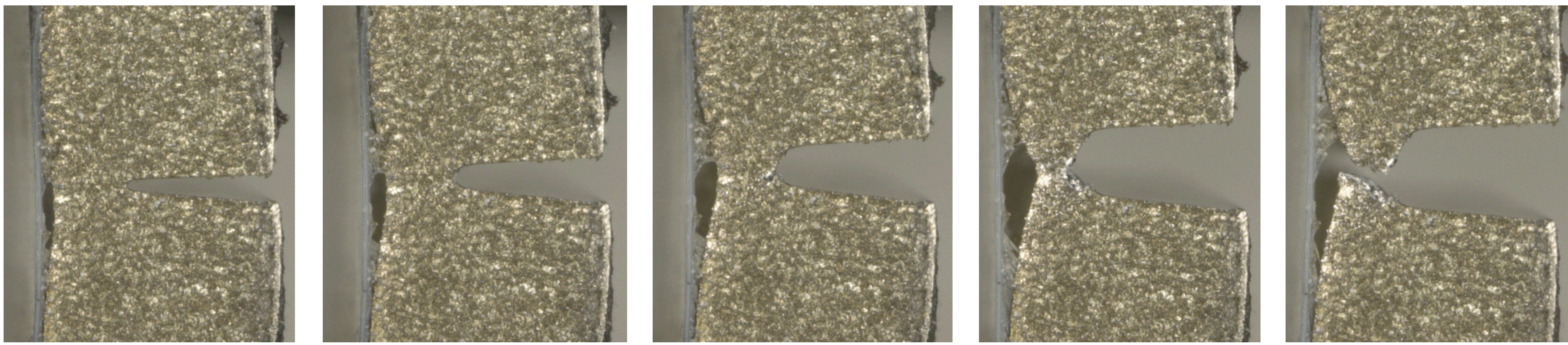
SAND2013-3276C

Exceptional service in the national interest

Sandia National Laboratories



A path towards incorporating the physics and numerics of 304L laser weld failure

Engineering Science Review Panel, April 25, 2013

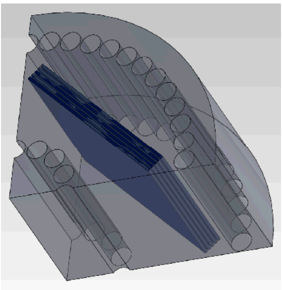
James W. Foulk III, John M. Emery, Michael G. Veilleux, Glen A. Hansen, Jakob T. Ostien, Alejandro Mota, WaiChing Sun, Jonathan D. Madison, Brad L. Boyce

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

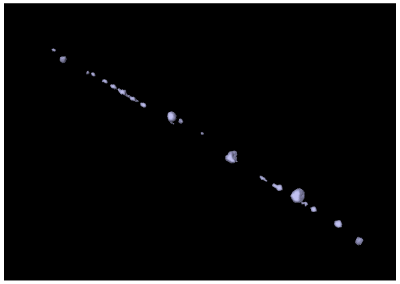
Understanding the risk of deeper welds

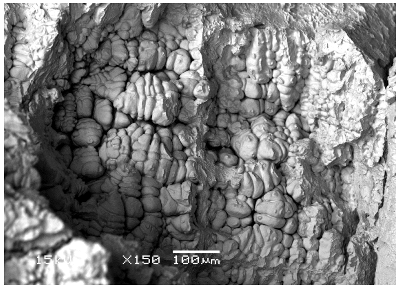
Sandia National Laboratories

Deeper-Penetration Welds

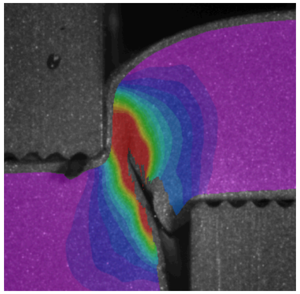


Tomography/Sectioning/Cataloging

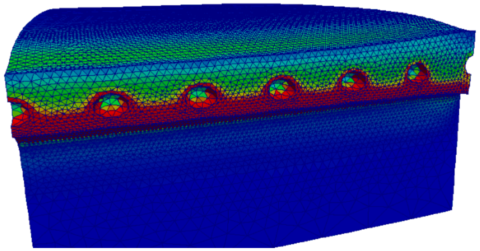


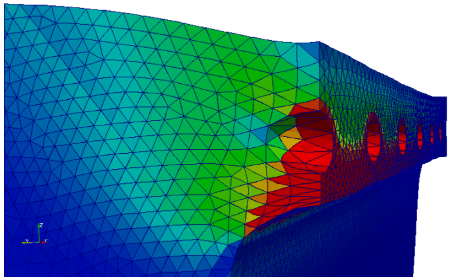


Shear Failure

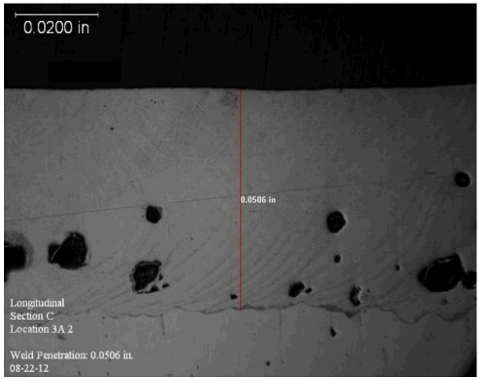


Resolve porosity





Predict necking



Laser Weld Damage Modeling (1 Year)

1. *Resolve pore shape, size, and location*
2. *Correlate pore structure to weld strength/ductility*
3. *Tools enable SNL to set guidelines for manufactured variability*

New requirements require deeper welds. We have no experience with deeper penetrations.

304L redefines failure

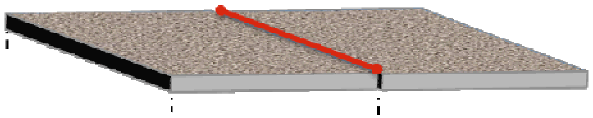
Why use 304L?

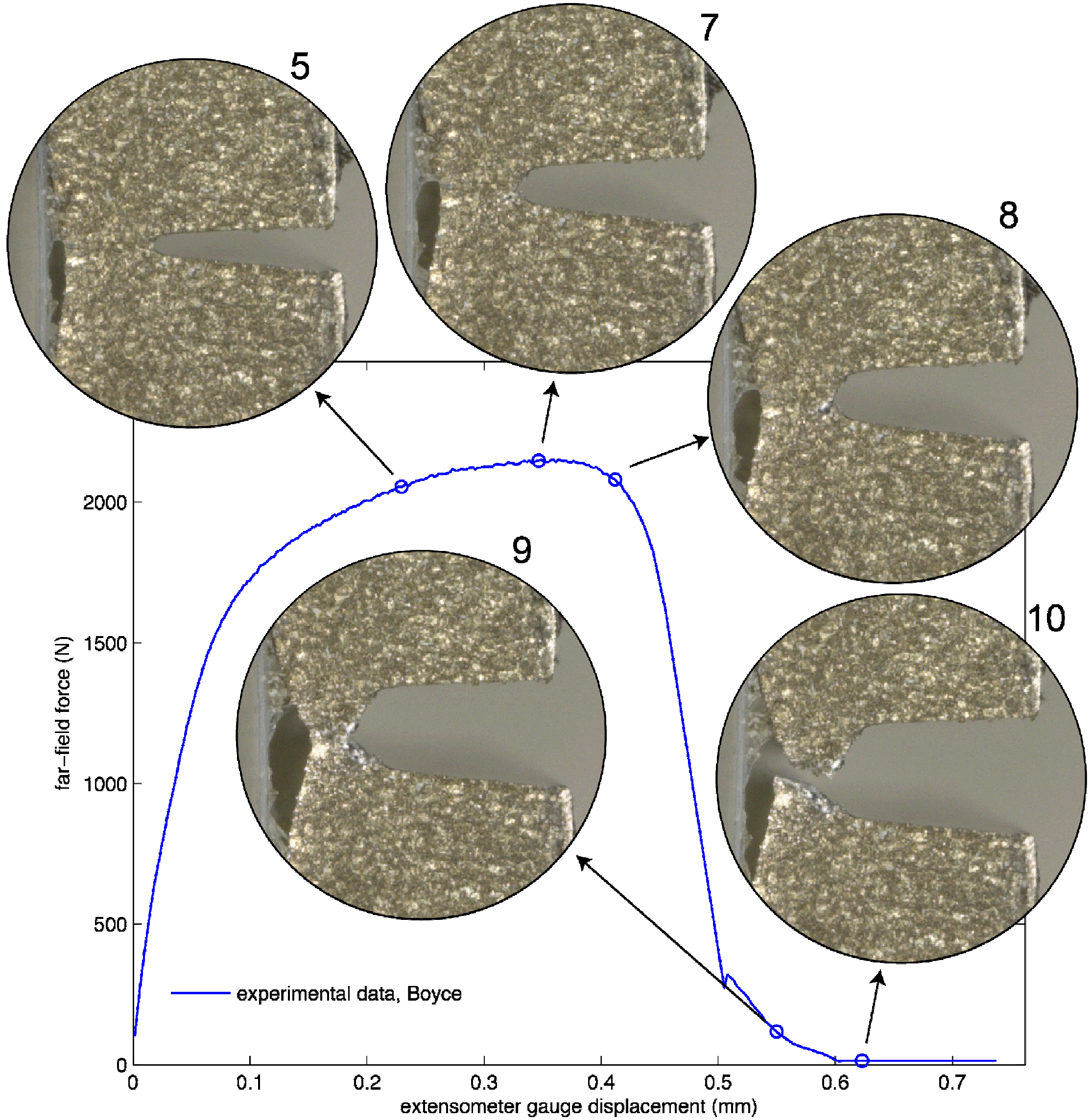
304L is one of the most damage tolerant materials on the planet

The failure of 304L is a necking problem. Free surface creation is a 2nd order effect.

Pore size and distribution can aid the necking process

1. *Modeling pore growth requires remeshing and mapping*
2. *Component and system models must model failure through necking*

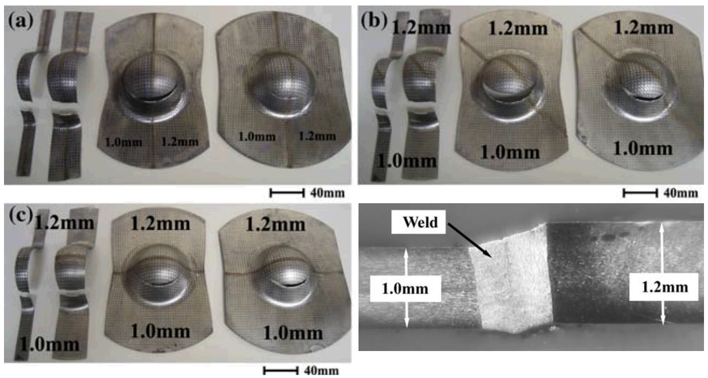




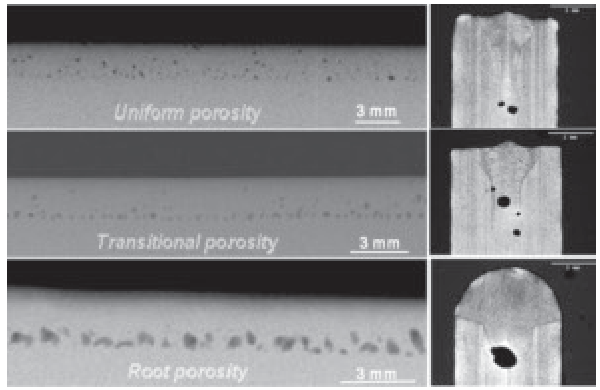
SNL application is unique to the literature

Sandia National Laboratories

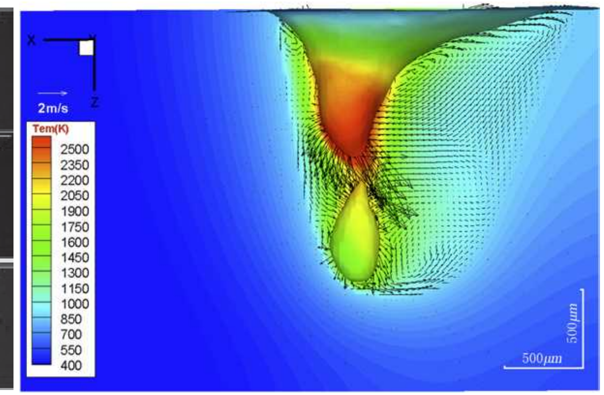
The need to predict the global necking and failure of 304L-304L laser welds with a substantial un-cracked ligament (crack) and large pores is unique to SNL applications.



