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Determination of Failure Criteria from Tensile Characterization Data

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U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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Outline

- Background
- Experimental material behavior – examples and complexities
  - Material variability and sensitivity to product form, manufacture, material specifications
  - Rate dependence
  - Temperature dependence
  - Orientation dependence
  - Starting condition (fully annealed?)
- Demonstrations using 304L Stainless Steel and various constitutive models
- Other experimental material behavior of concern
  - History dependence
- Summary

Background

- Stress-strain data from tensile tests are used to determine and/or infer many things about the material properties and response (from elastic modulus to failure criteria)

- Converting measured engineering stress-strain data to true stress-strain data used in FE simulations requires some method of converting data beyond the necking instability point

- Converted true stress-true strain data used in FE simulations of structural response can produce large prediction errors if important material responses that occur ***during the tensile test*** are not properly taken into account
    - Strain rate dependence
    - Temperature dependence (isothermal → adiabatic)
    - Temperature dependence (softening)
    - Geometric evolution of deformation and necking

Effect of Assumptions

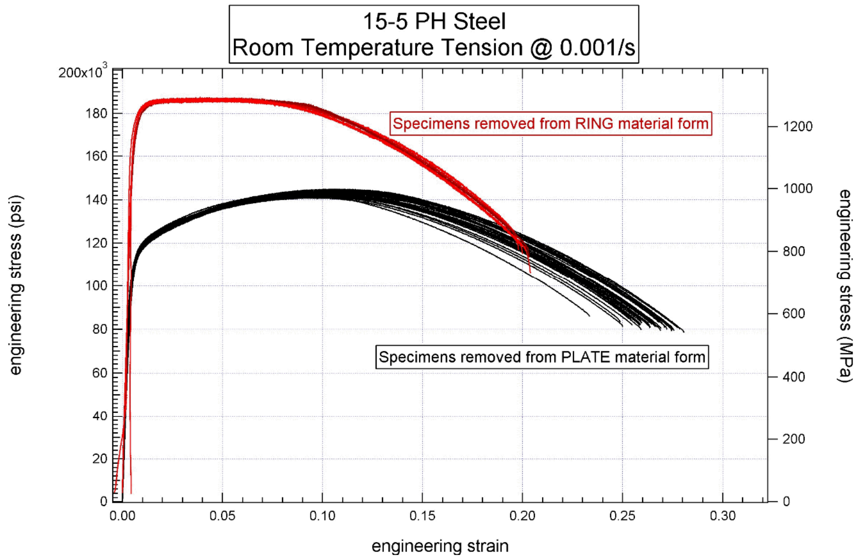
- Local stress and strain are affected by the rate dependence assumption.

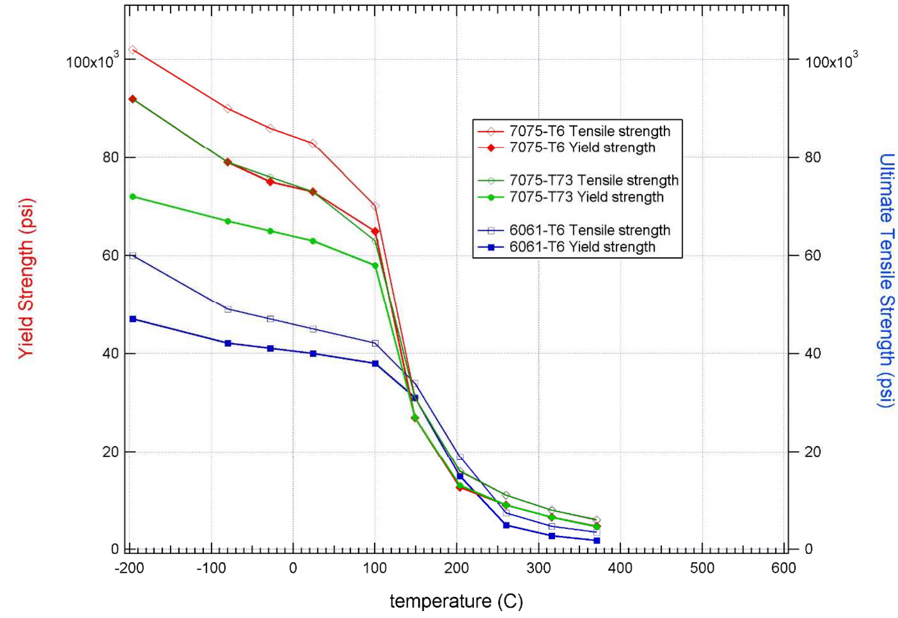
- Neglecting rate dependence when modeling a rate-dependent material will result in the simulation necking/localizing much sooner than it does in reality, predicting much higher local stresses and strains.
  - Substantial impact on the failure criteria inferred from the experiments
  - Leads to non-conservative failure predictions when using the characterization to model other loading conditions.

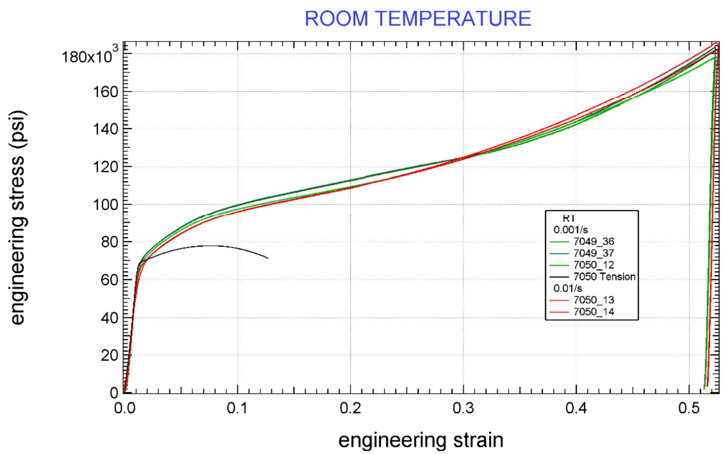
- Similar errors can result if the effect of temperature increases due to plastic dissipation is ignored in simulations of moderate to high-rate testing.

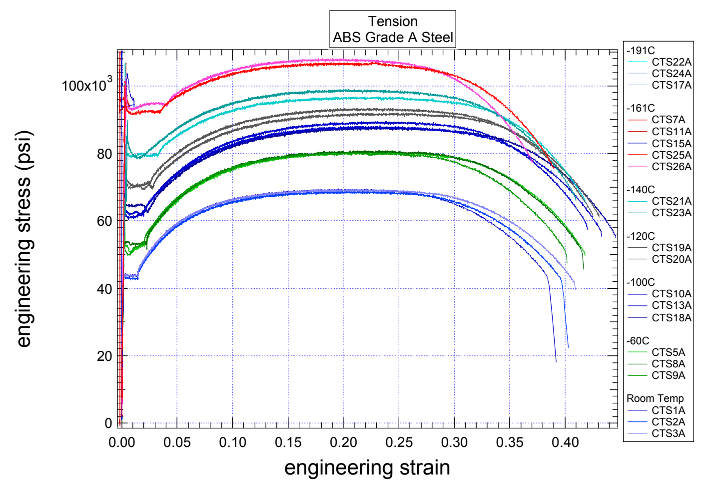
- We will use 304L stainless steel as an example of a rate dependent, ductile material to show the effect of ignoring material strain rate dependence, history dependence, thermal changes, and geometric evolution.

