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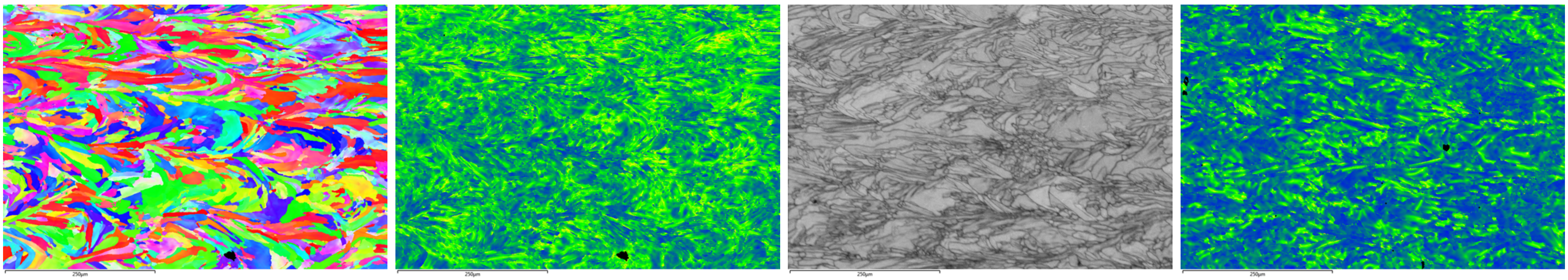

Strength, Fracture and Microstructure of Additively Manufactured Austenitic Stainless Steel

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Motivation

- Additive manufactured austenitic stainless steels show interesting strength characteristics
  - Questions remain about reproducibility of materials and microstructures
  - Defects appear to be an intrinsic characteristic
- New design paradigm with additive is particularly attractive for demanding applications in extreme environments
  - For example, applications that require hydrogen compatibility
- Many additive processes are intrinsically solidification based
  - Therefore, knowledge of the performance of weld microstructures may be transferrable in some cases

Selective Laser Melting of 304L: Ring builds

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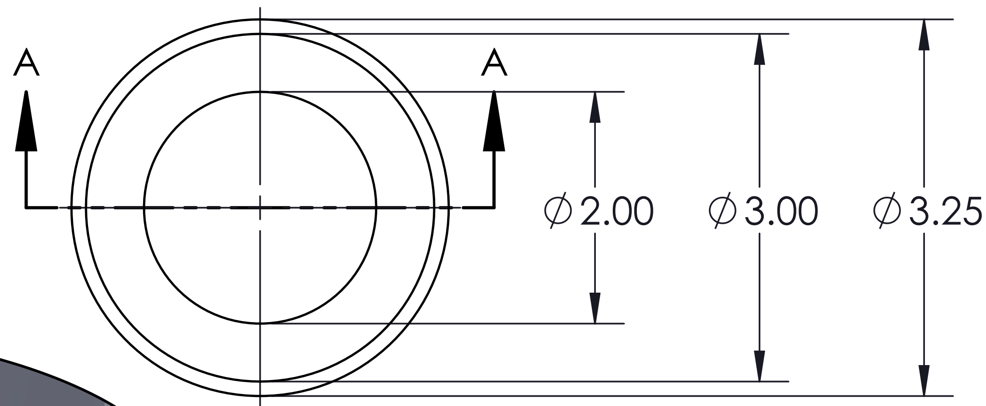
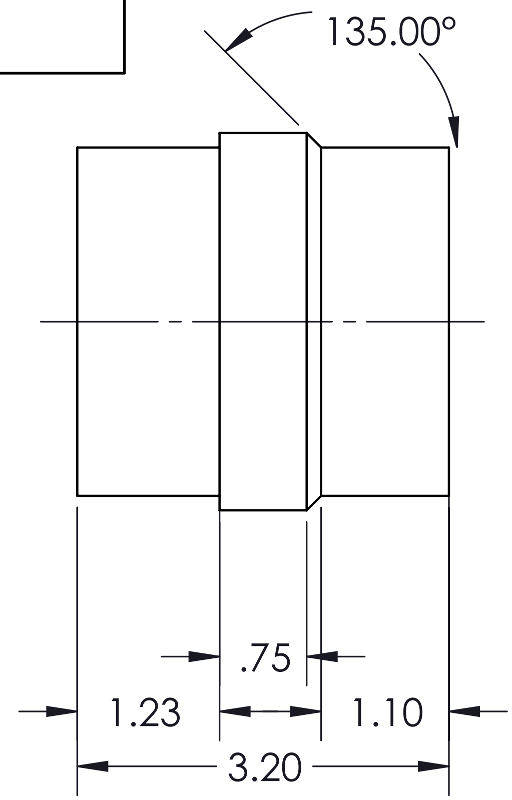
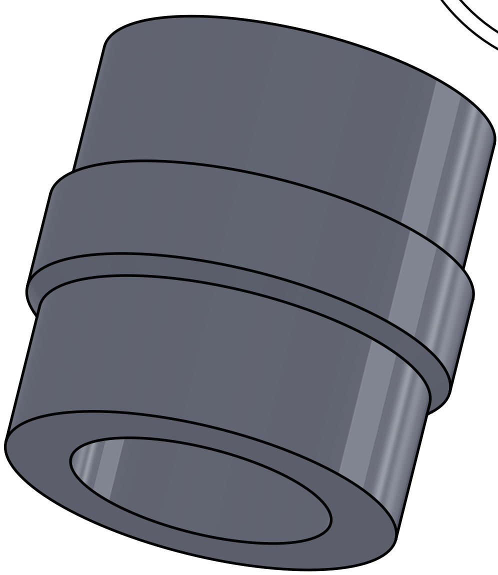
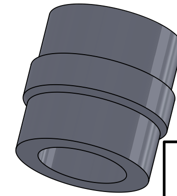
Rings manufactured at two sites (referred to as L and N), but otherwise nominally the same





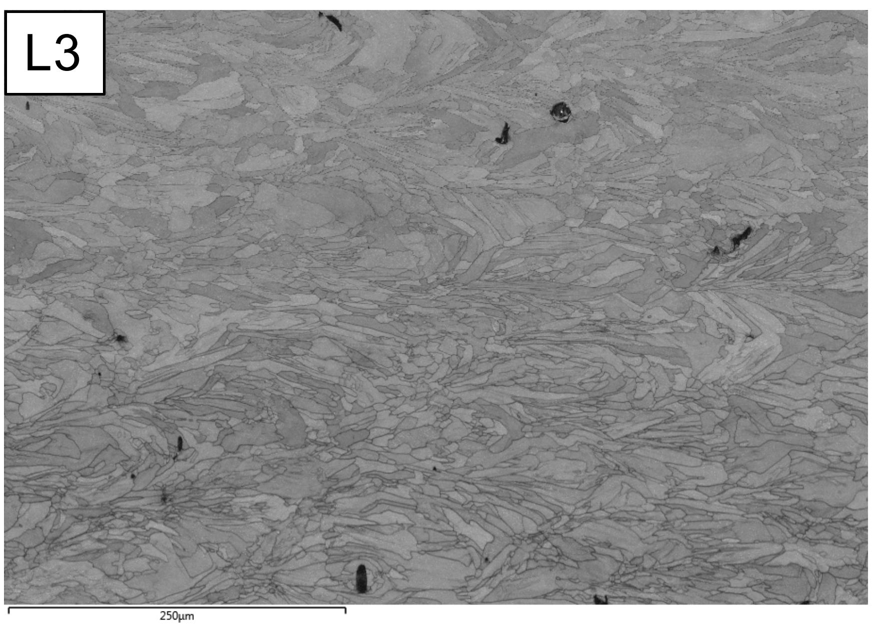


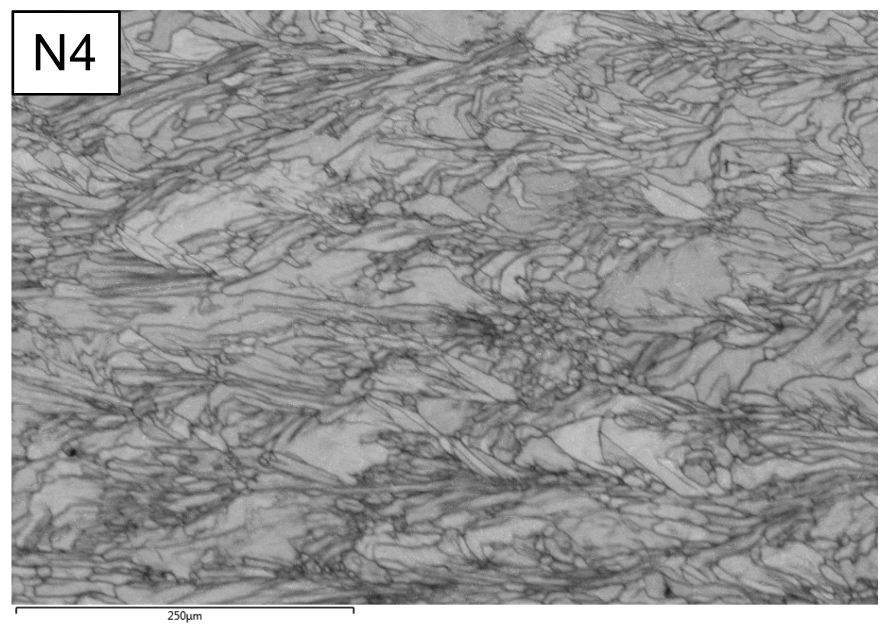
Materials characterization



	Fe	Cr	Ni	Mn	Si	C	N	O	S	P
L1	bal	18.55	9.58	1.37	0.59	0.013	0.050	0.042	0.004	0.012
N1	bal	18.35	9.92	1.41	0.54	0.010	0.047	0.043	0.004	0.013

