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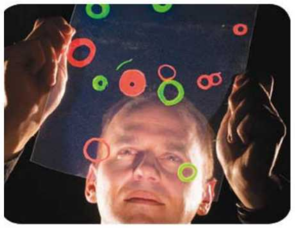

EFFECT OF HYDROGEN ON TENSILE STRENGTH AND DUCTILITY OF MULTIPASS 304L / 308L AUSTENITIC STAINLESS STEEL WELDS

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Motivation

- Quantifying hydrogen effects in austenitic stainless steel welds:
  - Varying amounts of ferrite depending on weld chemistry
  - Presence of ferrite exacerbates hydrogen embrittlement
- Examining differences in mechanical properties with position within larger multi-pass welds
  - Larger joint geometries can require multiple weld passes
  - Results in reheating of previously deposited material, which can drive phase transformations (e.g. ferrite → austenite, ferrite → sigma phase)
- *How do tensile properties in multi-pass austenitic stainless steel welds vary with position and with hydrogen exposure?*

Materials

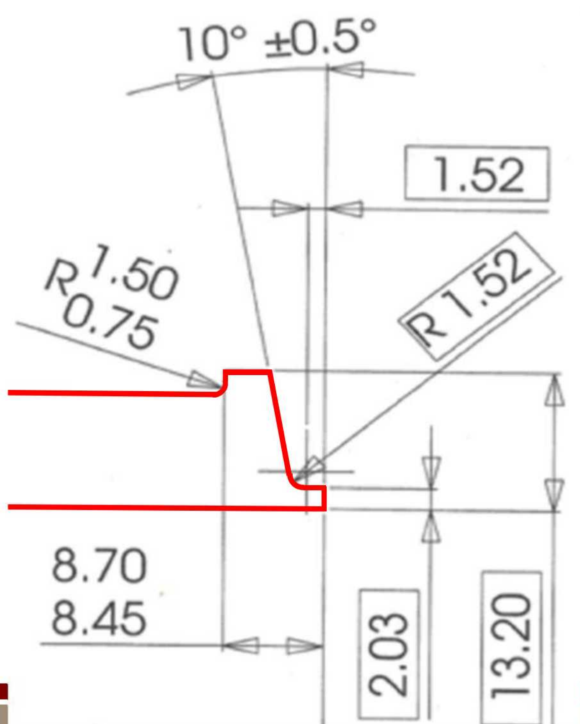
- 304L base material, as 1.25” thick cross-rolled plate
- 308L weld wire, 1.14 mm diameter

Material	Fe	Cr	Ni	Mn	Si	Mo	Co	C	N	P	S
Base metal	Bal.	19.25	10.25	1.7	0.67	0.079	0.064	0.021	0.019	0.029	0.0011
Weld wire	Bal.	**20.5**	10.3	1.56	0.50	< 0.010	0.068	0.028	0.055	0.006	0.012

- Higher Cr content in weld wire to promote primary ferrite solidification, minimize solidification cracking
  - Results in ~ 5 vol% δ-ferrite remaining in weld after cooling to room temperature
  - Presence of δ-ferrite leads to greater embrittlement by hydrogen

Weld geometry, parameters

- Gas tungsten arc (GTA, or TIG) weld with 6 passes
- Plate geometry: 20.4 cm x 6.2 cm x 1.1 cm
  - J-groove joint geometry (mm)



Weld pass	Voltage (V)	Current (A)	Travel speed (mm/s)	Wire feed rate (mm/s)
1	9.8	195	1.27	14.8
2	9.8	200	1.27	10.6
3	9.5	210	1.27	13.1
4	9.5	220	1.27	13.1
5	9.5	205	1.27	14.0
6	9.5	195	1.27	10.6

