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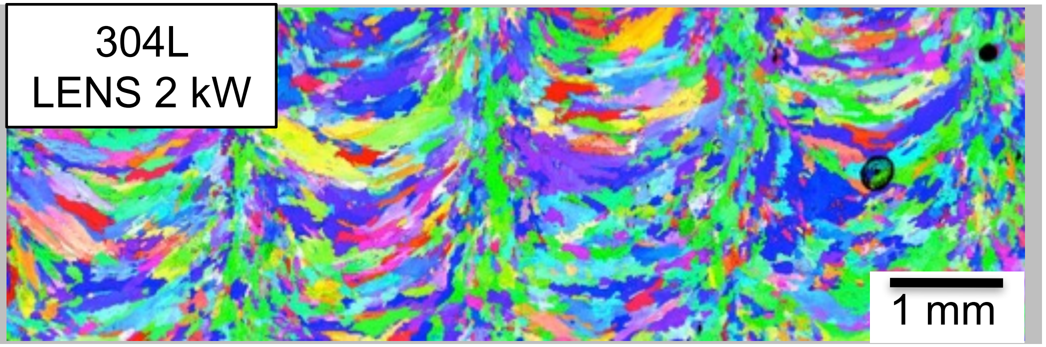

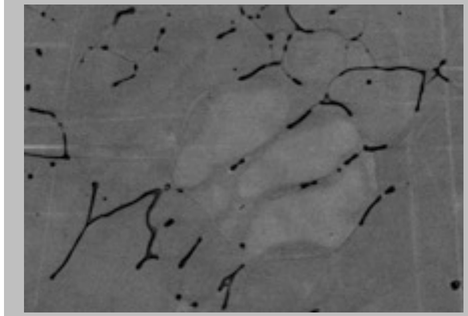

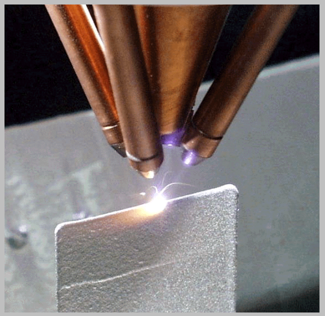

Fracture and Fatigue Behavior of Additively Manufactured Austenitic Stainless Steel

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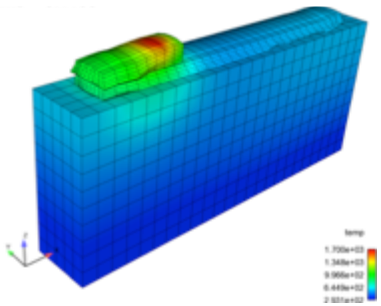
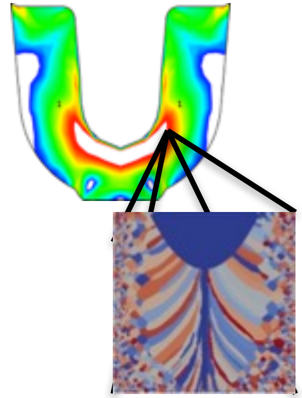
Motivation:
Develop Lifecycle Analysis Framework for Additive Manufacturing

Process Design and Simulation
Advanced process controls and diagnostics enable simulation tools to "grow" near-net-shape structure

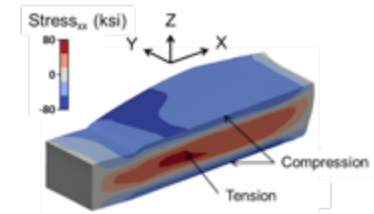


Microstructure and Properties



Internal state variable models account for microstructural evolution and distribution of properties (related to spatial variations of thermal history)

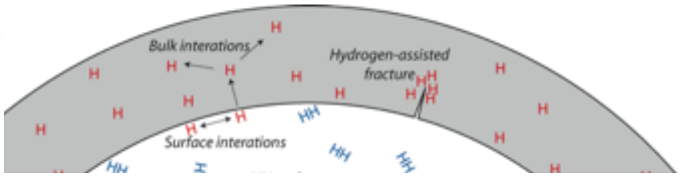
Residual Stresses



Solidification and thermal history result in strong residual stresses, which can impact performance

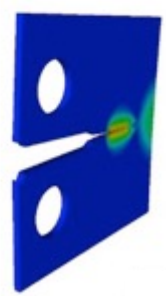
- Predictive uncertainties result in large safety factors, reduced lifetimes, and increased costs.
- Our approach develops tools to reduce uncertainty, increase understanding, and enhance predictive capability.

Assembly and Service
Multiphysics approaches for fully coupled simulation of chemical/thermal transport, mechanical loading, etc. to predict performance

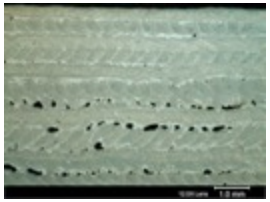


(includes unique service environments, such as hydrogen embrittlement, corrosion, microstructural aging, etc)

Crack Initiation, Growth and Failure
Transition from crack initiation to failure is not well characterized and depends on microstructure and defects

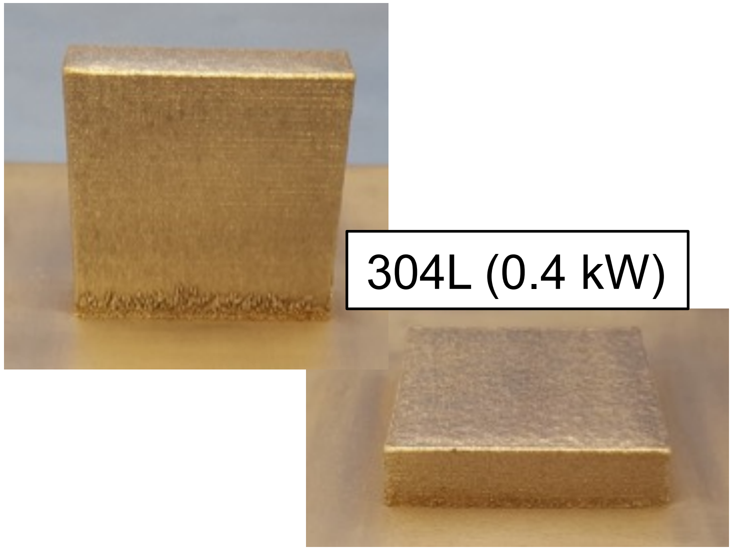


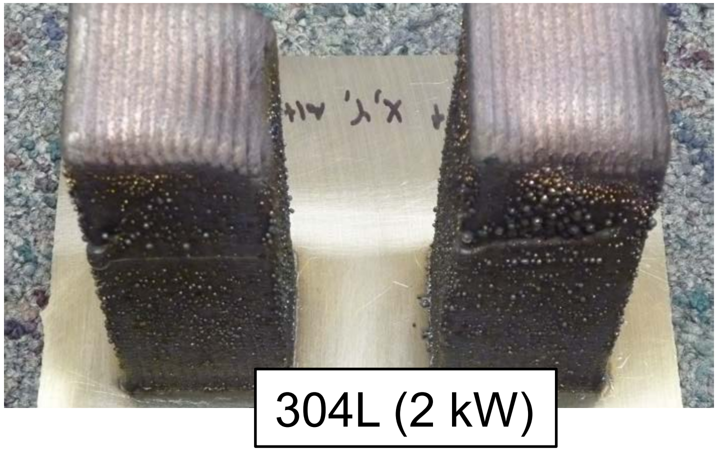
Margin/Uncertainty → Design Life
Service requirements may dictate design iteration to assure sufficient margin based on predictive uncertainties.
The lifecycle analysis provides a tool to enable design optimization to meet the requirements.



