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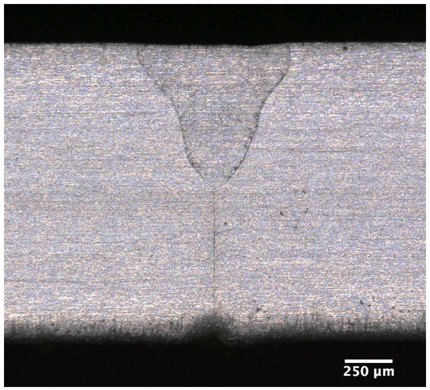

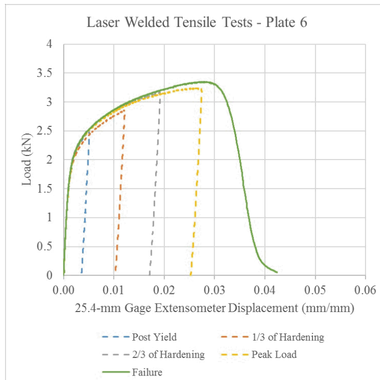

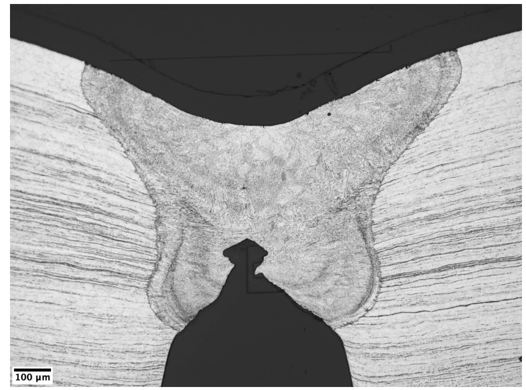

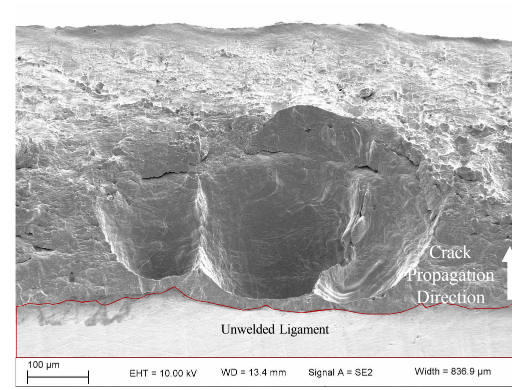

Damage Evolution in 304L Stainless Steel Partial Penetration Laser Welds

Sharlotte Kramer, Amanda Jones,
John Emery, Kyle Karlson, and Jay Foulk

SEM Annual Conference

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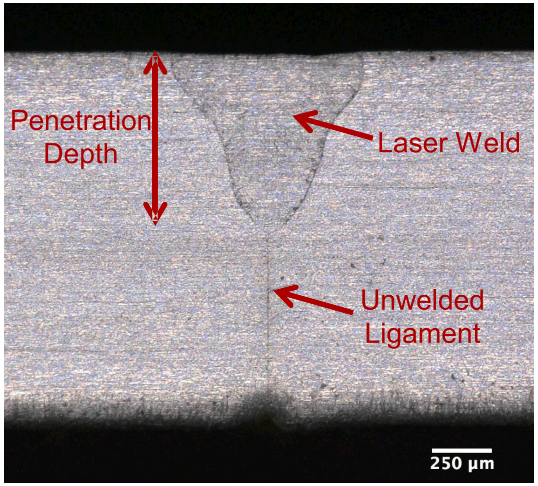
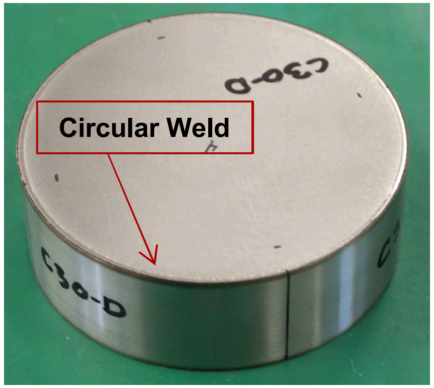
Fundamental understanding of damage evolution of laser welds is crucial to predicting their behavior.

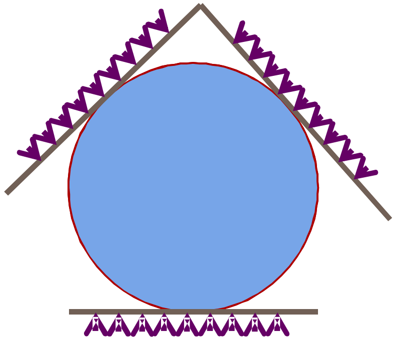
- A laser weld is a joint produced by the fusion of two metals using a high-powered laser without the need for a third material.
- Mechanical behavior of welds is affected by environment, laser weld schedule, weld depth, porosity, materials, and parent material geometry.

Side Profile of Partial Penetration Butt-Type Laser Weld in 304L SS

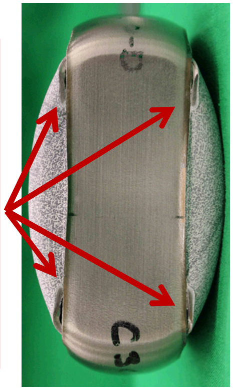


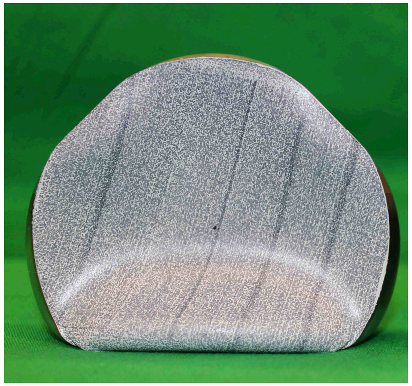
Failure of a Laser Welded Can Under Compression





