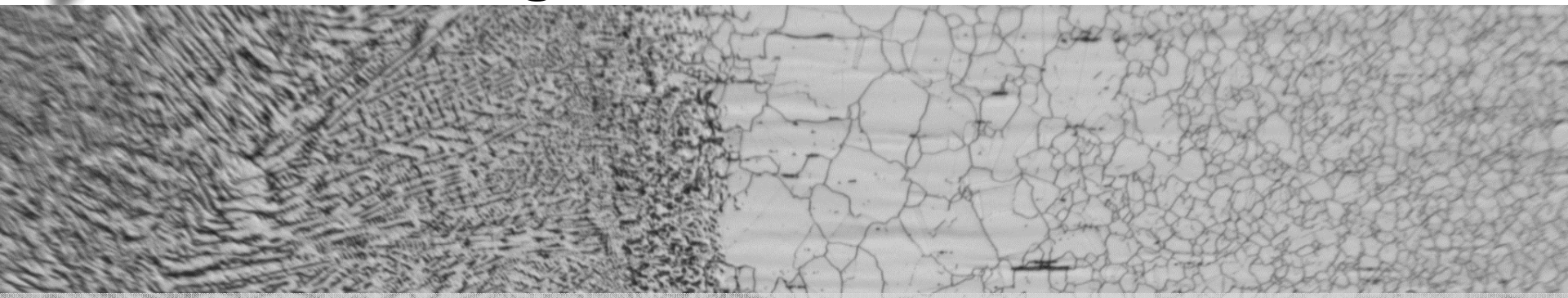
Fracture Toughness of Hydrogen Precharged Stainless Steel GTA Welds

SAND2014-3808C



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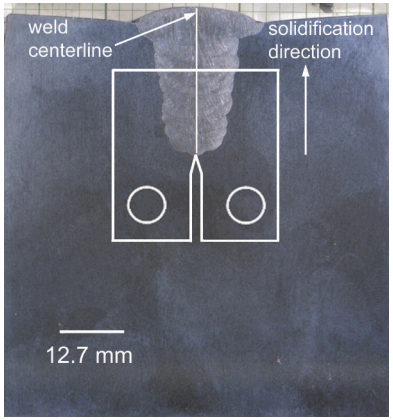
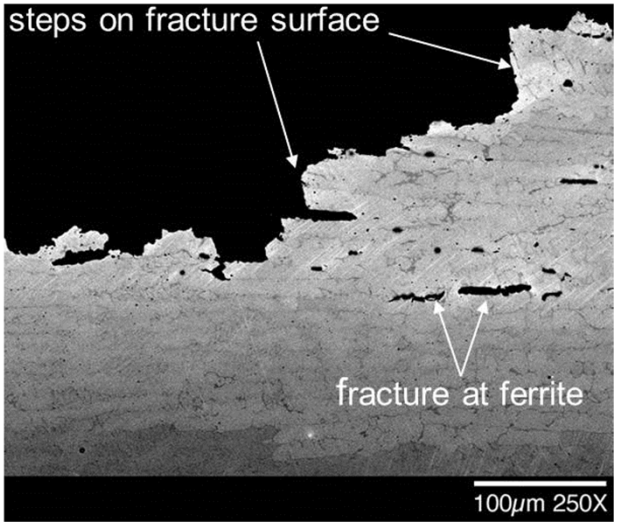
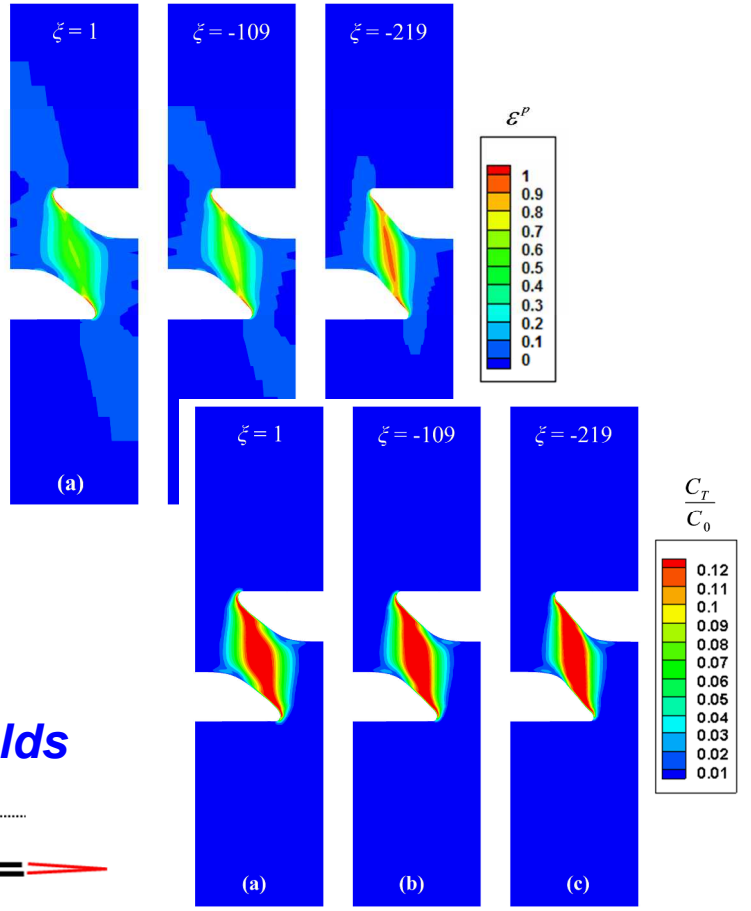
Review: H induces microcracking at δ-ferrite and may enhance deformation in γ ligaments

21-6-9/21-6-9 GTA weld

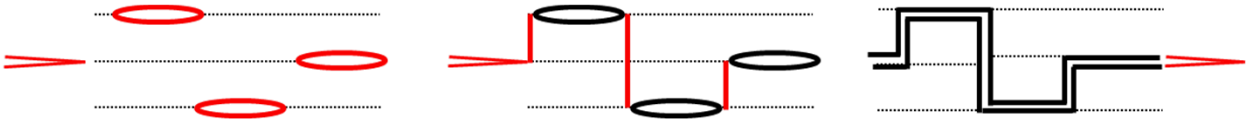


Fracture profile in H-charged 21-6-9/21-6-9 GTA weld





Model for H-assisted crack extension in GTA welds



microcracks form along dendritic structure away from main crack

microcracks link *via* localized deformation

crack advances creating "stepped" fracture surface

C_o=230 wppm
ξ = -109 (20% max. softening)
ξ = -219 (40% max. softening)

