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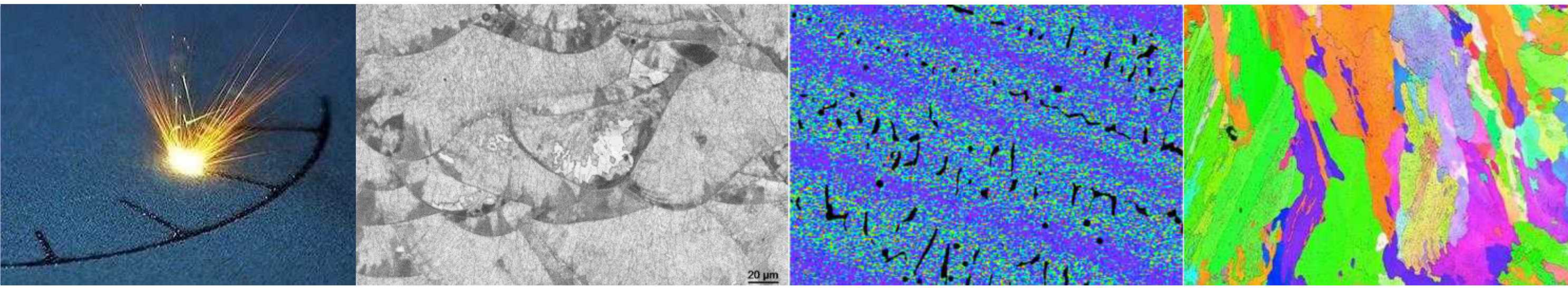

Weld Cracking Susceptibility of Materials Additively Manufactured by a Laser Powder Bed Process

Dan Tung and Jeff Rodelas

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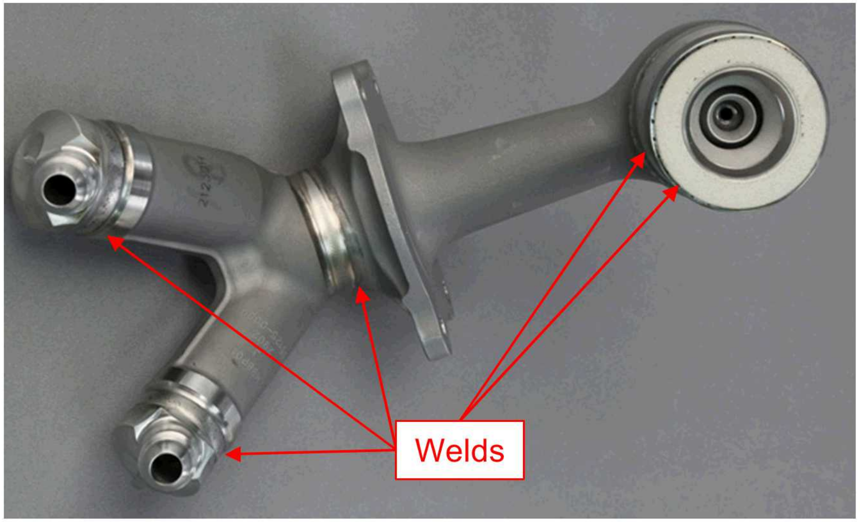
Why Examine the Weldability of Metal AM Components?

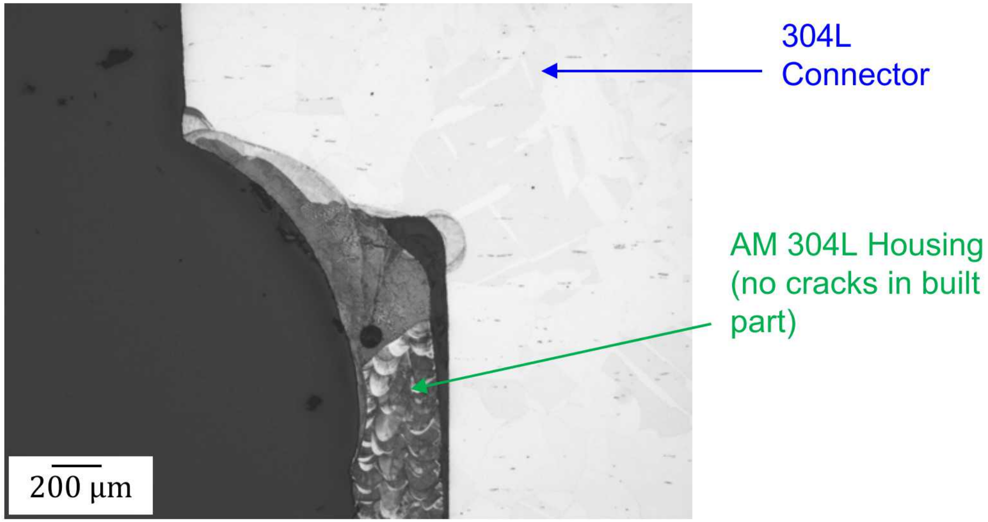
- Geometric freedom afforded by AM can reduce the need for welding in component designs; however, some designs will still require welding for final assembly
- Weldability considerations for metal AM components need to be addressed

General Electric LEAP Fuel Nozzle



Fuel/air fittings and swirler require welding to AM mid-section

Example:
AM 304L Housing Laser Welded to 304L Connector



Why Examine the Weldability of Metal
A

- Ge
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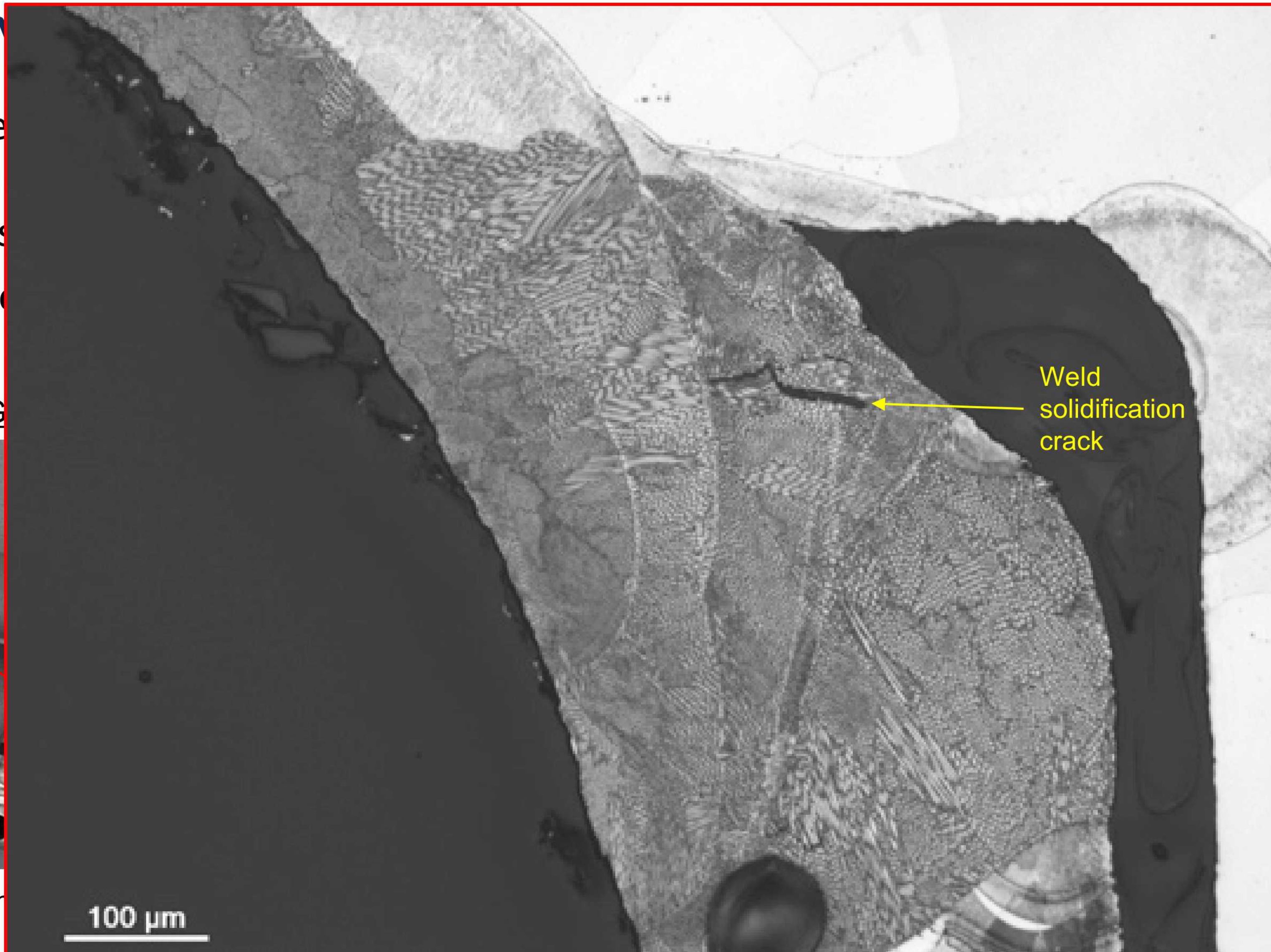
Fuel/air fittir

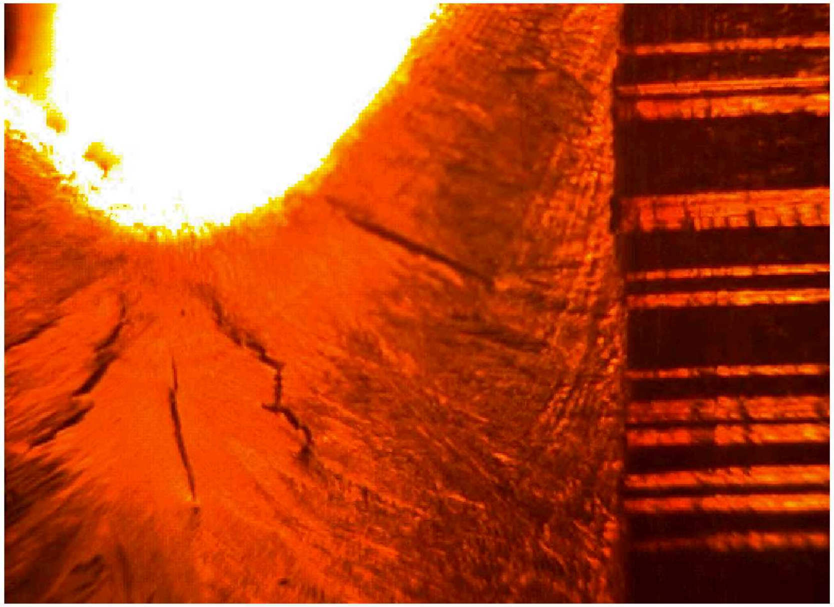


hector

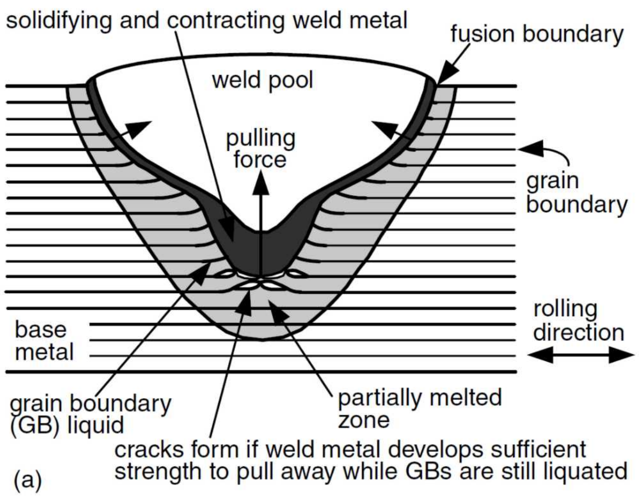
Housing
ks in built

Elevated Temperature Weld Cracking

- Welds commonly crack when shrinkage stresses/strains exceed material strength/ductility at elevated temperatures
  - Many mechanisms result in decreased strength/ductility
- "Hot" cracking occurs at temperatures where liquid is present
  - Solidification Cracking refers to bulk failure of the weld fusion zone
  - Liquation Cracking refers to liquid presence at grain boundaries in the partially-melted region of the Heat Affected Zone (HAZ)
    - Local composition variations may result in solidus temperatures lower than that of the surrounding material
- "Warm" cracking occurs at elevated temperatures where liquid is not present ($\approx 0.5\ T_m$)
  - Ductility Dip Cracking occurs within an elevated temperature range with reduced ductility
- Many other weld cracking forms exist



Solidification cracks, courtesy C. Robino



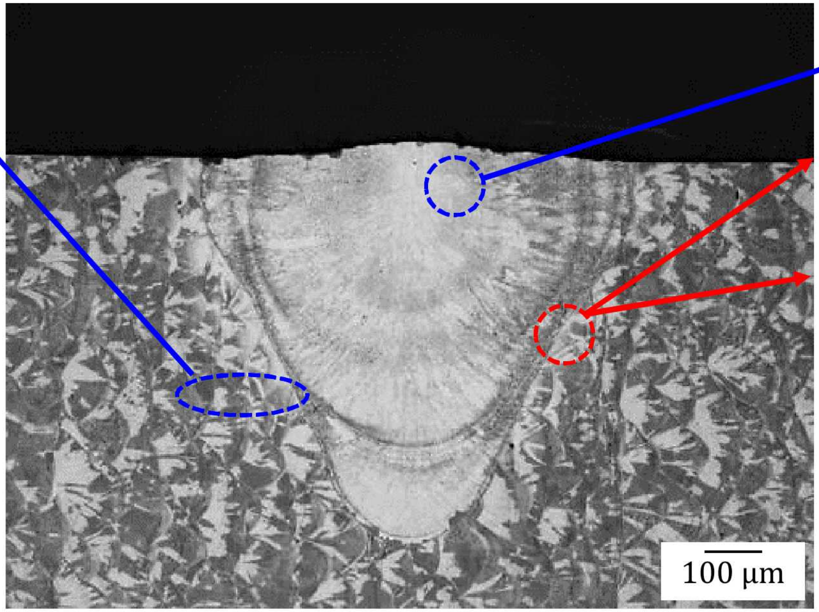
Schematic of HAZ liquation cracking from S. Kou, *Welding Metallurgy, 2003*

Fabrication Weldability Considerations

- Solidification structure of AM parent material introduces some weldability concerns generally reserved for multi-pass welds and rewelded samples
- Multiple testing techniques utilized to examine general weldability of laser powder bed additively manufactured 304L parent materials

Heat Affected Zone Weldability Concerns

- Liquation Cracking
- Ductility Dip Cracking
- Sub-Solidus HAZ Embrittlement
- Liquid Metal Embrittlement
- Reheat/Strain-Age Cracking
- HAZ Sensitization
- Lamellar Cracking