Cheng (2007) 304L, Formability of butt-welded tailor welded blanks (TWBs)

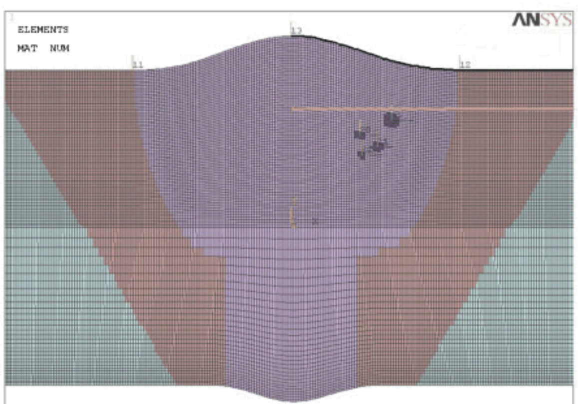


SNL (2011) 304L, Role of process parameters on pore formation

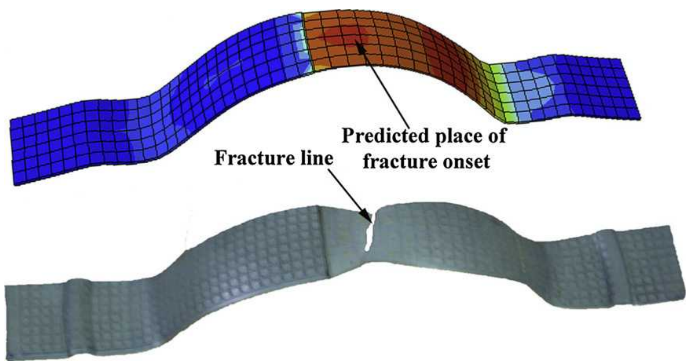


Pang (2011), Al alloy, Modeling weld pool dynamics for deep penetration welds

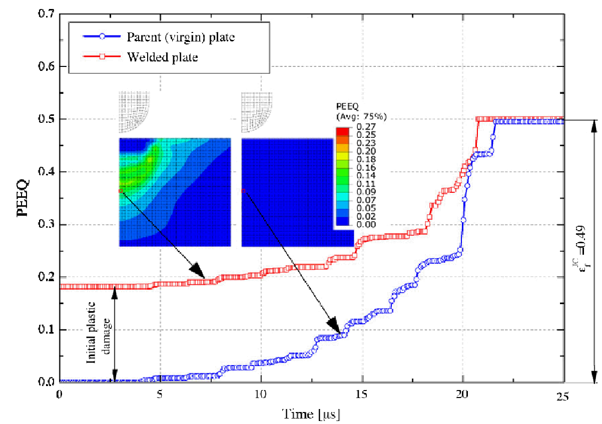
---



Casavola (2010), 304L, Effect of pores on fatigue life (stress analysis)

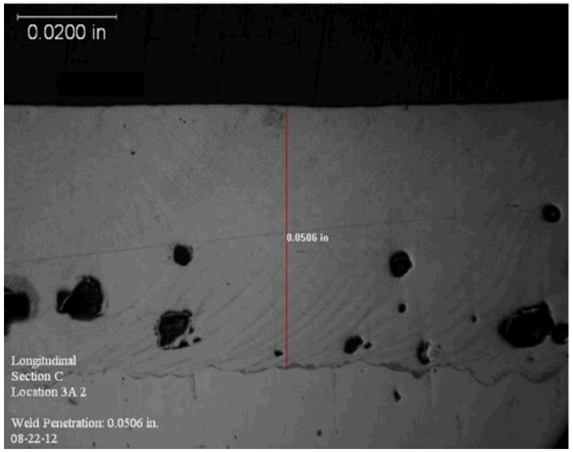


Abbasi (2012), IF-steel, FLD of tailor welded blank with local damage model (GTN)



Flores-Johnson (2012), TIG of 316L, Failure under ballistic loading

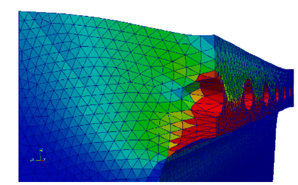
Sandia National Laboratories

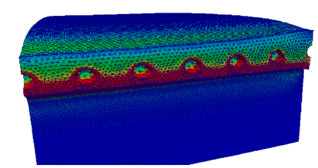


Getting this right sooner than later requires

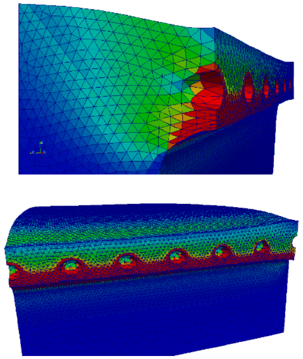
- Knowledge of the void structure
- Experimental characterization (sheet/weld)
- Nice elements, solvers, and L_2 projections
- A robust remeshing/mapping procedure
- Production code base (SierraSM)

1. A tale of increasing complexity
2. Where are we? Can we do it in one year?
3. What does success look like?





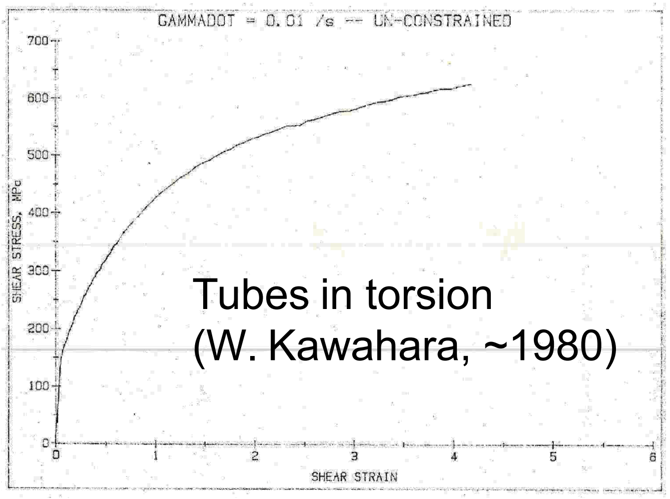
A tale of increasing complexity

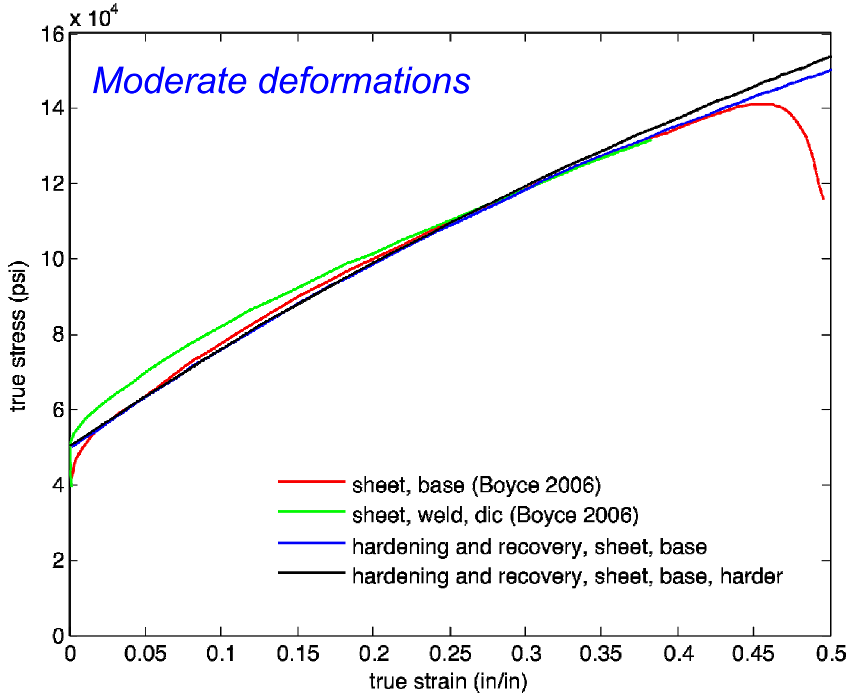


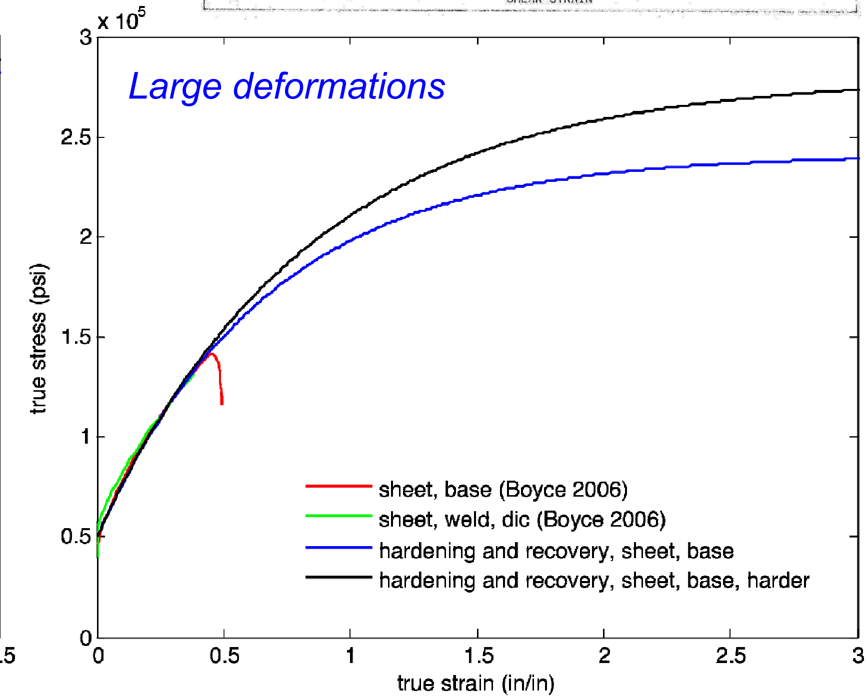
The tale begins with the simple interaction of an analyst and a researcher. Despite many attempts, the analyst could not predict the gross deformation behavior of a laser weld. Is it really that hard? Yes. For good reason…..