Somerday et al., Met Trans A, 2009

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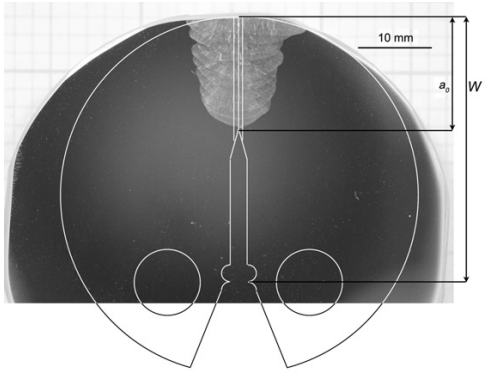
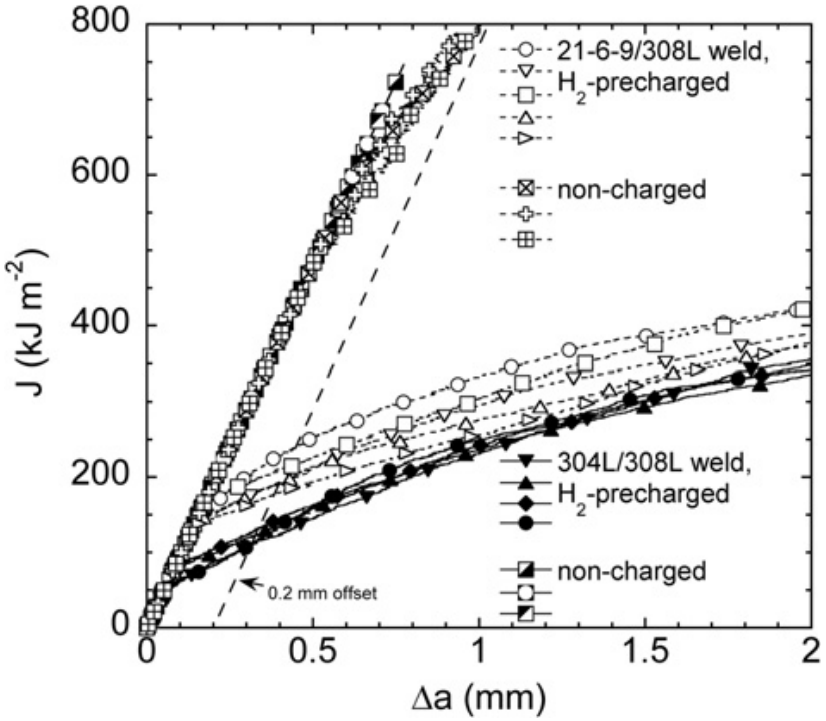
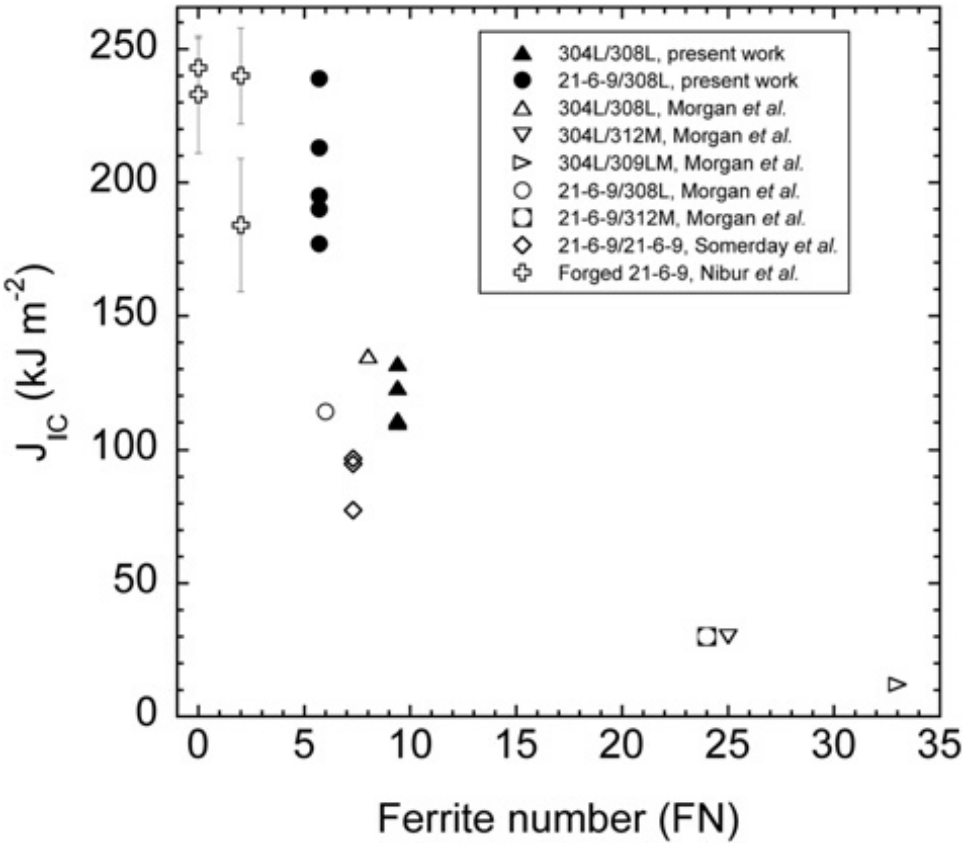
Review: fracture toughness of H-charged GTA welds dictated by δ-ferrite content

304L/308L and 21-6-9/308L GTA welds





H-charged stainless steel: forged base metal and GTA welds



Jackson et al., Corr Sci, 2012

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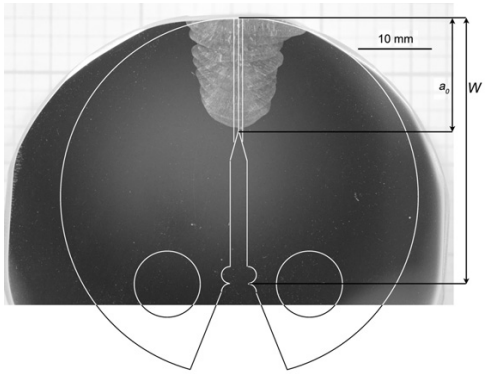
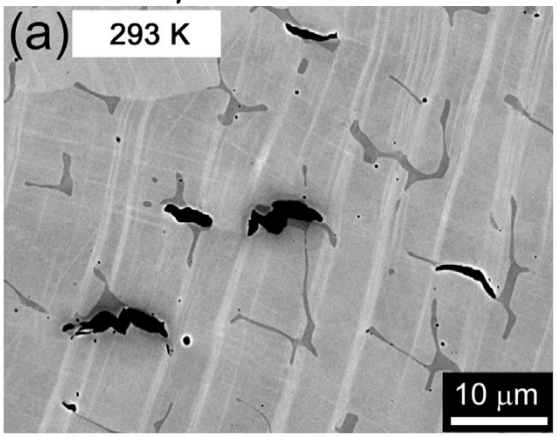
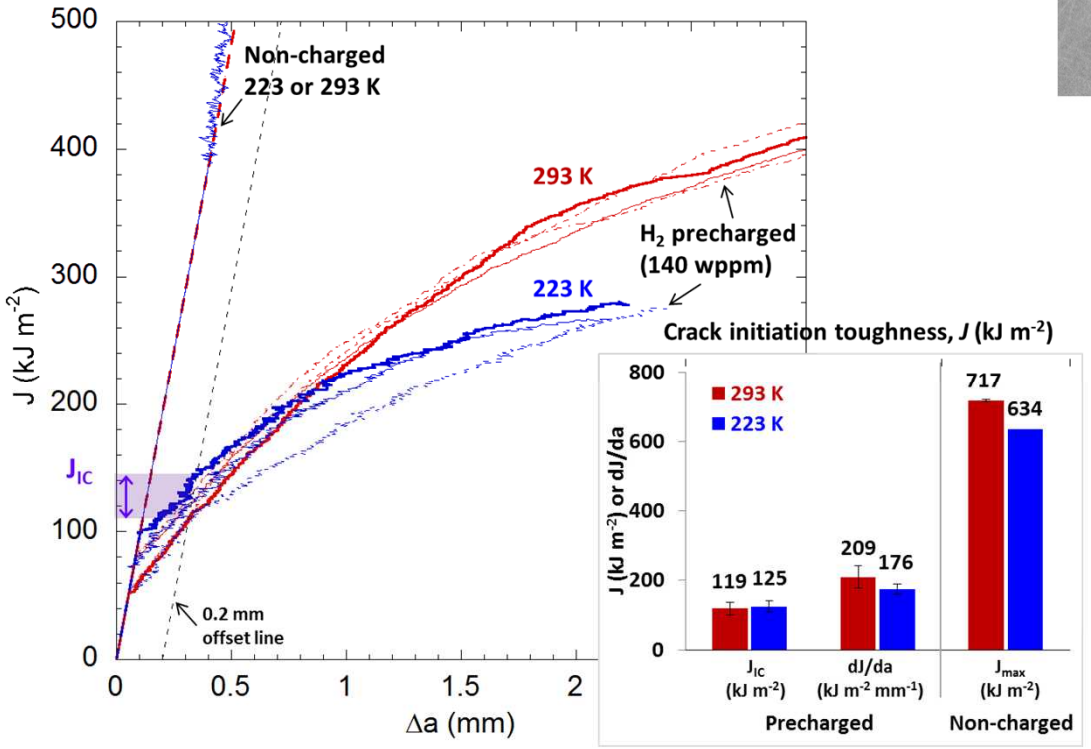
Review: low temperature does not affect fracture toughness but modifies damage mechanism

304L/308L GTA welds



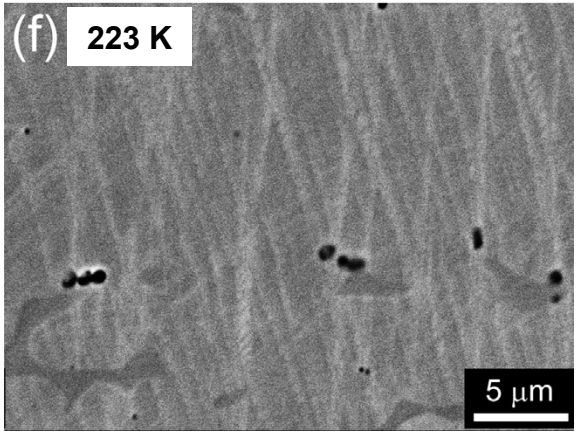
H-induced damage: microcracks in δ or at δ/γ interfaces





Crack initiation toughness, *J* (kJ m^{-2})

H-induced damage: microvoids in γ near δ/γ interfaces



Jackson et al., Corr Sci, 2013

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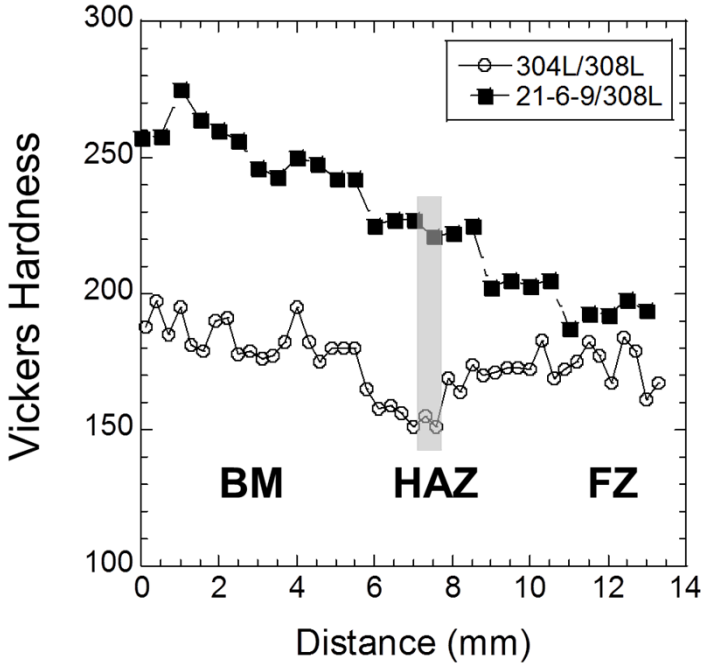
Forged Stainless Steel Composition