Density (Archimedes) ~ 99.5% for both materials

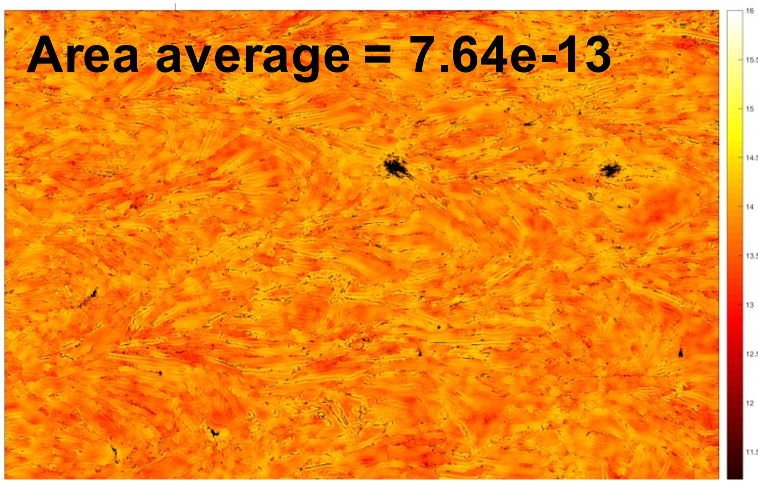




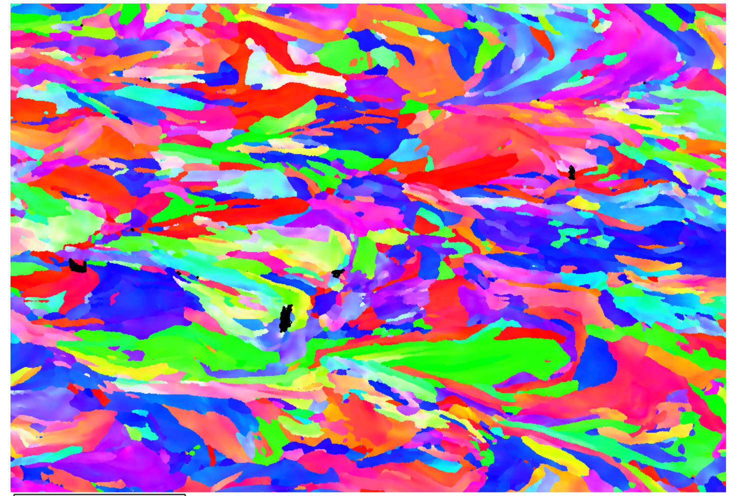
Microscopy: EBSD mapping

Dislocation density (m^{-2}) map

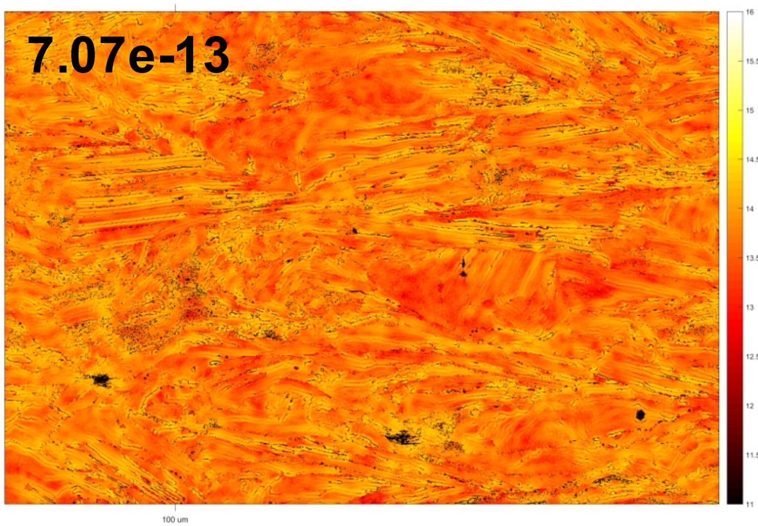
Inverse pole figures



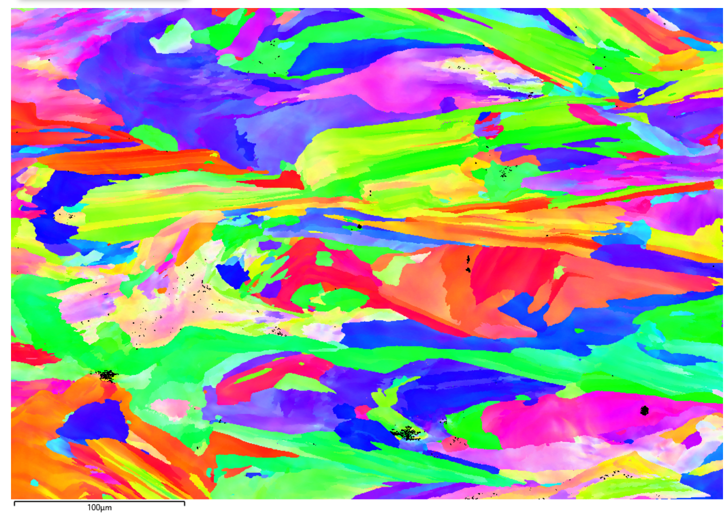
L3



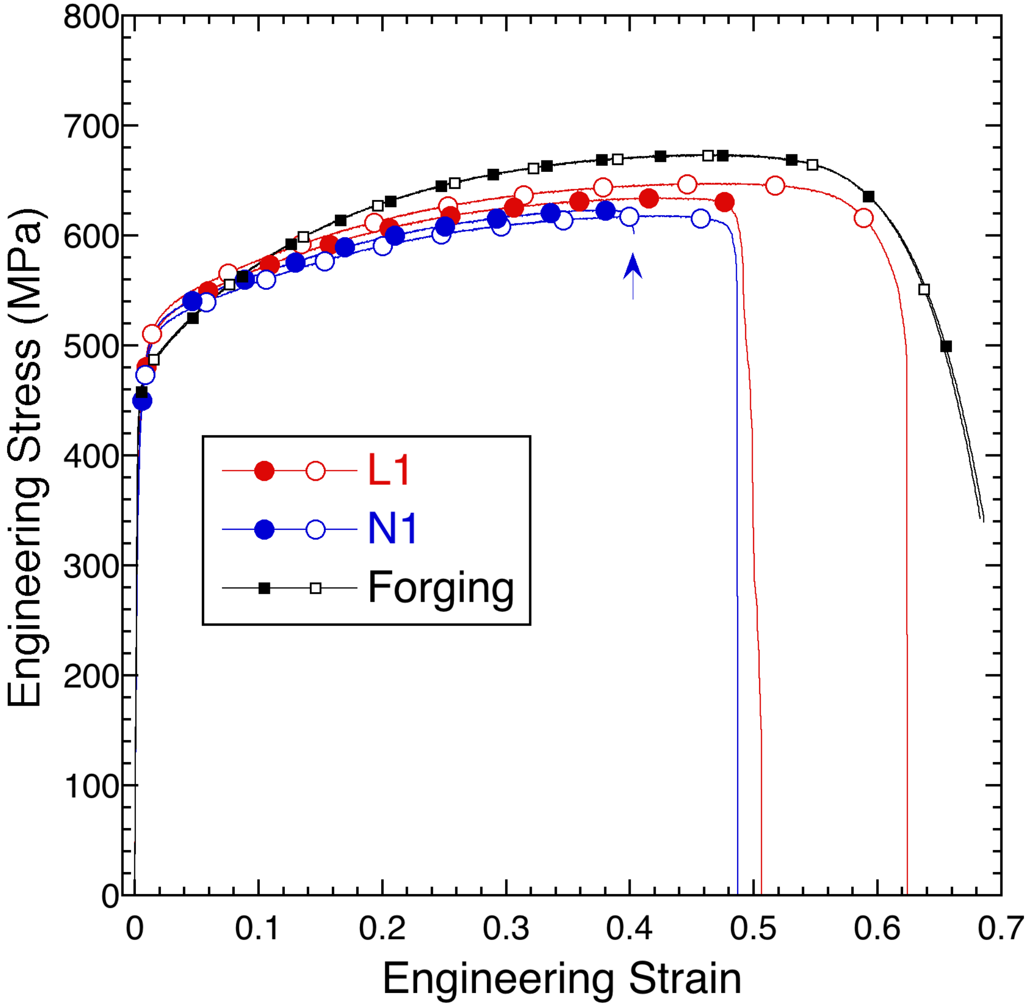
100µm



N4



Strength properties are consistent, ductility is variable



- Elongation to failure of SLM material is lower than expected for wrought 304L
- Elongation varies between 40-60% for these two materials

