TMS 2015 Annual Meeting and Exhibition

SAND2015-1811C

Variability in Mechanical Properties of Laser Engineered Net Shaping Material

Jay D. Carroll[1], David P. Adams[1], Michael C. Maguire[1], Joseph E. Bishop[1], Benjamin Reedlunn[1], Bo Song[1], Joseph R Michael[1]
Todd Palmer[2]
John S. Carpenter[3], Bjorn Clausen[3], Donald W. Brown[3]

[1]Sandia National Laboratories
[2]Pennsylvania State University
[3]Los Alamos National Laboratory

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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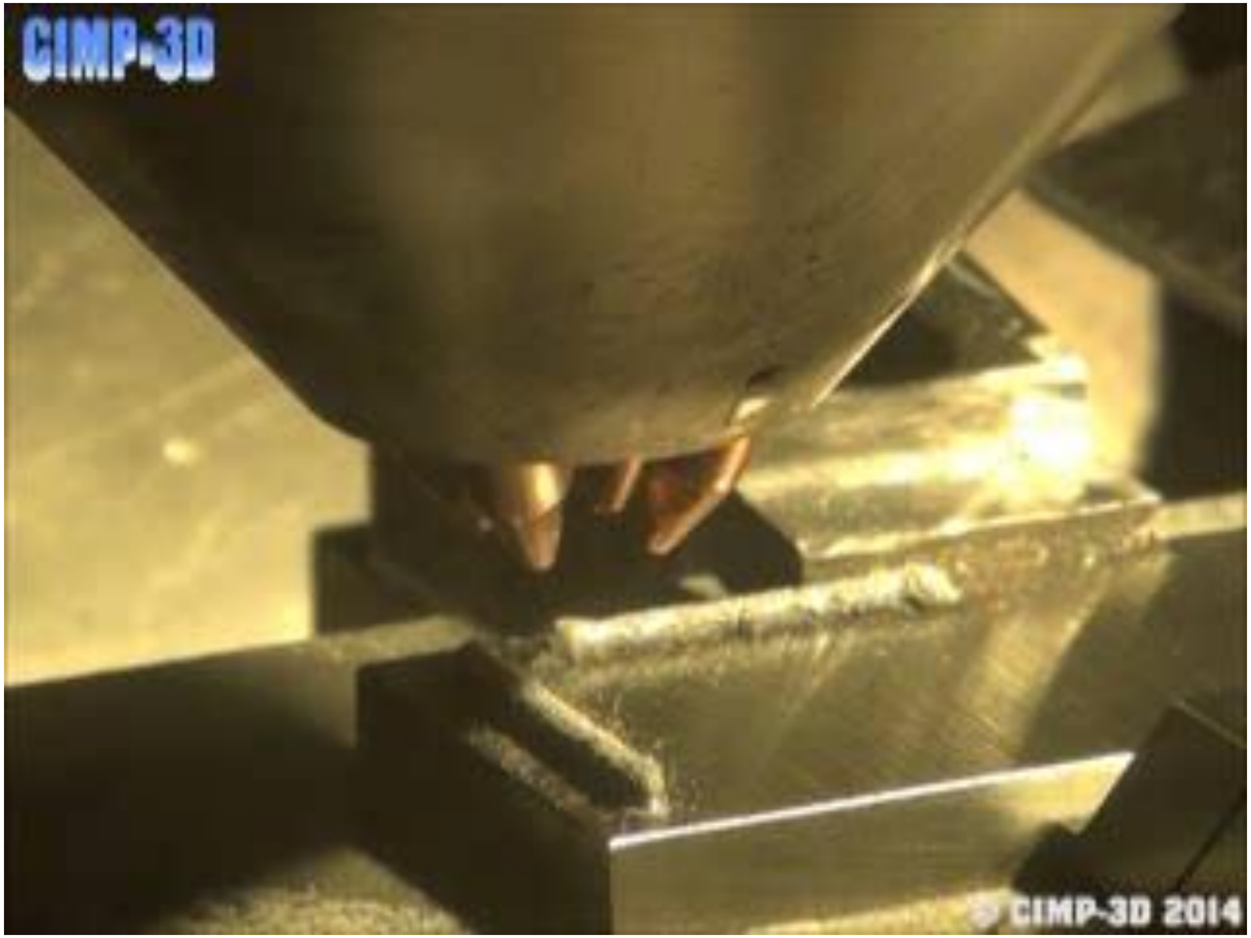
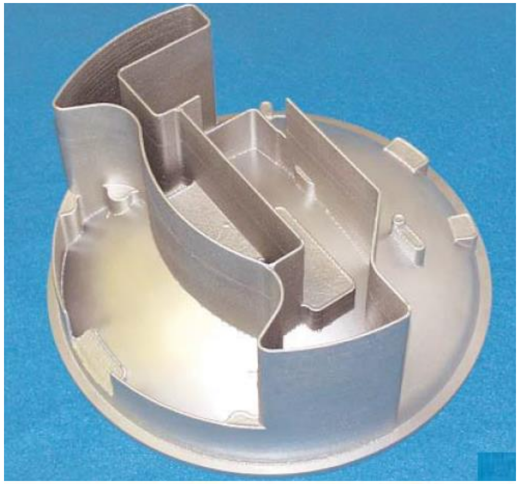
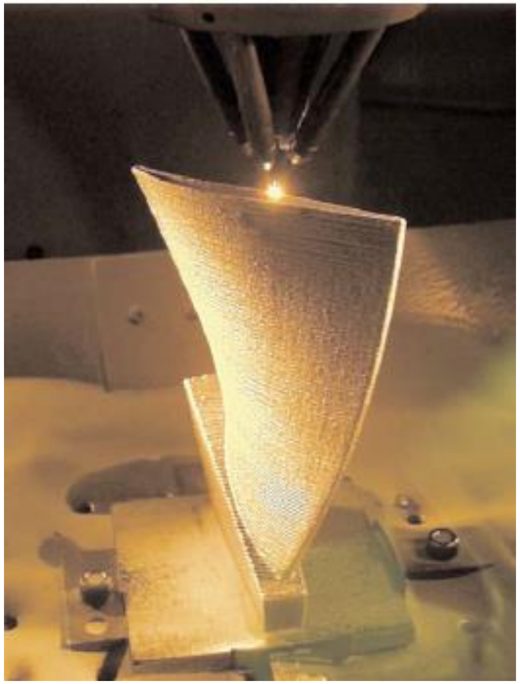
3/10/2015

As opposed to powder-bed technology, the LENS process builds material by injecting powder feedstock with laser heating.

LENS = Laser Engineered Net Shaping







Courtesy of Todd Palmer, Pennsylvania State University

Project: Strain rate effects, variability, and modeling of LENS-like 304L

Quasistatic $10^{-5} – 10^{0}$

Dynamic $5\times10^{2} – 3\times10^{3}$

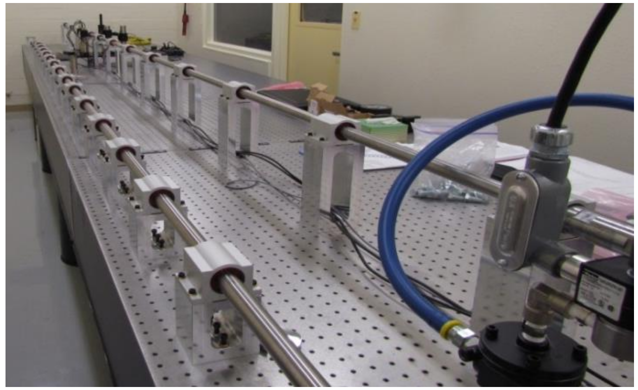
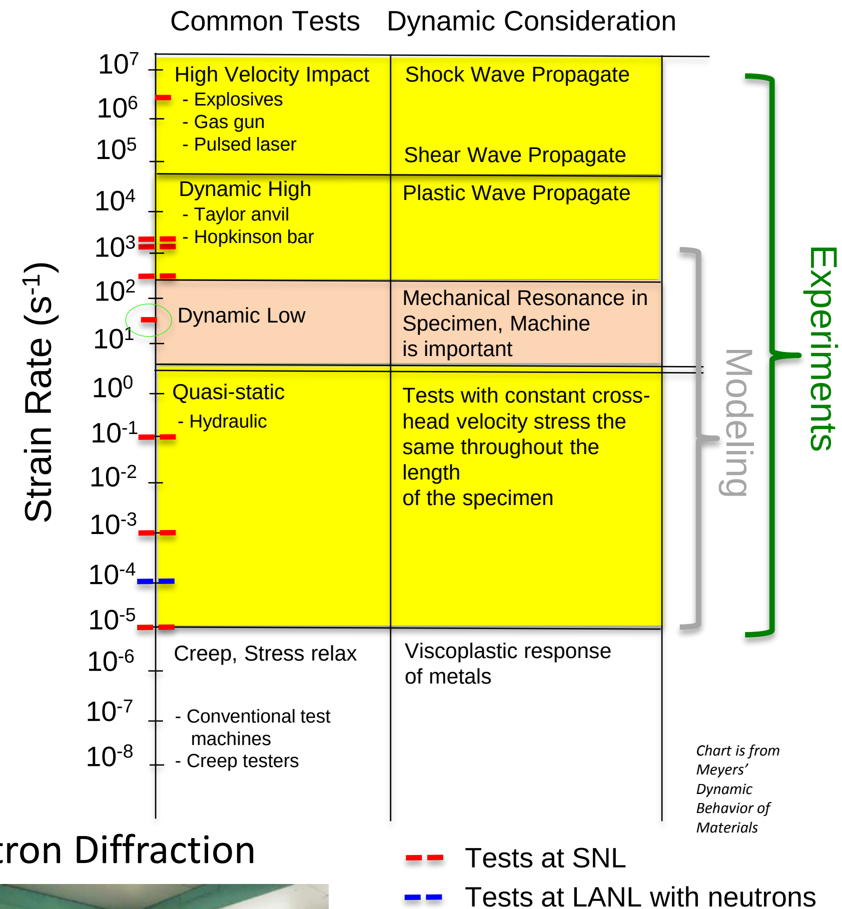


Plate Impact $10^{7} – 10^{9}$



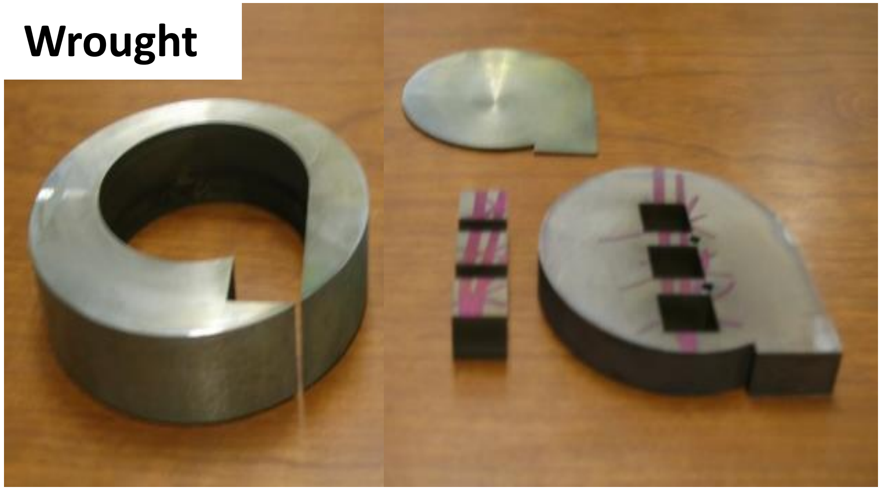
Crystal Plasticity Modeling

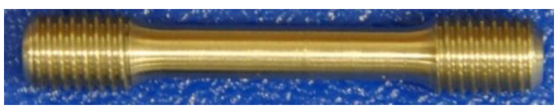
Microscopy

Neutron Diffraction

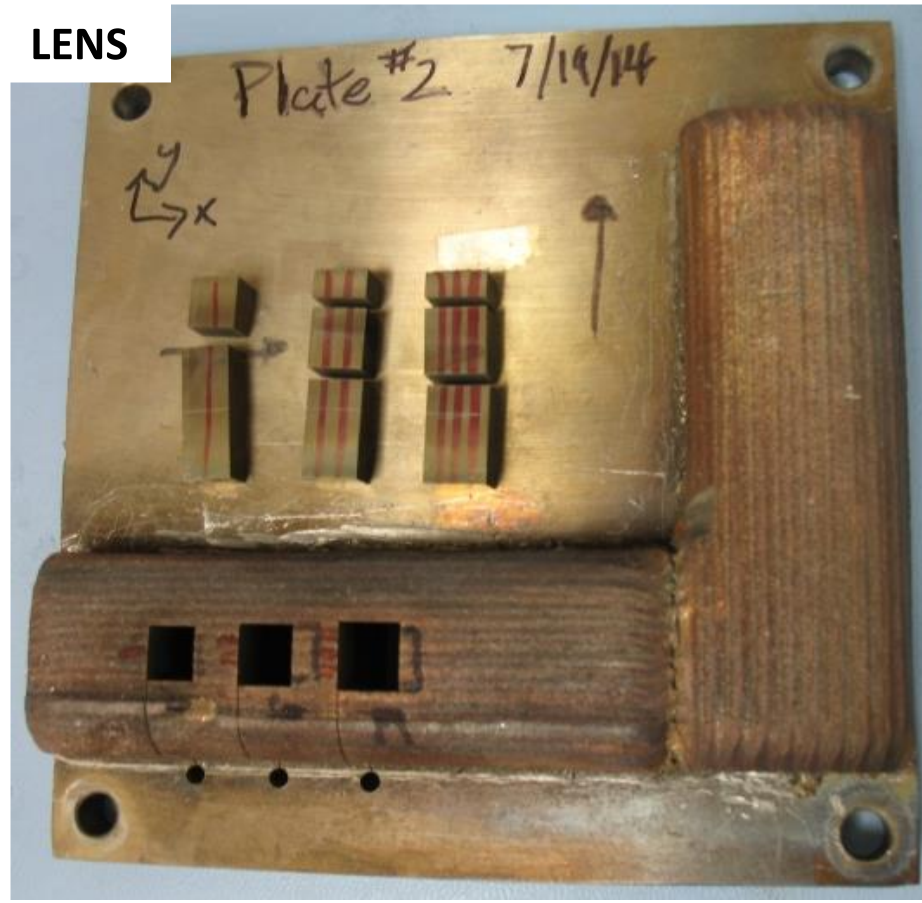
Specimens cut from wrought and LENS bars for comparison.