Base Metal	Fe	Cr	Ni	Mn	Si	C	N	P	S	YS (MPa)
21-6-9	Bal	21.06	7.16	9.11	0.53	0.031	0.28	0.015	0.001	610
304L	Bal	19.4	10.4	1.7	0.57	0.027	0.02	0.021	0.002	423
308L Filler WR-226809	Bal	20.5	10.3	1.56	0.50	0.028	0.055	0.006	0.012	-

Material	Description	Forging Temperature (°F)
21-6-9	Forging	1550
304L	Forging	1550 (anneal 1600)



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Comparison of Forged Microstructure

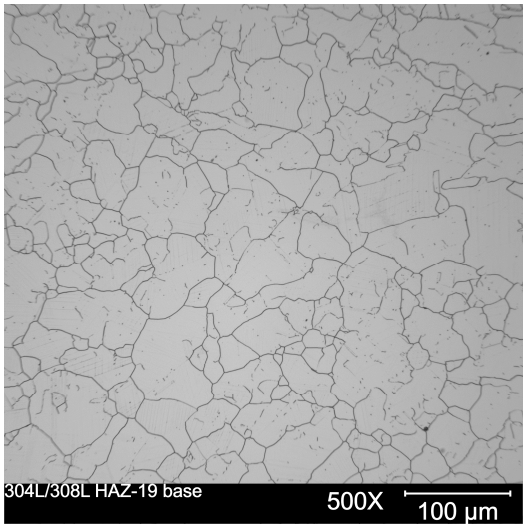
Forged Base Metal

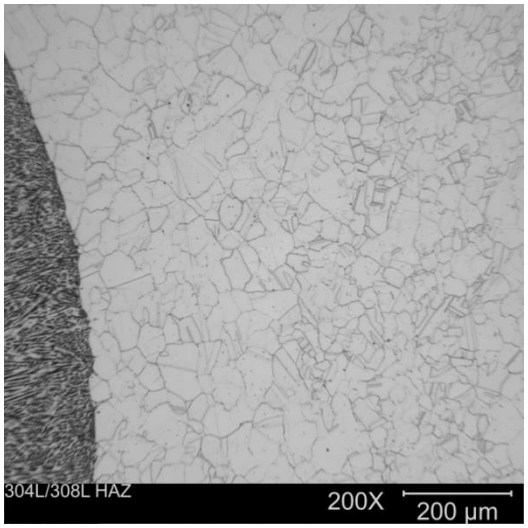
HAZ

Radial

Axial

304L

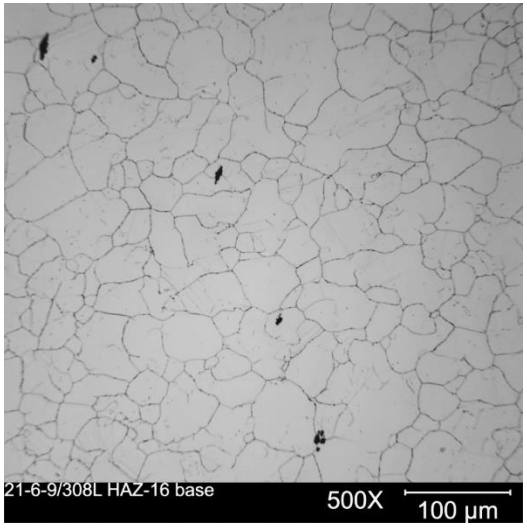


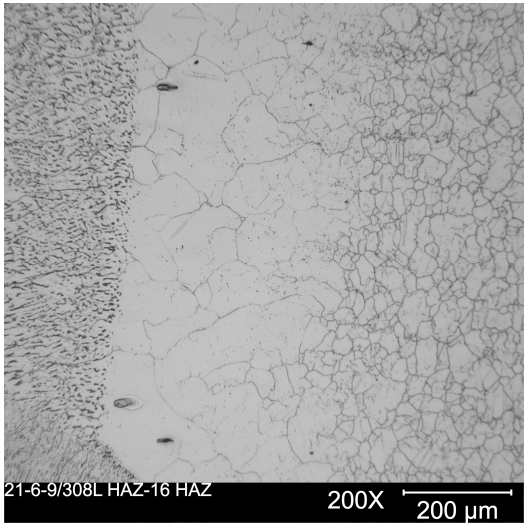


Similar grain size in forged base metals

Slightly larger grain size in 21-6-9/308L HAZ

21-6-9





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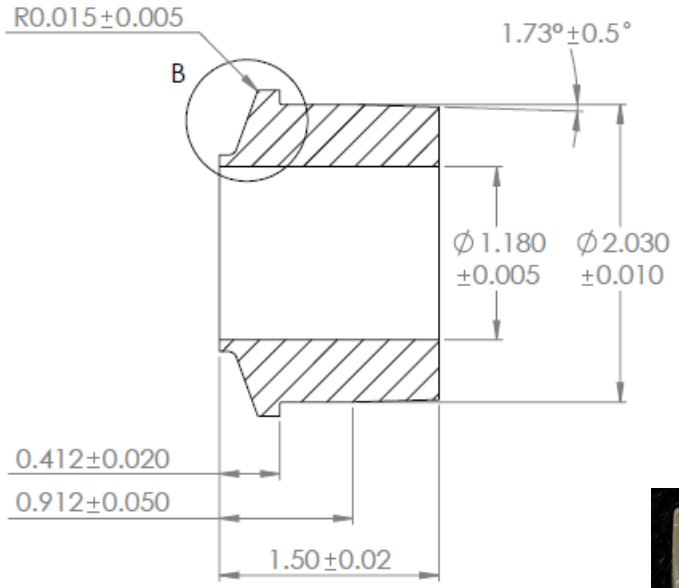
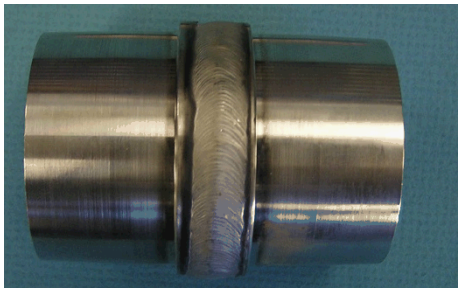
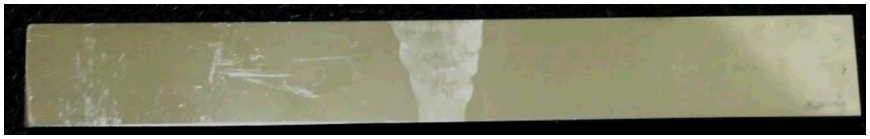
Fabrication of GTA welds from Forged Stainless Steel

- **Gas Tungsten Arc Weld (GTAW)**
  - **Two weld pieces (J-groove) form 'Single-U' joint**
  - **6-7 weld passes using 308L filler metal**
  - **Removed rectangular 3-pt bend (3PB) blanks from weld rings**





3PB



4.8 mm

9.6 mm

Single U joint

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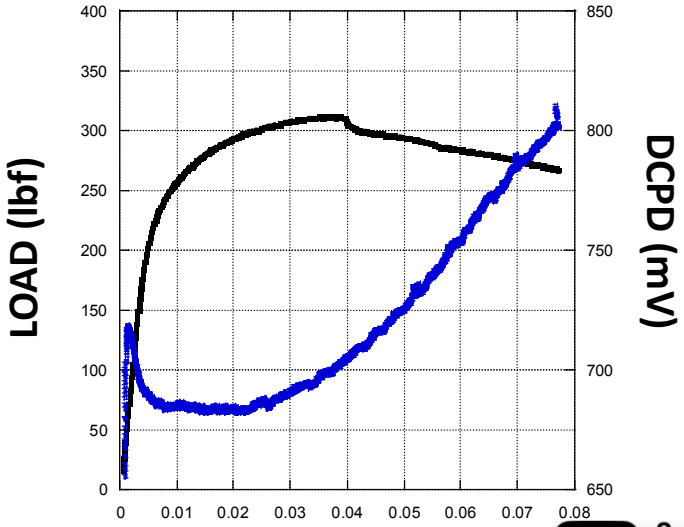
Thermal H_2 Precharging & Fracture Testing of 3-pt Bends

- Precracking was performed in air
- Gaseous Hydrogen Precharged
  - 573 K (300 °C) in 99.9999% H_2 at 138 MPa (20 ksi)
  - 16+ days
  - 140 wppm for 304L (0.8 at%*)
  - 220 wppm for 21-6-9 (1.3 at%*)
- Tested in air at 295 K (21 °C)
- Elastic-Plastic Fracture Mechanics
  - (J-R curves)
- Constant rising displacement 0.2 mm/min (0.6 MPa $m^{1/2}$ s^{-1})
- DCPD signal was used to detect crack initiation



*San Marchi *et al*. *Int J Hydrogen Energy* **32** (2007) 100.