Large Cracks in Welds Where Flat Platen Applied Load



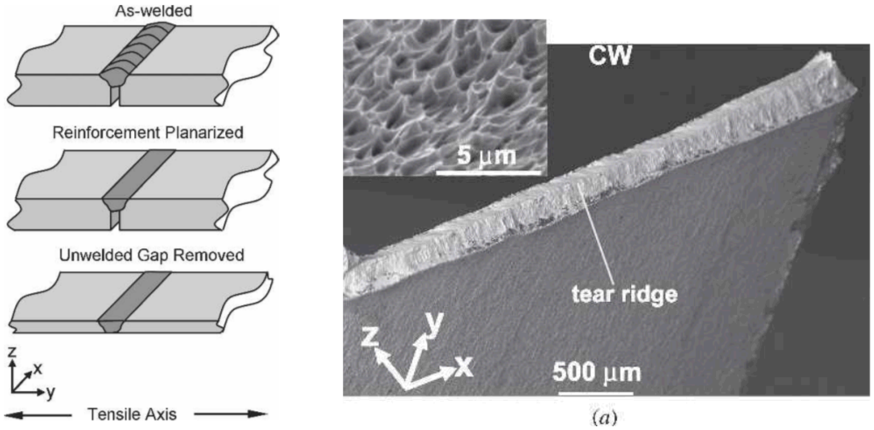


Purpose: Discovery of damage mechanisms in laser welds to

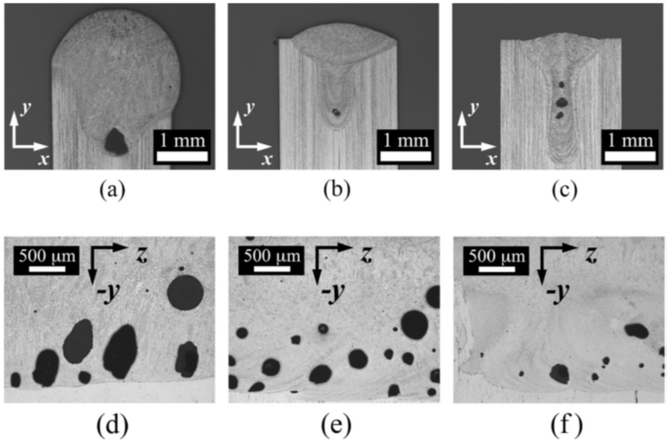
- **Understand overall mechanical behavior**
- **Develop and calibrate better computational models of systems with laser welds**
- **Improve design of laser welds**

Previous laser weld research has mostly been pragmatic without consideration of local damage.

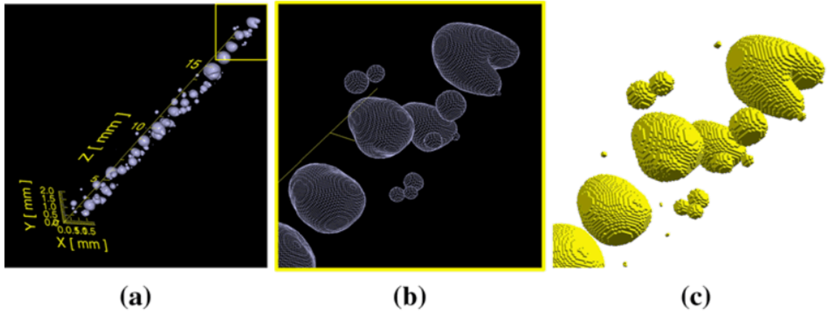
Tensile study of 304L SS weld without the unwelded ligament showed weld material is similar to base material. [Boyce, et.al. **Metal. and Mat. Trans A** ***2006]***



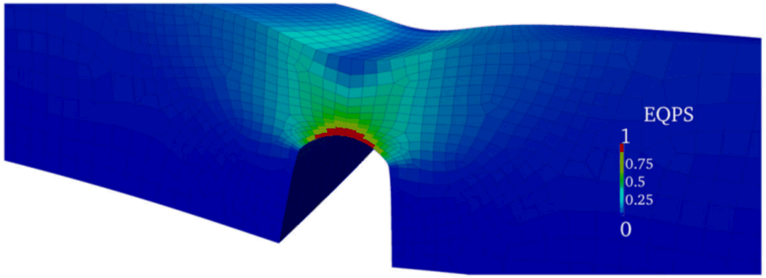
Pore size decreases in standing edge 304L laser welds with increasing laser travel speed (left to right). [Madison, et.al. Integ. **Mat. Manuf. Innovation** ***2014]***



Computational models of welds without unwelded ligaments, including meshes with explicit pores, show reasonable agreement with experiments, but do not have damage. {(a-b) visualization of micro-CT scans of pores; (c) mesh of pores} [Madison, et.al. **MMA** ***2013]***



A computational study of laser weld deformation in 304L SS combined the material and geometric effects into a surrogate model to represent the laser weld deformation for a component-level analysis with some success. [Emery, et.al. **Int. J. Numer. Meth. Engng 2015]**



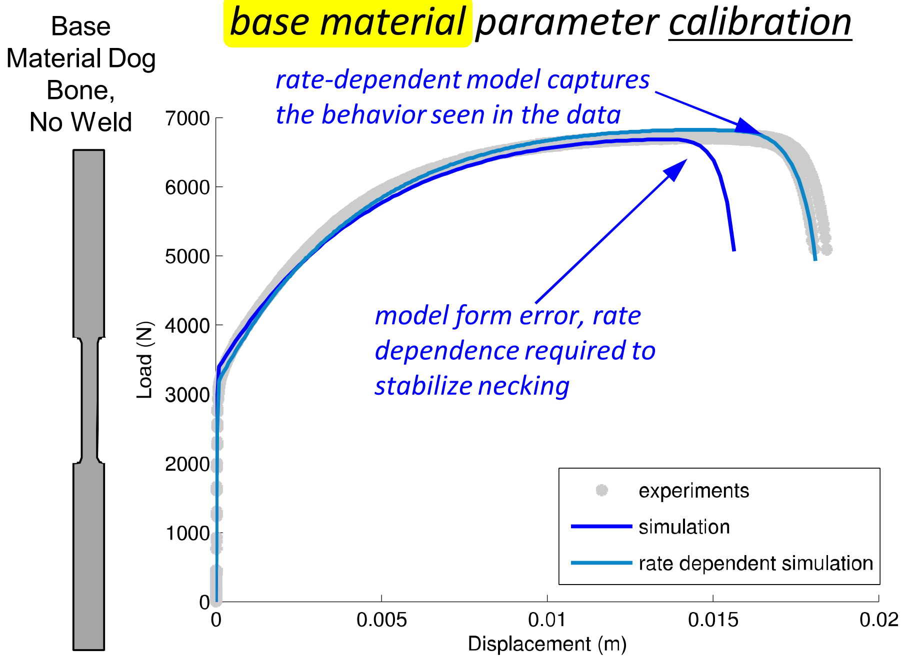
Current computational modeling methods for laser welds could not predict new experimental observations.

Calibration of a rate- and temperature dependent model based on base material tests could not predict either EDM-notched or laser-welded 304L SS tensile specimens.

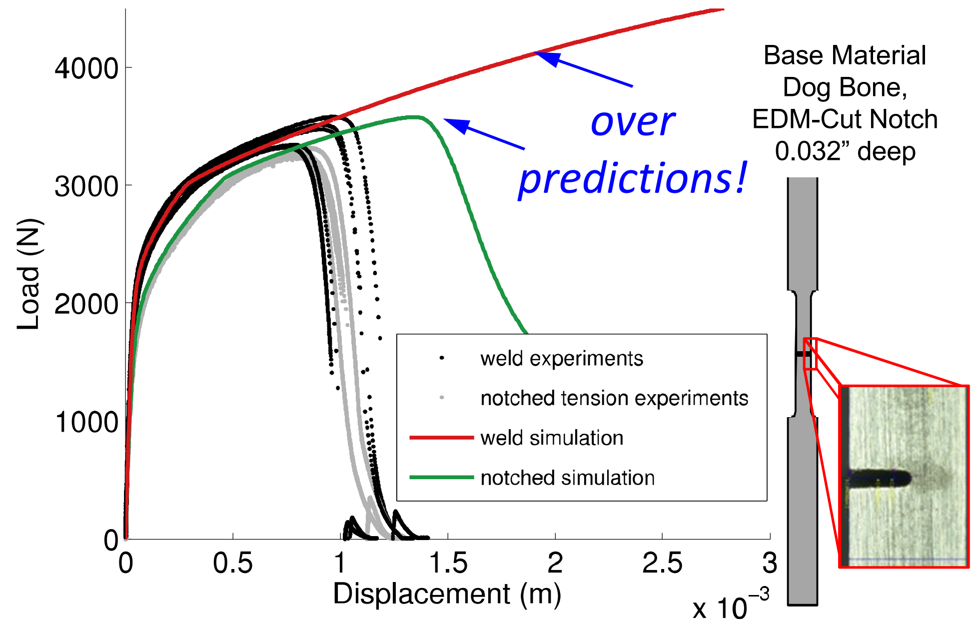
rate- and temp-dependent hardening

$$\sigma_y = Y(\theta)\left\{1+\sinh^{-1}\left[\left(\frac{\dot{\epsilon}}{f}\right)^{1/n}\right]\right\} + \frac{H}{R_d}\left(1-e^{-R_d\epsilon_p}\right)$$