Wrought

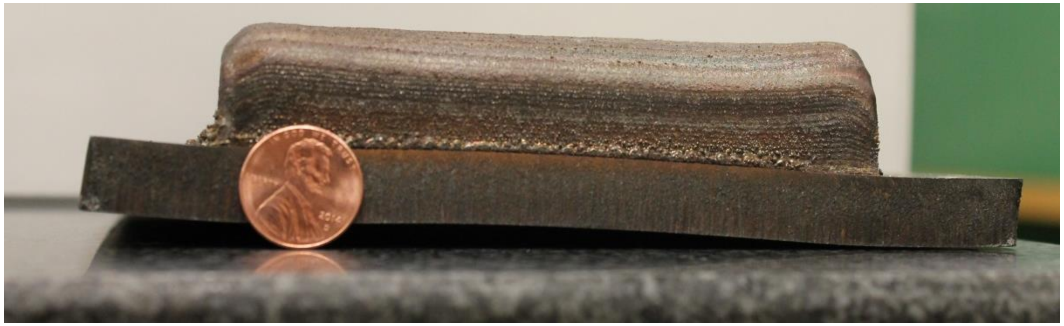




LENS



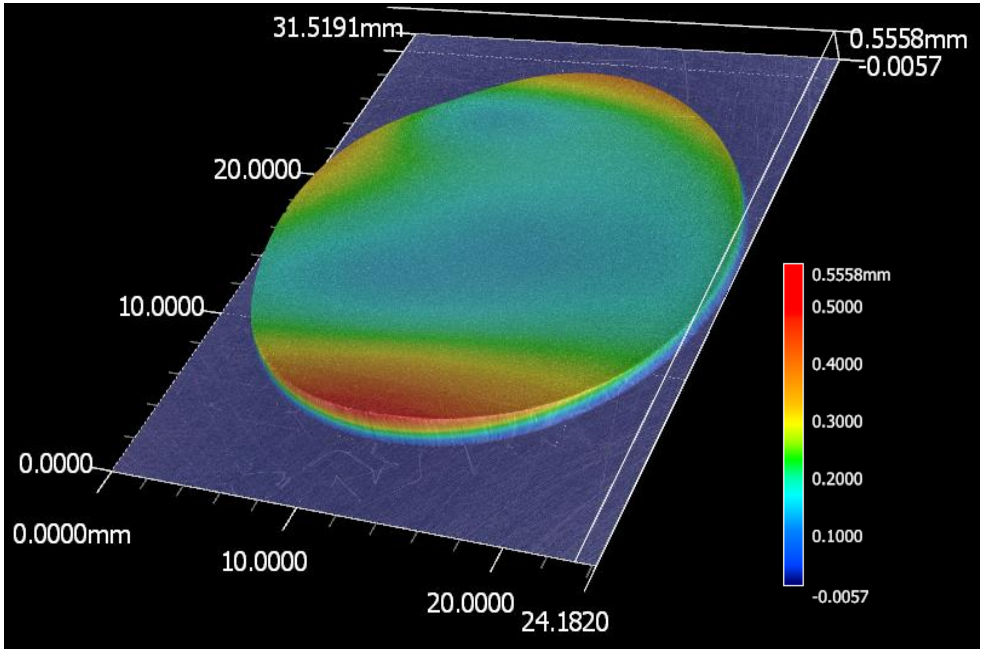
LENS residual stresses are not as extreme as feared



Lattice parameters in specimens show little difference

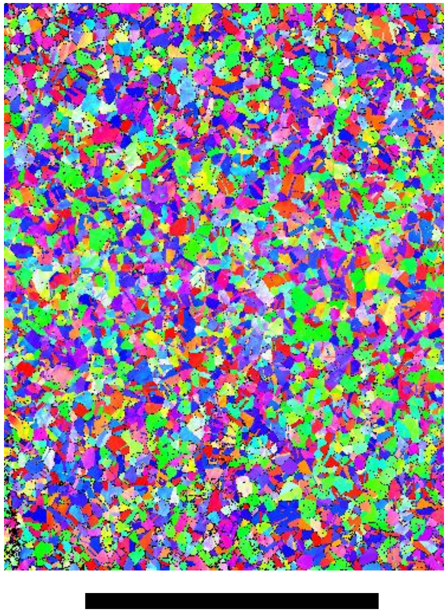
	Austenite parameters	
	a_l	a_t
Wrought	3.5932 Å	3.5900 Å
LENS 3.8kW //	3.5938 Å	3.5904 Å
LENS 2kW +	3.5941 Å	3.5908 Å

- **Base plate warped significantly (12 mm thick).**
- **Lattice parameters in specimens cut from bars show little difference.**
- **100 µm disk cut with very little warping (0.5 mm max over 25 mm).**



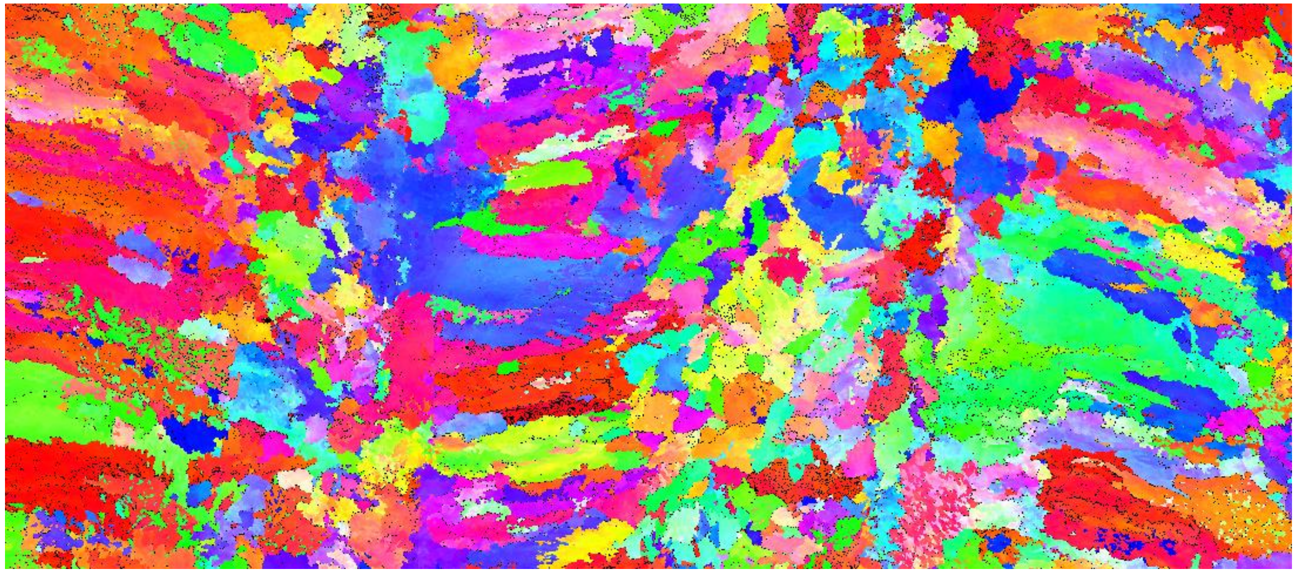
LENS grain size is much larger than wrought 304L SS. Same chemistry.

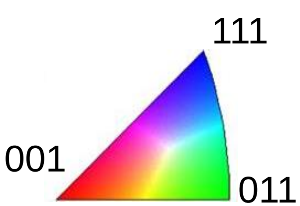
Wrought



1 mm

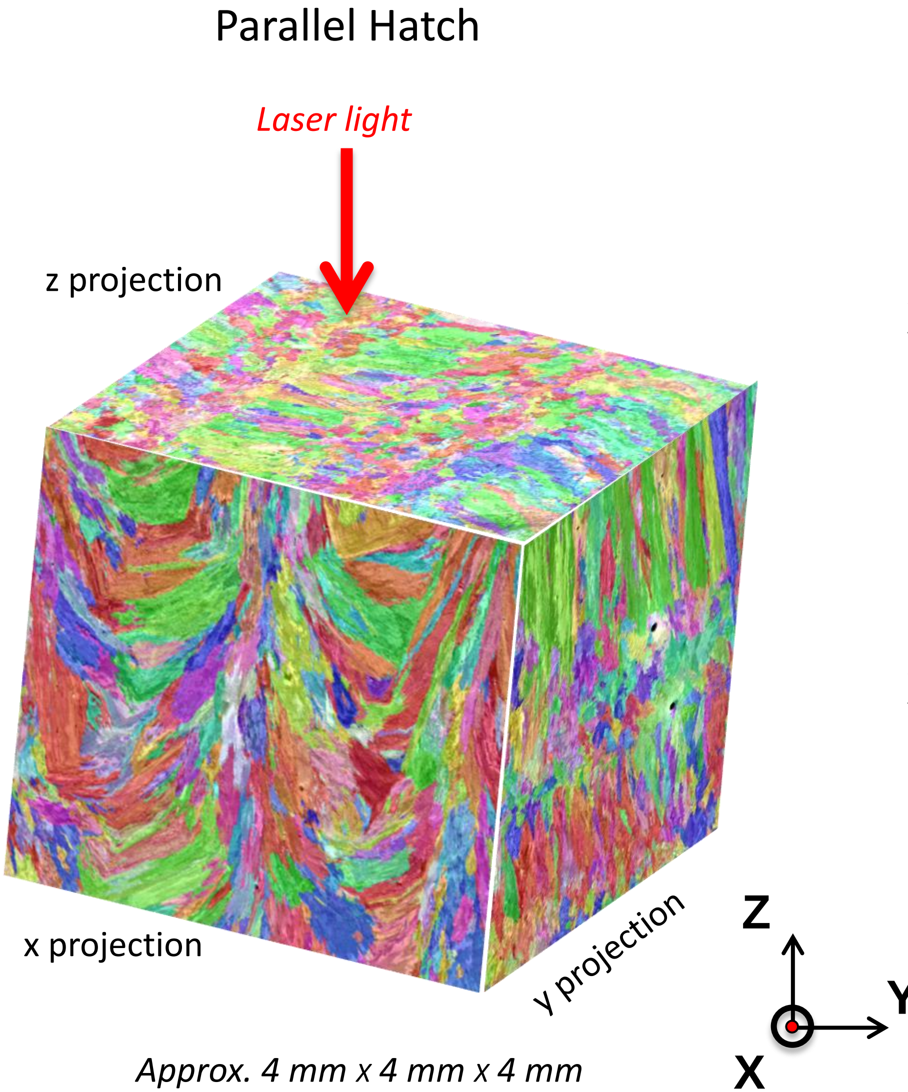
LENS



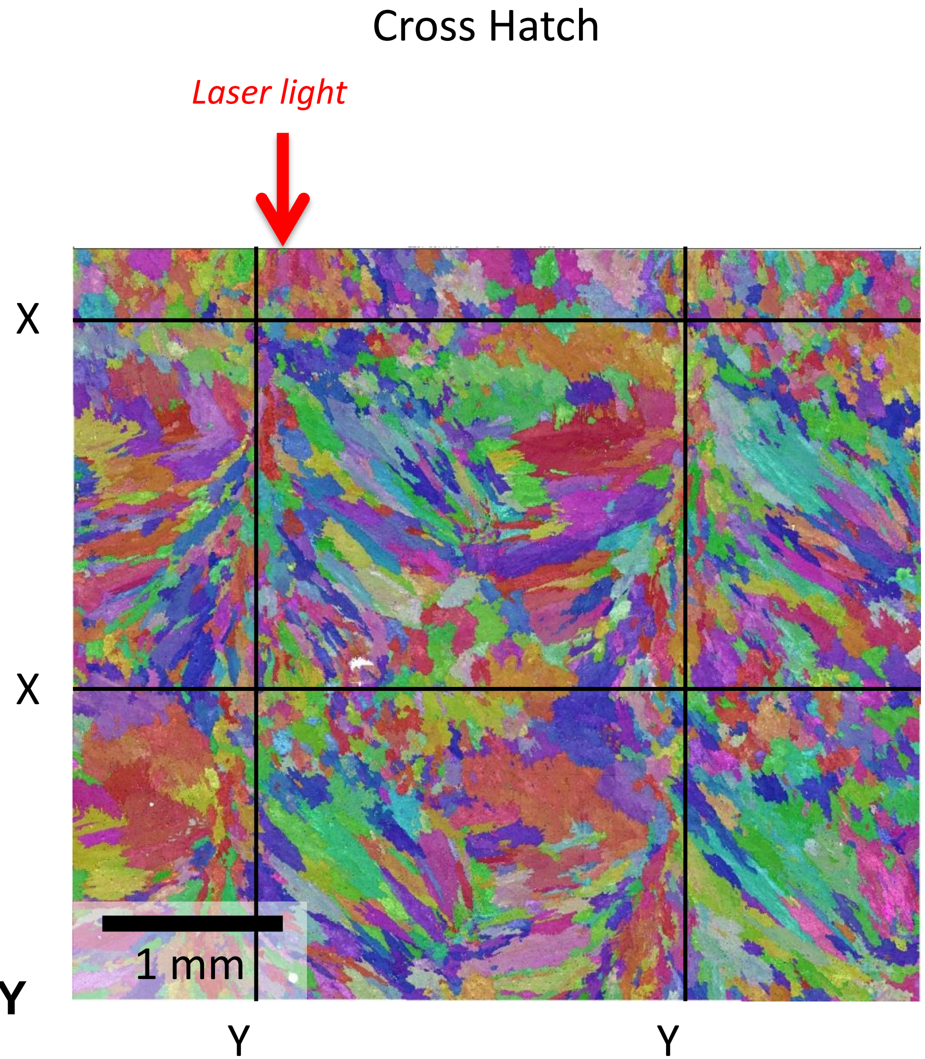


Fe	Cr	Ni	Mn	Si	Mo	Cu	V	C	P	S
bal	19	10.3	1.55	0.55	0.04	0.03	0.02	0.01	0.01	0.01

3D grain structure of AM material is a mixture of small and large grains.



