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SCC Behavior of cold-worked Alloy 690 and Alloy 690 HAZ – Microstructure and CGR Testing

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Office of Science

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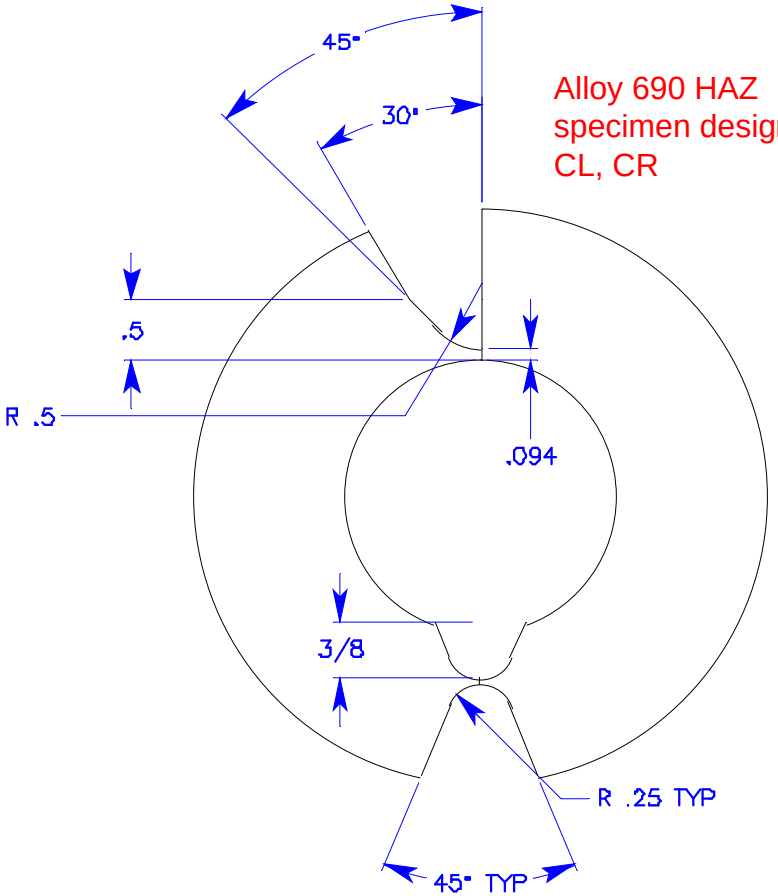
Presentation Topics

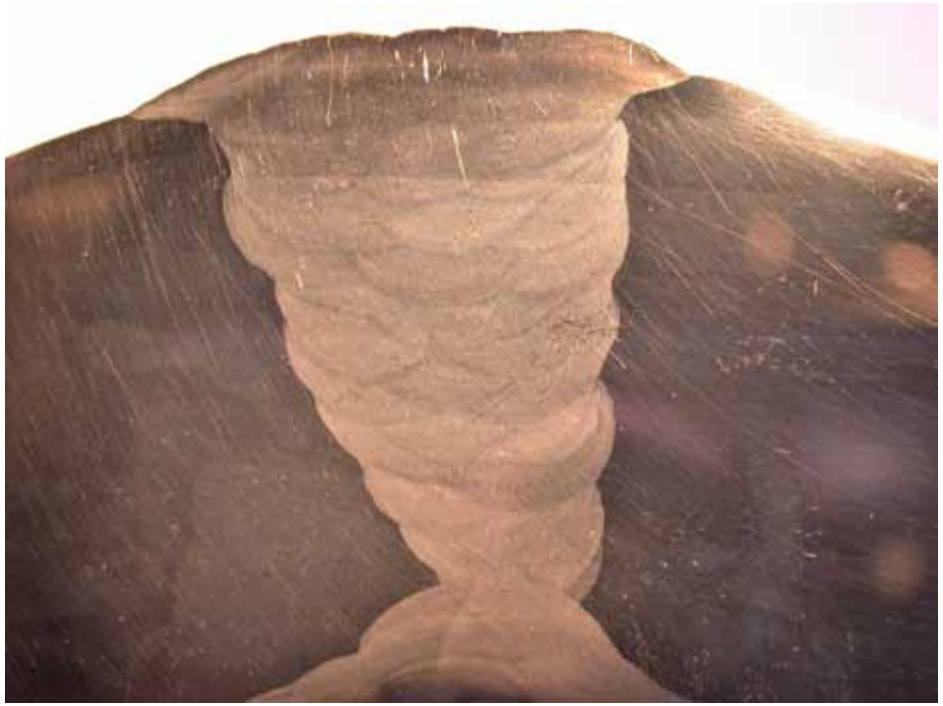
- CGR testing of Alloy 690 HAZ
  - present microstructural analysis
  - present CGR data
  - present and discuss fracture surface

- Cracked carbides – a possible explanation for the high rates observed in several heats of Alloy 690 in cold-worked condition

Alloy 152 Welds on CRDM Nozzle (2541-Heat WP142)



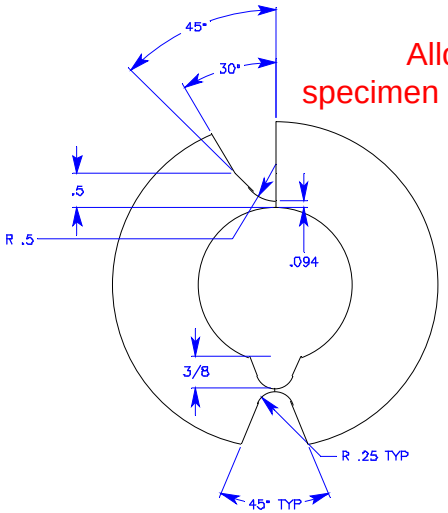
Alloy 690 HAZ
specimen designation CF690
CL, CR



Alloy 152 Weld (B-P7)
specimen designation C152
CR, LR

- Alloy 152 Heat WC43E9 (Special Metals)

CRDM Alloy 690 HAZ – microstructure vs. distance to fusion line



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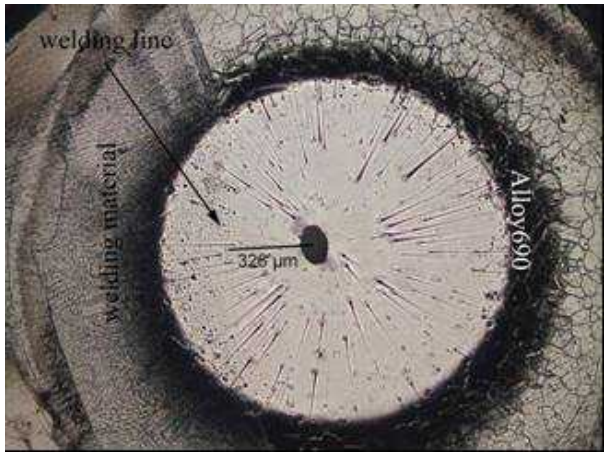
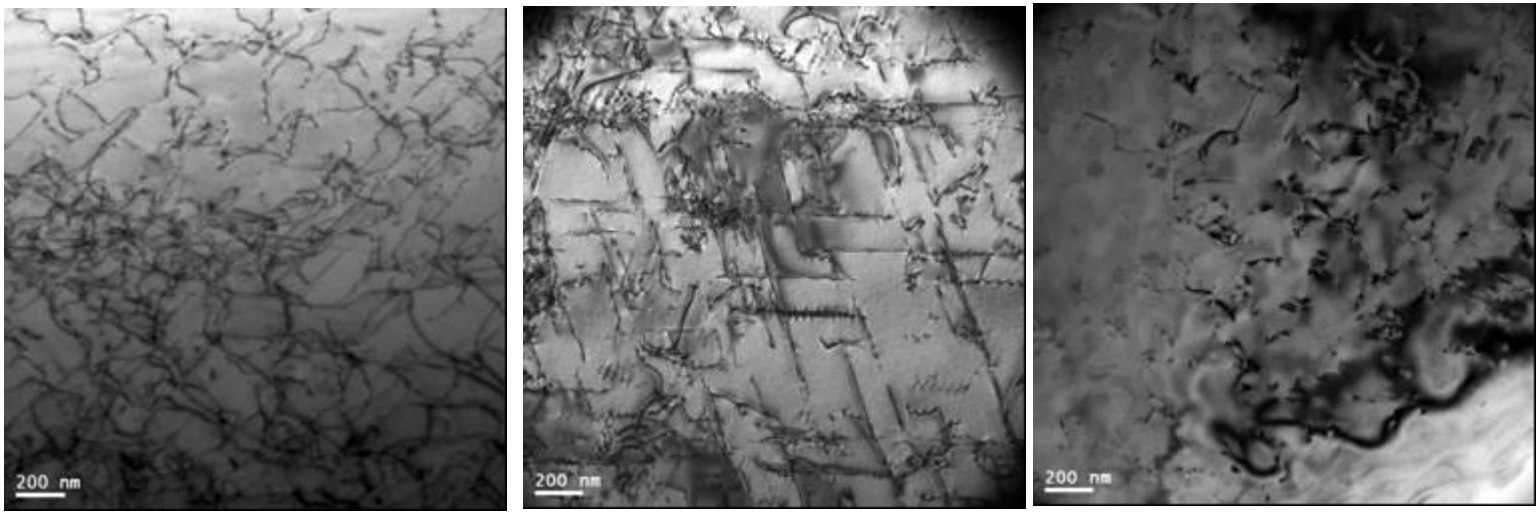
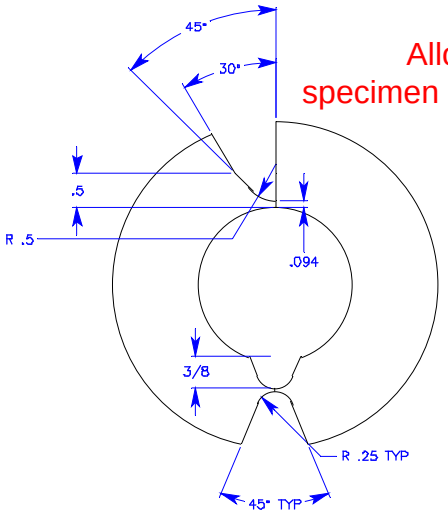


Distance to fusion line (µm): 131 326 866



- Dislocation segments become longer, evolve as tangled dislocation network

CRDM Alloy 690 HAZ – microstructure vs. distance to fusion line



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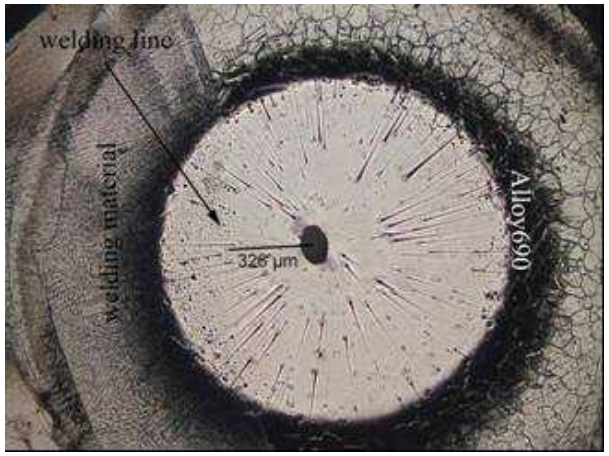

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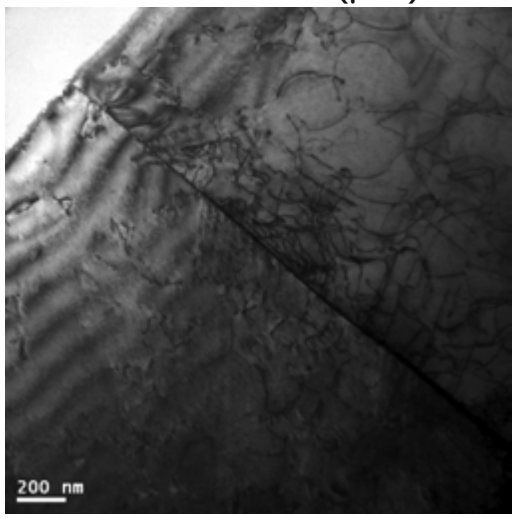
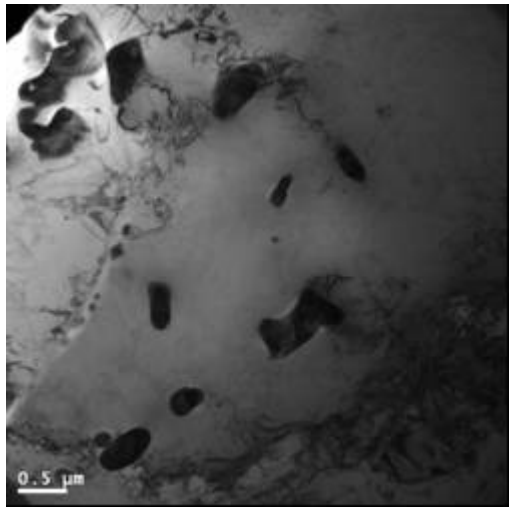
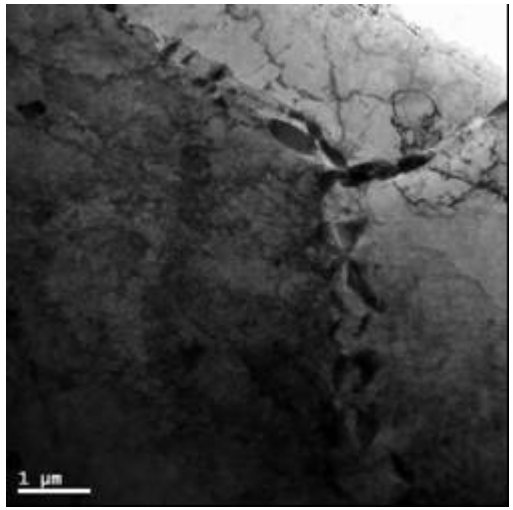
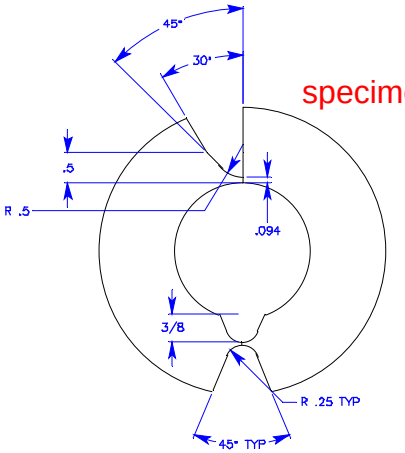






- Microstructure: GB carbides, matrix carbides, carbide-free near fusion line

CRDM Alloy 690 HAZ – Microstructure near the fusion line



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specimen designation CF690
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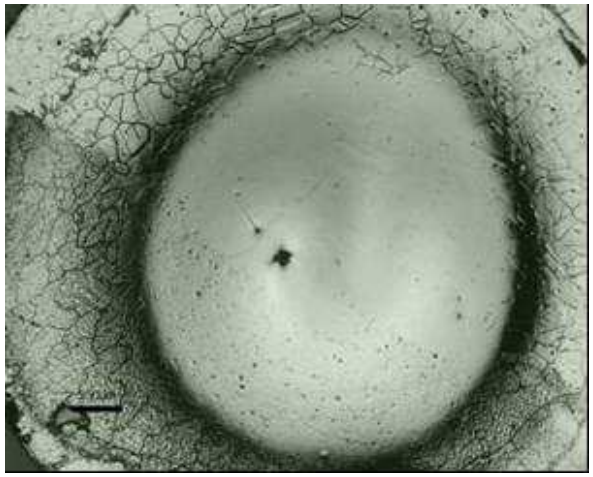
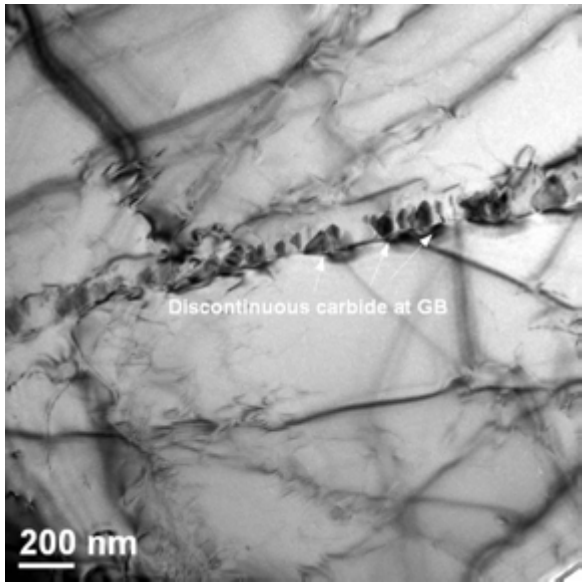
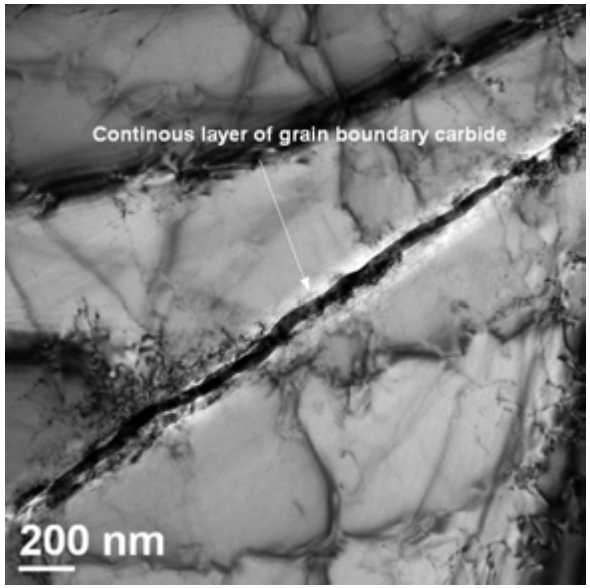
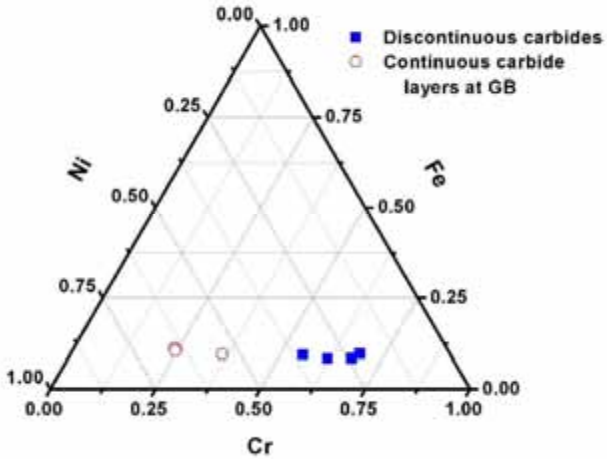