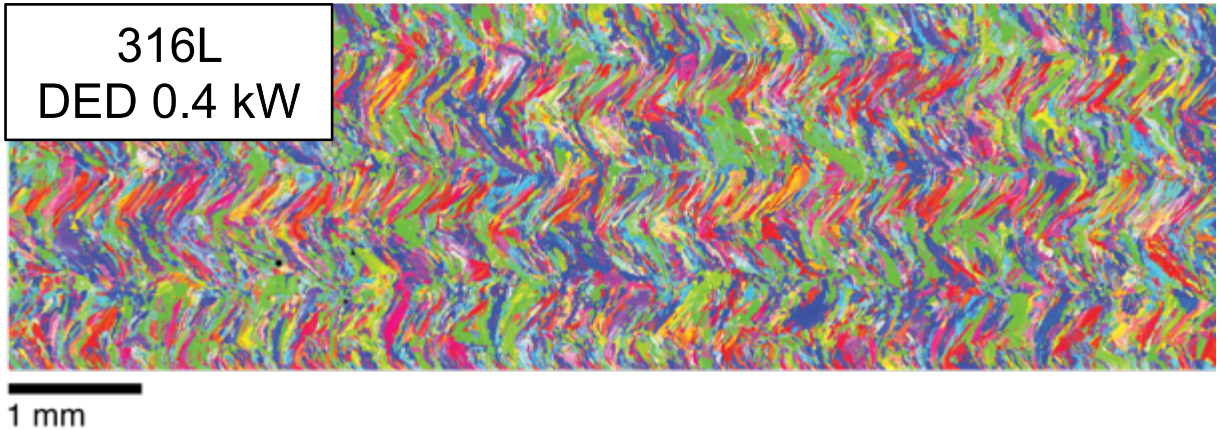
Materials

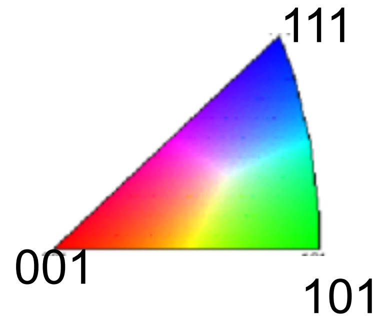
Nominal Powder Composition	Designation /Process	Test configurations
316L	DED (0.4 kW)	Tension Fatigue Fracture
304L	DED (0.4 kW)	Tension
304L	DED (2 kW)	Tension Fatigue Fracture
304L	SLM (0.5 kW)	Fracture
304L	DED	Fracture

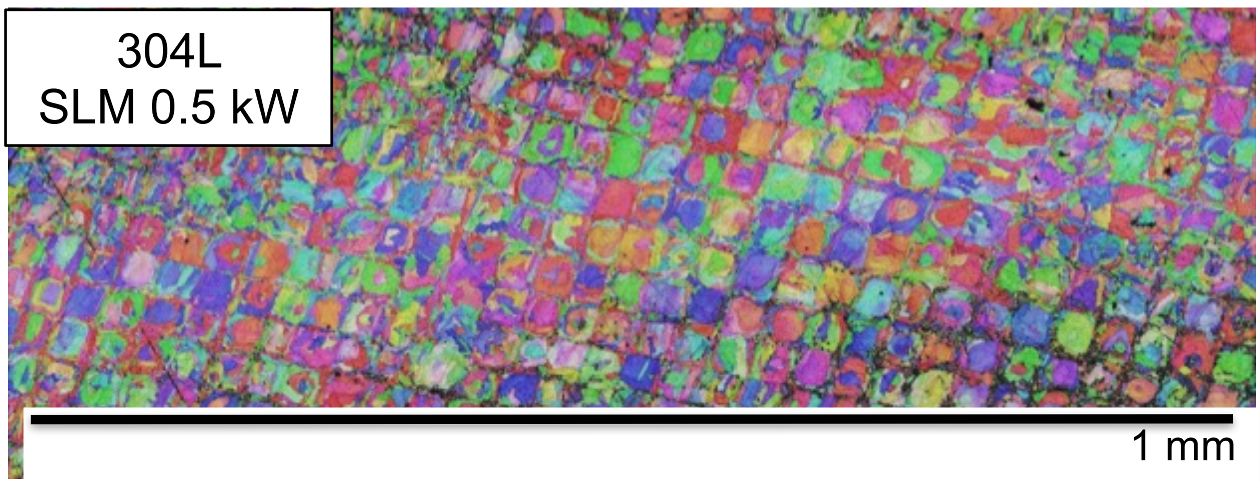


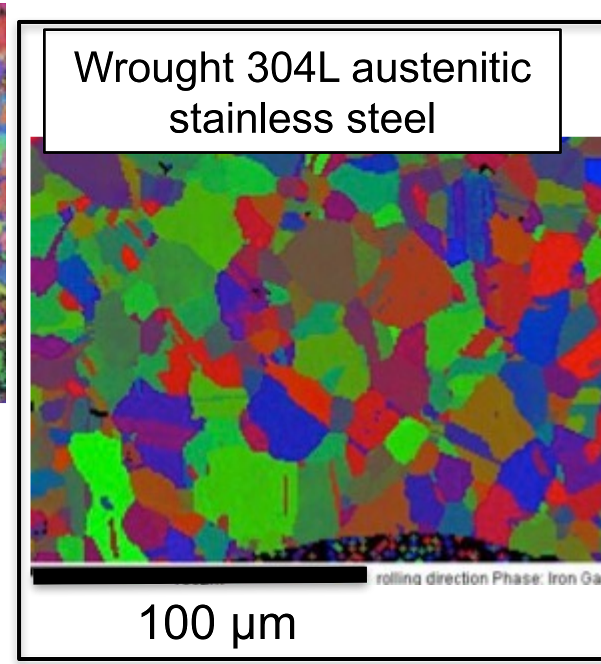


Grain structure is distinct from wrought materials, similar in some aspects to weld microstructure