Approx. 4 mm x 4 mm x 4 mm



Wave speeds in wrought and LENS cubes indicate anisotropy in LENS material.

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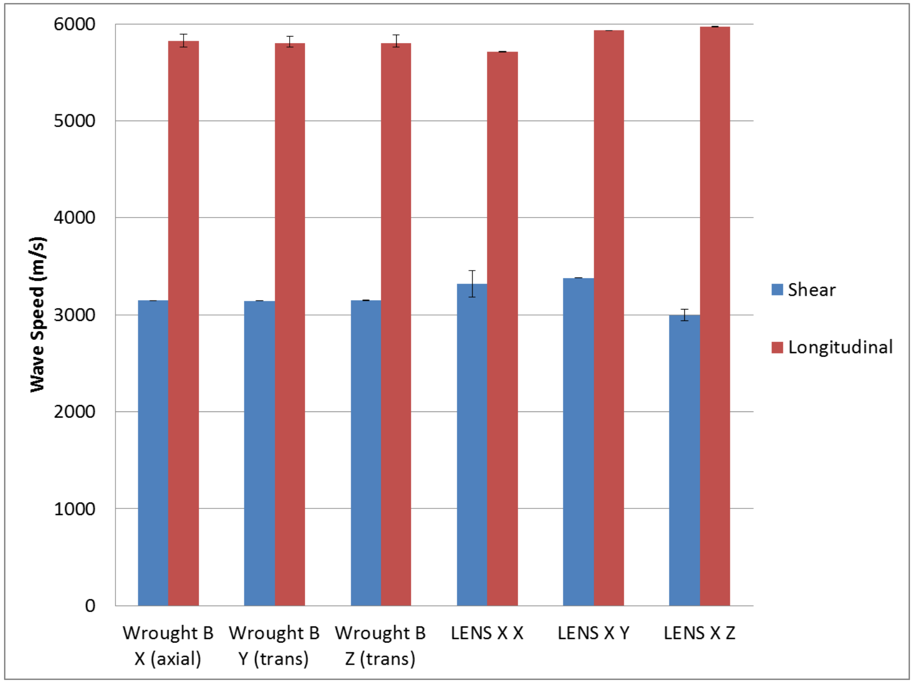


- **Measure shear wave speed, C_s**
- **Measure dilatational wave speed, C_d**
- **Measure density, ρ**

Material	Direction	Density (kg/m^3)	Shearmod (GPa)	Poisson's Ratio	Elastic Modulus (GPa)
Wrought B	X (axial)	7854.5	**77.8**	**0.29**	**201.3**
Wrought B	Y (trans)		**77.6**	**0.29**	**200.5**
Wrought B	Z (trans)		**77.8**	**0.29**	**201.0**
LENS X	X	7842.9	**86.6**	**0.24**	**215.5**
LENS X	Y		**89.6**	**0.26**	**225.7**
LENS X	Z		**70.5**	**0.33**	**187.6**
		99.85	% dense		

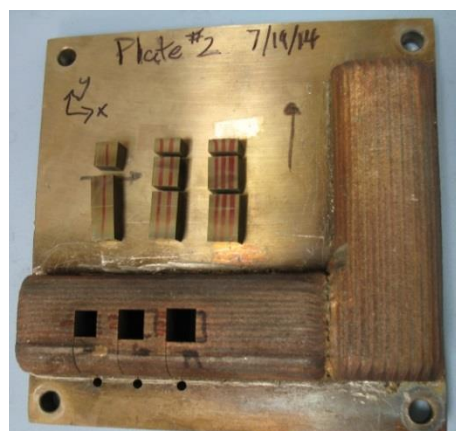
$$C_s = \sqrt{\frac{\mu}{\rho}}$$

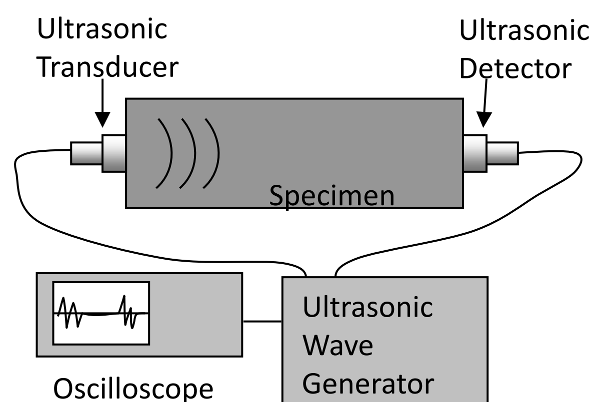
$$\mu = C_s^2 \rho$$

$$C_d^{pl-\varepsilon} = \sqrt{\frac{2(1-\nu)\mu}{(1-2\nu)\rho}}$$

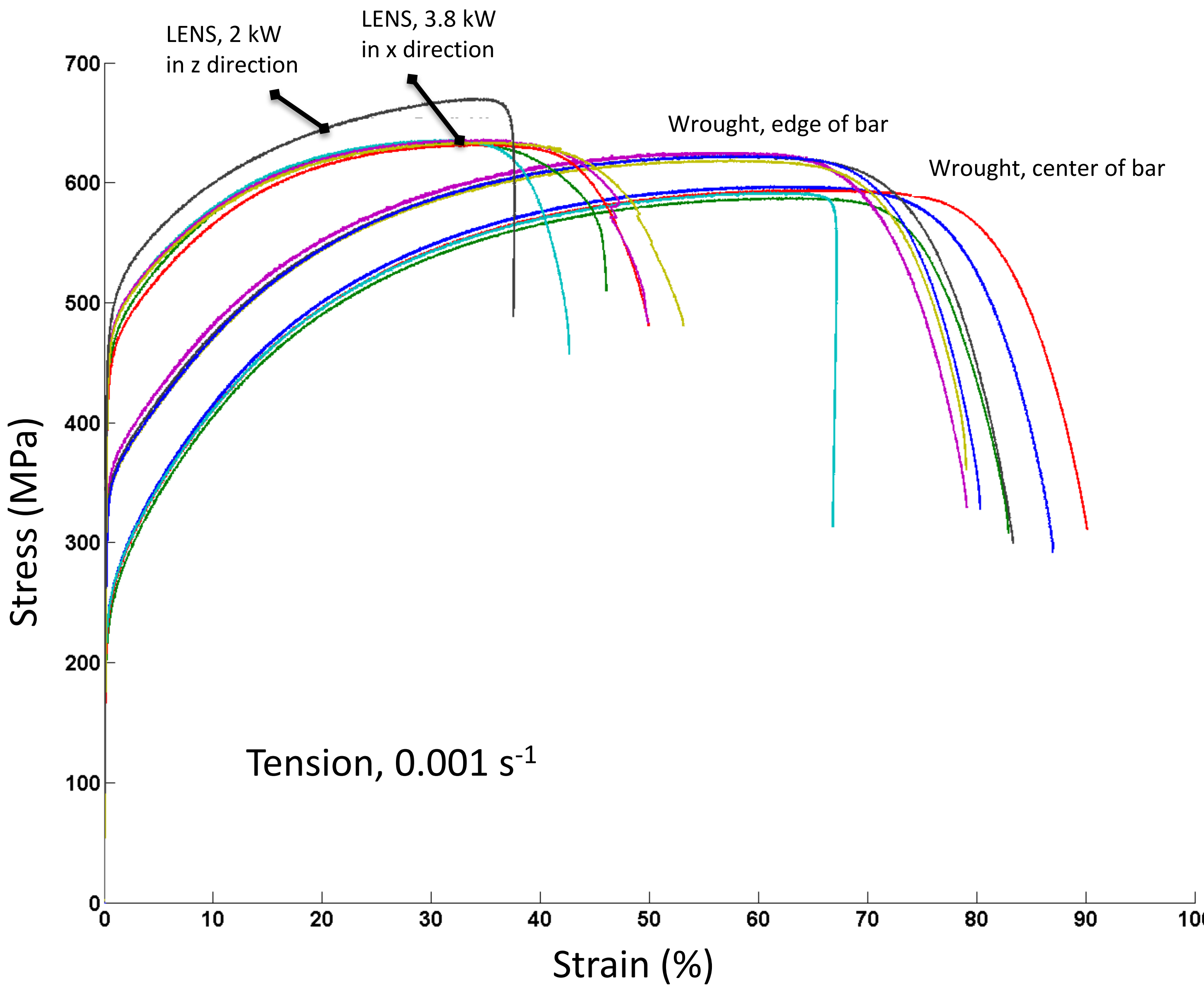
$$\nu = \frac{\frac{1}{2}\left(\frac{C_d}{C_s}\right)^2 - 1}{\left(\frac{C_d}{C_s}\right)^2 - 1}$$

$$E = 2\mu(1+\nu)$$

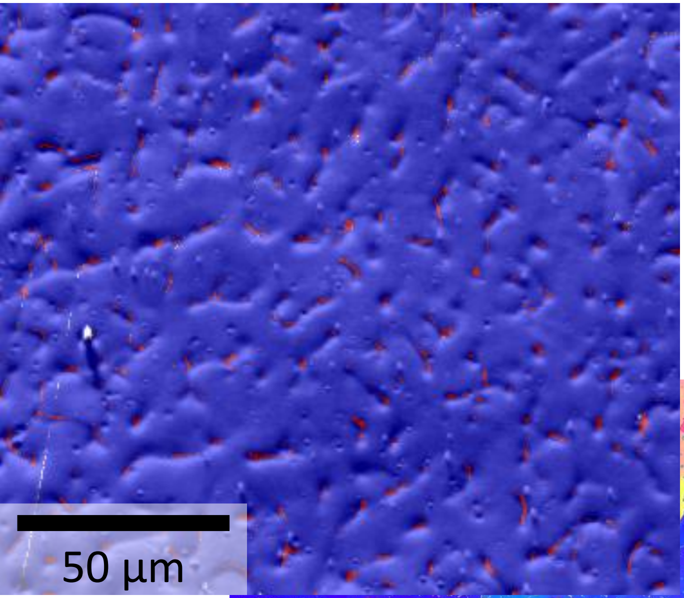


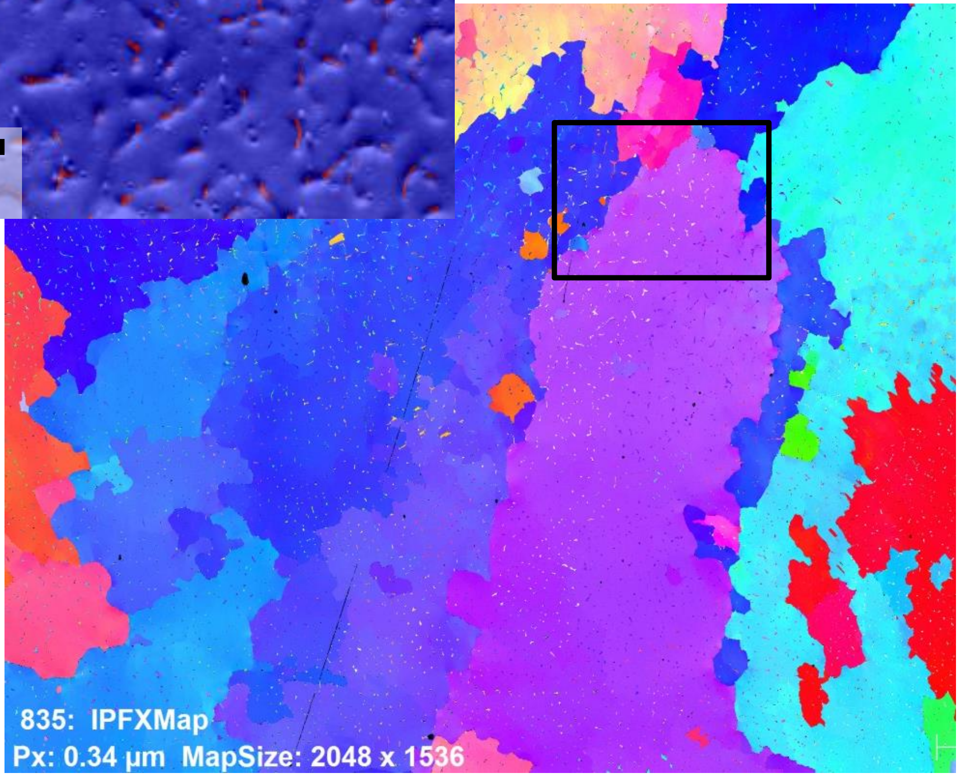


LENS material is significantly stronger than wrought, contrary to the Hall-Petch expectation based on grain size.