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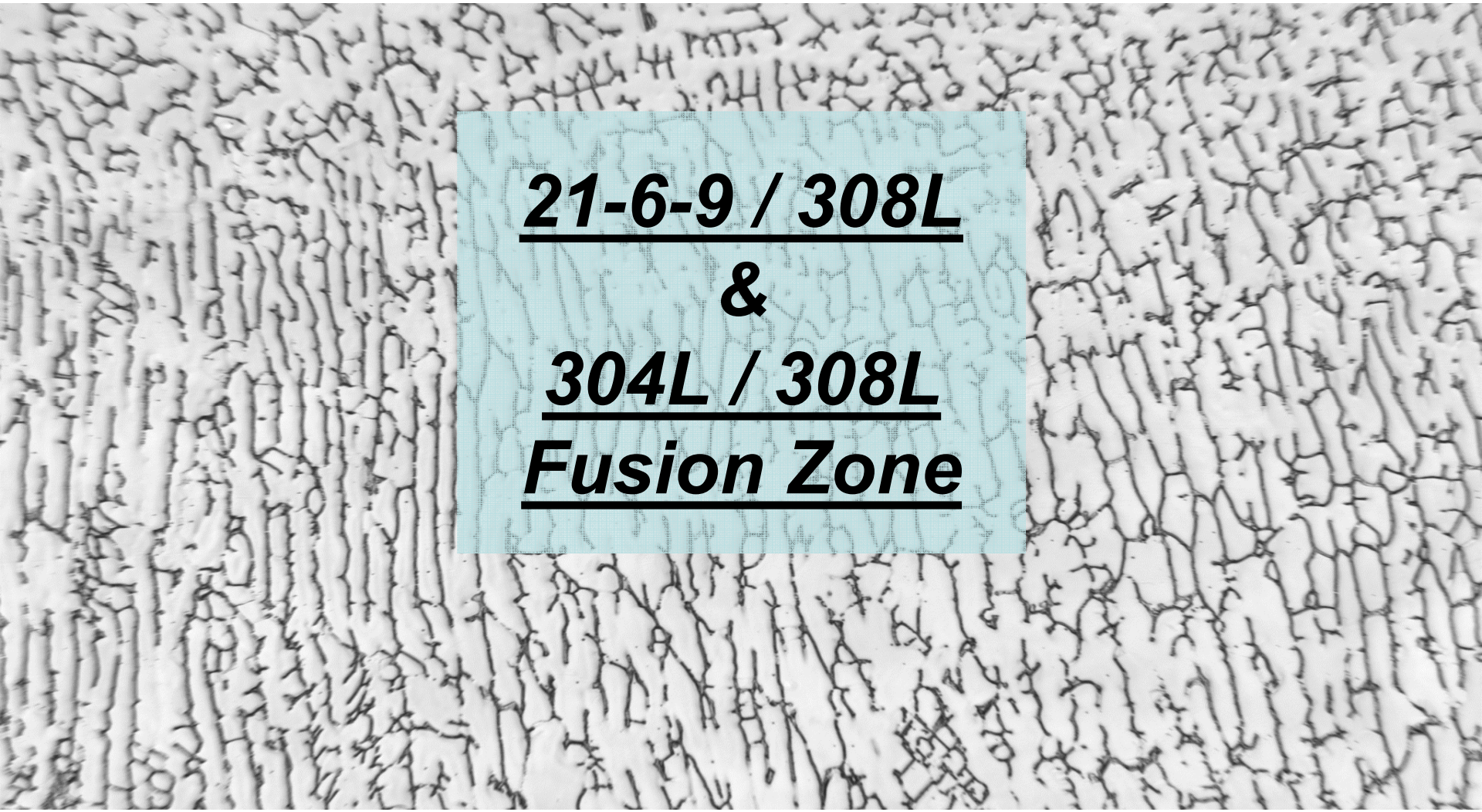

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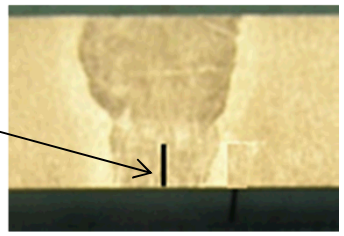
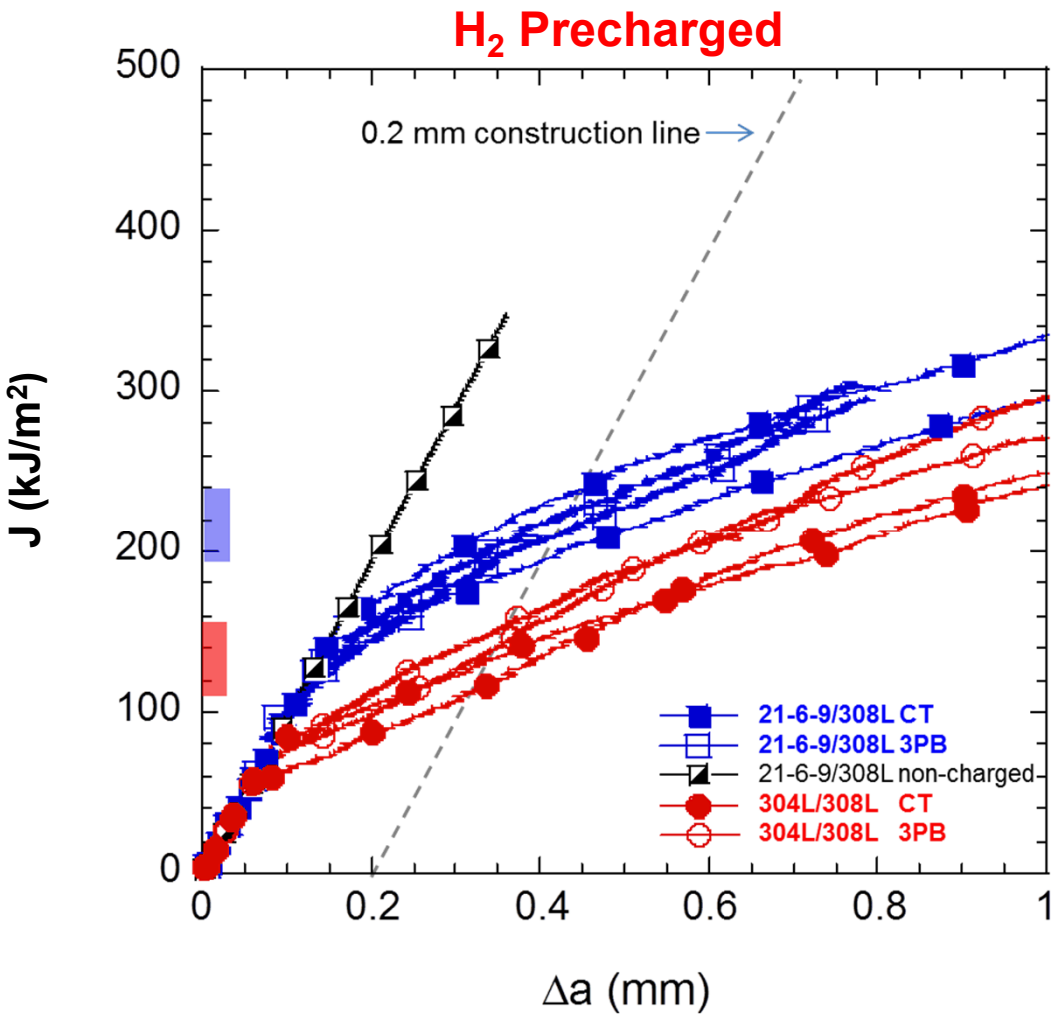
H_2 Assisted Crack Extension in Fusion Zone

- Higher Fracture Toughness in 21-6-9/308L was greater than 304L/308L
  - Consistent with previous results from Jackson *et al.** for CT specimens of annealed base metal
- K_{JQH} = 215 MPa $m^{1/2}$ 21-6-9 / 308L
- K_{JQH} = 177 MPa $m^{1/2}$ 304L / 308L