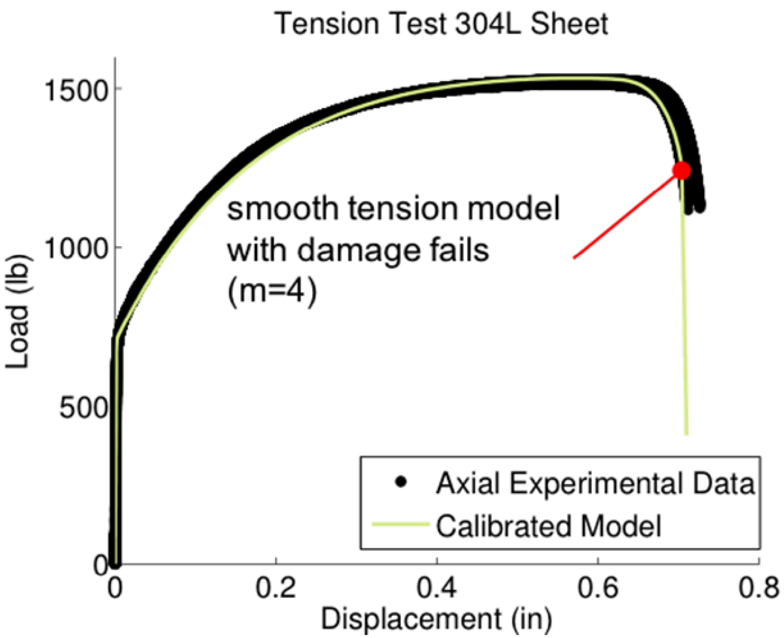
base material parameter calibration

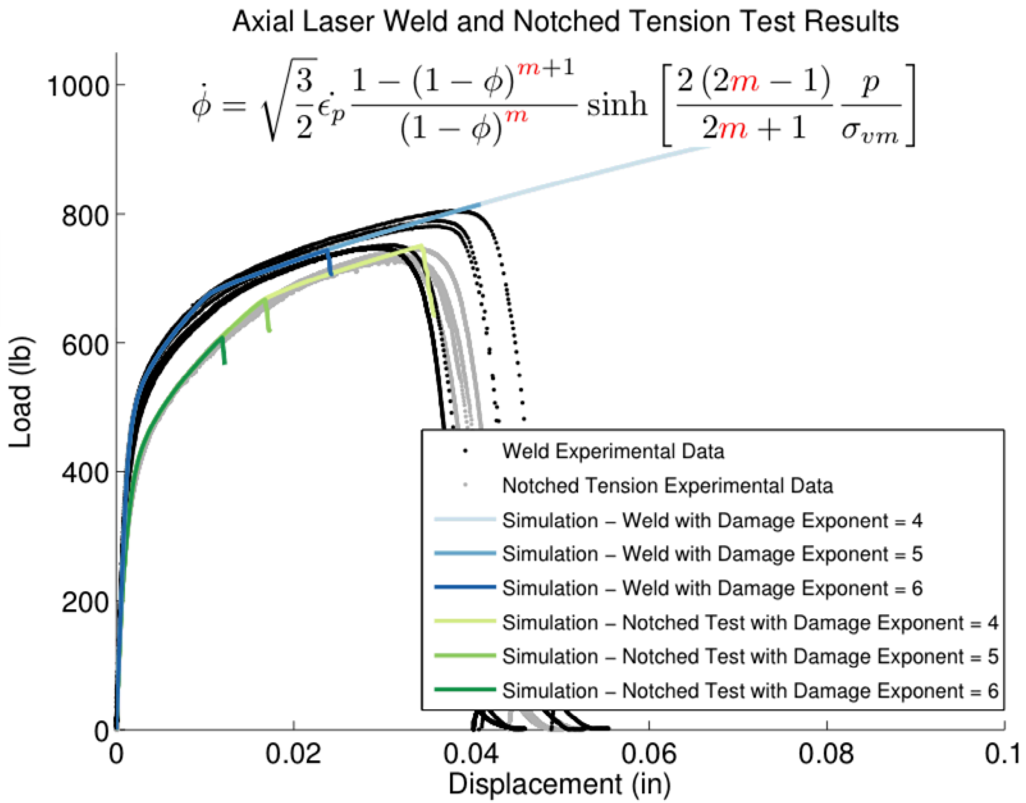


notched & welded specimen predictions (rate and temperature dependent)



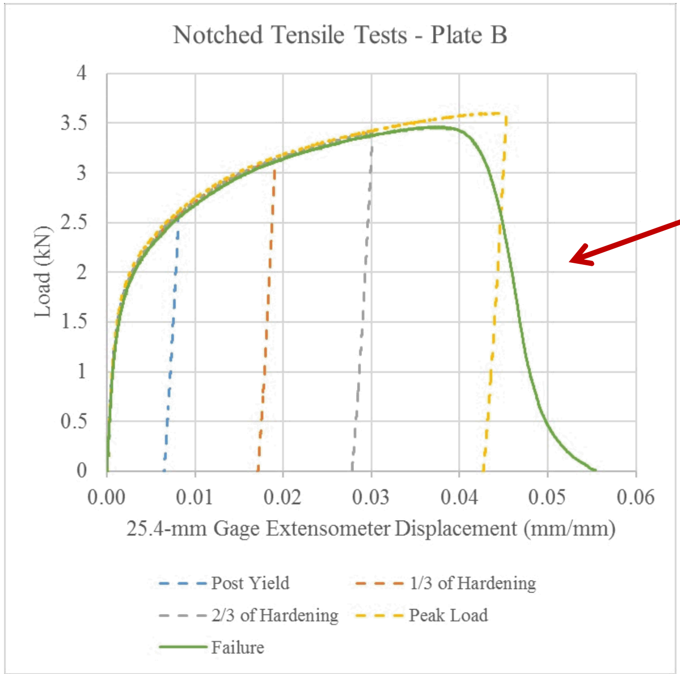
Computational modeling of laser welds currently lacks experimental basis for damage evolution.