Hall-Petch is not limited to grain size. Small ferrite islands could be responsible for hardening.





- **Small ferrite islands**
- **Subgrains and grain substructure associated with geometrically necessary dislocations.**
- **Initial BCC phase: 1.2% for Wrought and 2.3% for LENS (ferritescope)**
- **Ferrite content appears to increase slightly with loading (~3%)**

Ferrite content in LENS samples may increase slightly with tensile loading (Neutron Diffraction at LANL)

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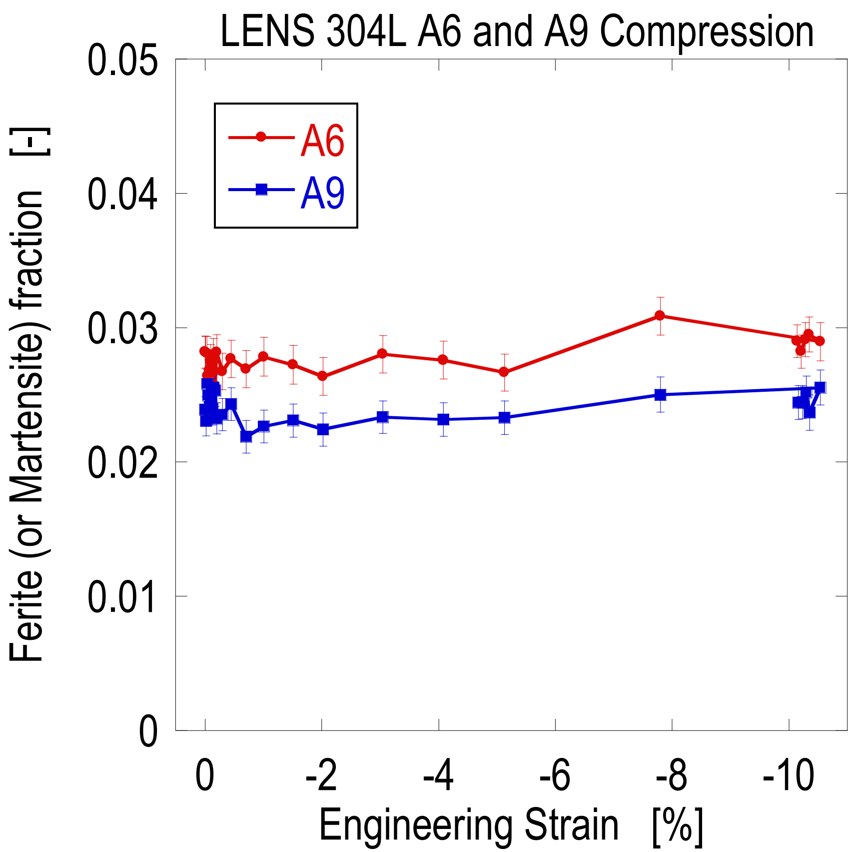
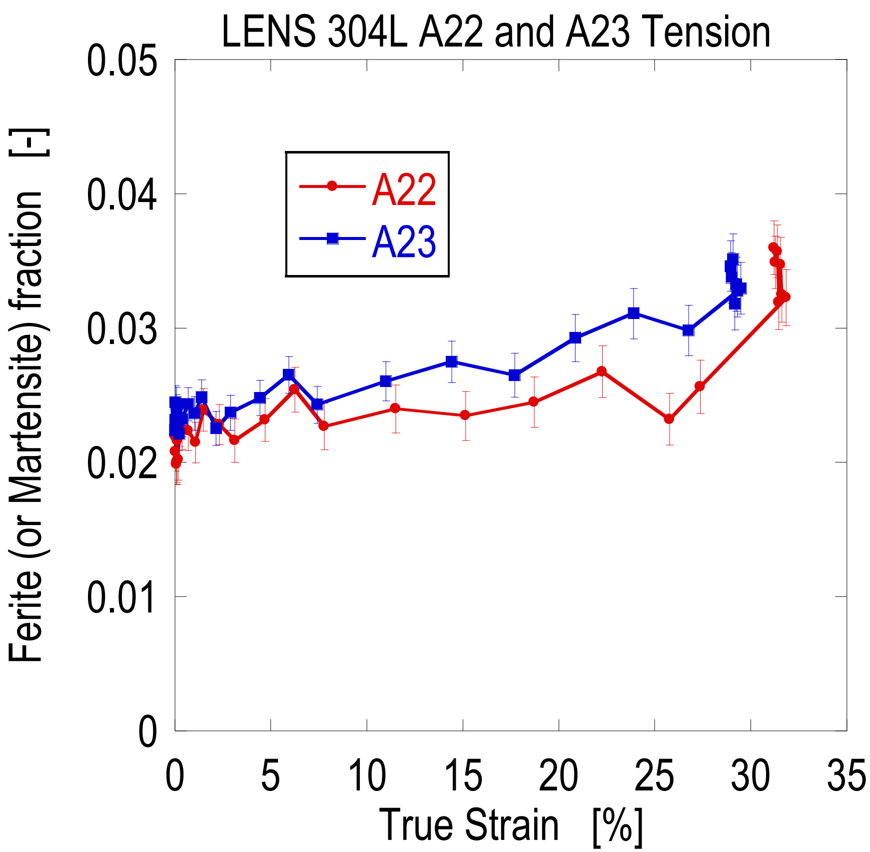
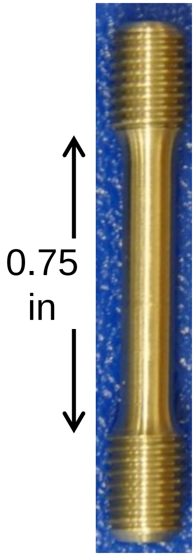
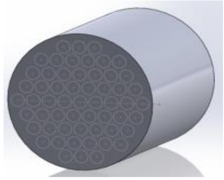
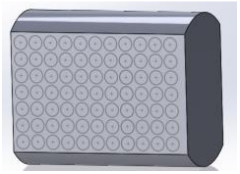


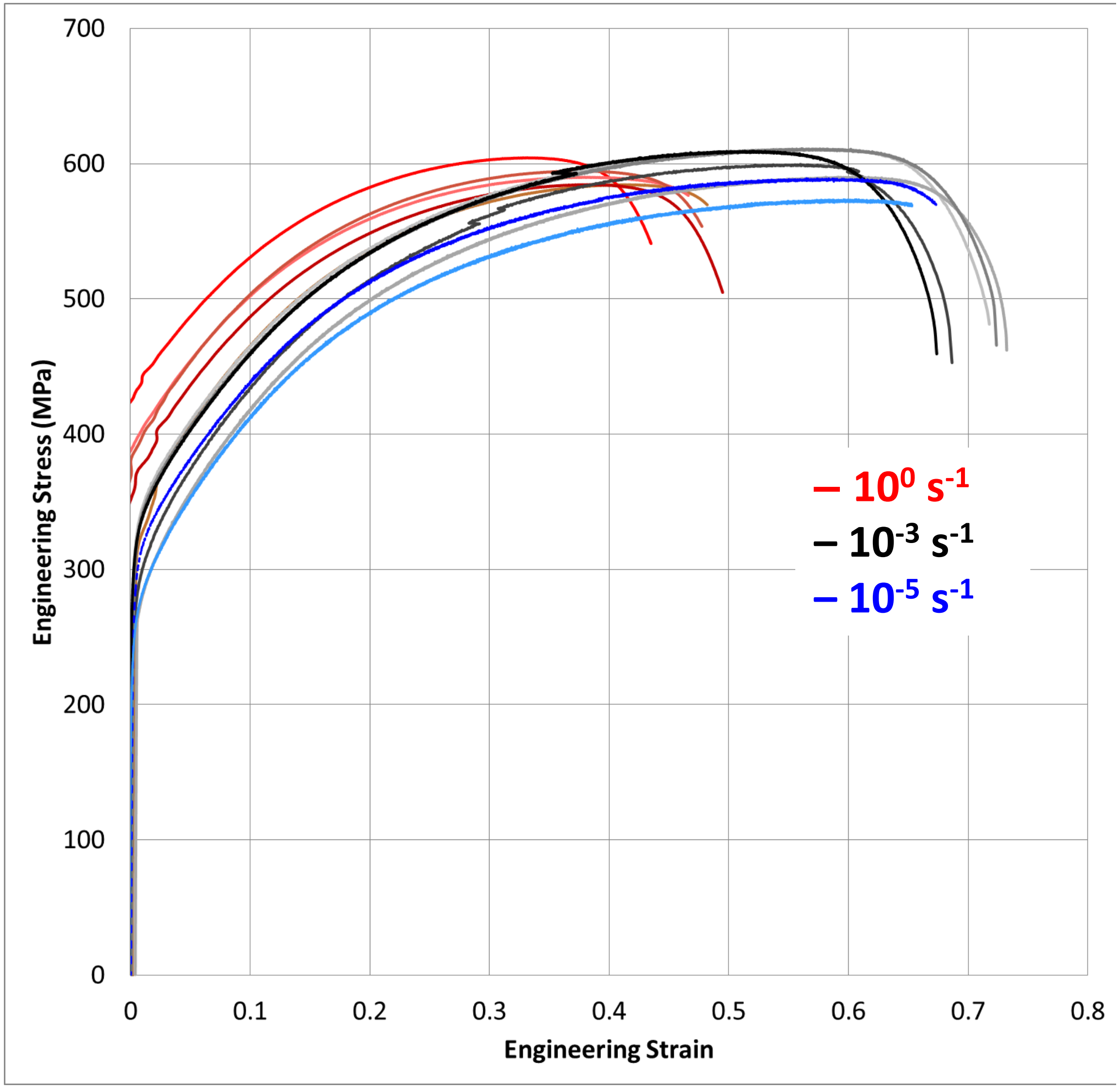


Quasistatic tension on wrought SS304L exhibit some moderate strain rate dependence.









Dynamic compression on conventional SS304L exhibit some moderate strain rate dependence.