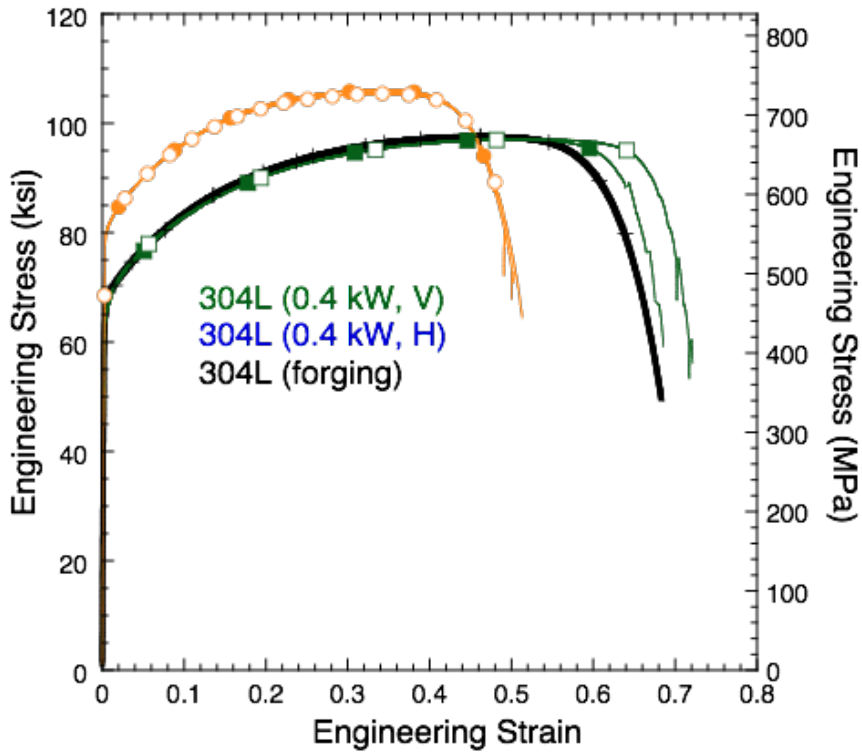


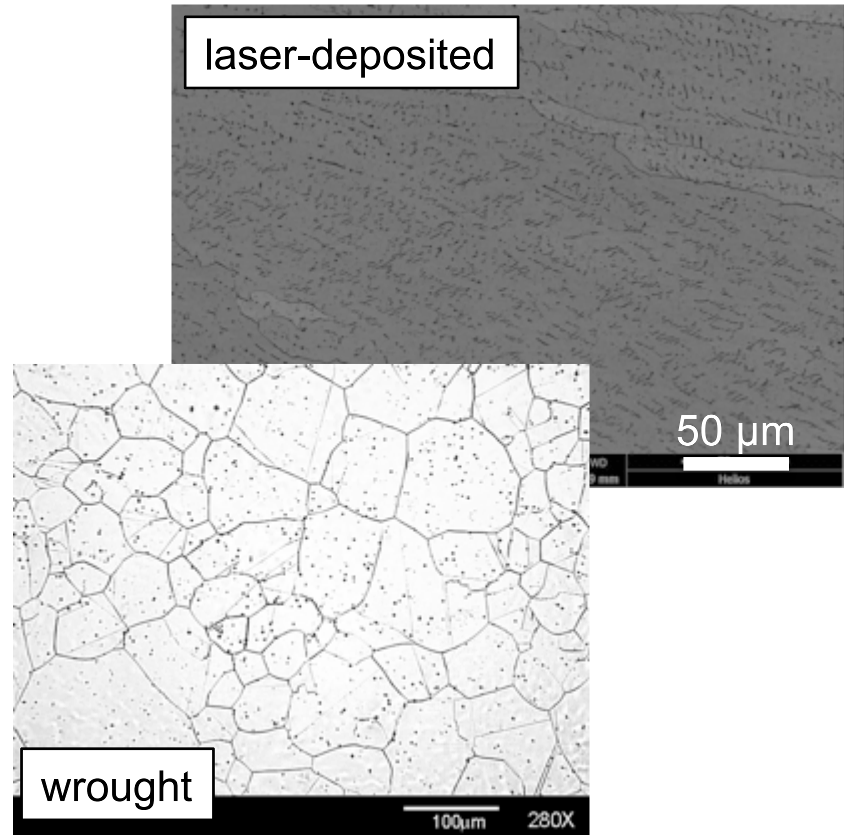




- AM microstructures depend on processing conditions
- ***What is the effect on structural properties?***

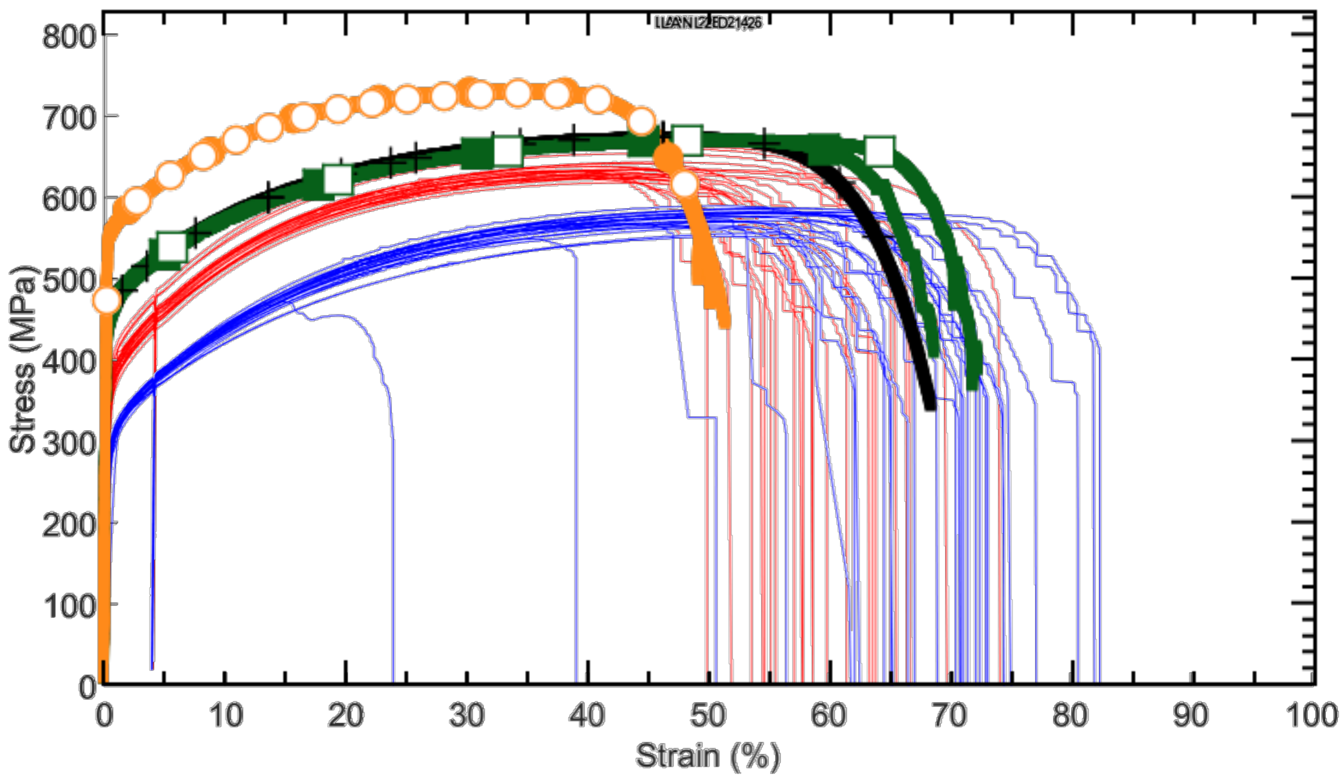
Tensile response can compare favorably to wrought materials





- **Laser-deposited and wrought materials show similar tensile strength and ductility despite very different microstructures**
- ***How does the fracture response compare?***

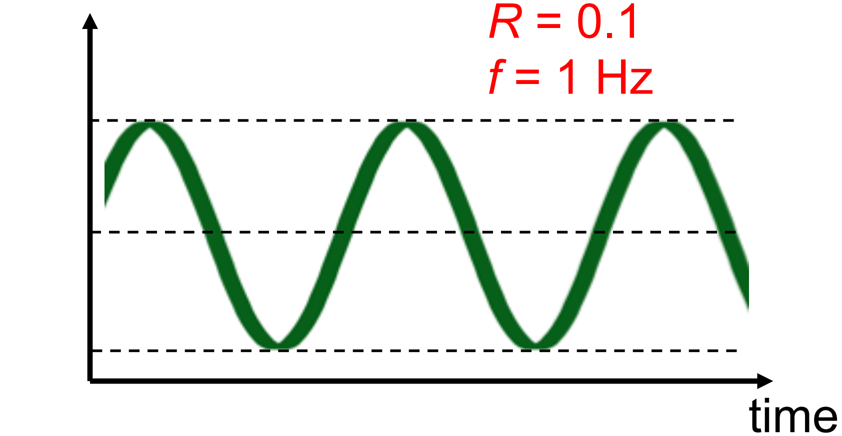
Comparison of DED 304L materials with different pedigree



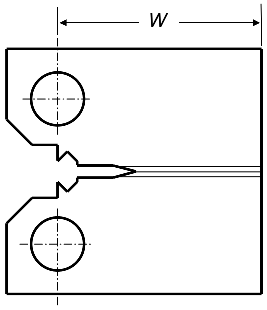
- **Strengthening in AM austenitic stainless steel is not well understood**
  - **Strength will likely impact fracture resistance**

Fatigue and fracture measurements

- Fatigue crack growth: da/dN
  - ASTM E647, constant load amplitude
- Fracture resistance: J_{IC}
  - ASTM E1820, elastic-plastic analysis using J-R curve determination



- **Compact tension geometry**
  - B ~ 13 mm (thickness)
  - W ~ 26 mm (width)