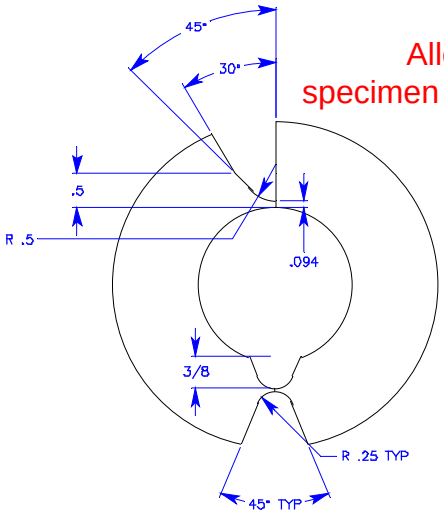






- Discrete (discontinuous) and continuous and GB carbides

CRDM Alloy 690 HAZ - Hardness



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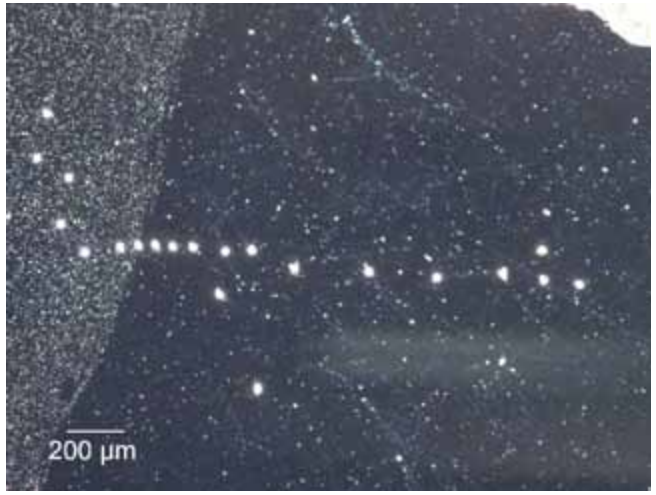
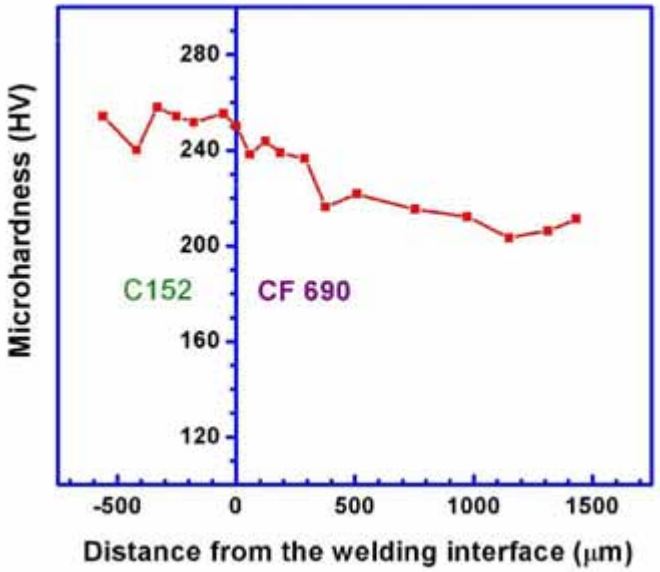
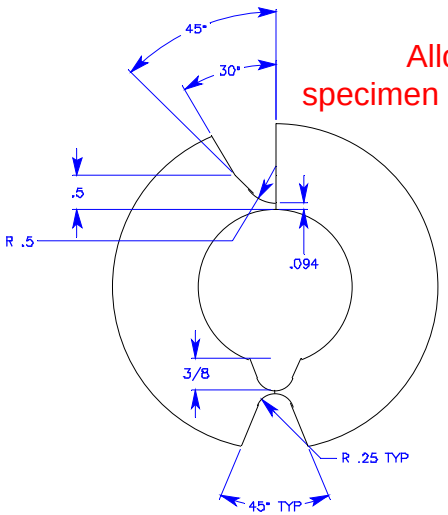
CL, CR



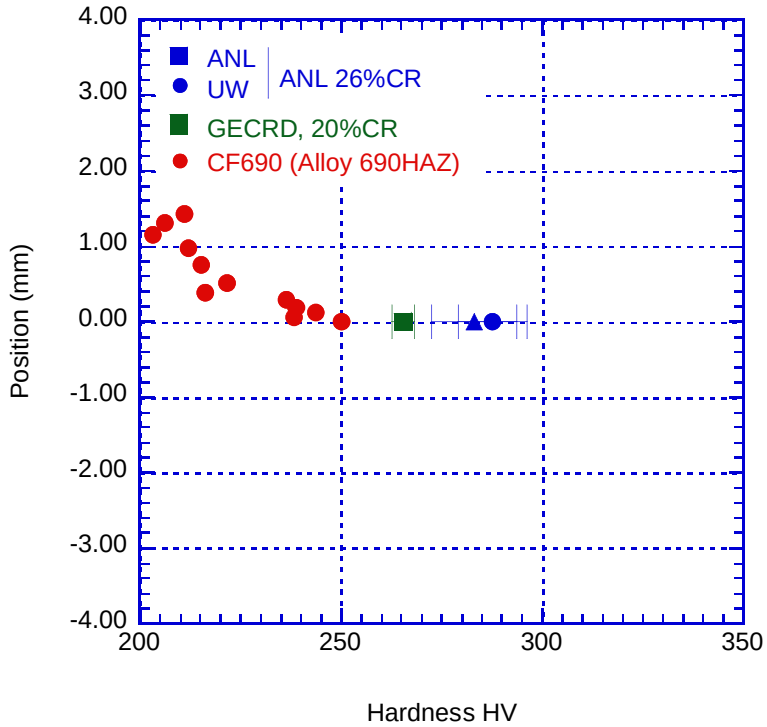


- Hardness near the fusion line higher by approx. 13% vs. matrix

CRDM Alloy 690 HAZ Specimens

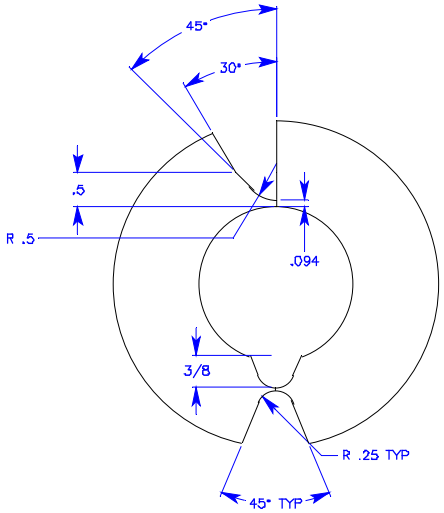


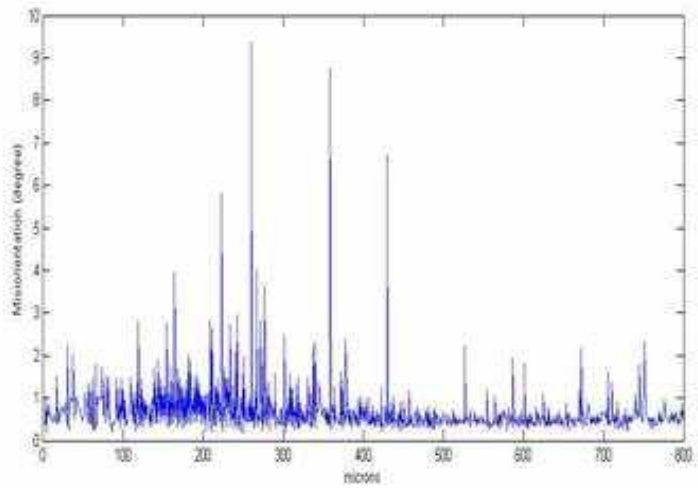
Alloy 690 HAZ
specimen designation CF690
CL, CR

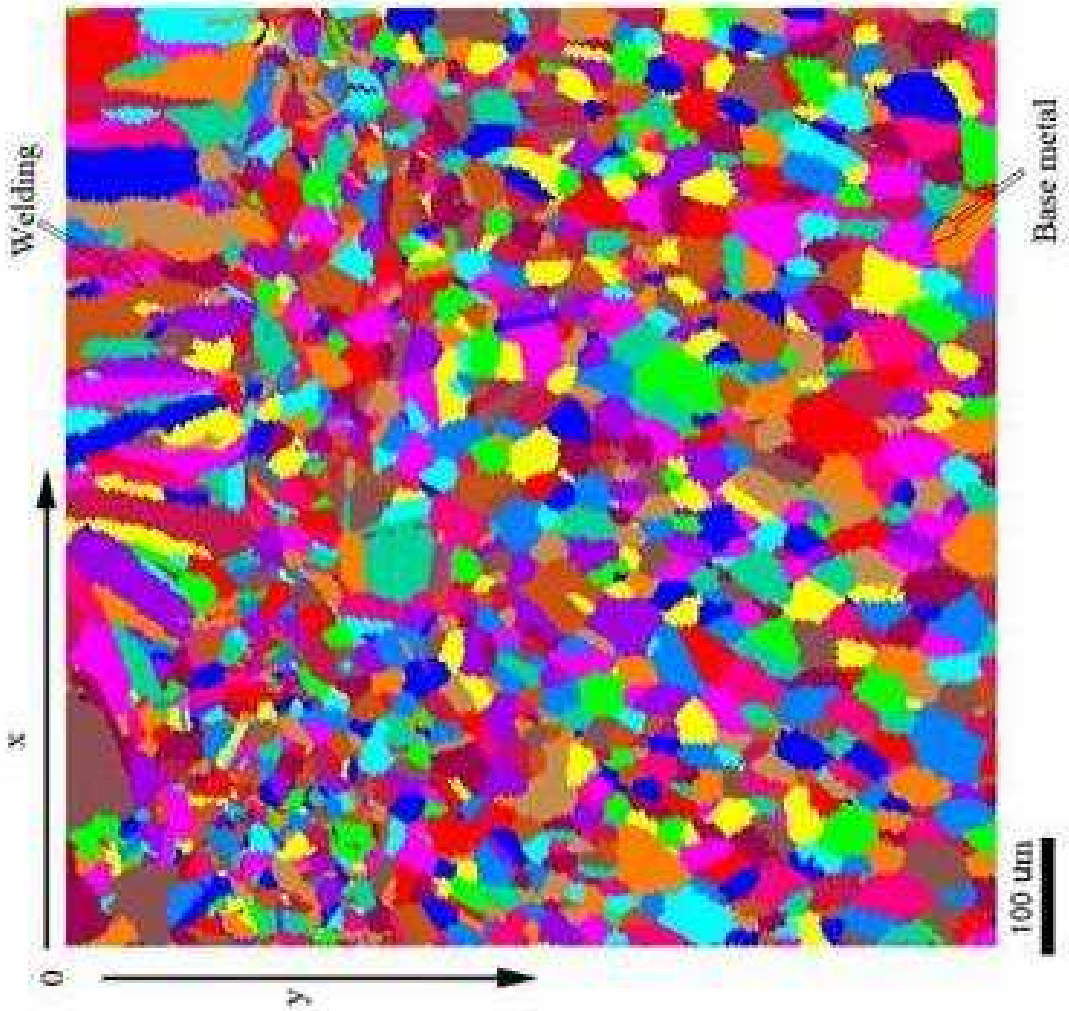


- Hardness near the fusion line lower than that of the mid-plane of cold-rolled plate by 10-17%

CRDM Alloy 690 HAZ - Strain by EBSD

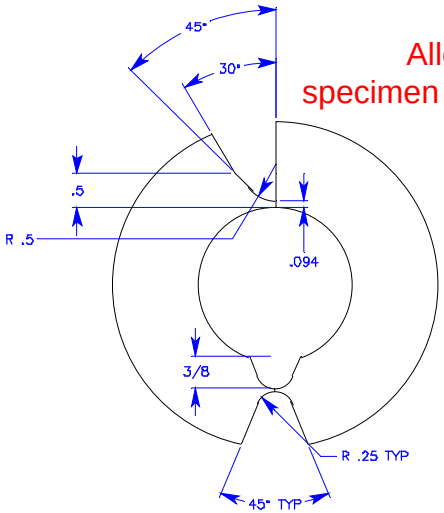




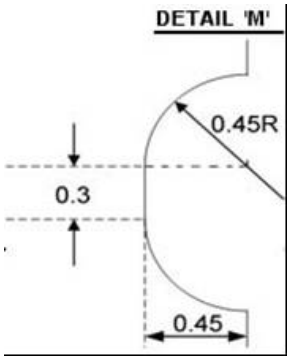


- Approx. 10% at 200-300 μm from the fusion line

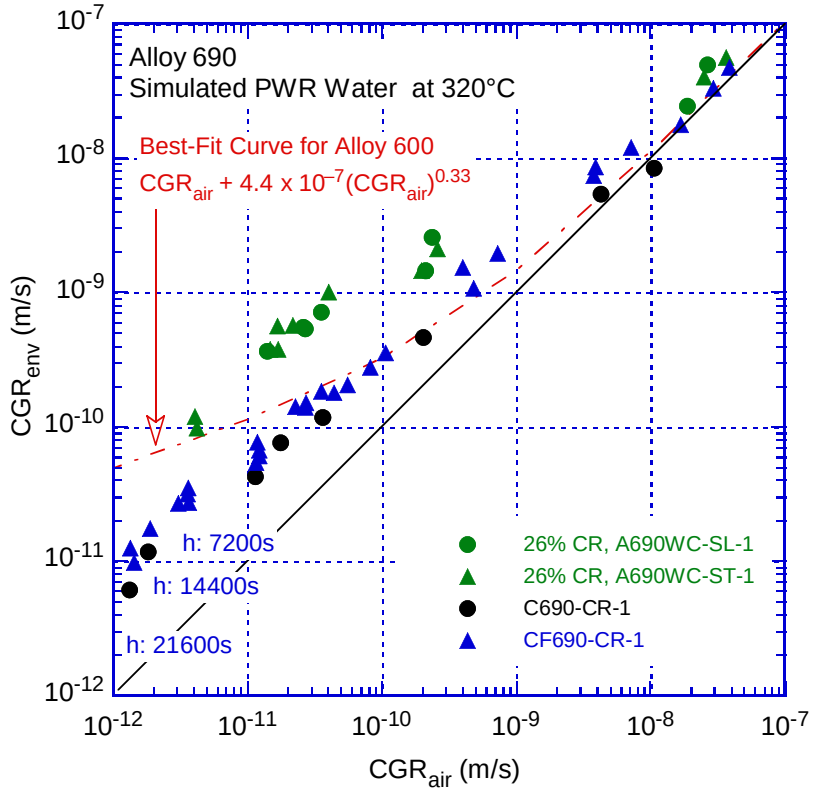
CRDM Alloy 690 HAZ Specimens



Alloy 690 HAZ
specimen designation CF690
CL, CR

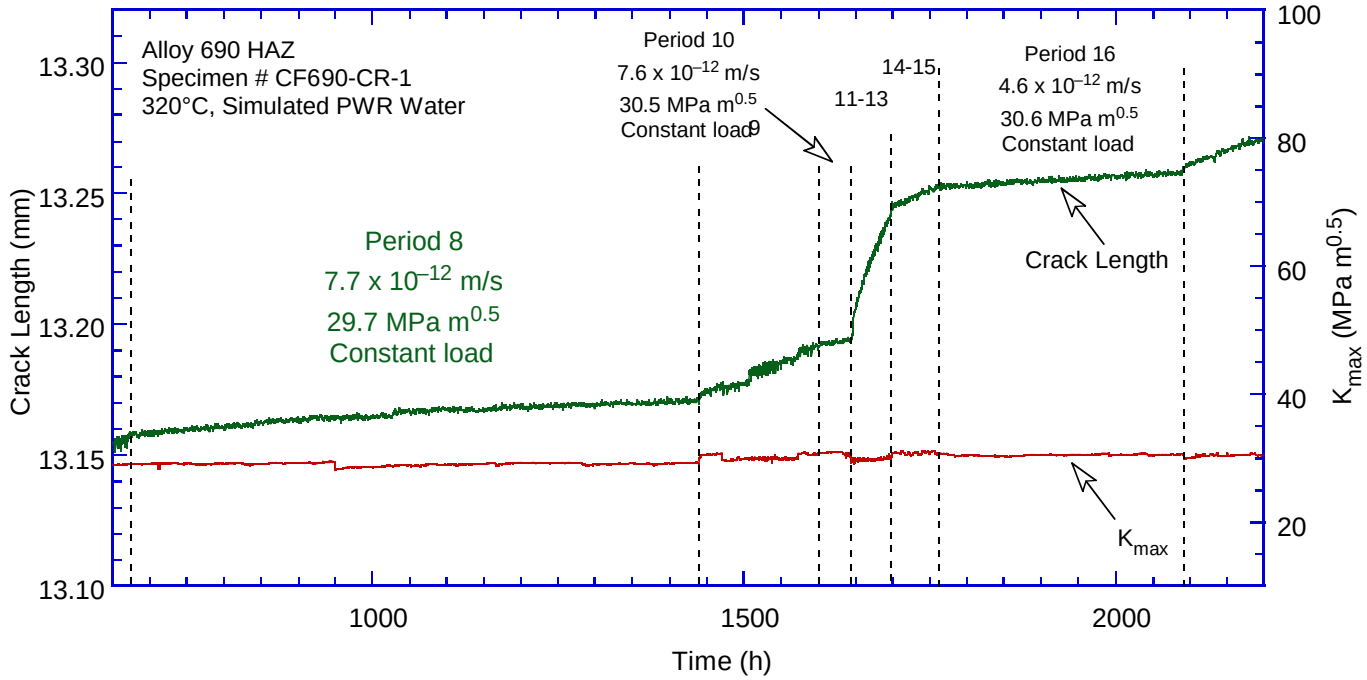


Cyclic CGR data for Alloy 690 HAZ



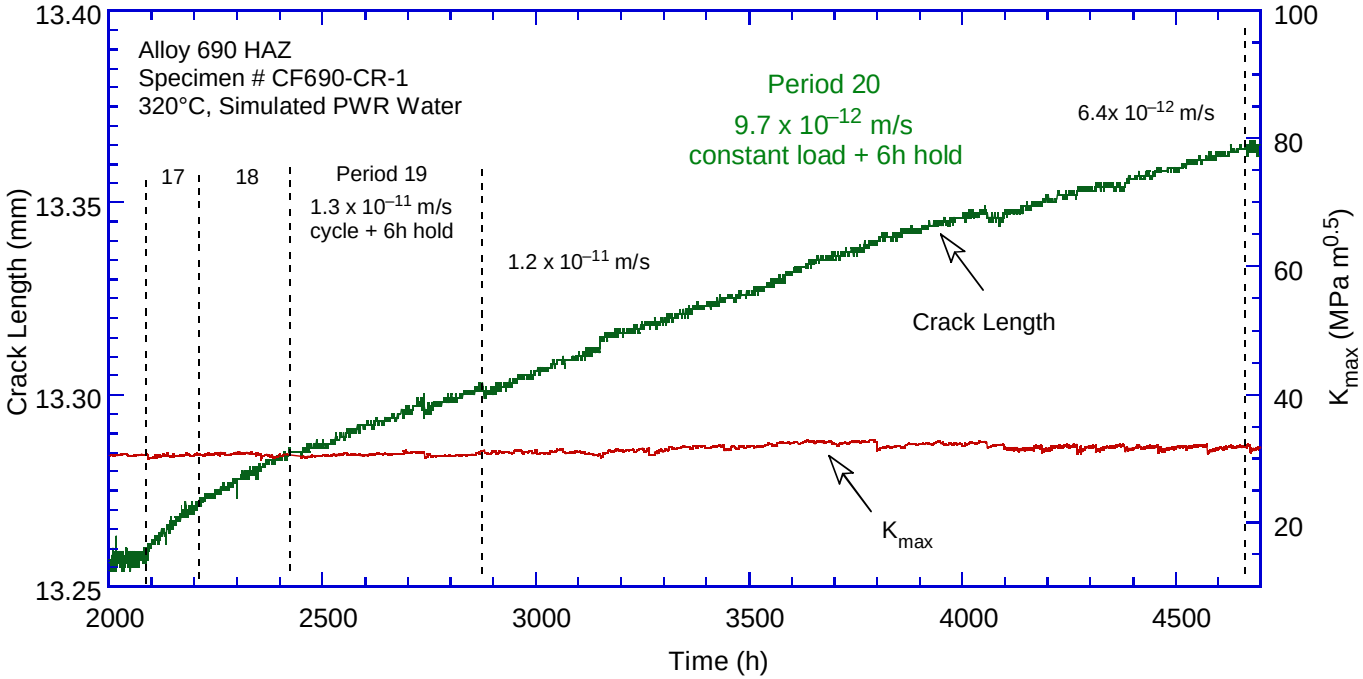
- Cyclic CGR rates for Alloy 690 HAZ (CF690) appear slightly higher than those for the as-received condition (same orientation, CR)