Weld microstructure: transverse mosaic

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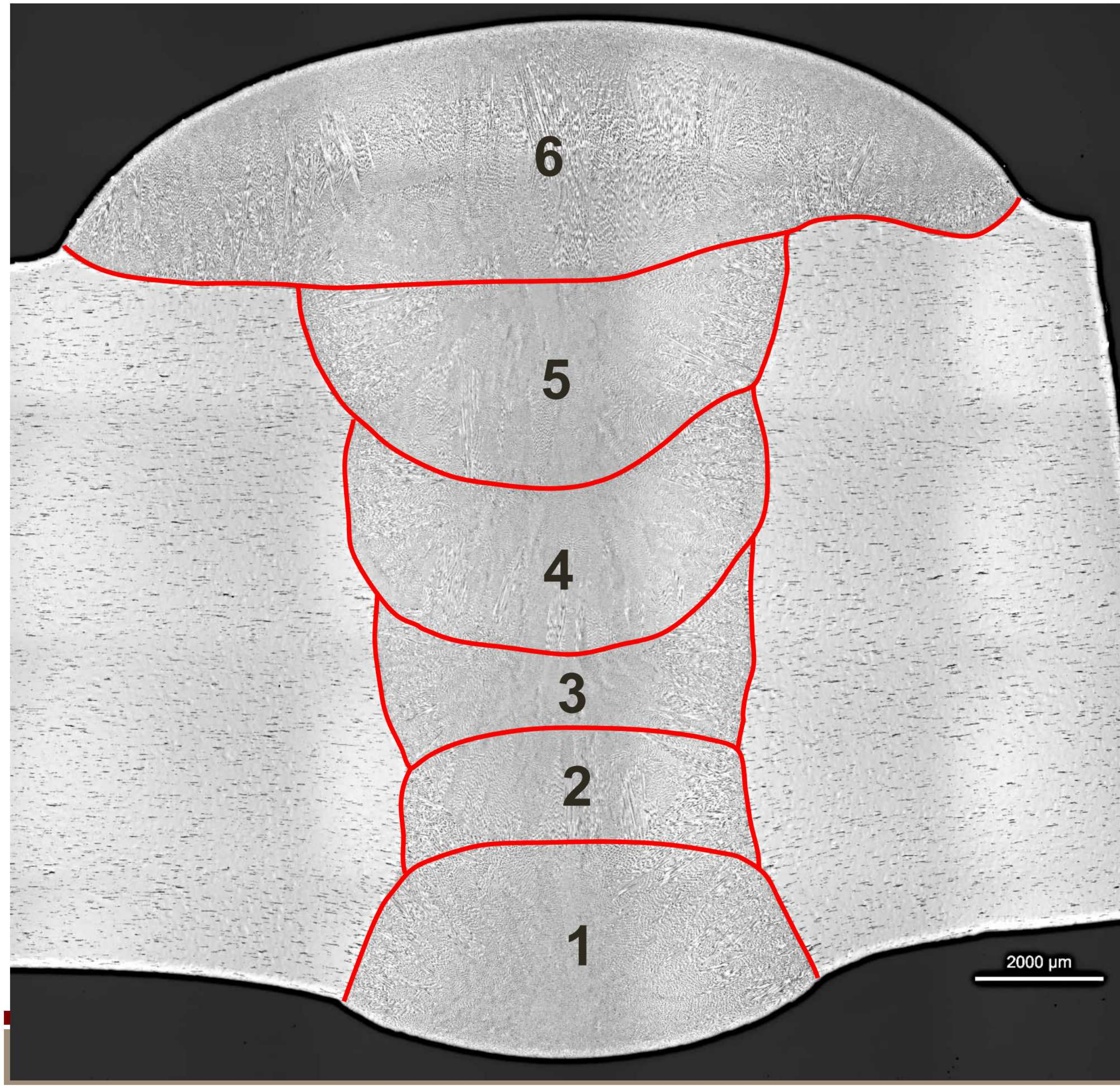
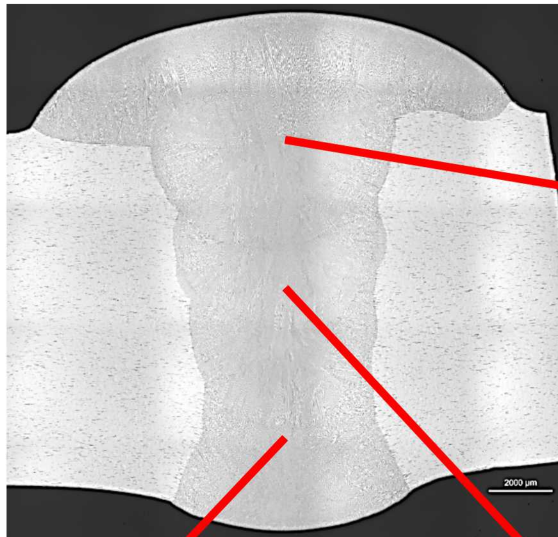
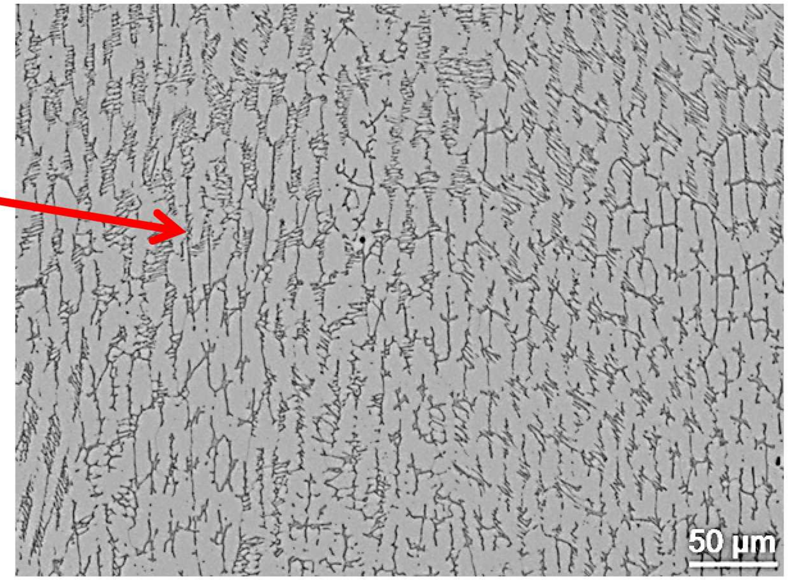


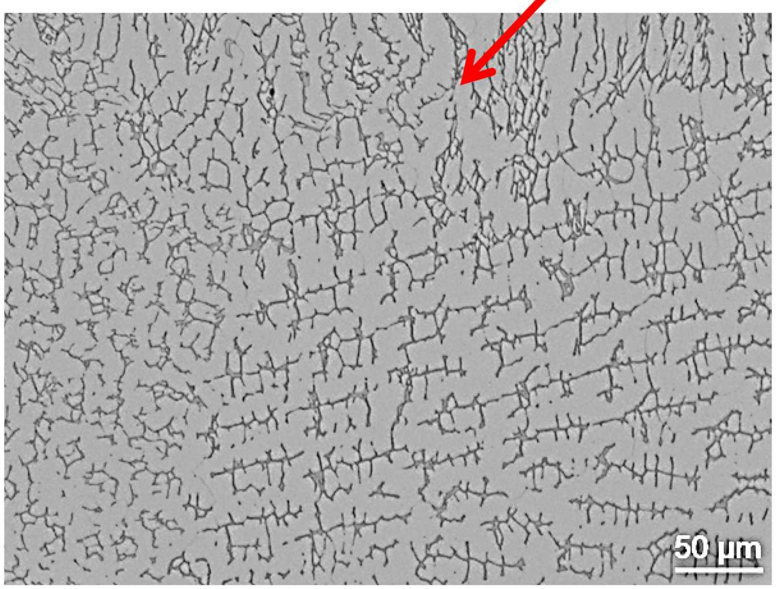
- Good drop-through with complete obliteration of the weld joint
- Six weld passes are clearly evident
- Typical austenitic stainless weld microstructure, containing residual δ-ferrite (FN ~ 4)

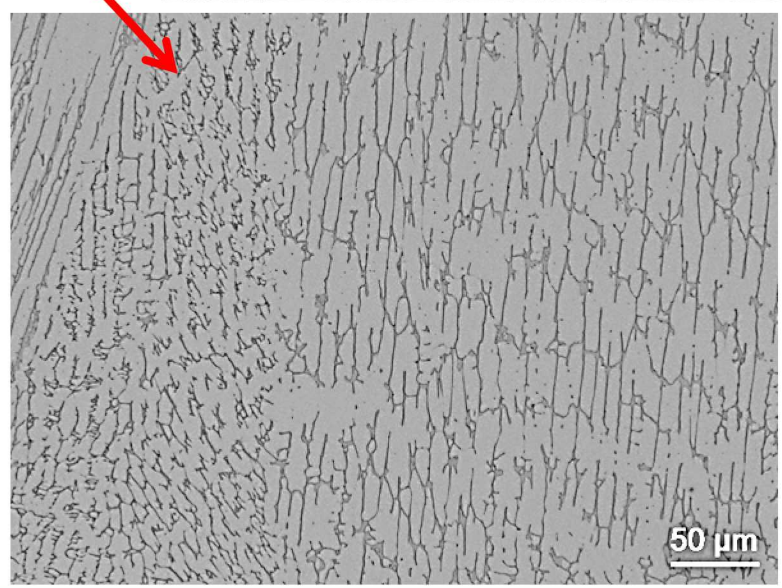
Weld microstructure detail: transverse

- Skeletal δ-ferrite morphology at all positions, but with some minor orientation differences