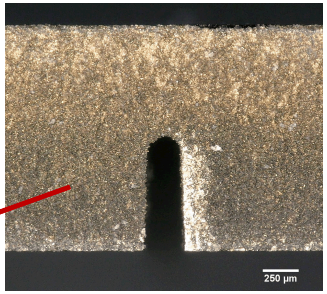


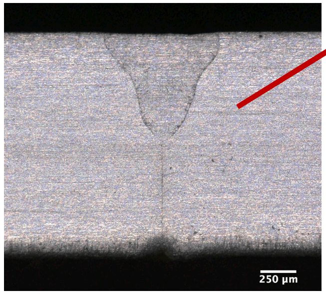


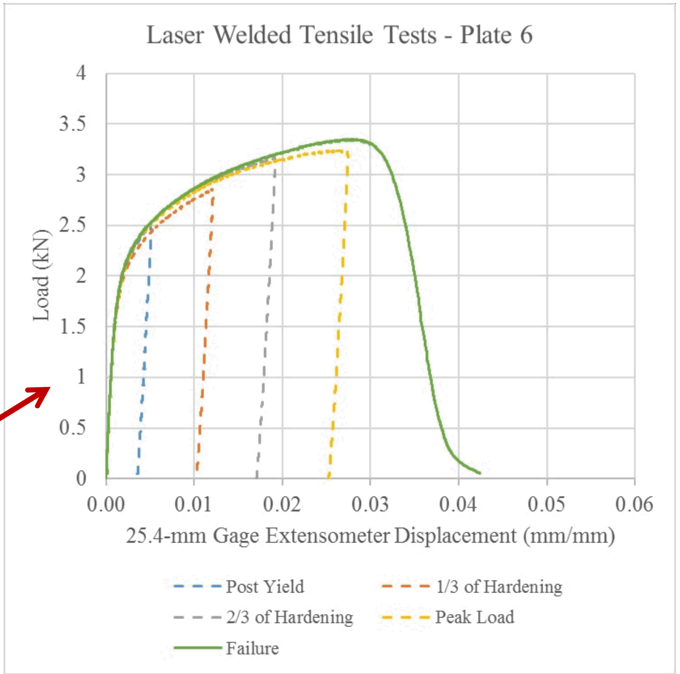
Inclusion of a damage model improves the prediction of the EDM-notched and laser-welded tensile behavior, but experimental evidence in needed to know how the damage evolves to develop the appropriate computational model.

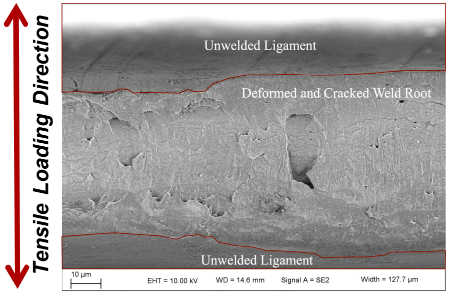
Interrupted tensile testing and post-test characterization reveal evolving damage.



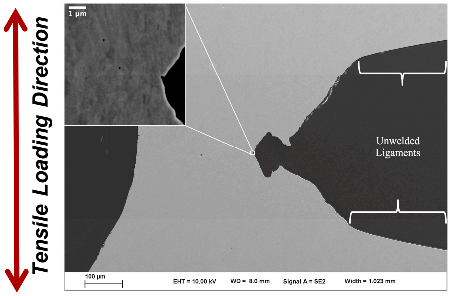


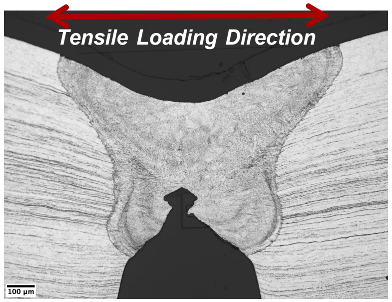




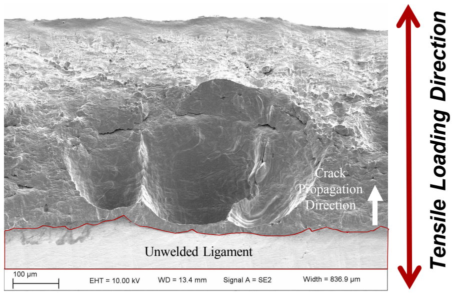


SEM Imaging From Weld Root Perspective: LWAxi06C [11% Disp. To Failure; 76% of Est. Peak Load]



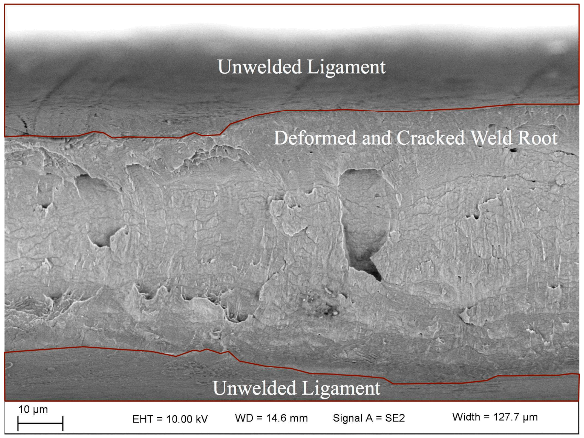


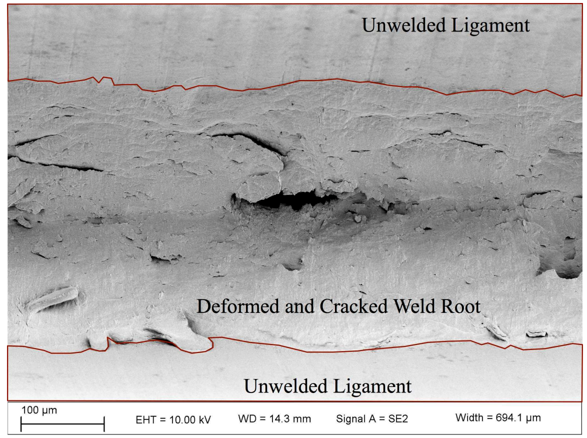
Imaging of Central Cross-Section: (Left) SEM Image of Polished Surface and (Right) Microscope Image of Etched Surface of LWAxi05G [82% Disp. To Failure; 90% of Peak Load (After Peak)]

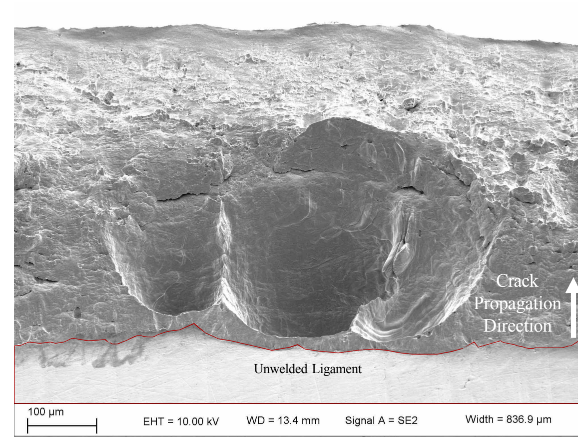


SEM Imaging of the Fracture Surface: LWAxi05F

Comparing damage in laser-welded and notched 304L SS reveals dominant damage mechanisms.