CRDM Alloy 690 HAZ



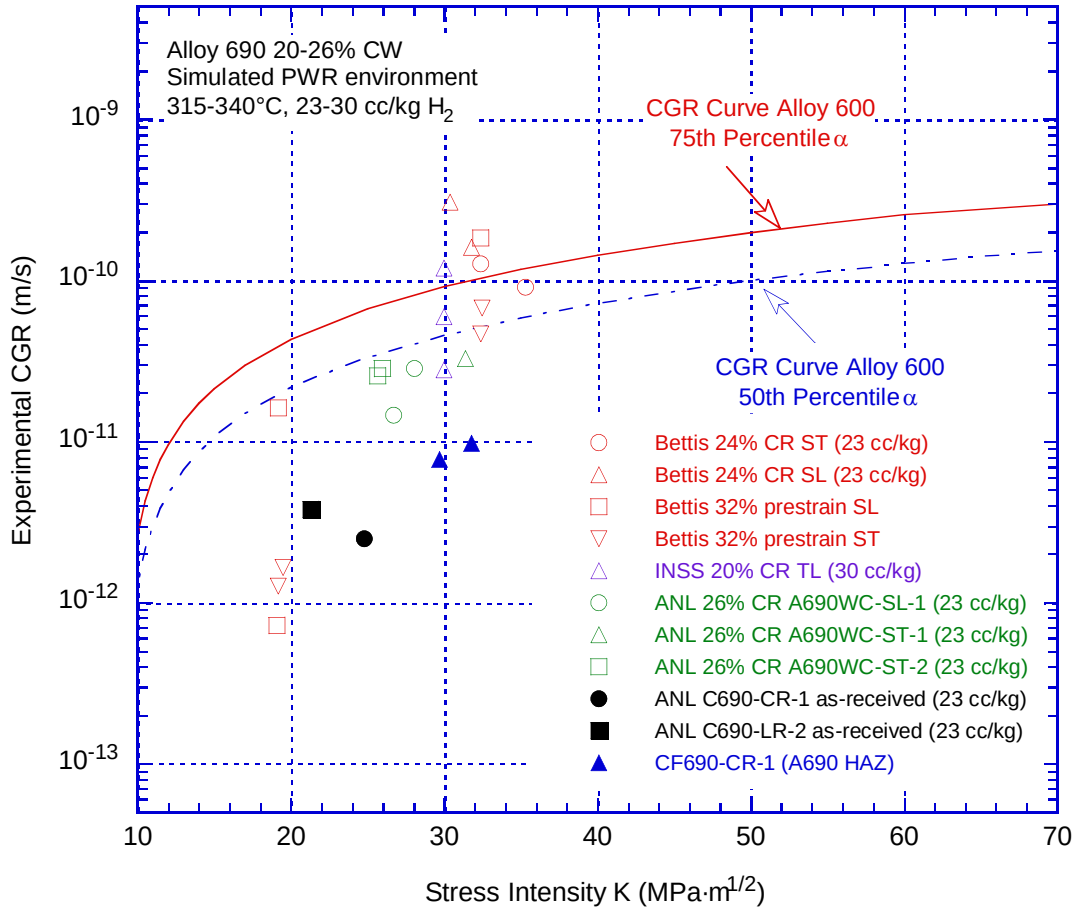
- Constant load CGRs ≈ 7.7×10^{-12} m/s (despite previous cycle + hold data suggesting that the SCC CGR would be larger)

CRDM Alloy 690 HAZ



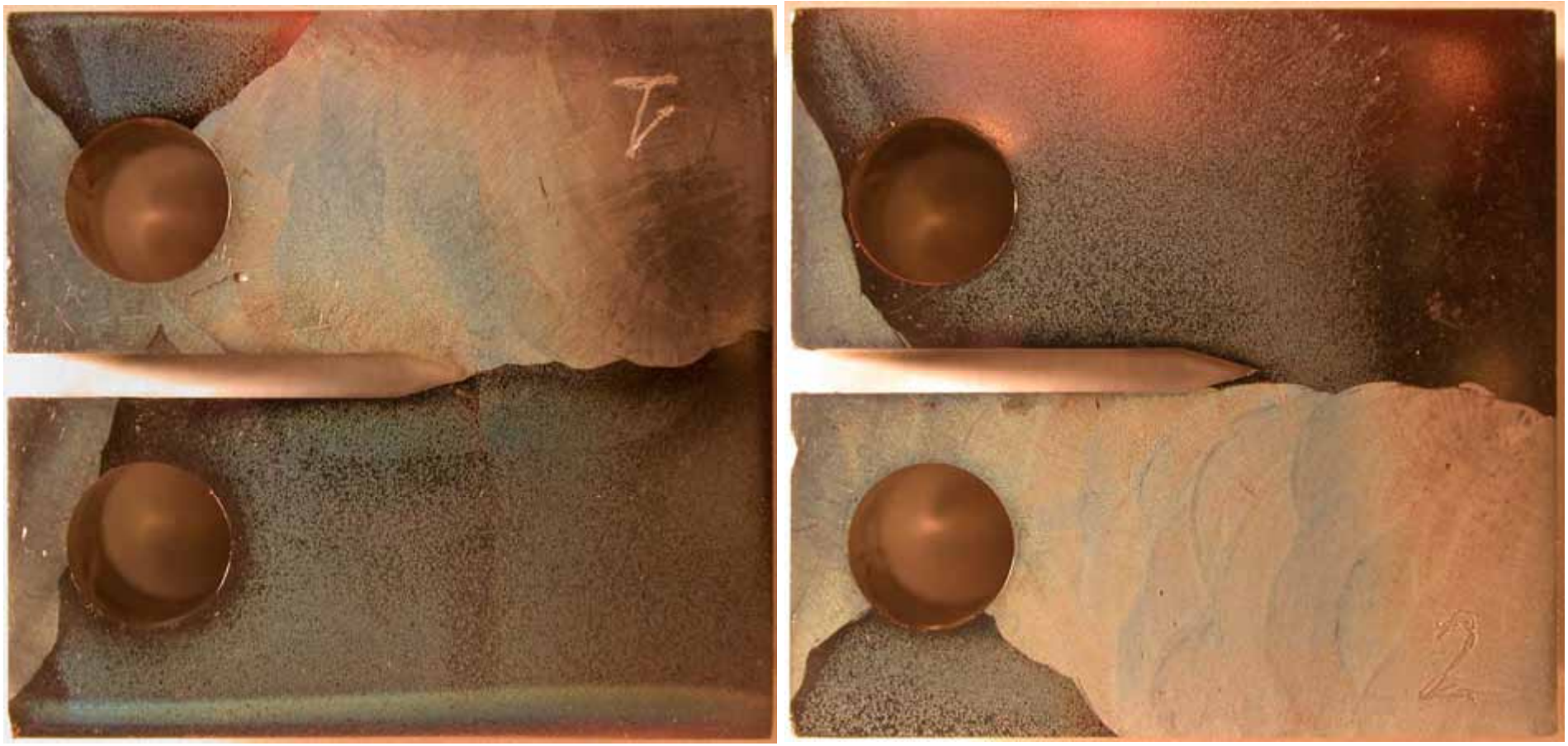
- Approach: minimize mechanical fatigue component + preserve environmental enhancement, allow the crack to find weakest path
- Constant load with periodic unloading (6 h) CGR ≈ 1.2 $\times 10^{-11}$ m/s initially

SCC CGRs vs. K for Alloy 690 HAZ

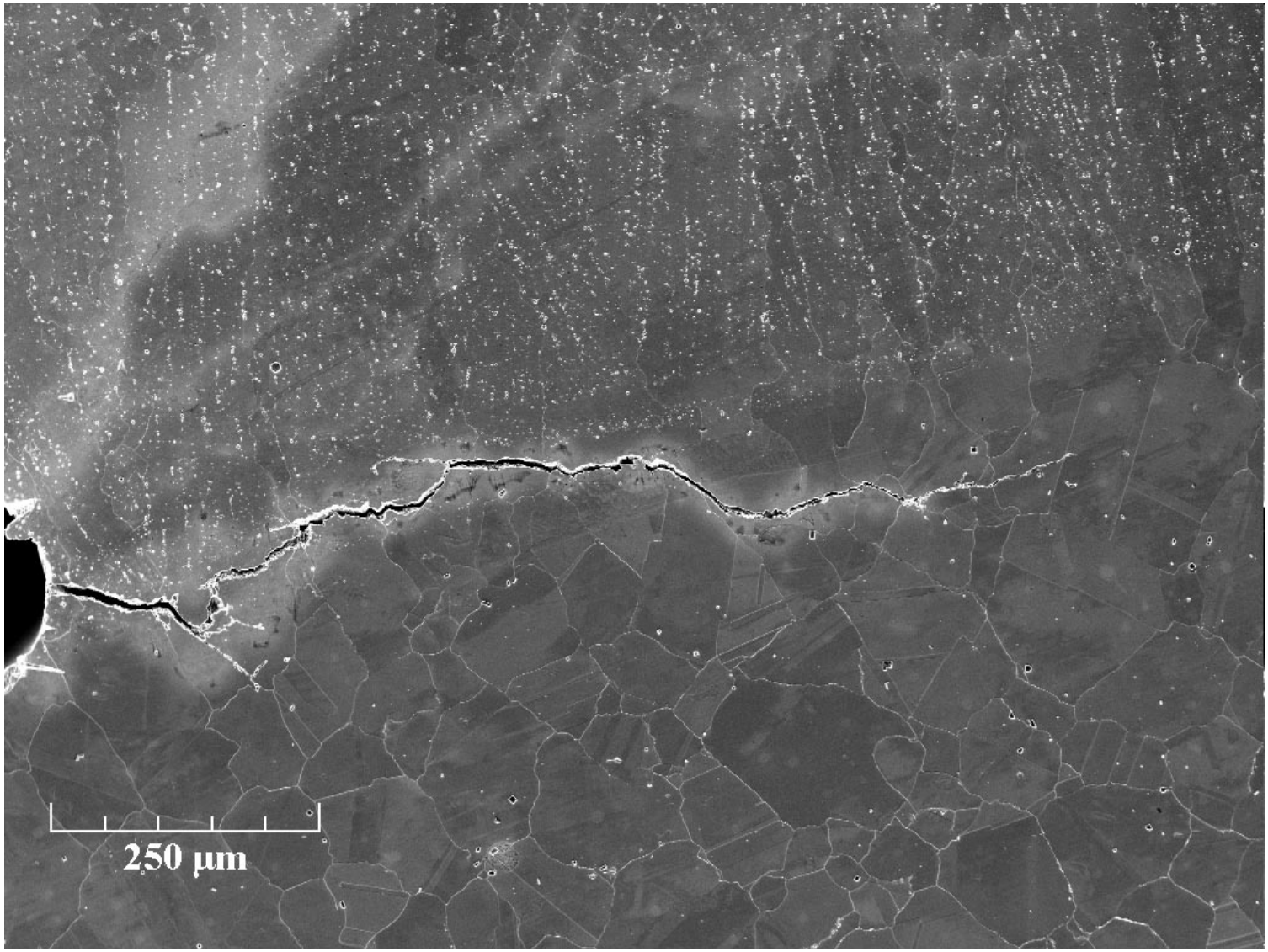


- As-received condition: lower CGRs than those for cold-rolled alloy
- HAZ CGRs similar or only slightly higher than as-received condition

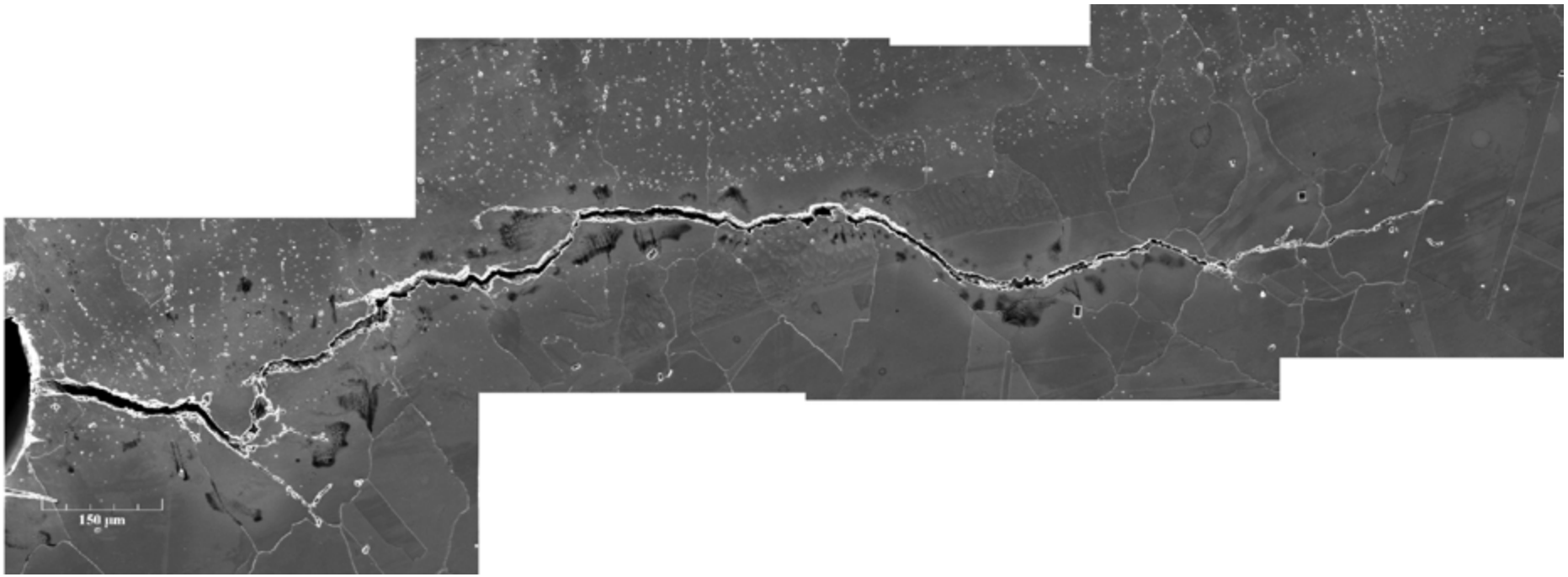
CF690-CR-1 Lateral surfaces (post test)



CF690-CR-1 Lateral surface 1

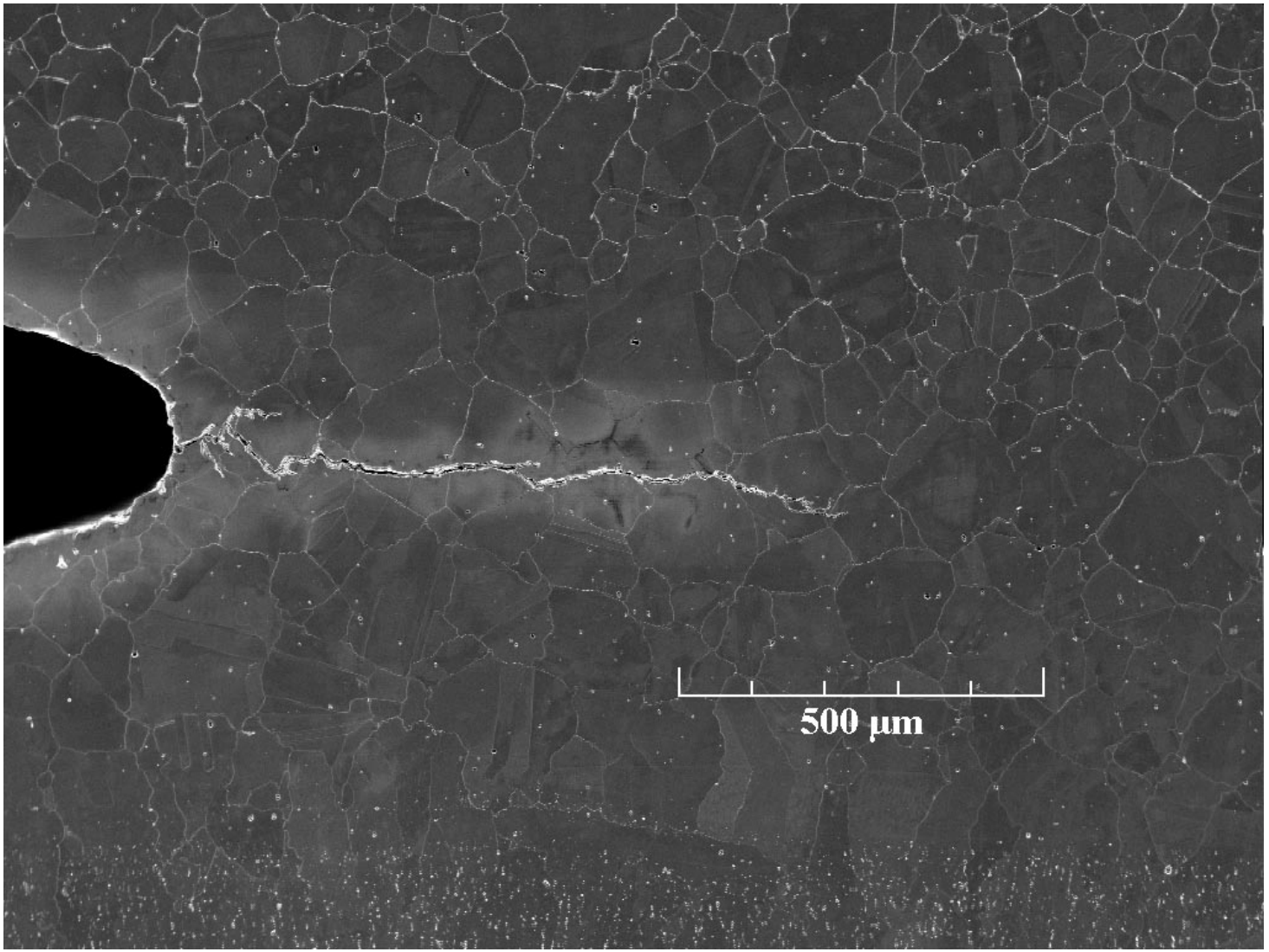


CF690-CR-1 Lateral surface 1

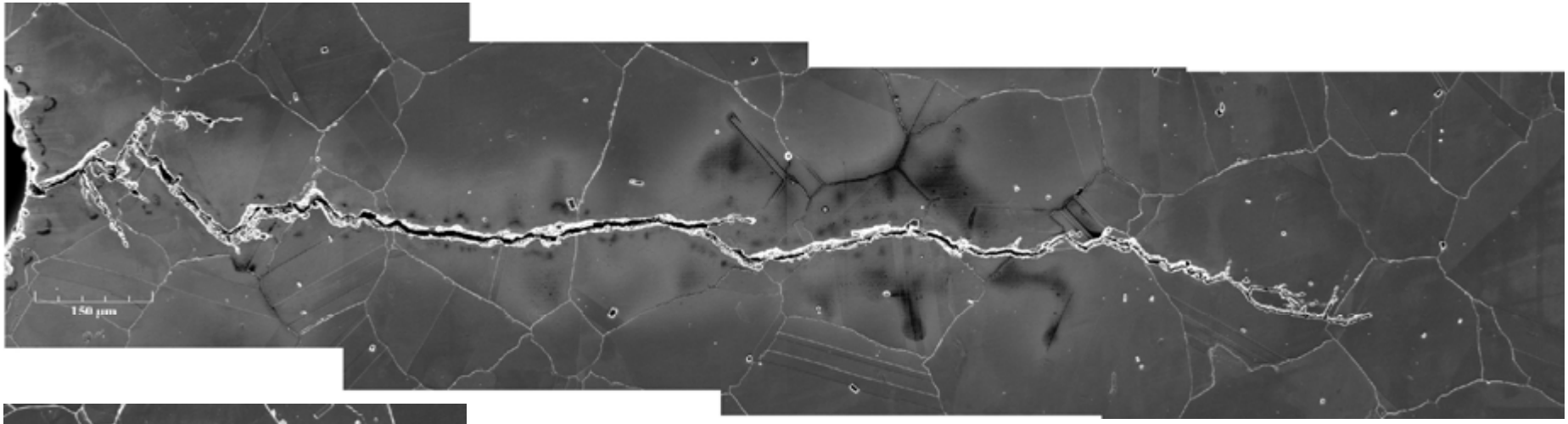


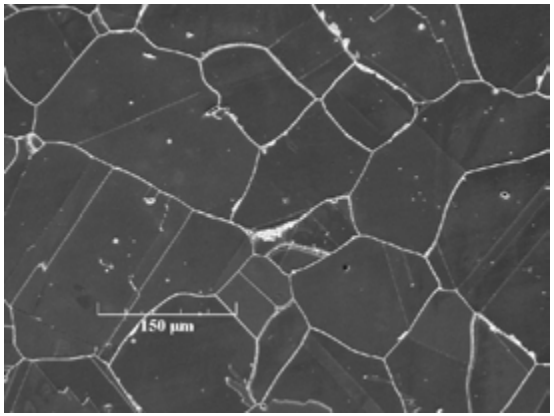
- Crack seems to follow the fusion line
- Crack branching, possible IG and TG modes,