Weld microstructure detail: longitudinal

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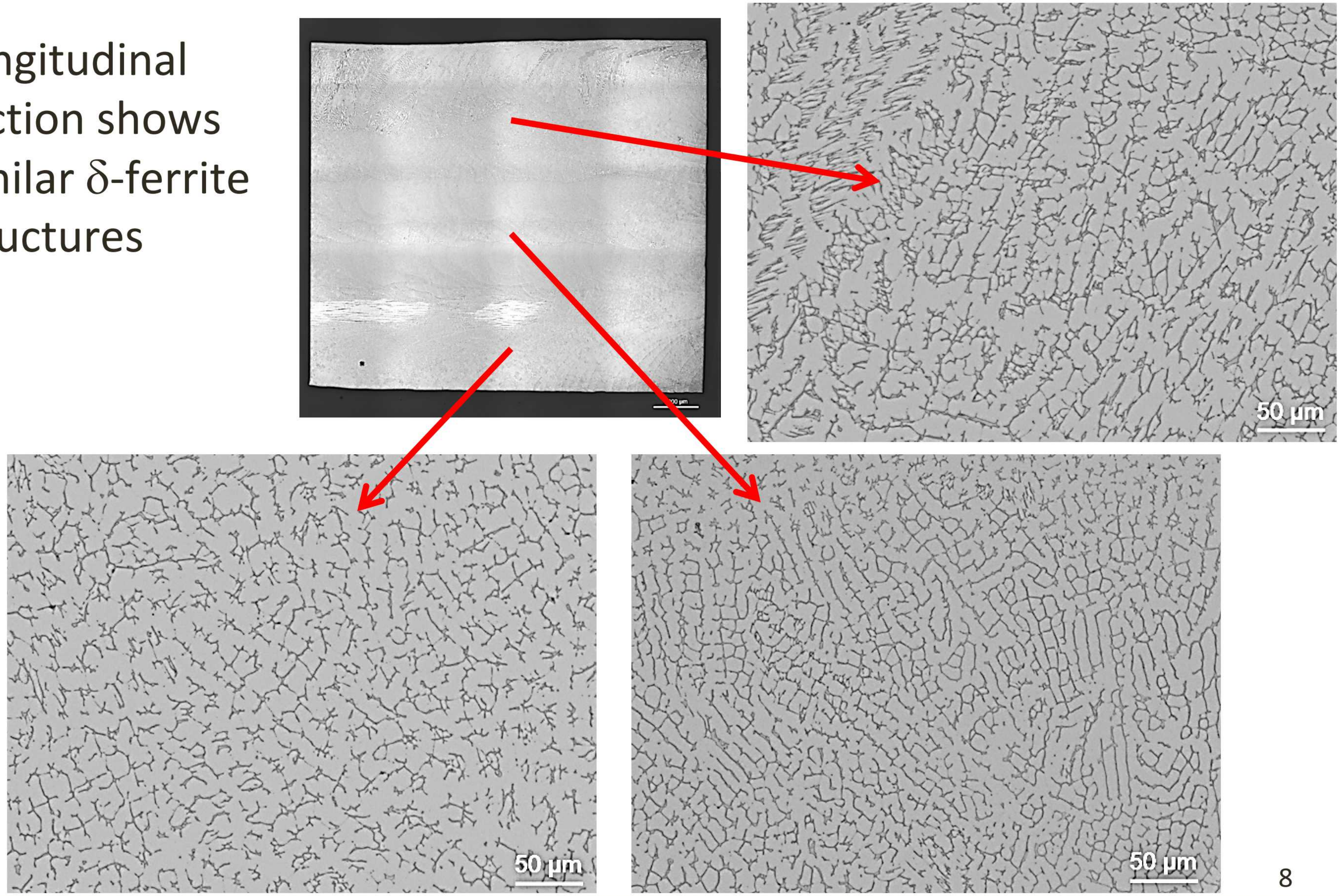
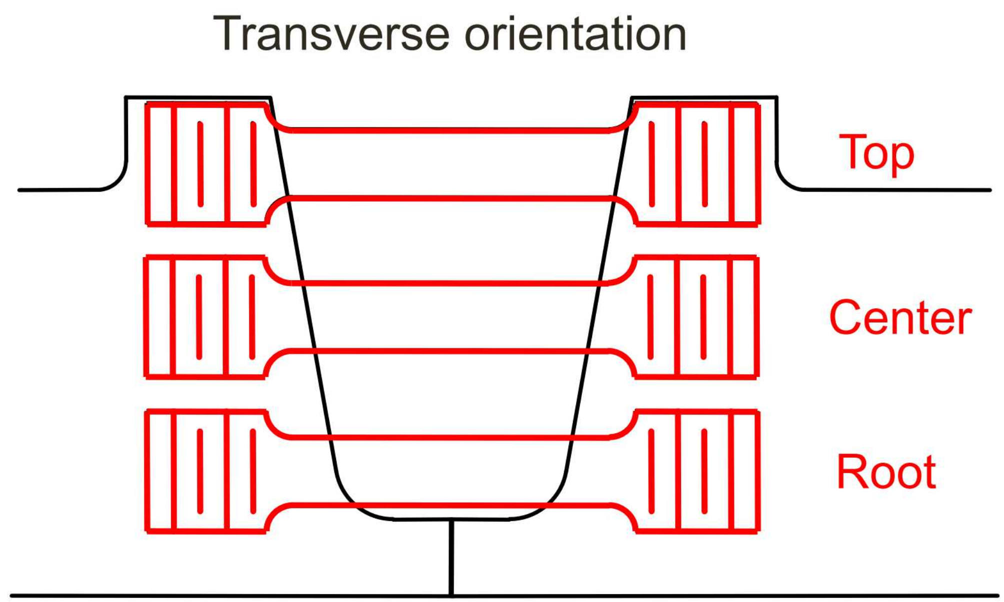
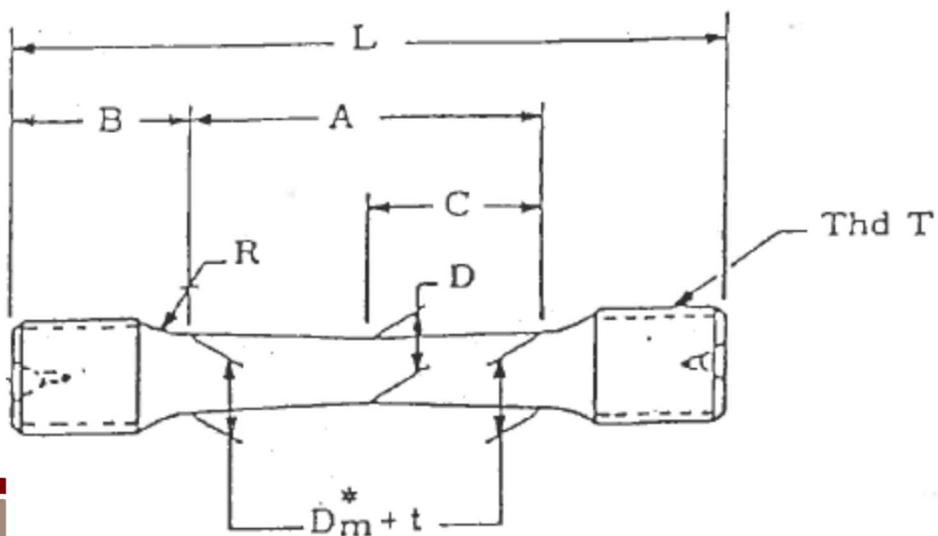
- Longitudinal section shows similar δ-ferrite structures



