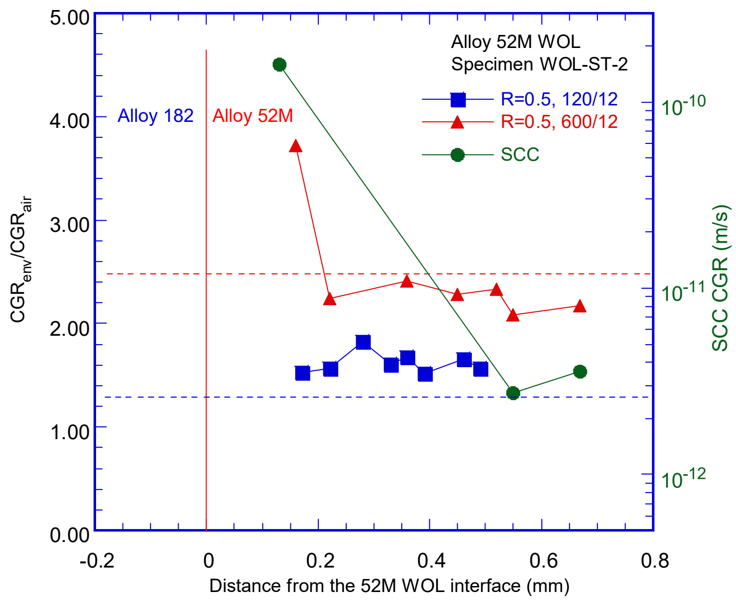
EPRI Alloy 52M repair weld Specimen EP52M-R-1



- Large drop at the interface between the two welds
- No difference between the repair and the original weld
- SCC CGR response in the EPRI Alloy 52M repair and original is low

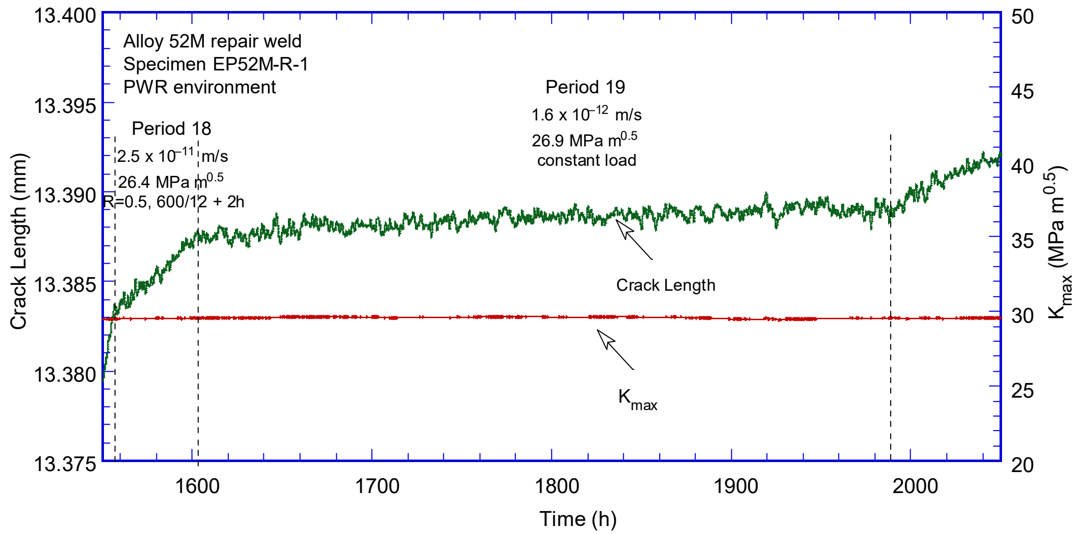
EPRI Alloy 52M repair vs. ANL 52M-182 WOL