Examples of Tensile Material Behavior

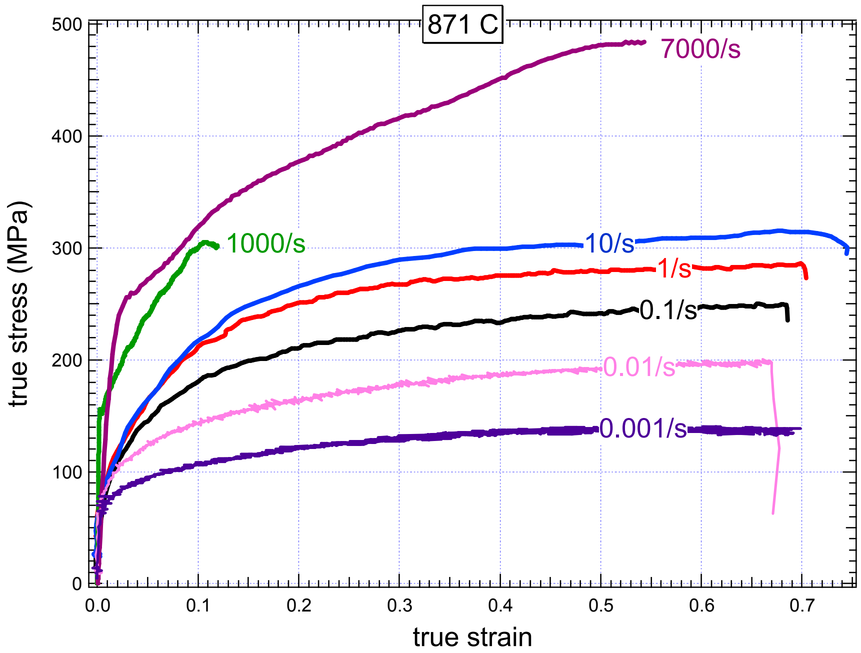


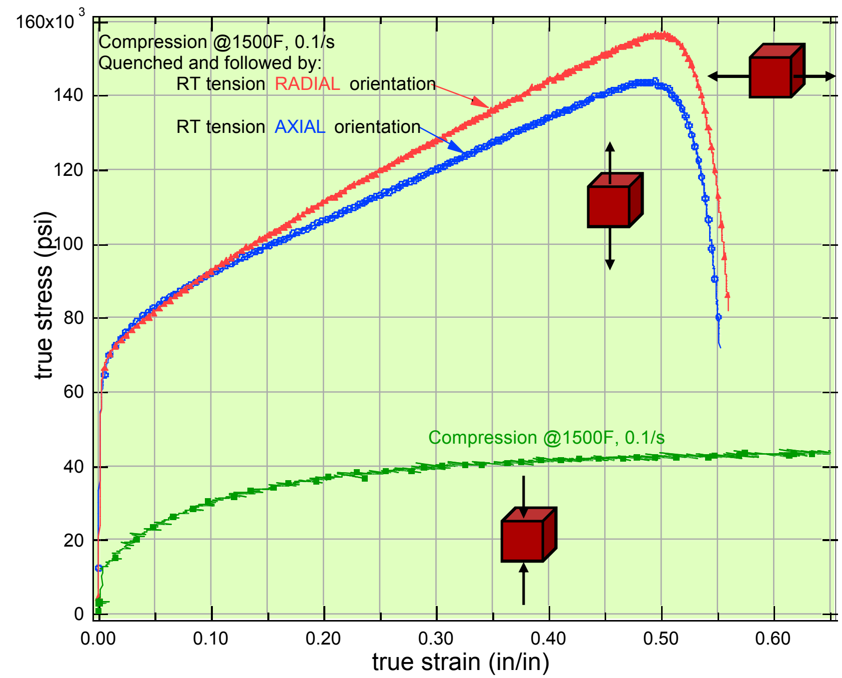




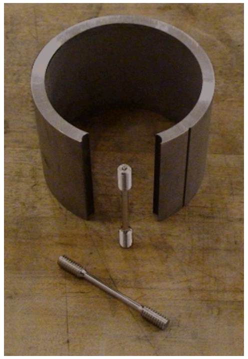


Examples Material Behavior (Compression)





- No Reversal effects on Yield
- Radial Direction hardens more than axial direction



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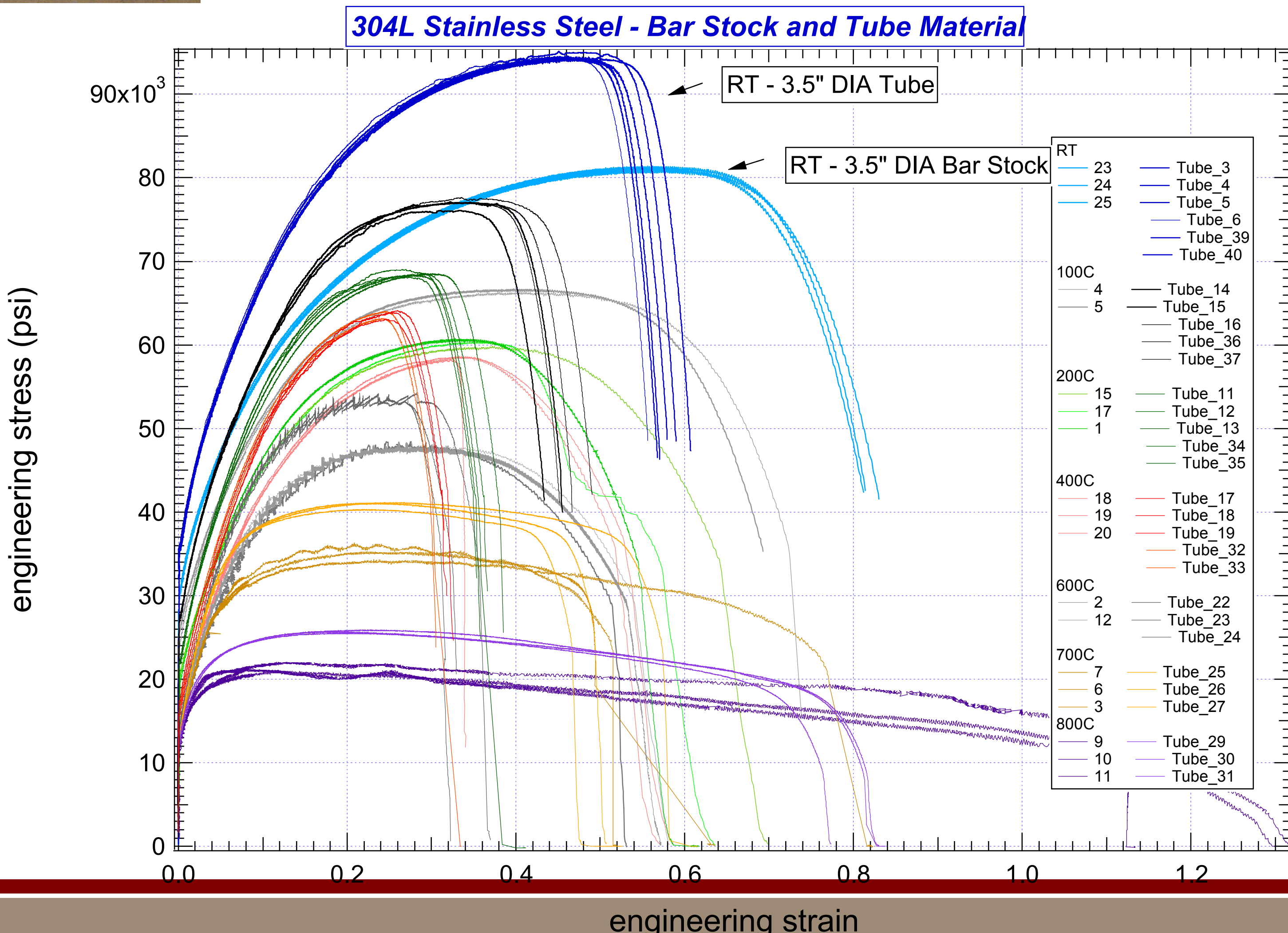
The data below are comparing two different material forms of 304L, one is 3.5” DIA bar stock and the other is 3.5” DIA, 0.25” wall thickness tube (for PB). Both materials were annealed after machining. The main difference here comes from material form, not heat treatment.