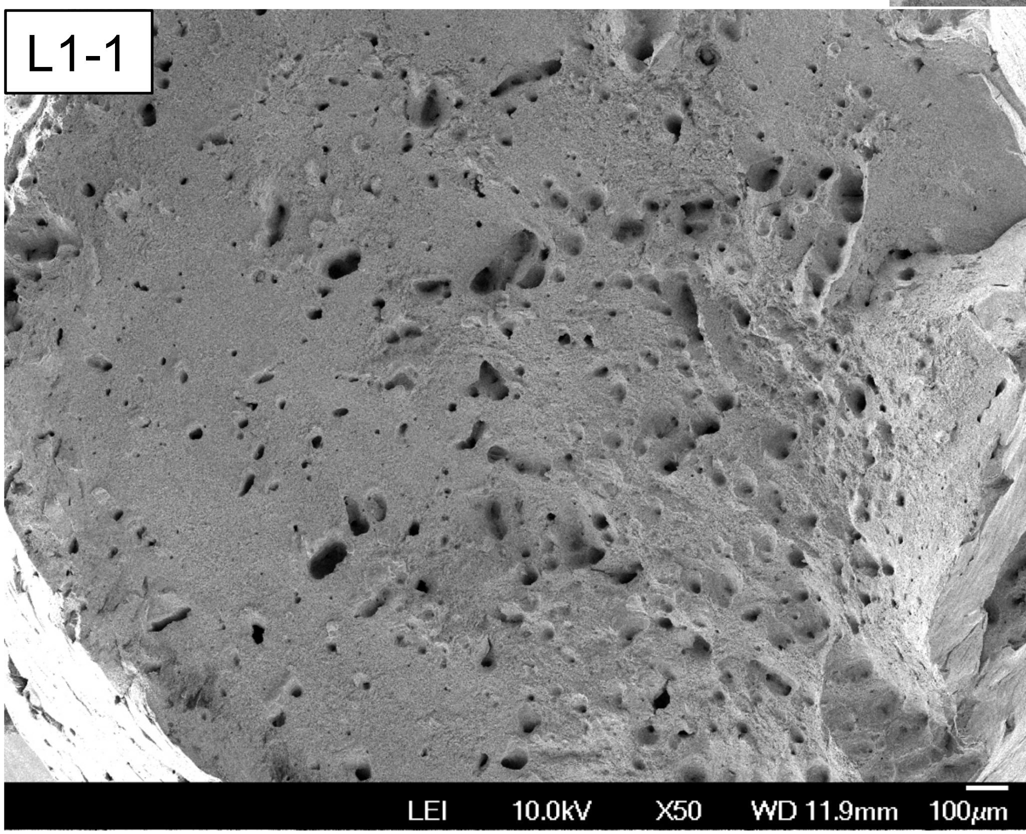
Tensile properties in the context of wrought materials

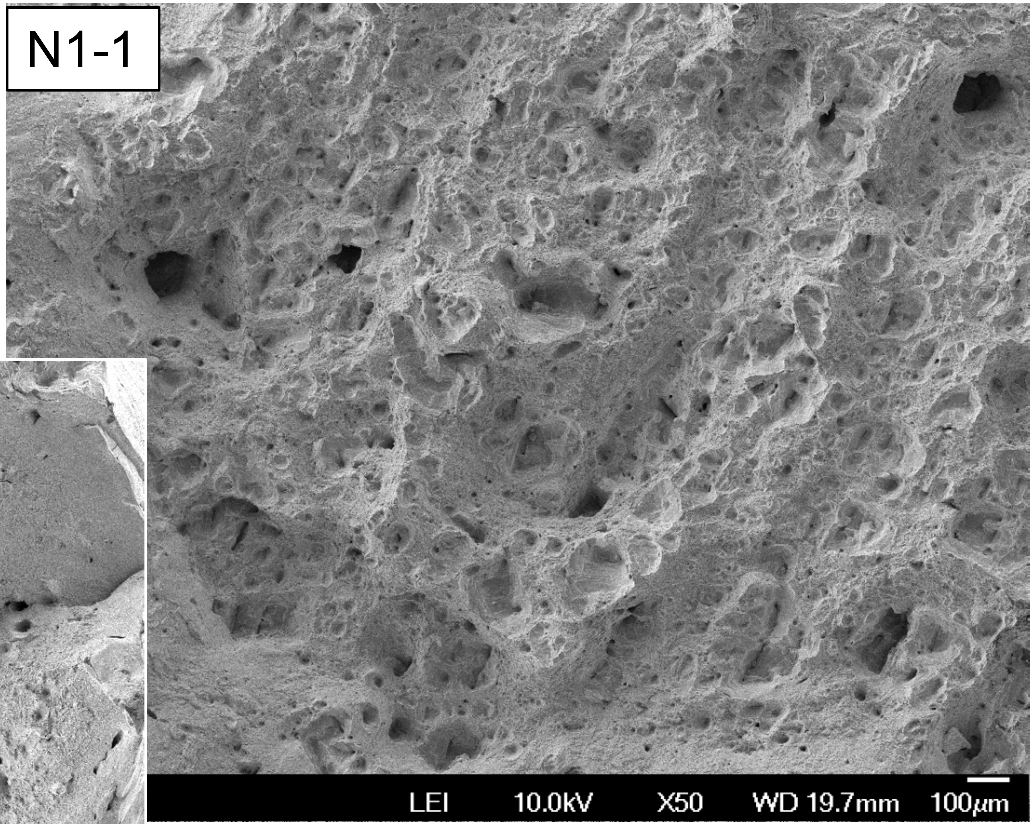
Build geometry	Designation	YS (MPa)	TS (MPa)	El (%)	RA (%)
SLM Ring	L1	414	641	57	49
SLM Ring	N1	413	621	45	39
Forging	55C	452	674	68	81
Forging	60C	506	694	66	82
requirement		380 520	585 min	35 min	40 min
ASTM A479, wrought bar strain-hardened 316		450 min	585 min	30 min	60 min

- ASTM E8 subsized cylindrical tensile specimens: 4 mm dia, 19 mm gauge
- Nominal strain rate 10^{-3} s^{-1} (constant crosshead)

Fractography reveals defects

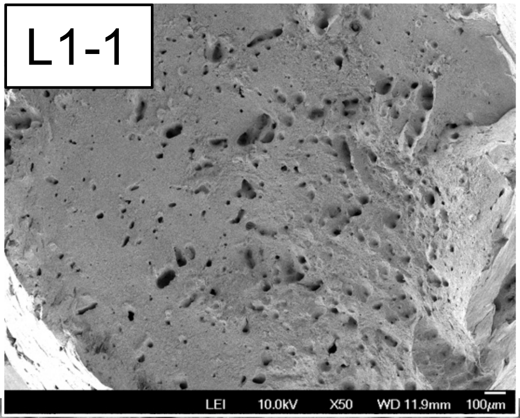
L1 material appears to have moderate density of distributed defects