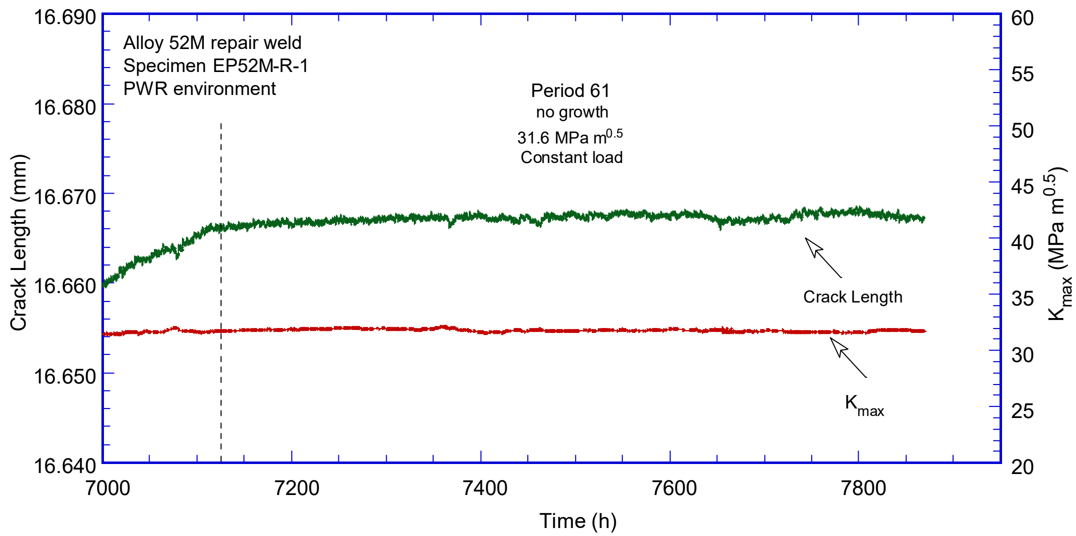




- Overall, the EPRI Alloy 52M weld has a lower cyclic and SCC CGR response than the ANL Alloy 52M-182 WOL

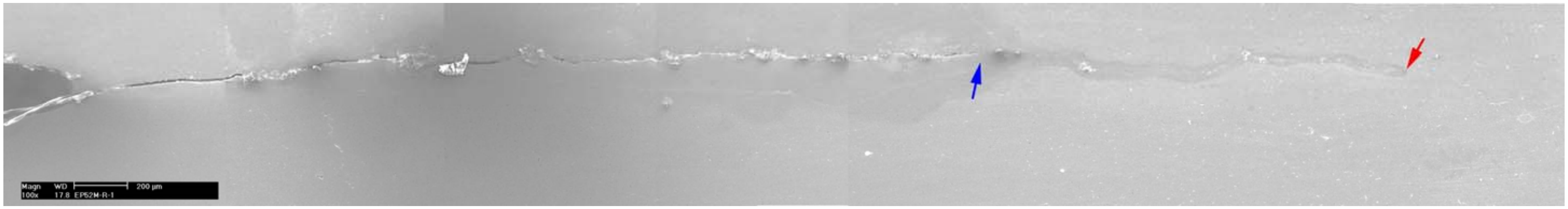
EPRI Alloy 52M repair weld Specimen EP52M-R-1