*Jackson *et al. 2012*

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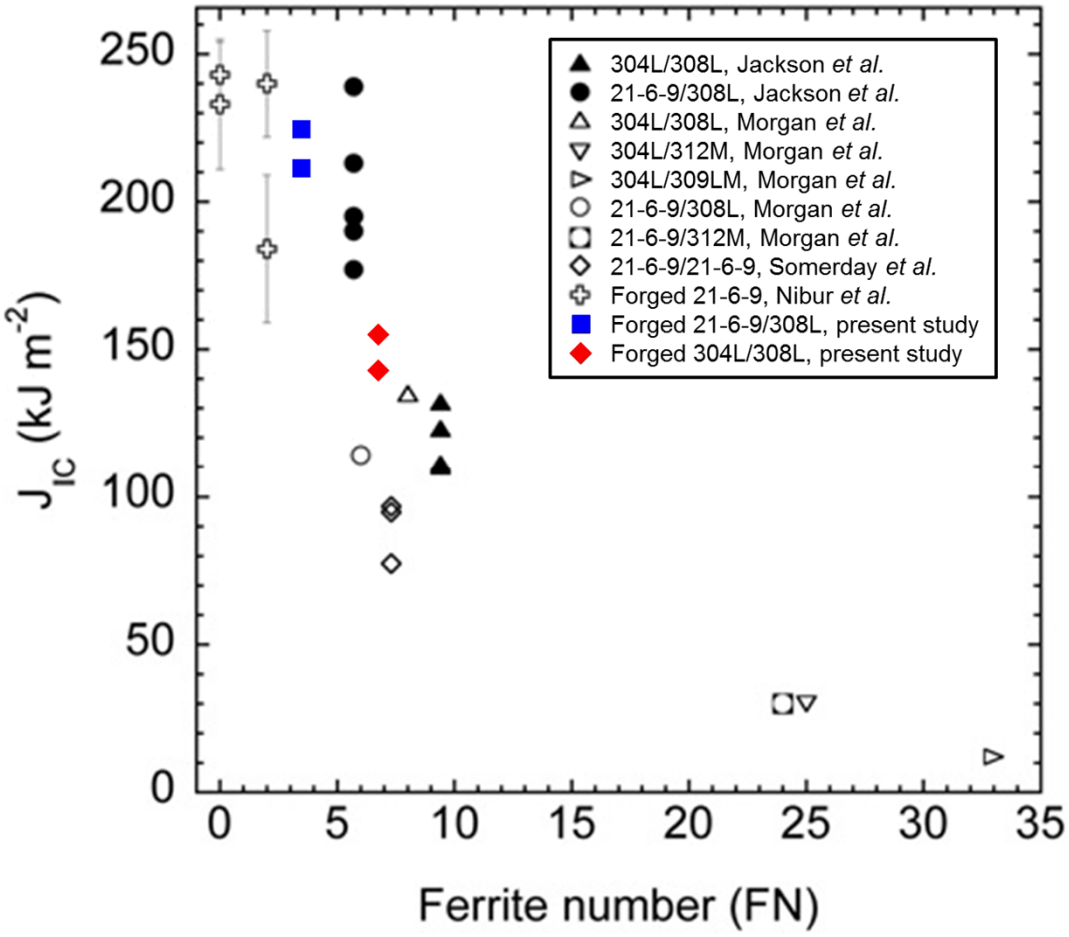
Ferrite in Fusion Zone Reduced Hydrogen Assisted Fracture Toughness

- Ferrite number (FN) in the weld was observed to have a degrading effect on fracture toughness*
- FN (21-6-9/308L) ~ 3-4%
- FN (304L/308L) ~ 7%
- Microcracks initiate at ferrite interfaces in weld
- Dendritic morphology promotes crack propagation



As δ – ferrite ⇧, fracture toughness ⇩

* **Jackson *et al.* (2012)**

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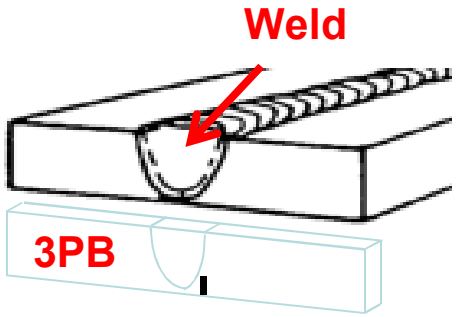
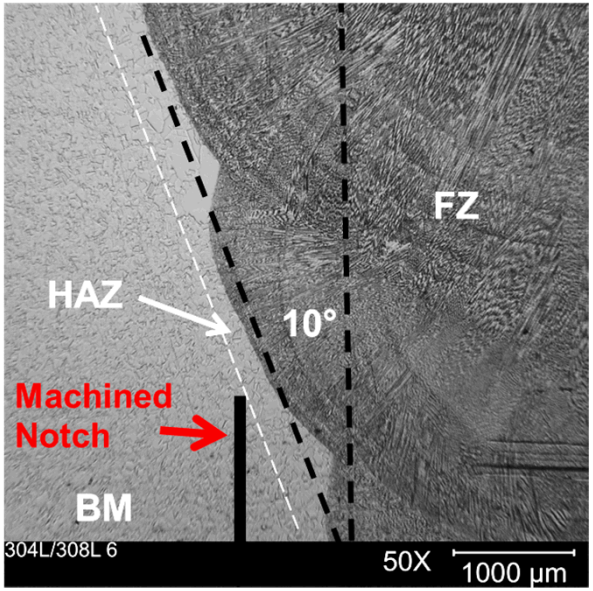
Heat Affected Zone (HAZ) Fracture Tests

Challenges in Using 'Single U' Joint GTA Weld for HAZ Testing

- Requirements: Position fatigue precrack for 3-pt bend (3PB) specimen in HAZ
- Current weld geometry: 'Single U' shape (10° taper weld pieces)
- Approach: Offset notch and grow fatigue crack into HAZ
- Challenges: Due to taper of weld and narrow HAZ, terminating the precrack precisely was crucial to testing the fracture toughness of HAZ



'single U' with adjacent precrack



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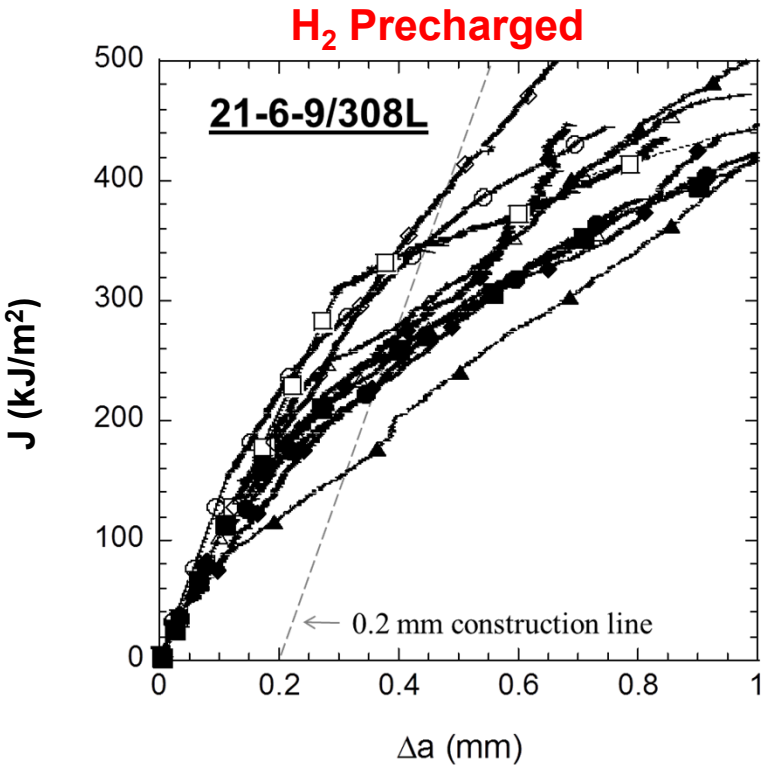
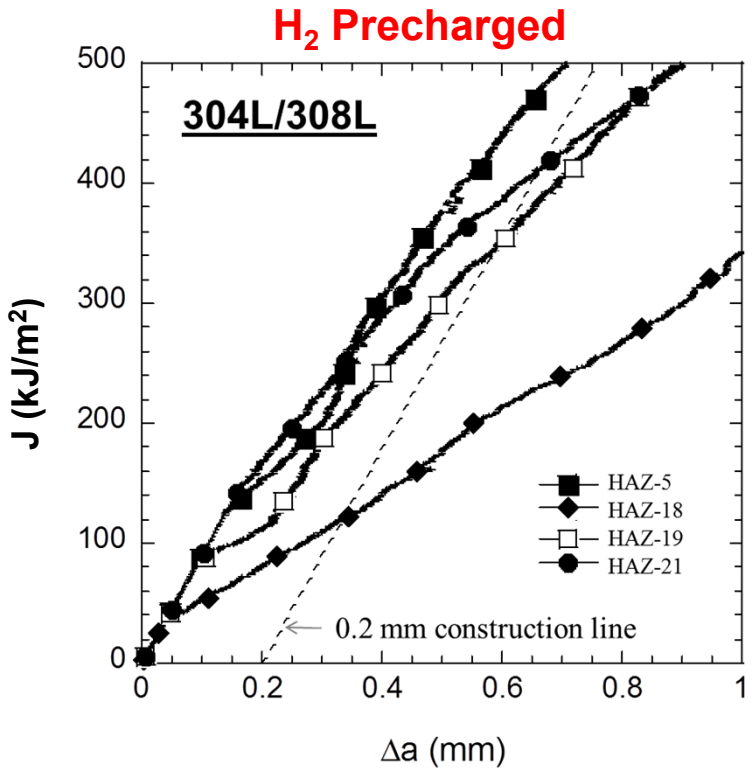
J-R Curves for HAZ Fracture Tests for 'Single U' Joint Geometry