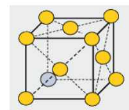
Weld Metal Weldability Concerns

- Solidification cracking
- Weld Metal Liquation†
- WM Ductility Dip Cracking†
- Hydrogen-Induced Cracking

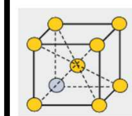
† Multi-Pass Welds, Relevant when welding over solidified additive structure

Alloy Chemistry and Microstructure are Critical Variables in Determining Weld Solidification Crack Susceptibility

Primary Austenite

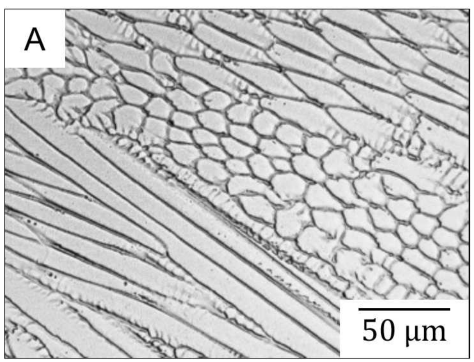


Primary Ferrite

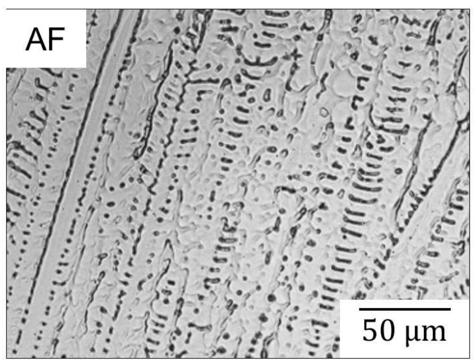


- <u>Increased solidification cracking concern</u>
  - Less tolerant of impurities (namely phosphorus + sulfur). Requires 'clean' alloys to preclude cracking.
  - Less tolerant of restraint

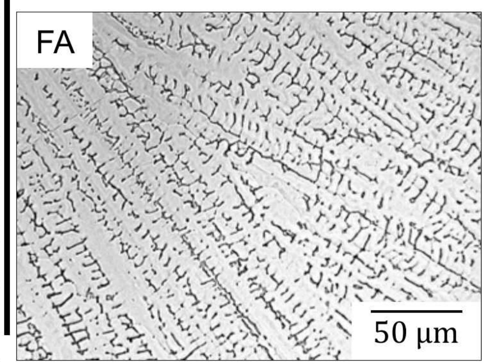
- <u>Desired solidification mode</u>
  - Increased resistance to solidification cracking
  - More tolerant of restraint and impurity elements



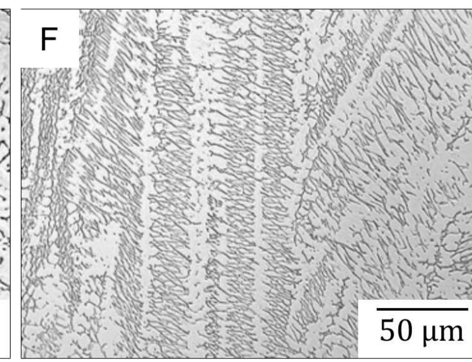
L → L + **A** → A



L → L + **A** → L + A + $(A+F)_{eu.}$ → A + $F_{eu.}$



L → L + **F** → L + F + $(A+F)_{eu./per.}$ → A + F



L → L + **F** → F → A + F

Austenite Promoters

<u>Ni</u>, C, N, Mn, Cu

Alloy Chemistry: Increasing Cr_{eq}/Ni_{eq}

Ferrite Promoters

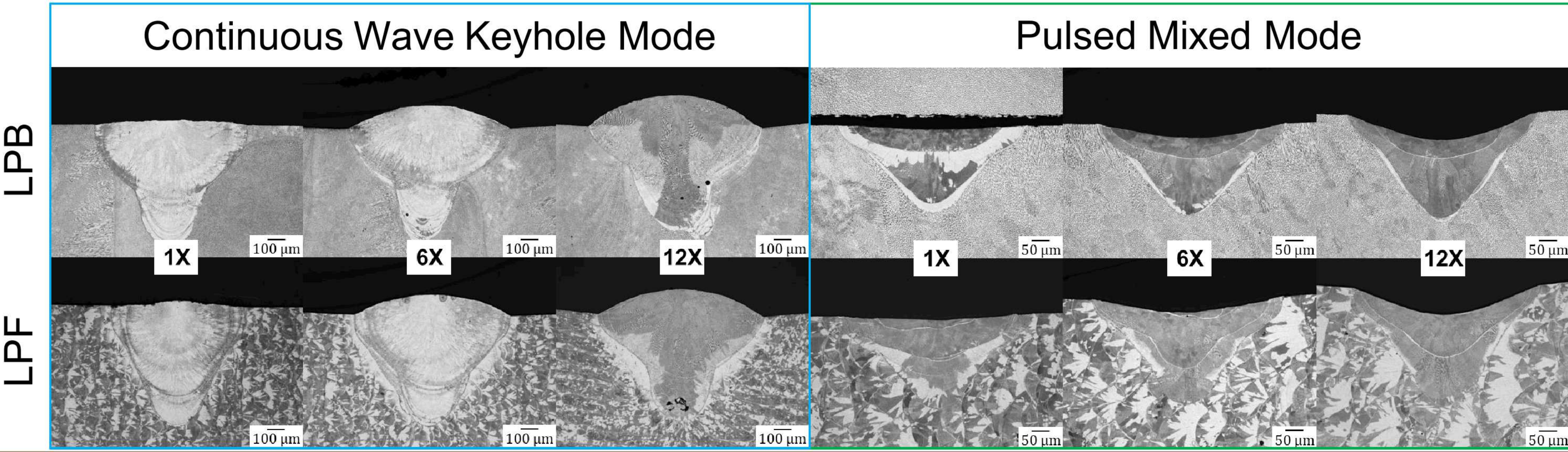
<u>Cr</u>, Mo, Si, Nb, Ti

Micrographs from: J.C. Lippold, D.J. Kotecki, *Welding Metallurgy and Weldability of Stainless Steels*, Wiley-Interscience, 2005.

Overall Composition and Solidification

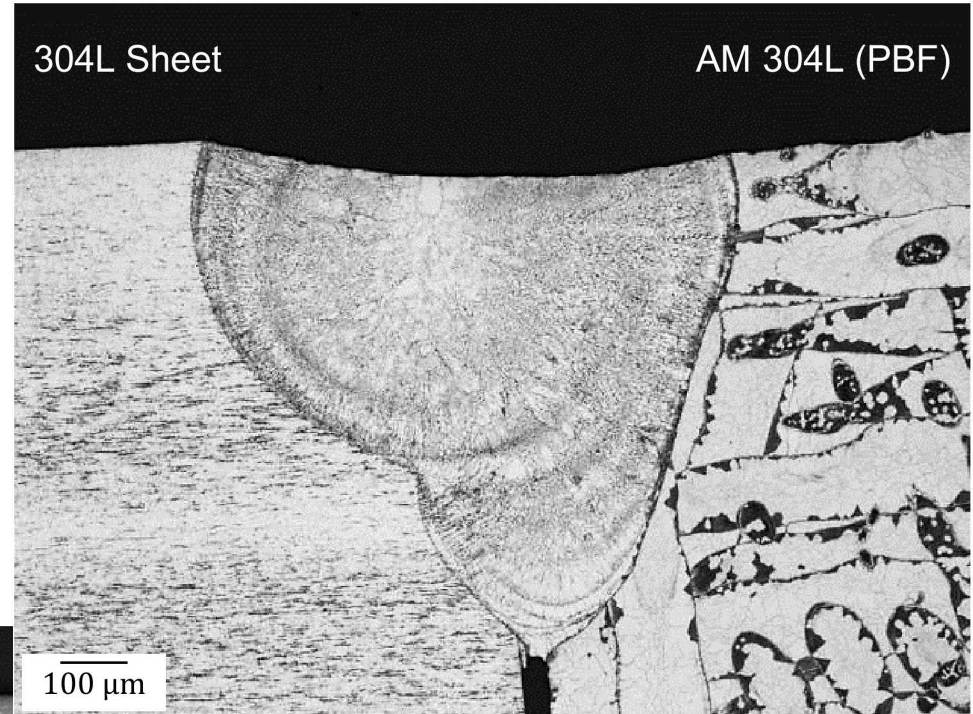
- As-solidified composition (WDS data, carbon omitted)
  - Changes with elemental vaporization during AM and welding
  - Similar starting composition drives similar solidification mode shift during welding
    - Continued elemental vaporization especially during conduction mode rewelding
    - Solidification mode reliant on Cr_{eq}/Ni_{eq}, expected to change similarly between materials

	Fe	Cr	Ni	Mn	S	Si	P
304L Spec	Bal	18-20	8.0-12.0	2.0 Max	0.03 Max	0.75 Max	0.045 Max
AM	69.482	19.145	9.372	1.38	0.005	0.61	0.006
Wrought	71.219	19.145	7.749	1.488	0.001	0.369	0.029



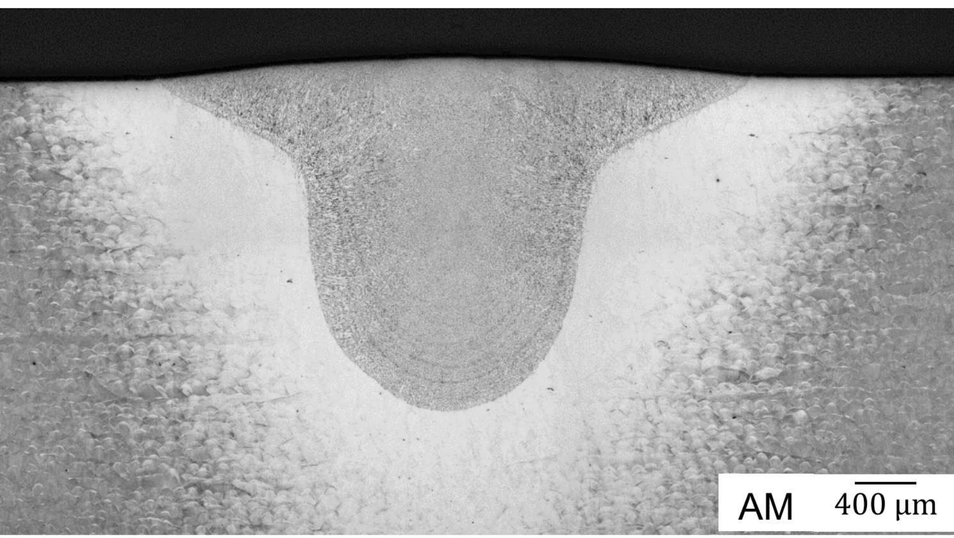
Weld Profile

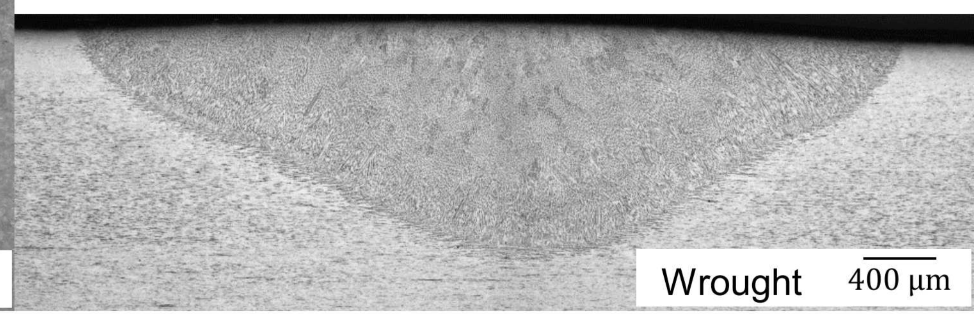
- Composition-related surface tension differences drive differences in weld pool shape
- O increase inherent result of AM
  - Oxidation of powder prior to consolidation
  - Oxidation of each build layer prior to subsequent layer consolidation