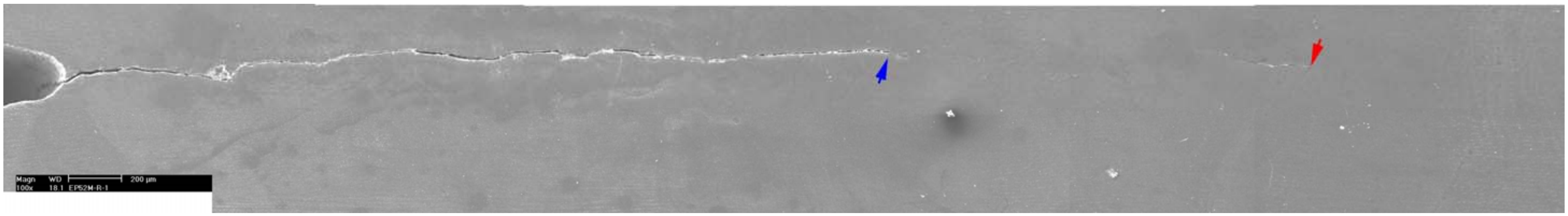


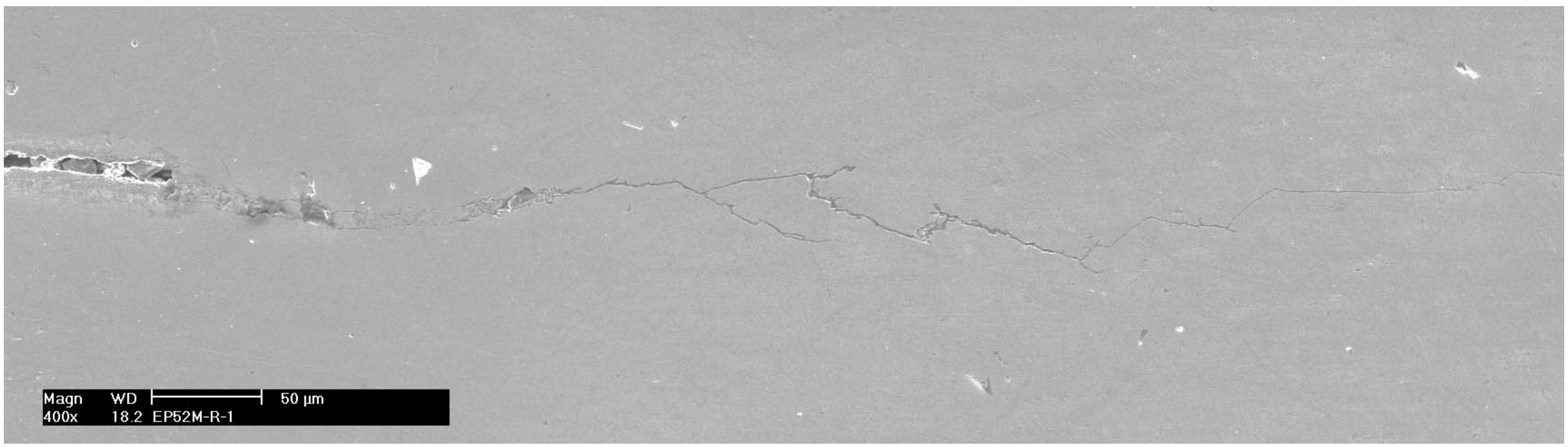


- Low SCC CGR response in the repair and original welds

EPRI Alloy 52M repair weld Specimen EP52M-R-1

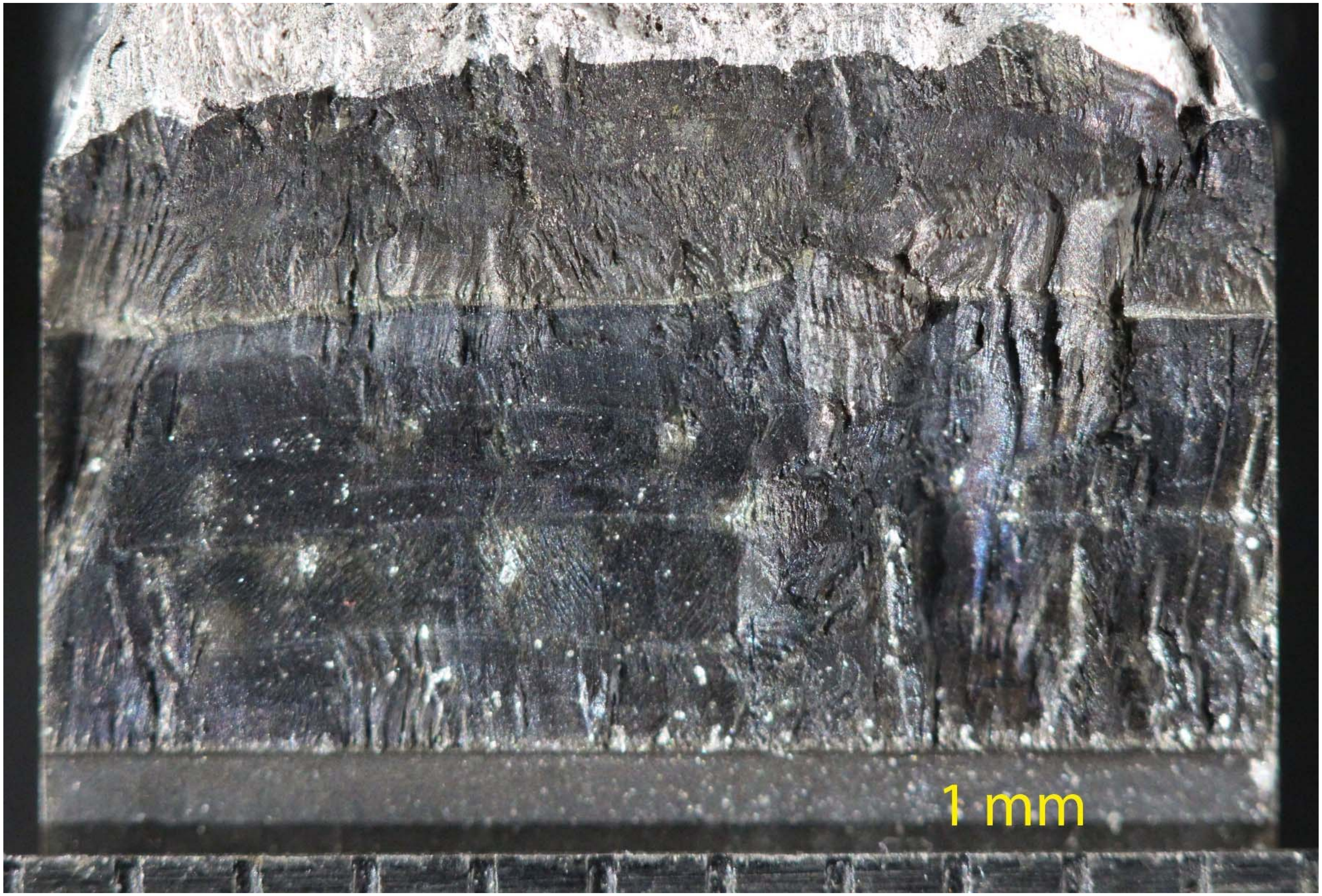