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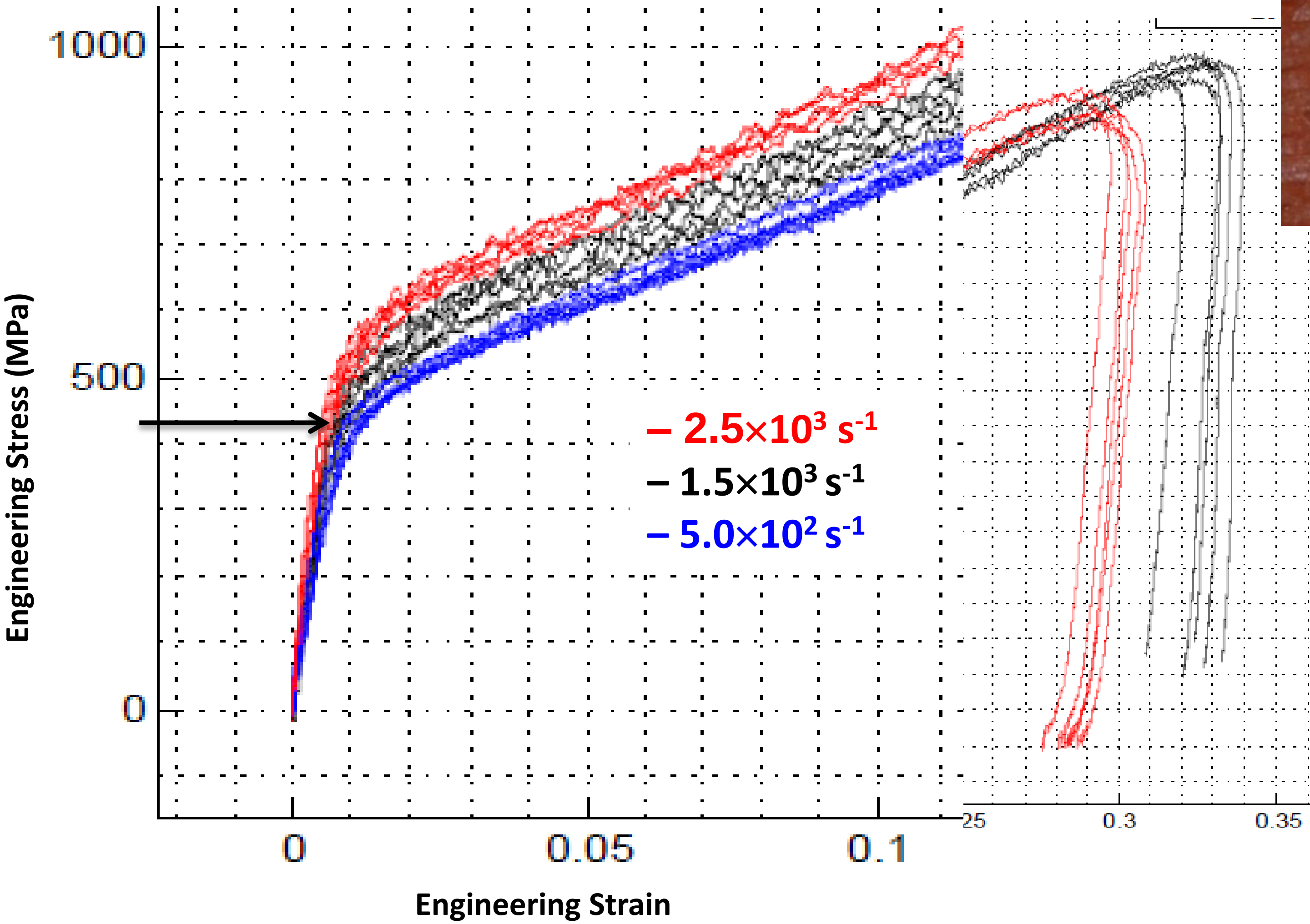
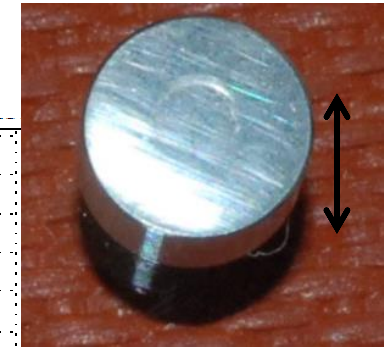
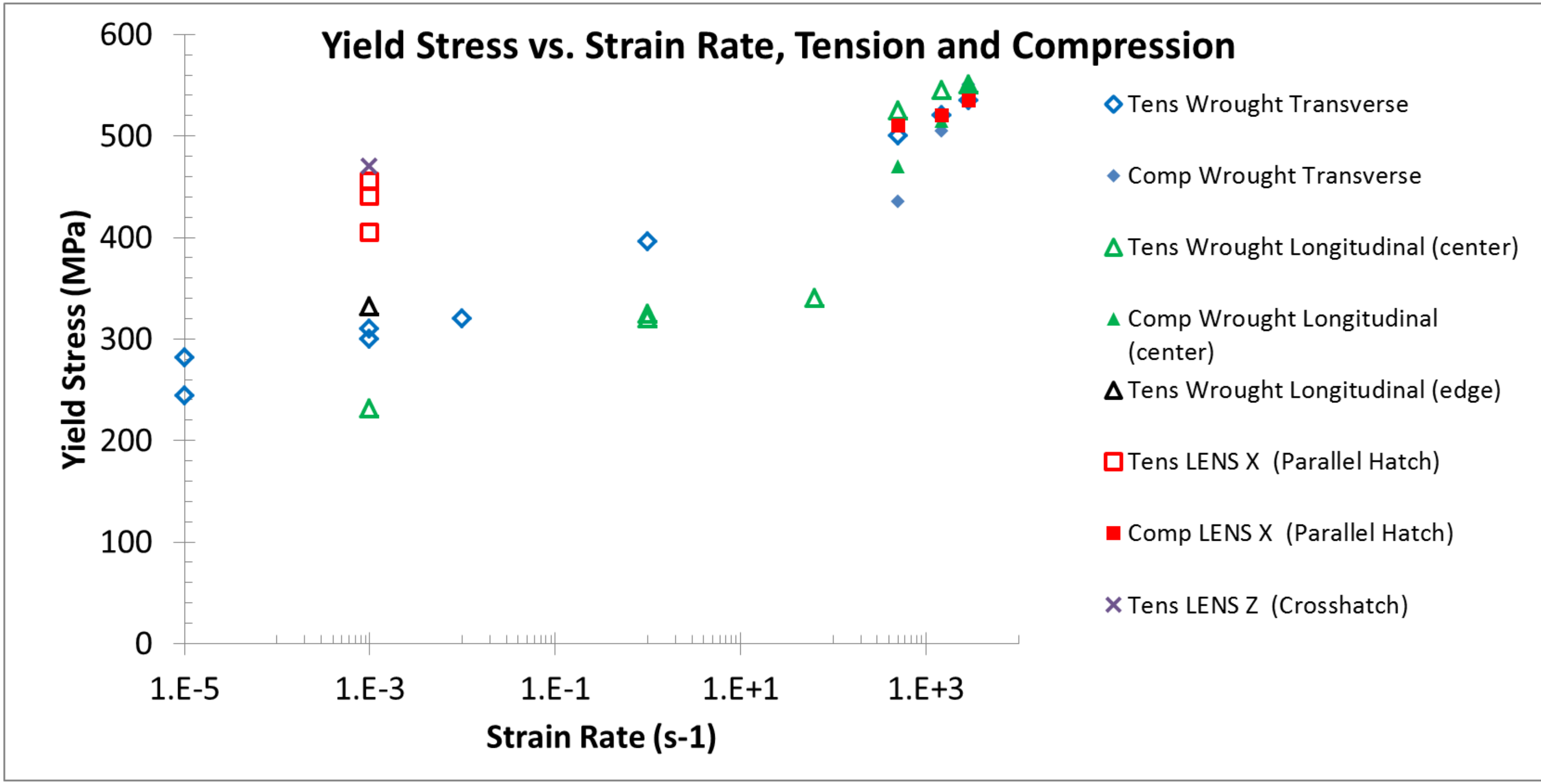




0.125 in

Ø 0.25 in

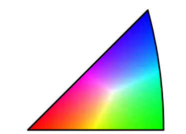
Strain rate effects of wrought and AM 304L in tension.

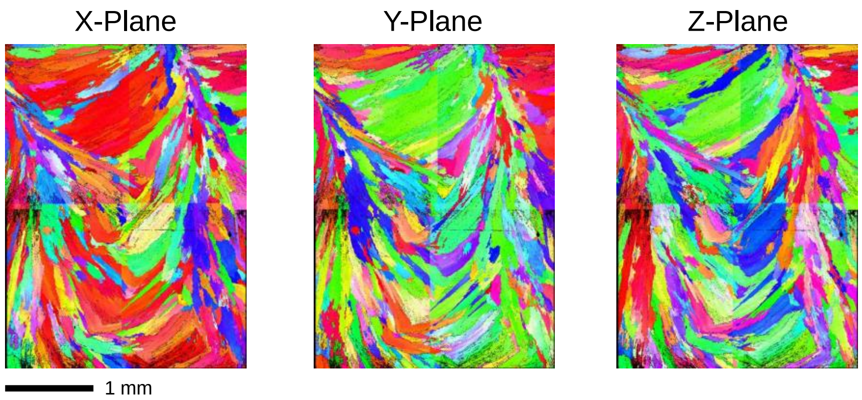


- **LENS material appears to be less strain rate dependent.**

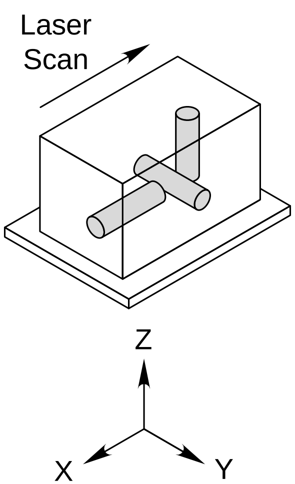
Preliminary Texture Study

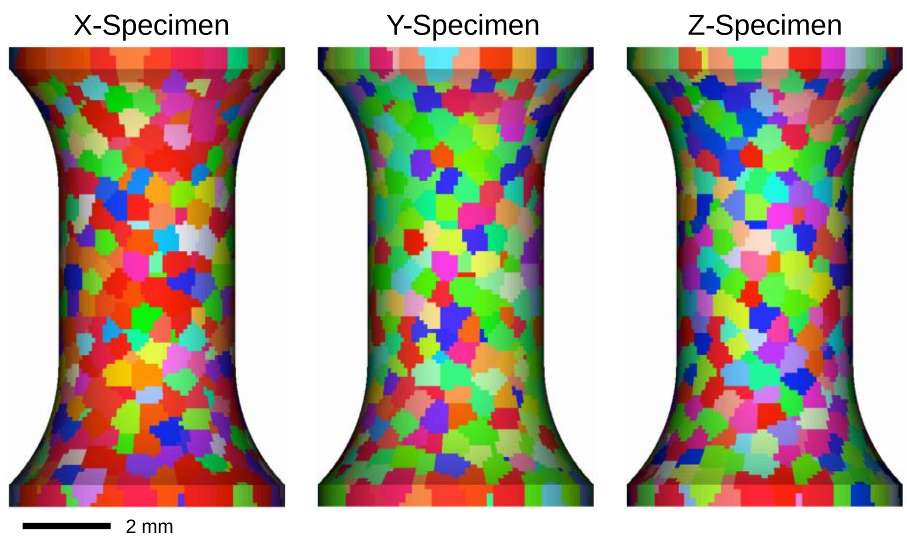
EBSD Orientation Maps



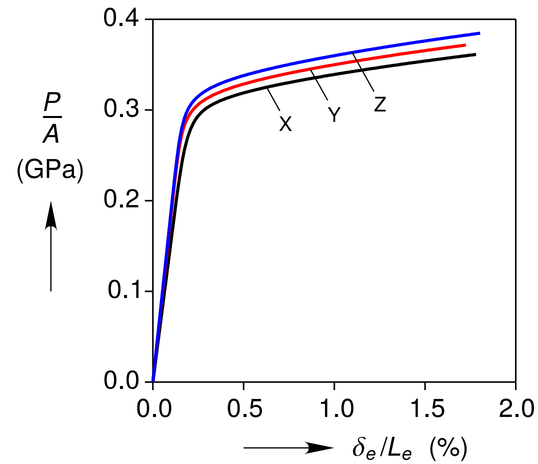


Tensile Specimens



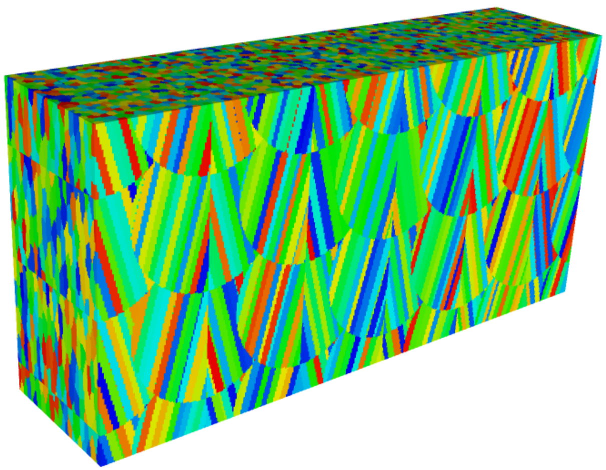


Mechanical Responses

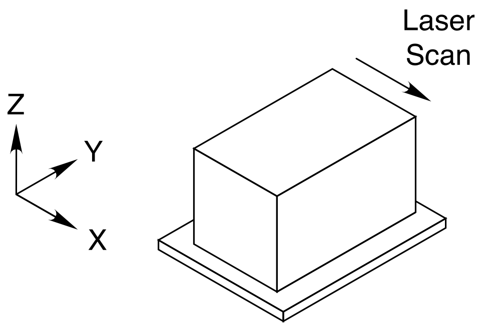


Modeling effects of grain morphology and orientation on mechanical behavior.