Idealized models for learning

- Quasi-statics
- Temperature & rate independence
- J_2 plasticity, isotropic hardening
- Prescribed hardening function
- Fit to experimental data prior to necking
- Extend through hardening minus recovery
- Sierra Solid Mechanics is the code base

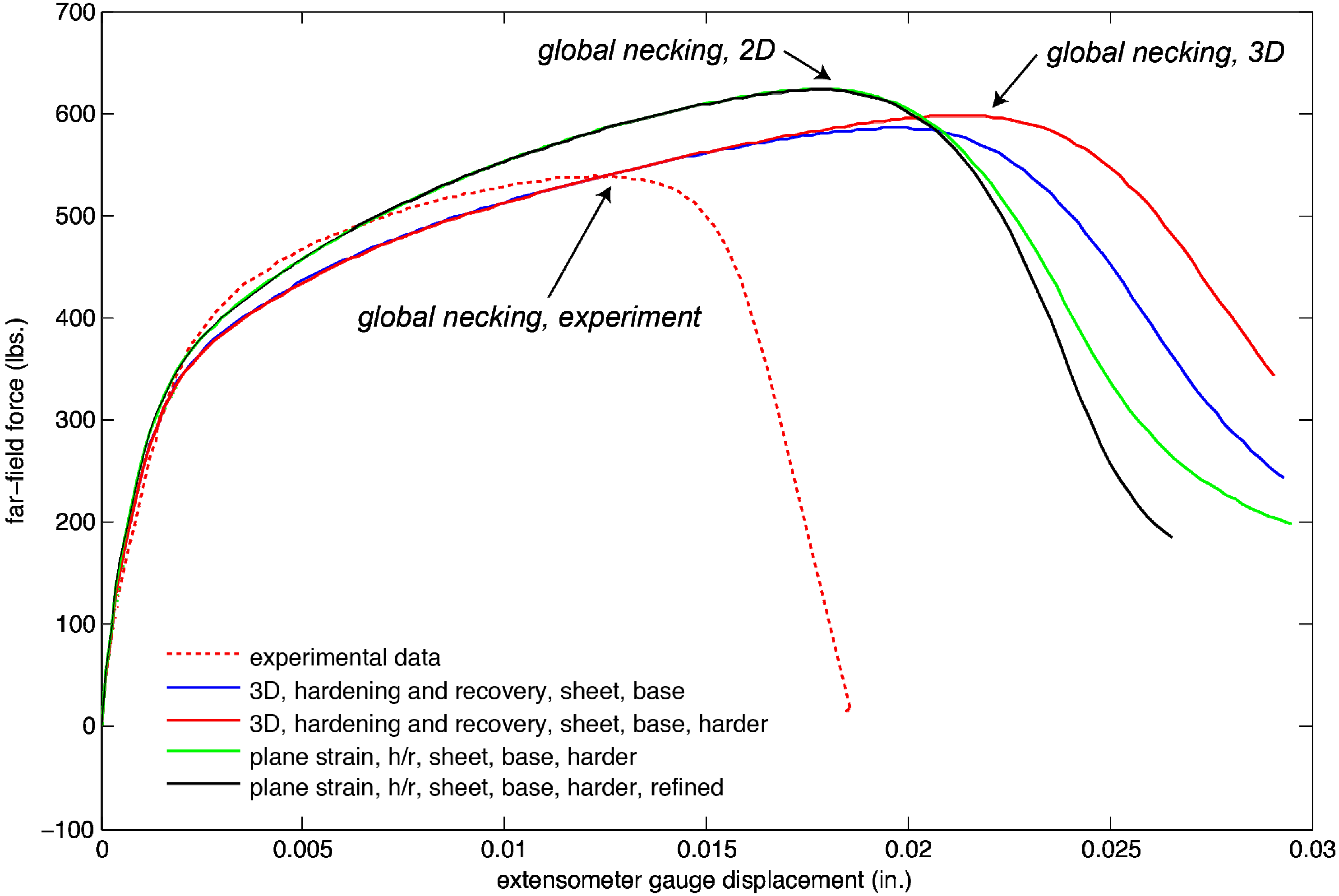




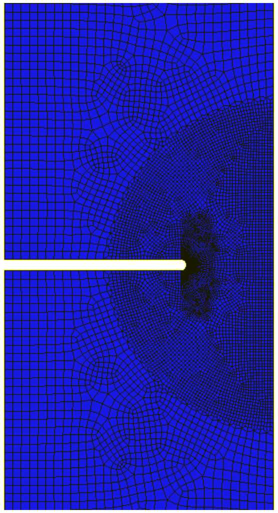


Experiments for sheet and sheet/weld w/constant cross-section

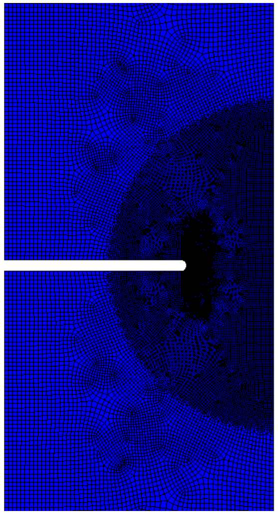
Initial simulations delay necking instability



baseline mesh



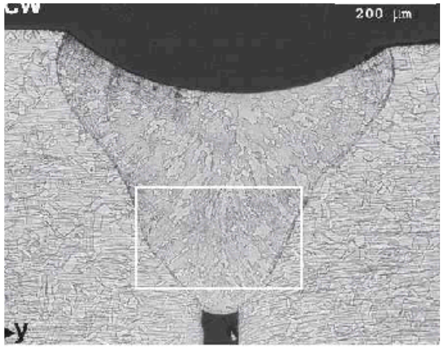
refined mesh

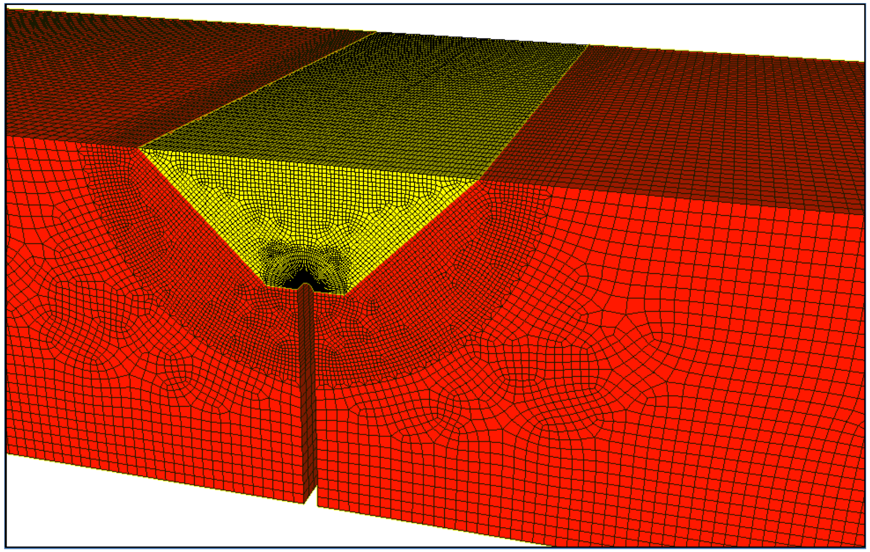


Although necking does occur, the lack of agreement with experimental findings suggests we *move to a two-material (sheet/weld) system* to include the weld material. Note the differences between 2-D plane strain and 3-D analysis.

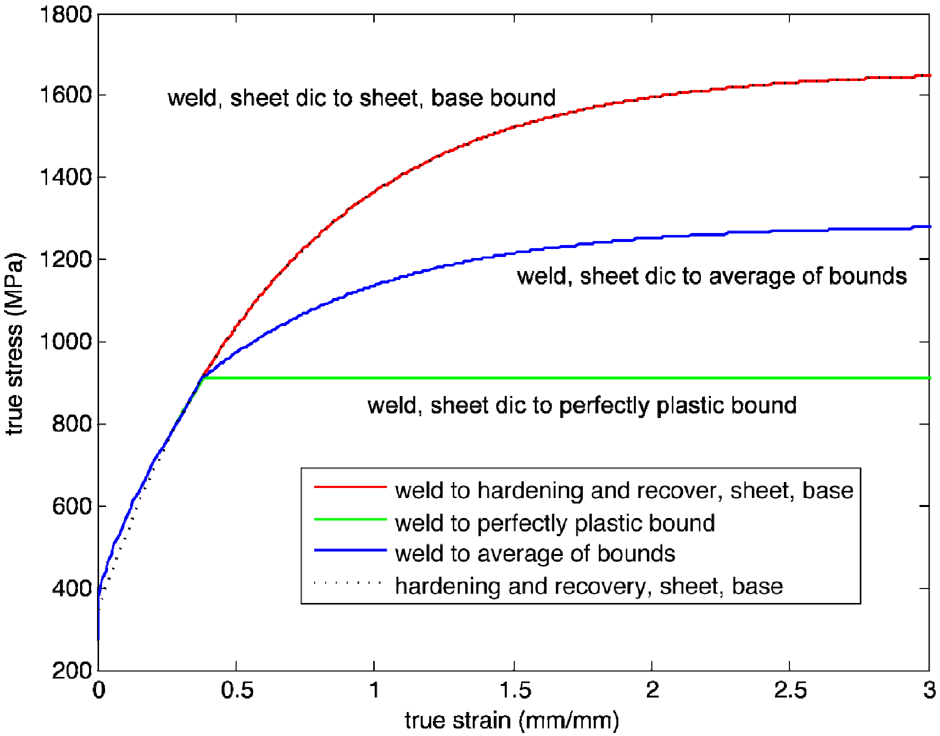
Varying large deformation weld hardening

Boyce, Reu, Robino
Met Trans (2006)