- In general, observed higher fracture toughness in HAZ than fusion zone
- Scatter in the J-R curves





- Microscopy was used to identify location in weld that fracture data was collected

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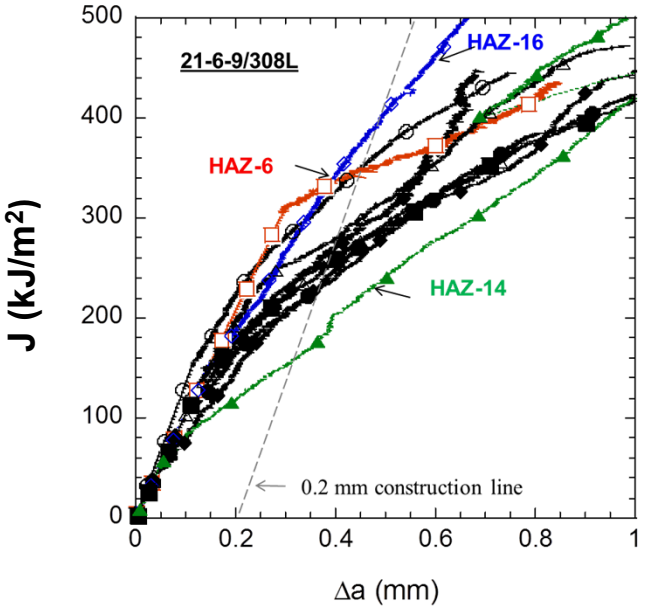
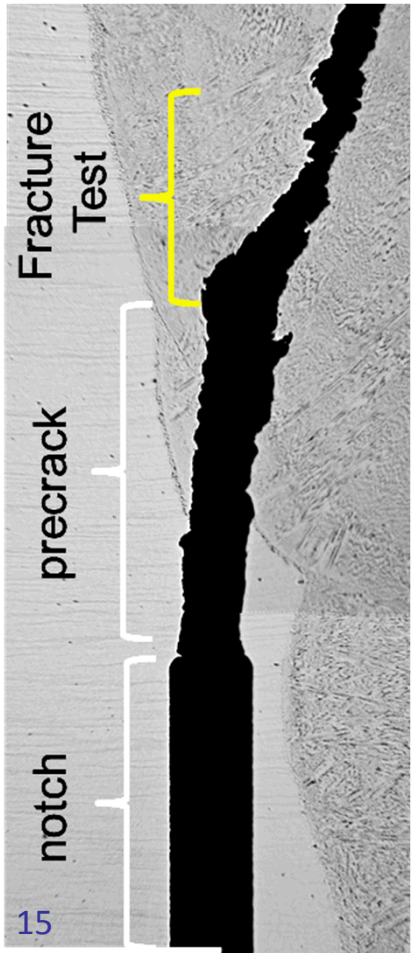
Extension of Precrack into Weld Metal in HAZ Samples

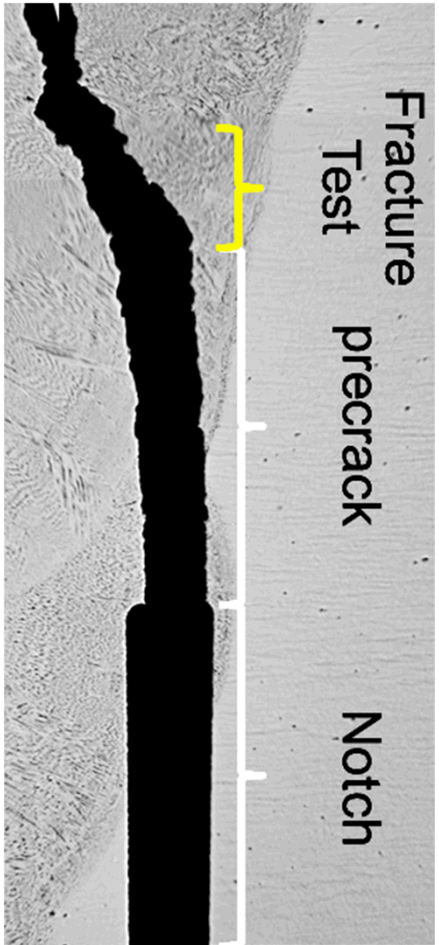
- Profile LOM images show propagation of precrack into FZ for HAZ-14 and HAZ-6
  - Significantly different J-R curves

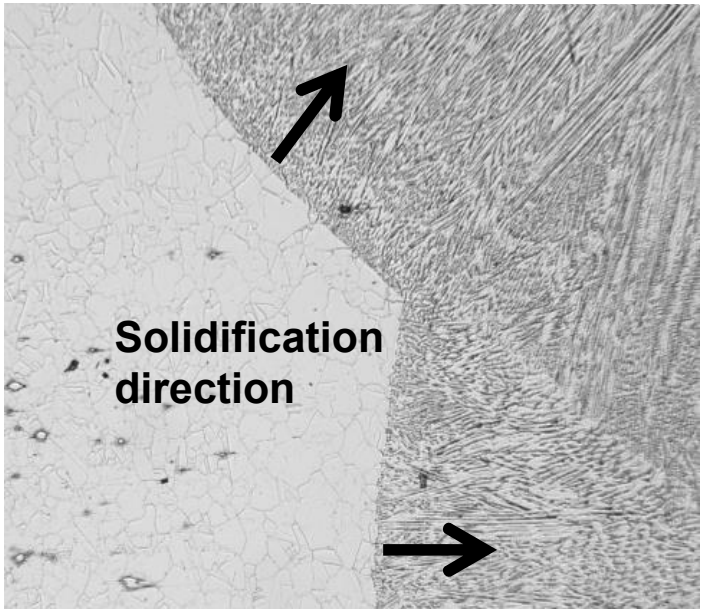


HAZ-14



HAZ-6





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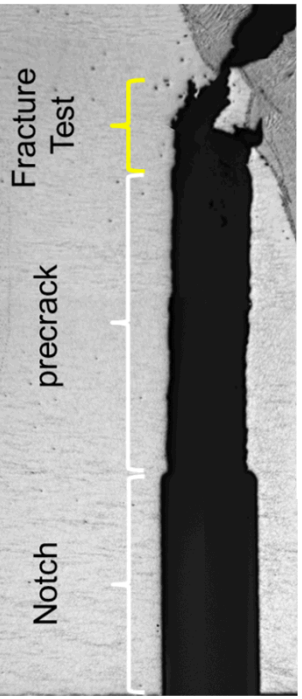
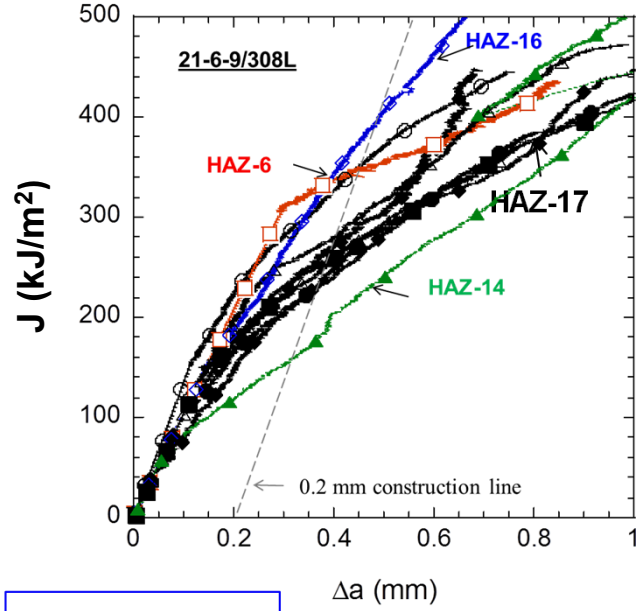
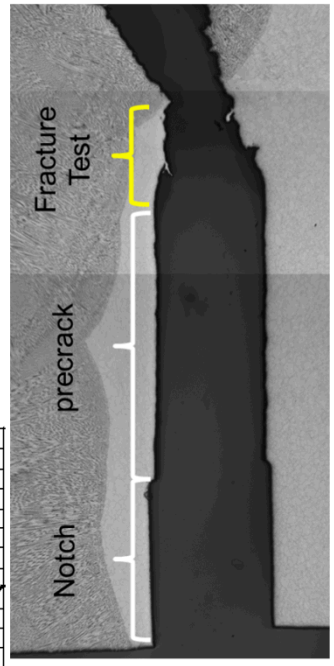
H_2-Assisted Crack Extension in HAZ