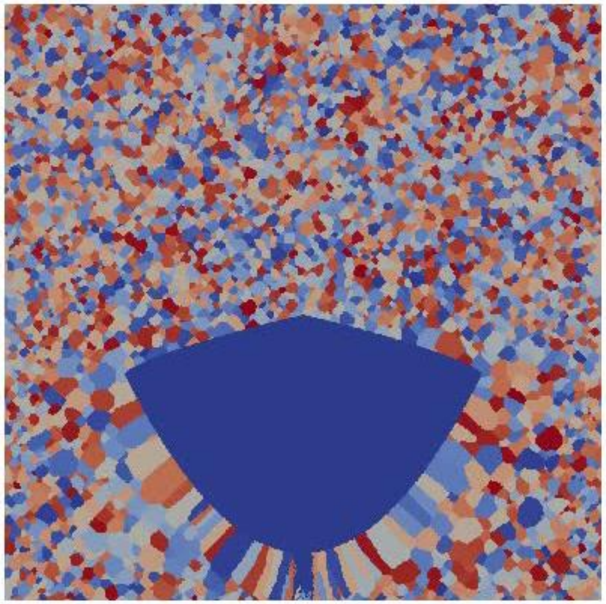
Initial Attempt:
Voronoi Tessellation



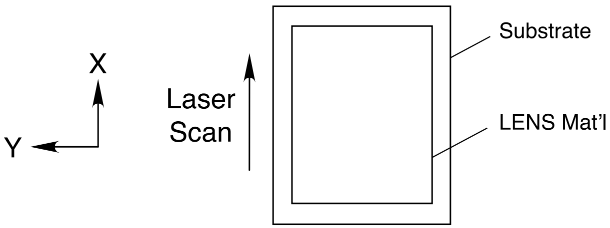
bead size = 1 mm
grain size = 40 microns



Future Direction:
Grain Growth



Video courtesy of Veena Tikare (Org. 1444) and John Madison (Org. 1814)

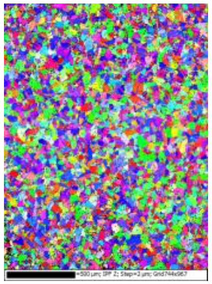


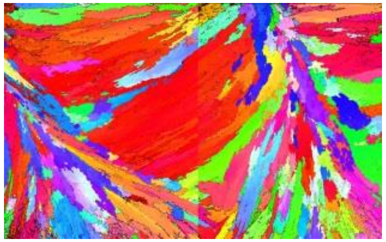
Conclusions

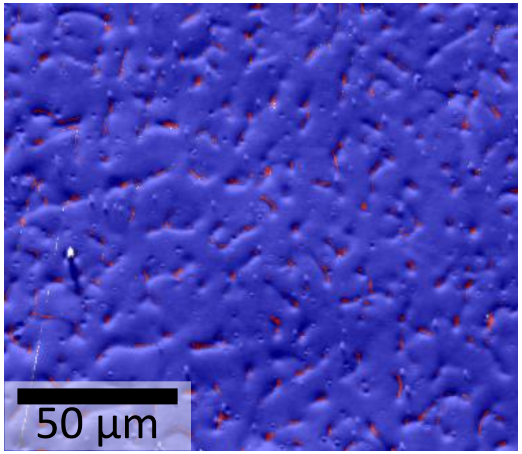
1. **Microstructure in LENS-like 304L is considerably different from conventional 304L.**

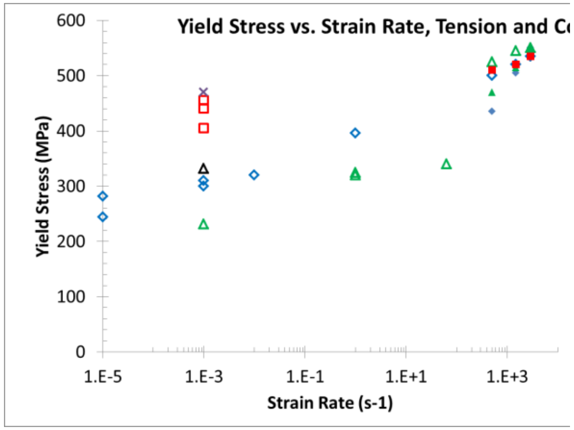
2. **LENS 304L is stronger despite larger grain size.**
   - **Ferrite islands at micron scale are likely responsible.**

3. **Strain rate dependence observed.**



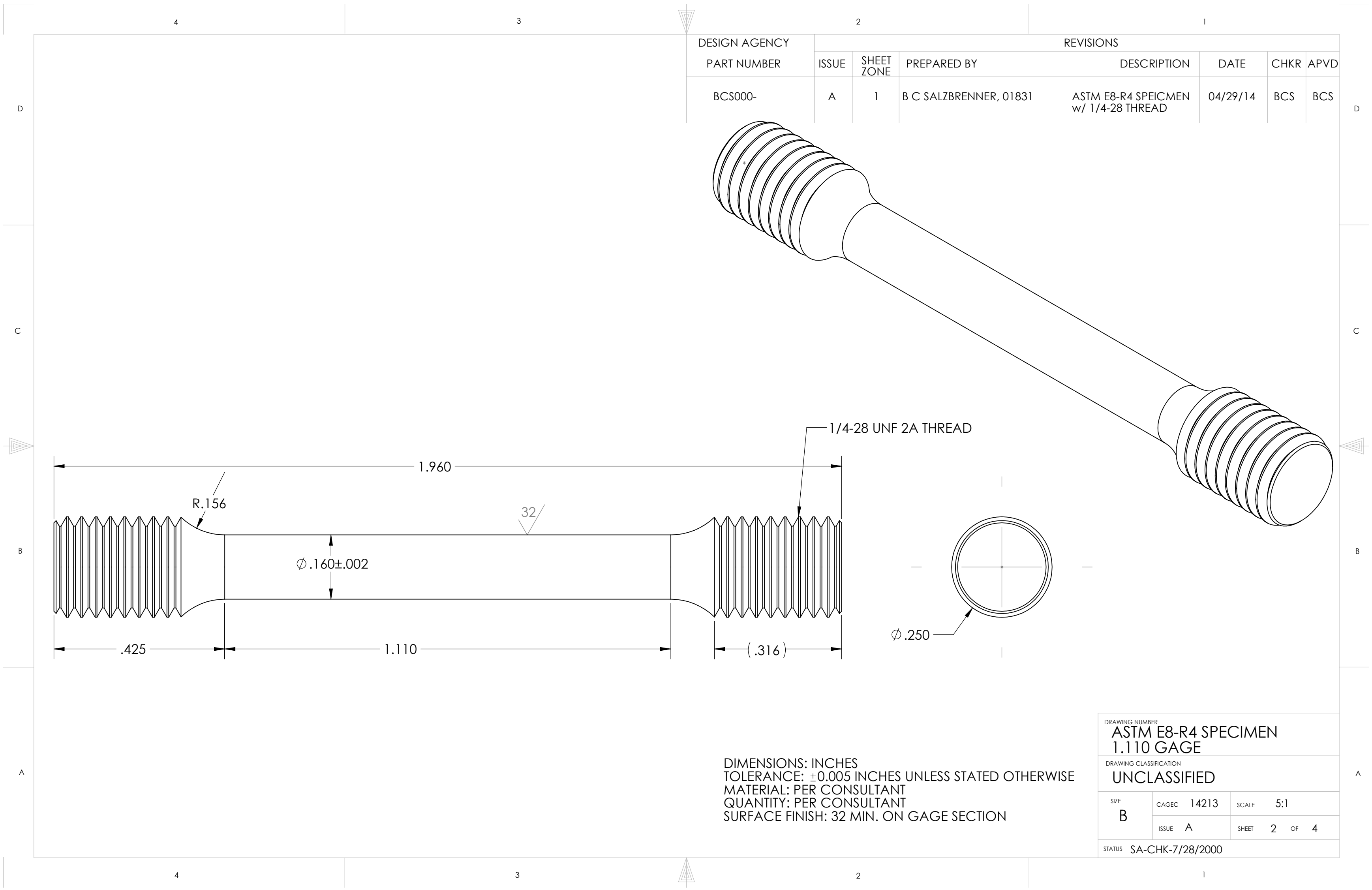




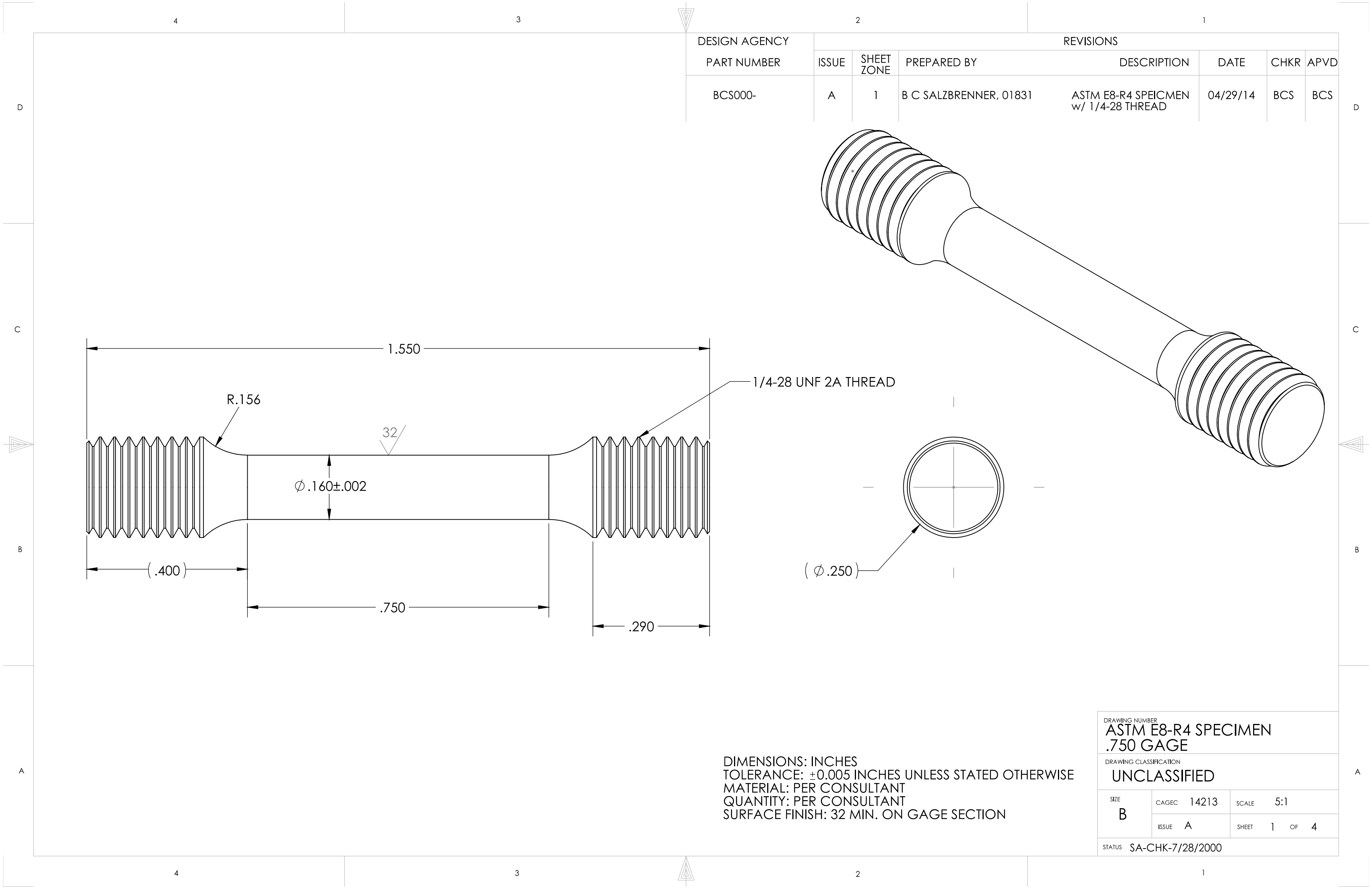


Extra Slides

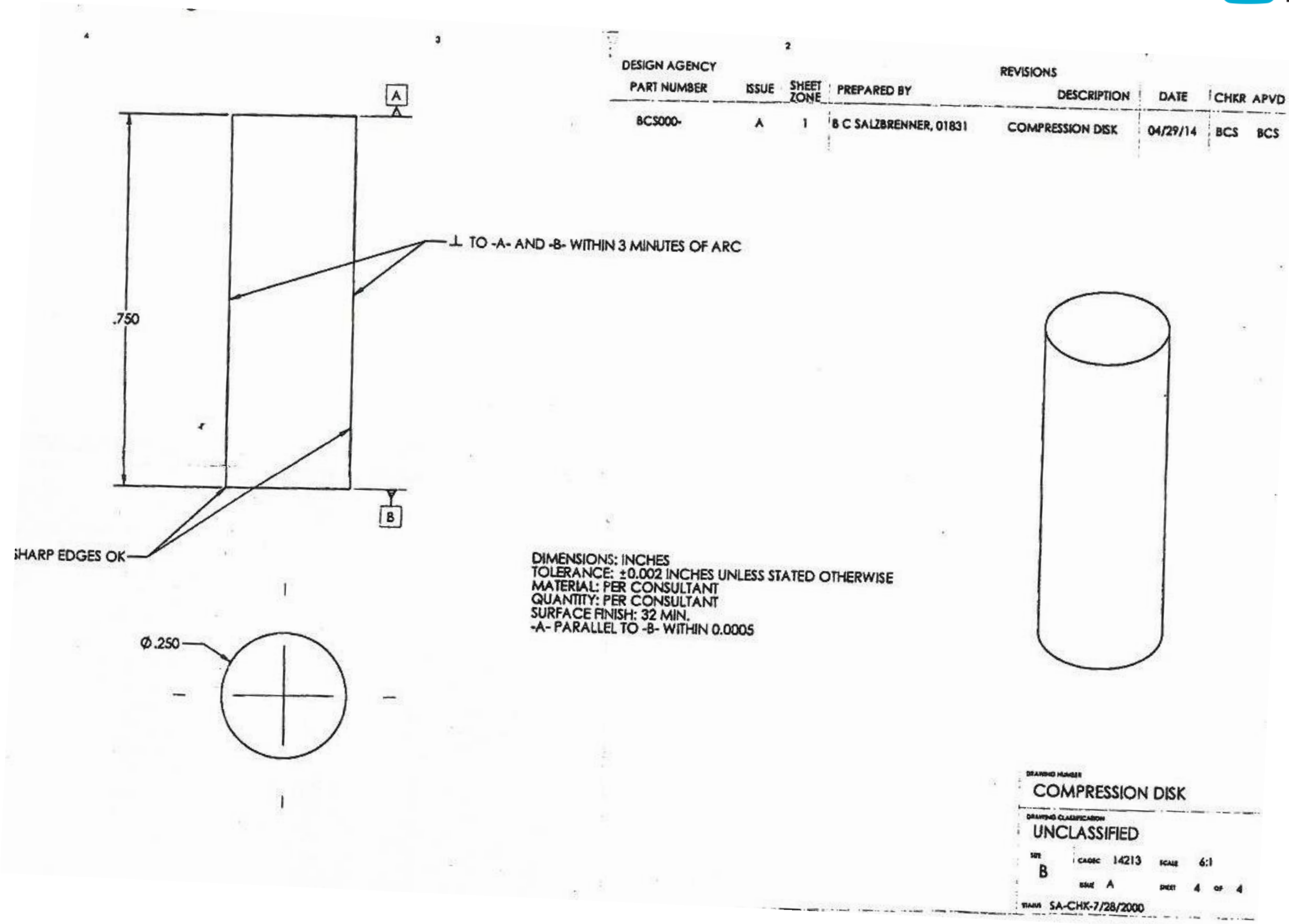
Tensile samples for testing (quasi-static)