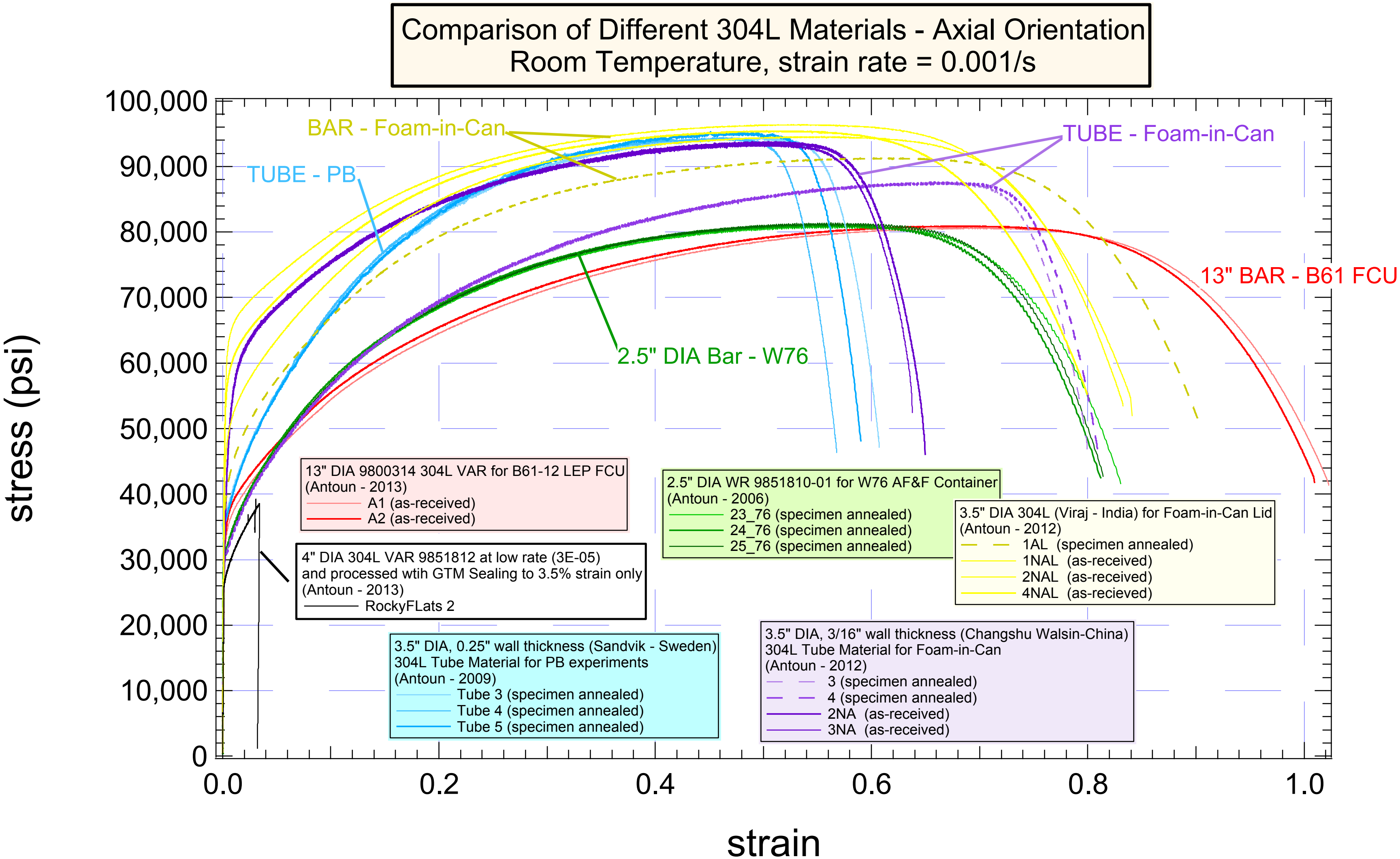


- At every temperature, the 304L tube material behavior was substantially different from the bar stock material behavior

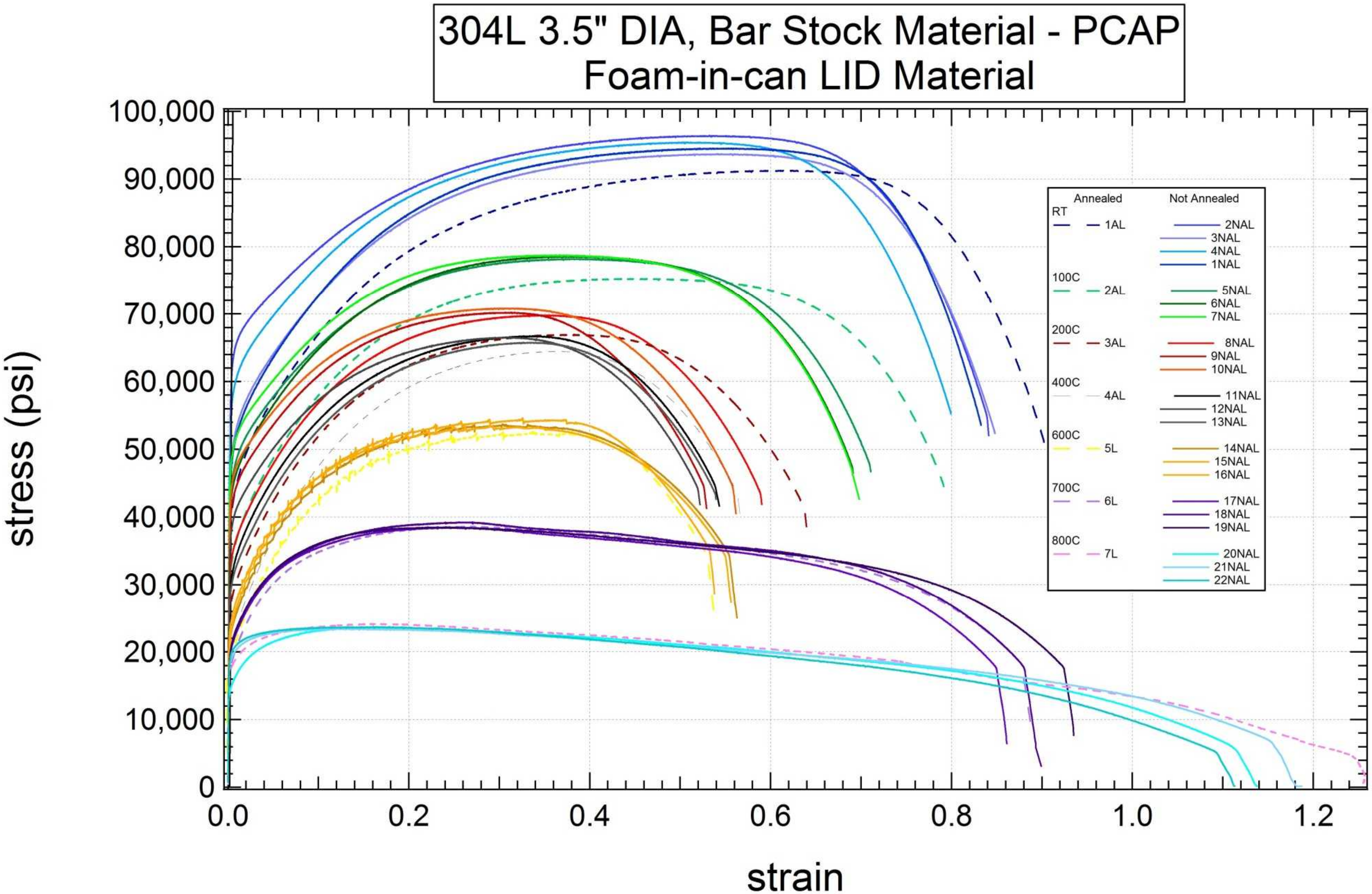
Comparing tube to bar stock:

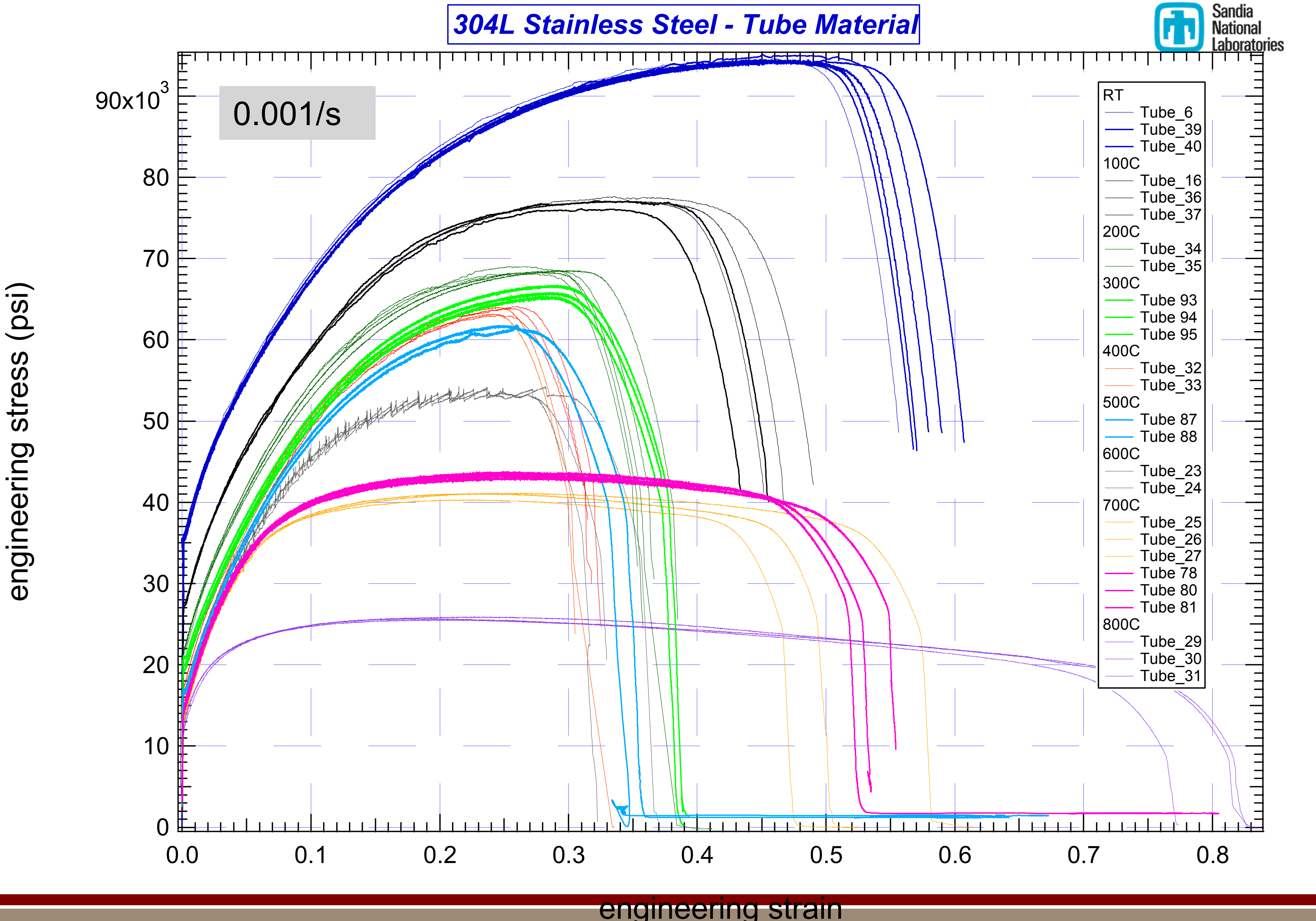
- ➢ Higher yield stress, especially at lower temps
- ➢ Higher flow stress
- ➢ Substantially lower strain to failure (lower ductility)

304L Stainless Steel: A Complex Material that is Sensitive to Form, Composition and Processing



Material Starting Condition – Fully Annealed or is state evolving ?