CF690-CR-1 Lateral surface 2



CF690-CR-1 Lateral surface 2



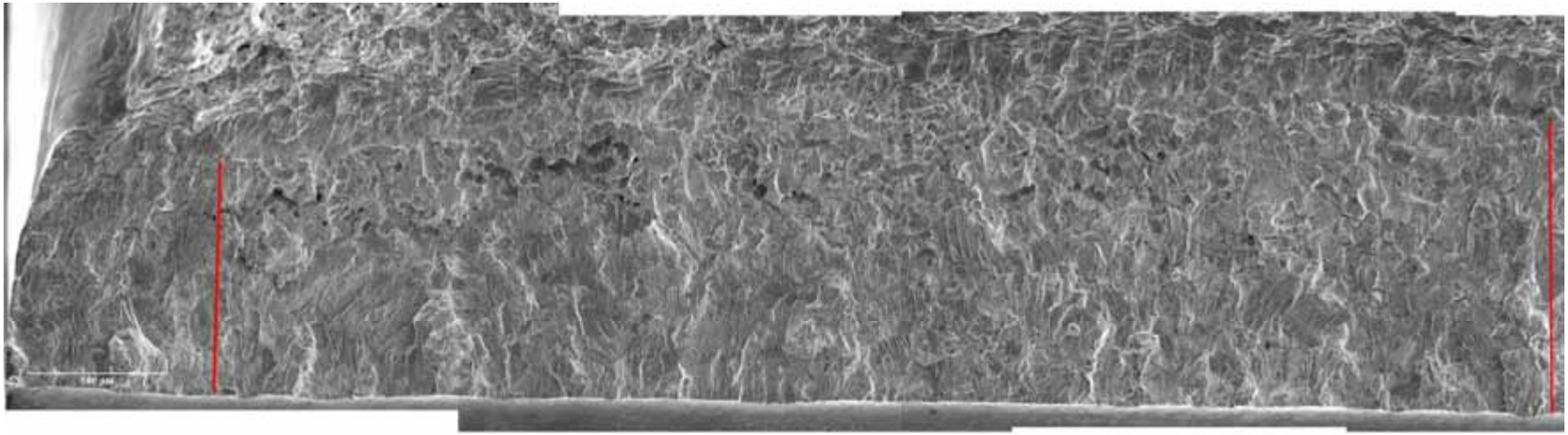


- Crack is straight
- Limited crack branching, predominant TG modes

Fracture surface of Alloy 690 HAZ

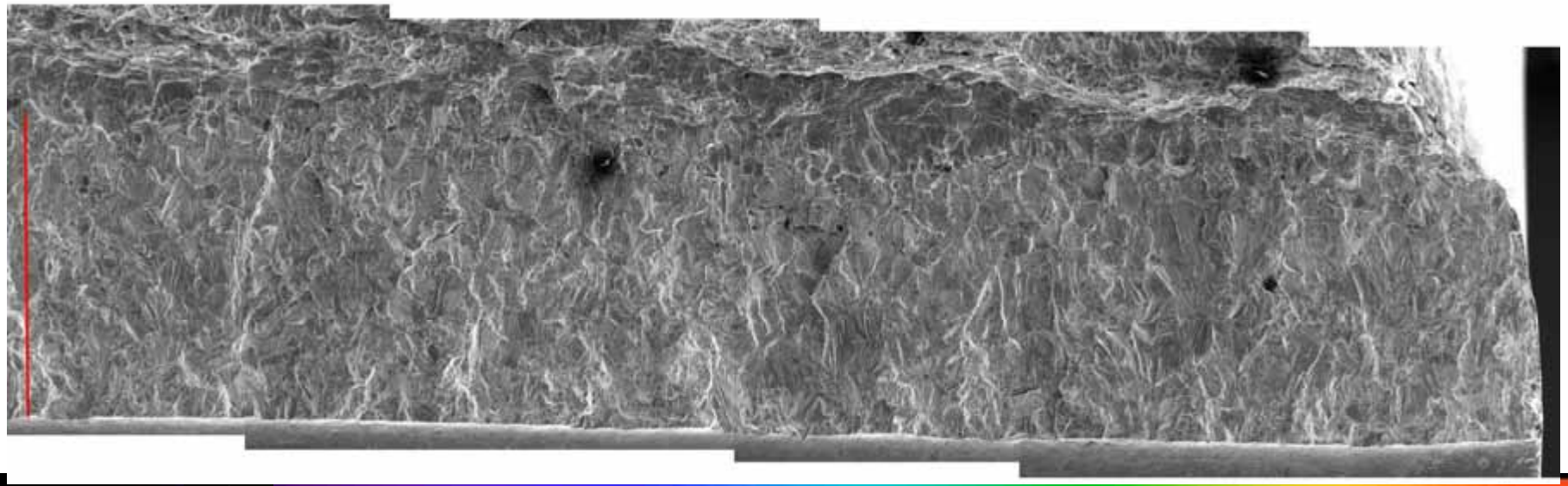
- 1st half

1



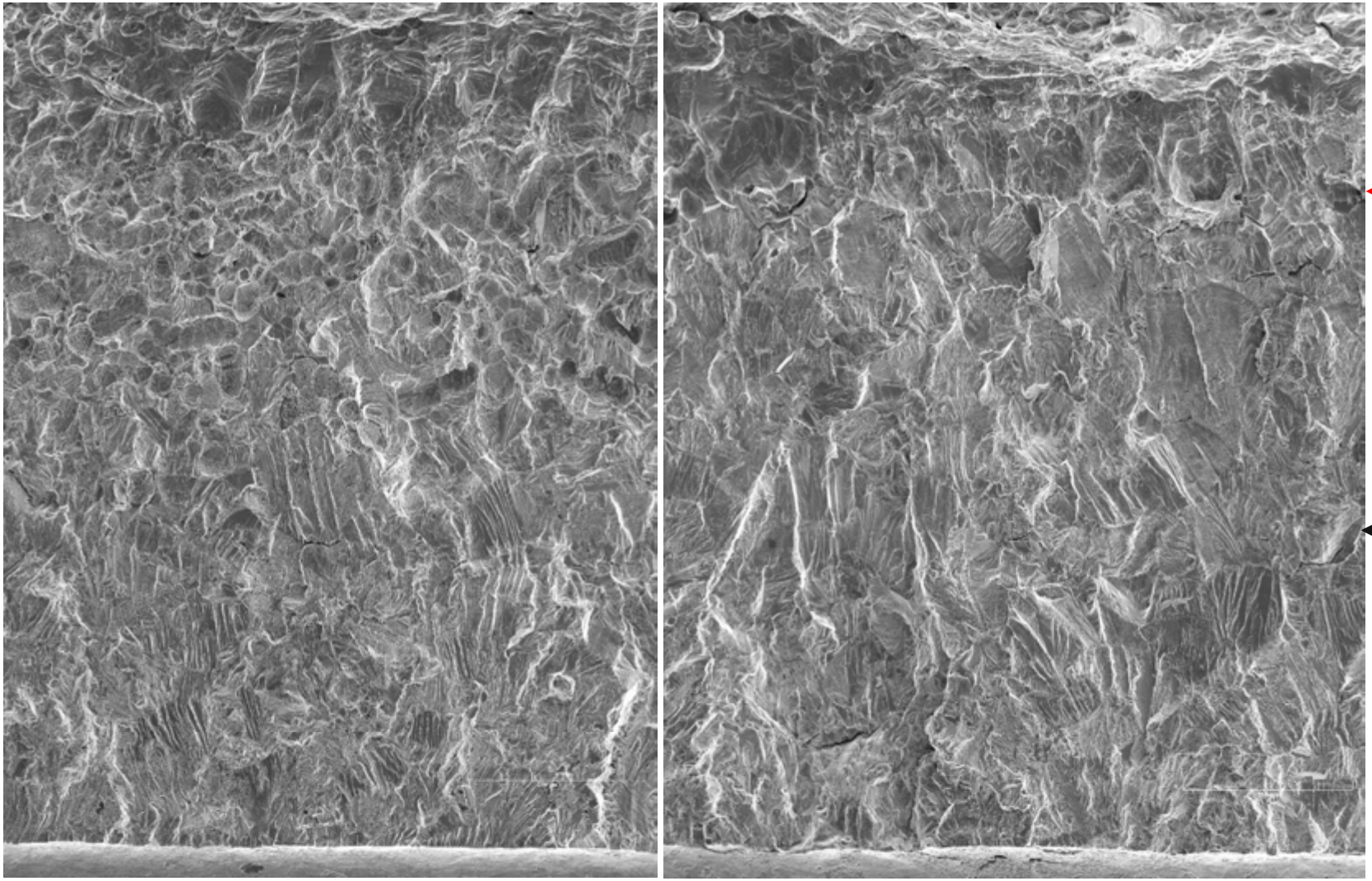
- 2nd half

2



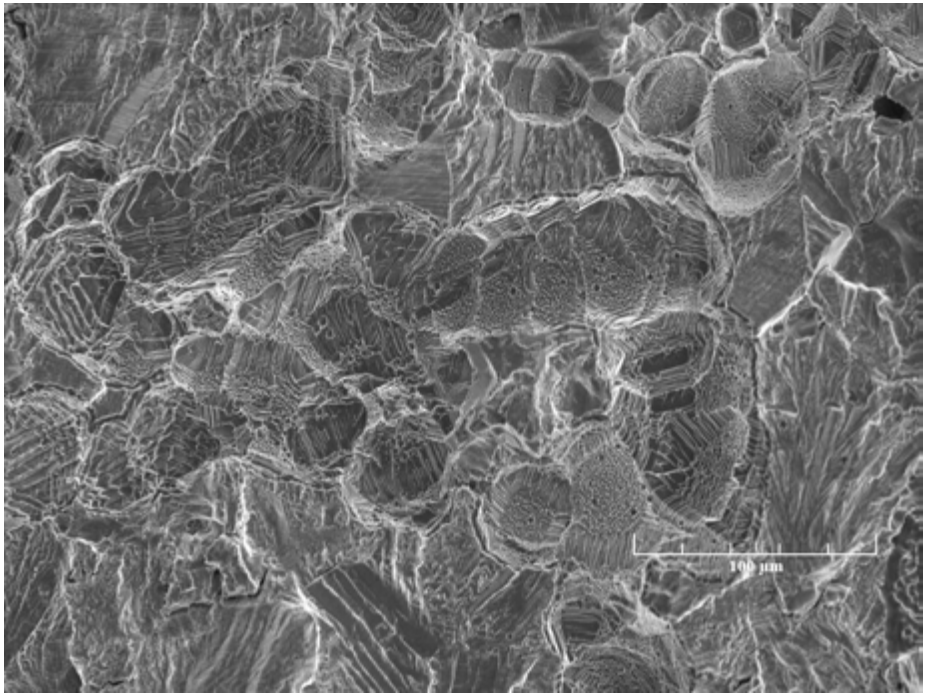
Fracture surface of Alloy 690 HAZ

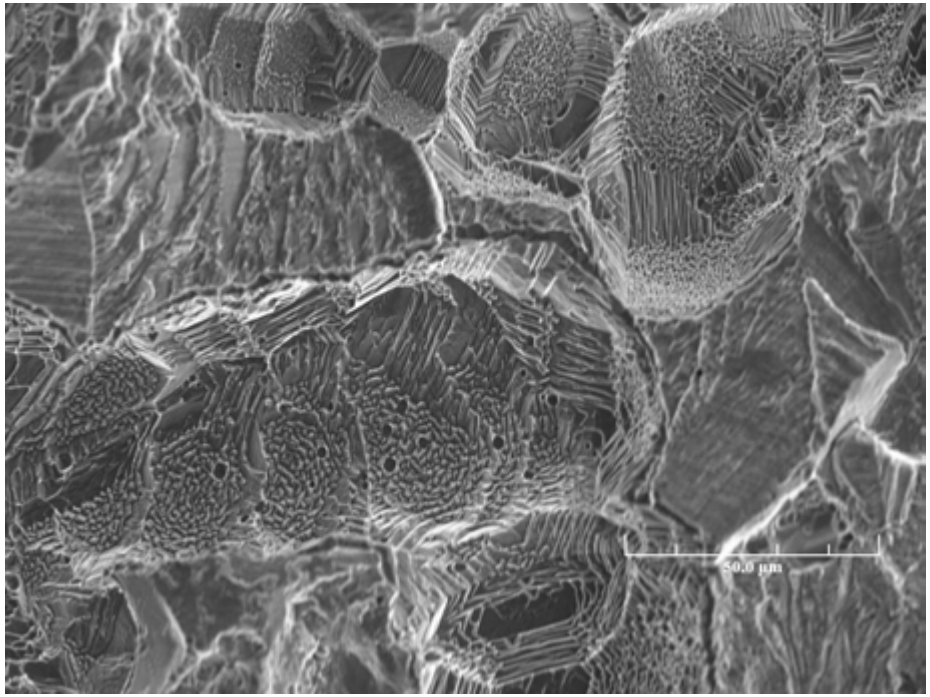
1 2



Pre-cracking

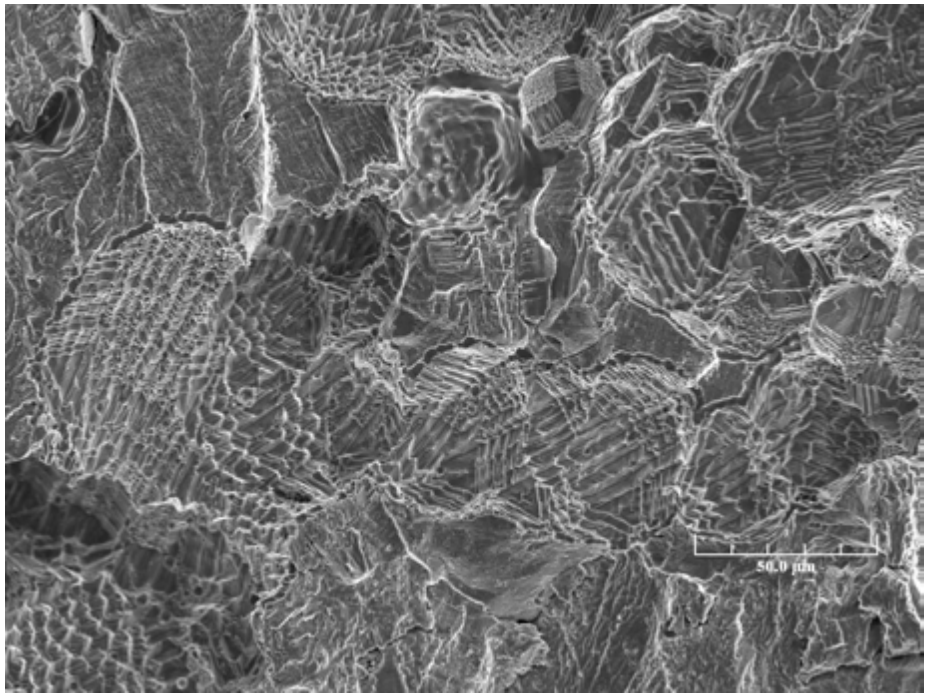
Fracture surface of Alloy 690 HAZ - region 1

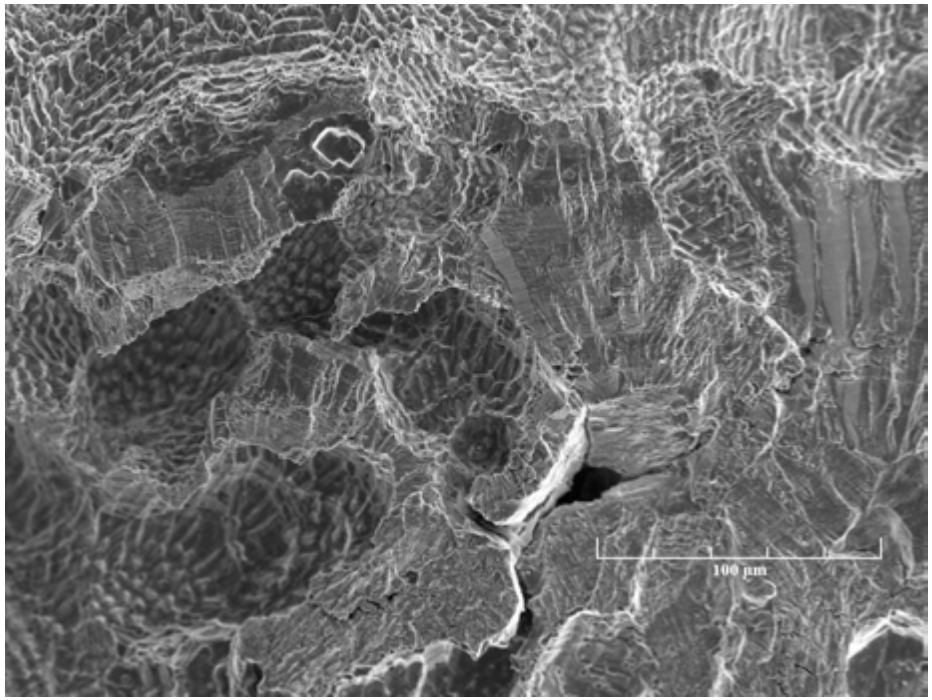




- Mixed fracture mode: predominantly “granular” with dendrites, TG and IG secondary cracks
- Possible particles on facets

Fracture surface of Alloy 690 HAZ - region 1





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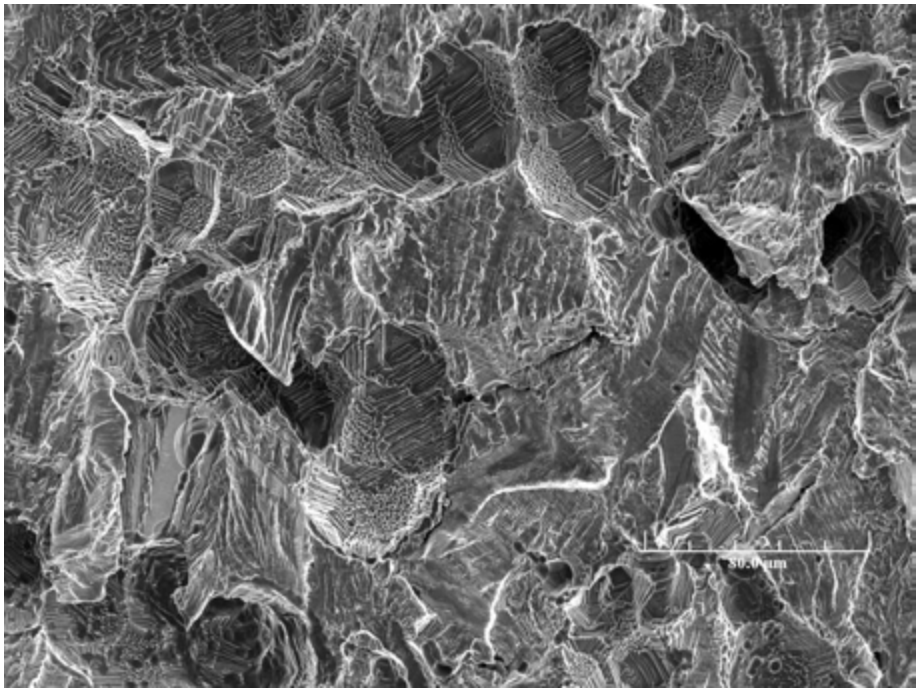
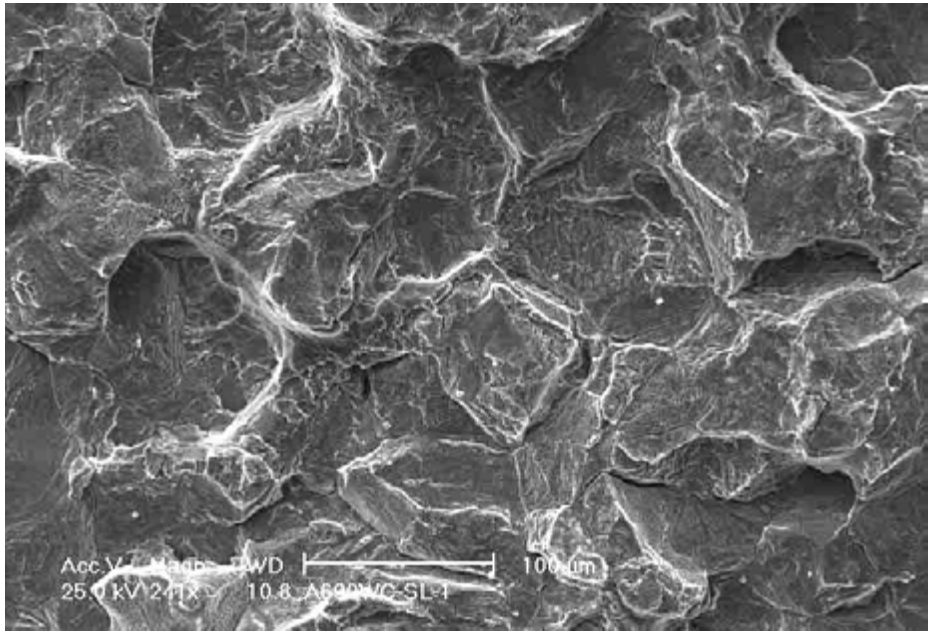
Fracture surface of Alloy 690 HAZ - region 1