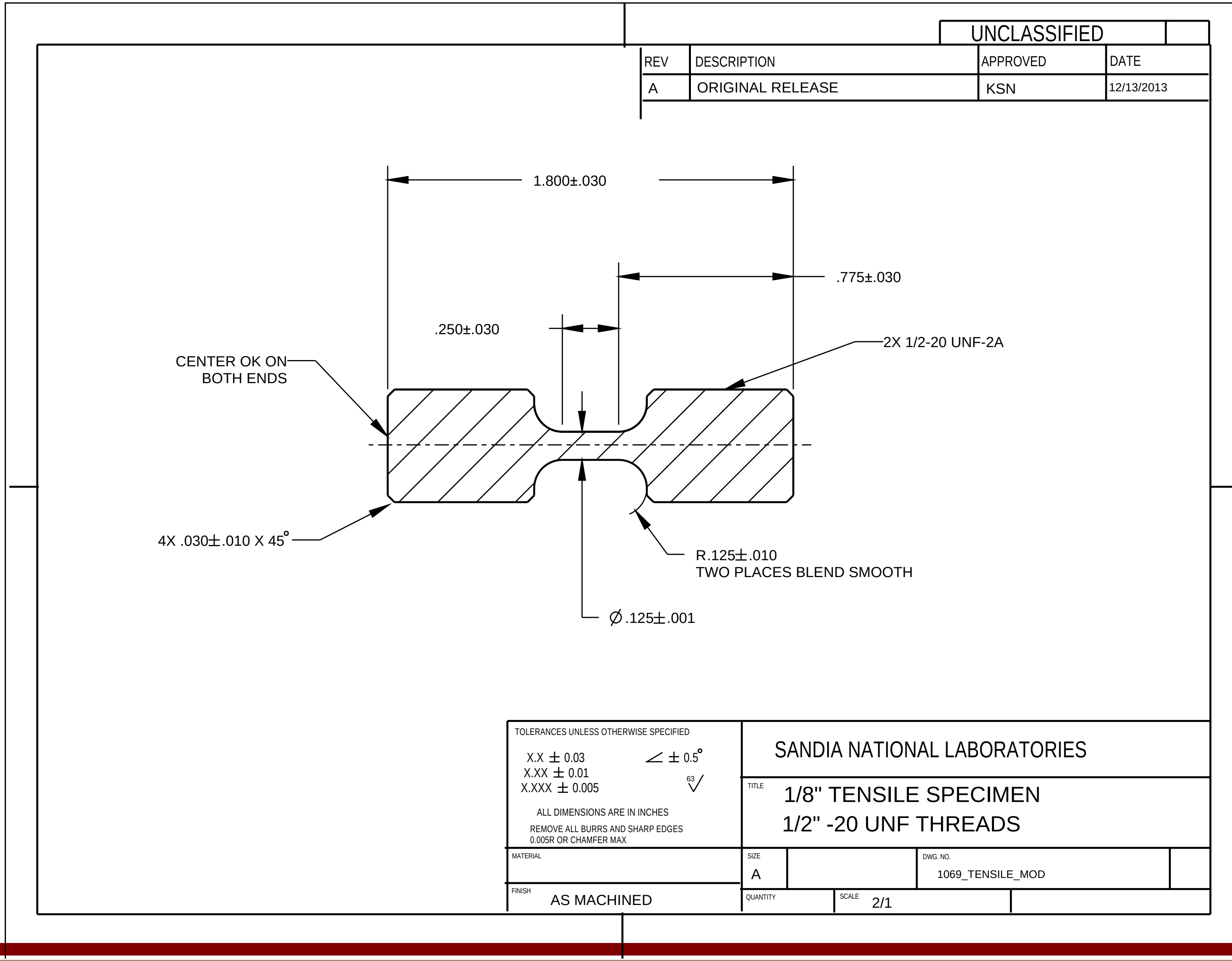
Tensile samples for testing (quasi-static)



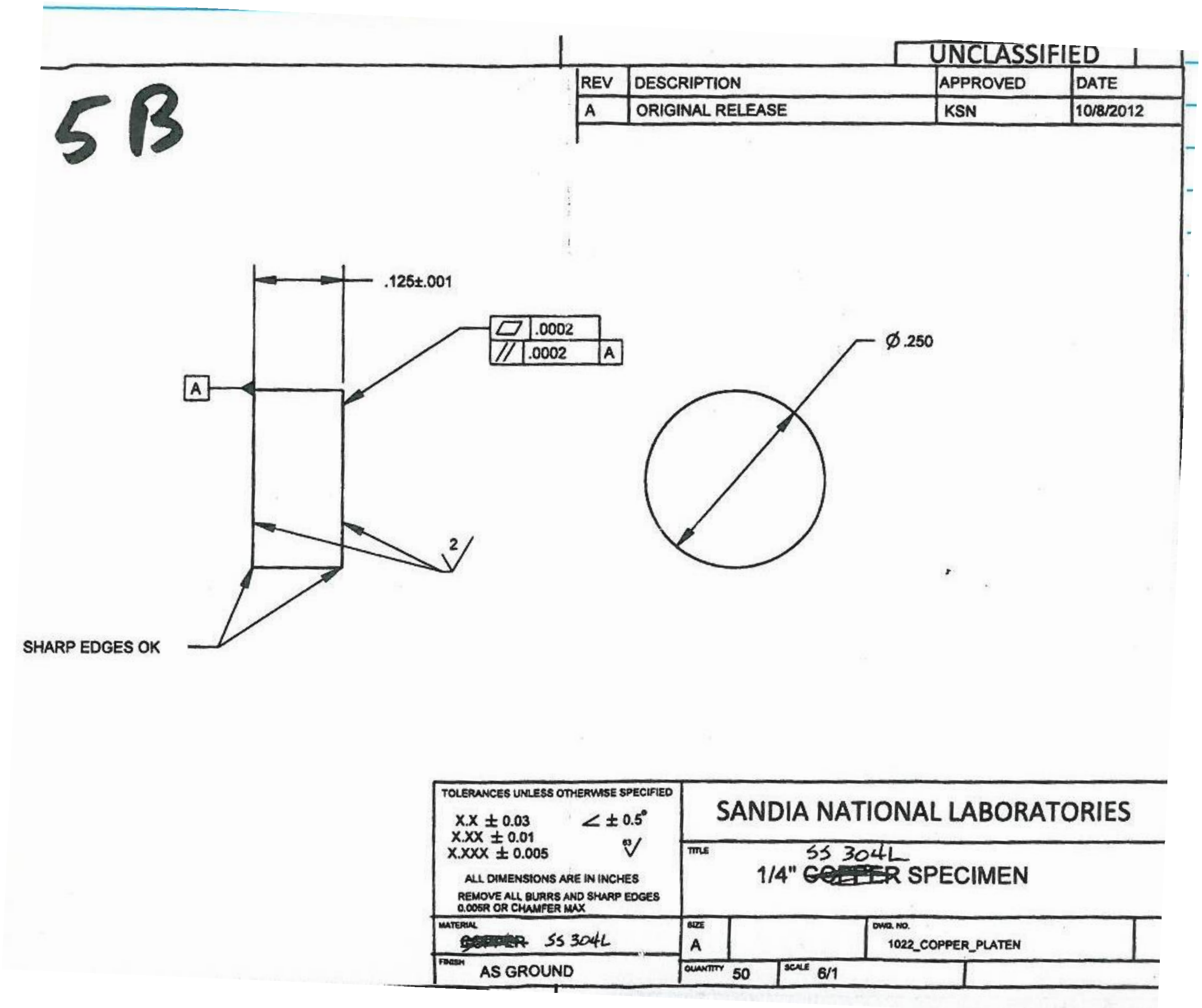
Tensile samples for testing (quasi-static, compression)



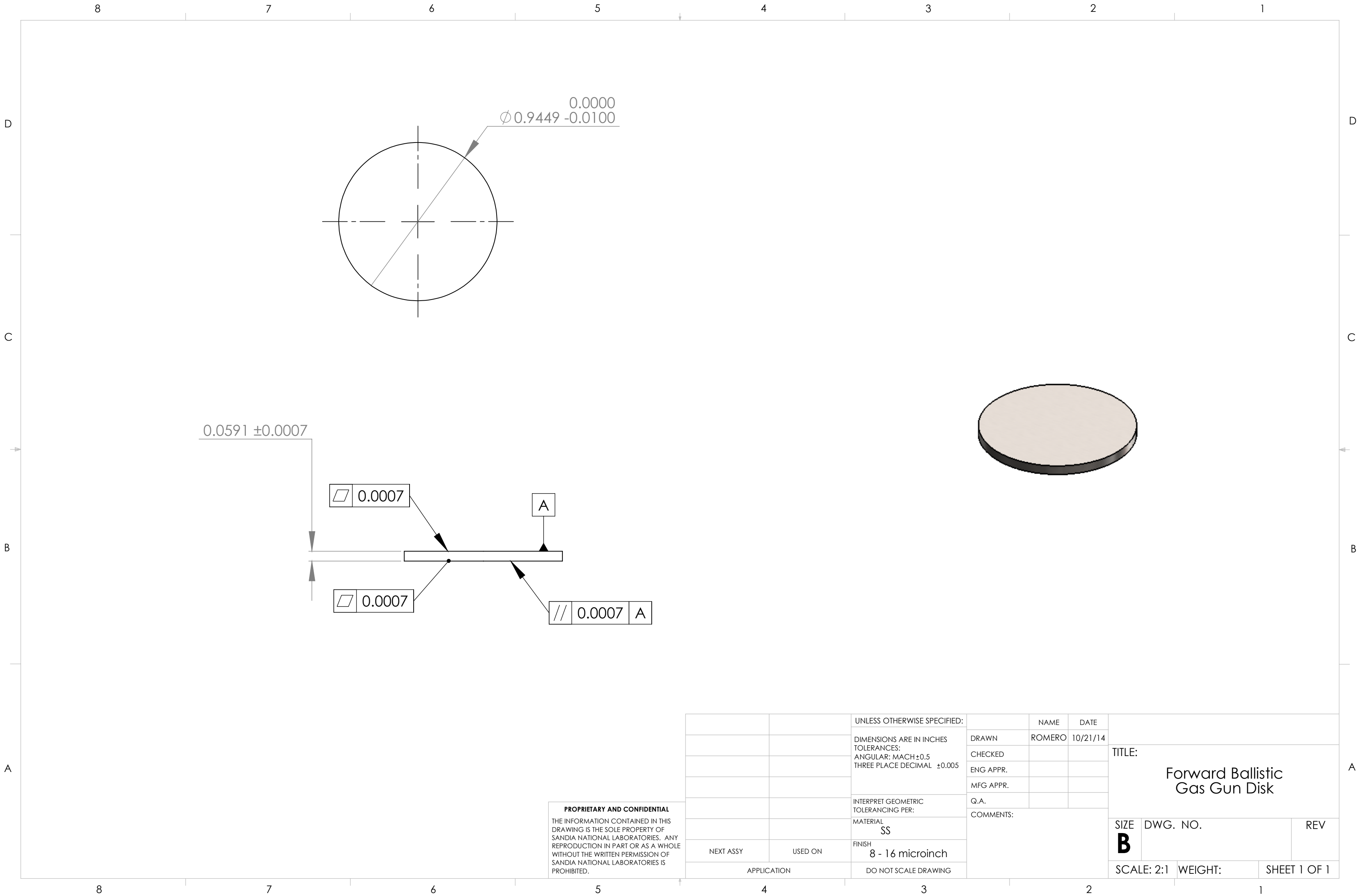
Tensile samples for testing (Hopkinson)