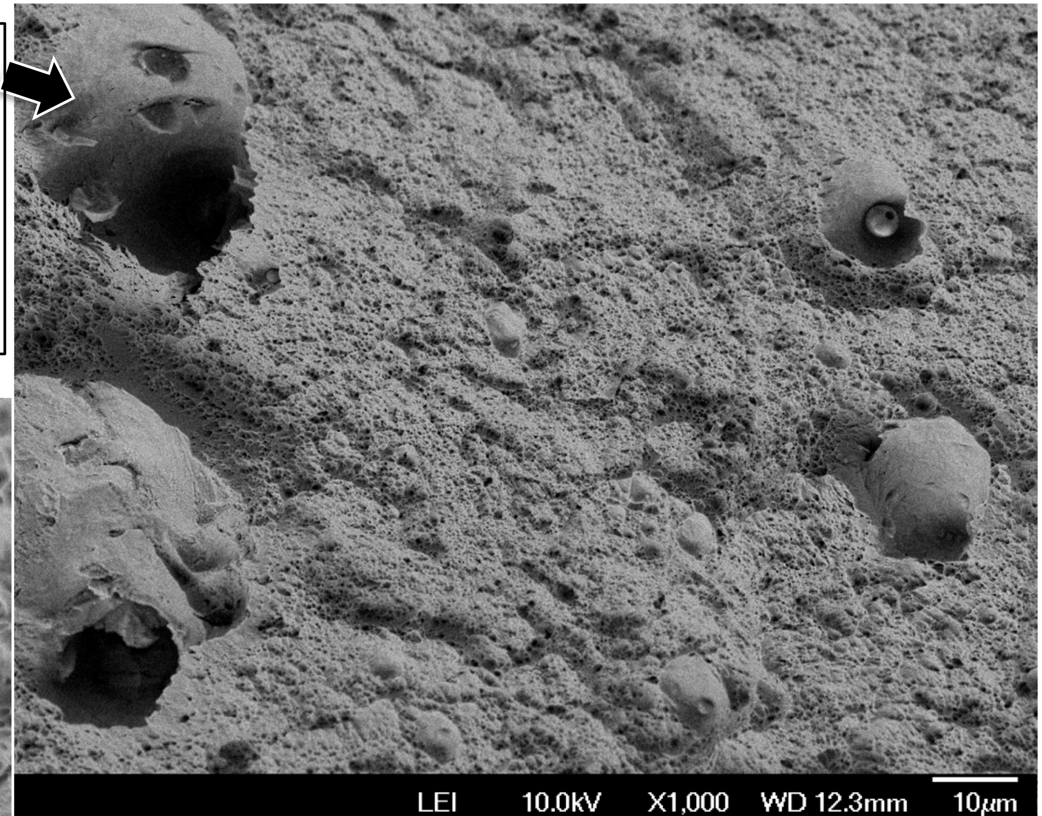


N1 material appears to have higher density of interacting defects

Defects in L1 material



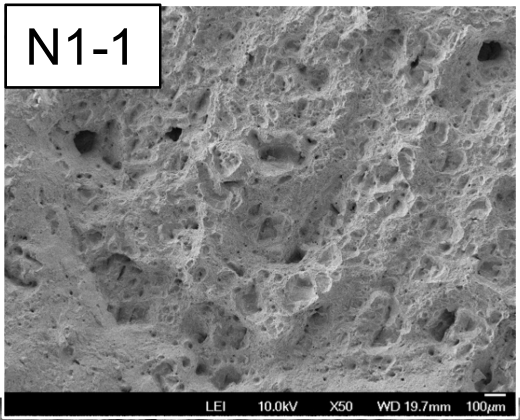
Relatively large defects, "isolated" from one another



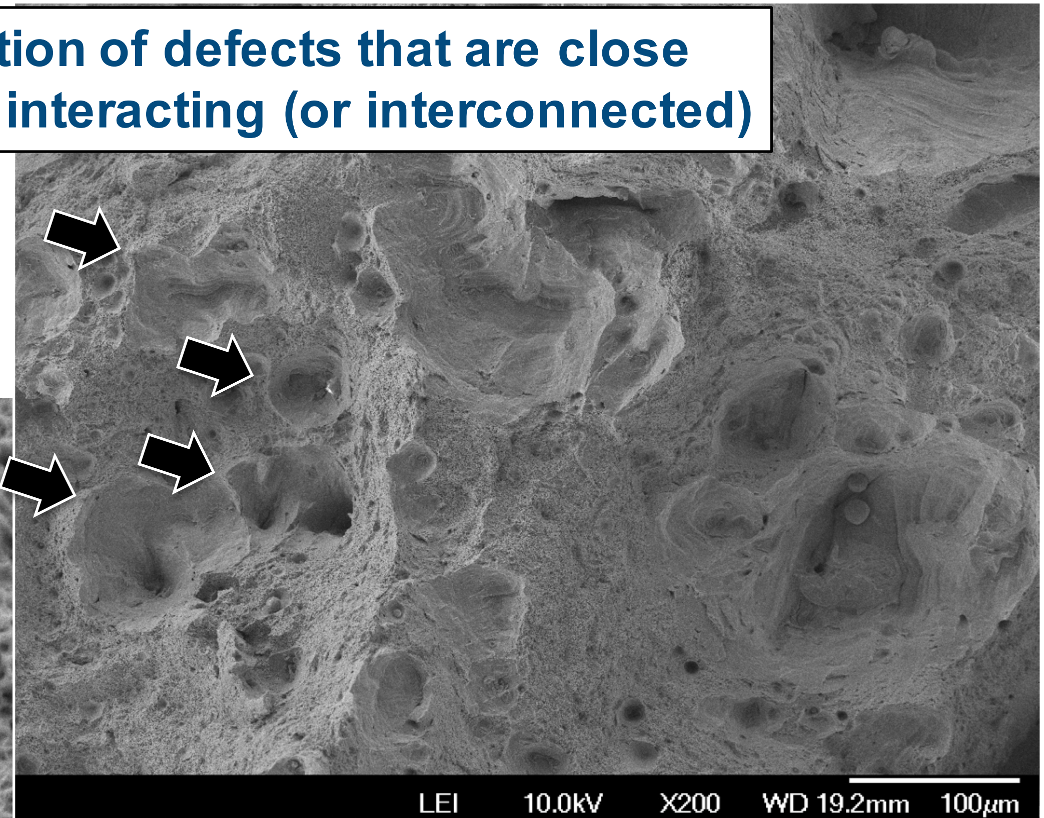
Very fine dimples, indicative of ductile deformation processes (microvoid coalescence)

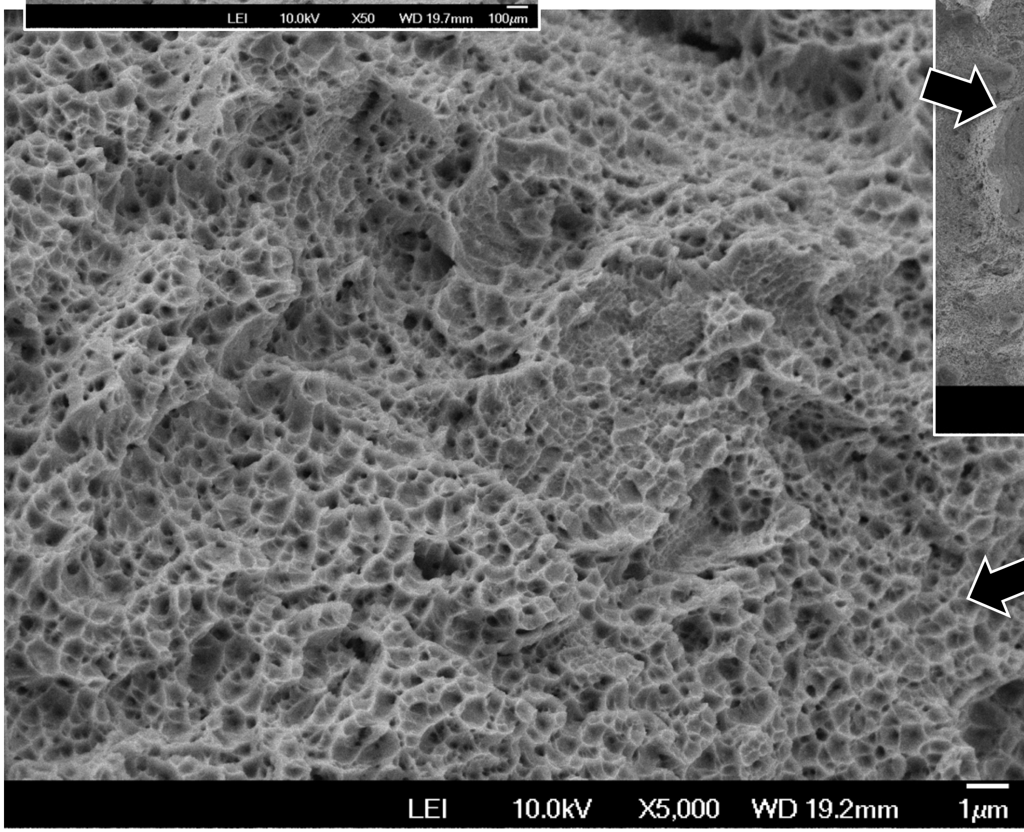
- **Dimples are order of magnitude smaller than wrought material**

Defects in N1 material



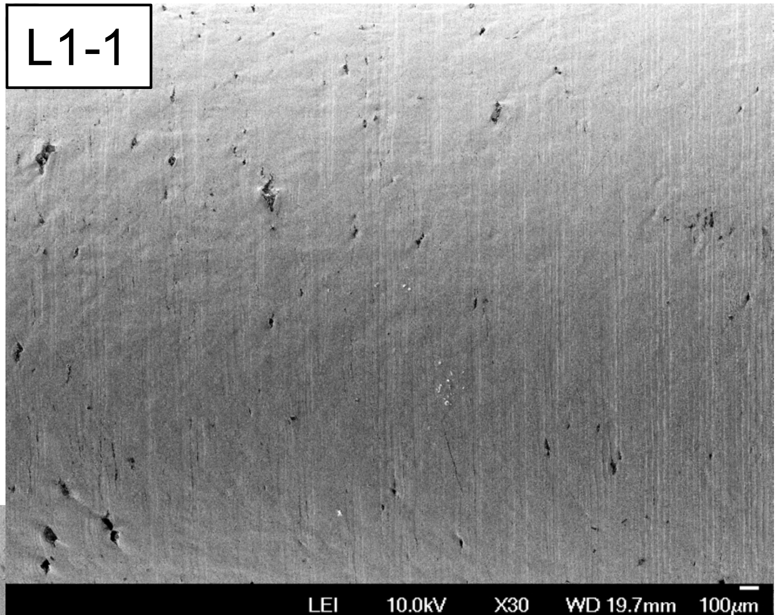
Large population of defects that are close enough to be interacting (or interconnected)