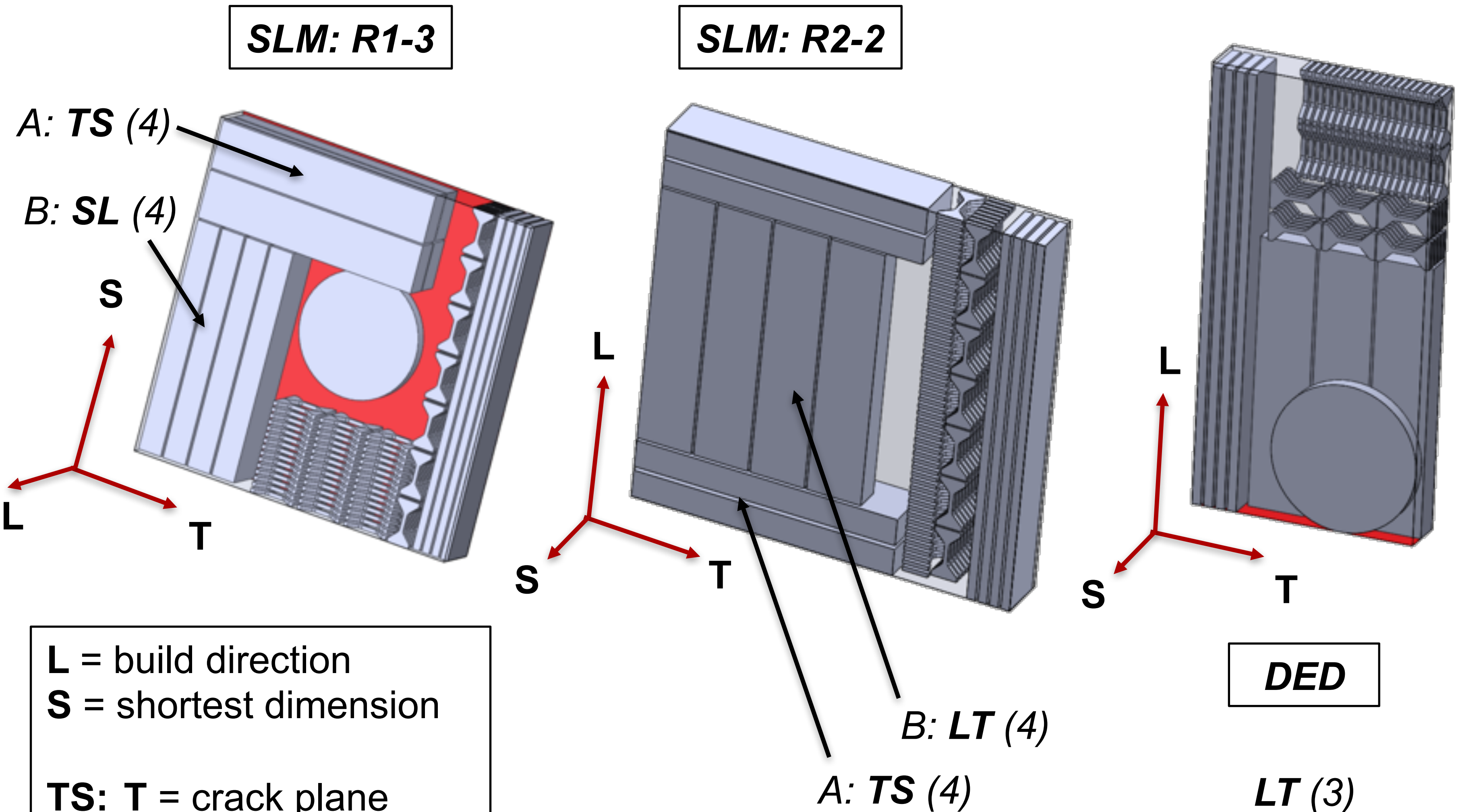


Fatigue test, then fracture test performed on same sample

- **3-point bend geometry**
  - B ~ 6.3 mm (thickness)
  - W ~ 13 mm (width)
  - S ~ 50 mm (span)

- Direct current potential difference (DCPD) method for in-situ monitoring of crack position

Specimen designation and orientation

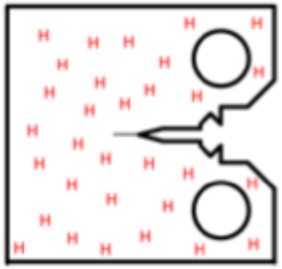


L = build direction
S = shortest dimension

TS: **T** = crack plane
S = crack direction

Testing in the H-precharged condition

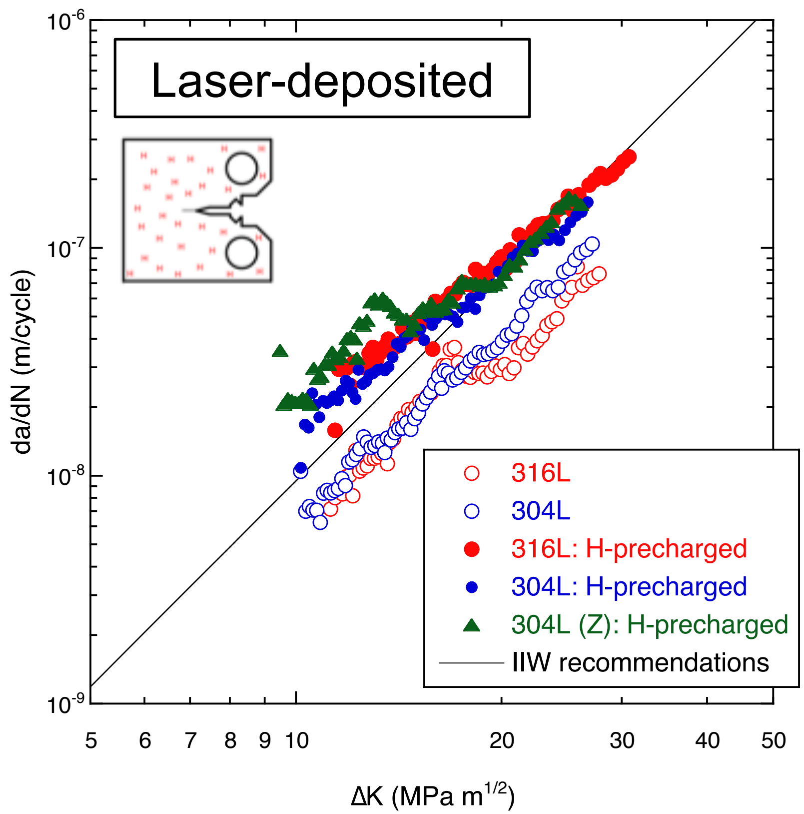
- Thermal H-precharging
  - Exposure to gaseous H2 until saturated with hydrogen (~60 days)
    - Pressure: 138 MPa
    - Temperature: 300˚C
  - Hydrogen content ~140 ppm (wt)