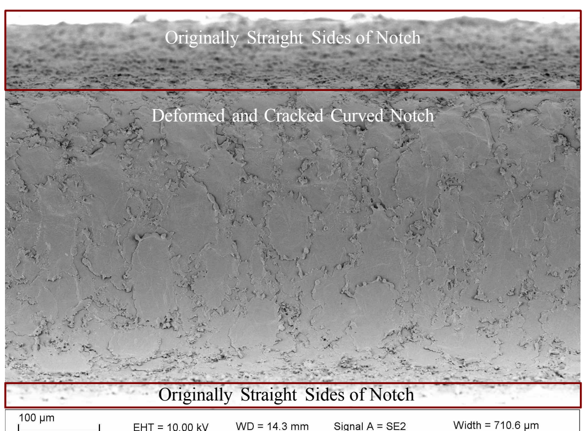


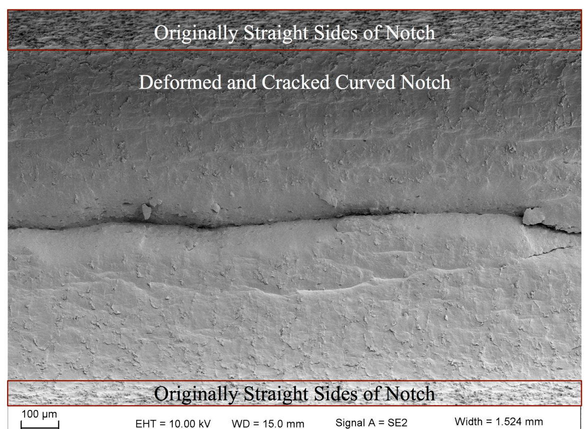


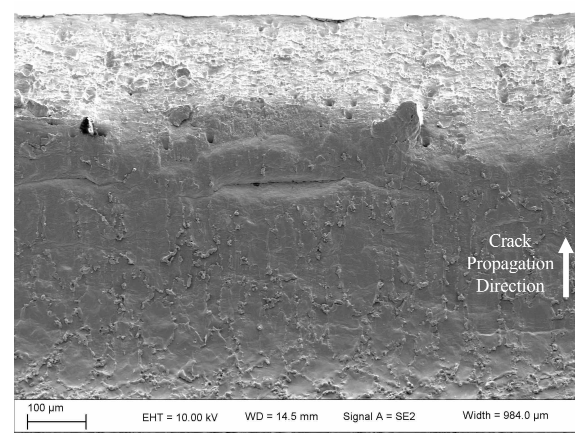
Cracking and Void Growth in LWAxi06C (Top) [11% Disp. To Failure; 76% of Est. Peak Load] Unlike NotchAxiB06 (Bottom) [14% Disp. To Failure; 71% of Est. Peak Load] With Mostly Plastic Deformation with Small Cracks at "Post-Yield"

Extensive Damage [Deep Central Crack, Stringer Cracks, Void Deformation] in LWAxi06F (Top) Compared to Deep Central and Stringer Cracks of NotchAxiA09 (Bottom) at Peak Load

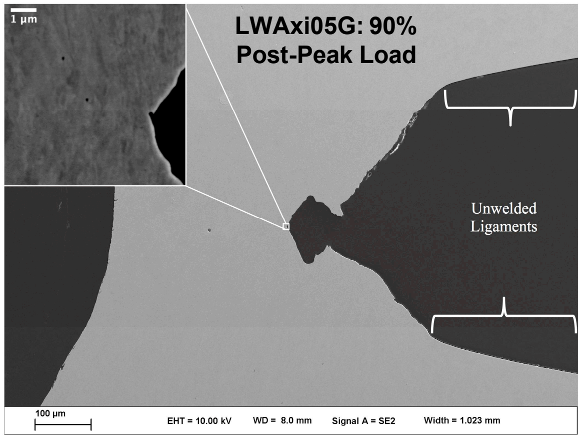
Fracture Surface of LWAxi05F Has Evidence of Large and Small Voids and Stringer Cracks in Addition to the Main Crack, While That of NotchAxiA04 Has No Large Voids and a Different Crack Morphology in the Stable Crack Regime

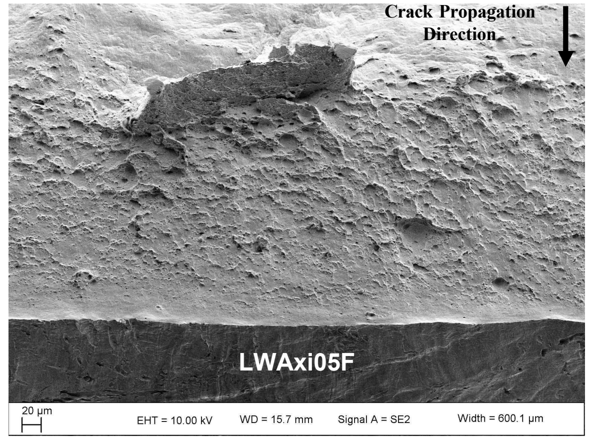


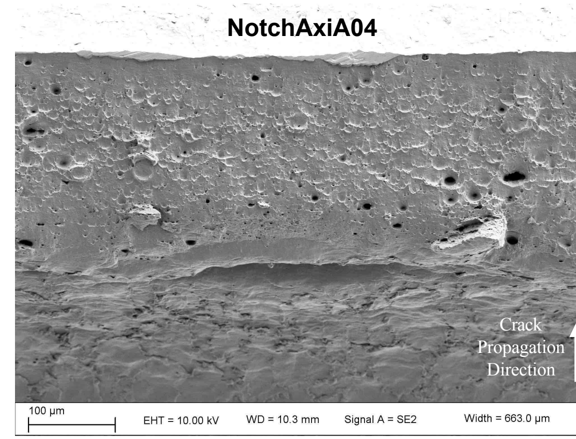




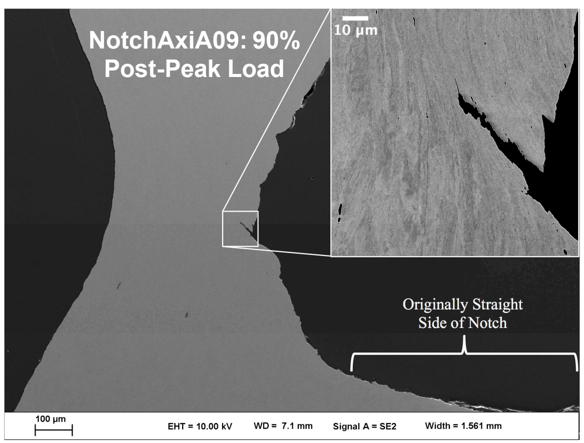
Traditional void nucleation and growth is present in the laser-welded and notched 304L SS.