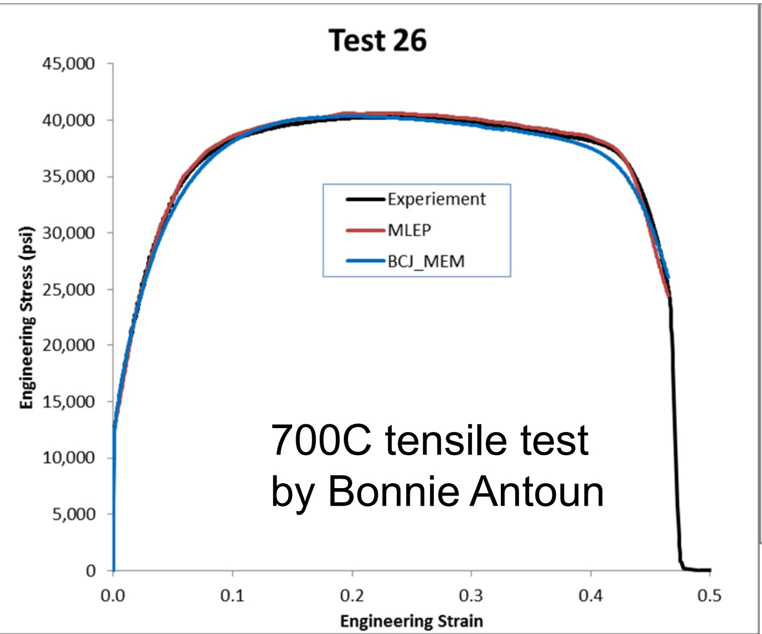


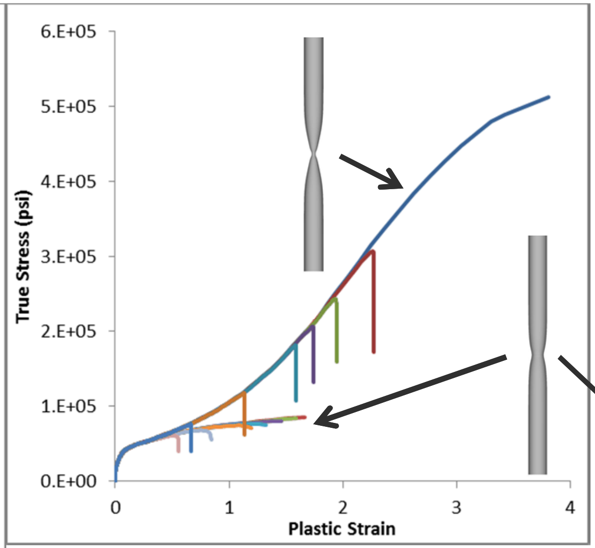


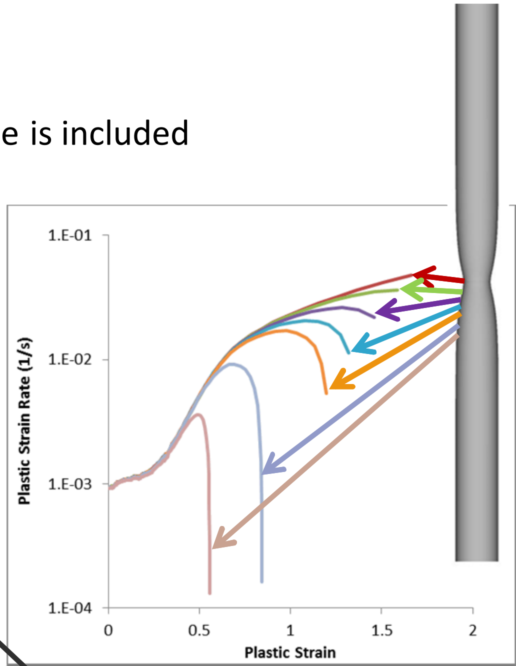
304L Stainless Steel - Tube Material
Sandia National Laboratories
0.001/s
engineering stress (psi)
engineering strain
90x10^3
80
70
60
50
40
30
20
10
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
RT
Tube_6
Tube_39
Tube_40
100C
Tube_16
Tube_36
Tube_37
200C
Tube_34
Tube_35
300C
Tube 93
Tube 94
Tube 95
400C
Tube_32
Tube_33
500C
Tube 87
Tube 88
600C
Tube_23
Tube_24
700C
Tube_25
Tube_26
Tube_27
Tube 78
Tube 80
Tube 81
800C
Tube_29
Tube_30
Tube_31

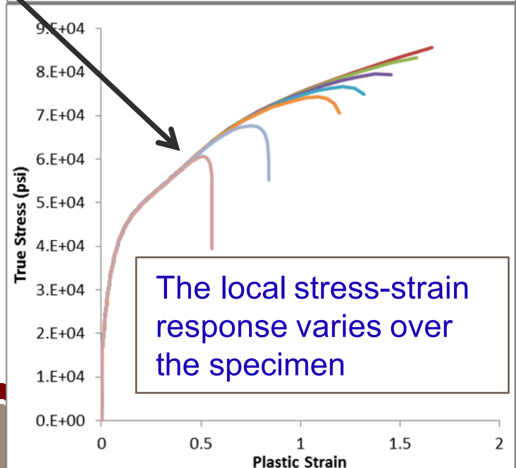
Non-uniqueness of characterization

- I then optimized the yield and hardening parameters to the tube material (see below)
- With rate dependence, the neck formation is delayed
  - As the neck starts to form, the local strain rate increases
  - The higher local rate increases the local yield stress, which inhibits necking
  - The resulting local strains and stresses are much lower when rate dependence is included









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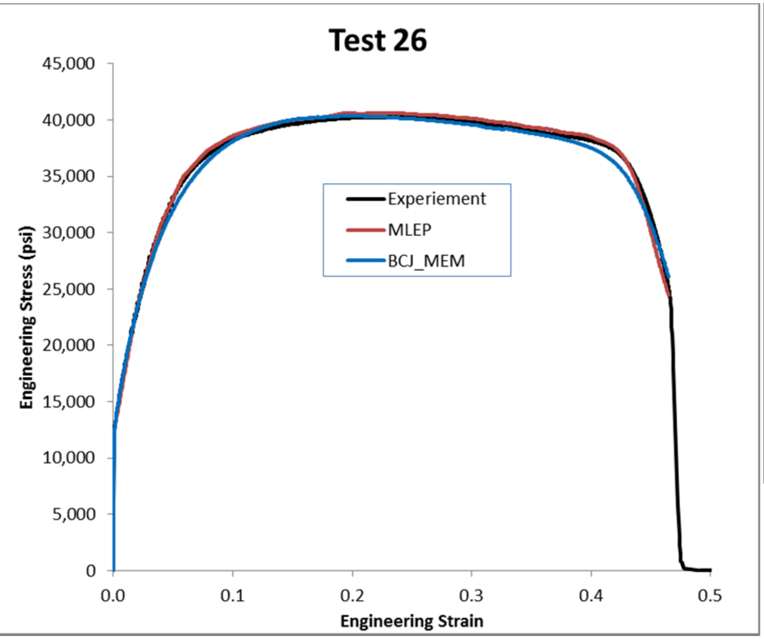