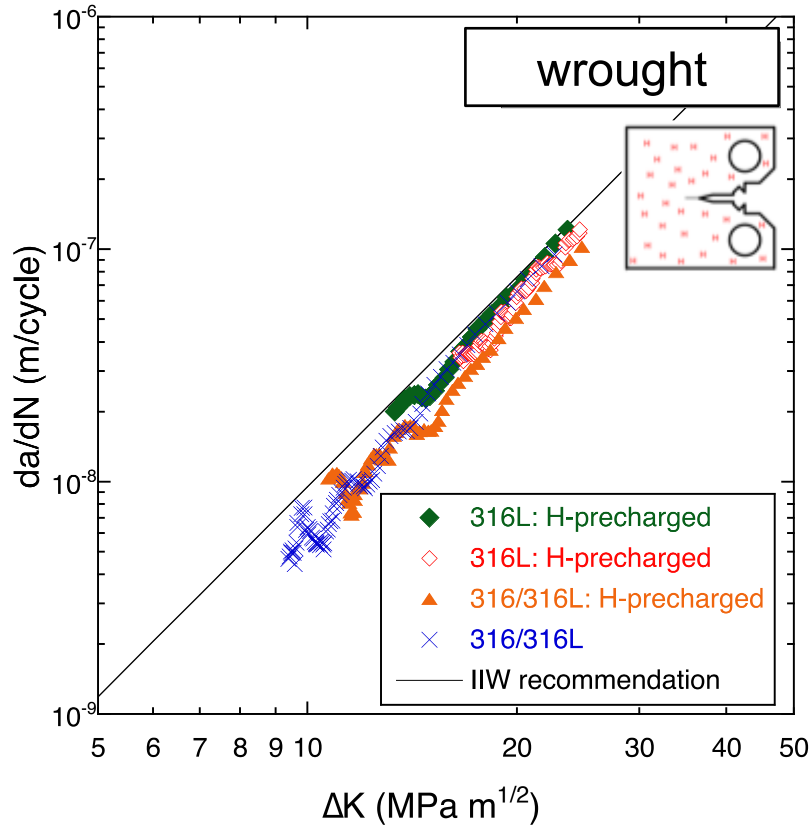


- Testing in air after precharging with hydrogen

- 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%*

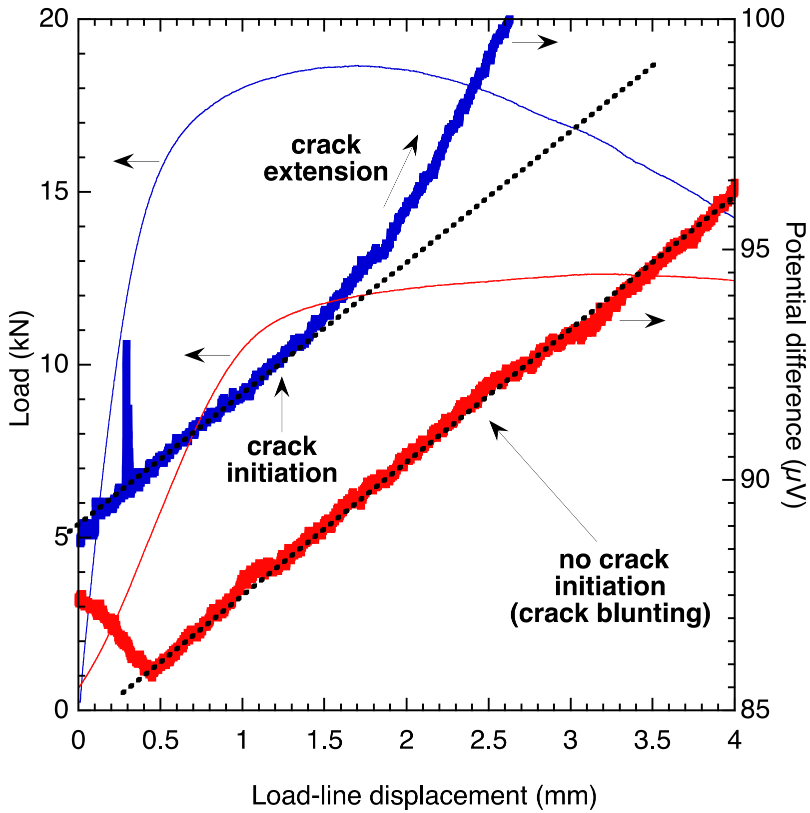
Fatigue crack growth measurements



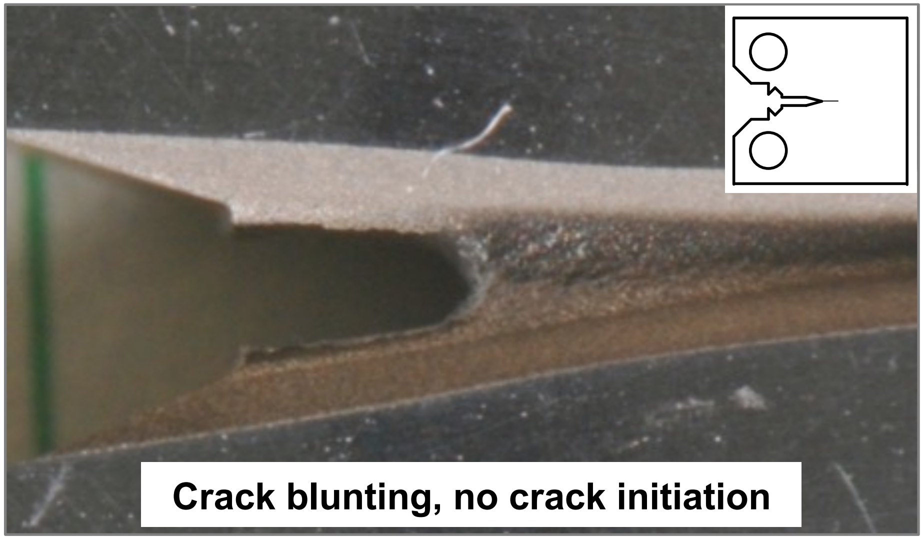


- Fatigue crack growth rates of laser-deposited type 304L & 316L are consistent with wrought steels
- Hydrogen accelerates fatigue crack growth in laser-deposited materials, unlike wrought materials

Laser-deposited materials display crack blunting



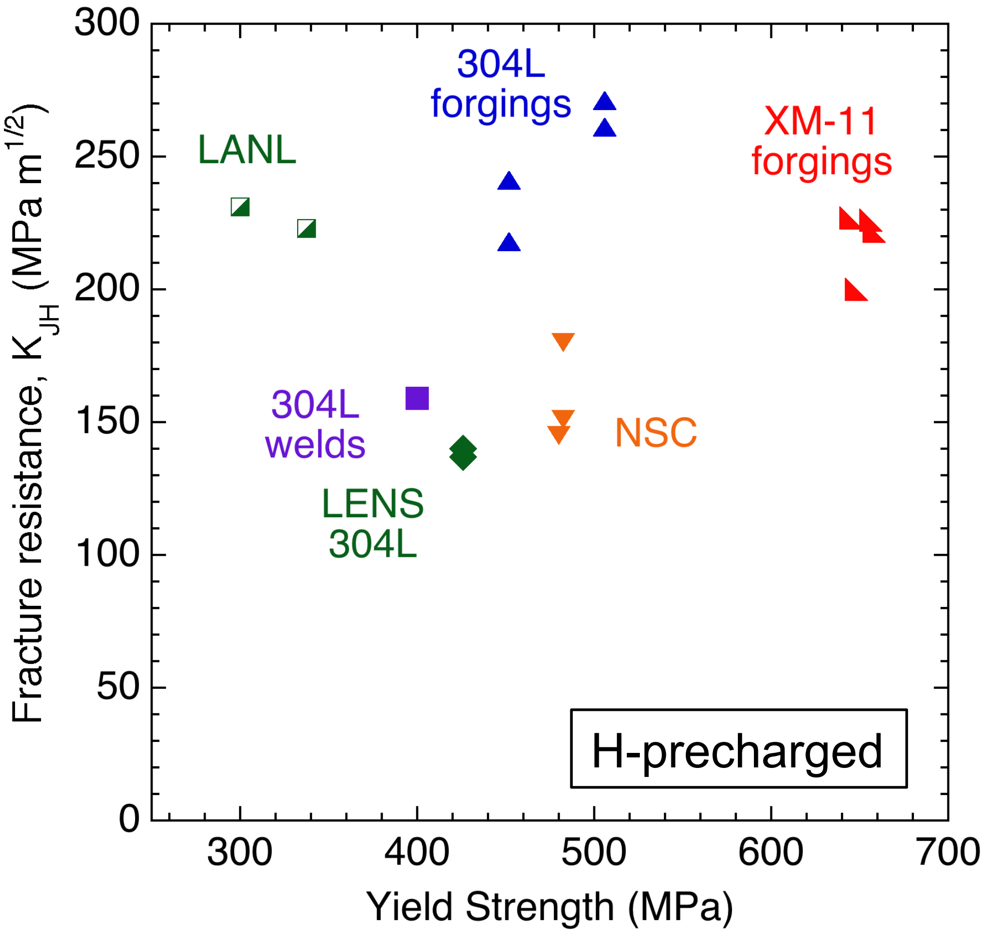
Crack blunting implies very high fracture toughness: >200 MPa m$^{1/2}$