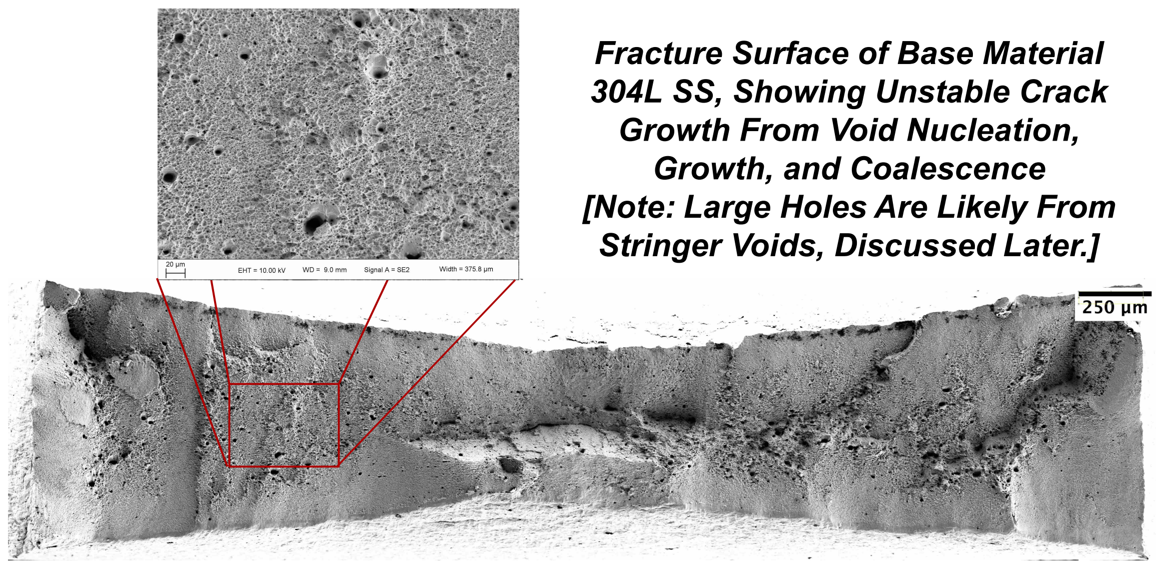




Fracture surface for both geometries reveals typical ductile fracture surfaces in the unstable crack regime post-peak.

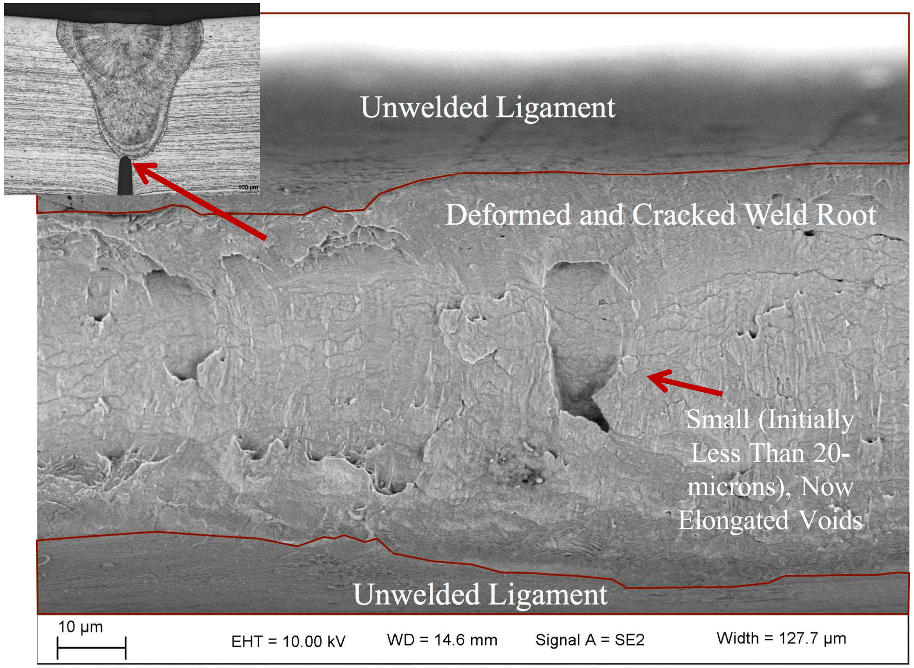


Voids evident ahead of the main crack for post-peak specimens in both geometries at all levels of deformation.

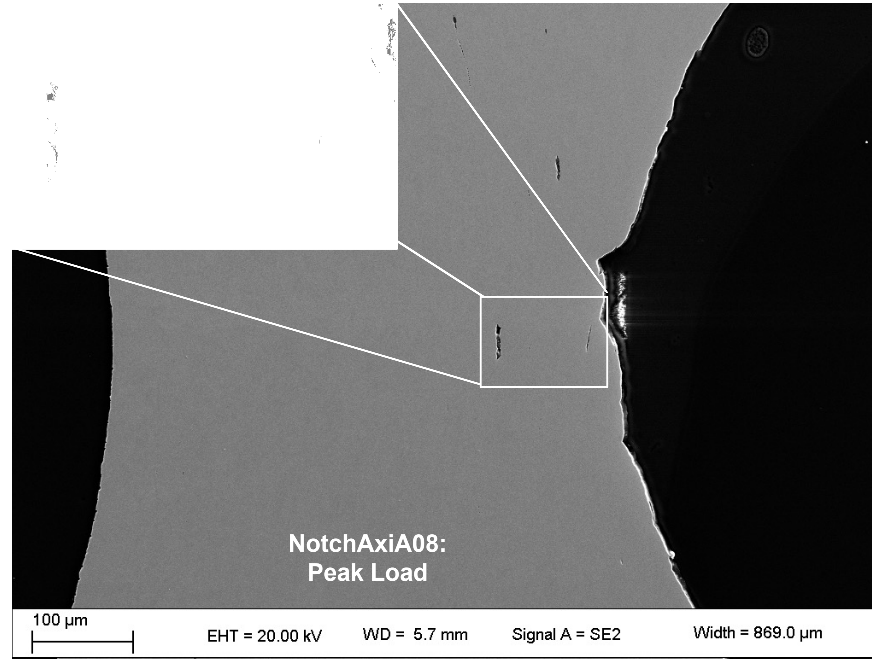


Fracture Surface of Base Material 304L SS, Showing Unstable Crack Growth From Void Nucleation, Growth, and Coalescence [Note: Large Holes Are Likely From Stringer Voids, Discussed Later.]

Small, pre-existing pores/voids act as local stress concentrations, promoting crack growth.

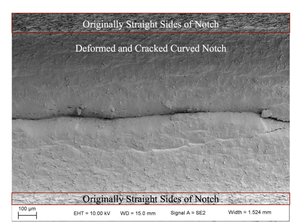


Above SEM image of LWAxi06C, the "post-yield" specimen, reveals elongated oval structures that originally were smaller than 20-microns (not detectable by micro-CT that showed 3-5 larger voids along the specimen weld).



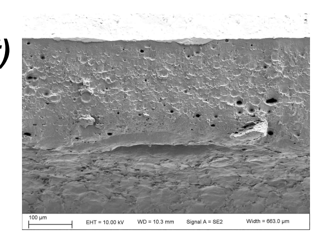
The 304L SS contains pre-existing stringer voids that formed around impurities in the melt mix. These stringer voids are destroyed in the welding process, so they are not present in the laser welds.

Small voids accelerate the damage process, contributing both to the main propagating crack and to smaller stringer cracks in the root of the weld / notch.