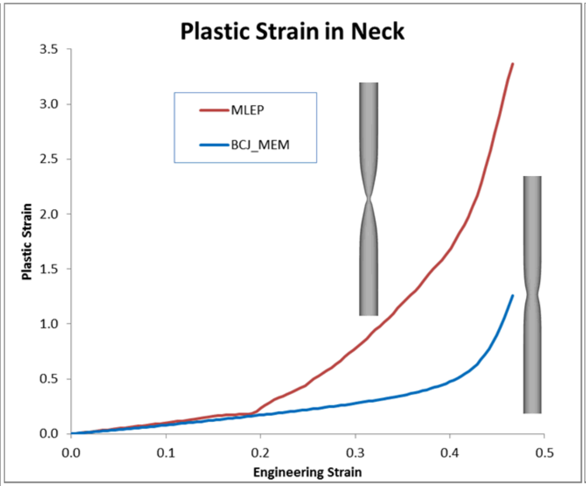

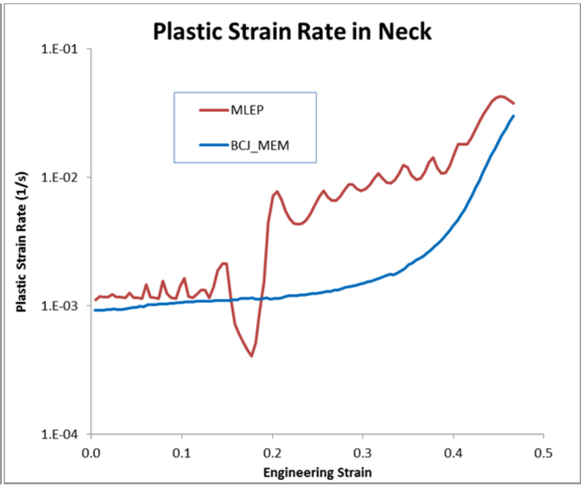

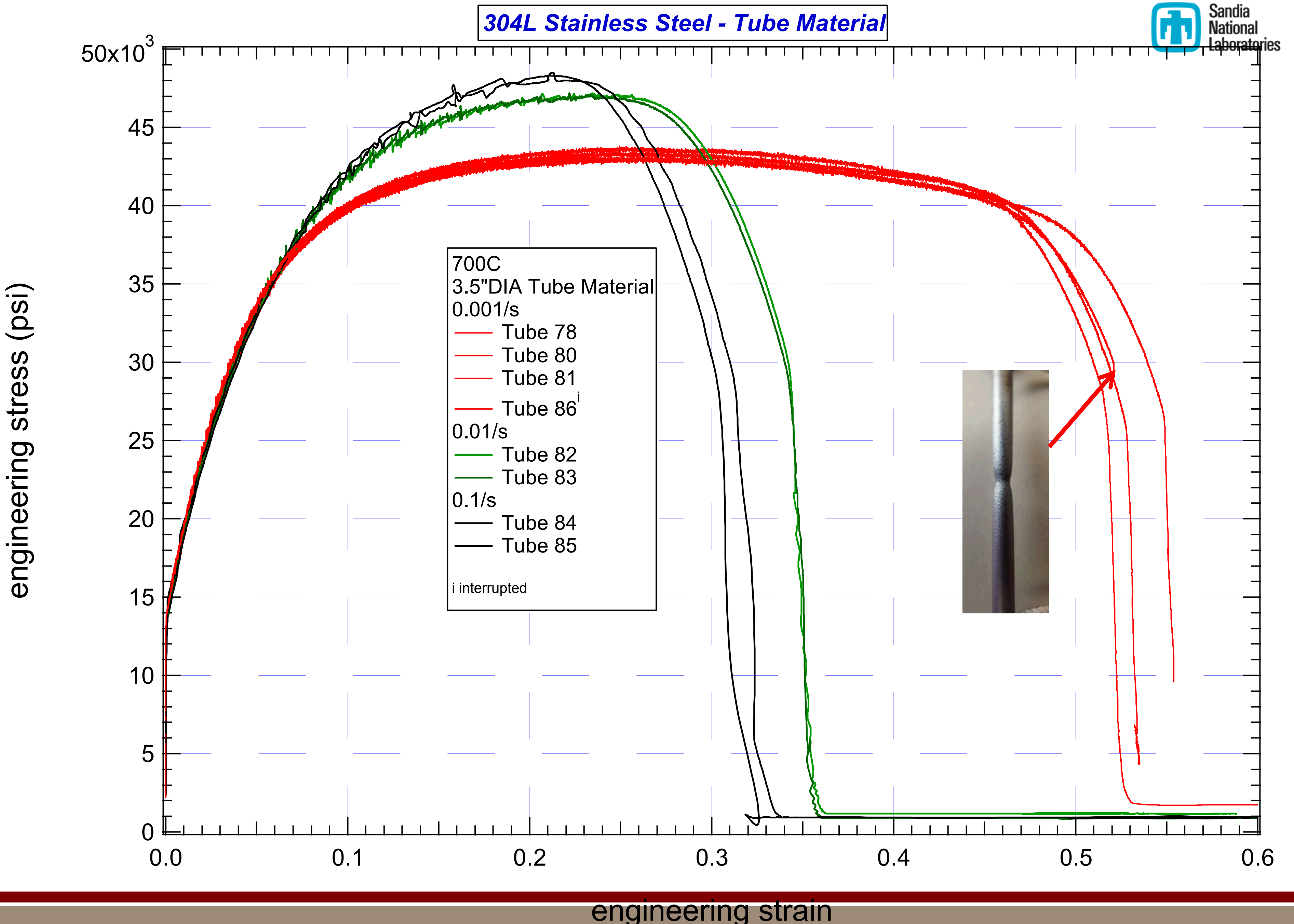
304L Stainless Steel - Tube Material
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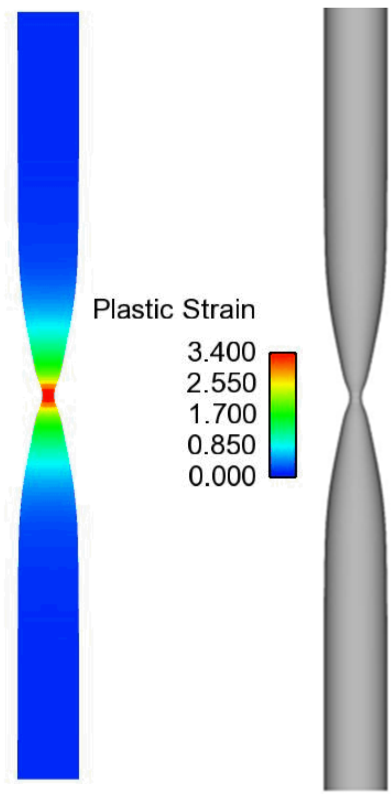
50x10^3
45
40
35
30
25
20
15
10
5
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
engineering stress (psi)
engineering strain
700C
3.5"DIA Tube Material
0.001/s
Tube 78
Tube 80
Tube 81
Tube 86i
0.01/s
Tube 82
Tube 83
0.1/s
Tube 84
Tube 85
i interrupted

Rate dependence has a large impact on neck shape and estimated local strain at failure

MLEP
(no rate dependence)

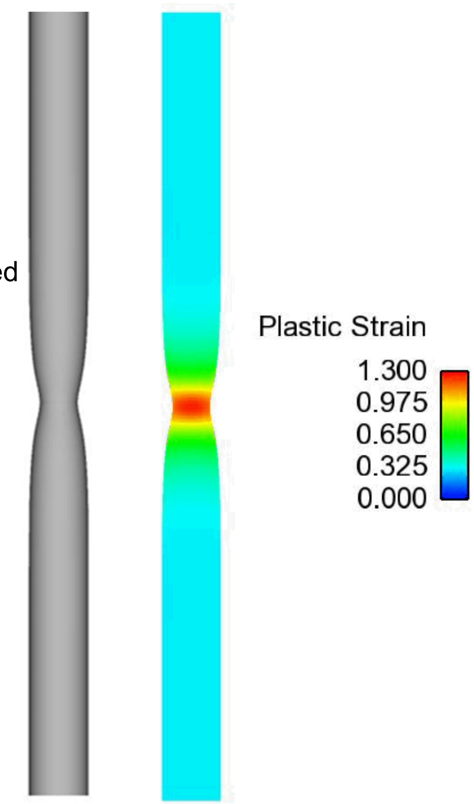


EQPS: 3.4

Pictures from
B. Antoun and
K. Connelly

BCJ_MEM
(rate dependent)