0.003 wt.% O
0.001 wt.% S

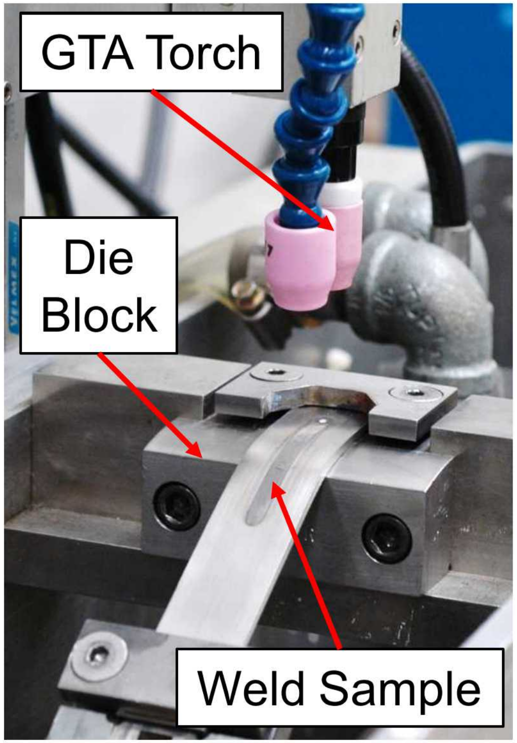
0.036 wt.% O
0.005 wt.% S

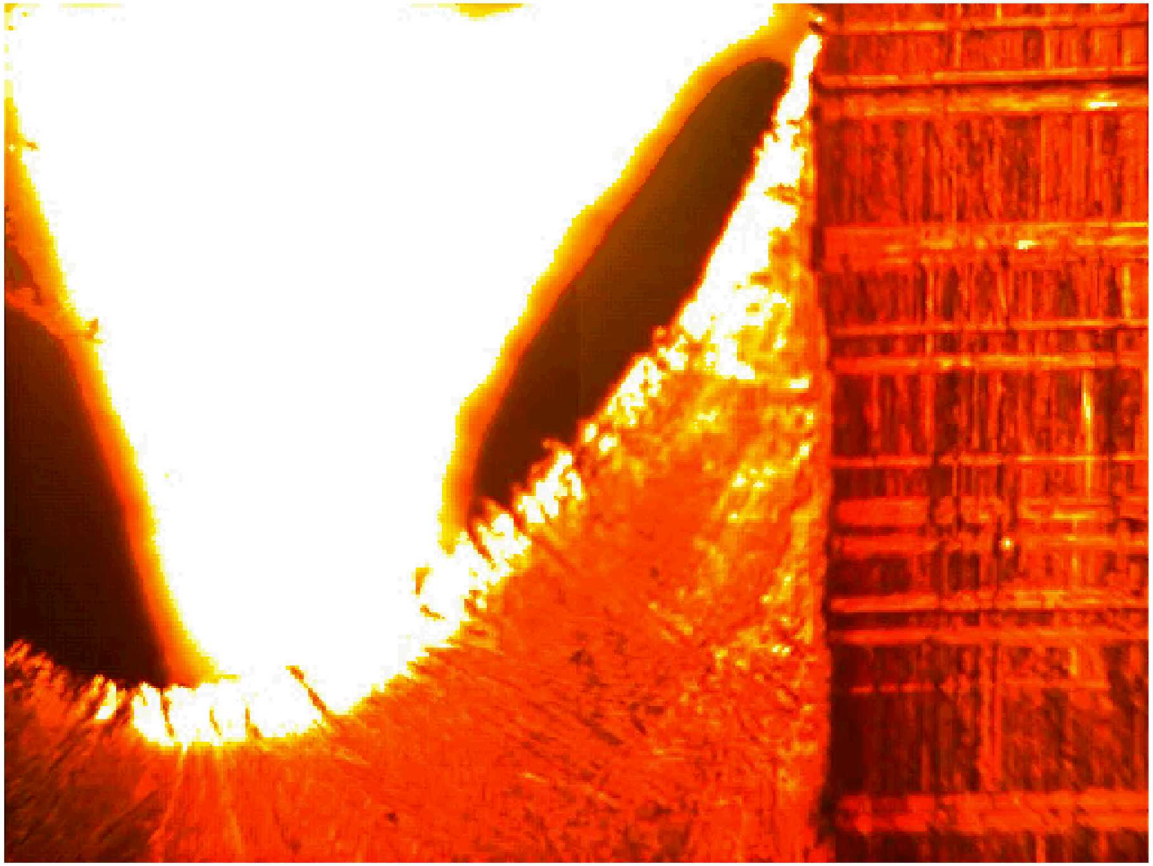




Solidification Cracking: Longitudinal Varestraint Testing

- Longitudinal Varestraint (variable restraint) is an augmented strain weldability test
  - Isolates both Fusion Zone and HAZ hot cracking mechanisms
  - Bend sample around die block **during** welding
  - Die block radius controls amount of strain
  - Crack analysis
  - Relative ranking of cracking susceptibility





Microstructure Comparison

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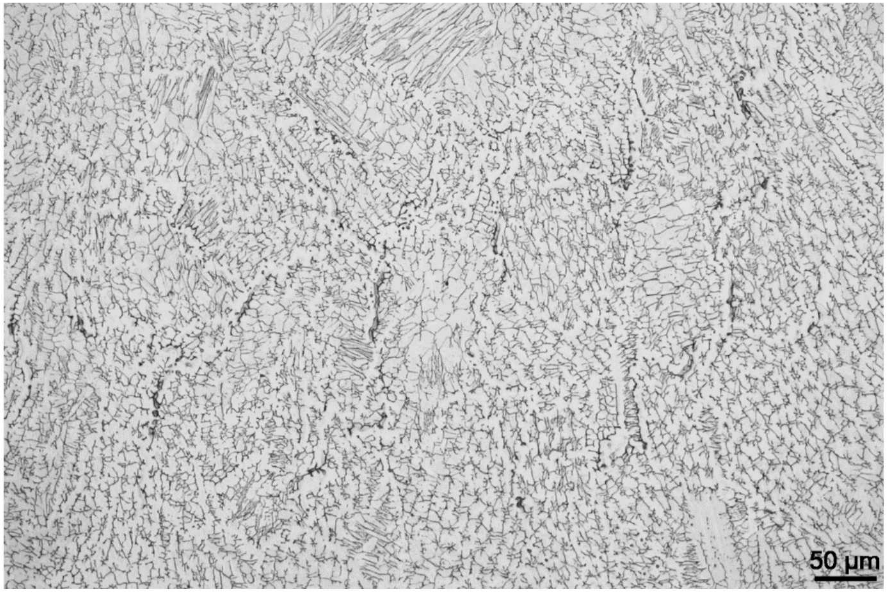
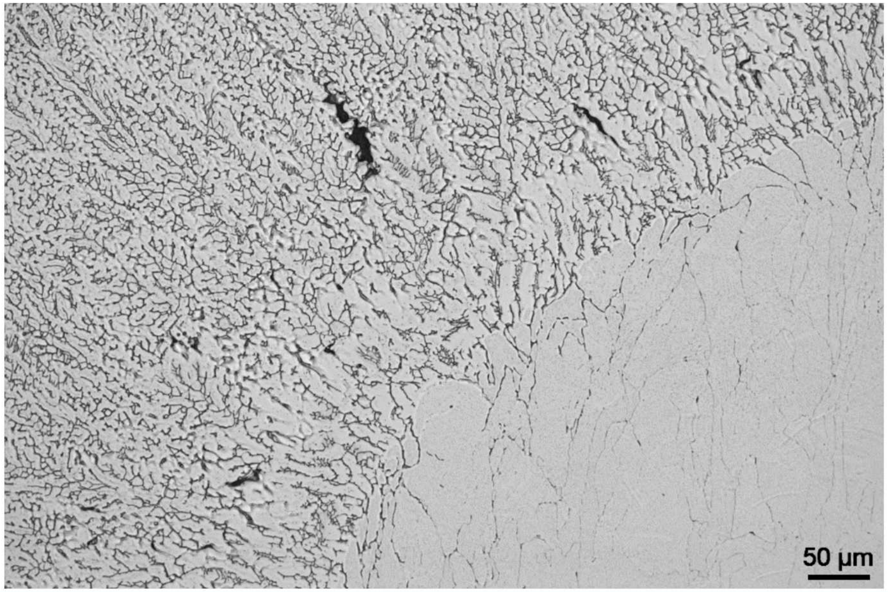
- Not enough surface cracks for statistical conclusions
  - Smallest die radius (highest restraint)
  - Cu die to provide higher cooling rate
- FA/F Mode solidification in both wrought and AM
  - <u>**Resistant**</u> to solidification cracking
- Minor cracking/crack-like features in both wrought and AM weld metal
  - Augmented strain regions
  - Not related to solidification mode shift/no susceptible microstructure
  - Possibly due to mechanical overloading rather than hot cracking



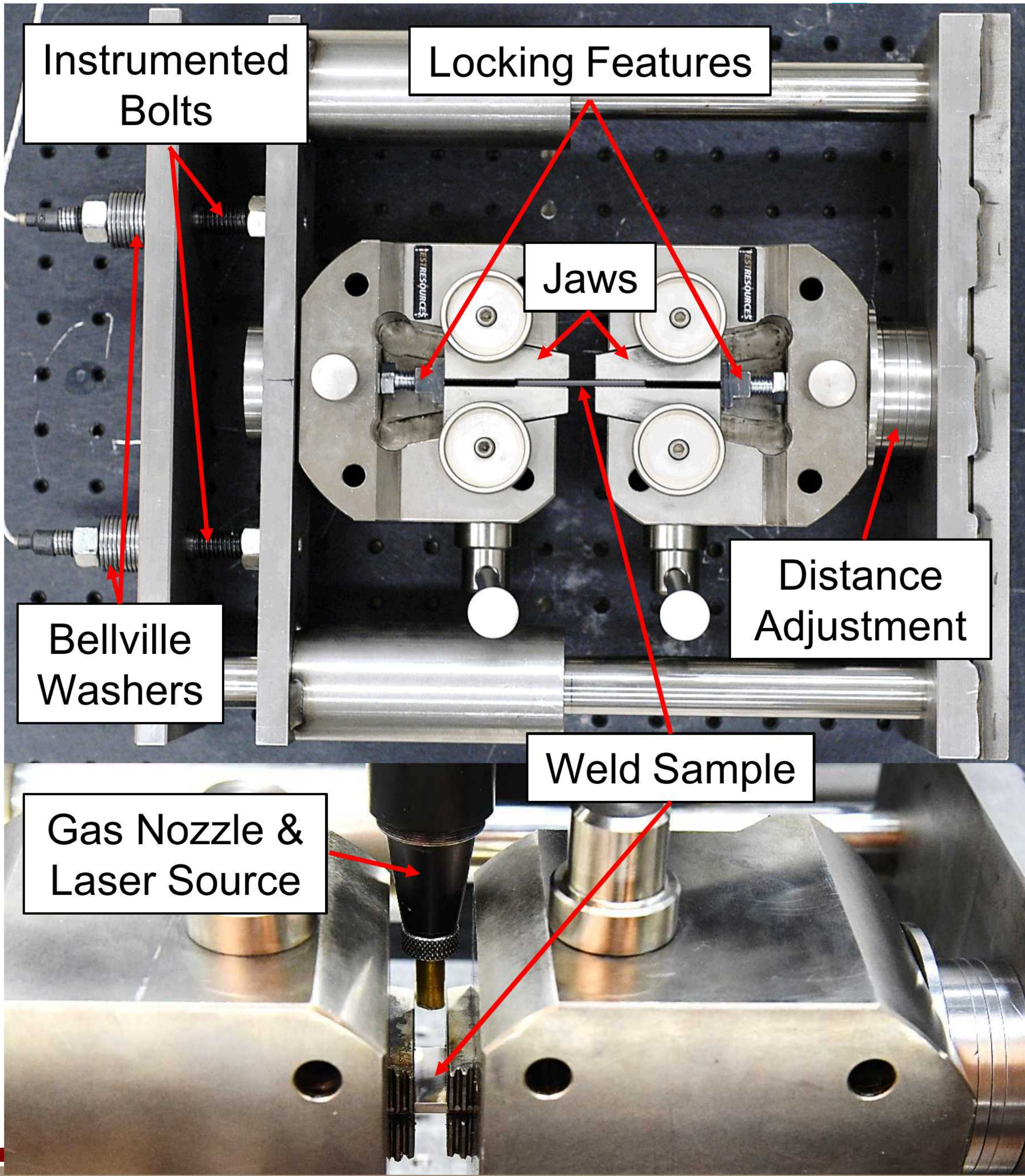
Wrought



AM

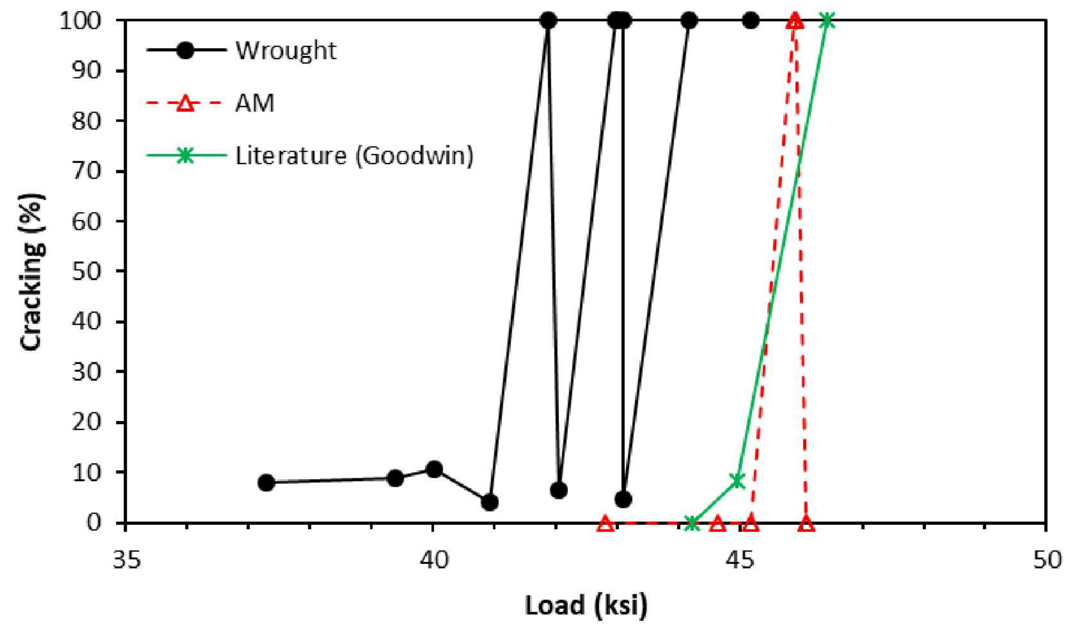
Solidification Cracking: Sigmajig Testing

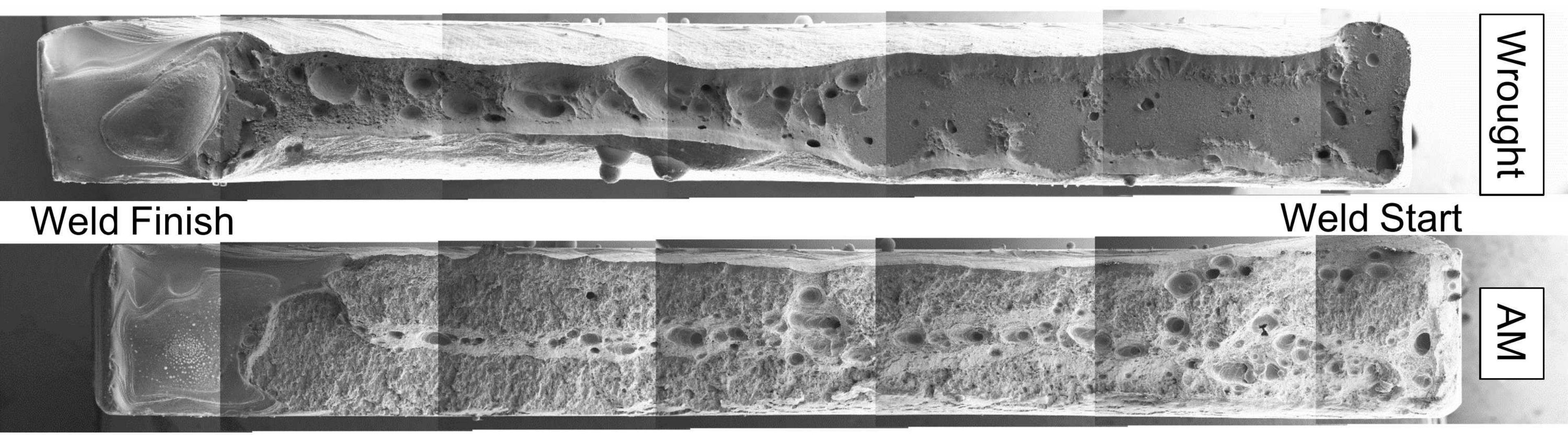
- Augmented stress weld cracking test
  - Applies tensile load **during** welding
  - Measure critical load for solidification cracking
- Advantages over Varestraint
  - Can be used with many welding processes
  - Higher possible applied stress
  - Higher resolution in stress variations
  - Ensure cracking threshold reached
  - Smaller sample size (limited AM bars)
- High Energy Density (Laser) welding provides unique set of variables
  - Higher solidification rates increase likelihood of solidification mode shift to susceptible microstructure