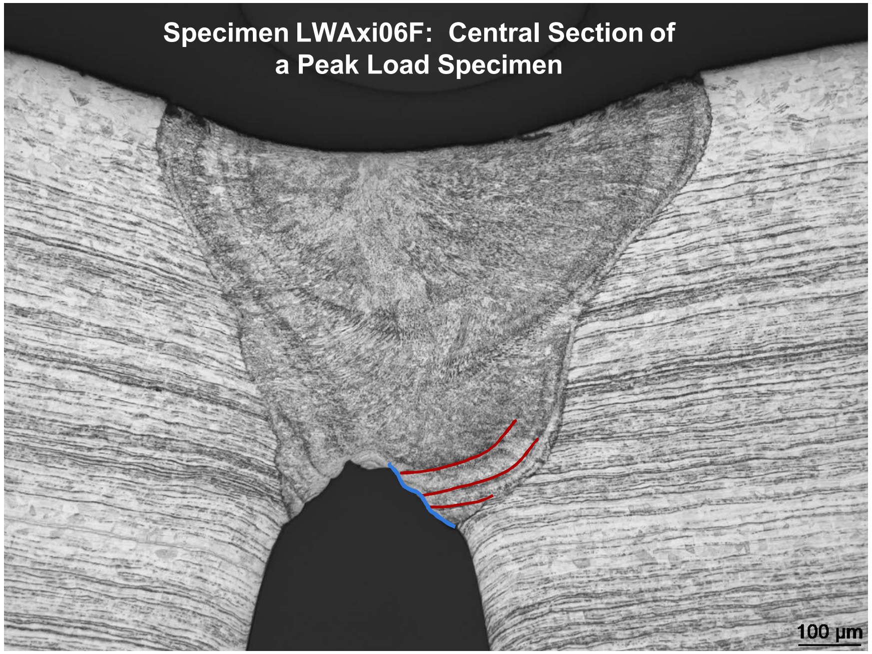
NotchAxiA09

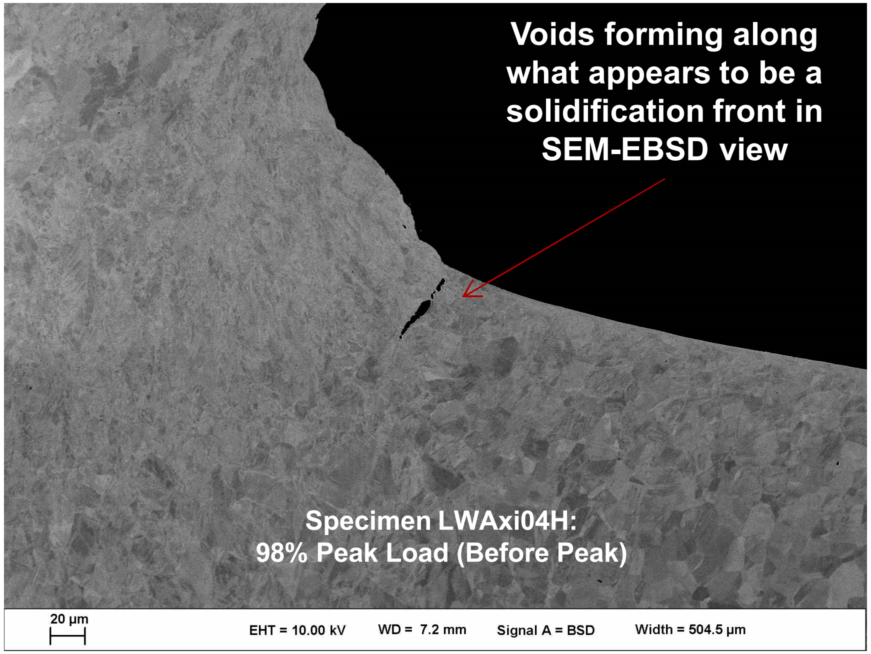
Stringer Cracks (Left) and Voids Larger Than Deformation-Induced Ductile Voids (Right)



NotchAxiA04

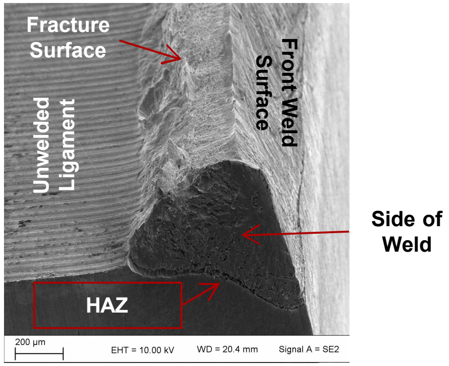
Solidification fronts in the laser weld potentially act like a void-sheet mechanism.



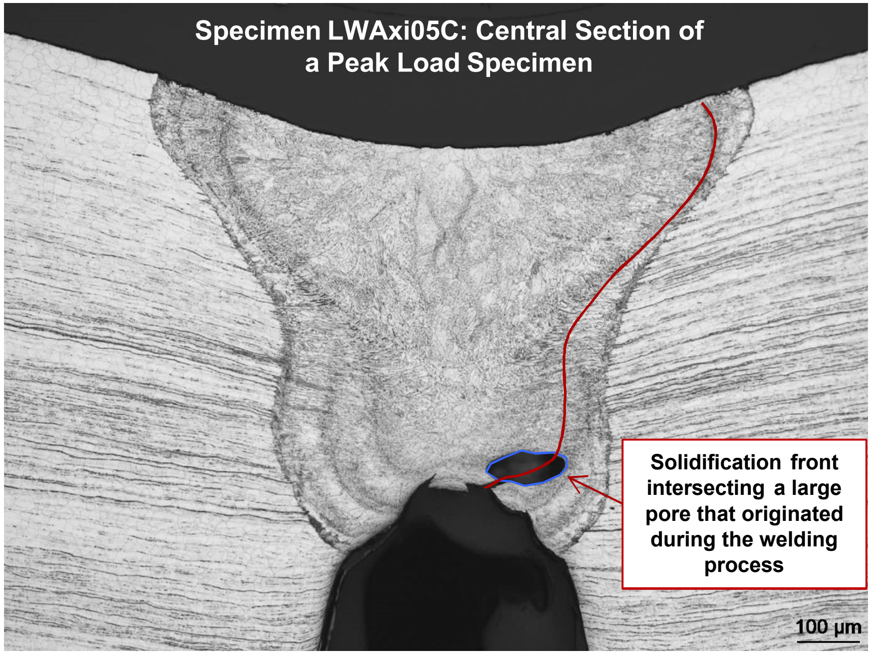


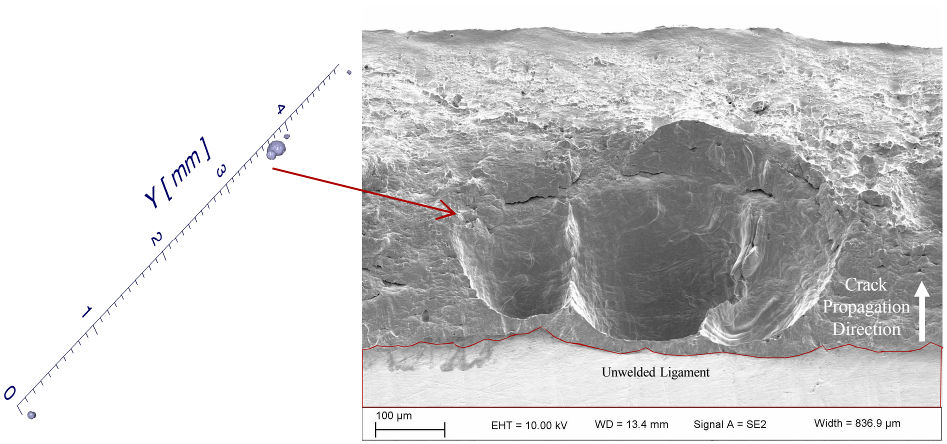
Solidification fronts affect the shape of the fracture surface, likely redirecting the crack growth to intersect the solidification front, leading to scalloped main crack in the laser welds. The main crack profile is smoother in the notched specimens, which do no have solidification fronts. Further research is needed to characterize the solidification fronts to confirm these as a damage mechanism.