Tensile specimen details

- Sub-sized tensile specimens (16.15 mm length, 1.80 mm gage diameter) taken at three different positions
- Two orientations:
  - Transverse: gage section is almost 100% weld
  - Longitudinal: 100% weld



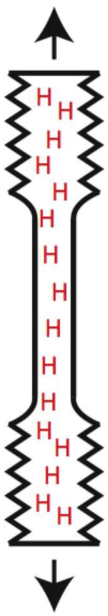


Dimensions (inches)

A	.33	± .0005
B	.153	± .003
C	.165	± .0005
D	.071	± .0005
L	.636	± .003
R	.028	- (or blended w/smooth curve)
T	5-40-UNC-2A	
t	0.00	
D_m	Same as D	

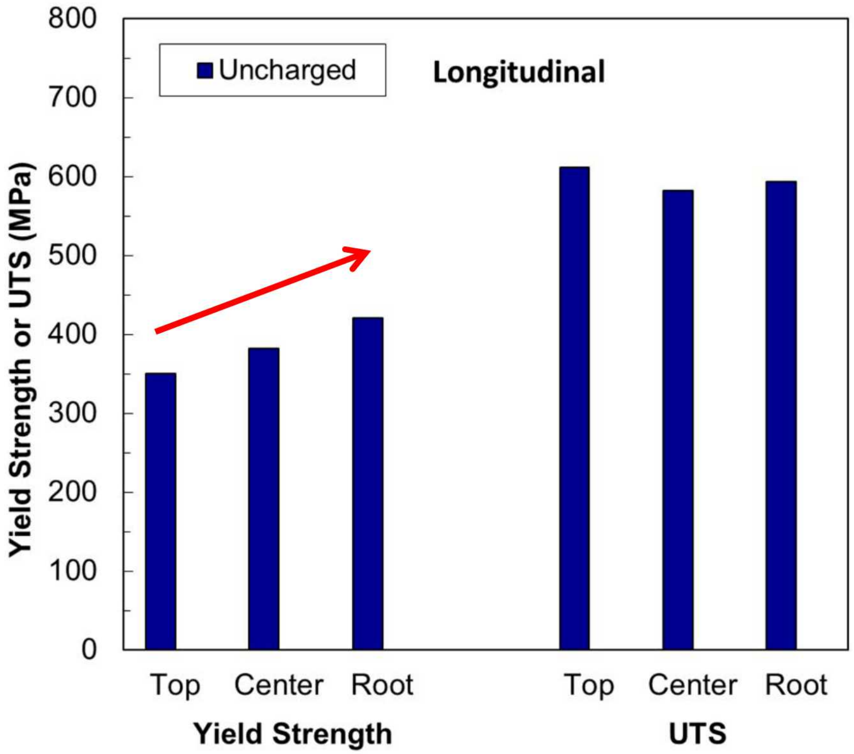
Tensile testing

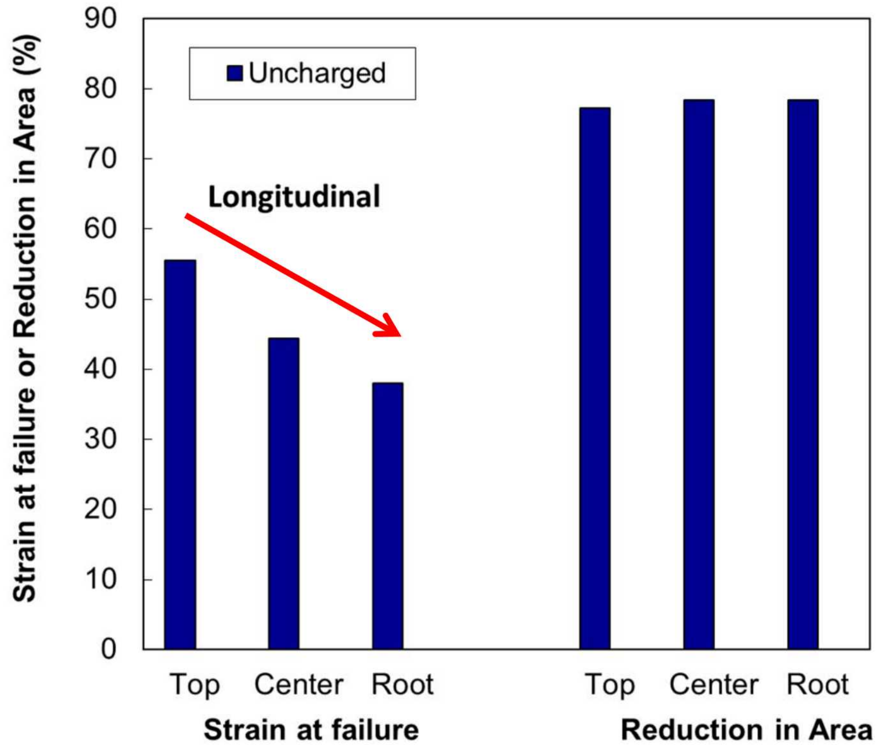
- Testing details:
  - All testing performed in air
  - Initial strain rate: 7.4×10^{-4}/s
  - Reported values are averages of duplicate tests
  - All specimens failed in weld
  - Half of the specimens were thermally precharged with H_2
    - 300ºC, 138 MPa (20,000 psi) pressure, 99.9999% purity, two week duration
  - Resulted in saturation of hydrogen at 7700 appm (140 wppm) concentration



Orientation	Condition	Position	S_y (MPa)	S_u (MPa)	El_u (%)	El_t (%)	RA (%)	RRA (%)
Longitudinal	As welded	Top	350	612	44	56	77	
		Center	382	583	31	44	78	
		Root	421	593	27	38	78	
	7700 appm H_2	Top	438	672	26	28	40	51
		Center	489	669	25	28	34	43
		Root	502	651	18	21	28	36
Transverse	As welded	Top	357	587	40	54	82	
		Center	390	590	29	43	80	
		Root	404	572	27	38	83	
	7700 appm H_2	Top	429	646	30	33	38	47
		Center	470	653	23	24	34	42
		Root	472	627	21	24	41	49