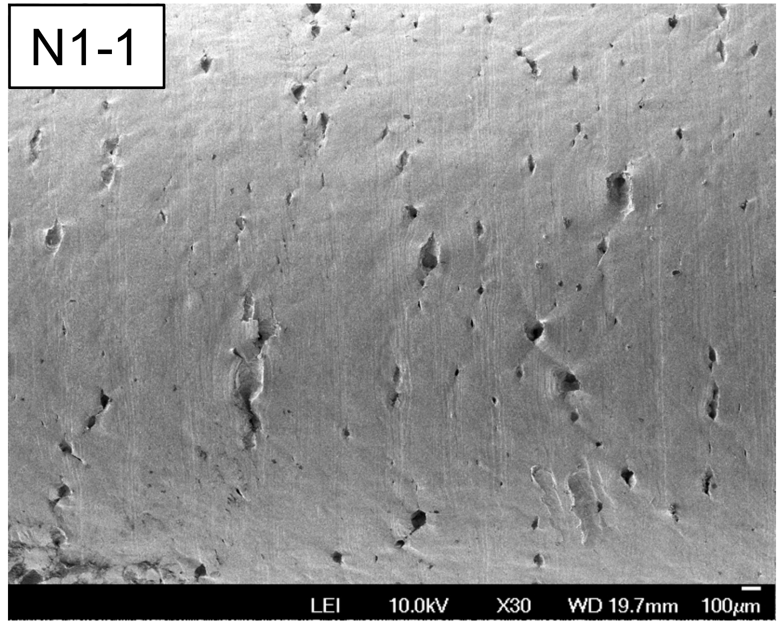


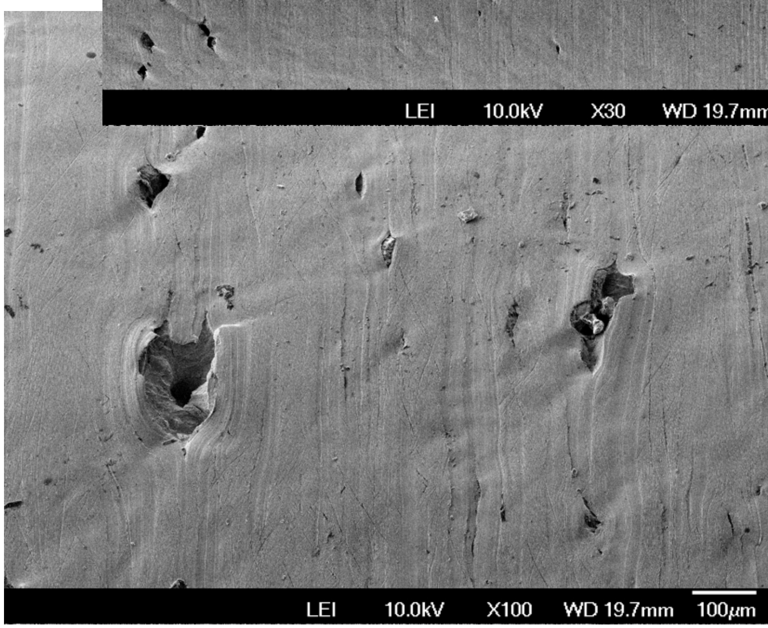


Very fine dimples, indicative of ductile deformation processes (microvoid coalescence)
- **Dimples are order of magnitude smaller than wrought material**

Surface damage reveals defects after tensile testing





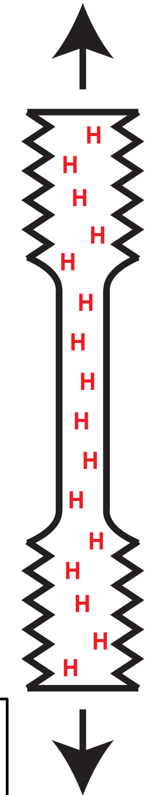


In all cases, shown after fracture and adjacent to fracture surface

- Surface defects apparent in both materials
  - Defect density seems greater in the N1 material (consistent with lower ductility)
- Extensive plasticity around the defects
  - evidence of deformation around defects (i.e., they appear roundish)

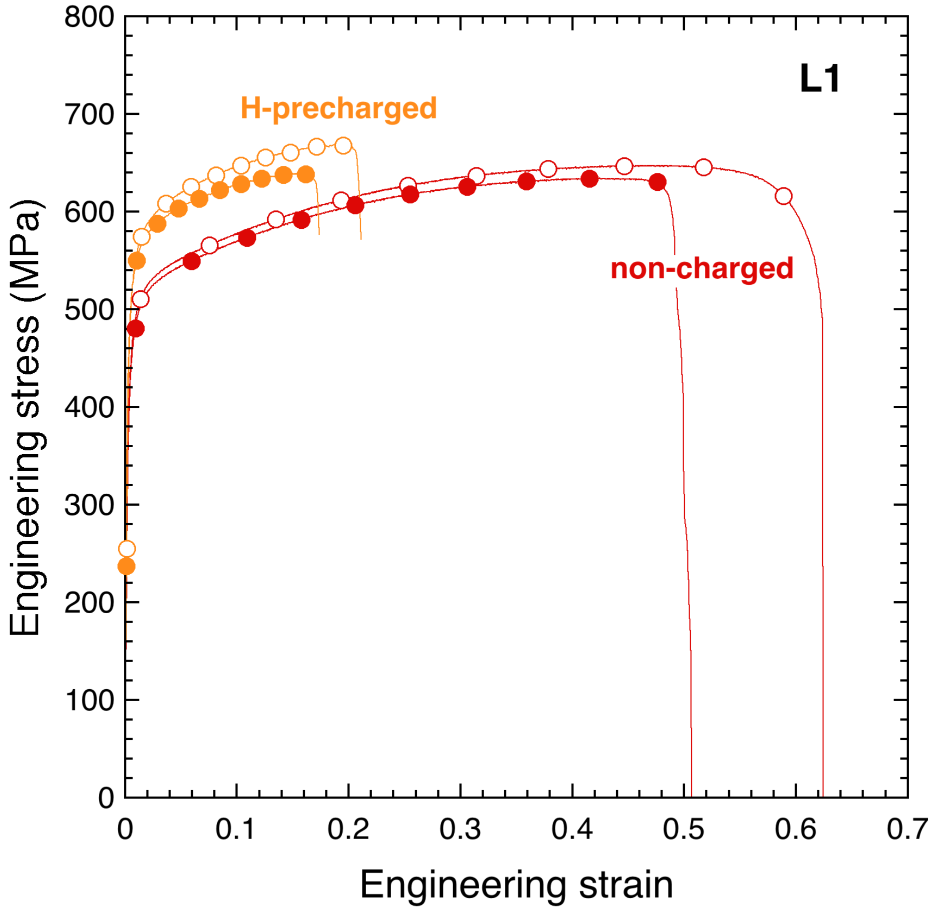
H-precharging is used to simulate hydrogen service environment

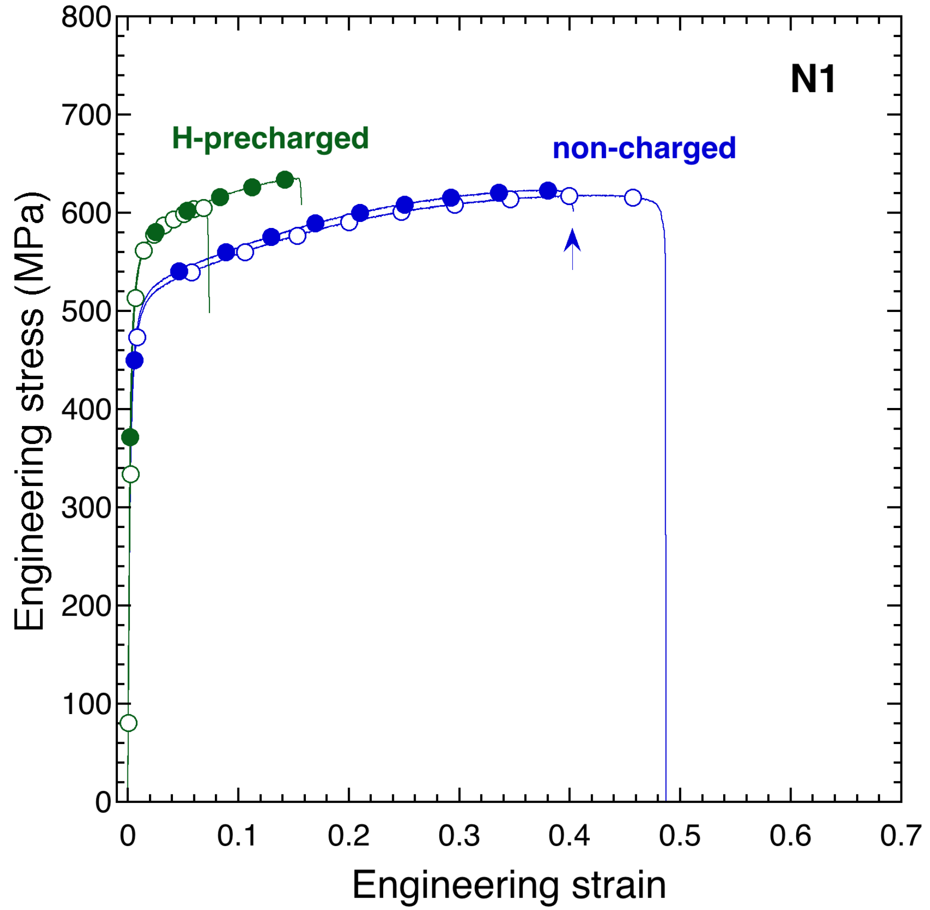
- Thermal H-precharging
  - Exposure to gaseous H2 until saturated with hydrogen (~10 days for 4 mm round bar)
    - Pressure: 138 MPa
    - Temperature: 300˚C
  - Hydrogen content ~140 ppm (wt)
- Testing in air after precharging with hydrogen