55-deg SEM View of Fracture Surface (LWAxi06D): See Weld Pulling Away From Base Material Along the Heat Affected Zone (HAZ), Which Likely Has Similar Strength to Solidification Fronts

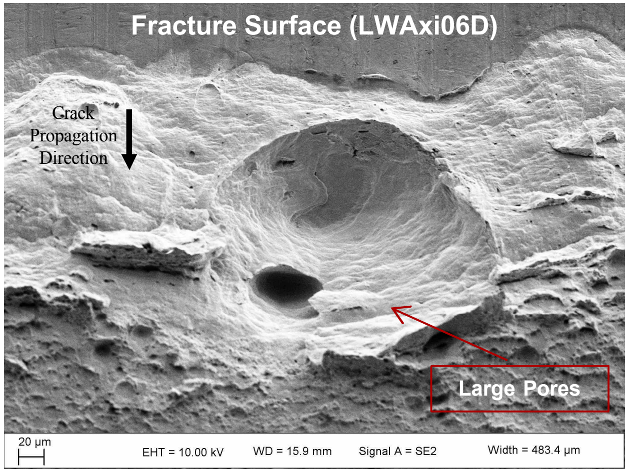


Large-scale porosity in the laser weld root can quickly progress the crack propagation.





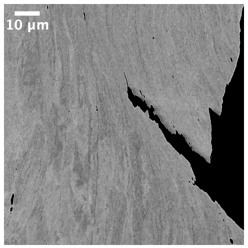
(Middle) Pre-Test Micro-CT Scans Revealed 5 Laser Voids Along the Laser Weld Length of LWAxi05F; (Right) Cluster of 3 Large Voids on Fracture Surface of LWAxi05F



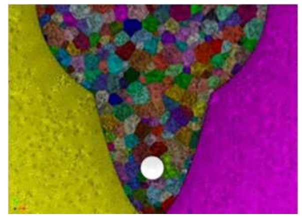
Large-scale porosity (greater than 20-micron voids), though not prevalent in this laser weld with only 3-5 large pores over 6-mm length of laser welds, do allow for rapid crack growth upon intersection with with main crack. These large pores can redirect the crack path. Since these pores are near the root of the weld, these are dominant in the stable crack growth regime of damage. These are not present in the notched specimens.

Further research will clarify the relative dominance of each mechanism, supporting model development.

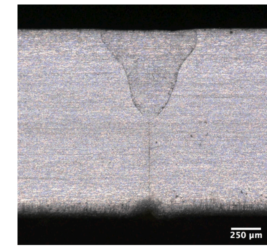
Additional SEM imaging of deformation-nucleated voids



Electron back-scattering diffraction of undeformed laser welds



Micro-probe and nano-hardness testing of undeformed laser welds



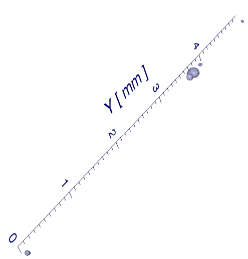
Traditional ductile fracture void nucleation, growth, and coalescence

Solidification fronts acting like a void-sheet mechanism

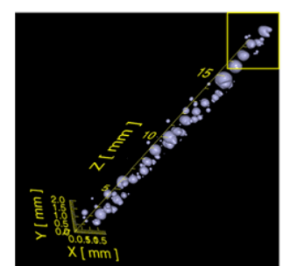
Mechanisms

Fine-scale porosity (sub 20-micron) evolution and coalescence

Large-scale porosity (greater than 20-micron) acting as stress / strain concentrators

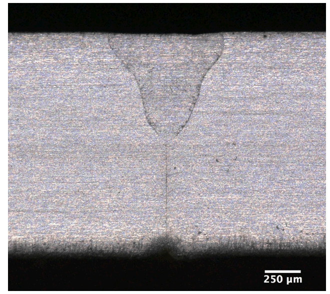


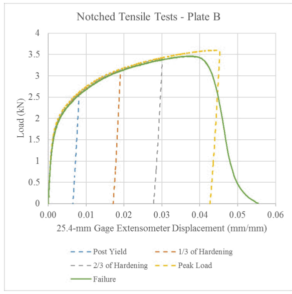
Serial sectioning with 3D reconstruction of undeformed laser welds

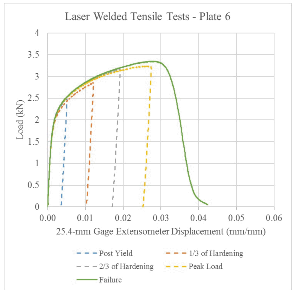


Damage drives large deformation mechanical behavior of partial penetration laser welds.

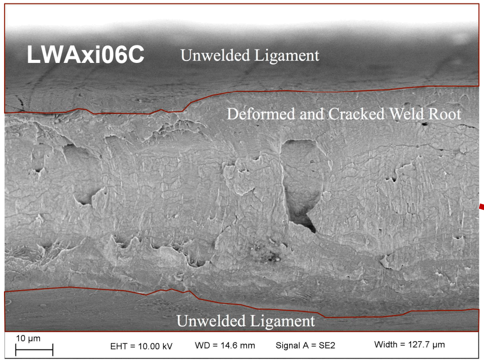
Interrupted Tensile Testing of Notched and Laser-Welded 304L SS to Characterize Damage Evolution

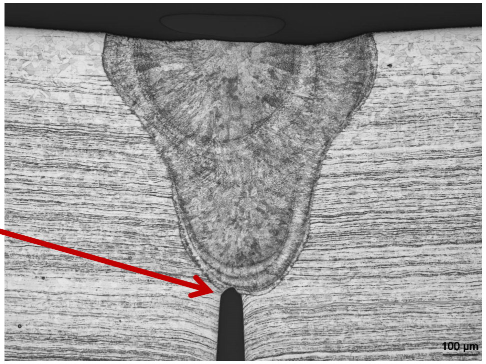






Damage Occurs Early in Global Deformation; Behavior is Not Only Governed By Plasticity





Four Damage Mechanisms Must Be Considered to Improve Modeling of Mechanical Behavior of Laser Welds

Traditional ductile fracture void nucleation, growth, and coalescence

Solidification fronts acting like a void-sheet mechanism

Fine-scale porosity (sub 20-micron) evolution and coalescence

Large-scale porosity (greater than 20-micron) acting as stress / strain concentrators