Crack blunting, no crack initiation

Crack initiation and extension:
not observed in laser-deposited materials

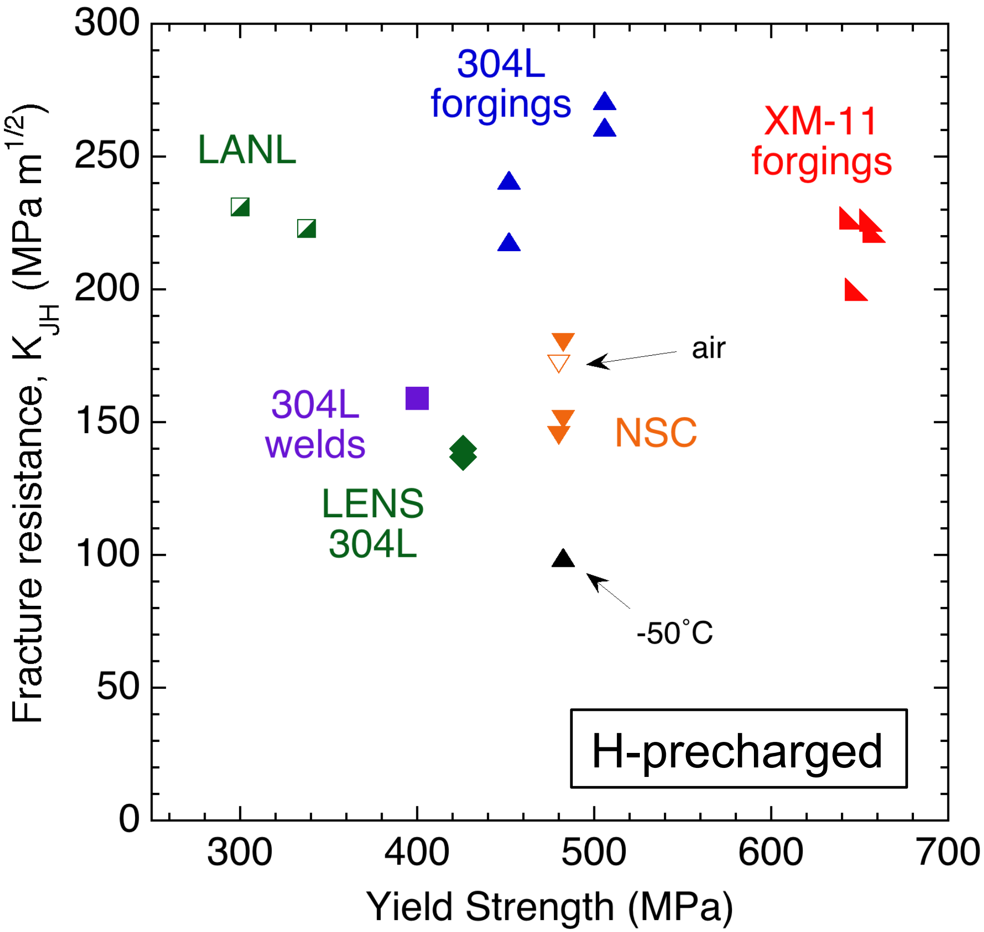
Fracture measurements



- Fracture resistance of H-precharged AM 304L is:
  - *similar to response of austenitic stainless steels welds*
- Lower fracture resistance compared to forgings is consistent with accelerated fatigue crack growth
- Lower strength results in higher fracture resistance (as expected)

304L forgings: Jackson, Metall Mater Trans 47A
XM-11 forgings: Nibur, Acta Mater 57
Welds: Jackson, Corros Sci 60

Fracture measurements

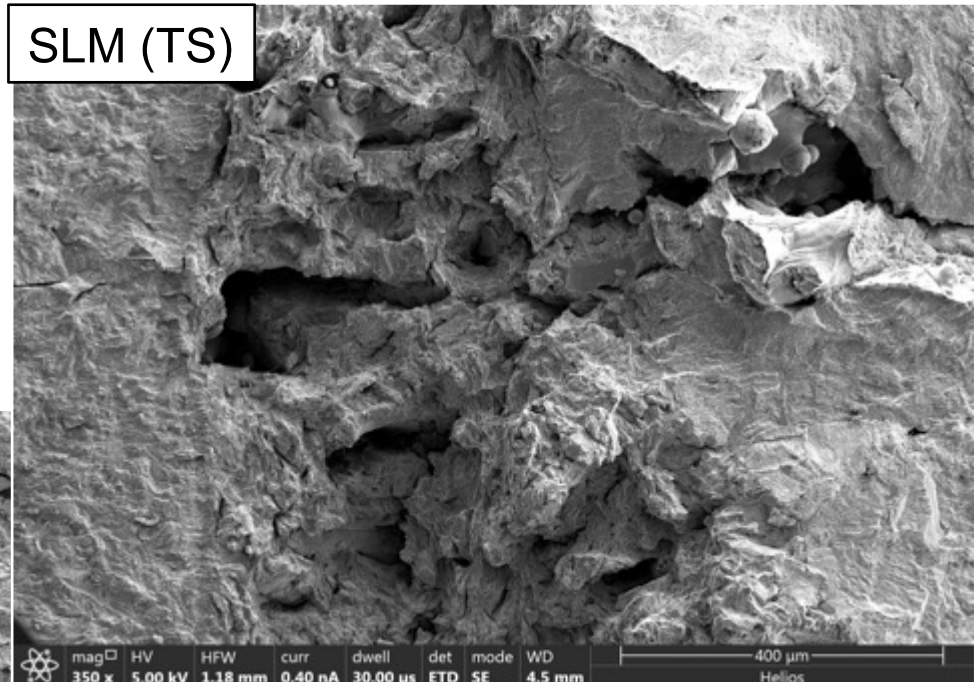


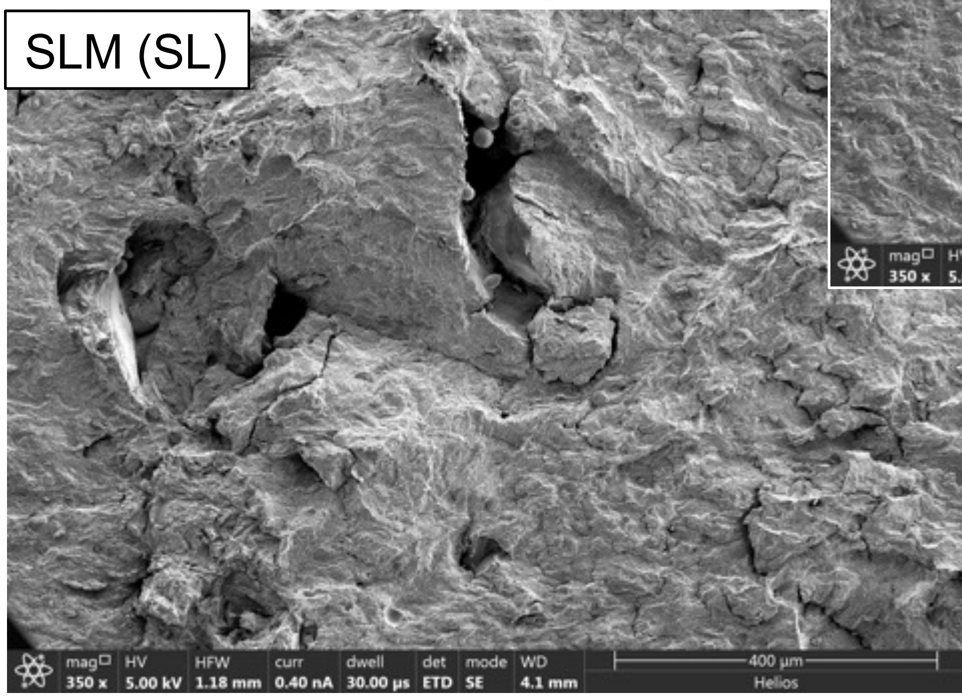
304L forgings: Jackson, Metall Mater Trans 47A
XM-11 forgings: Nibur, Acta Mater 57
Welds: Jackson, Corros Sci 60