- Mechanical testing in H-precharged condition is similar to *in situ* testing in high-pressure gaseous hydrogen for tension, fatigue and fracture
  - *Must consider the H-solute hardening: strength increase of 10-20%*

Ductility of SLM 304L is severely degraded when H-precharged





Ductility is lower than expected for H-precharged 304L

H-effects on tensile properties

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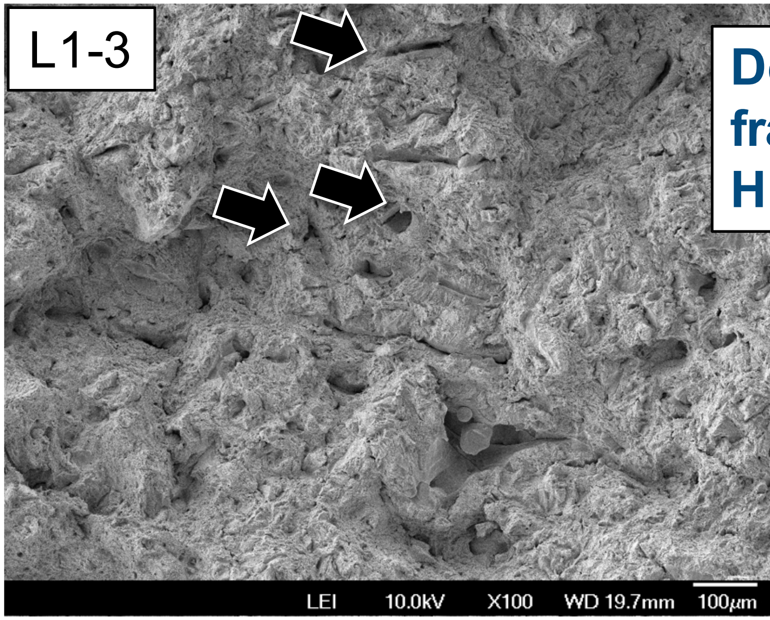
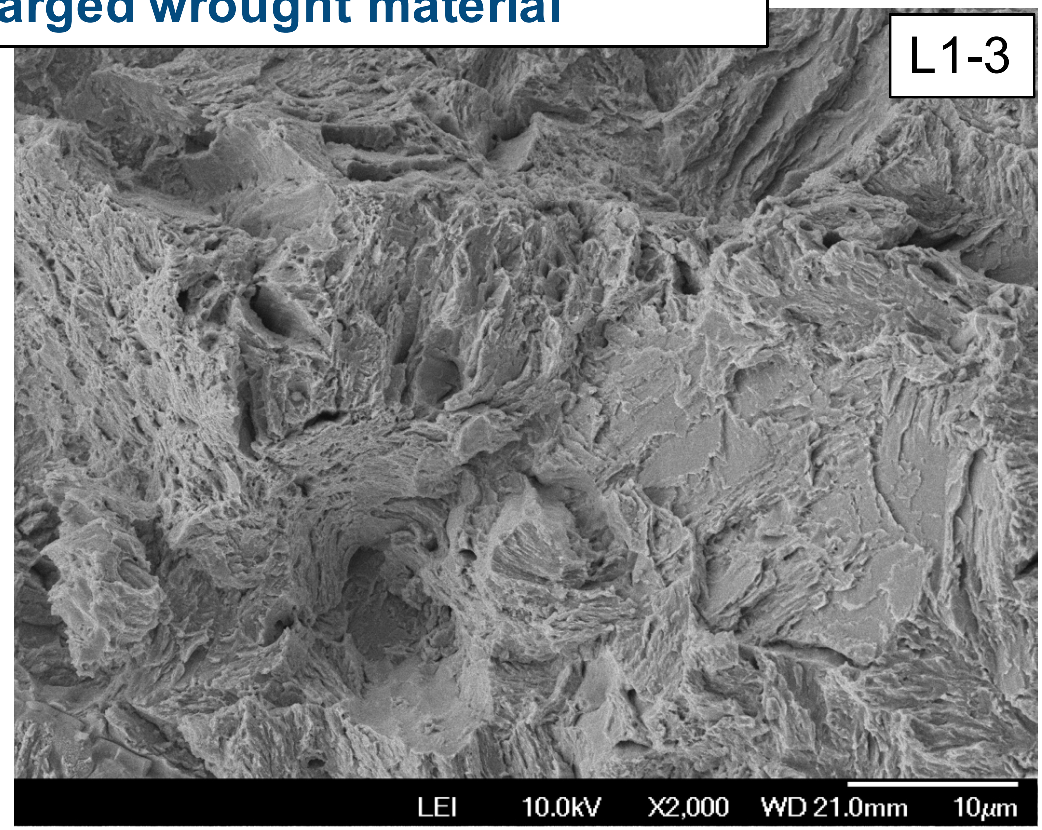
Build geometry	Designation	condition	YS (MPa)	TS (MPa)	El (%)	RA (%)
SLM Ring	L1	AR H	414 483	641 654	57 19 (17 min)	49 20
SLM Ring	N1	AR H	413 481	621 621	45 12 (7.4 min)	39 13
Forging	55C	AR H	452 484	674 758	68 58	81 49
Forging	60C	AR H	506 569	694 784	66 60	82 68

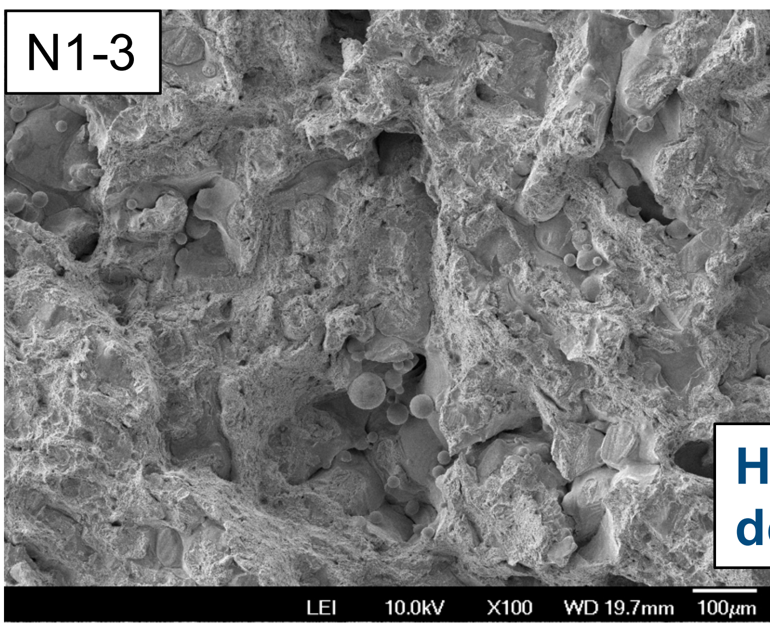
- Ductility of SLM 304L is significantly lower than forged 304L in the absence of hydrogen
  - RA = 40-50% (AM) vs RA = 80% (forged)
- Hydrogen reduces ductility in SLM 304L more than in forged 304L
  - RA = 13-20% (AM) vs 50+% (forged)

Fracture process is similar in SLM and forged



Defects appear isolated in L1 material, fracture details are consistent with H-precharged wrought material