Sigmajig

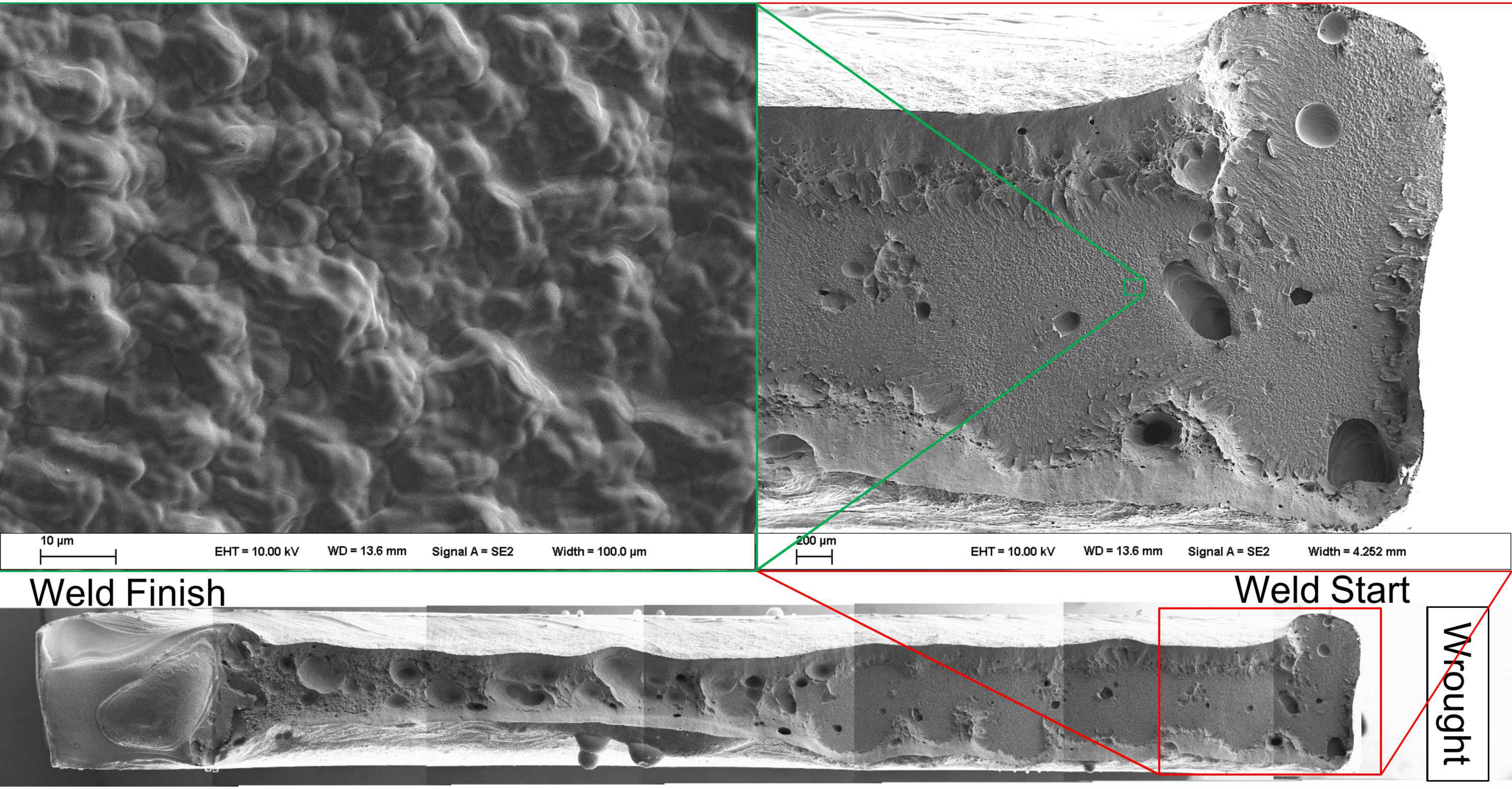
- Inconsistent results
- AM generally resistant to cracking at higher loads
- Lack of liquid film on fracture surfaces indicates failure by mechanical overload rather than a hot cracking mechanism





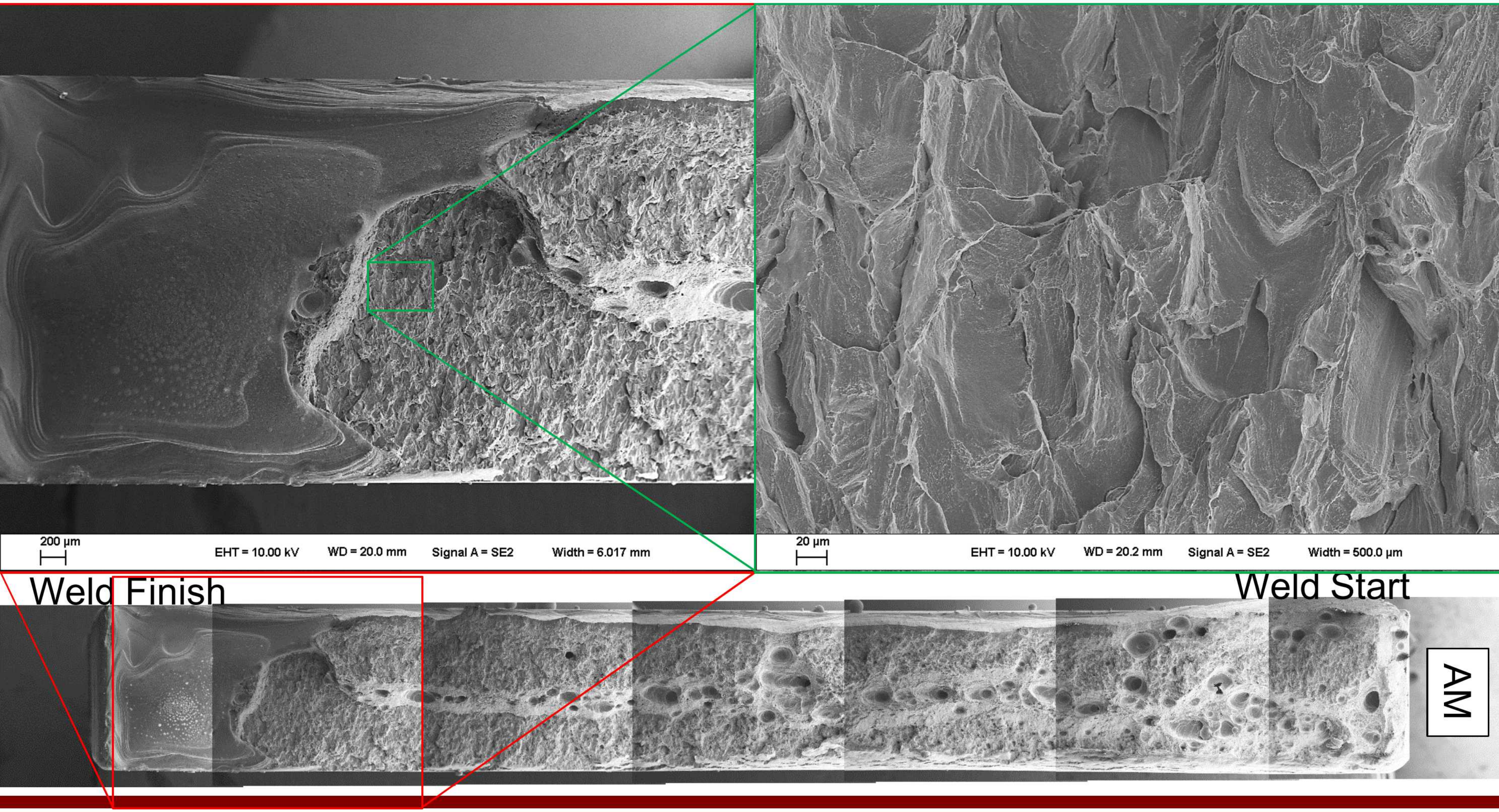
Wrought Fracture Surface

- Flat surface indicates failure across liquid-liquid films
  - Solidification features, but no evidence of solidification grain boundaries



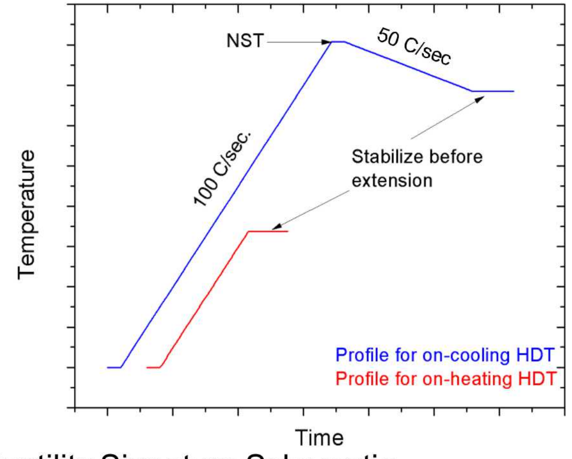
AM Fracture Surface

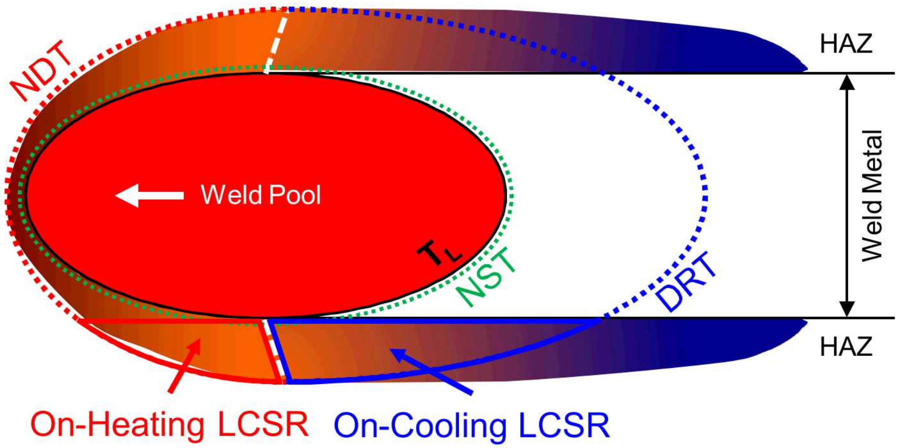
- No evidence of fracture involving liquid
  - Elongated dimples likely a result of failure immediately at high temperature



Liquation Cracking: Hot Ductility Testing

- Performed using Gleeble 3500 thermal-mechanical testing machine
- Measures ductility at HAZ-relevant temperatures and heating rates
  - NDT: Liquid encompasses GBs, no intergranular ductility
  - NST: Material cannot support a load, approximate fusion boundary temperature
    - T_L cannot be determined from this test
  - DRT: Solidification of GB liquid after heating above NDT
  - NST-NDT: On-heating liquation cracking susceptibility
  - NST-DRT: On-cooling liquation cracking susceptibility





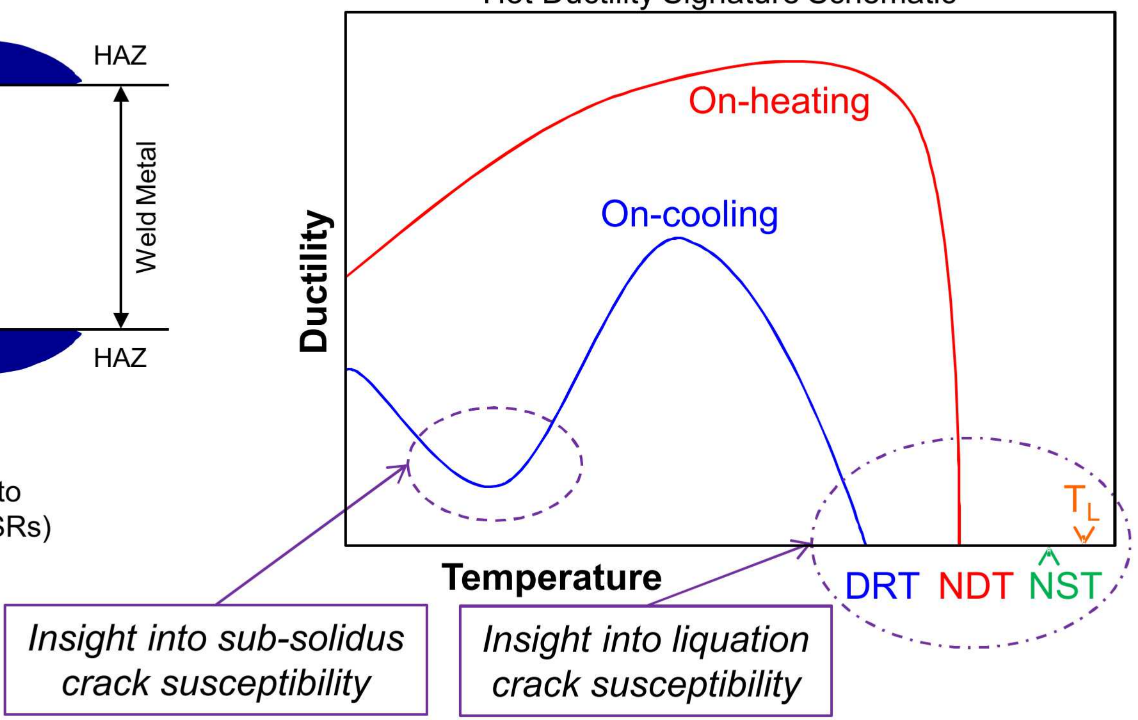
Translation of Measured HDT Temperatures to HAZ Liquation Crack Susceptible Regions (LCSRs)