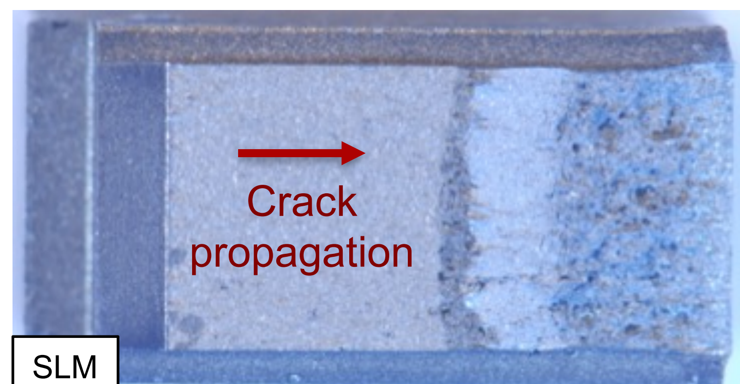
- Fracture resistance in air can be significantly lower than H-precharged forgings
- But generally, fracture resistance in air is high (not shown >200 MPa m$^{1/2}$)
- Low temperature appears to significantly reduce fracture resistance
  - Work is under way to substantiate
  - Probably related to unique microstructures

Fractography illuminates defect structure

- Macroscopic defects are associated with interlayers of build (when H-precharged)



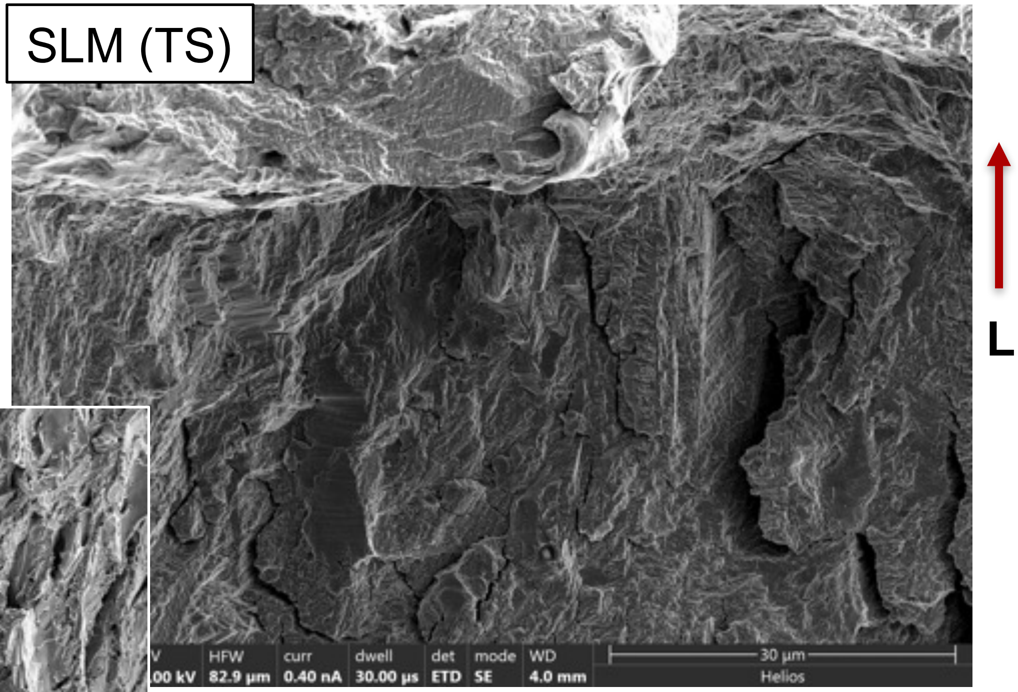


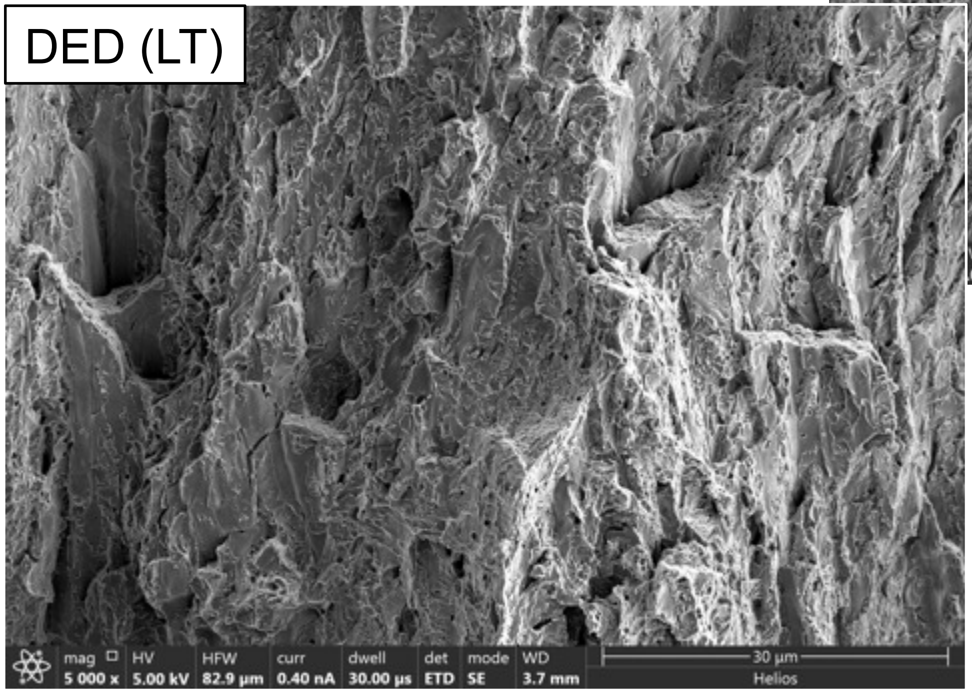


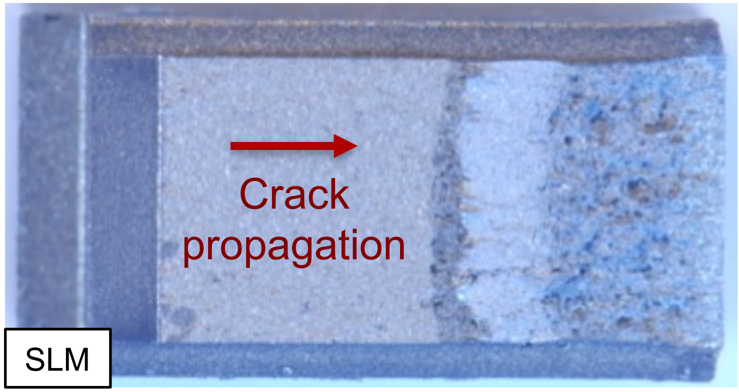
Fine fracture features consistent with H-assisted fracture and microstructure