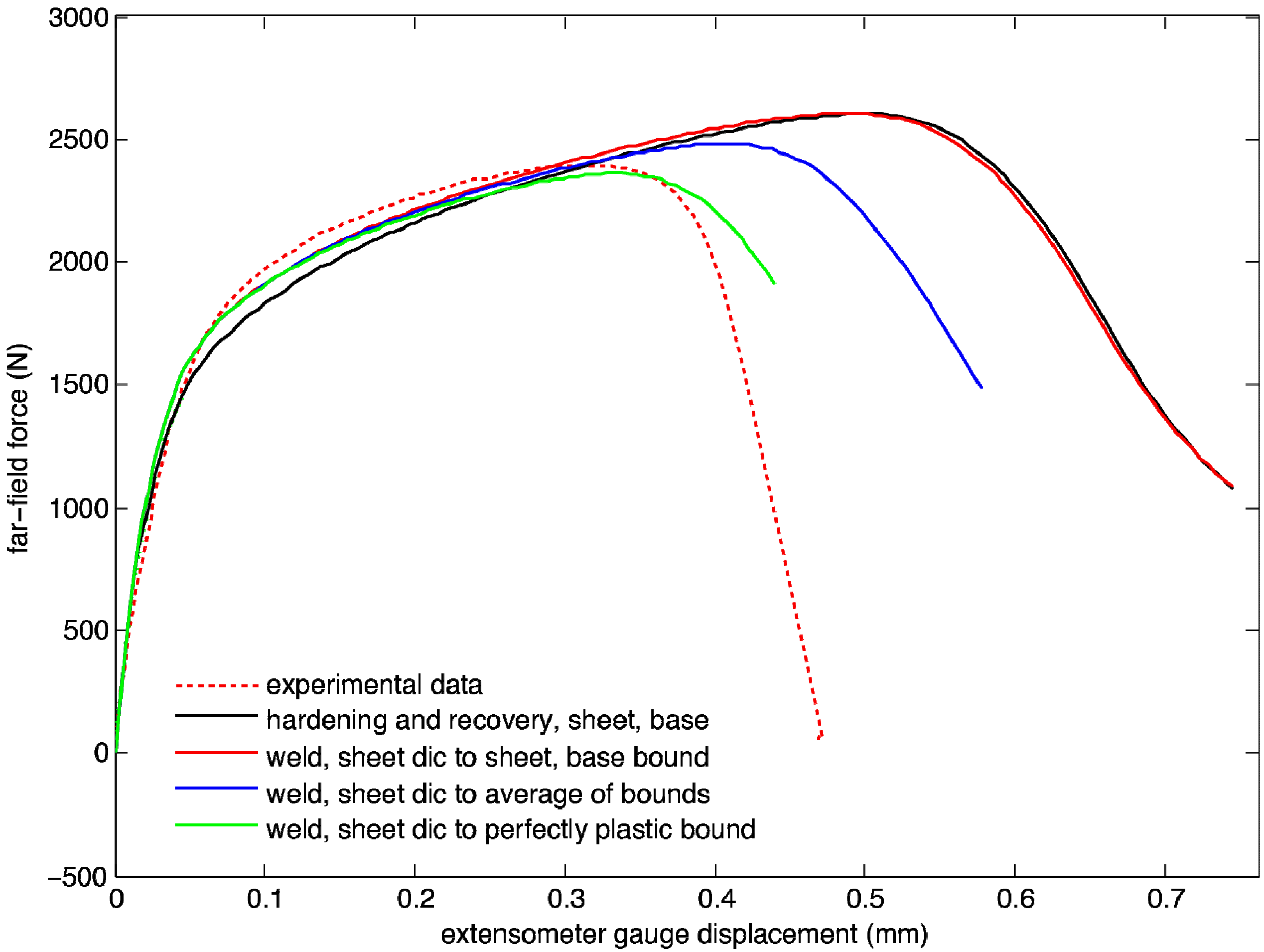
Initial models are vastly simplified. We only seek to understand general trends. Nodes: 313,701, Elements: 295,750. Employing q1p0 linear elements (hex8).



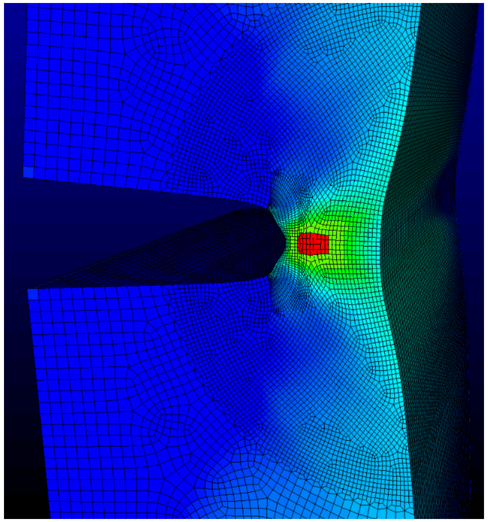
We employ the experimental curve and parameterize (bound) the large deformation behavior to better understand neck formation.

NOTE: Substantial plastic deformation begins ~ 350 MPa

Perfectly plastic bound captures behavior



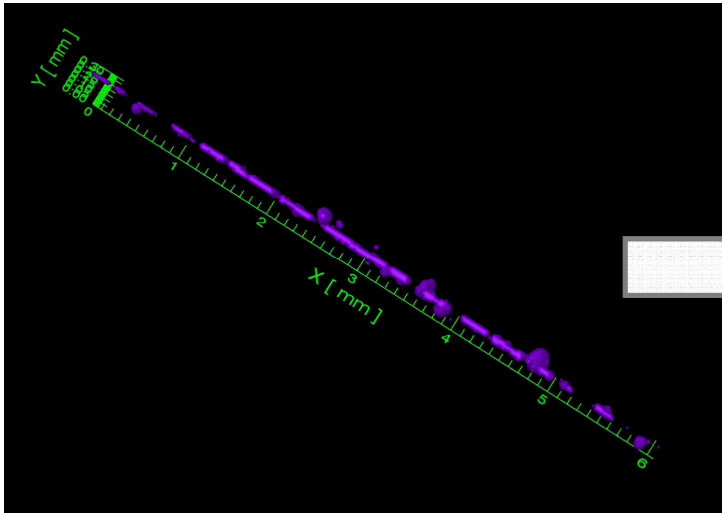
After initial hardening, we must assume perfect plasticity to correlate with experimental findings.



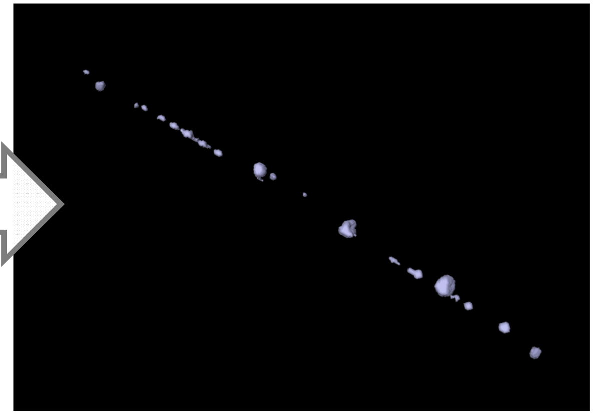
Peak load for hardening/perfect plasticity

These limited findings illustrate the need for including more than plasticity. Limited softening from porosity evolution might explain the discrepancies.

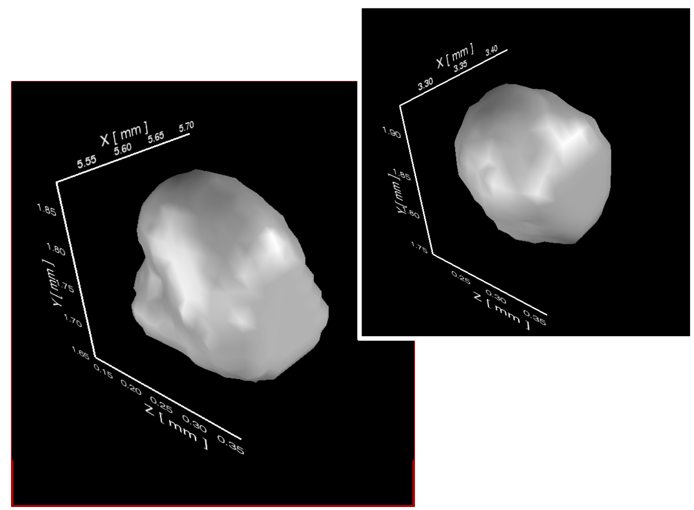
Characterization of welded structures

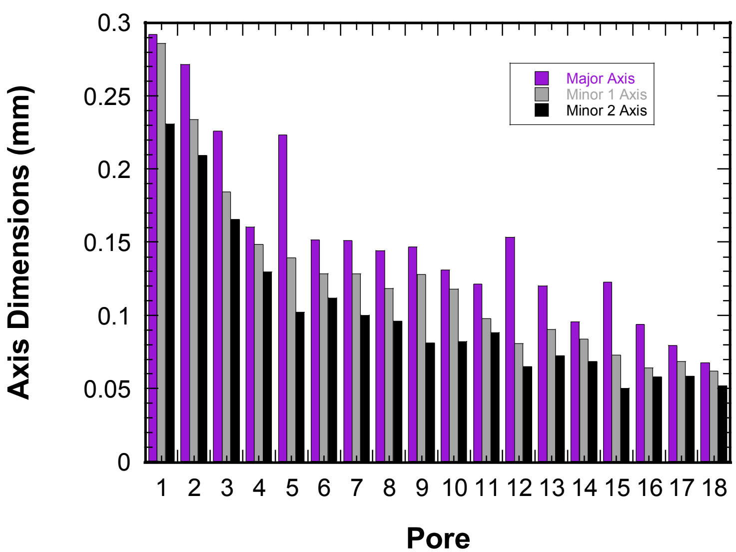


μ-Computed Tomography



Magnification: 9X
Voxel size: 14 μm
Energy: 130 keV

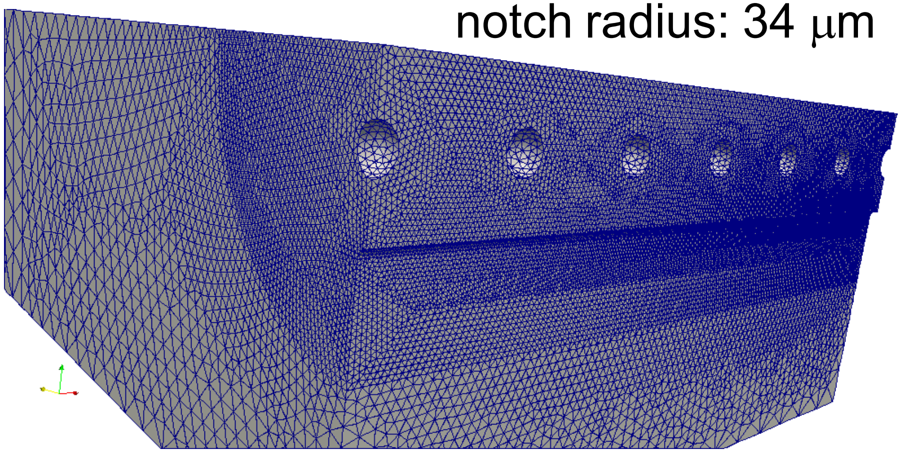




J. Madison, L. K. Aagesen, *"Quantitative Characterization of Porosity in Laser Welds of Stainless Steel"* SCRIPTA MATERIALIA (2012)