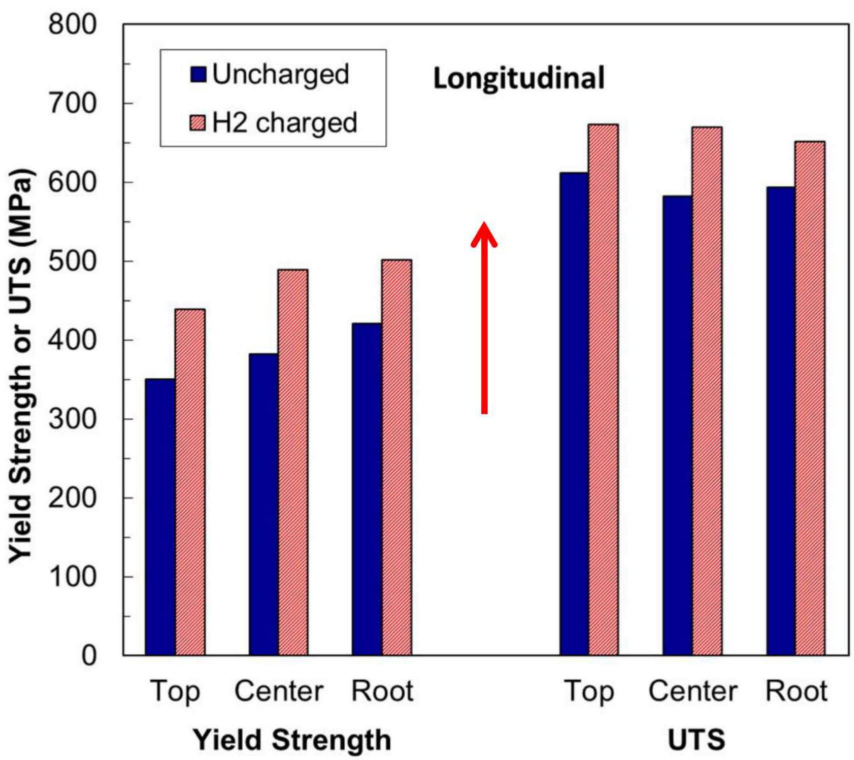
Longitudinal tensile properties

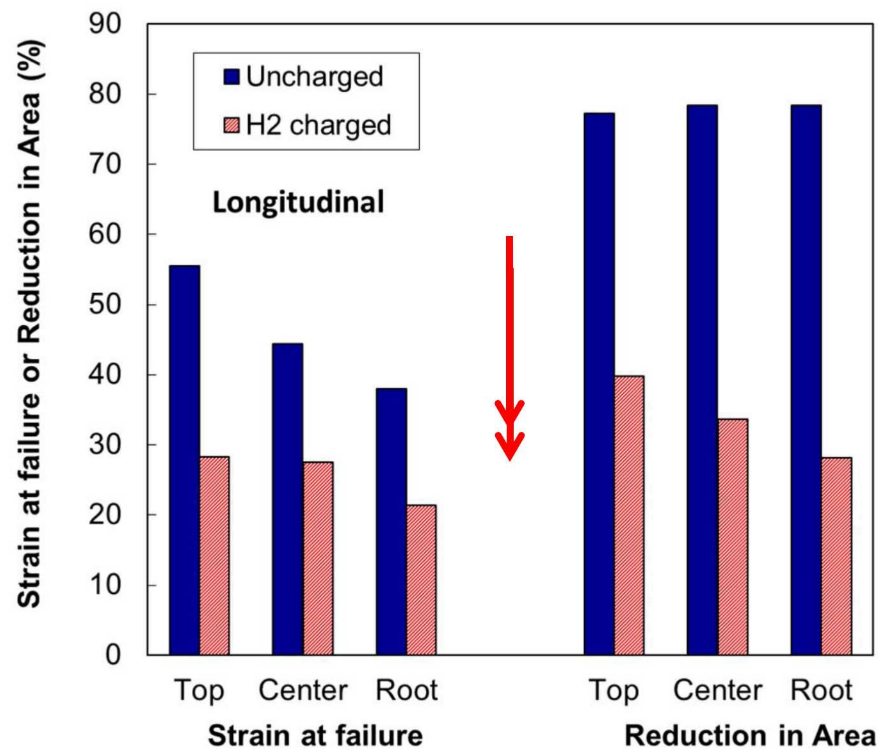




- Yield strength ***increases ~ 20%*** from top to root of weld
- Strain at failure ***decreases ~ 30%*** from top to root
- Ultimate tensile strength and RA remain roughly constant