- Hydrogen induces boundary fracture

⊗ L



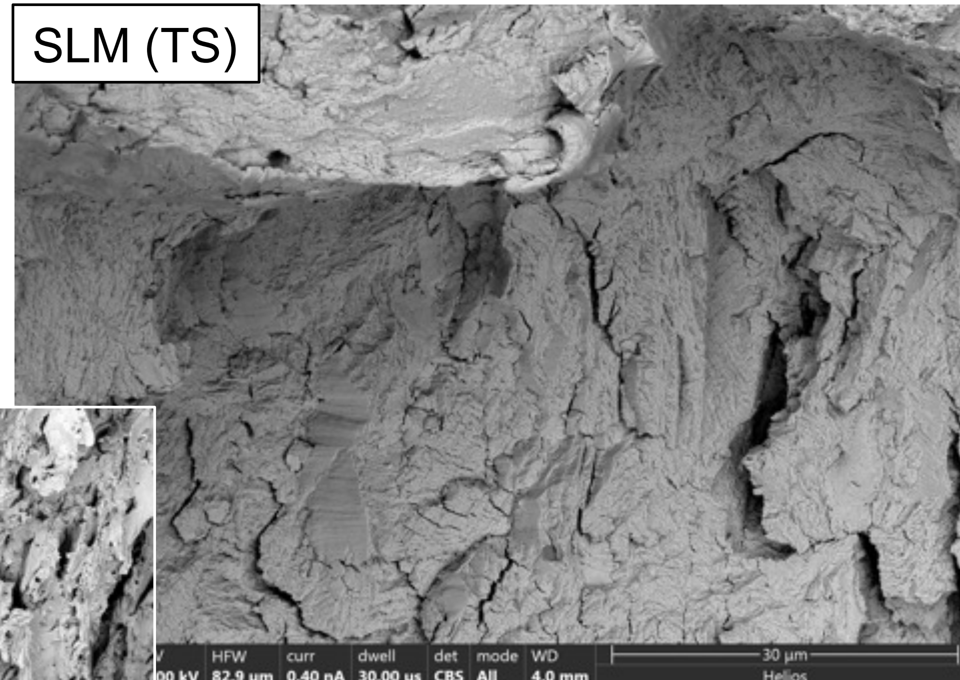




Fine fracture features consistent with H-assisted fracture and microstructure

- Macroscopic defects associated with interlayers of build

⊗ L



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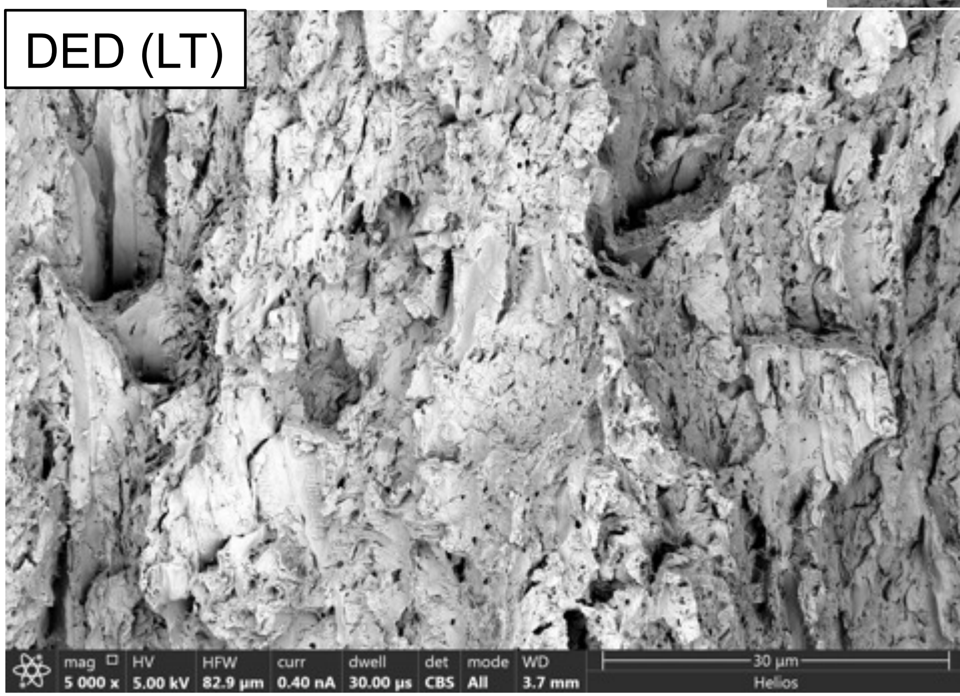
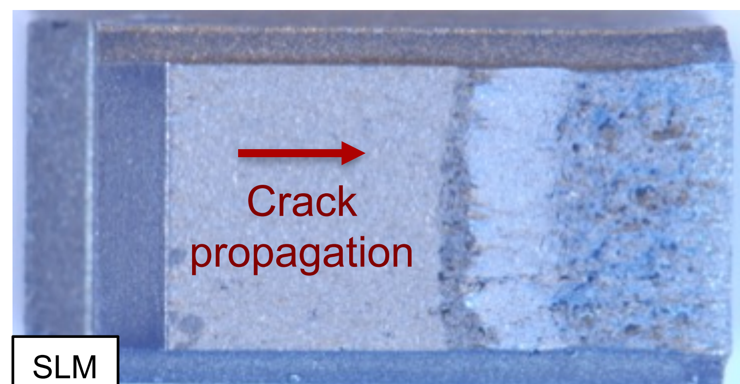
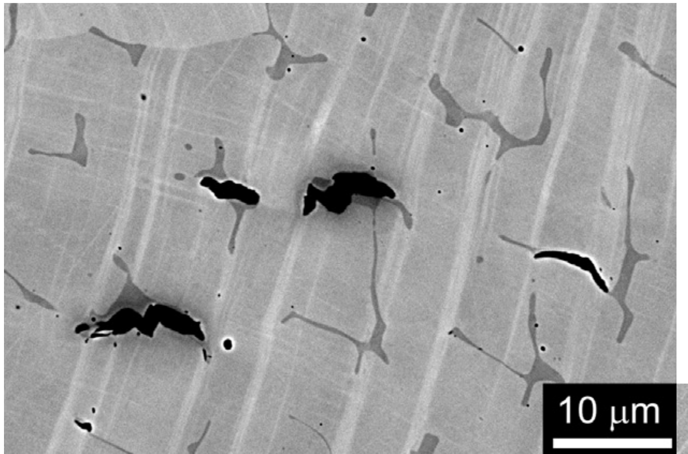




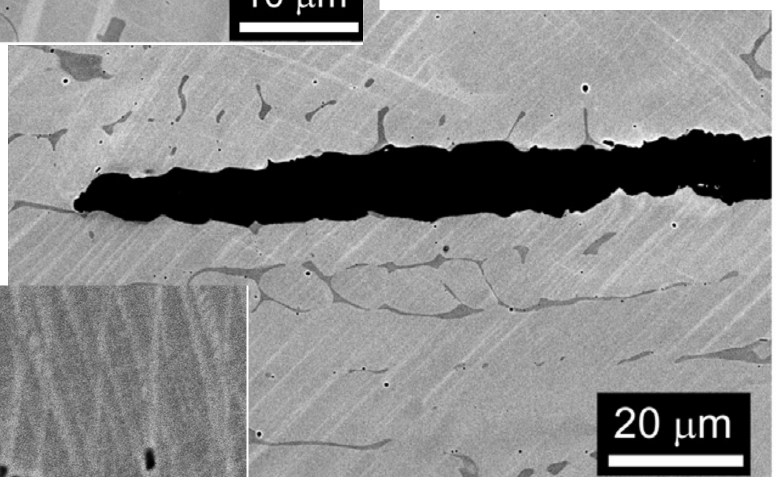
Mechanisms of fatigue and fracture may be similar to observations for welds

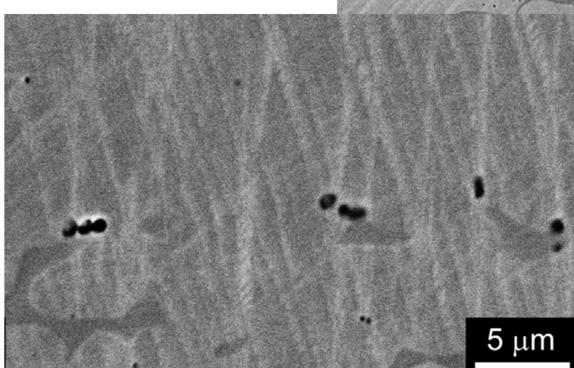
Cross sections just below the fracture surface from fracture tests of H-precharged 304L/308L welds show:

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

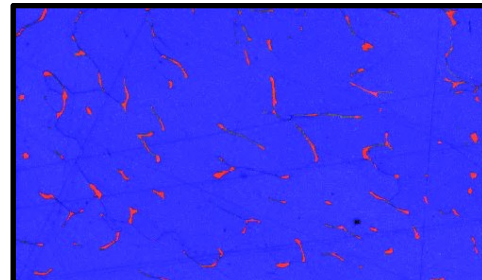


304L/308L welds





from: Jackson, Corros Sci 60



Laser-deposited 304L

Hydrogen-induced damage in *welded austenitic stainless steels* has been reported to be associated with the *ferrite phase*

Summary

Sandia National Laboratories

- Additively manufactured **austenitic stainless steels** feature good combination of strength and fracture resistance
  - Combination of properties is inferior to forged material
  - Quality AM materials are similar to welds
- Generally AM materials show greater sensitivity to hydrogen-assisted fracture than wrought materials
  - Mechanisms of hydrogen interactions appear qualitatively similar to welded microstructures
  - Unique microstructures of AM product may be more sensitive to temperature