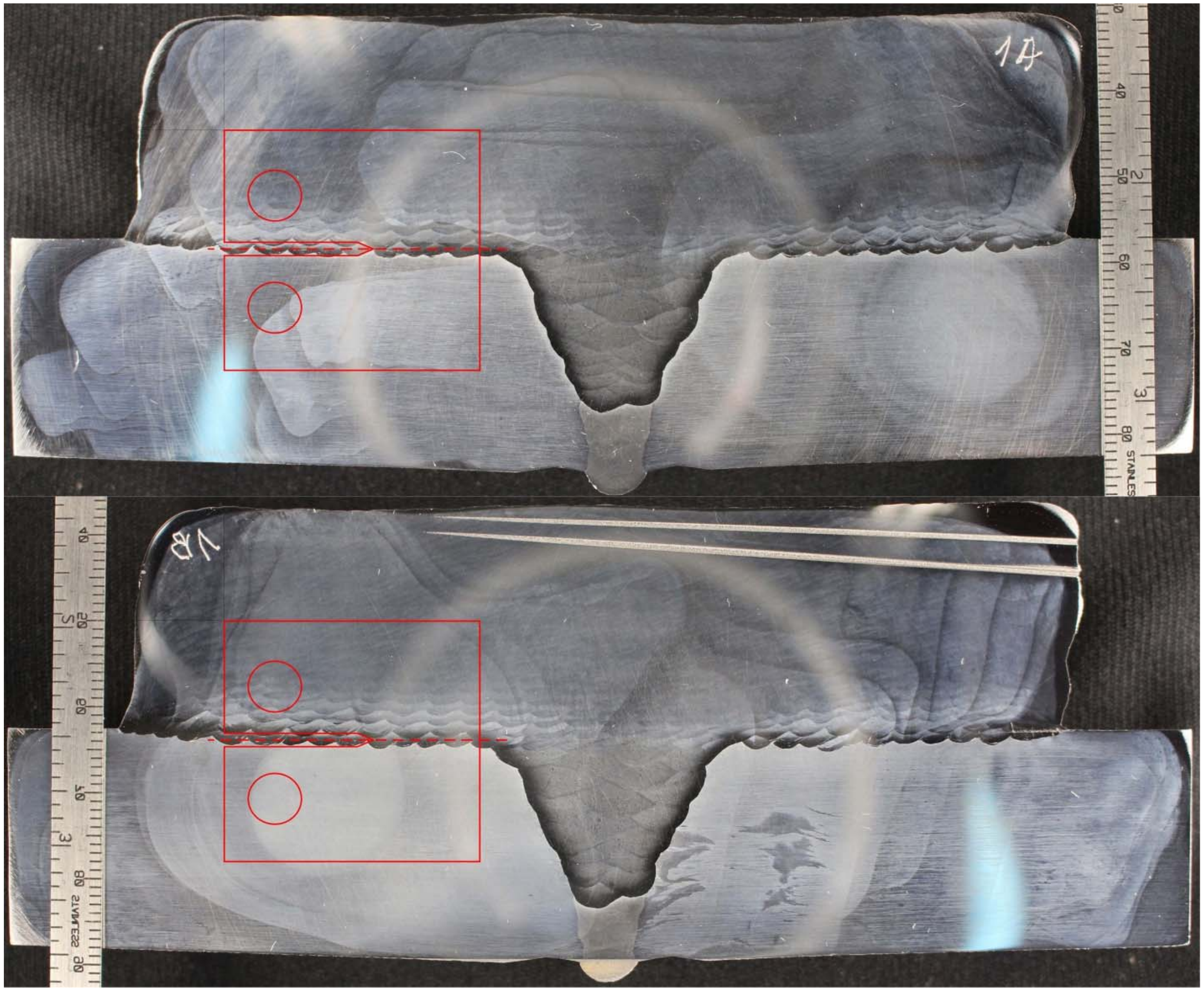
- Original weld (HAZ) appeared more resistant to fatigue during the test
- Observation correlated with the smaller crack opening in the original weld