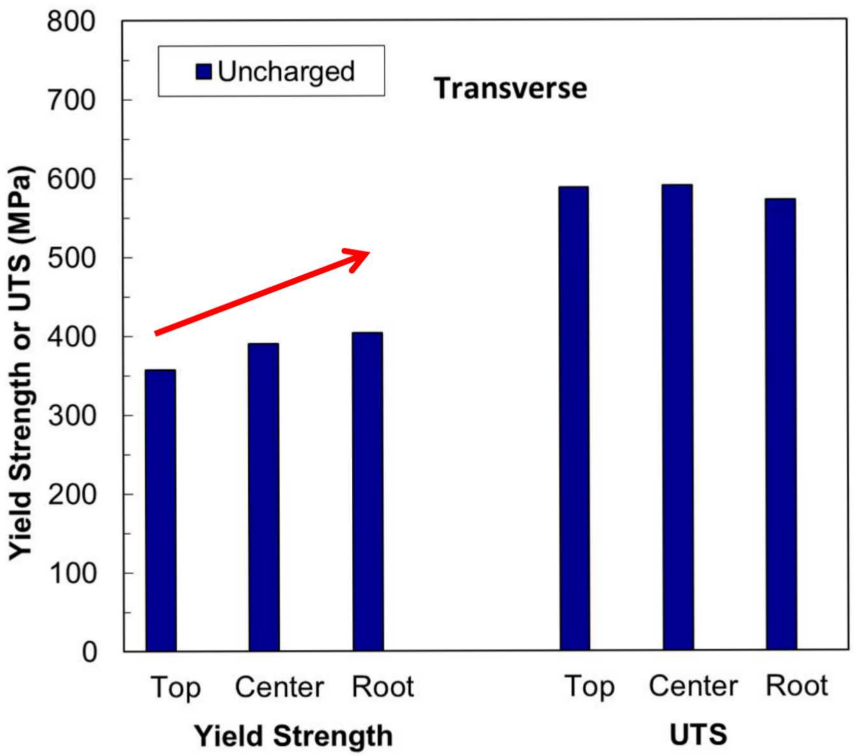
Longitudinal tensile properties

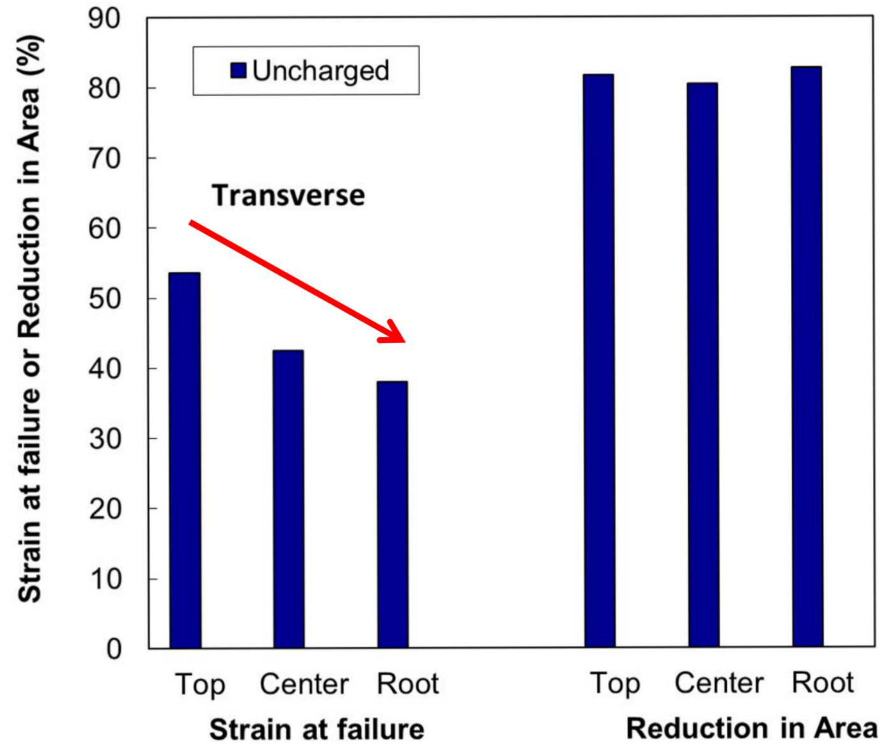




- 7700 appm H ***increases strength*** (YS ~ 20%, UTS ~ 10%)
- 7700 appm H ***decreases ductility*** (ε_f ~ 45%, **RA ~ 60%**)

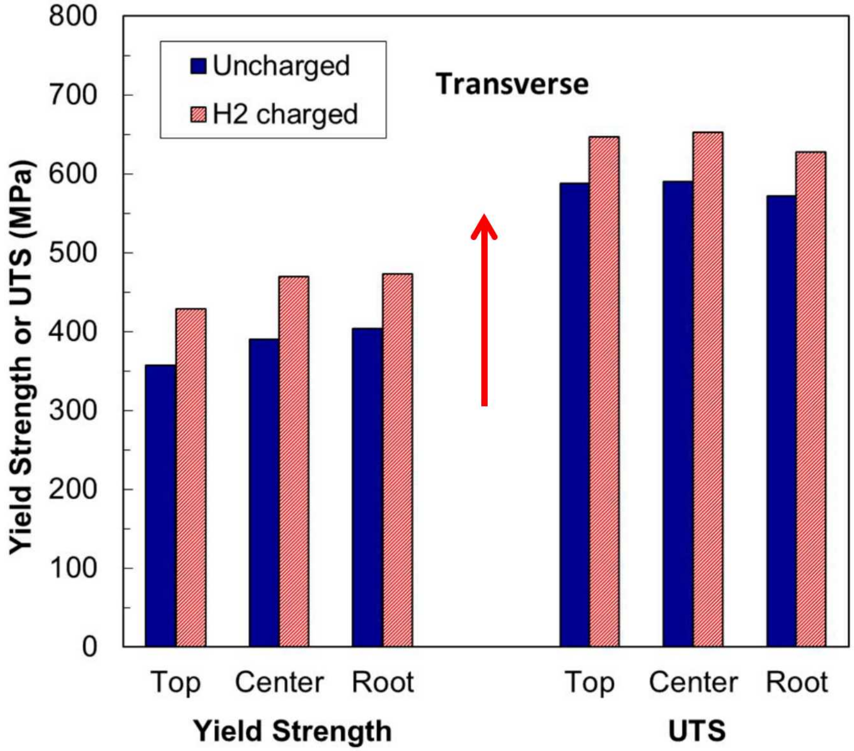
Transverse tensile properties

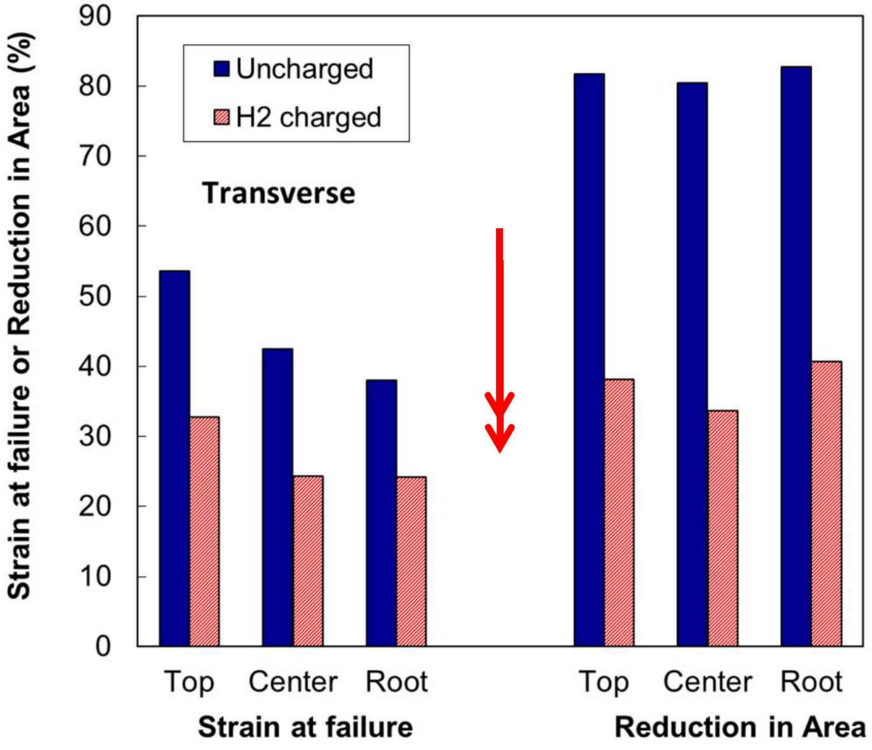




- Similar trends for transverse specimens:
  - Yield strength ↑, failure strain ↓, moving from top to root of weld
  - Ultimate strength and RA constant with position