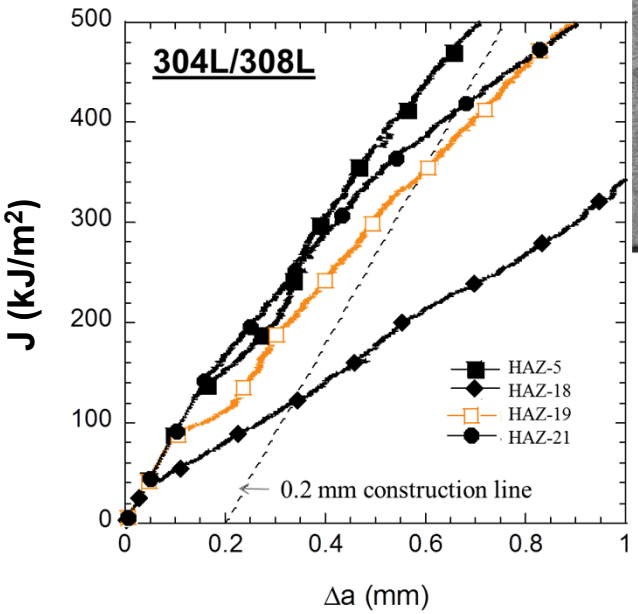




21-6-9/308L
HAZ-16

304L/308L
HAZ-19





- **Both fracture test data appear to be located in HAZ**

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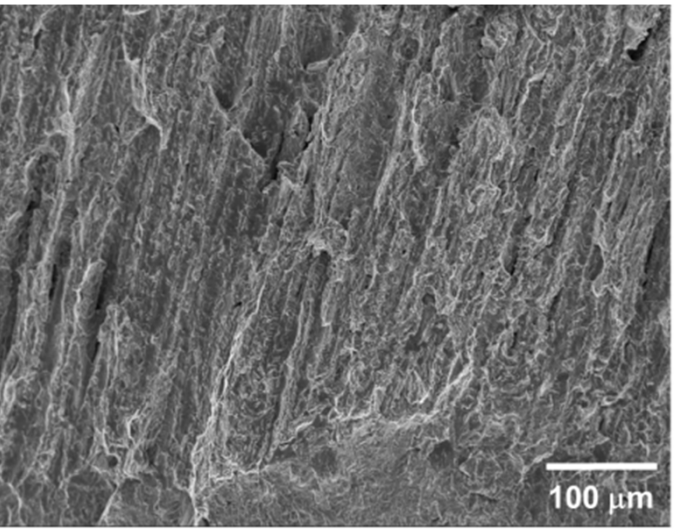
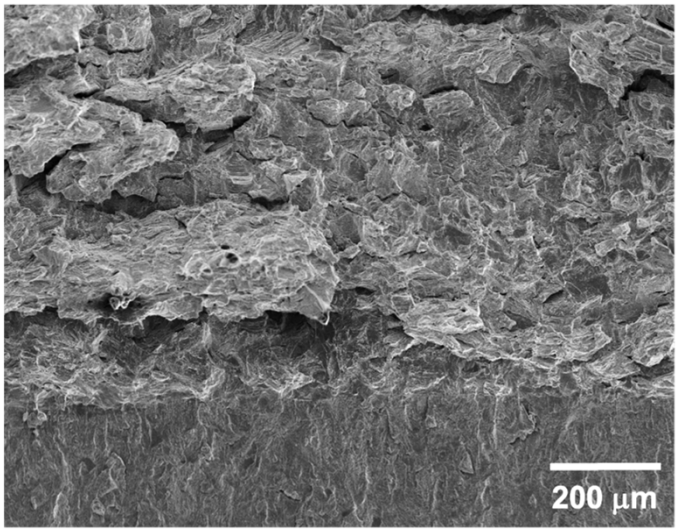
Elongated Fracture Surface Features Indicate Crack Propagation in Fusion Zone

304L/308L FZ-7

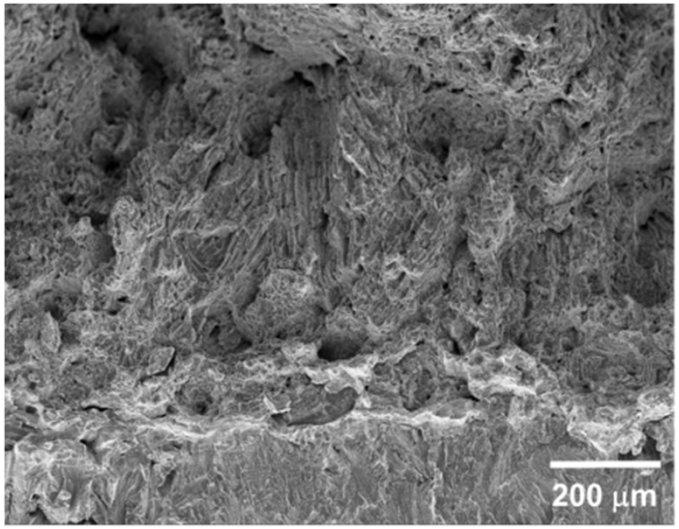


Crack growth direction

304L/308L HAZ-19



21-6-9/308L HAZ-17



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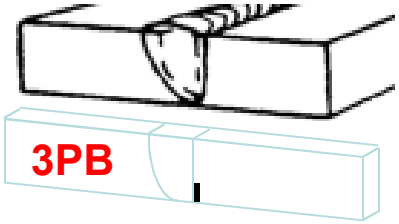
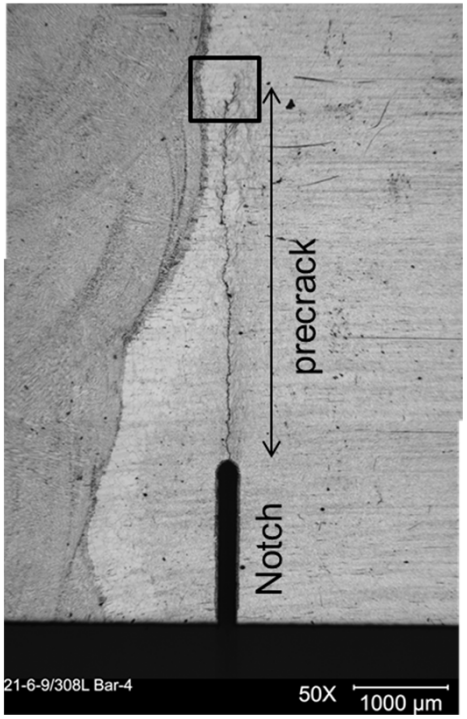
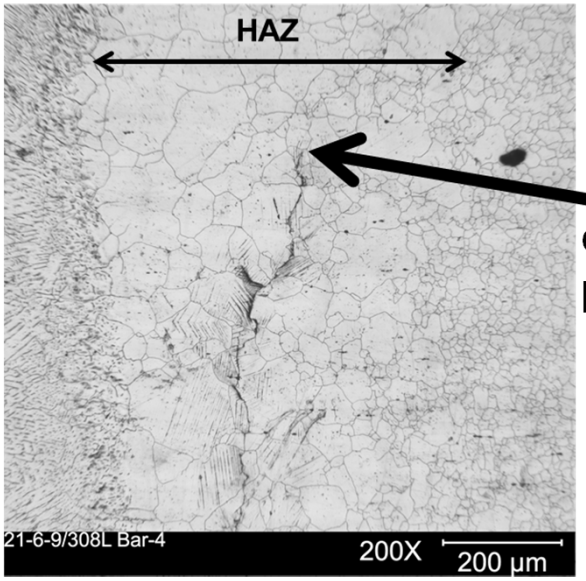
Modified 'Single J' Weld Joint Geometry of GTAW to Improve Consistency of Testing HAZ

- **Challenge:** Consistently terminating precrack in HAZ
- **Solution:** Modified weld pieces to 'single J' geometry
  - Precrack in 3PB specimen grows more parallel to fusion zone boundary and provides greater potential for terminating precrack in HAZ