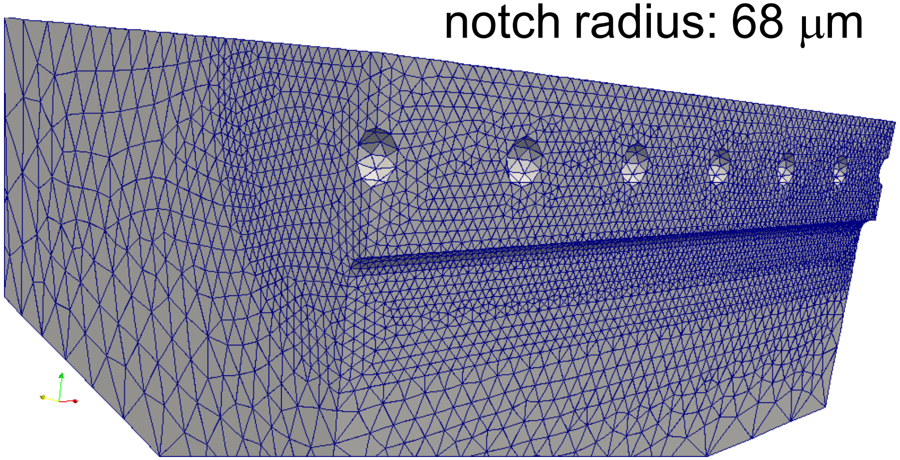
Idealize 3-D spherical void structures

notch radius: 34 μm



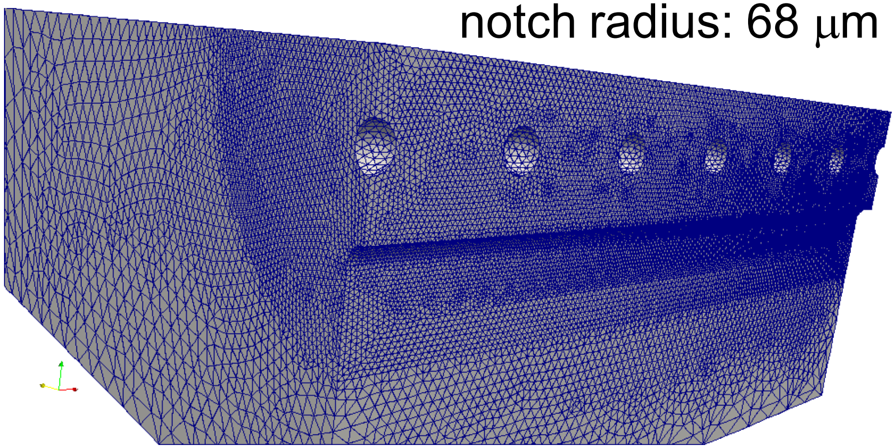
Sheet thickness: 1.6 mm
Ligament length: 508 μm
Number of voids: 6
Void diameter: 150 μm
Area fraction: 0.066 (~target)
Location: centerline of ligament
Coarse element size: 24 μm
Finer element size: 12 μm
Element type: composite-tet (10 nodes)
Hardening law: Sheet dic to sheet base bound

notch radius: 68 μm



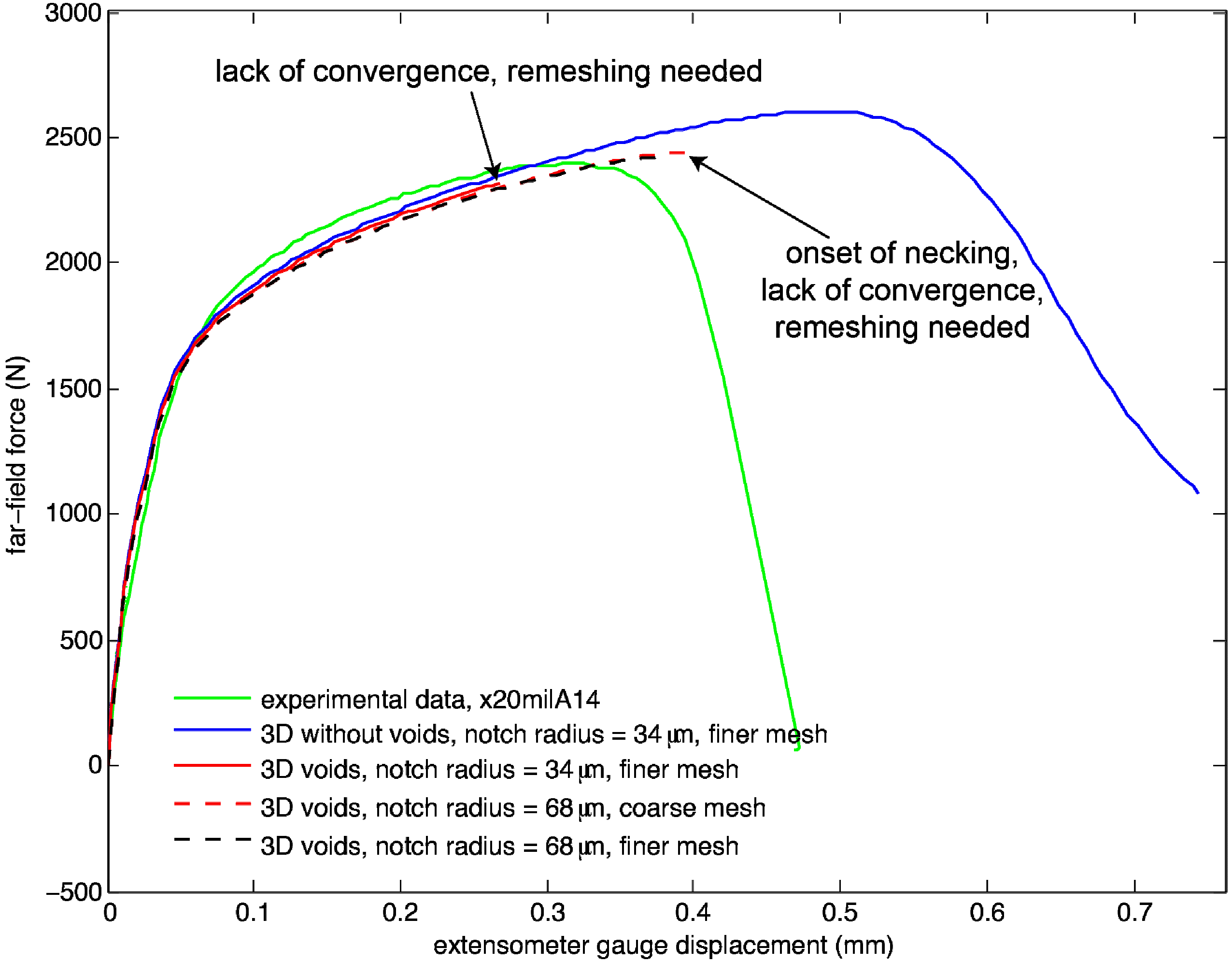
nodes: 297,893, elements: 212,361

notch radius: 68 μm

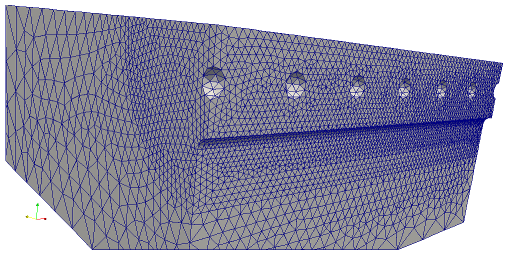


nodes: 2,324,437, elements: 1,698,888

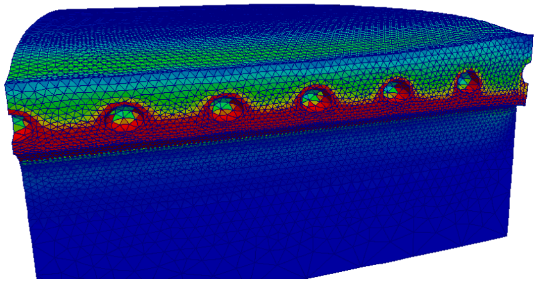
Necking enhanced through 3-D voids



notch radius: 68 μm



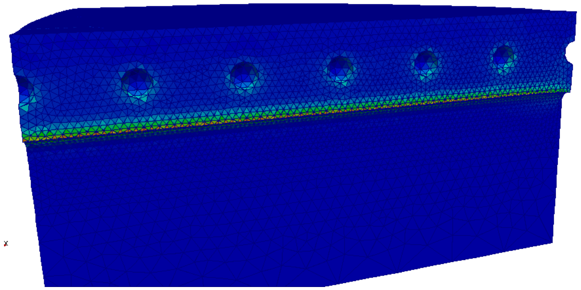
Onset of necking
notch radius = 68 μm
coarse mesh