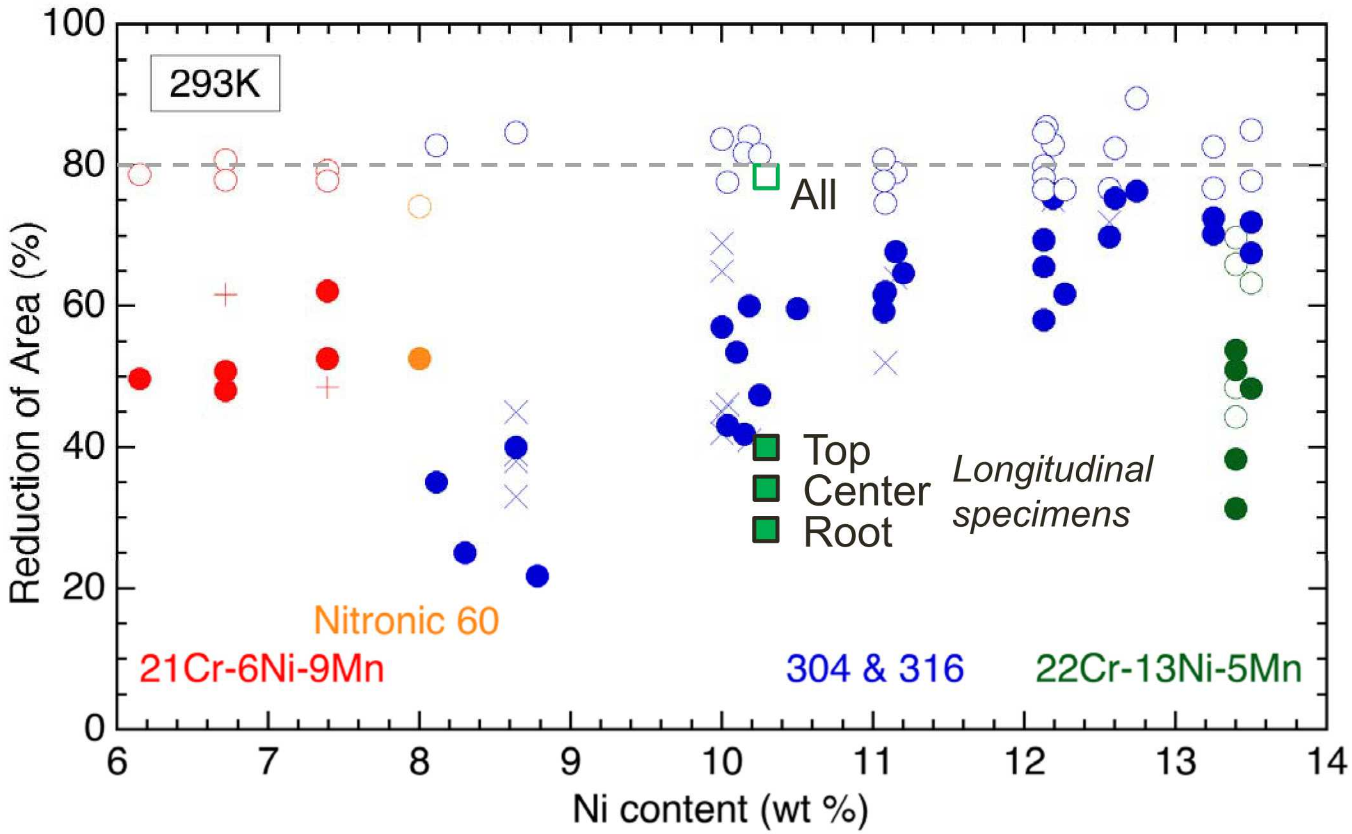
Transverse tensile properties





- Same effect of hydrogen in transverse orientation:
  - H ***increases strength*** (YS ~ 20%, UTS ~ 10%)
  - H ***decreases ductility*** (ε_f ~ 40%, **RA ~ 55%**)

Welds w/ H_2 have reduced ductility



Open symbols: Air/inert

Closed symbols: H-precharged

Other symbols: Tests in H_2

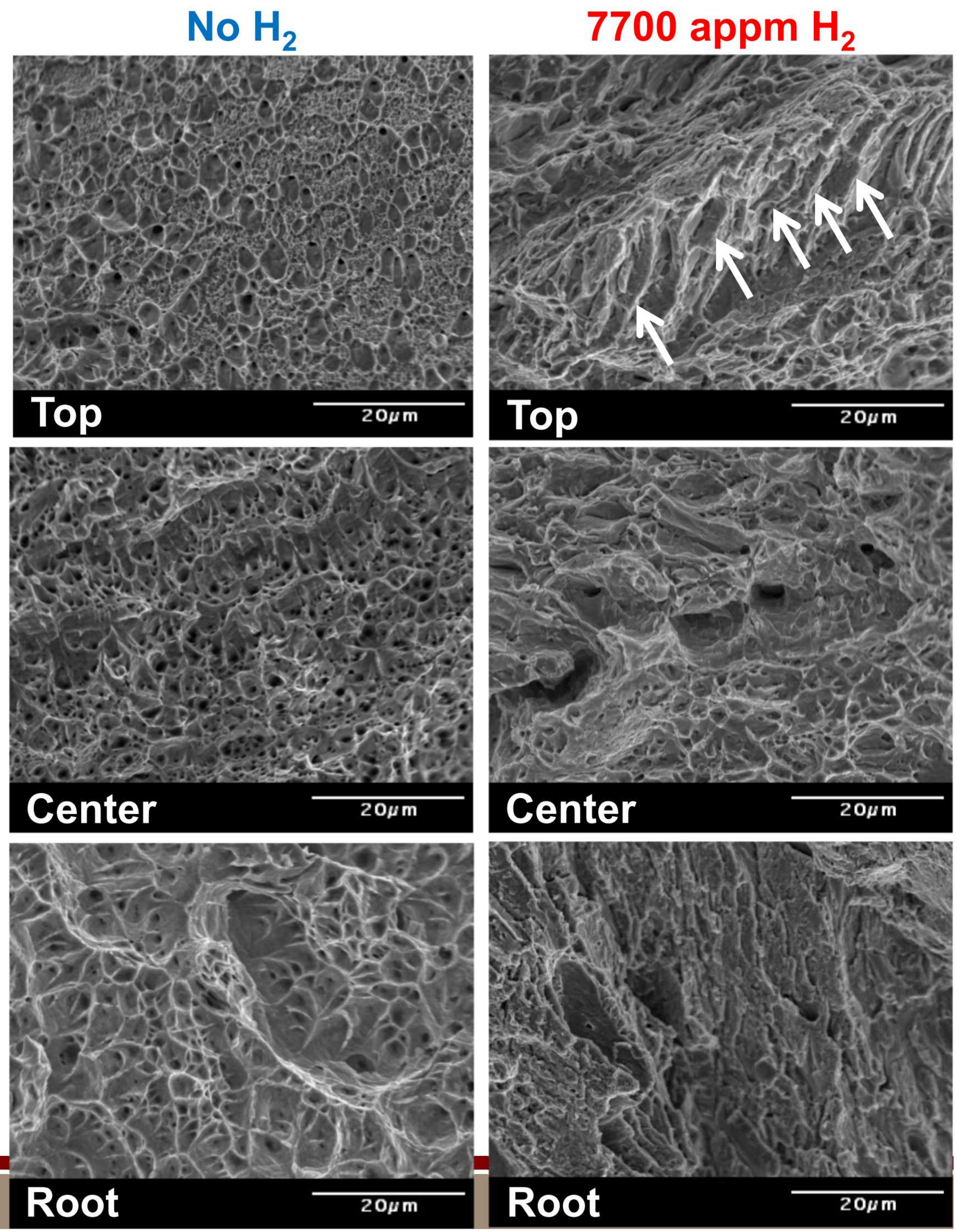
This study

Ni content is a particularly important materials variable for understanding hydrogen-assisted fracture

Weld RA is lower than wrought material at the same Ni content: effect of δ-ferrite, compositional gradients?