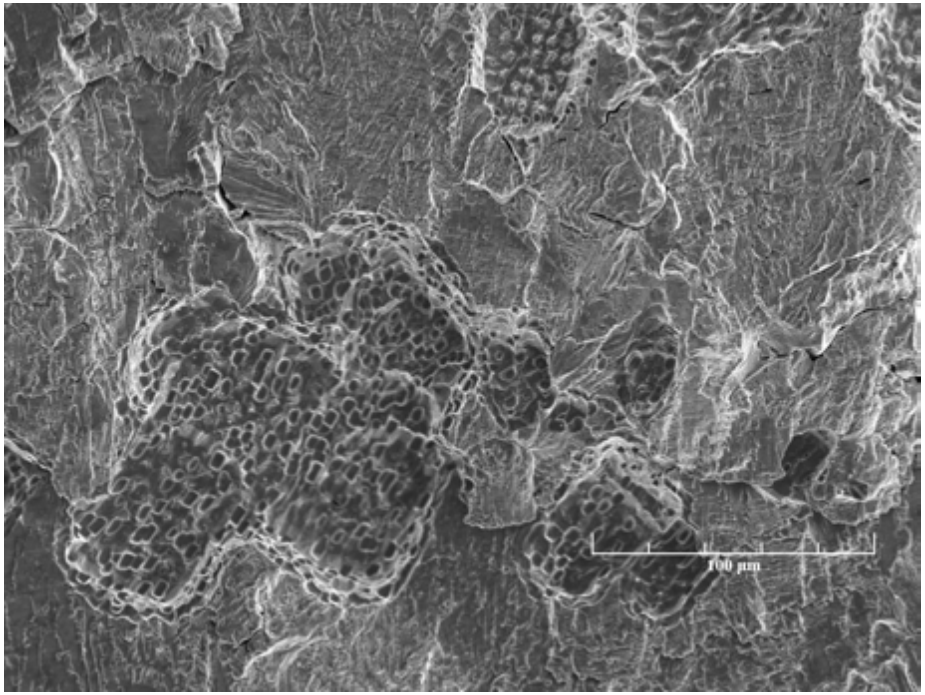
CF690-CR-1, Alloy 690 HAZ



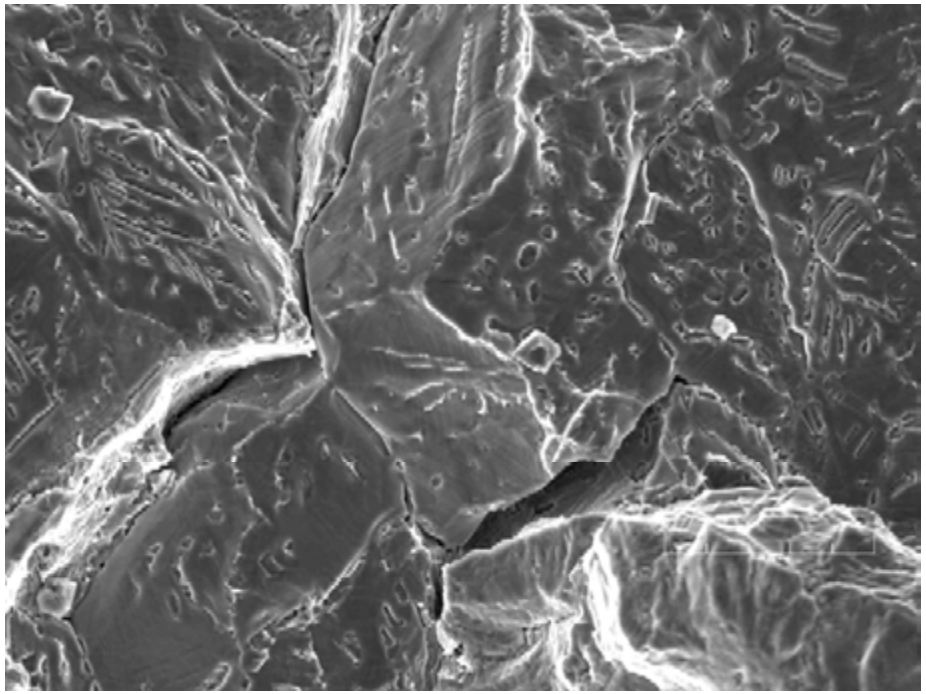
A690WC-SL-1, 26% CR

- "Granular" appearance is similar to that observed on 26% CR alloy – possible effect of cold work

Fracture surface of Alloy 690 HAZ - region 1



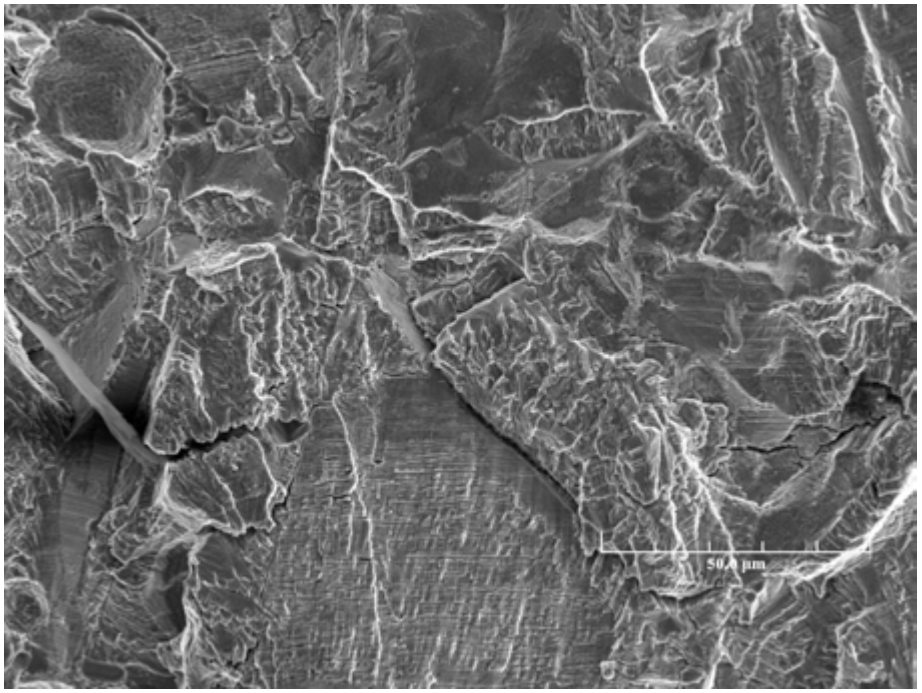
CF690-CR-1, Alloy 690 HAZ

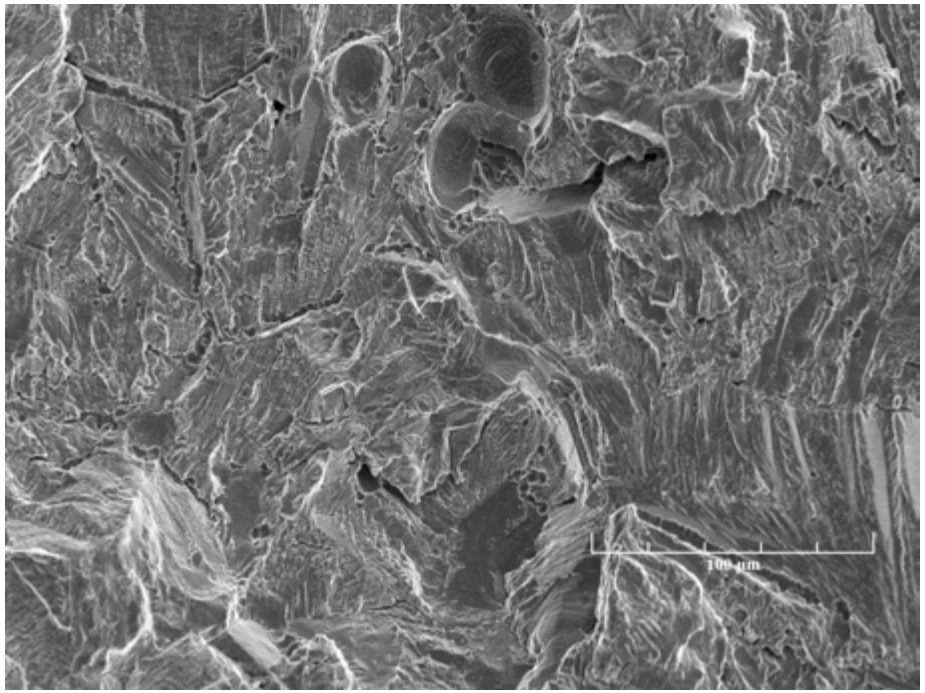


A690WC-SL-1, 26% CR

- Particles on facets - rare - similar to those observed on 26% CR alloy – possible cracked carbides

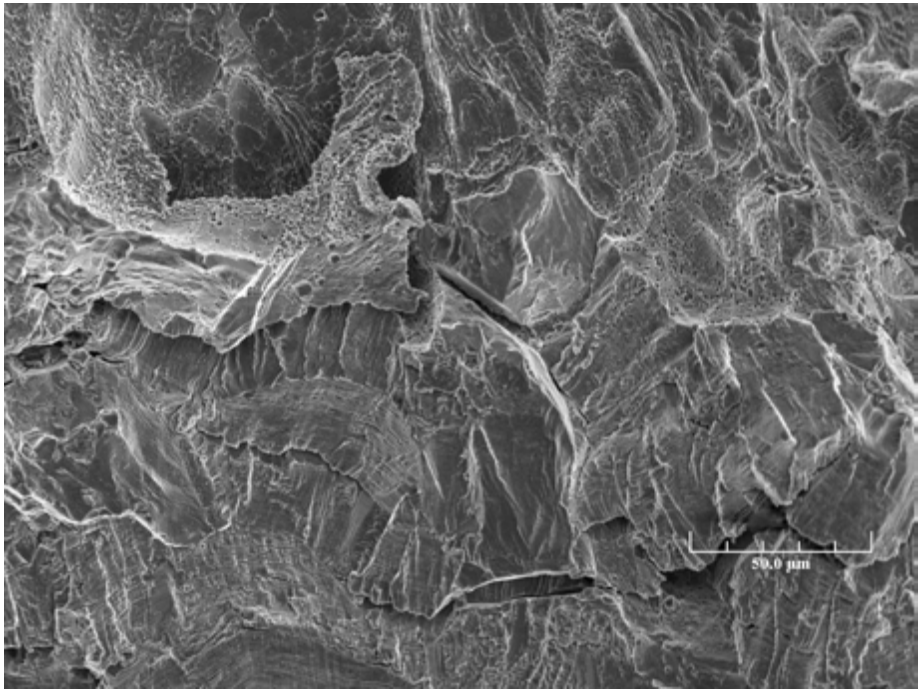
Fracture surface of Alloy 690 HAZ - region 2

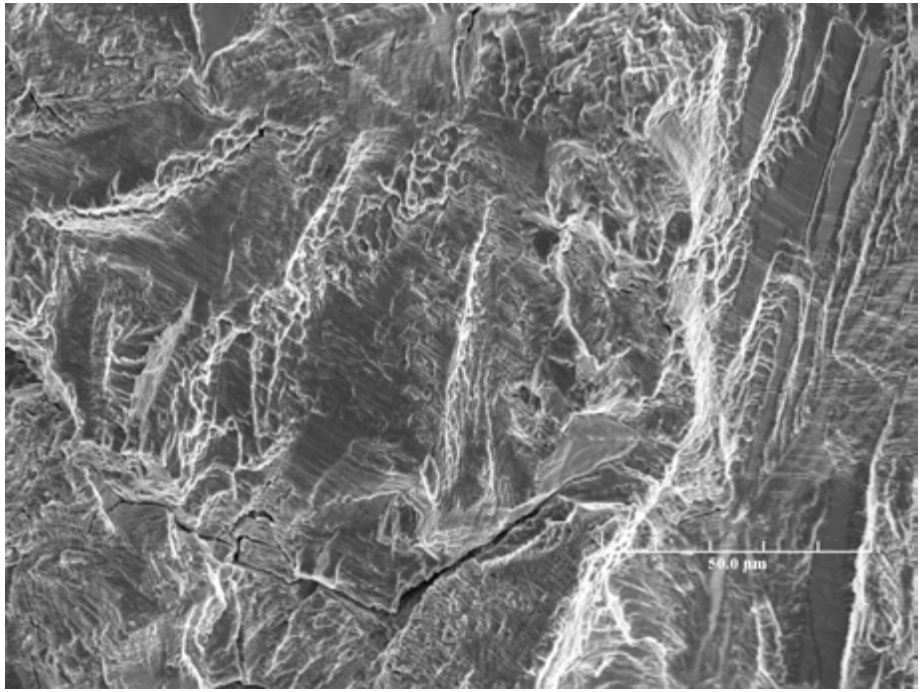




- Similar to the alloy in the as-received condition: predominantly TG with IG secondary cracks

Fracture surface of Alloy 690 HAZ - region 2





- Similar to the alloy in the as-received condition: predominantly TG with IG secondary cracks

Alloy 690 HAZ Summary

- Hardness, EBSD indicate low level of cold work in the HAZ (approx. 10%)
- GB carbide coverage non-uniform: discrete, continuous, carbide-free GBs
- The cyclic CGRs of Alloy 690 HAZ appear to shows slight difference vs. as-received Alloy 690
- The SCC CGRs for Alloy 690 HAZ appear to be slightly higher that those for the as-received condition tested
- Fracture mode appears to depend on the proximity to the fusion line:

  - granular appearance (dendritic features), with TG facets, IG secondary cracks near the fusion line

  - predominantly TG with occasional facets, IG secondary cracks away from the fusion line

Presentation Topics

- CGR testing of Alloy 690 HAZ
  - present microstructural analysis
  - present CGR data
  - present and discuss fracture surface

- Cracked carbides – a possible explanation for the high rates observed in several heats of Alloy 690 in cold-worked condition
  - summarize microstructural characteristics for susceptible heats
  - explain how cracked carbides are consistent with a grain boundary deformation mechanism for SCC

Summary of microstructural features for heats with measured SCC CGRs > 1×10^{-11} m/s

Laboratory/Alloy heat and/or other designation	Tensile properties available	Level of cold work (CR or other)	Hardness	General microstructure[1] (SEM, TEM, OIM)	Banding	Cracked carbides
ANL (NX3297HK12)	✓	26% CR	✓	✗	✓[2]	✓[3,4]
Bettis Lab (AOD-1,AOD-2, VIM-1)	✗	12% CR 24% CR 32% tensile	✗	✗	✗	✓[4]
GE (B25K)	✗	20% CR	✓	✗	✓	✓[3]
INSS	✗	20% CR 50% CR	✗	✗	✗	✓[4]

[1]Anything unusual/unexpected except for banding and cracked carbides

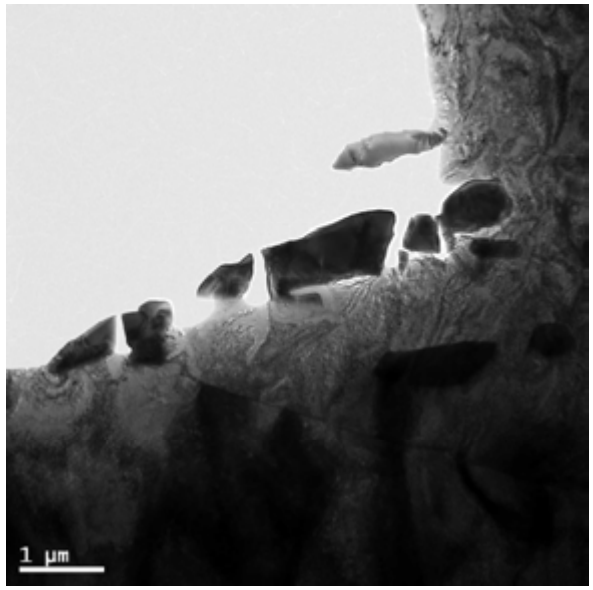
[2]Not in the mid-plane that was tested

[3]Observed by TEM or SEM

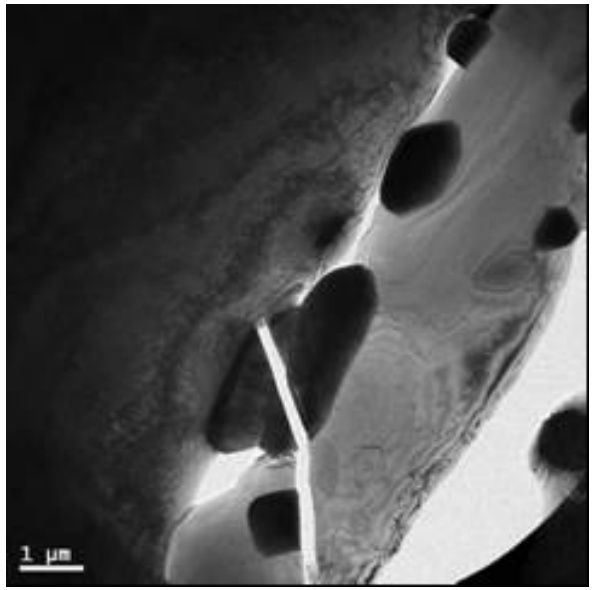
[4]Observed on fracture surface

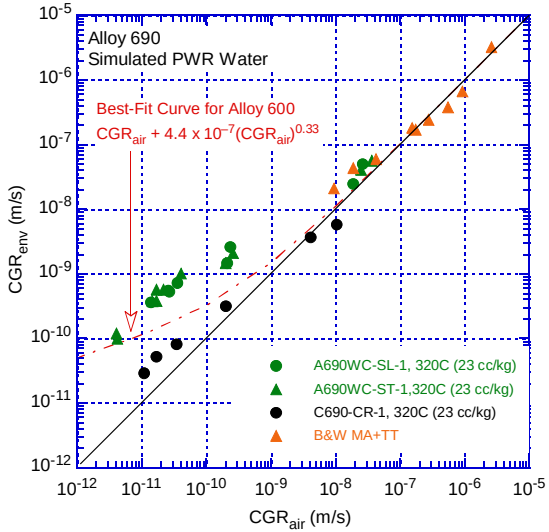
Cracked GB carbides in the mid-plane of 1-D Cold-Rolled Alloy 690 plate (ANL and GE)