These simulations were performed before neck profiles were available



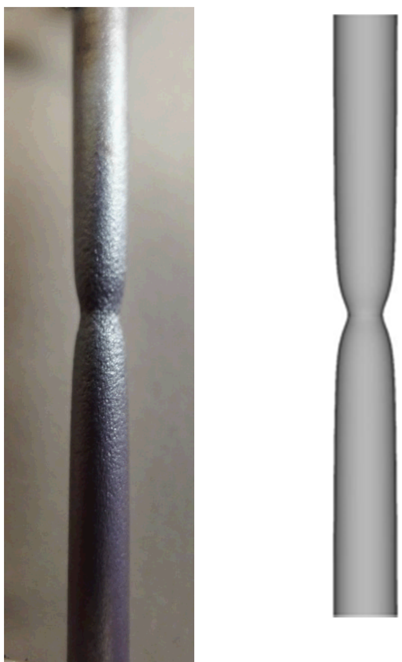
EQPS: 1.3

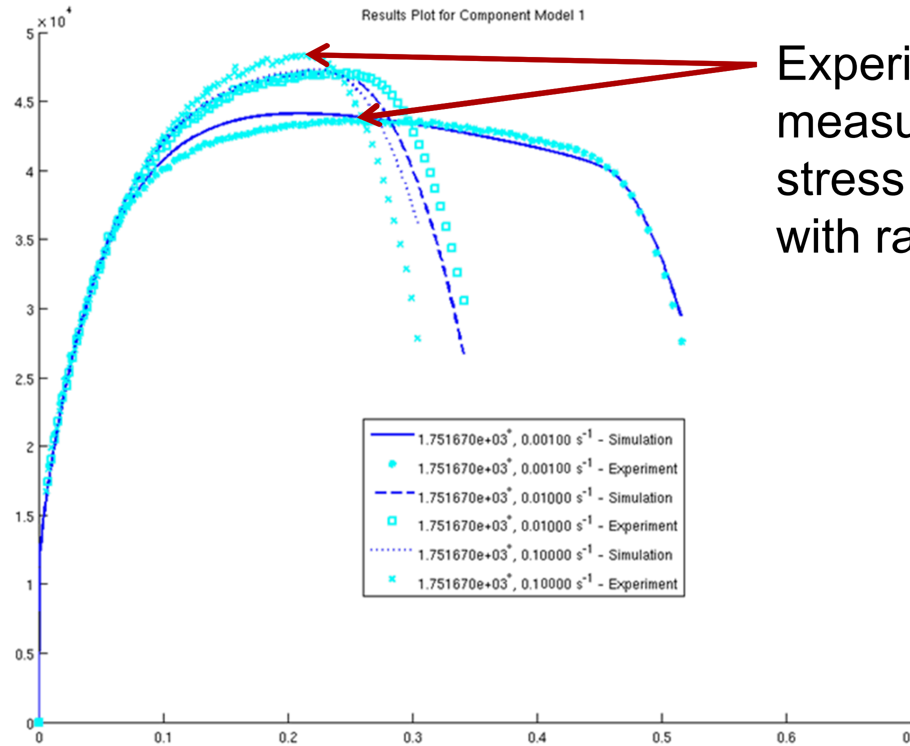
Pipe Bomb Tube Characterization

- After all of the work in the previous slides was completed, we performed two additional tension tests at higher rates (0.01/s and 0.1/s) for 700C
- Kyle Karlson's parameter optimization tool, MatCal, was used to optimize the rate-dependent parameters to the experimental data for the three rates at 700C
- Using the actual rate dependence of the tube material, BCJ_MEM gave a similar neck profile

Strain rate (0.001/s)