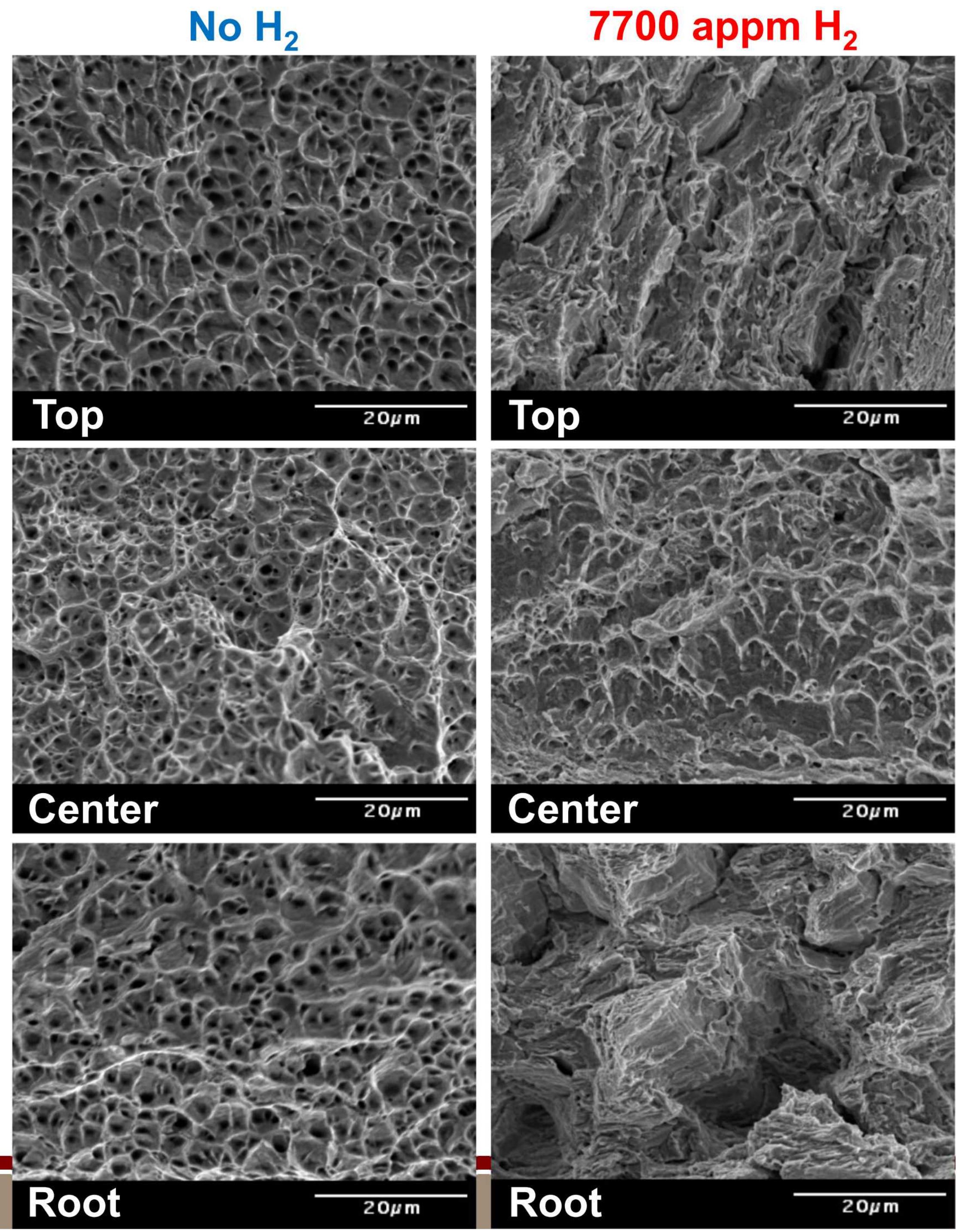
Longitudinal fracture surfaces

- Without hydrogen:
  - Microvoid growth and coalescence
  - Some variation in dimple size / morphology with position
- With hydrogen:
  - Clear change with hydrogen but still primarily ductile, with elongated dimples (arrows)

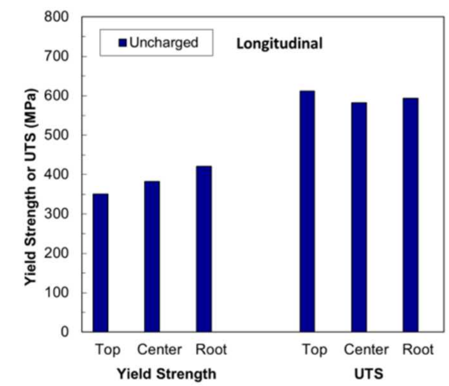


Transverse fracture surfaces

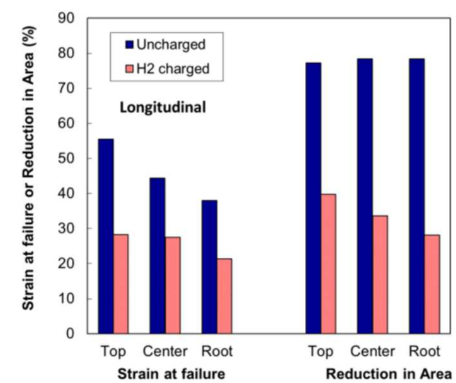
- Without hydrogen:
  - Microvoid growth and coalescence
  - More uniform dimple size and morphology
- With hydrogen:
  - Primarily ductile behavior at Top and Center
  - Root location displays more transgranular nature with some secondary cracking



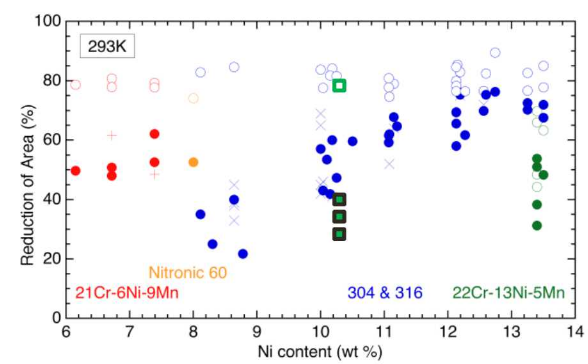
Conclusions



- There is consistent variation of tensile strength and ductility with position
  - Strength increases, ductility decreases, moving from top to root of weld



- Addition of 7700 appm hydrogen increases strength and sharply decreases ductility
  - Decreases in reduction of area as high as 60%



- Microstructure plays a key role in behavior of these welds, particularly in the presence of H_2
  - Ferrite content / morphology, and potential compositional variations