ANL, 26% CR



GE, 20% CR

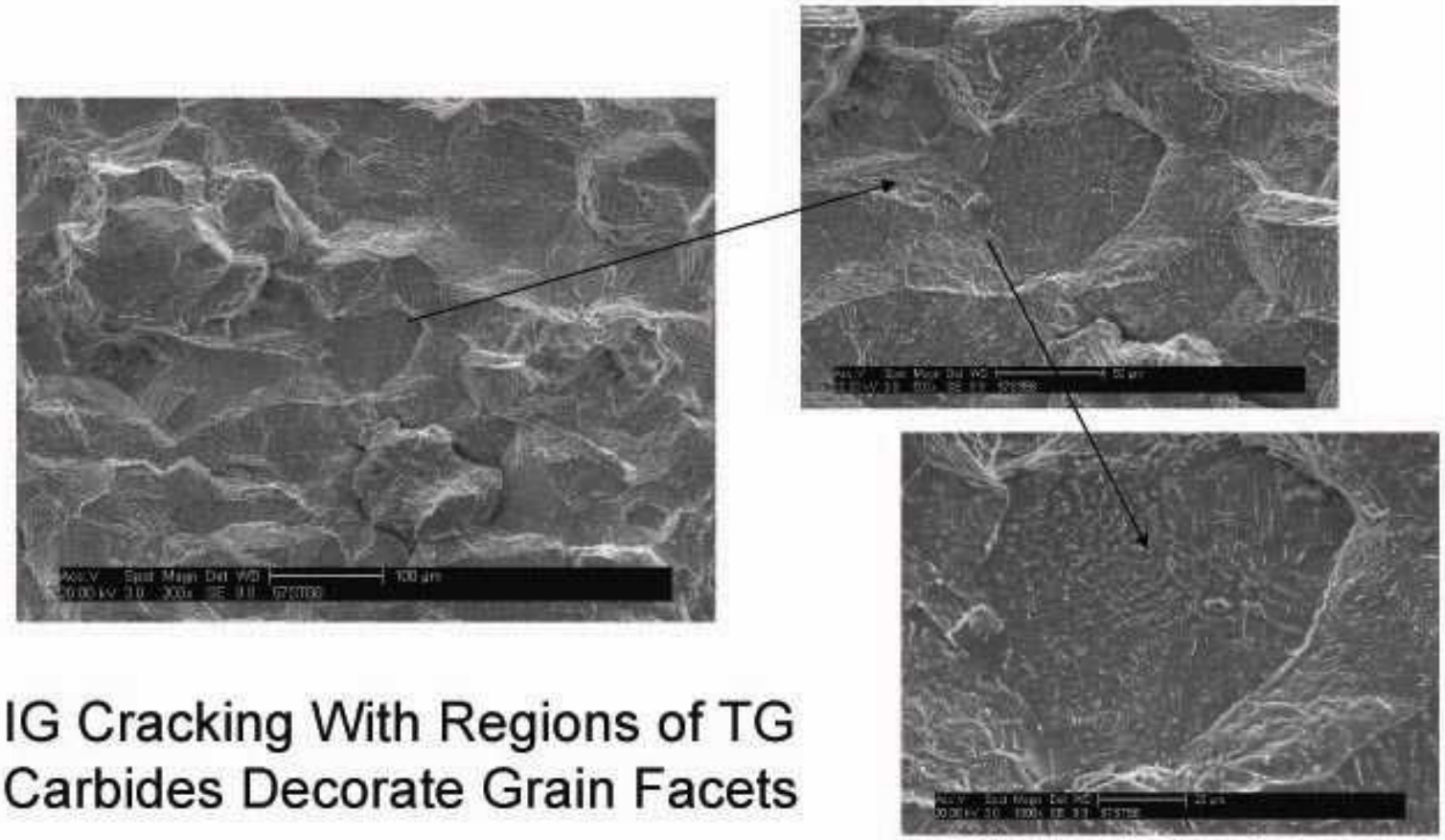




- Cracked grain boundary carbides, fatigue properties during precracking seem un-affected (ANL)

Cracked carbides in Bettis Alloy 690 cold-rolled by 24%

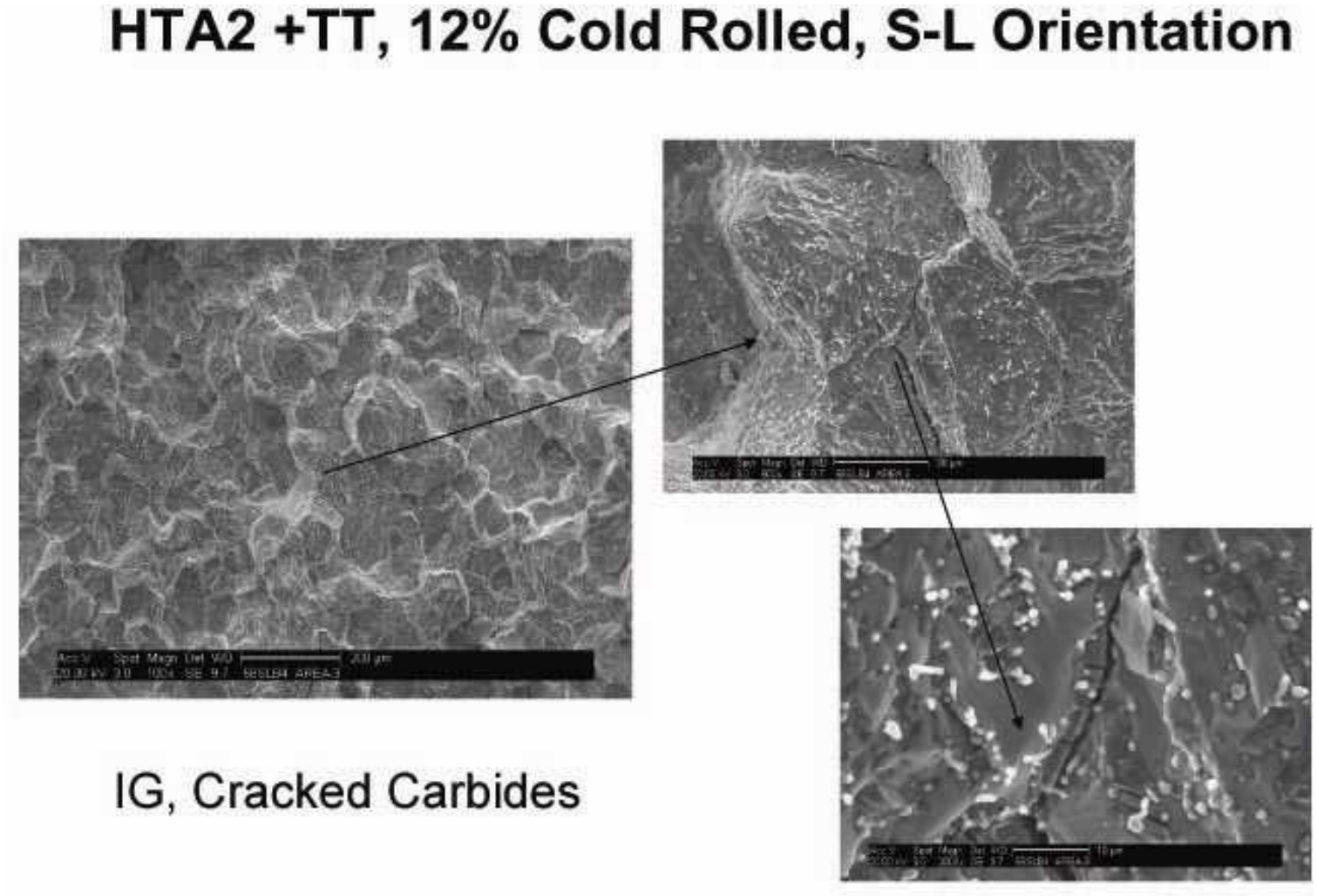
HTA1 +TT, 24% Cold Rolled, S-T Orientation



IG Cracking With Regions of TG Carbides Decorate Grain Facets

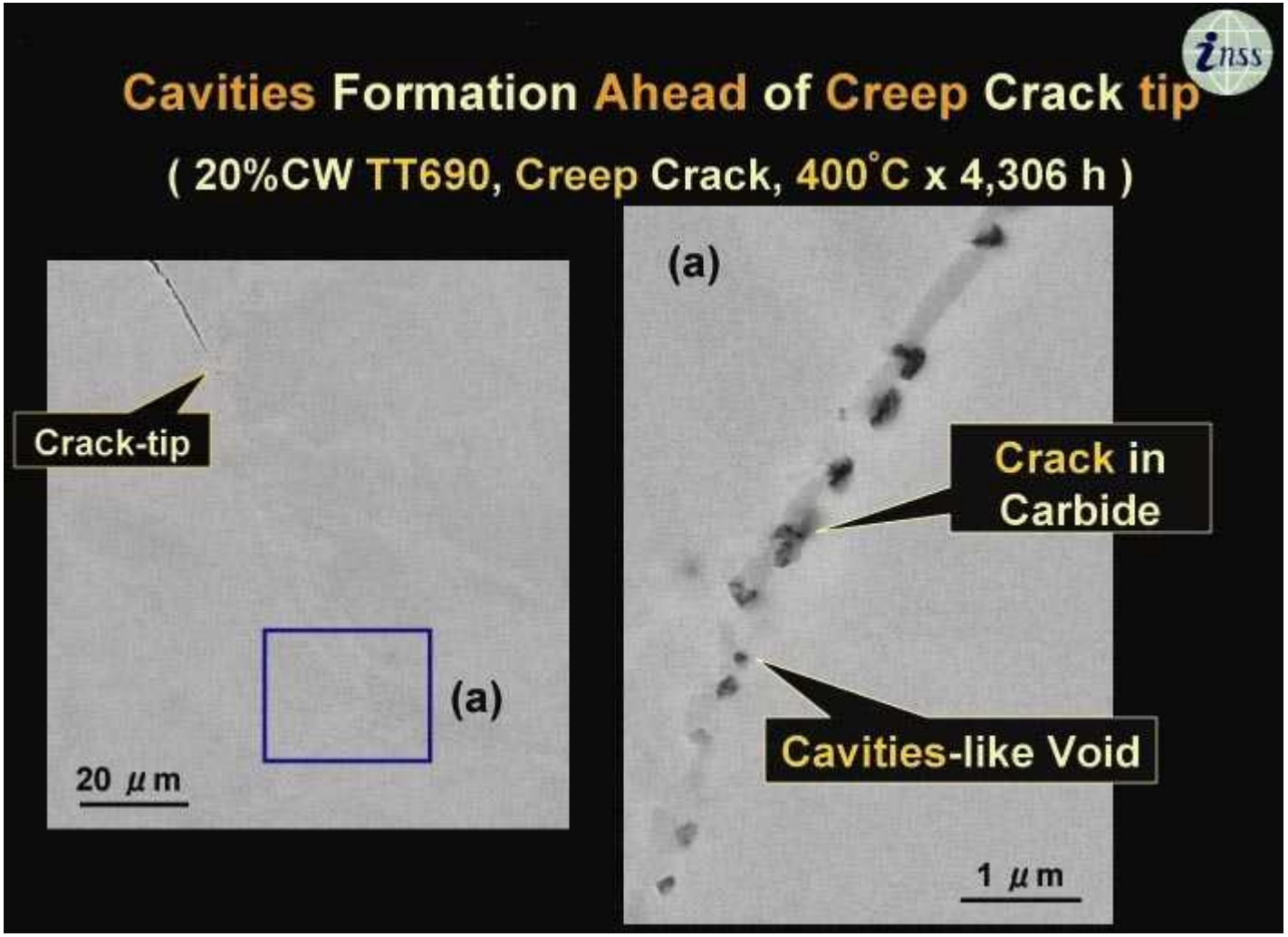
- Paraventi et al. 2006

Cracked carbides in Bettis Alloy 690 cold-rolled by 24%



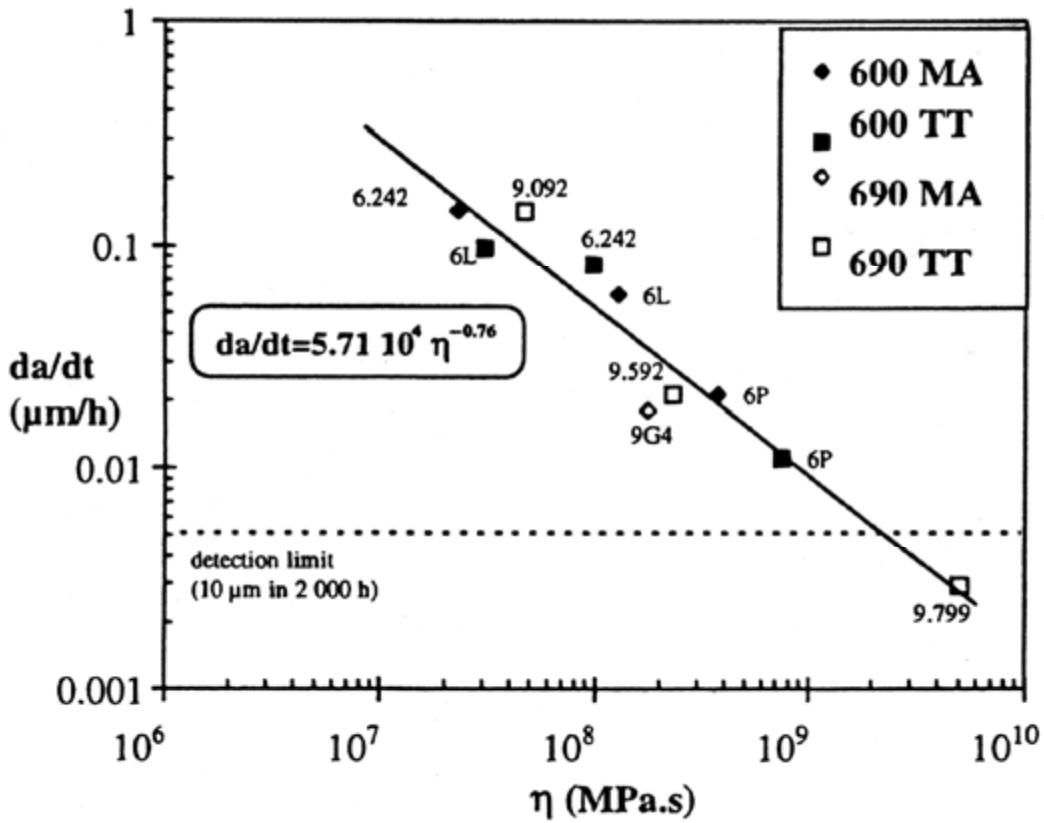
- Paraventi et al. 2006

Cracked GB carbides in INSS Alloy 690 cold-rolled by 20%



- Arioka et al. 2009

Relationship between cracking and GB deformation in Alloys 600 and 690



Vaillant et al. 1999

$$da/dt = 5.71 \times 10^4 \eta^{-0.76}$$

η = grain boundary viscosity

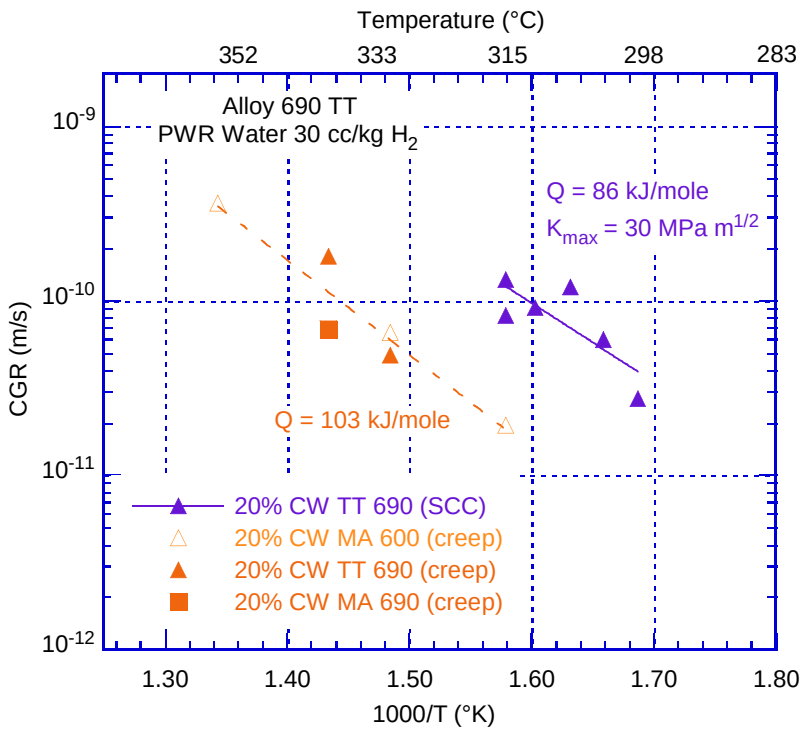
$$\eta = \frac{4b\sigma}{\pi \dot{S}}$$

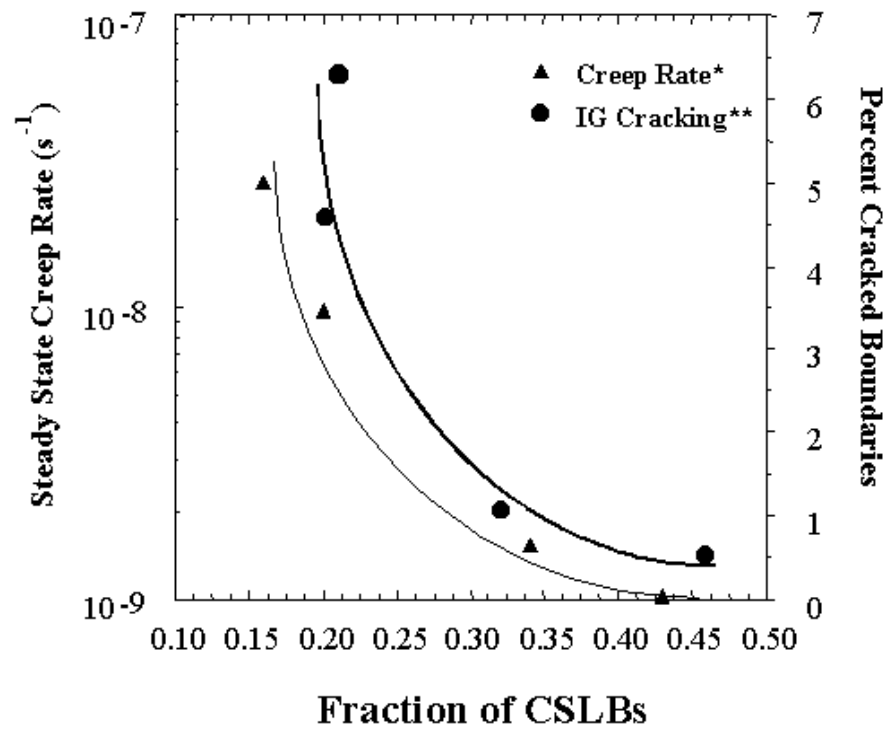
$\dot{S}$ = grain boundary sliding rate

$$da/dt \propto \dot{S}^{0.76}$$

- Cracked carbides can affect cracking via the sliding rate

Relationship between creep and cracking in Alloys 600 and 690





*Thaveeprungsriporn and Was, *Met. Trans.* A 28 9 (1997) 2101
**Crawford and Was, *Met. Trans.* A 23 (1992) 1195