NST: Nil-Strength Temperature

NDT: Nil-Ductility Temperature

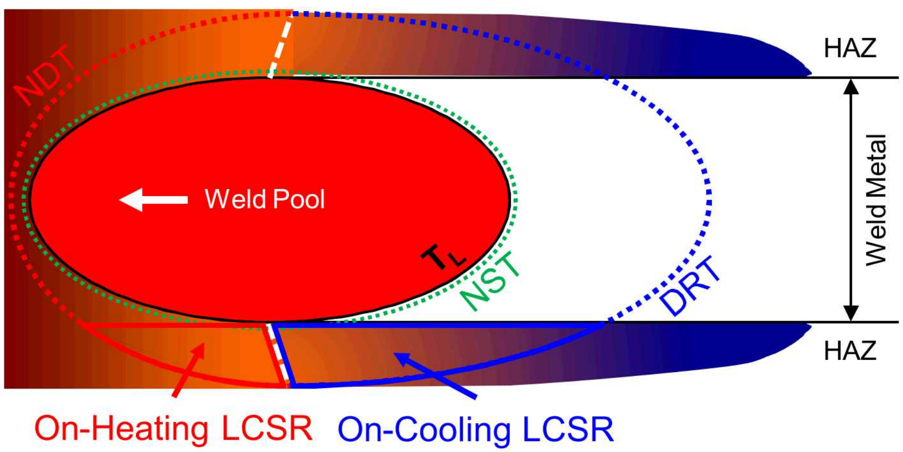
DRT: Ductility Recovery Temperature

Hot Ductility Signature Schematic



Liquation Cracking: Hot Ductility Testing

- NST, NDT, DRT all similar temperatures
  - Minimal liquation cracking susceptibility in both materials
  - AM does not produce segregation at grain boundaries to cause significant local change in melting behavior



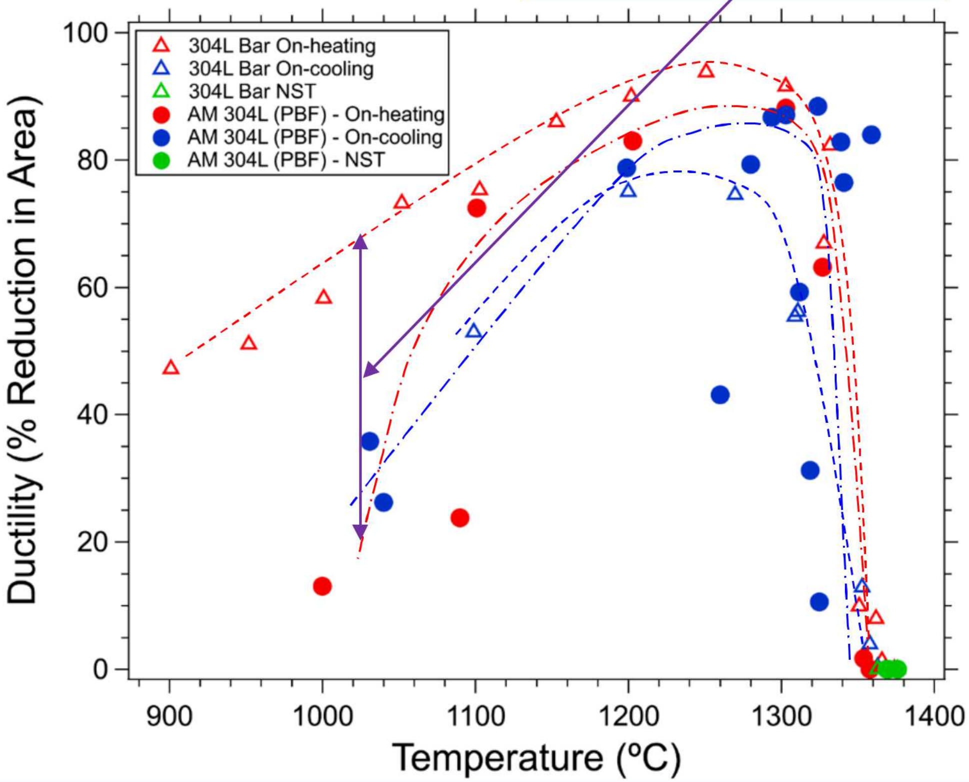
Translation of Measured HDT Temperatures to HAZ Liquation Crack Susceptible Regions (LCSRs)

NST: Nil-Strength Temperature

NDT: Nil-Ductility Temperature

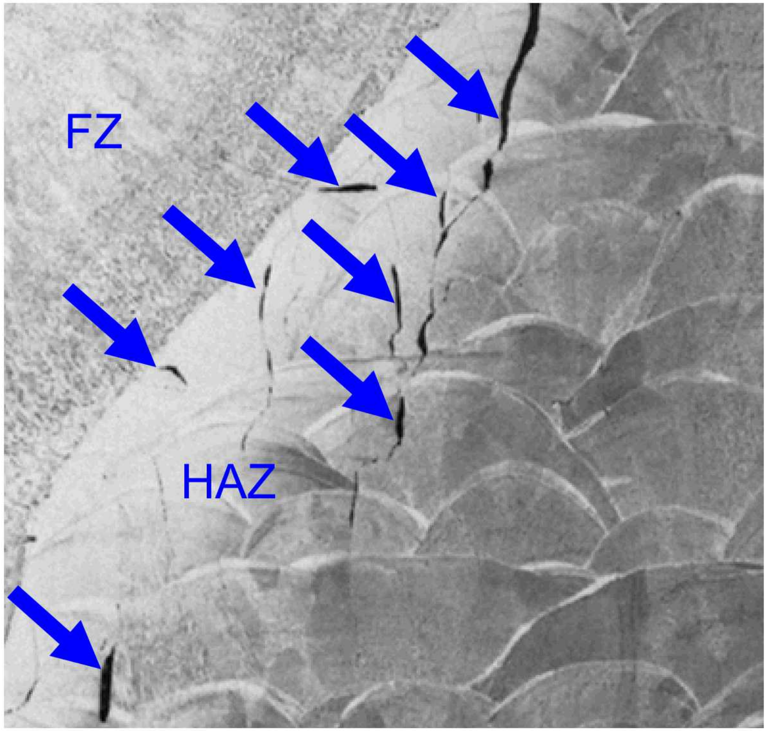
DRT: Ductility Recovery Temperature

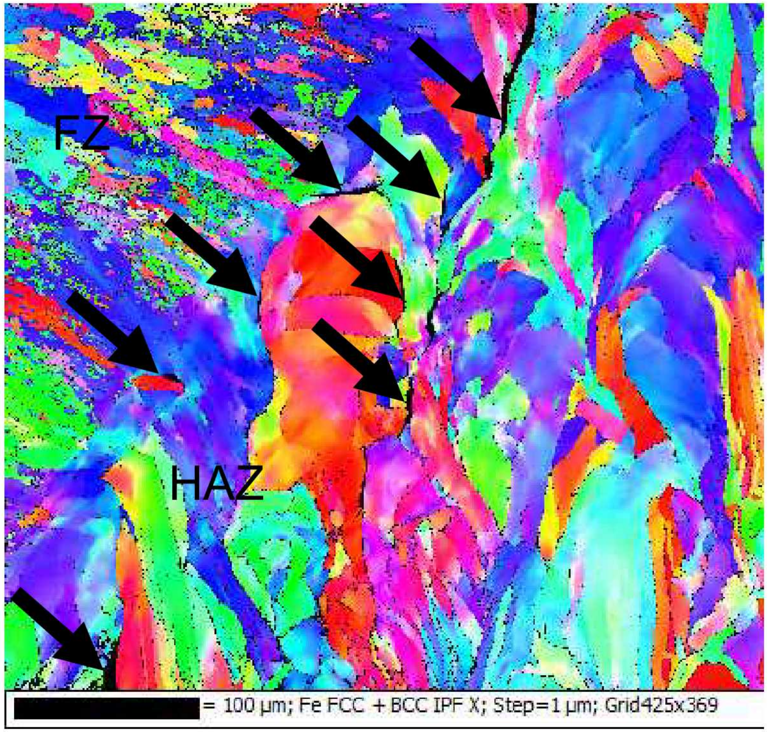
Insight into sub-solidus crack susceptibility



Ductility Dip Cracking

- Ductility dip found in some materials may result in in intergranular cracking
  - Occurs along straight FCC grain boundaries in HAZ or prior-pass FZ in multi-pass welds
- Extensive cracking found in AM but absent in wrought as predicted by hot ductility testing
  - Only found in rewelds; no pattern of increased cracking observed
    - Continued epitaxial nucleation and growth in small welds produces initially straight boundaries
    - Additional time at temperature allows boundaries to straighten
  - Mitigation techniques include alloying to cause boundary-pinning precipitation and limiting weld heat input





Conclusions

- Reweld study revealed no significant difference in the number of conduction mode rewelds required to cause a solidification mode/composition shift
- Compositional analysis revealed AM and wrought are compositionally similar in terms of austenite promoting elements and Cr_{eq}/Ni_{eq} ratio
  - AM contains additional oxygen and impurities which impacts weld pool flow and shape
- Typical hot cracking comparisons were found with neither Varestraint nor Sigmajig testing
  - Any failures occurred via sub-solidus overload rather than hot cracking
  - Neither material displayed a crack-susceptible microstructure
- Hot ductility testing revealed no major differences in the Nil Strength Temperature, Nil Ductility Temperature, or Ductility Recovery Temperature
  - Small range between NST and DRT indicates low susceptibility to liquation cracking
- Overall conclusions for the specific materials explored in this study:
  - AM and wrought materials are similarly hot crack resistant
  - AM and wrought materials are hot crack resistant enough that hot cracking is unlikely during typical WR welding
  - Process controls, impurity content, and composition (especially Cr_{eq}/Ni_{eq}) must be maintained to ensure the welding behavior observed here occurs in future builds
  - Understanding and mitigation of HAZ Ductility-Dip Cracks requires further research

Questions?

Sandia National Laboratories

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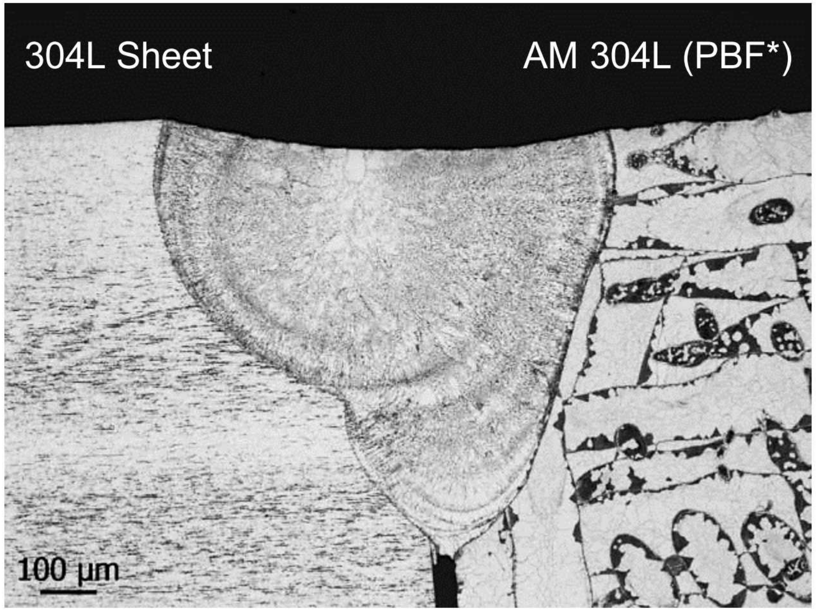
BACKUP SLIDES

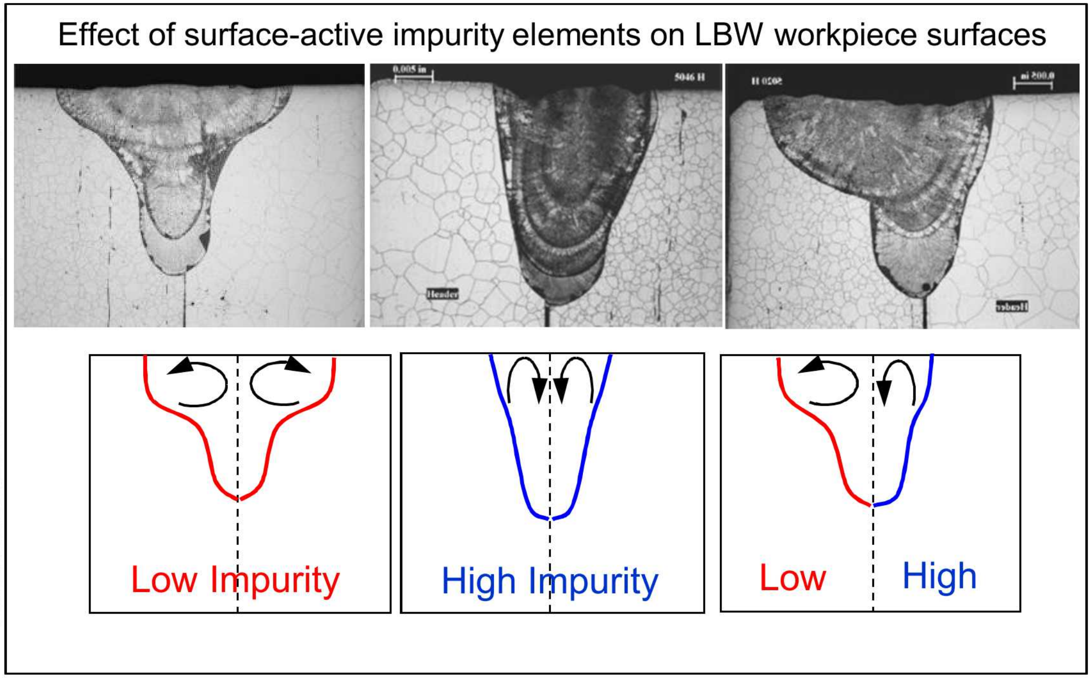
Increased Oxygen Content of PBF AM 304L Can Result in Asymmetric Dissimilar Weld Profiles

- Bulk oxygen concentration of PBF AM 304L can be substantially higher than typical conventional 304L levels
- Past SNL investigations have observed similar weld profile asymmetry when laser welding 304L components with varying levels of surface oxide
- Asymmetry not intrinsically deleterious, but can pose post weld inspection challenges for some applications