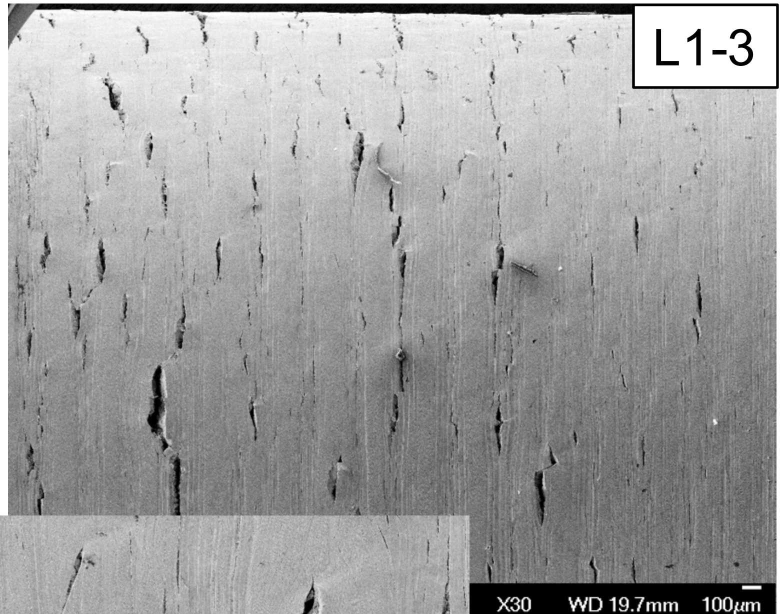


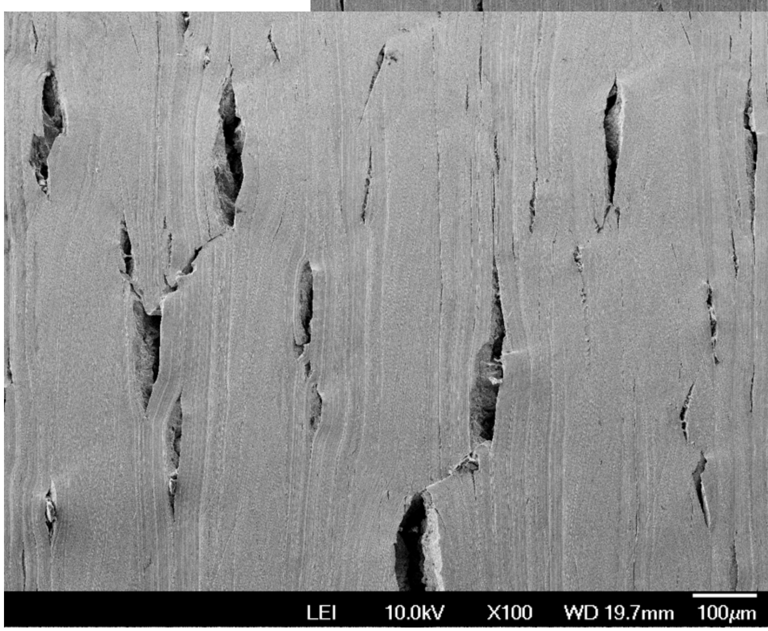


Hydrogen exacerbates defects in N1 material

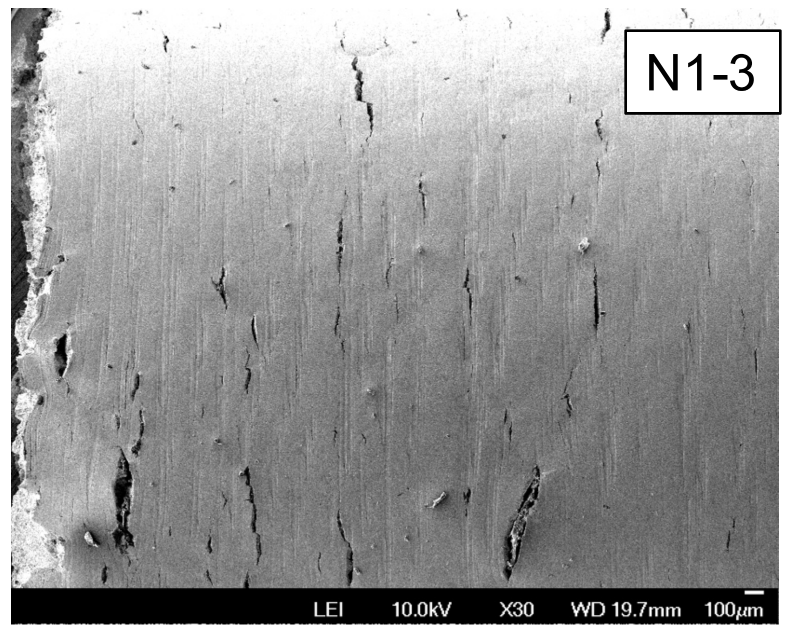
Extensive surface cracking in H-precharged materials

In all cases, shown after fracture and adjacent to fracture surface

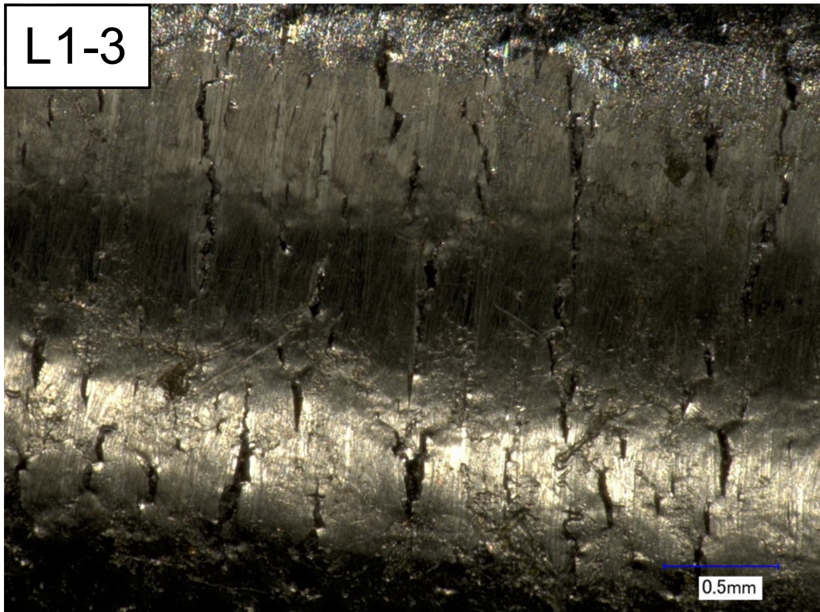




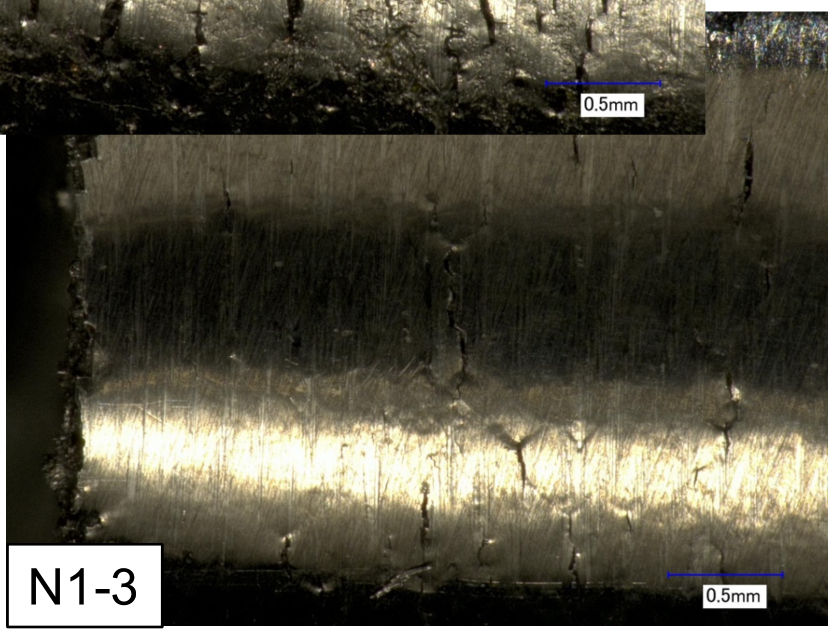
- When H-precharged, surface defects manifest as sharp cracks
  - Striking contrast to surface defects in the absence of H
- Such extensive surface cracking is generally not observed in wrought material