- Arioka et al. 2009
- Was et al. 1998

Cold-worked Alloy 690 – microstructure and SCC

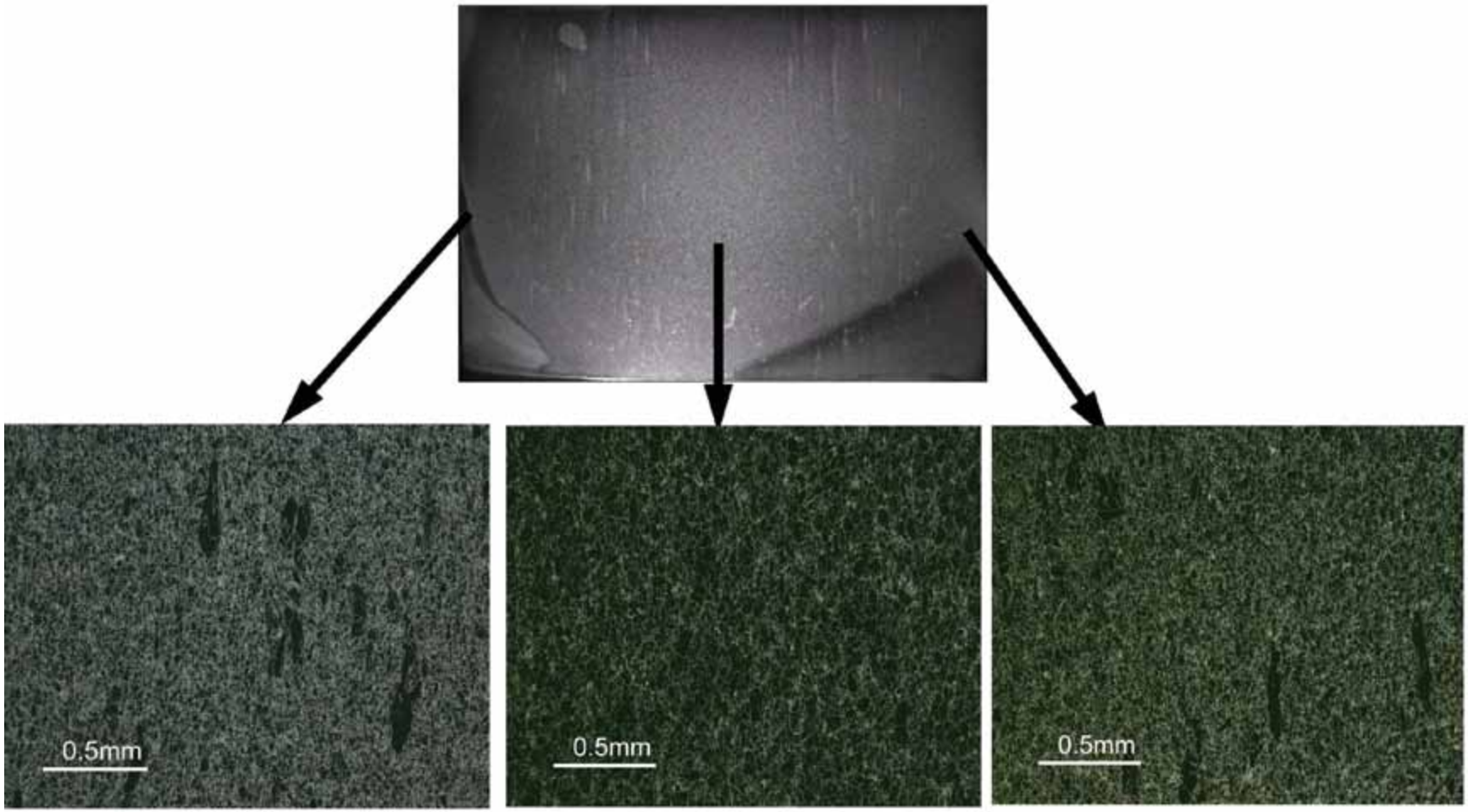
- For all cold-worked heats showing relatively high SCC CGRs (>10^{-11} m/s) there is evidence of cracked carbides

- Cracked carbides as a cause for the enhanced SCC CGRs are consistent with a grain boundary deformation mechanism for SCC

- Unresolved issues:
  - show that non cold-worked variants do not have cracked carbides
  - demonstrate that non cold-worked variants do no crack

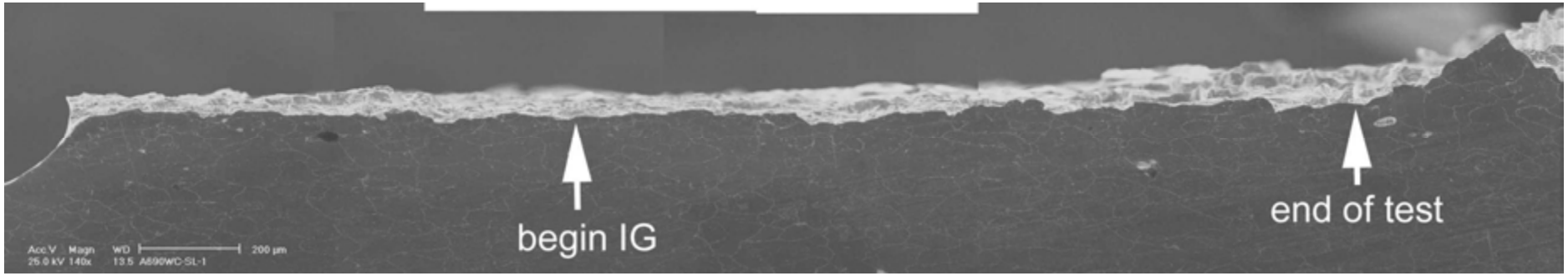
- Moving forward (approach similar to that for Alloy 600)
  - understand (mechanistically) the role of Cr in solution and as carbides
  - determine the level of cold work that causes carbides to crack (and could potentially impact SCC behavior)
  - investigate the effects on carbides at weld HAZ (combination of solutionized, discrete, continuous + cold work)

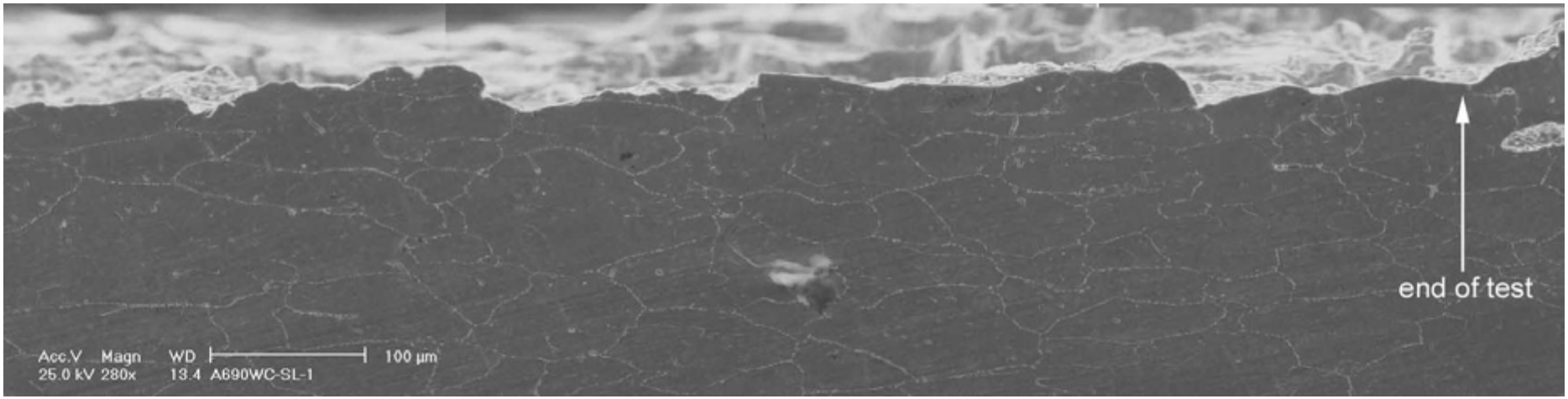
Alloy 690 Plate (Heat NX3297HK12)



- Carbide and grain size banding observed at the edges but not in the mid-plane

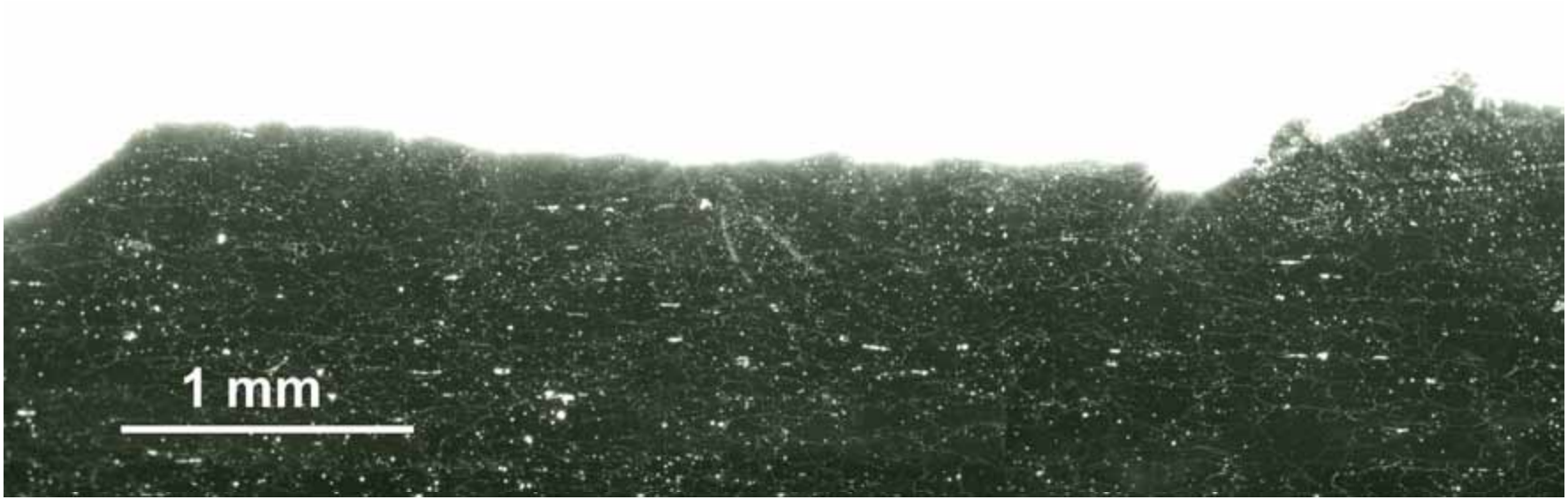
Cross section of specimen A690WC-SL-1 tested in PWR water (Heat NX3297HK12, cold rolled by 26%)





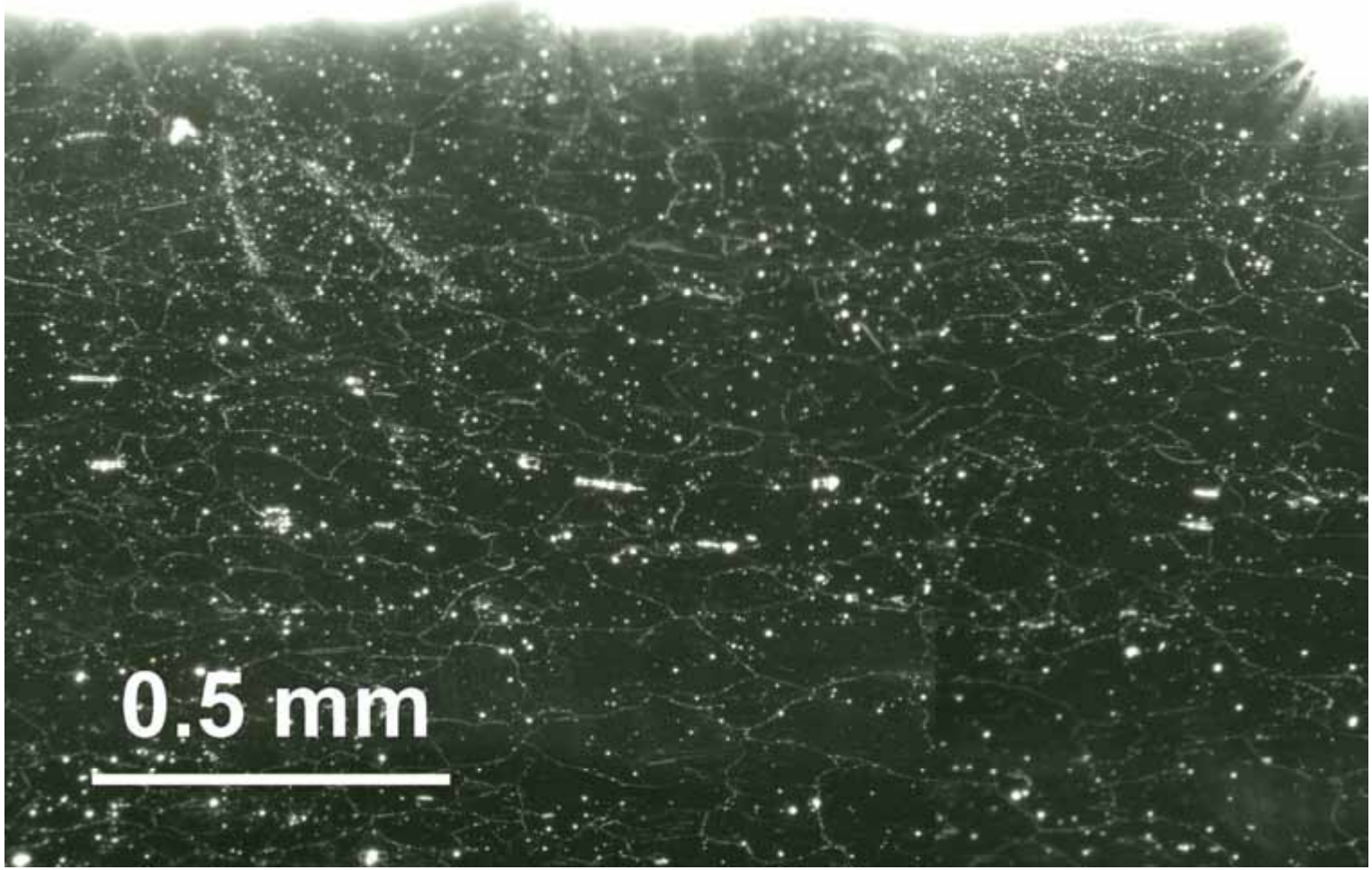
- Crack propagation appears straight

Cross section of specimen A690WC-SL-1 tested in PWR water (Heat NX3297HK12, cold rolled by 26%)



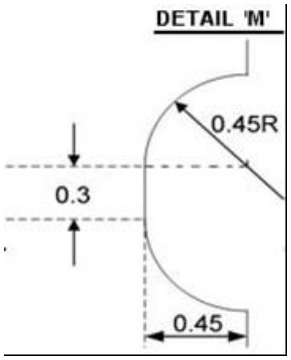
- Crack propagation appears straight

Cross section of specimen A690WC-SL-1 tested in PWR water (Heat NX3297HK12, cold rolled by 26%)