0.003 wt.% O
0.001 wt.% S

0.036 wt.% O
0.005 wt.% S



Courtesy of D. Susan & C. Robino

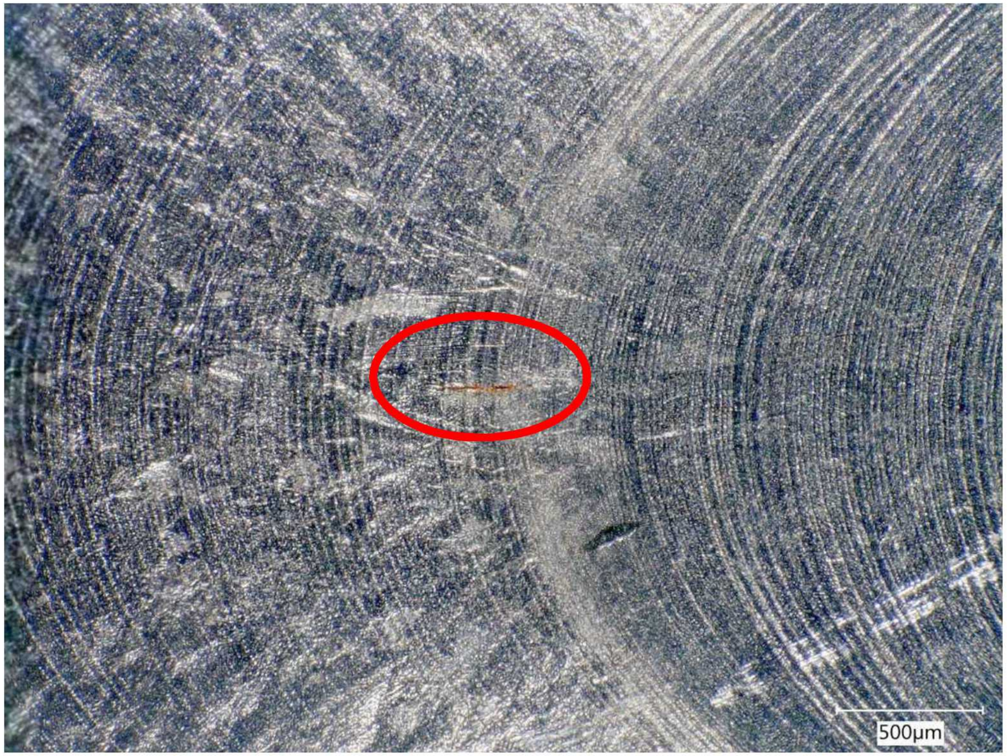
WDS on Varestraint Bars

		Measured wt%								Normalized wt%							
		Si	P	S	Mn	Ni	Cr	Fe	Total	Si	P	S	Mn	Ni	Cr	Fe	Total
	304L Spec	0.75 Max	0.045 Max	0.03 Max	2.0 Max	8.0-12.0	18-20	Bal		0.75 Max	0.045 Max	0.03 Max	2.0 Max	8.0-12.0	18-20	Bal	
AM Weld	AM-1_Weld_Bend_Tr1, 200 pts																
	Minimum	0.14	-0.014	-0.013	1.193	4.838	18.032	66.444	94.973	0.14	-0.014	-0.013	1.232	4.848	18.213	67.335	100
	Maximum	1.066	0.024	0.033	2.391	11.013	23.539	71.14	101.756	1.075	0.024	0.034	2.41	11.082	23.745	70.72	100
	Average	0.587	0.006	0.003	1.363	9.362	18.766	68.641	98.727	0.594	0.006	0.003	1.38	9.479	19.009	69.528	100
	Sigma	0.086	0.006	0.007	0.124	0.989	0.697	0.898	1.042	0.088	0.006	0.007	0.121	0.966	0.703	0.768	0
AM Base	AM-1_Weld_Bend_Area-2_Tr2, 200 pts																
	Minimum	0.427	-0.016	-0.01	1.183	8.929	18.076	66.544	95.794	0.428	-0.017	-0.01	1.174	8.914	18.295	67.682	100
	Maximum	0.689	0.024	0.02	1.739	10.267	20.225	72.17	103.22	0.71	0.024	0.02	1.726	10.362	20.071	70.376	100
	Average	0.601	0.006	0.005	1.361	9.243	18.883	68.529	98.629	0.61	0.006	0.005	1.38	9.372	19.145	69.482	100
	Sigma	0.041	0.007	0.005	0.073	0.171	0.42	1.088	1.413	0.045	0.007	0.005	0.07	0.172	0.291	0.369	0
	AM-1_Weld_Bend_Base-Material, 1 pt																
		0.419	0.007	0.007	0.415	9.695	18.141	70.507	99.191	0.422	0.007	0.007	0.418	9.774	18.289	71.082	100
	AM-1_Weld_Bend_Base-Material_Tr1, Extra Trace, 33 pts																
	Minimum	0.467	-0.006	-0.008	1.175	8.281	17.972	64.952	94.149	0.476	-0.006	-0.008	1.198	8.465	18.324	68.172	100
	Maximum	0.712	0.018	0.014	1.595	9.328	20.204	69.878	99.337	0.738	0.019	0.014	1.652	9.614	20.48	71	100
	Average	0.563	0.007	0.005	1.363	8.811	18.709	68.086	97.544	0.577	0.007	0.005	1.398	9.036	19.18	69.796	100
	Sigma	0.059	0.006	0.005	0.116	0.373	0.47	1.403	1.324	0.065	0.006	0.005	0.126	0.453	0.372	0.712	0
Wrought Weld	Wrought-25_Weld_Bend_Weld_Tr1, 200 pts																
	Minimum	0.076	0.002	-0.012	1.315	5.3	17.815	67.274	94.316	0.076	0.002	-0.012	1.346	5.302	18.083	68.866	100
	Maximum	0.445	0.053	0.037	1.79	10.147	22.199	73.704	102.925	0.452	0.054	0.037	1.82	10.323	22.207	72.485	100
	Average	0.343	0.026	0.001	1.46	7.773	18.537	70.202	98.341	0.349	0.026	0.001	1.485	7.903	18.85	71.387	100
	Sigma	0.056	0.009	0.006	0.094	0.825	0.6	1.046	1.114	0.058	0.01	0.006	0.092	0.823	0.591	0.724	0
Wrought Base	Wrought-25_Weld_Bend_Area2_Tr2, 200 pts																
	Minimum	-0.001	-0.011	-0.016	1.27	4.543	17.896	66.623	93.967	-0.001	-0.012	-0.016	1.328	4.755	18.175	69.776	100
	Maximum	0.416	0.046	0.012	1.666	9.305	22.485	71.605	99.648	0.422	0.047	0.012	1.686	9.404	23.535	72.241	100
	Average	0.364	0.029	0.001	1.467	7.64	18.865	70.188	98.552	0.369	0.029	0.001	1.488	7.749	19.145	71.219	100
	Sigma	0.036	0.008	0.006	0.076	0.763	0.528	0.754	0.796	0.036	0.008	0.006	0.074	0.748	0.619	0.53	0

VARESTRAINT

Traditional Varestraint Results

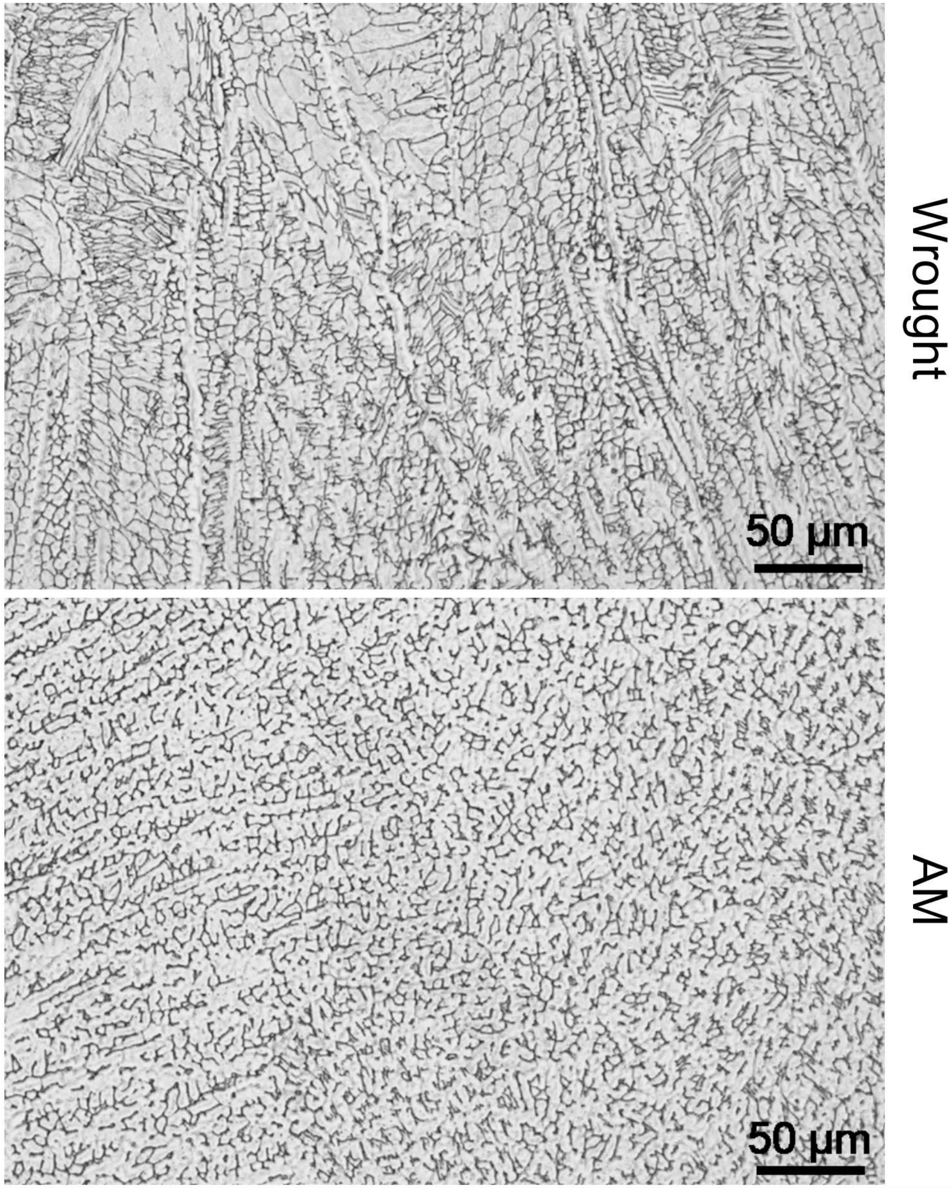
- Compared Wrought vs AM 304L
- Image at 50x magnification
  - Count cracks under various strain conditions
  - Relative ranking of cracking susceptibility
- Not enough cracks for statistical conclusions
  - Smallest die radius (highest restraint)



Wrought 304L
100x magnification (original image)
Only crack in all welded samples

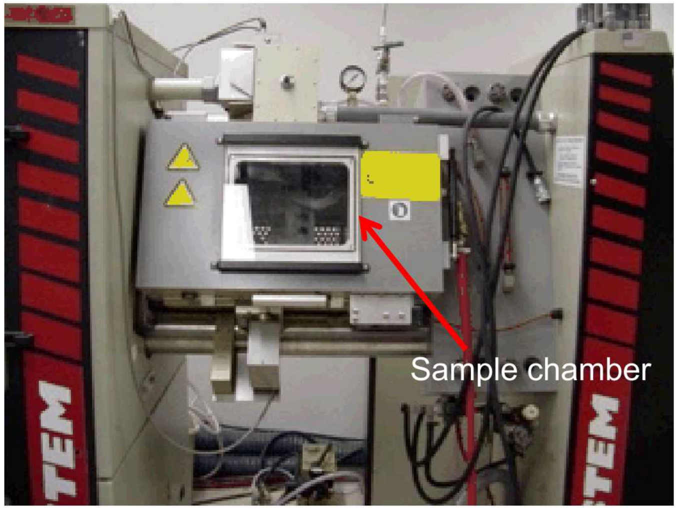
Microstructure Comparison

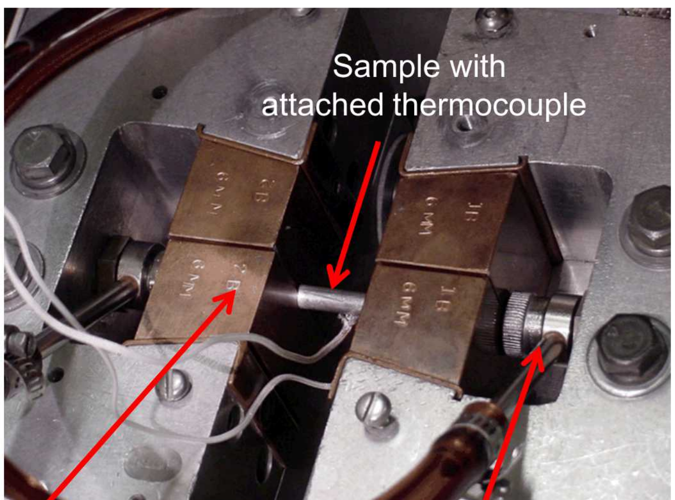
- FA/F Mode solidification in both wrought and AM
  - **Resistant** to solidification cracking



HOT DUCTILITY TESTING

Gleeble Thermophysical Simulation & Evaluation of HAZ Microstructures



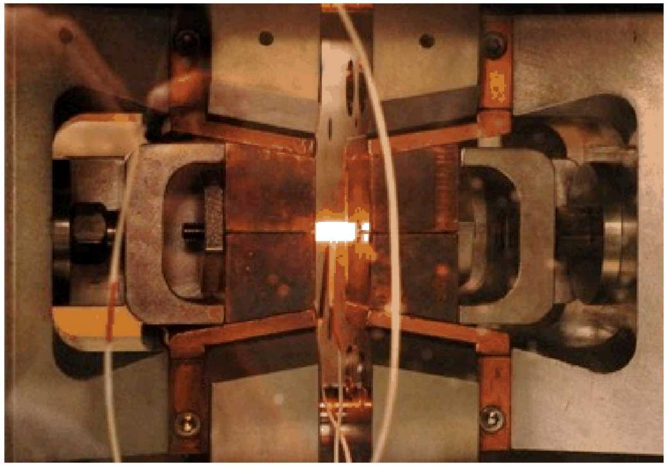


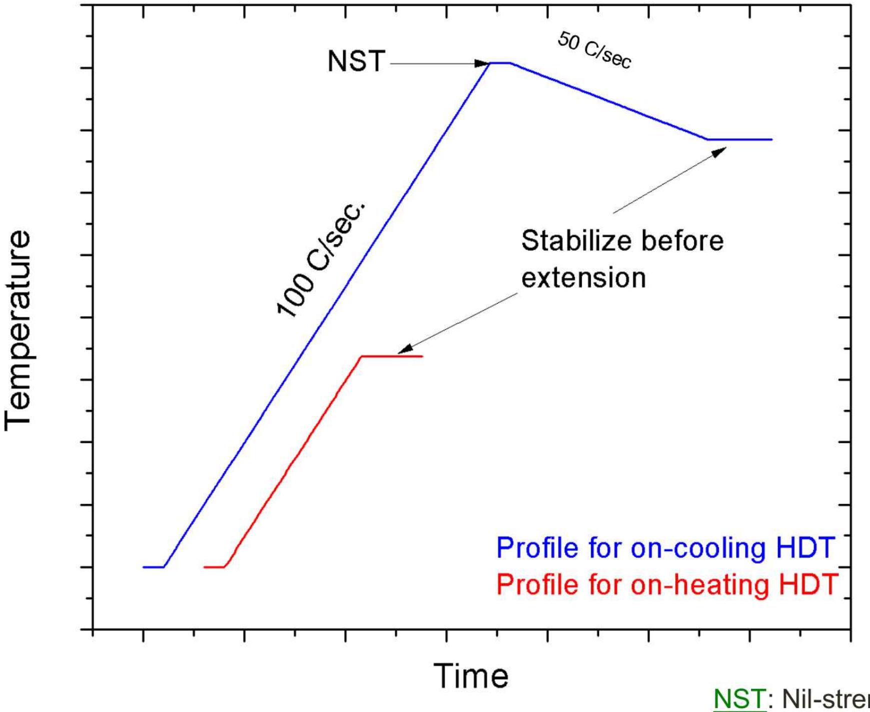
- Gleeble 3500 enables physical simulation of microstructures produced by highly dynamic processes such as <u>weld HAZ microstructures</u>, complex heat treatments, etc.