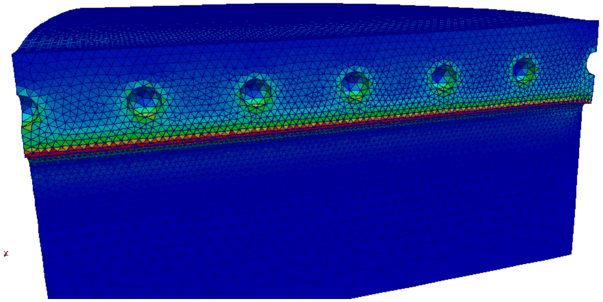


NOTE: Same constitutive model employed for cases with and without voids

Local necking may drive global necking

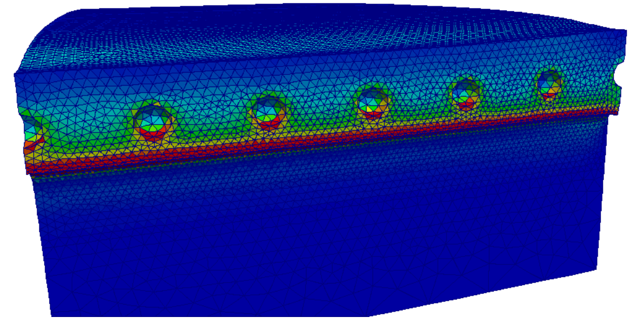
t = 0.20 s



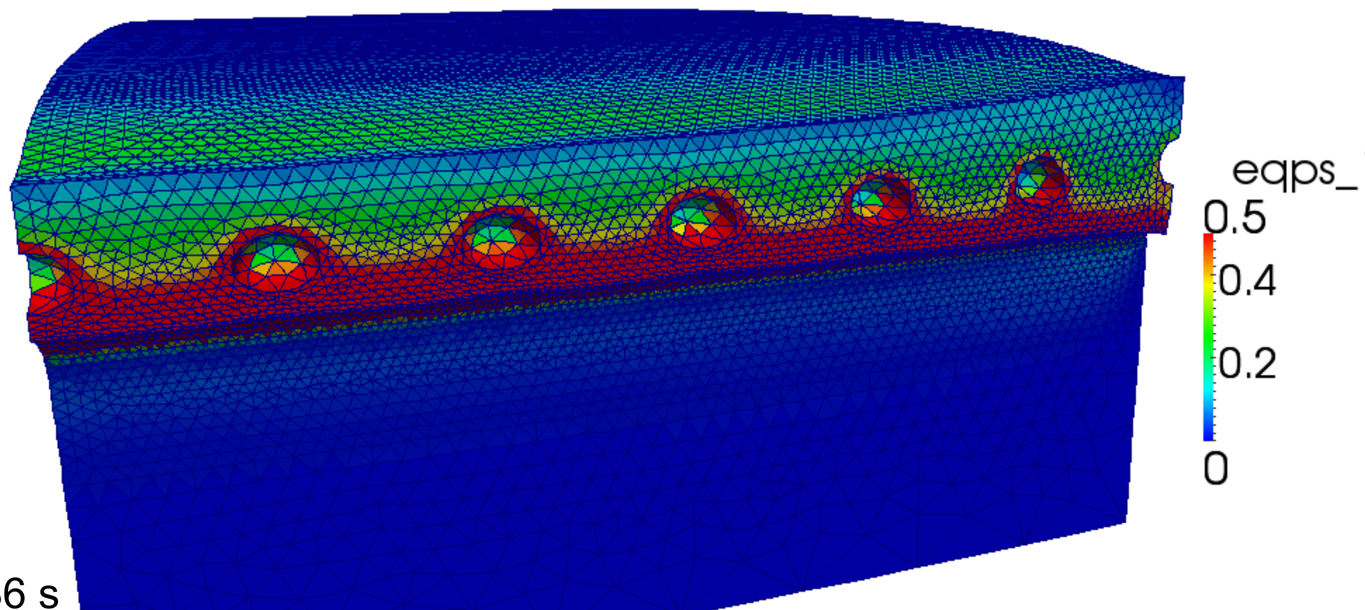


t = 0.40 s

t = 0.60 s



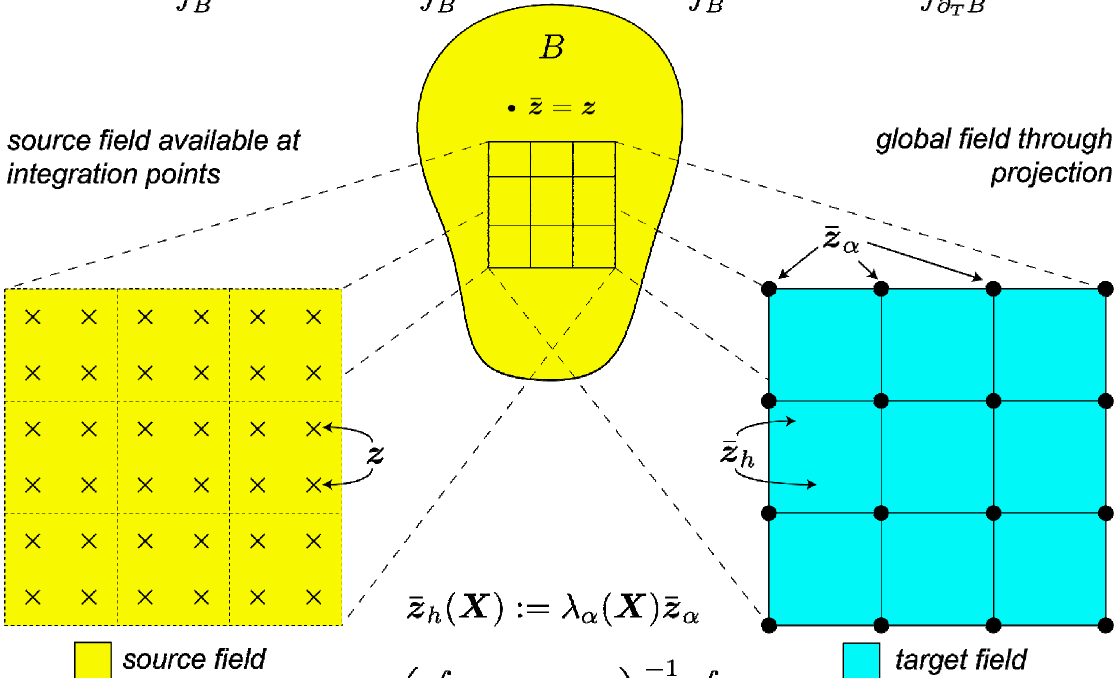
Large notch-void deformations (eqps > 0.5) accompany localized necking between the notch and the voids. This phenomena may be driving global neck formation.



t = 0.86 s

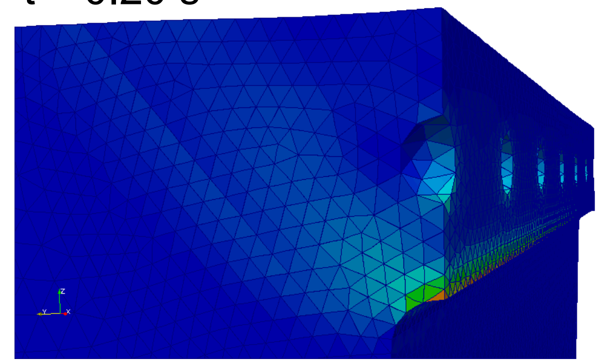
Remeshing and mapping needed

$$\Phi[\boldsymbol{\varphi}, \bar{\boldsymbol{z}}, \bar{\boldsymbol{y}}] := \int_B W(\boldsymbol{F}, \bar{\boldsymbol{z}})\, dV + \int_B \bar{\boldsymbol{y}} \cdot (\bar{\boldsymbol{z}} - \boldsymbol{z})\, dV - \int_B \rho_0 \boldsymbol{B} \cdot \boldsymbol{\varphi}\, dV - \int_{\partial_T B} \boldsymbol{T} \cdot \boldsymbol{\varphi}\, dS$$

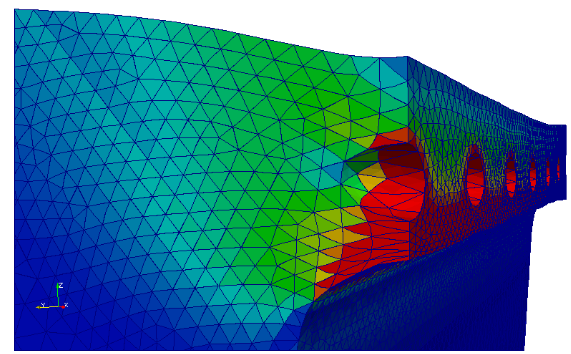


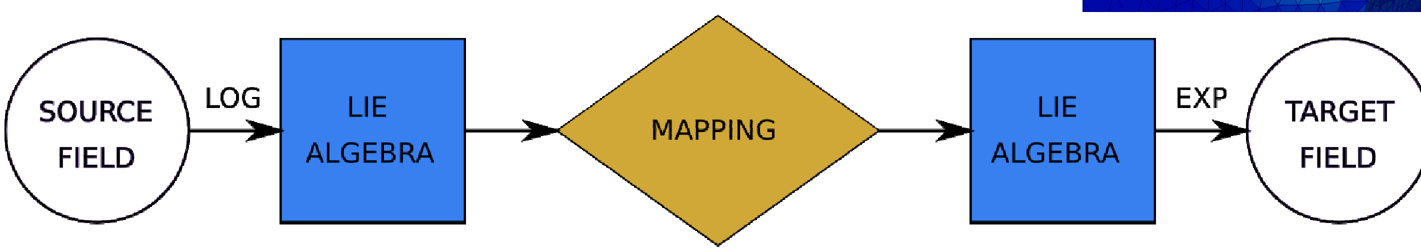
$$\bar{\boldsymbol{z}}_h = \lambda_\alpha \left(\int_B \lambda_\alpha \lambda_\beta \boldsymbol{I}\, dV \right)^{-1} \int_B \lambda_\beta \boldsymbol{z}\, dV$$

t = 0.20 s



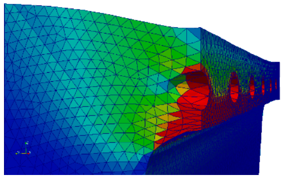
t = 0.84 s

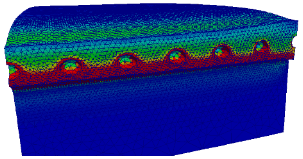




Mota, Sun, Ostien, Foulk, and Long [2012], recently submitted to *Computational Mechanics*

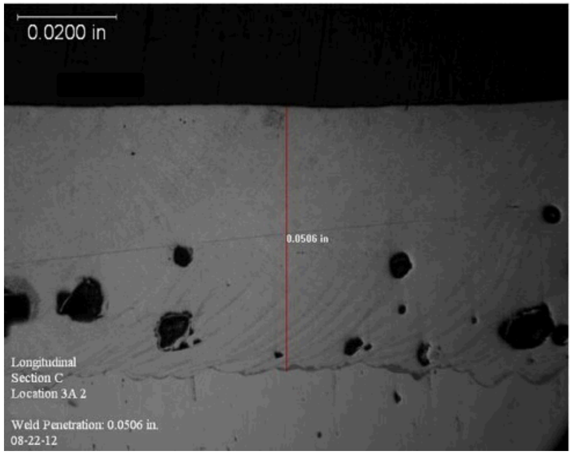
Where are we? Can we do this in one year?



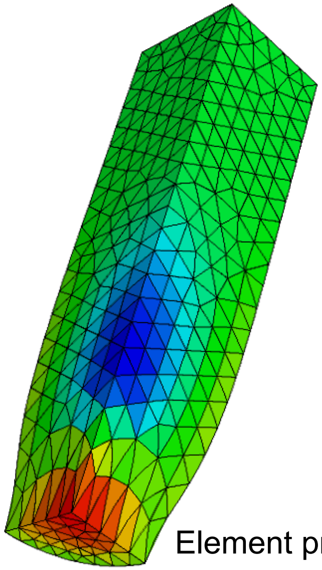


Accomplishments and future work

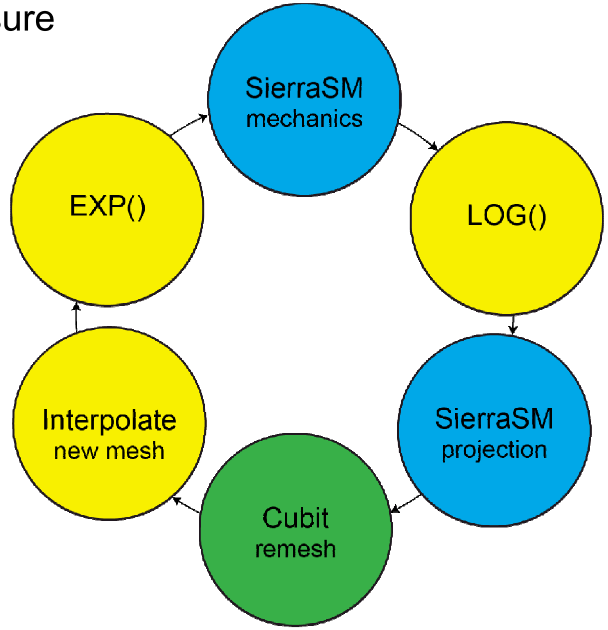
- Experimental program turned on in (March)
- Remeshing/mapping (June)
- Model of the pore structure forthcoming (Aug.)
- Simulations of deeper penetration welds (Sept.) to understand the impact on strength/ductility



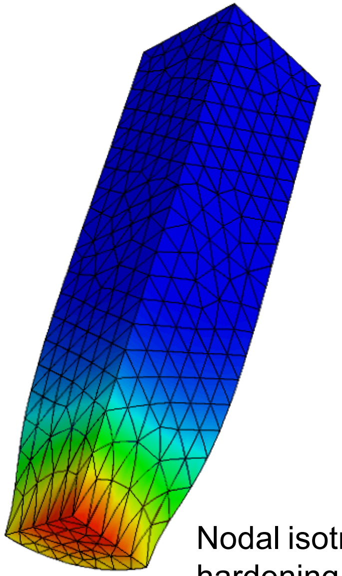
Quadratic Tet10 w/constant pressure



Element pressure



L_2 projection of internal state variable

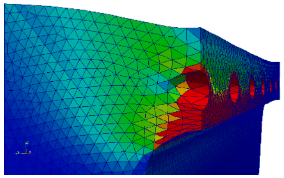


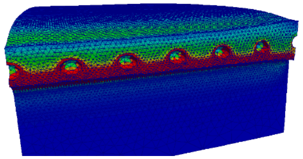
Nodal isotropic hardening

RISK: We are delivering the experimental and computational findings simultaneously!

What does success look like?

(*1*+)

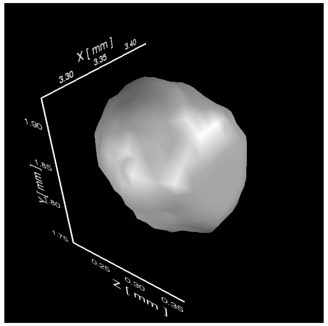


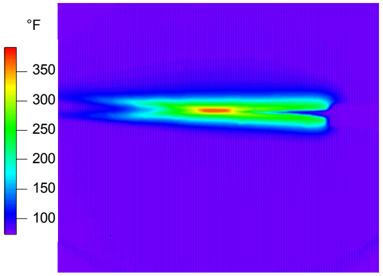


Changing the standard of practice

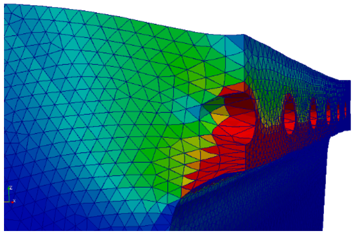
We use 304L VAR because it is extremely damage tolerant. It is tough and forgiving. It meets our current standards and provides margin through superior ductility. Should we expect anything less of our experimental and computational tools? No.