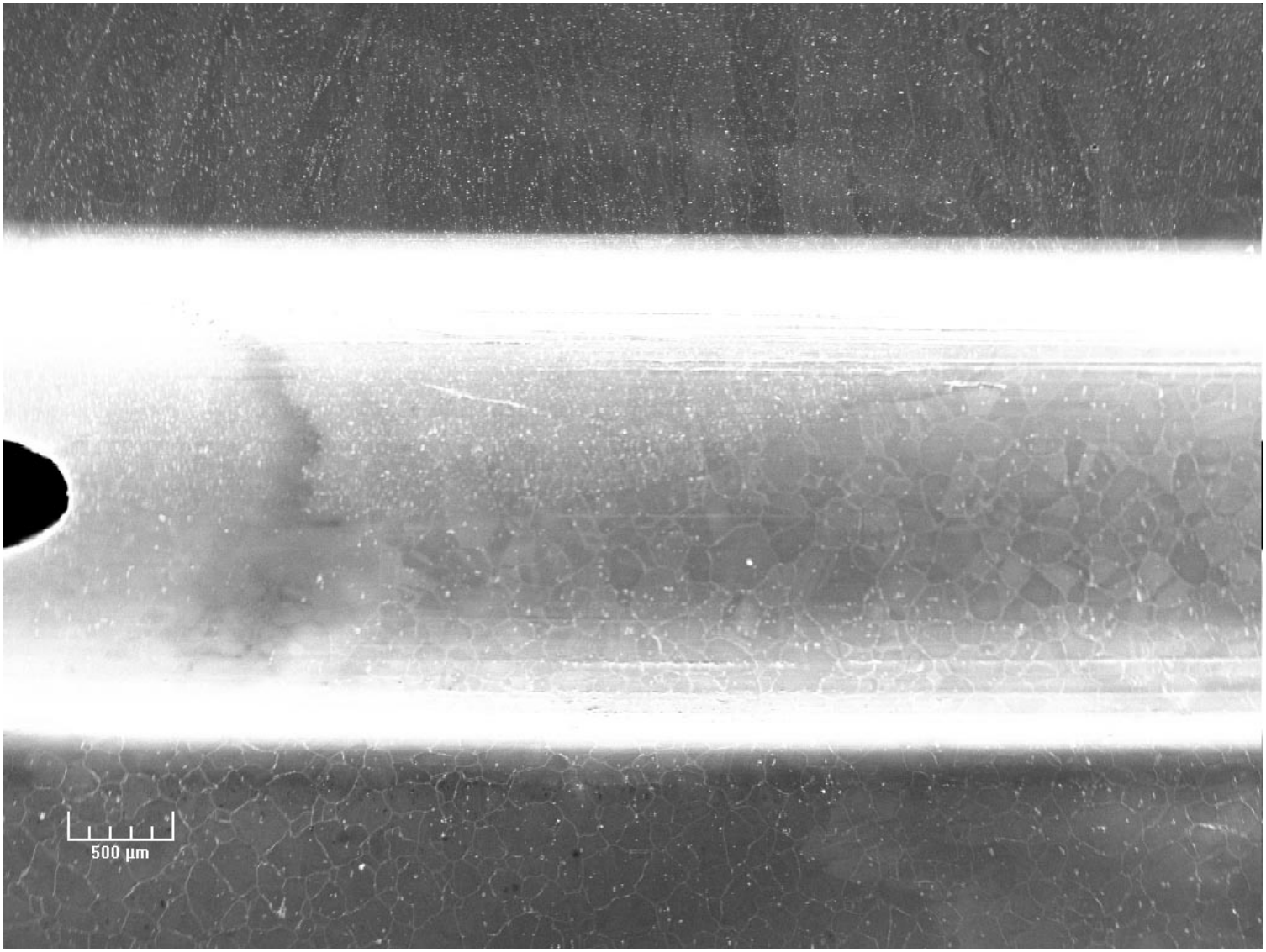
- Crack propagation appears straight

Next Alloy 690 HAZ specimen: CF690-CR-3

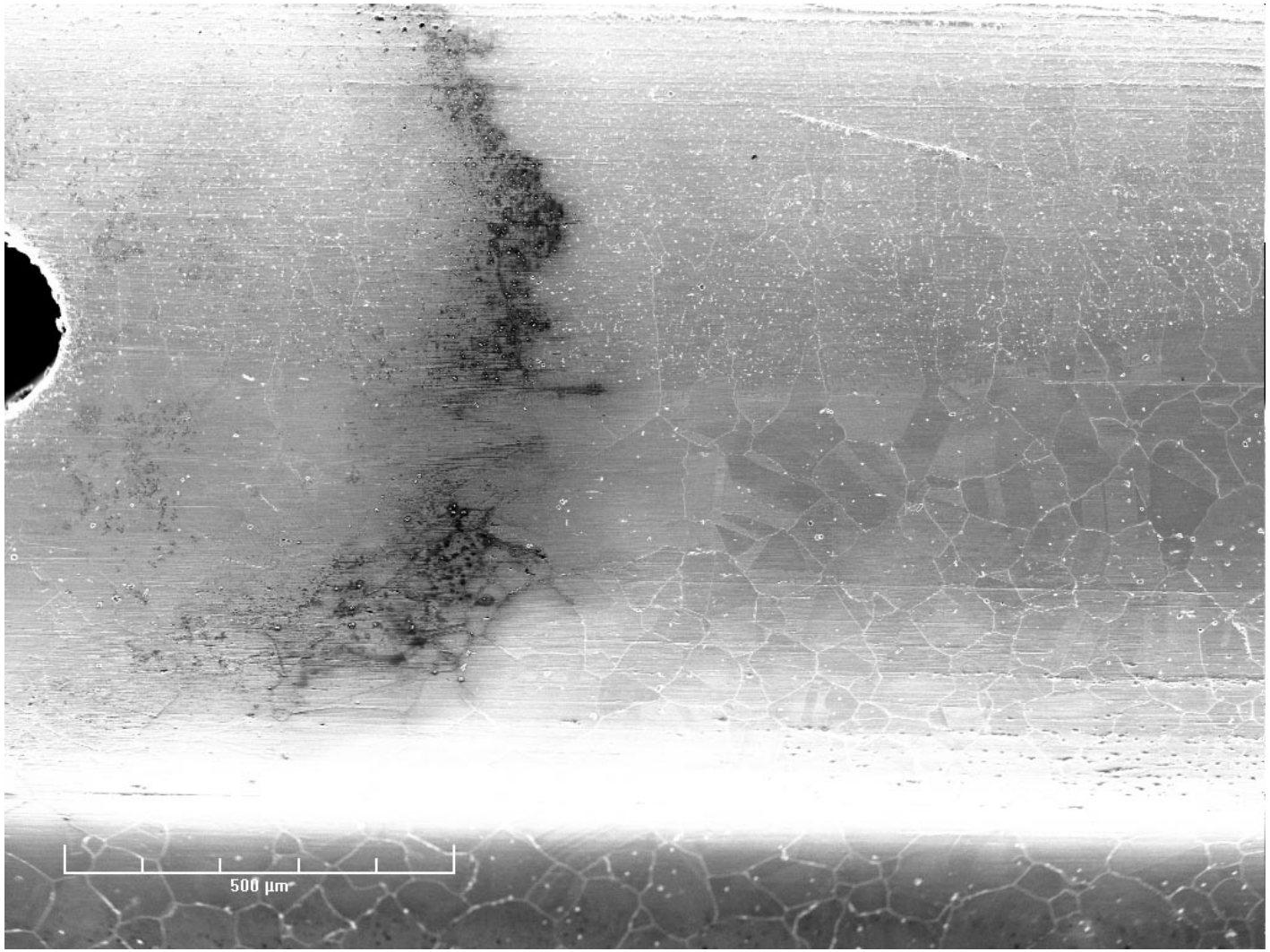


- 1.2 mm tall side grooves

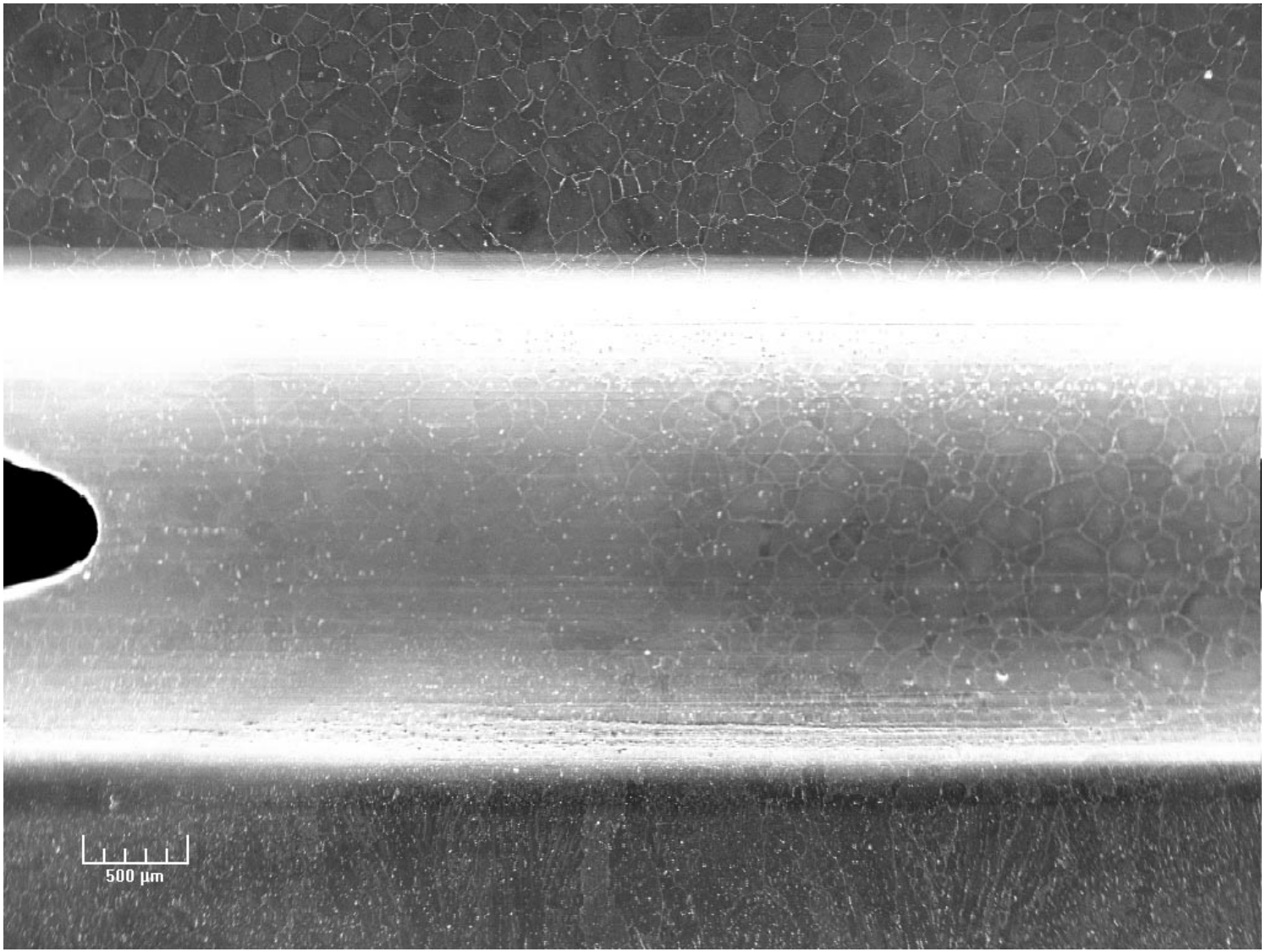
Next Alloy 690 HAZ specimen: CF690-CR-3 (side groove A)



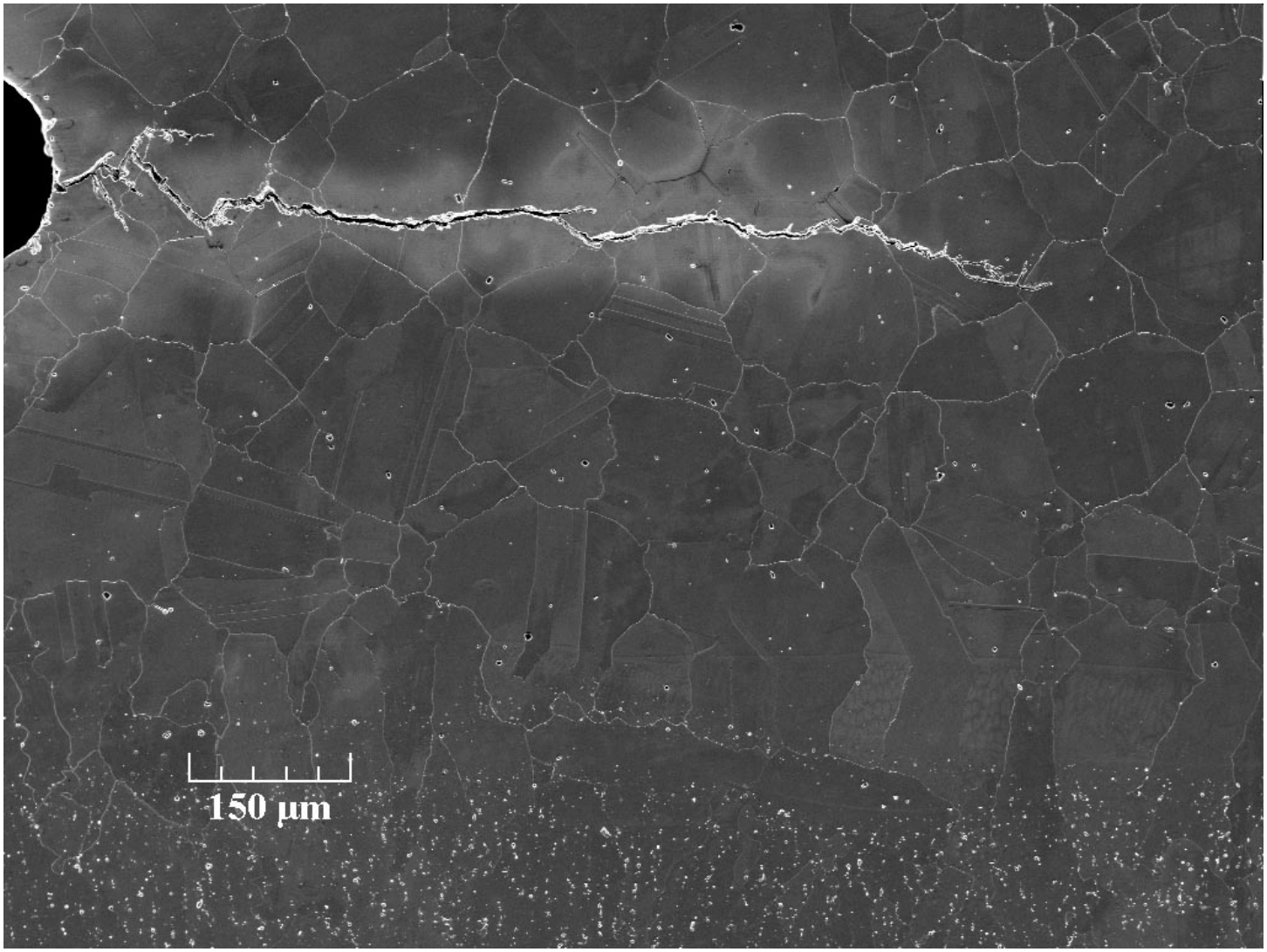
Next HAZ specimen: CF690-CR-3 (side groove A)



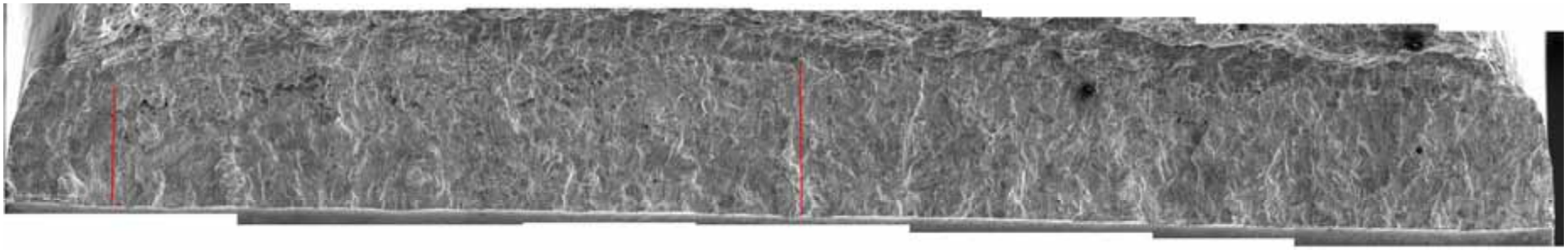
Next HAZ specimen: CF690-CR-3 (side groove B)

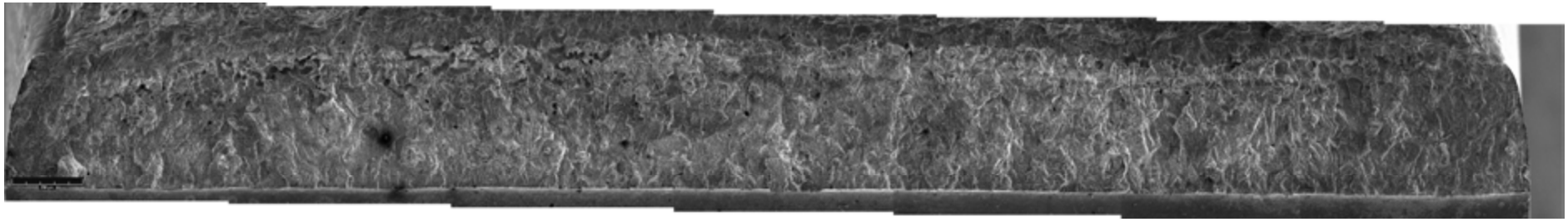


CF690-CR-1 Lateral surface 2

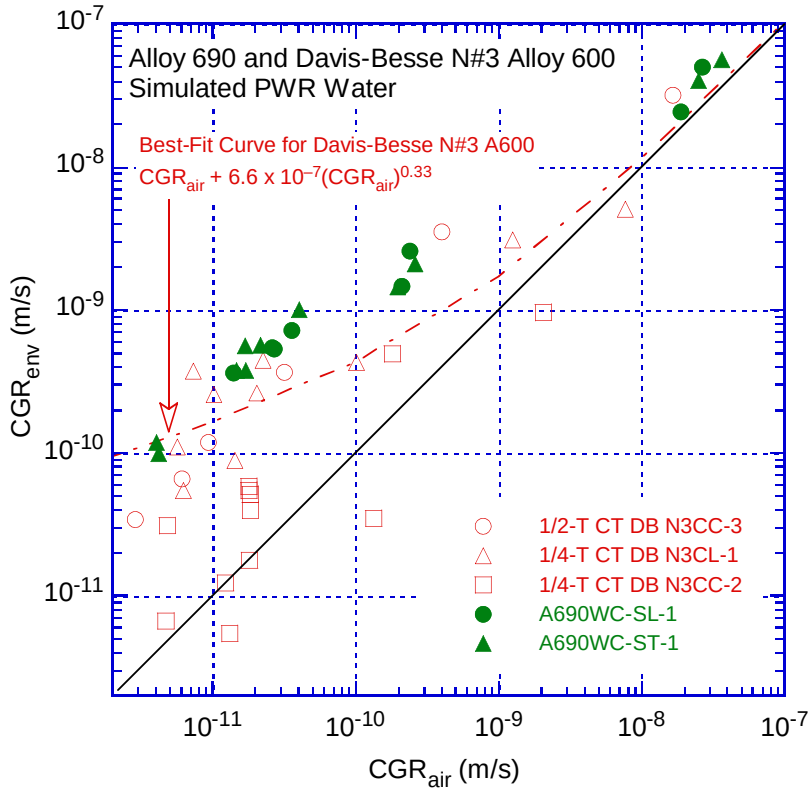


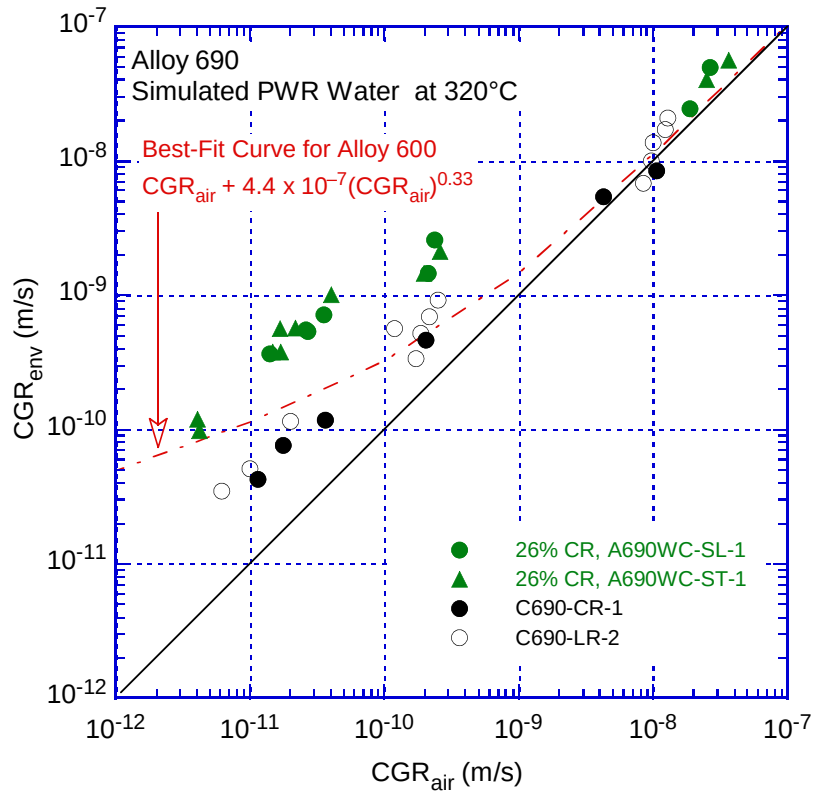
Fracture surface of Alloy 690 as-received and HAZ

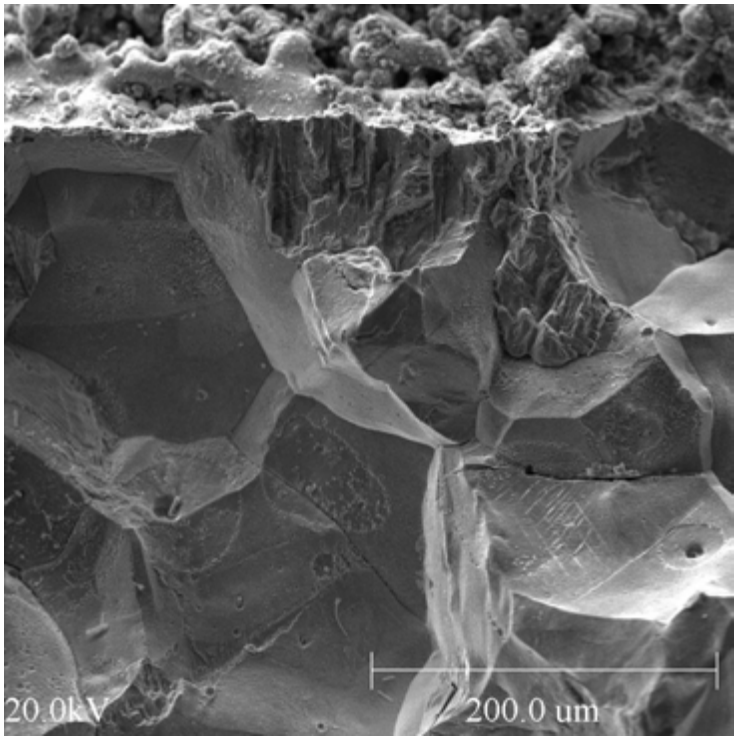
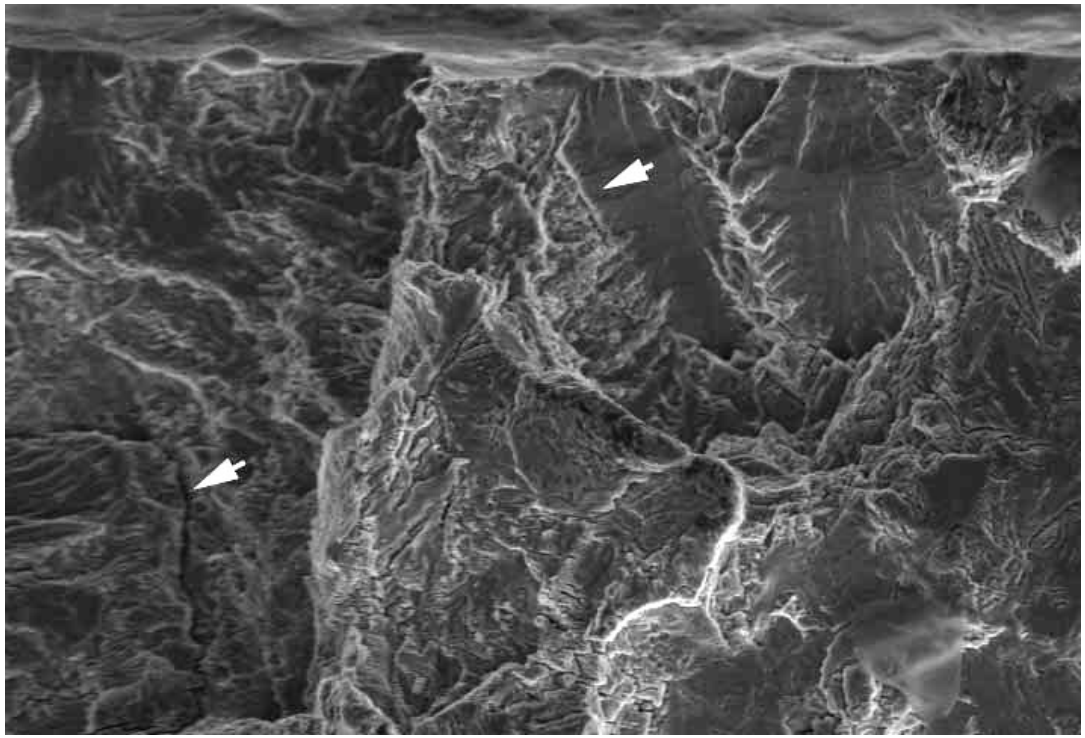




Cyclic CGR data for Alloy 690





- Alloy 690 cold-rolled shows significant environmental enhancement, comparable to Alloy 600 from Davis-Besse (Nozzle #3)
- Cyclic CGR rates for as-received alloy lower than those for cold-rolled alloy

Precracking in Davis-Besse Alloy 600 and Alloy 690 26% CR