- Capabilities
  - Thermal
    - Heating rates as high as 10^4 K/s
    - Gaseous or liquid quenching
    - quad channel thermal acquisition
  - Mechanical
    - Up to 20 kip tensile and compressive force
    - Up to 2 m/s extension rate
  - Atmosphere
    - Inert gas (Ar)
    - High vacuum (diffusion pump)
  - Contact and Non-contact Dilatometric Measurement Capability
  - Integrated Laser Extensometer

Gleeble Hot Ductility Testing

- Hot ductility testing develops a temperature-dependent ductility ‘signature’ for a material.
- Ductility is measured via specimen reduction in area
- No standardized test method for hot ductility testing; however, commonly-used test parameters are based on work by Lin and Lippold†





NST: Nil-strength temperature

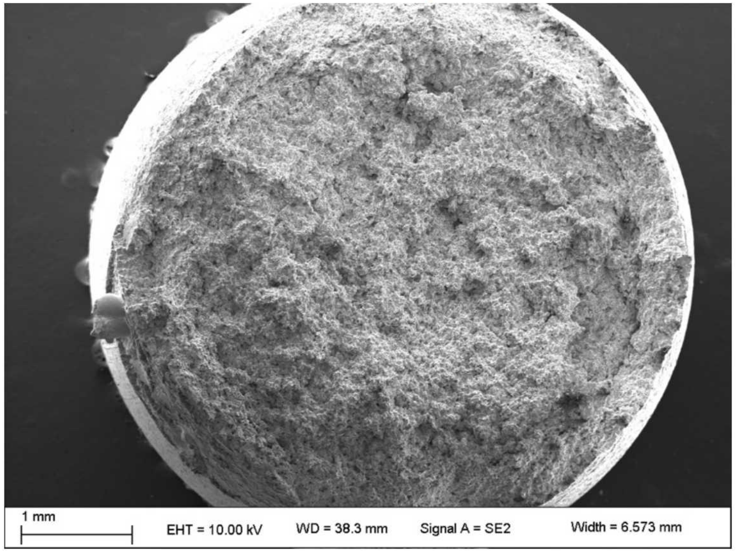
†W. Lin, J. C. Lippold, and W. A. Baeslack, *Welding Journal,* vol. 72, pp. S135-S153, Apr 1993.

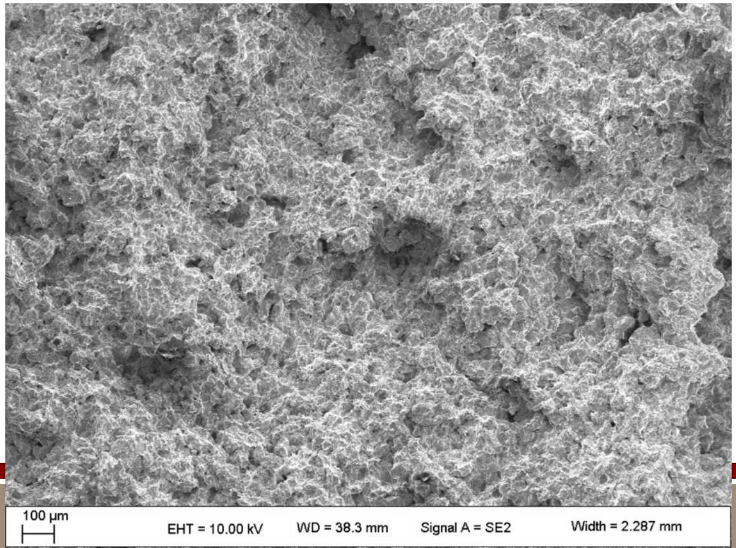
Fractography of Nil-Ductility Temperature (NDT) Specimens

- Test temperature represents on-heating brittle behavior associated with onset of melting
- AM PBF 304L shows unique fracture behavior compared to conventional 304L despite similarity in measured NDT

Conventional 304L Bar (ASTM A276)

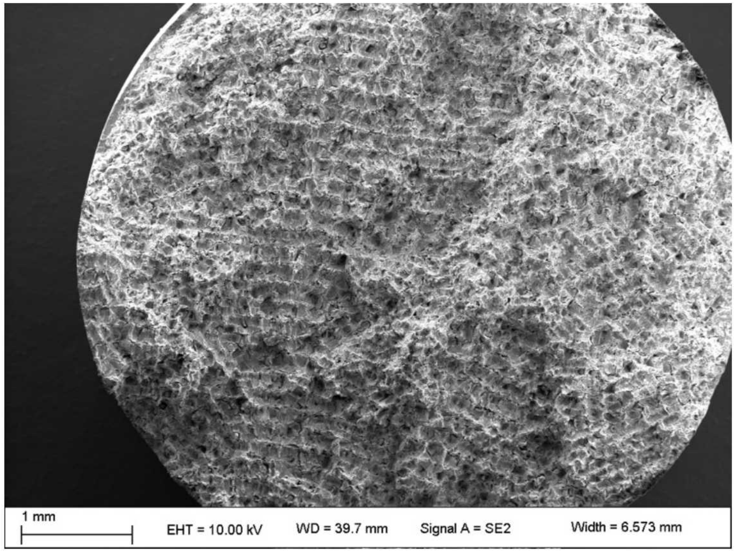
OH: 1351°C ; 7 % RA

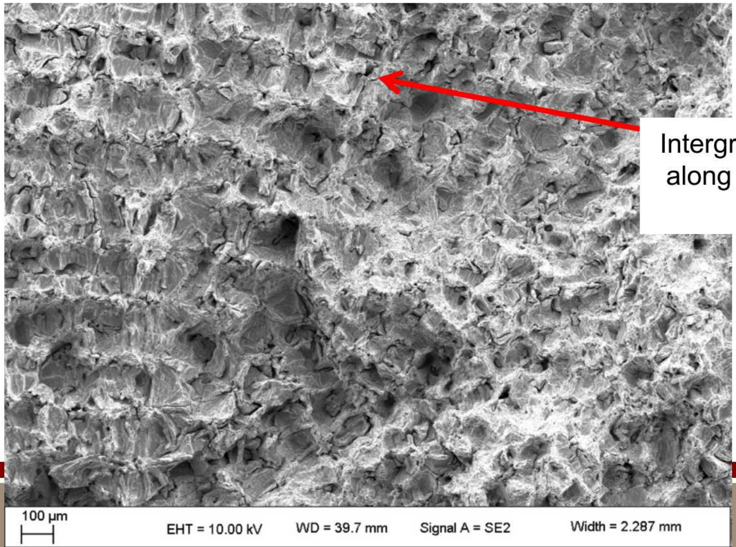




NSC AM PBF 304L

OH: 1354°C ; 2% RA



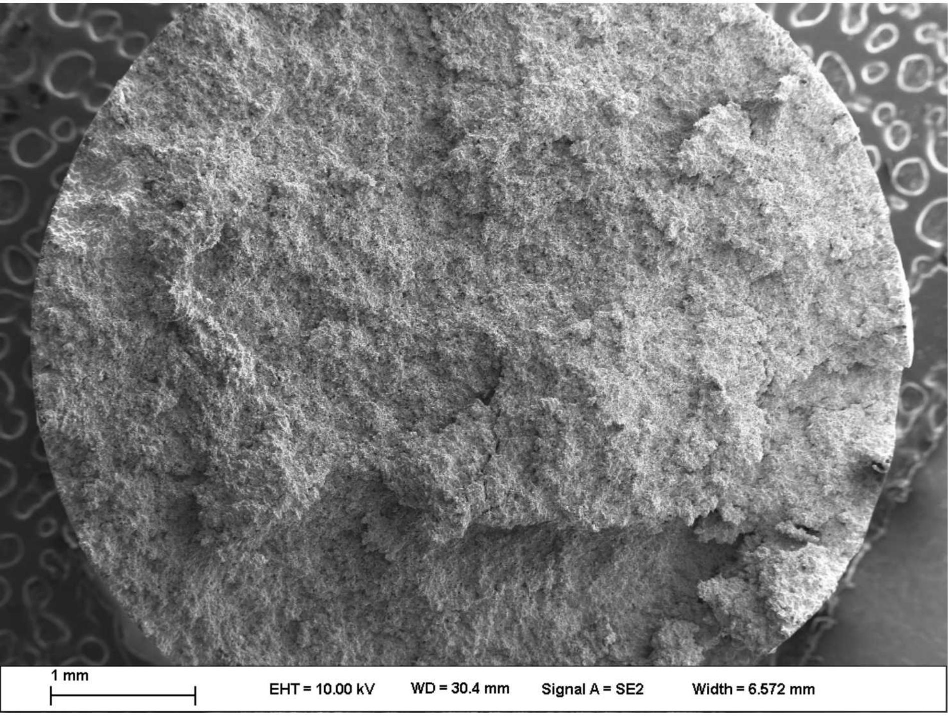


Intergranular failure along solidification grains

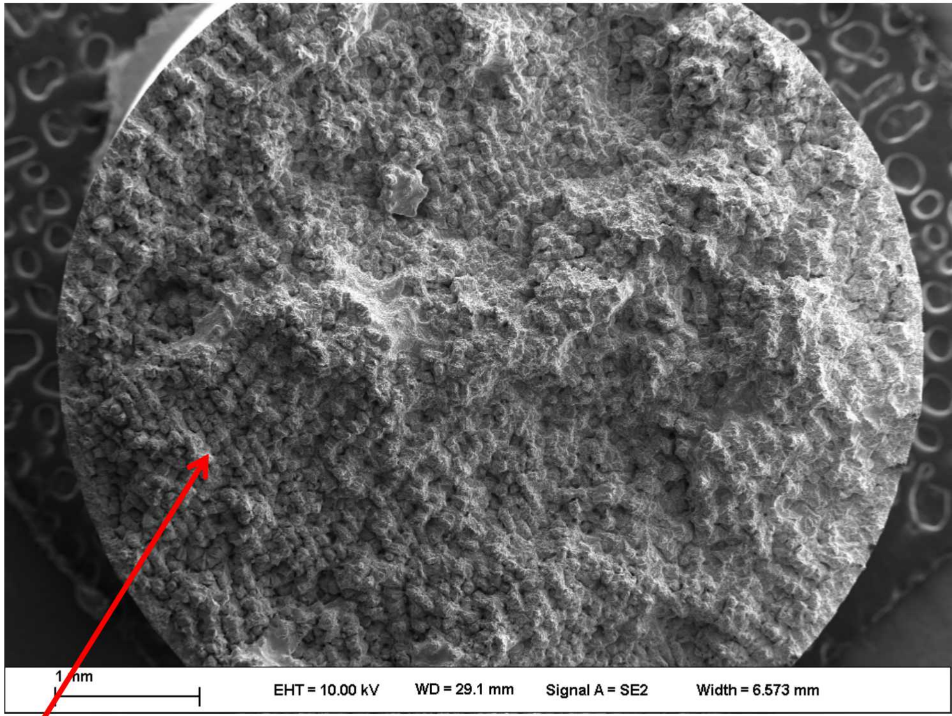
Fractography: Nil-Strength Temperature (NST)

- Temperature at which material has negligible (<30 psi) strength due to incipient melting and formation of grain boundary liquid films
- Both conventional and AM PBF 304L have similar measured NST temperatures despite distinct fractographic features

Conventional 304L Bar (ASTM A276)
NST: 1373°C



NSC AM PBF 304L
NST: 1371°C

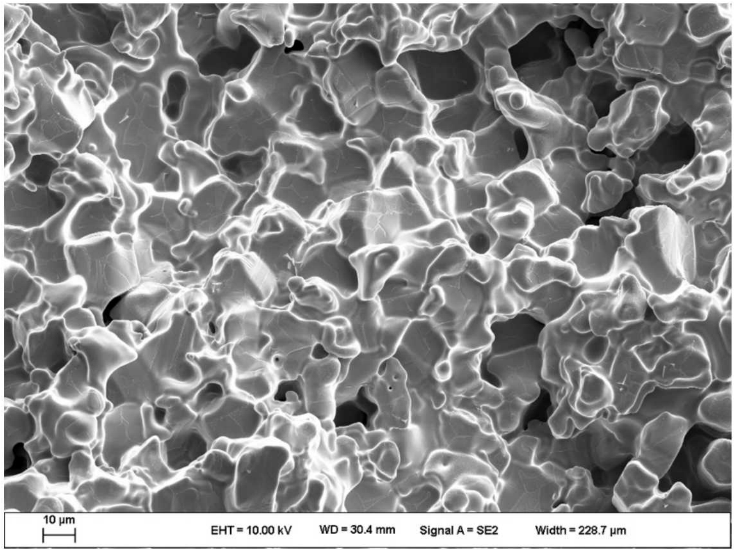


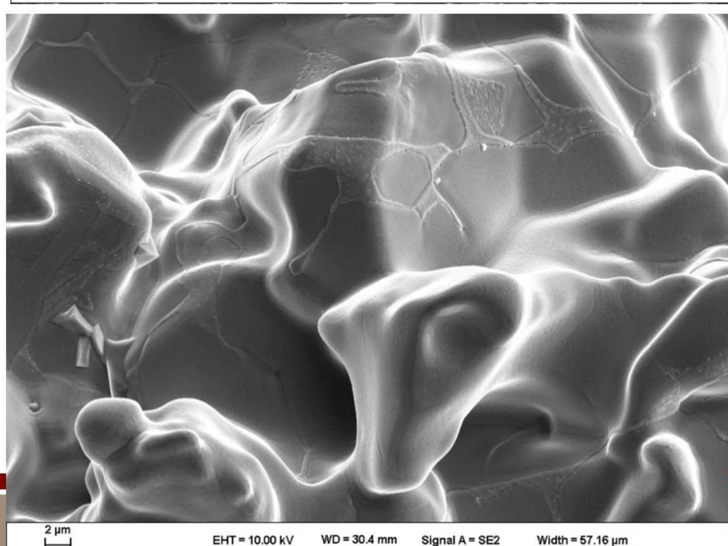
Fracture appears to correspond to PBF raster pattern