- Experimental studies do more than acquire far-field information
  - Understand initial conditions through tomography
  - Measure fields (displacement, temperature)
  - Isolate welds through measurement/smaller samples
  - Investigate multiple rates and modes of loading
- Computational tools are equally robust (damage tolerant)
  - Mesh tets with impunity (freedom from harm, loss)
  - Adaptively remesh/map within production code
  - Embrace thermomechanical coupling
- Researches and analysts can now focus on
  - Extending structure/property to abnormal environments
  - Setting guidelines for manufactured variability
  - Developing appropriate multiscale methodologies





B. Antoun



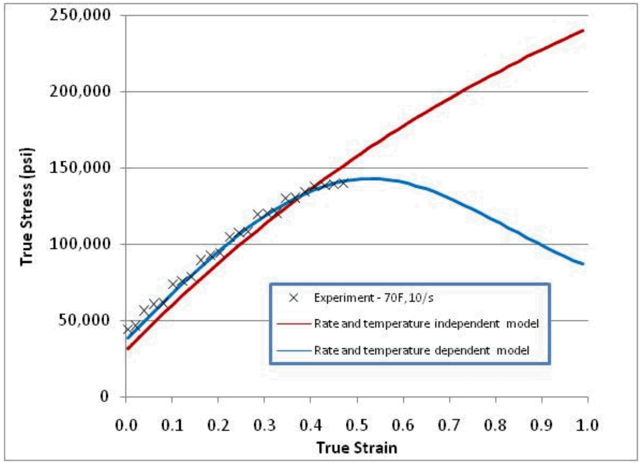
Sandia National Laboratories

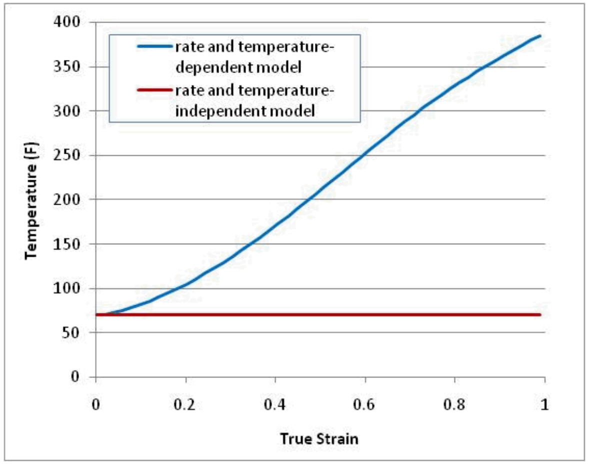
SUPPORTING SLIDES

The need for thermomechanical coupling

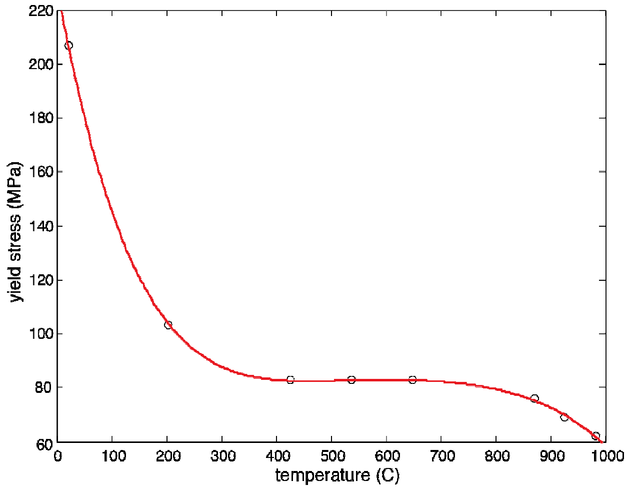
- Abnormal environments can generate elevated strain rates
- Significant plastic work
- Low thermal conductivity
- Temperature rise significant
- Drop in yield strength immense
- *Illustrate impact on necking response*

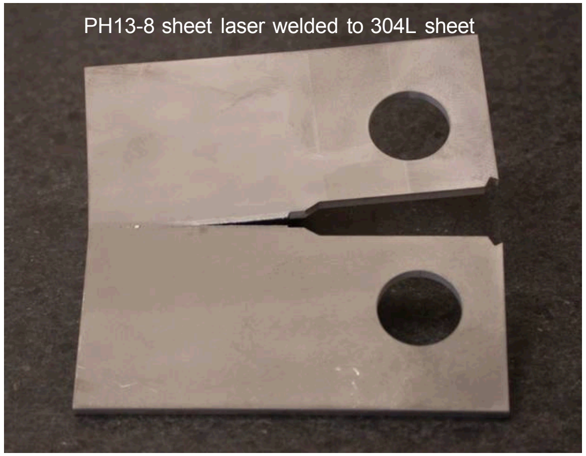
Uniaxial tension w/adiabatic assumption at 10/s (A. Brown, SNL)

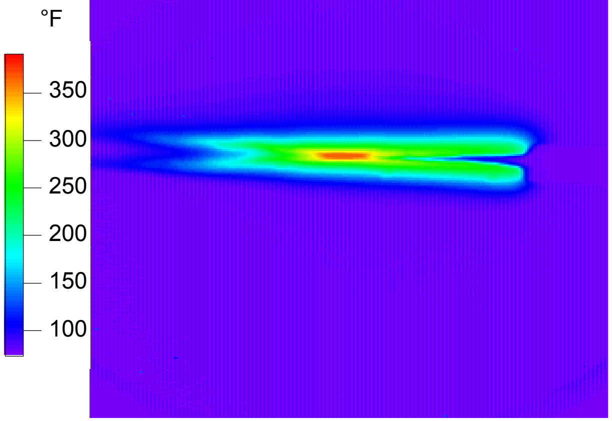




Is a temperature rise of 150C (300F) realistic?

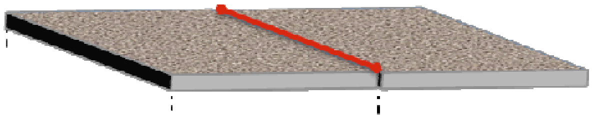




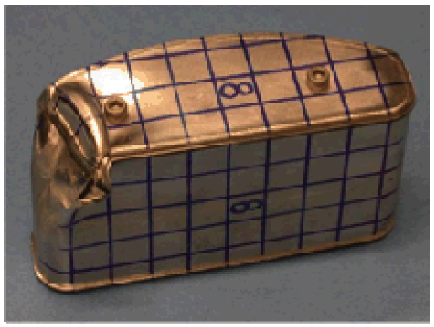


(Bonnie Antoun, SNL)

Background for 304L laser welds

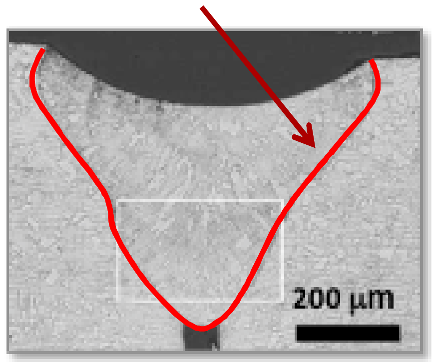


304-L butt weld



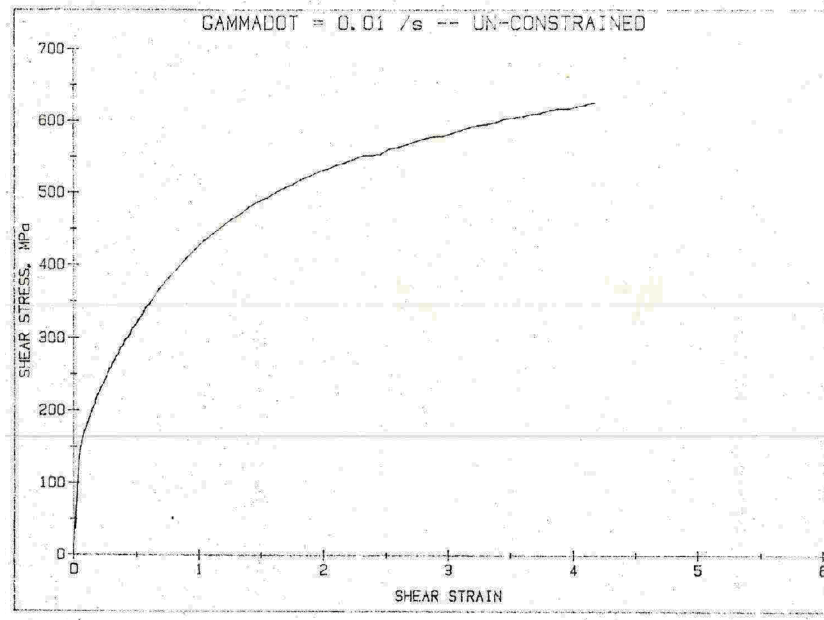
drop environment

welded region

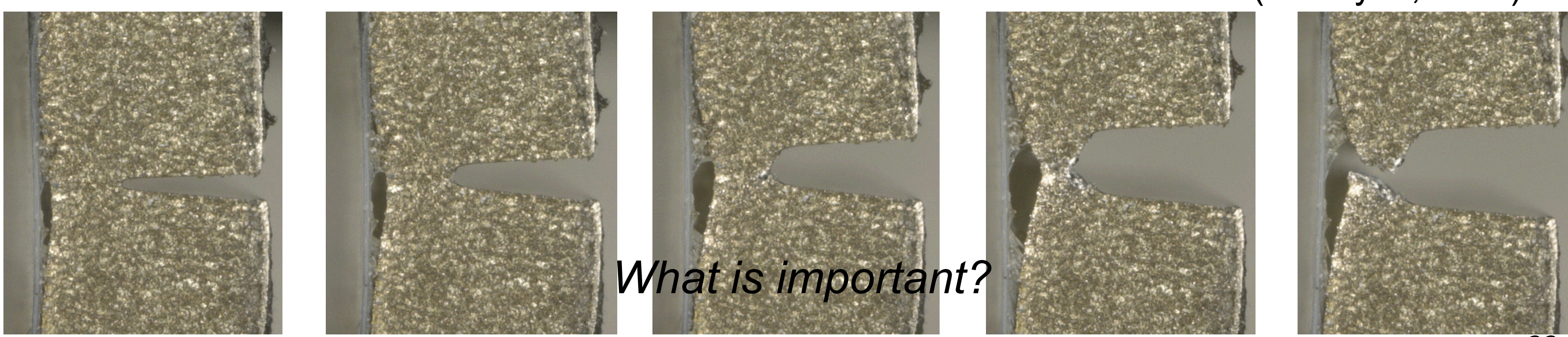


Boyce, Reu, Robino
Met Trans (2006)

Thin tubes in torsion (W. Kawahara, ~1980)



(B. Boyce, 2011)