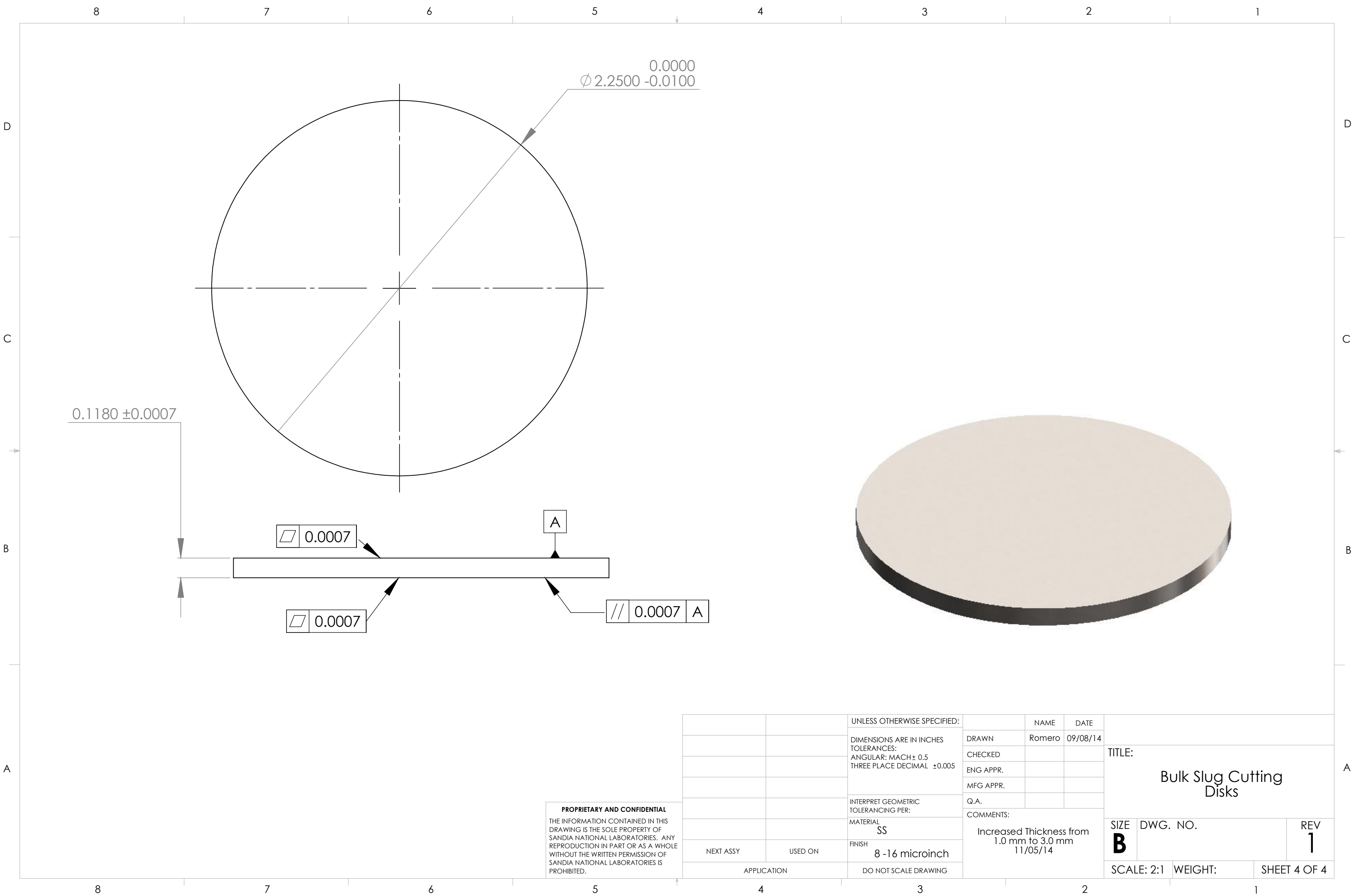
Tensile samples for testing (Hopkinson, compression)



Tensile samples for gas gun testing (forward ballistic)



Tensile samples for gas gun testing (reverse ballistic)



FY14 Accomp. (Mechanical Tests)

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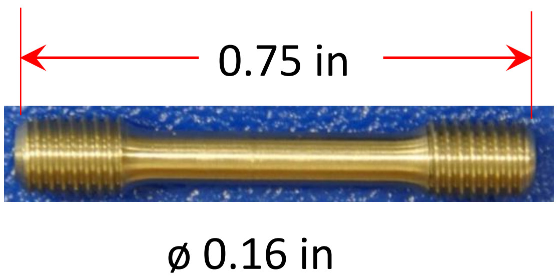
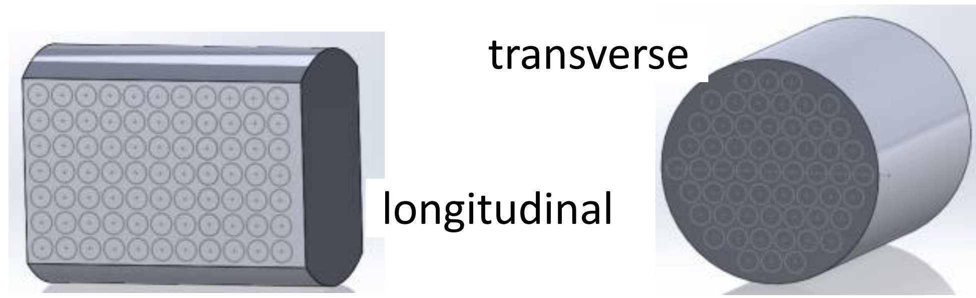
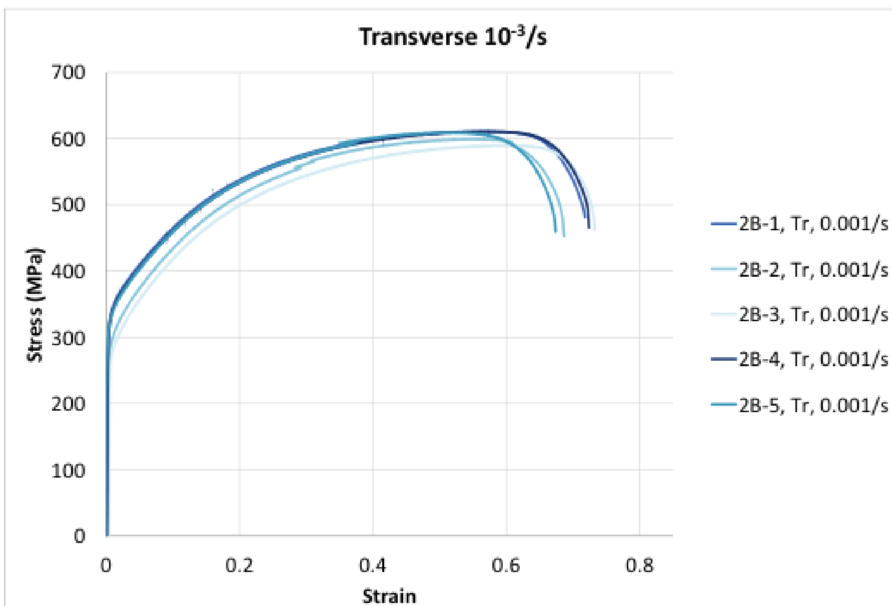
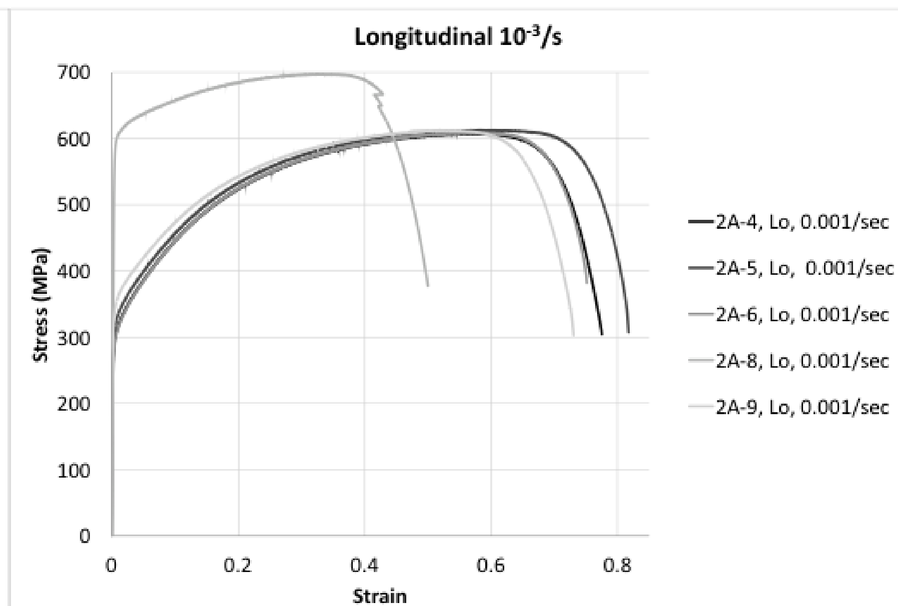
Quasistatic mechanical tests on wrought 304L SS





Stress-strain curves





Temperature and strain rate dependence of 304L

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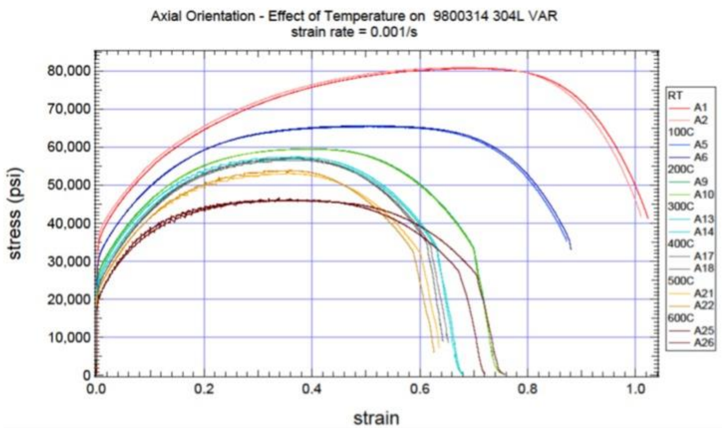
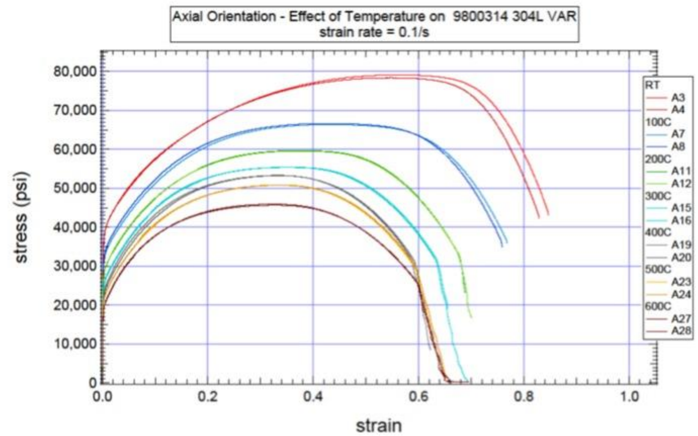
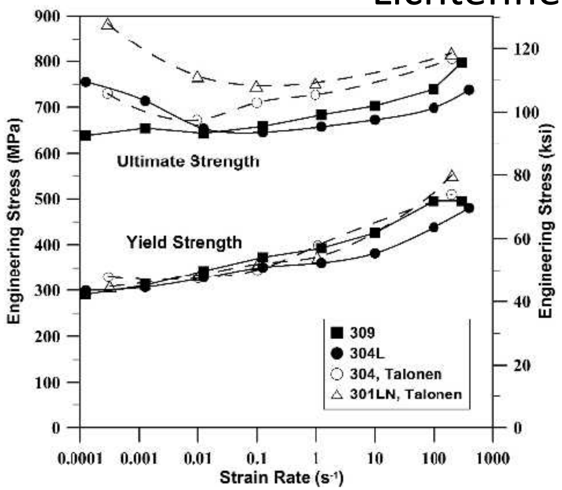
Antoun (Sandia)





Lichtenfield et al. 2006



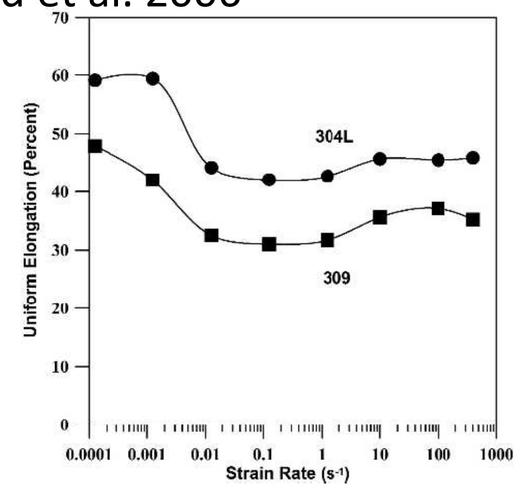


Fig. 5—Var
for 309 and

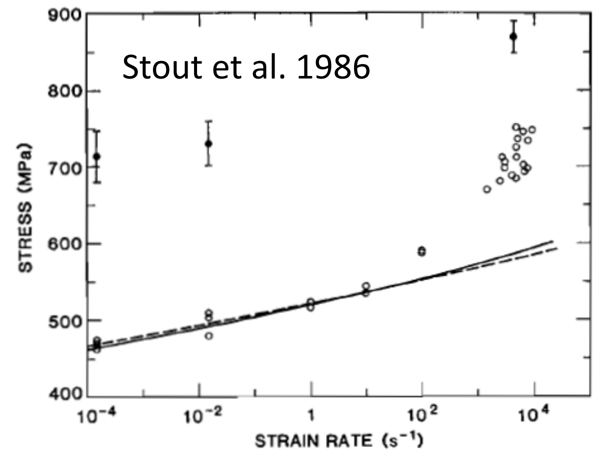


Fig. 13 Comparison of the flow stress values (circles) with equation (14) (solid line) and the power law, equation (7) (dashed line), with Q = 522 MPa and m = 0.0123. Also included in this plot are the measured mechanical threshold stress values (solid circles with error bars).

- **Temperature has a significant effect on strength and ductility.**
- **Higher strain rate has little effect on strength, but a noticeable effect on ductility.**