end of precrack

- Initial Trials with Annealed 21-6-9

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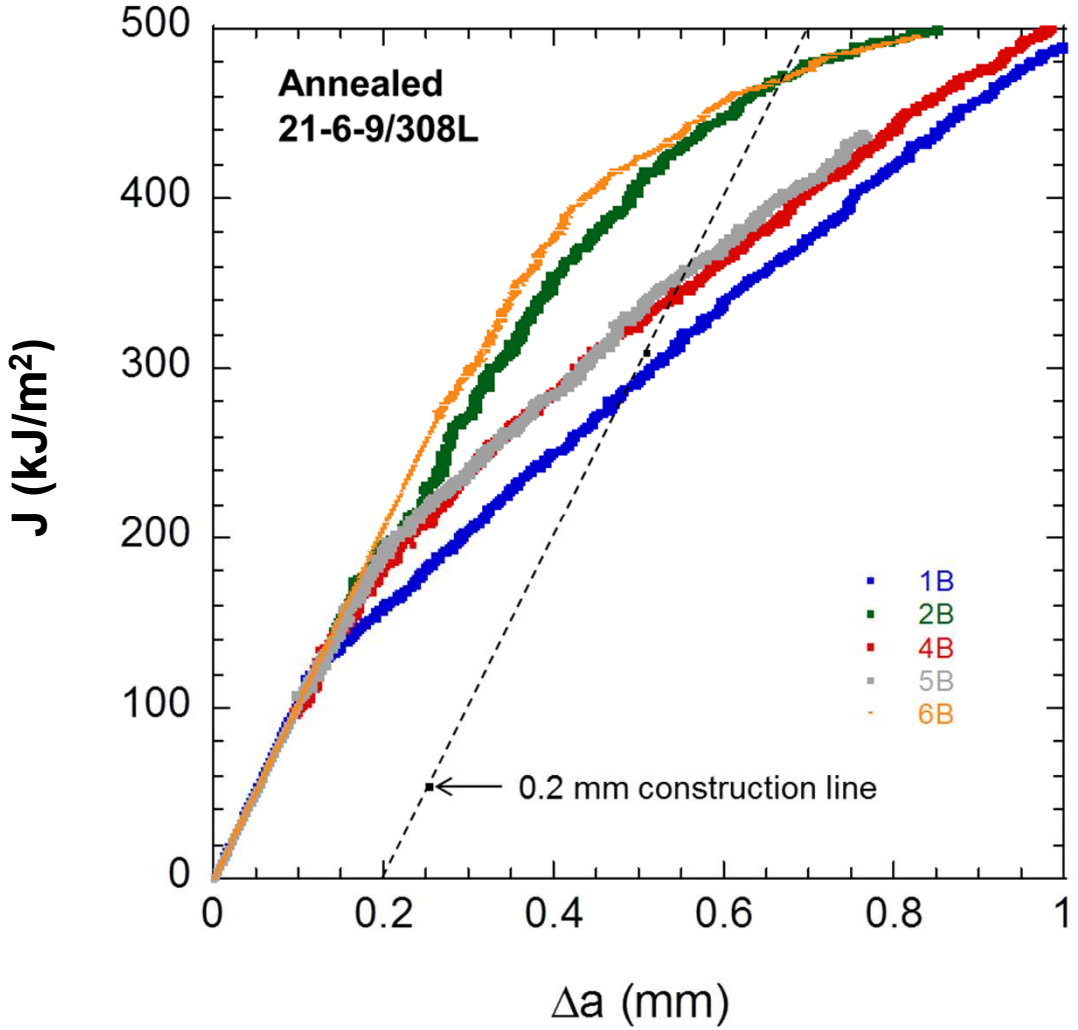
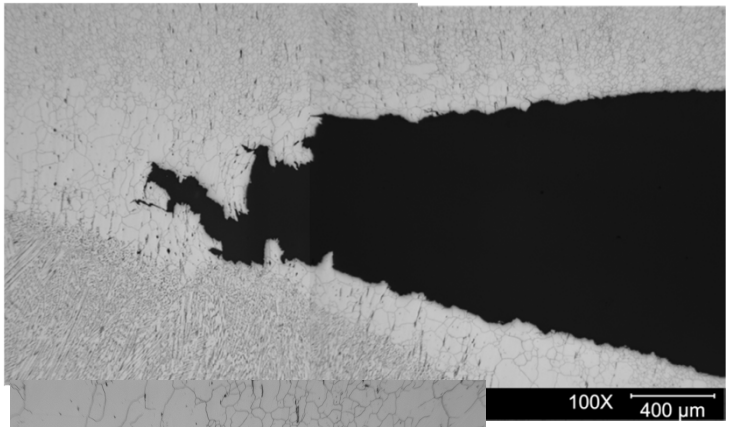
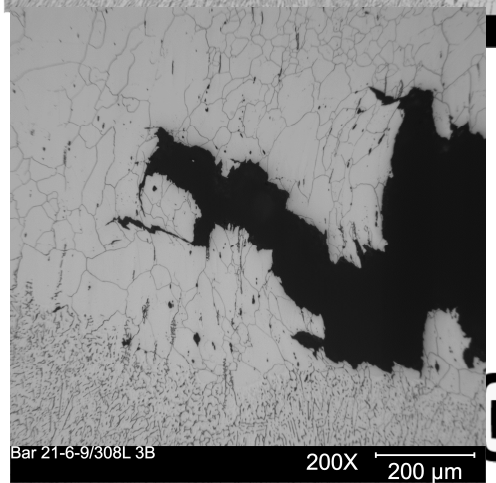
Annealed 21-6-9/308L HAZ Fracture Test



Sample	J_{QH} (kJ/m^2)	K_{JQH} (MPa m$^{1/2}$)
1B	275	241
2B	427	300
4B	340	268
5B	332	365
6B	467	314





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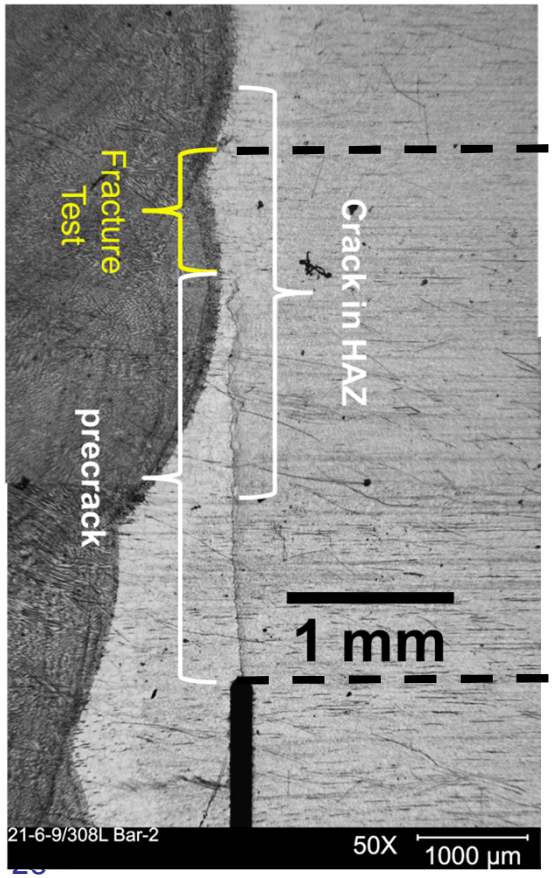
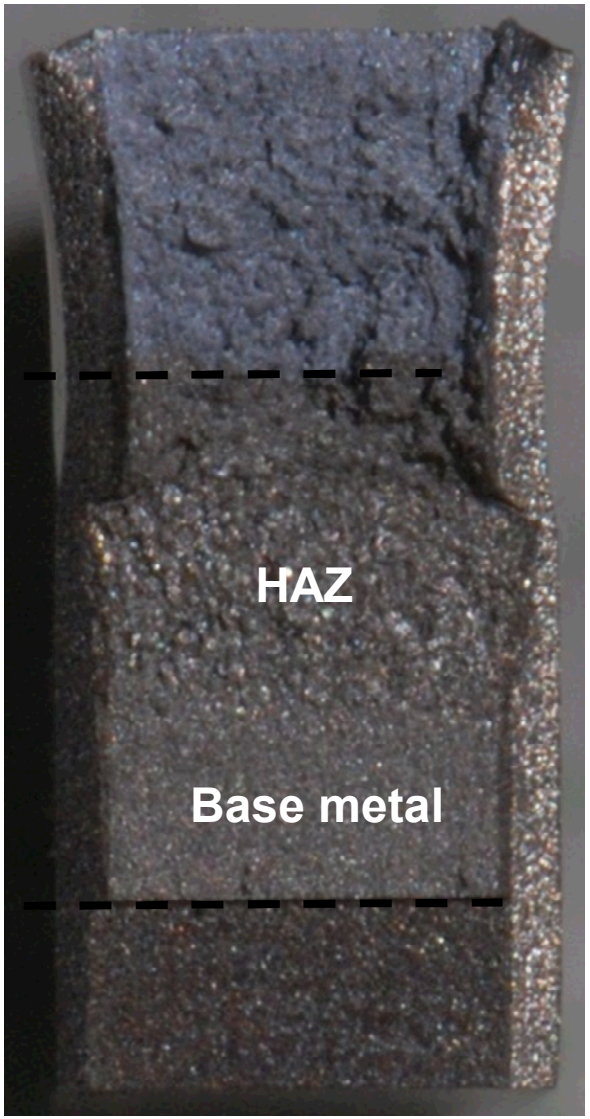
‘Single J’ Geometry Increases Probability of Testing HAZ

Image captured after precrack



Fracture Surface



- Precrack in HAZ is visibly different than in base metal
  - Grain size difference
    - BM ~ 12 µm
    - HAZ ~ 50 µm

Entirety of fracture test appears to be in HAZ

Sandia National Laboratories

Conclusions

- **3-pt bend testing was performed on thermally H_2 precharged forged 304L/308L and 21-6-9/308L GTAW specimens**

- **Fusion zone fracture toughness of 304L/308L and 21-6-9/308L was degraded by hydrogen**
  - K_{JQH} = 215 MPa $m^{1/2}$ for 21-6-9 / 308L
  - K_{JQH} = 177 MPa $m^{1/2}$ for 304L / 308L
- **Crack propagation was predominantly along δ-ferrite dendrites**

- **Heat Affected Zone (HAZ) fracture toughness variability was attributed to inconsistency in terminating precrack in HAZ**
  - **Current weld joint geometry (single-U) not effective at HAZ testing**

- **Modified 'Single-J' geometry provides greater probability of terminating precrack in HAZ**
  - **Preliminary testing on annealed 21-6-9 / 308L demonstrates higher probability in testing HAZ**