EPRI Alloy 52M repair weld Specimen EP52M-R-1



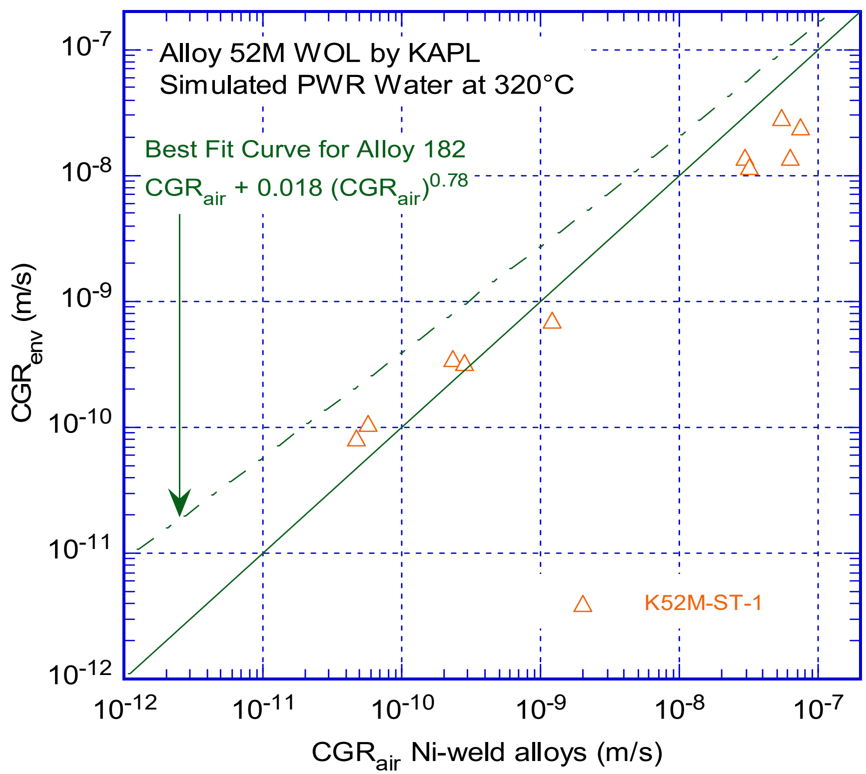
- Straight crack front, no/low IG fracture (consistent with low/no growth)