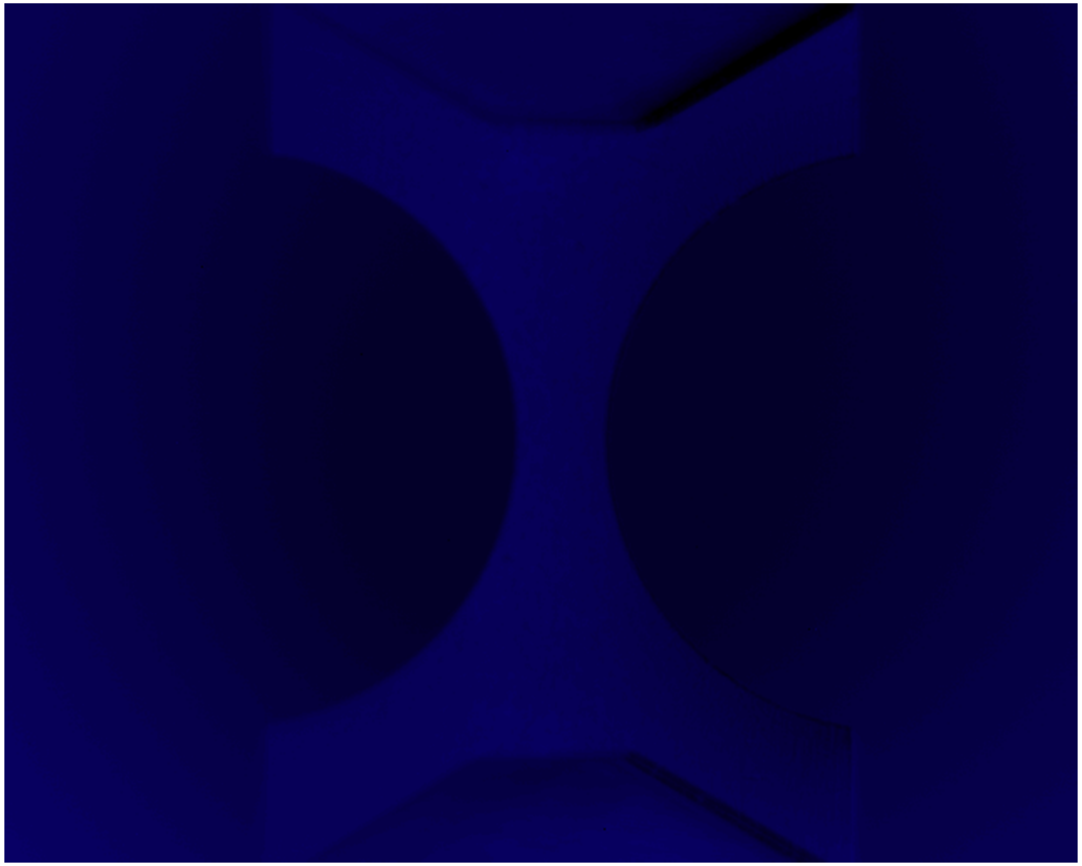
Expt Simulation

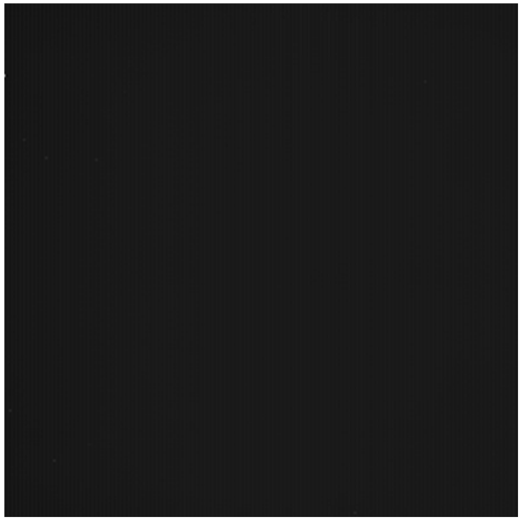


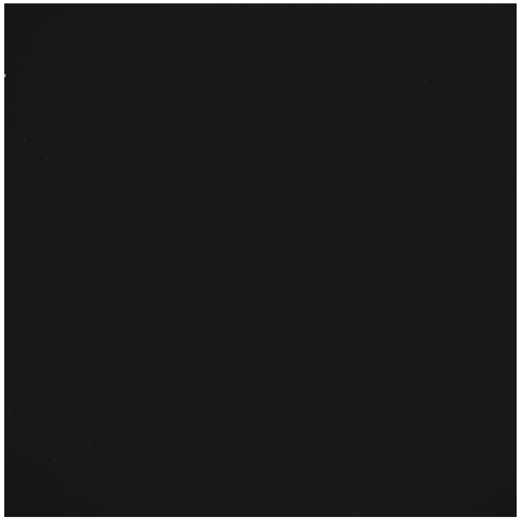


Experimentally measured peak stress varies with rate

Examples of Temperature Evolution during Deformation

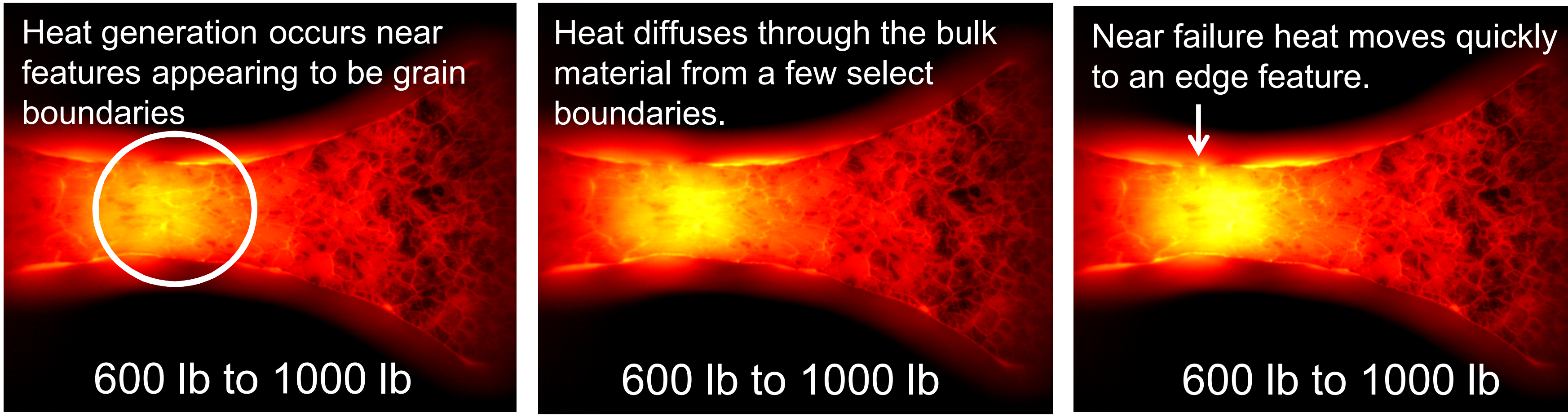


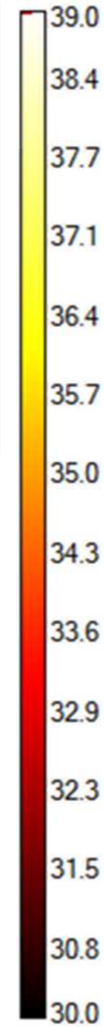




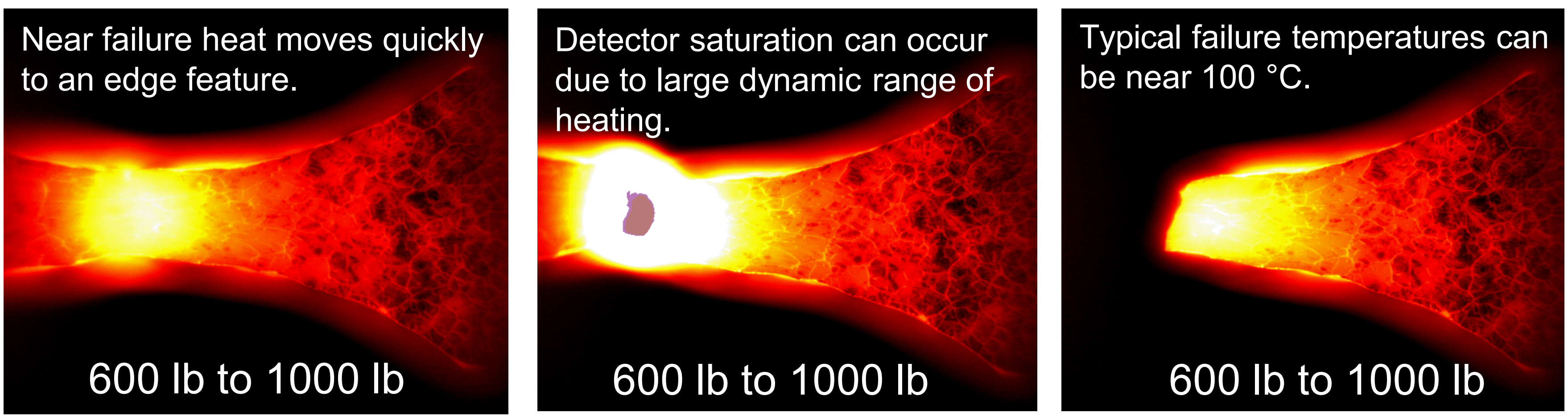
A Closer Look: Temperature Events Leading to Failure

Increasing plasticity →





With high plastic work, grain boundaries appear to begin heating (see white circle above). Heat nucleates from this region in the sample and propagates to an edge feature (see white arrow).



During failure, temperatures >100 °C can be reached.

Experimental History Dependence

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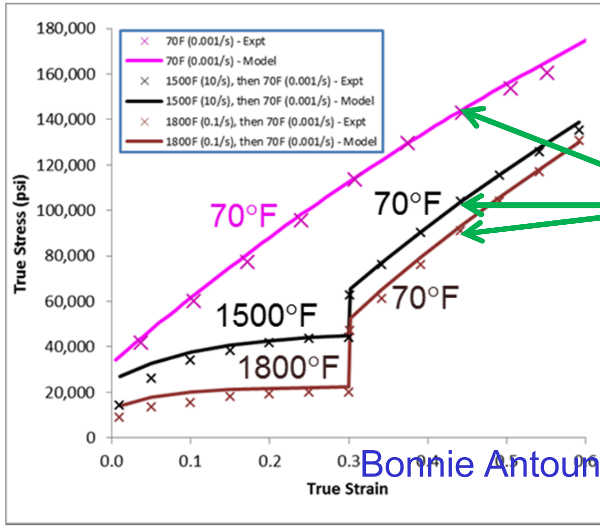
- History dependence is evident in rate-change or temperature-change tests
  - 304L Stainless Steel



These three data points all have the same temperature, strain, and strain rate, but very different stresses due to history effects

  - OFHC Copper

394 *A.B. Tanner, D.L. McDowell / International Journal of Plasticity 15 (1999) 375–399*

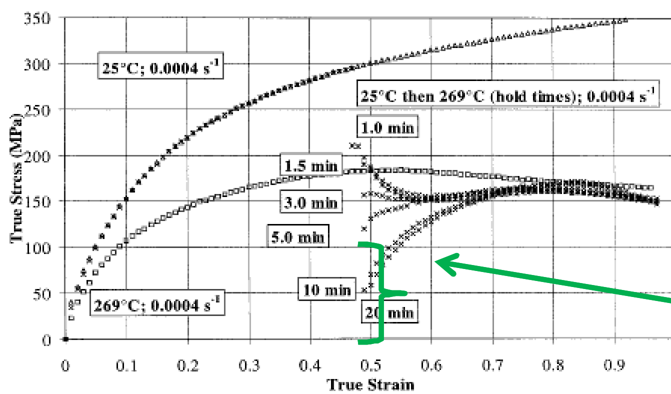


Fig. 20. Temperature history effects of OFHC Cu in compression (25°C, $0.0004\,s^{-1}$ then 269°C, $0.0004\,s^{-1}$) for increasing times held in furnace prior to compression.

History effects on response can be substantial

These data points all have the same temperature, same strain, and same strain rate, but very different stresses

Model Comparisons

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Tanner and McDowell, IJP (1999) for OFHC copper

- Optimization of material parameters

Johnson-Cook

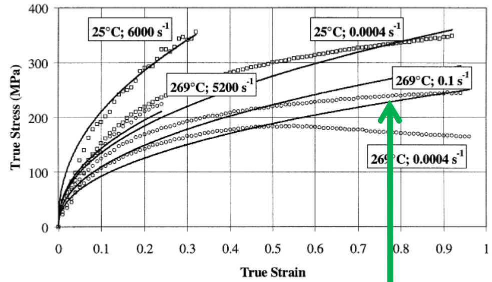


Fig. 2. Correlation to OFHC Cu data using Johnson/Cook model. The model correlations are shown using solid lines, while the experimental data are shown with open symbols.

Mechanical Threshold Stress (MTS)

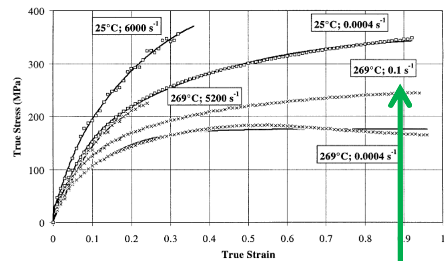


Fig. 10. Correlation to OFHC Cu compression data using the MTS model. The model correlations are shown using solid lines, while the experimental data are shown with open symbols.

BCJ (without recrystallization)

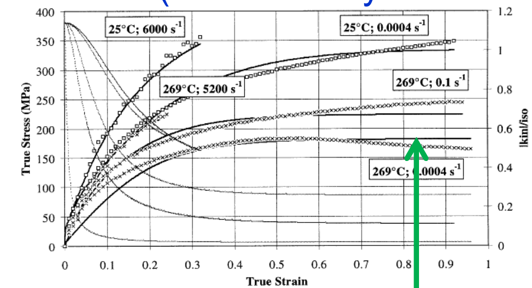
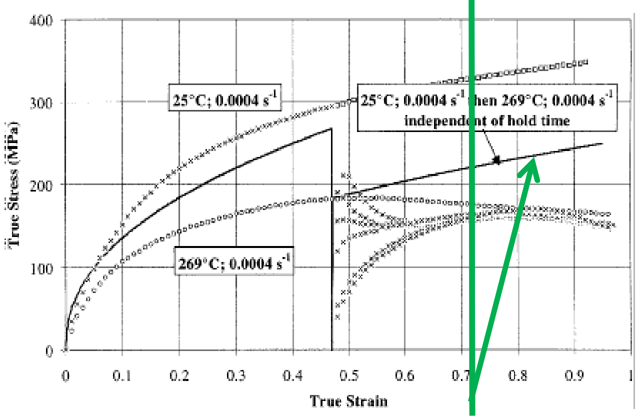


Fig. 18. Correlation to OFHC Cu compression data using the BCJ–SNL model. The model correlations are shown using solid lines, while the experimental data are shown with open symbols. The ratio $|\alpha|/\kappa$ are displayed using short dashed lines.