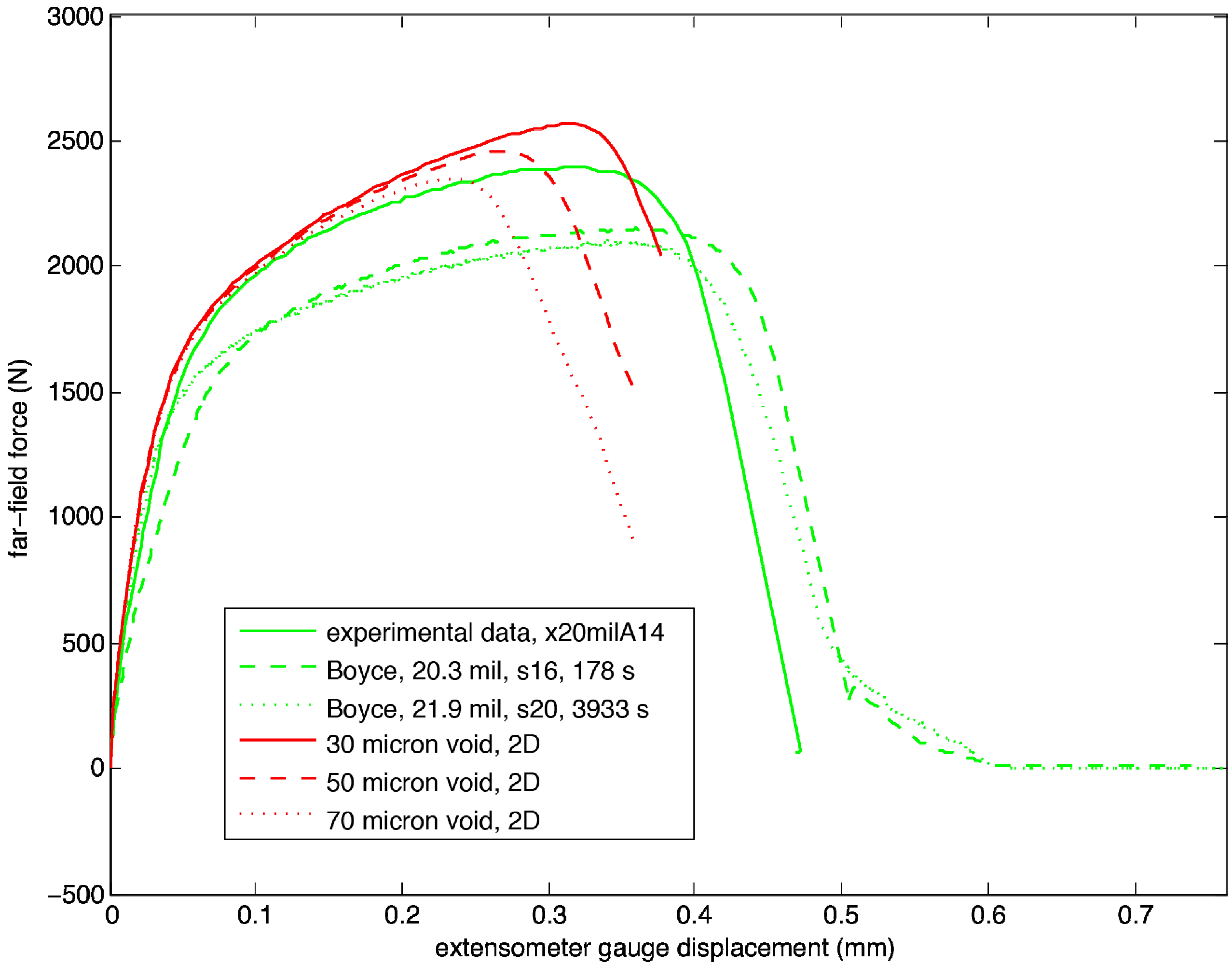


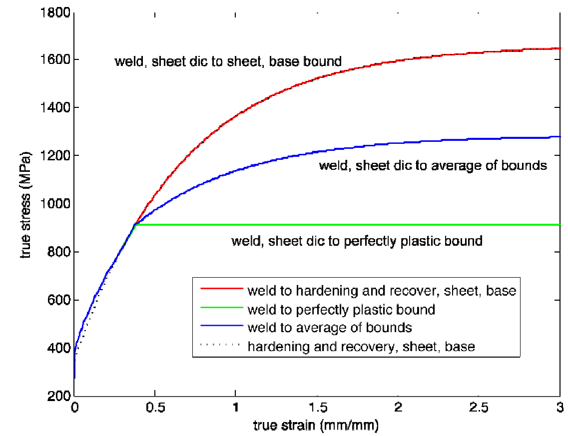
What is important?

pw-20mil-plate2-s16.dat

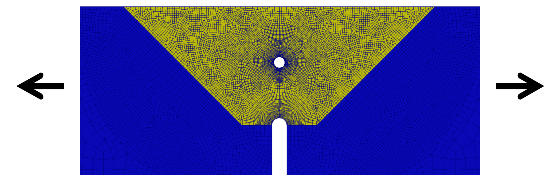
Void growth in plane strain aids instability

To facilitate our understanding, we begin with 2-D plane strain.

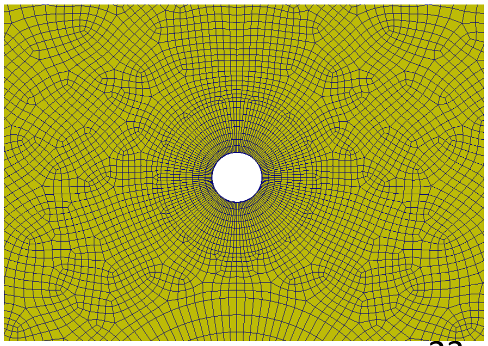




weld, sheet dic to sheet, base bound



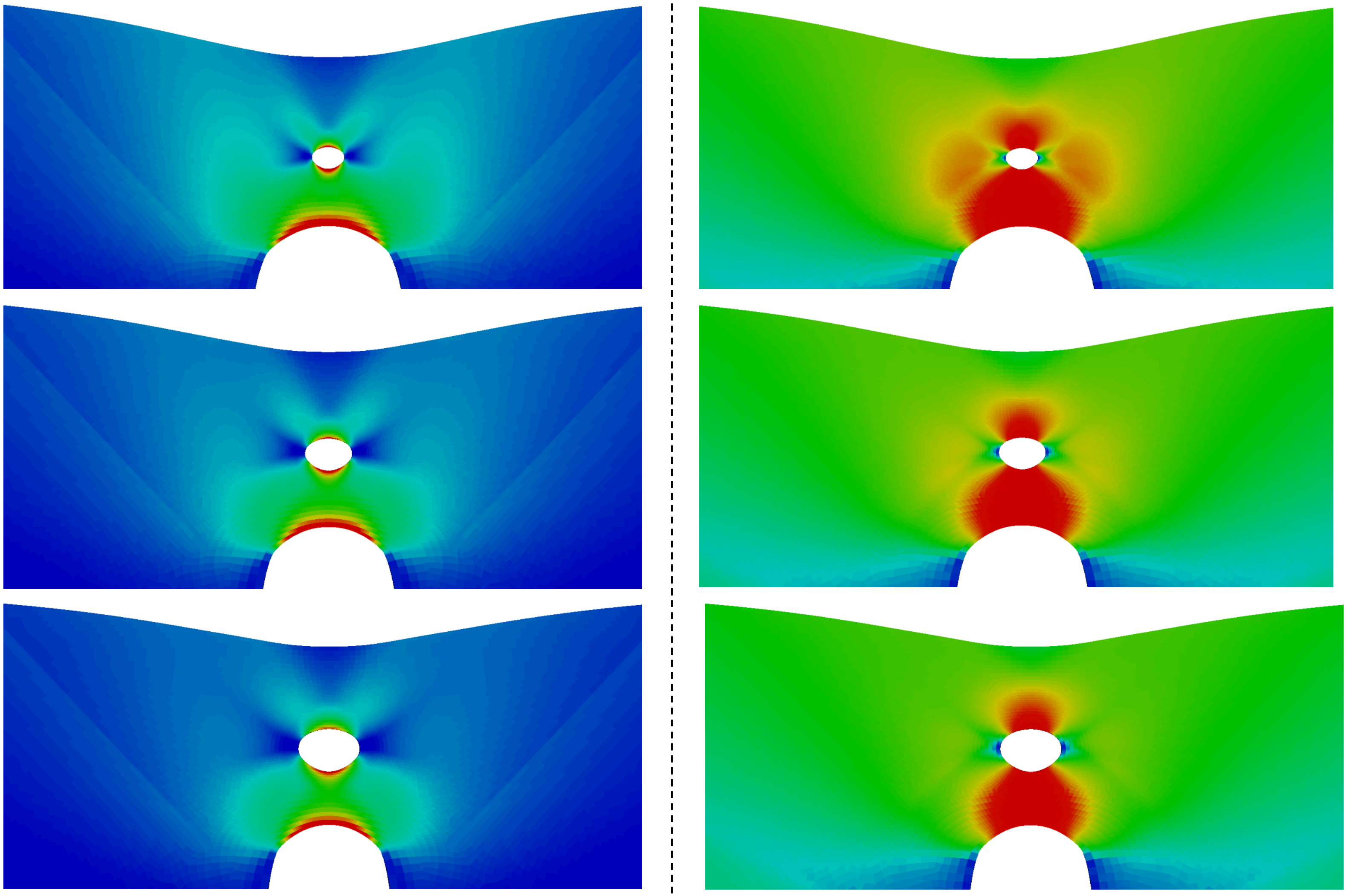
50 μm pore centered in ligament



Void-notch necking at peak load

The peak load is heavily influenced by the void interaction with the notch and the free surface

Thin tubes in torsion (W. Kawahara, 1980)



30 μm pore
$A_F = 0.059$
$P_{max} = 2570$ *N*
$\Delta = 0.314$ *mm*

50 μm pore
$A_F = 0.098$
$P_{max} = 2460$ *N*
$\Delta = 0.270$ *mm*

70 μm pore
$A_F = 0.14$
$P_{max} = 2350$ *N*
$\Delta = 0.236$ *mm*

$0 < \varepsilon_p < 1$

$0 < \sigma_{axial} < 1.5$ *GPa*

On track with risk

- Experimental program turned on in March
  - Welding vacuum-arc remelted (VAR) 304L with production lasers in April
  - Systematically varying the depth of penetration (0.76, 1.0, 1.3, 1.5 mm)
  - Machining and tomography completed by June
  - Structural tests (tension) and material tests (weld) completed by September
- Model of the pore structure forthcoming
  - Working with previous welding schedules
  - Developing statistical representations for void shape, size, location
- Remeshing/mapping within production environment by June
  - Employing tetrahedral elements for ease of meshing w/Cubit
  - Transitioned to quadratic tet elements with 4^{th} order cubature (11 int. pts.)
  - Using Sierra for mechanics and L_2 projection
  - Developing a lightweight code for mapping – log()/interpolation/exp()
  - Verifying all aspects of the process. Beginning to simulate idealized cases.
  - Re-establishing equilibrium the dominant risk. Other items are plumbing.
- Simulations of porosity for deeper penetration welds by September
  - Simulate limited samples to determine the applicability of approach
  - Employ models of void structure to investigate sensitivity to failure (necking)

RISK: We are delivering the experimental and computational findings simultaneously!

Necking of a bar w/remeshing & mapping

This is a placeholder. We would like to simulate the necking of a bar with multiple element types (hexes, tets) to illustrate the remeshing & mapping methodology. We hope to have this finished by the review.