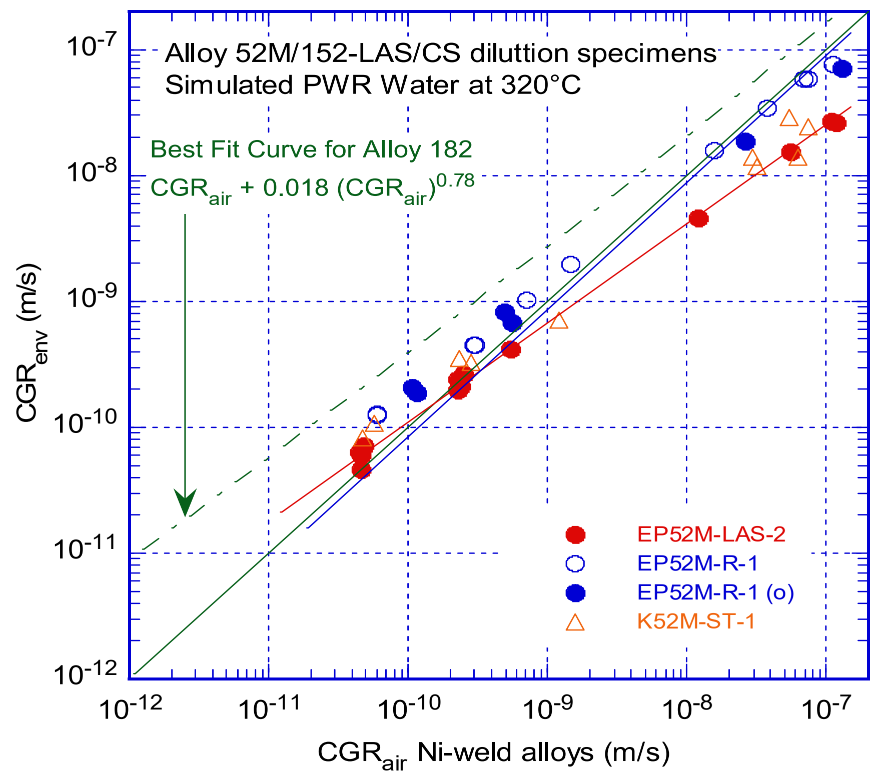
KAPL Alloy 52M-182 WOL



- ST orientation: 1st layer Alloy 52M - SS

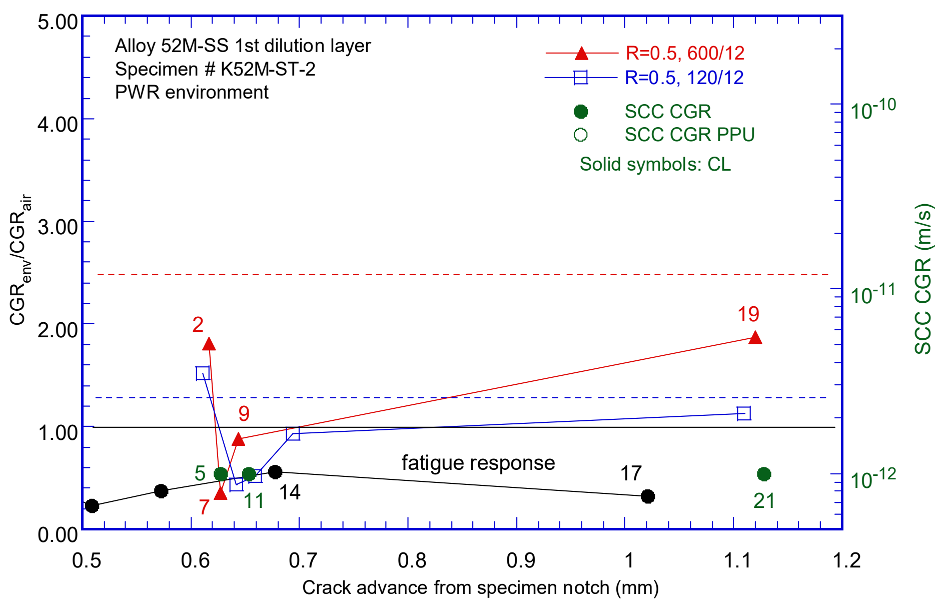
KAPL Alloy 52M-182 WOL

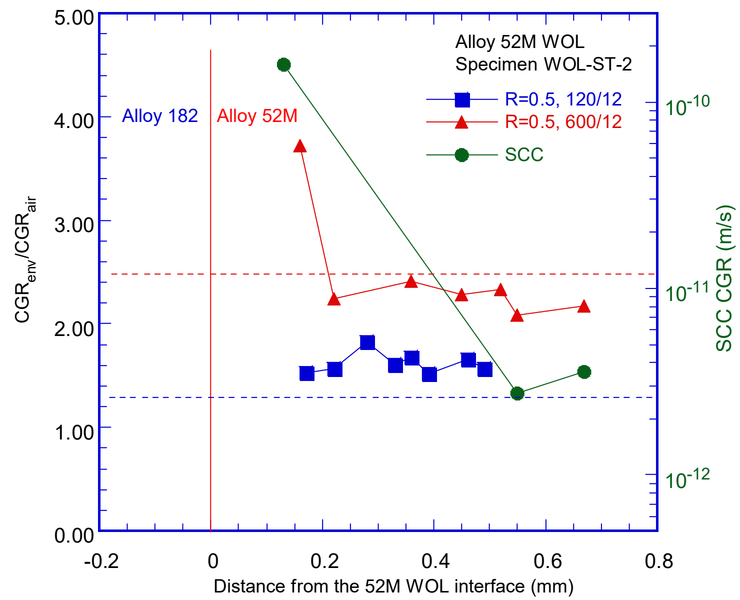