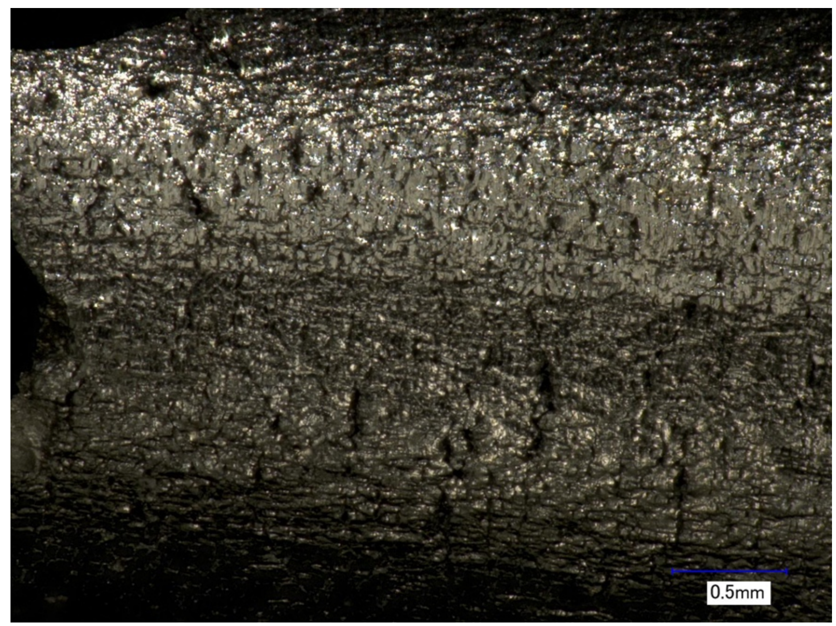


Forged materials show significantly less surface cracking when H-precharged

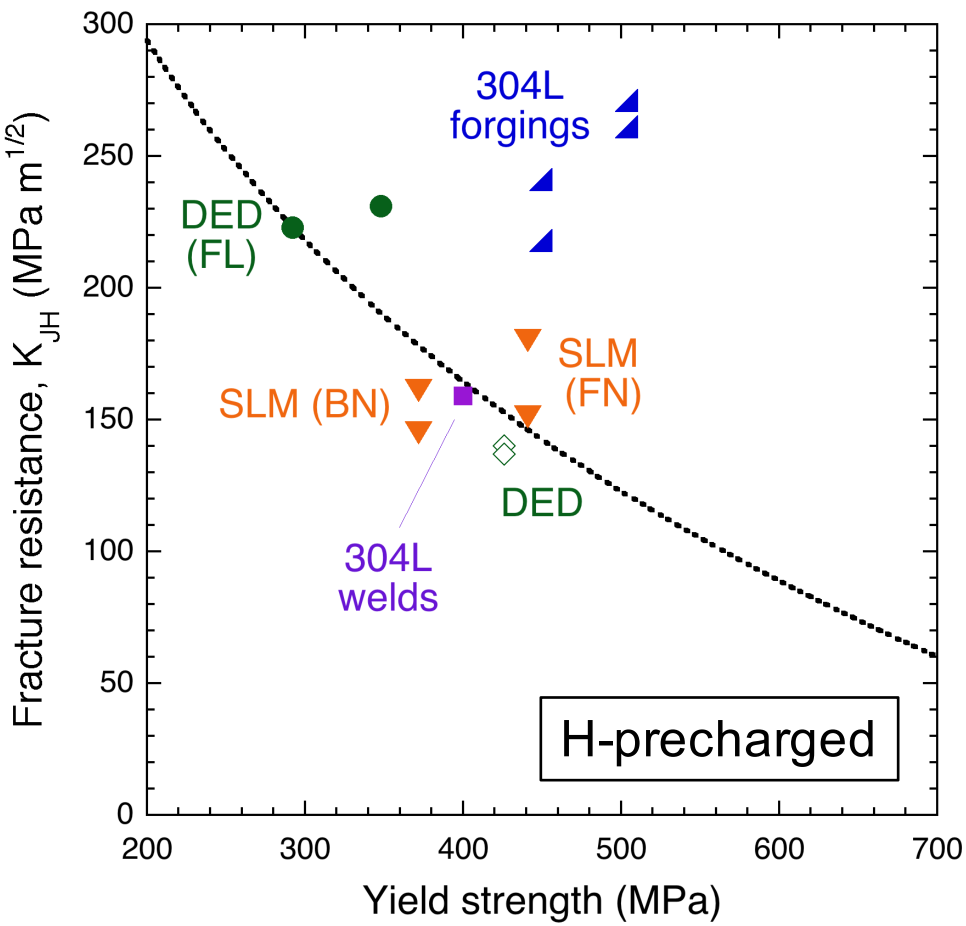


- AM materials show extensive cracking
  - But otherwise maintain machined-like surfaces due to low elongation to failure (<20%)
- Forged materials appear “puckered” due to much higher surface strains (elongation to failure >50%)





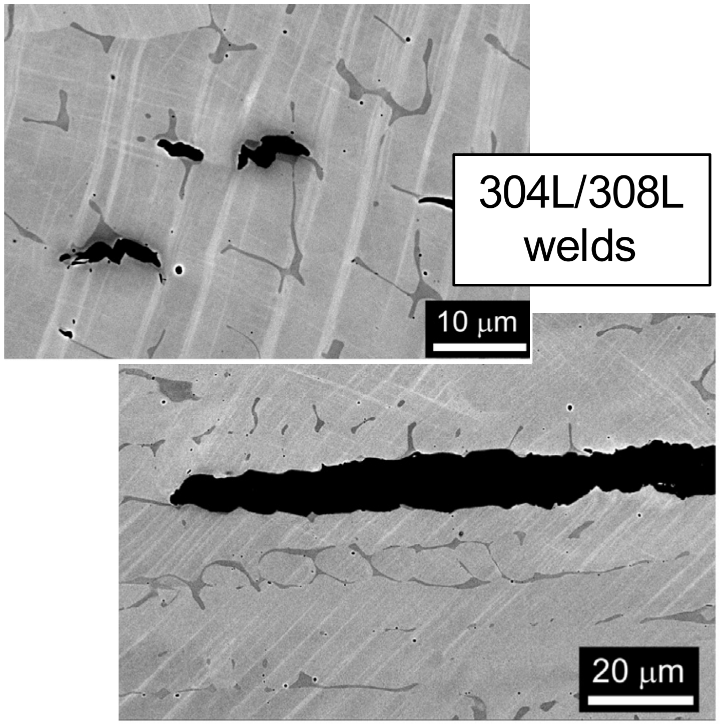
H-assisted fracture in AM austenitic stainless steels is similar to welded material



304L forgings: Jackson, Metall Mater Trans 47A
Welds: Jackson, Corros Sci 60
AM: San Marchi, Intern Conf Metals & Hydrogen 2018

- **Fracture toughness of AM stainless steels can be very high in air (not shown but >300 MPa $m^{1/2}$)**
- **When H-precharged, fracture resistance of AM materials is less than forged material**
- **AM materials appear consistent with:**
  - **Welds**
  - **Expected trend with strength**

Mechanisms of fracture may be similar to observations for welds



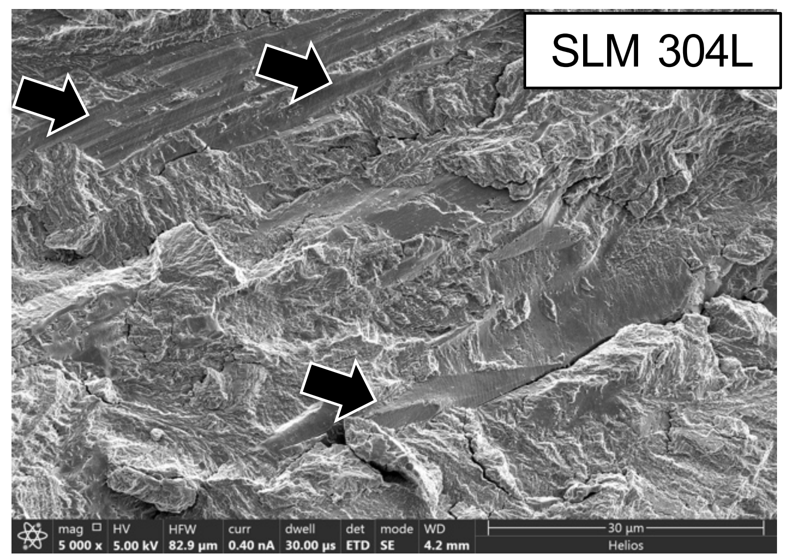
from: Jackson, Corros Sci 60

H-precharged 304L/308L welds show:

- Fracture of ferrite
- Fracture at γ/δ boundaries
- Void nucleation at ferrite boundaries

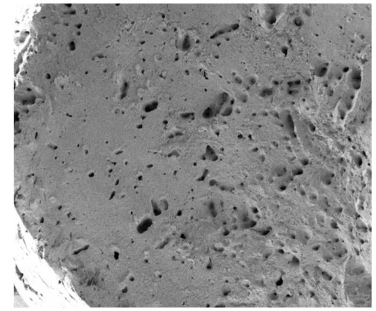
SLM material shows:

- Elongated flat fracture features that may be related to underlying solidification structure

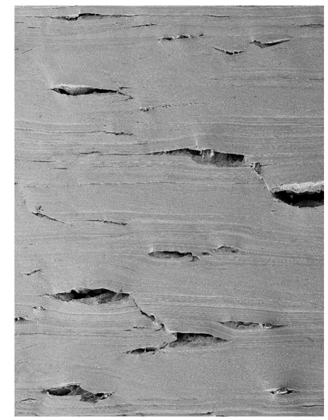


Like in welds, hydrogen-assisted fracture in AM austenitic stainless may be related to *ferrite* and *compositional microsegregation*

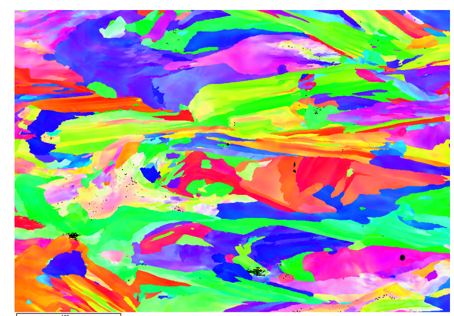
Summary



- SLM 304L features strength consistent with strain-hardened (forged) wrought 304L
  - Strength properties can be reproducible
  - Ductility can varying significantly in SLM materials



- SLM 304L is more sensitive to H-assisted fracture than wrought materials
  - Significant degradation of elongation and RA
  - Fracture resistance is lower than wrought material when H-precharged, but consistent with welds



- Mechanisms of hydrogen interactions appear qualitatively similar to welded microstructures