Fractography: Nil-Strength Temperature (NST)

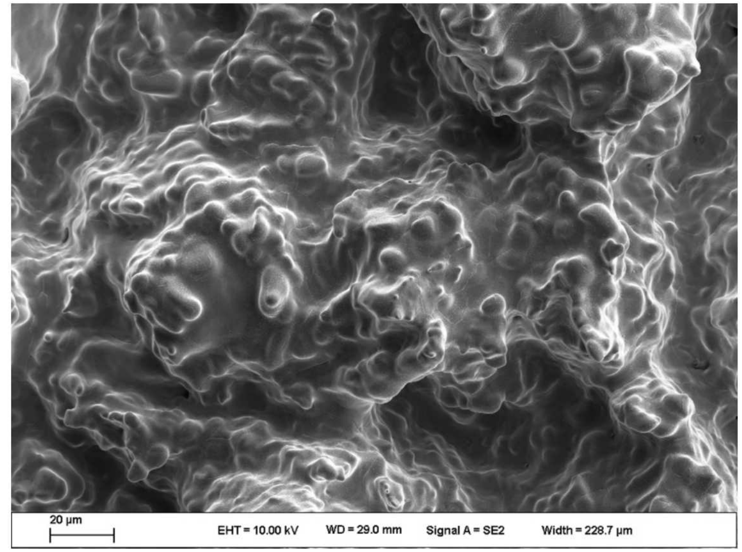
- High magnification examination of both conventional and PBF NST specimens indicates failure along grain boundary liquid films

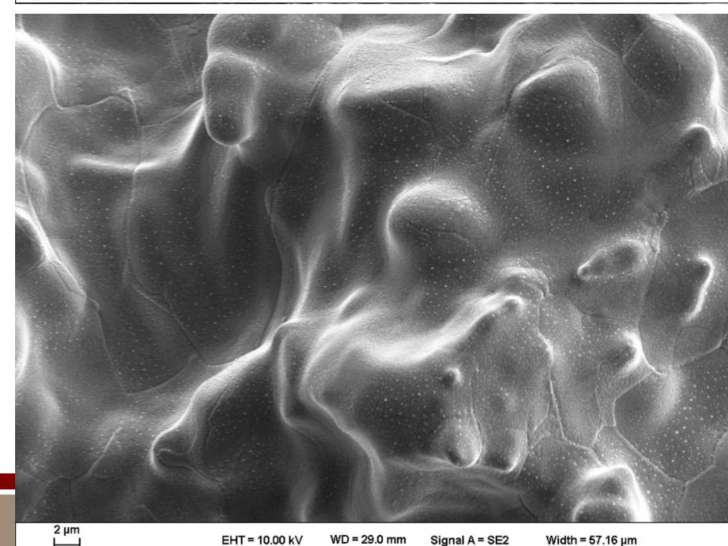
Conventional 304L Bar (ASTM A276)
NST: 1373°C





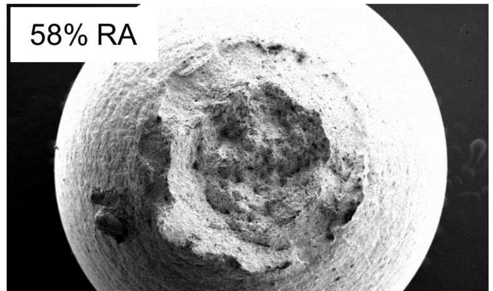
NSC AM PBF 304L
NST: 1371°C

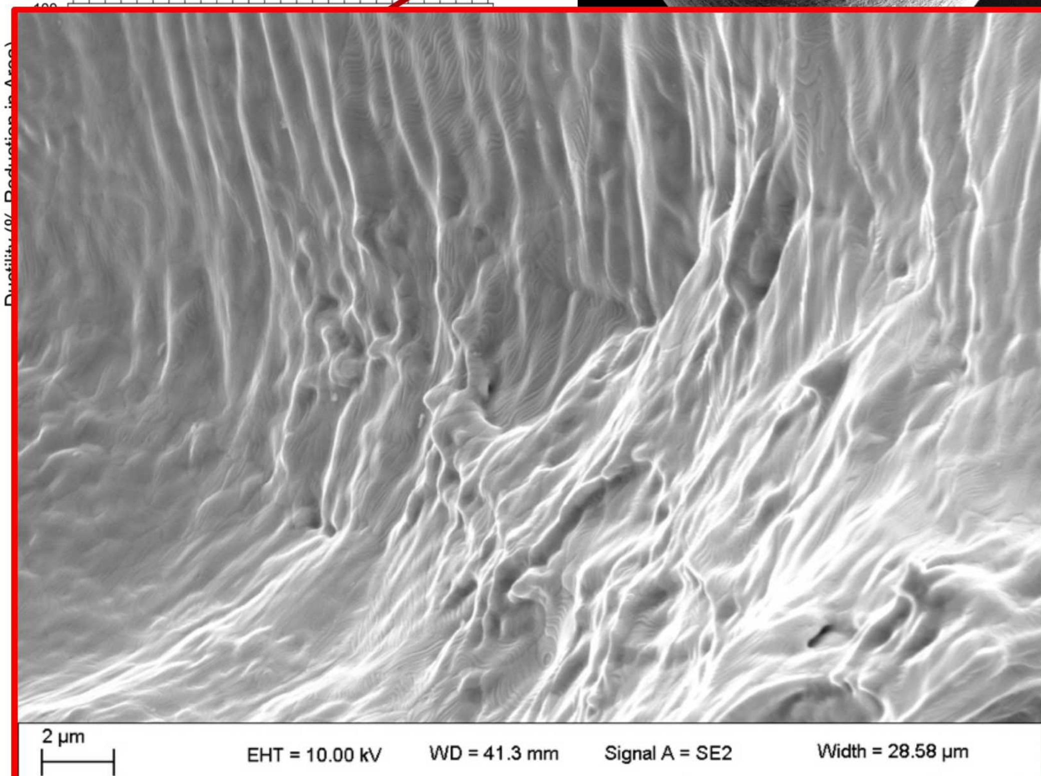


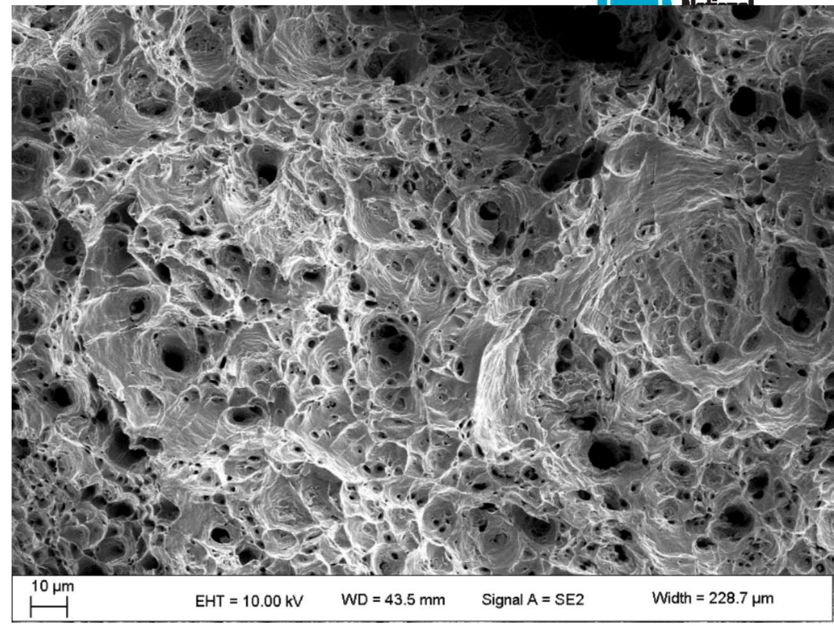


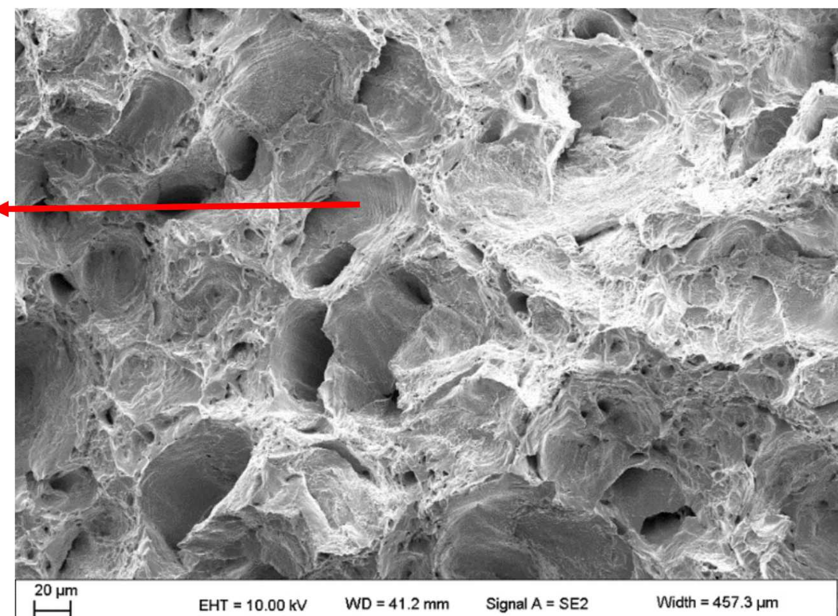
Intermediate Temperature Ductility Loss Observed for AM 304L

- Loss in high temperature ductility for AM 304L specimens tested near ~1000°C accompanied by intermittent fracture along solidification grain boundaries with no microscopic ductile fracture features



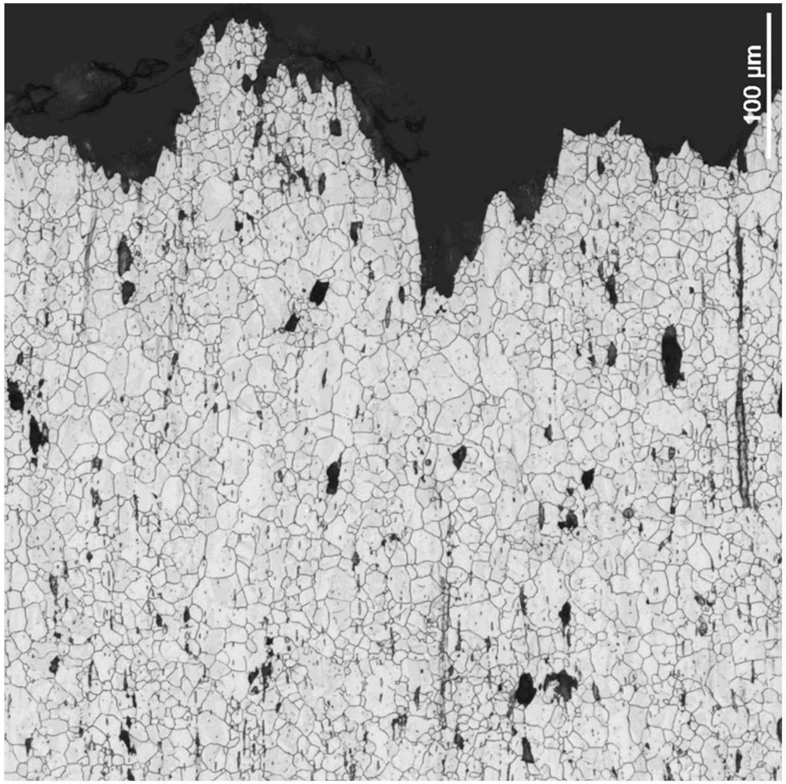


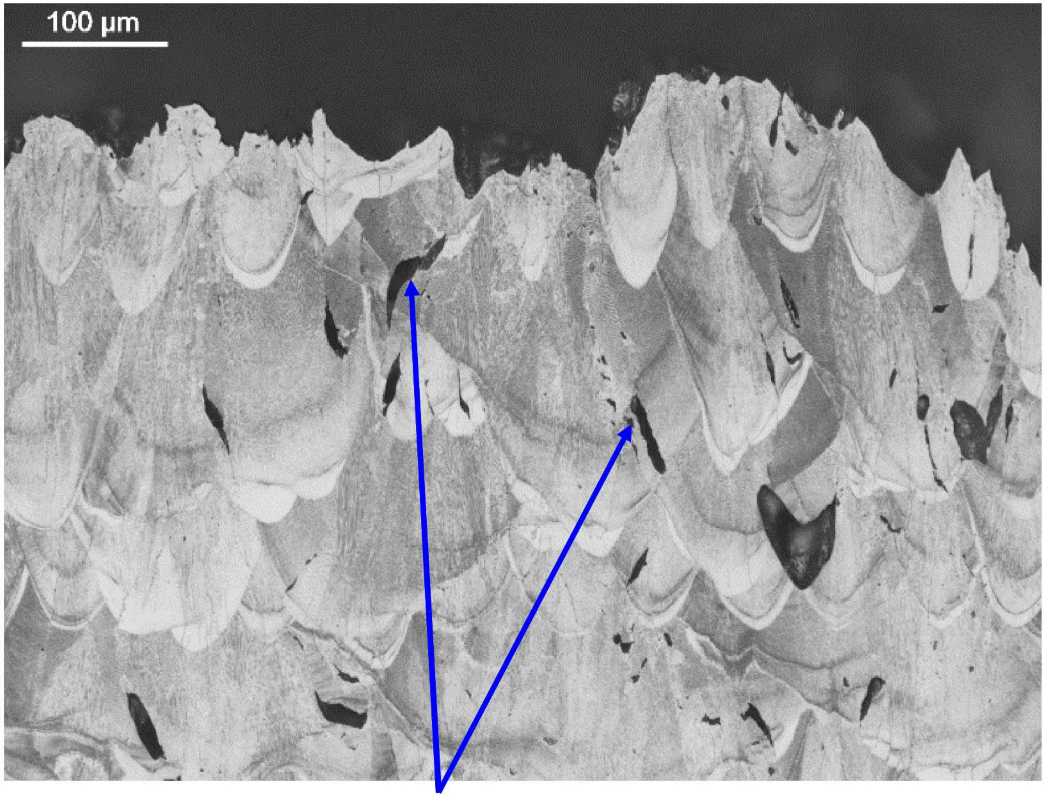




Near-fracture Longitudinal Cross Section

- Both AM and conventional 304L show void nucleation near fracture
- Most voids and cracks appear to be along solidification grain boundaries in AM PBF 304L
- Higher fidelity testing (i.e., Strain-to-Fracture testing) likely needed to explore possible DDC behavior in AM 304L HAZ





Initiation of voids along solidification grain boundaries