- Alloy 52M-SS 1st layer butter resistant to fatigue
- Observation consistent with that observed on EPRI Alloy 52M butter (deposited on LAS)

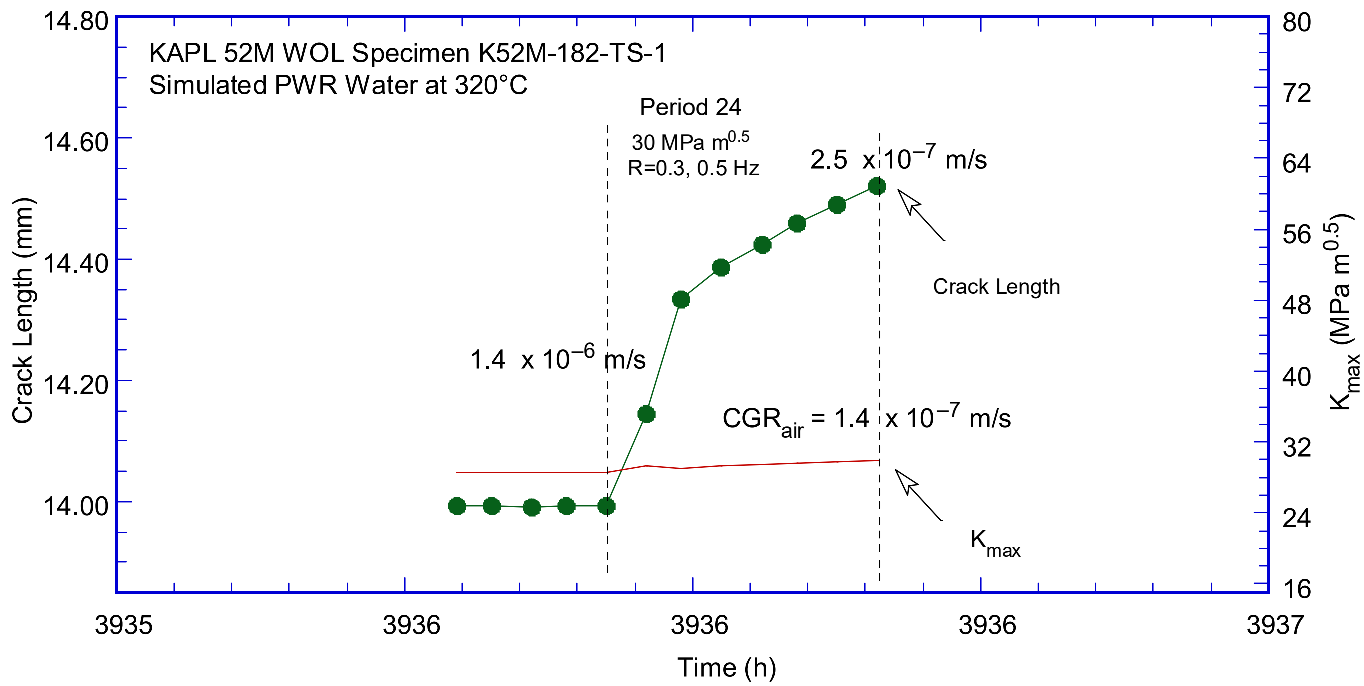
KAPL Alloy 52M-SS vs. ANL Alloy 52M-600/182





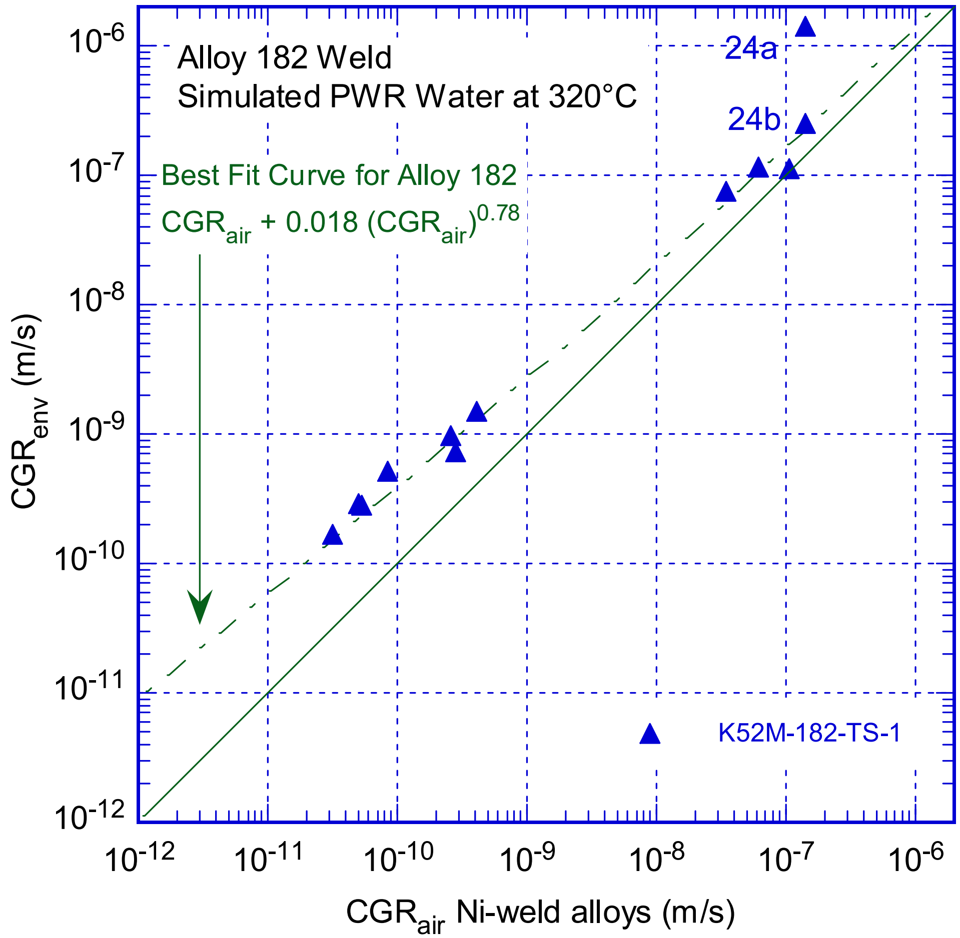
- Overall, the cyclic and SCC CGR response for KAPL Alloy 52M-SS 1st layer is smaller than the ANL Alloy 52M-600/182 1st layer
- Could Fe-rich swirls impede crack propagation (transitioning to IG SCC)?

KAPL Alloy 52M-182 WOL: K52M-ST-1



- Test period 24, 0.5 mm from the interface

KAPL Alloy 52M-182 WOL: K52M-ST-1



- Test period 24, 0.5 mm from the interface