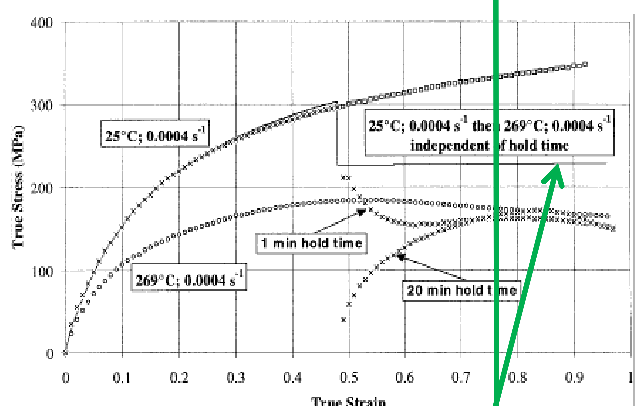
- Validation (prediction using parameters from above)

Johnson-Cook



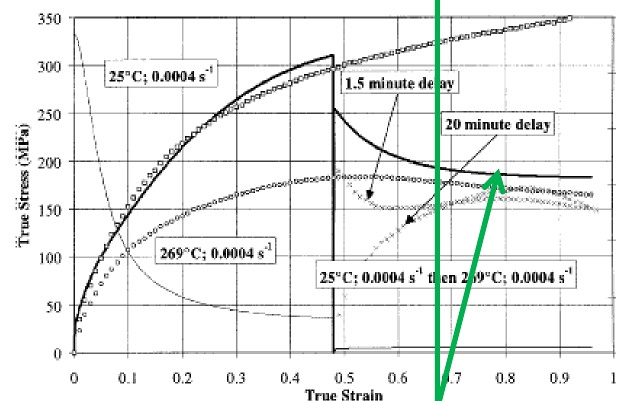
JC has no history dependence (i.e. has same hardening regardless of prior loading)

Mechanical Threshold Stress (MTS)



MTS has history dependence, but no softening due to recovery

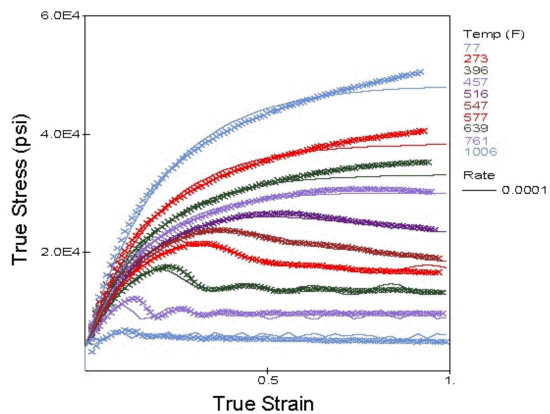
BCJ (without recrystallization)

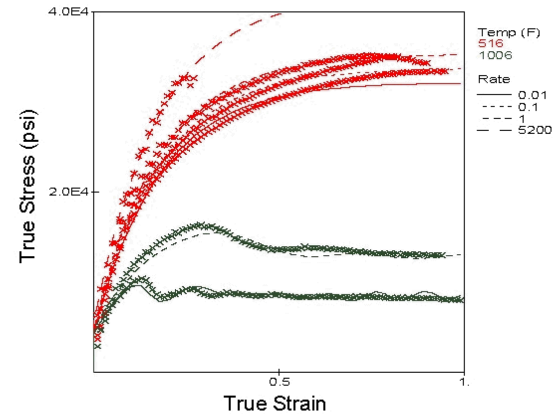


BCJ has history dependence and softens due to recovery

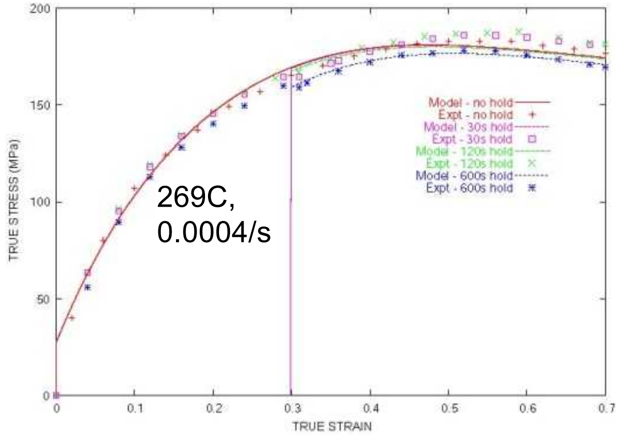
Model Validation

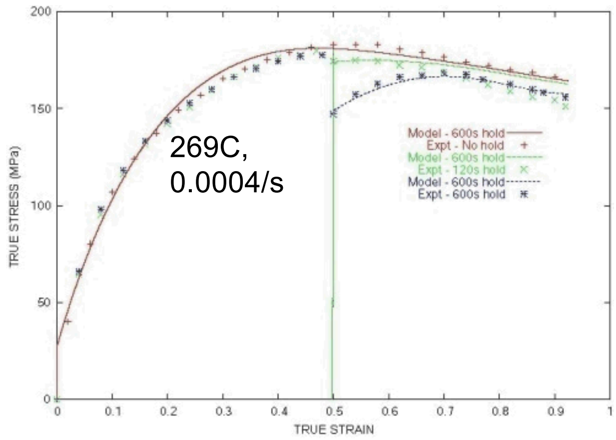
- OFHC Copper Tanner and McDowell, IJP (1999)
  - Optimization of material parameters to dynamic recrystallization data

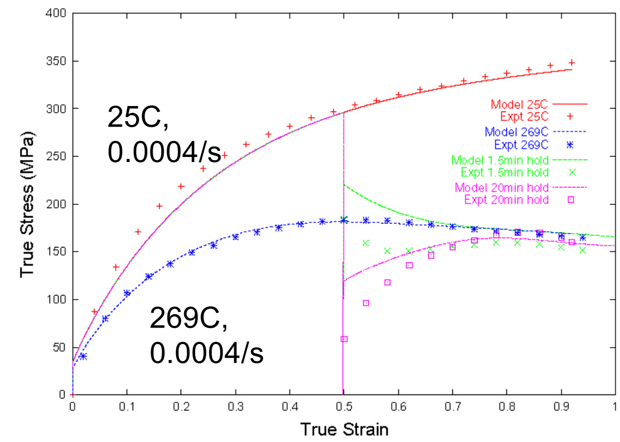




  - Validation (prediction of static and dynamic recrystallization using same parameter set)



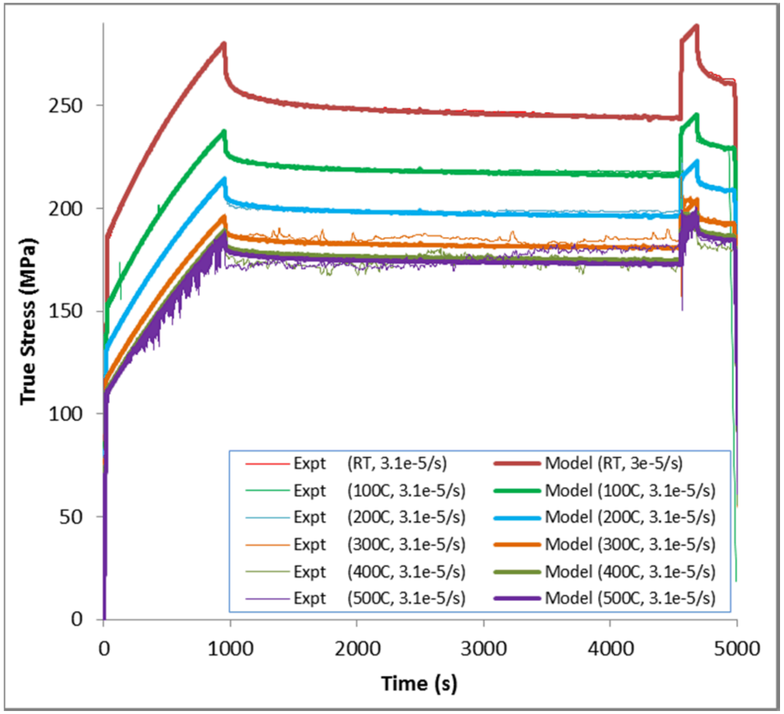




Brown and Bammann, IJP (2012)

Example:Glass-to-Metal Seals (GTM)

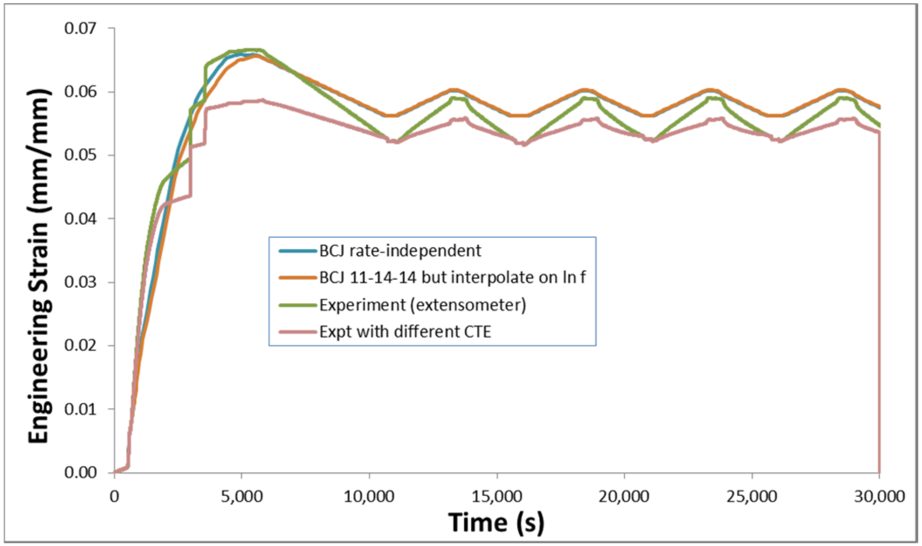
- Dynamic strain aging is evident
  - Model not capable of capturing this mechanism yet
- For now, this latest parameter set focuses on the 3e-5/s data
  - Rate dependence is fit to the relaxation curves (instead of to the 3e-6/s data)
  - The model will underpredict the yield at lower rates until DSA is included
- Later, the model will be enhanced to account for DSA

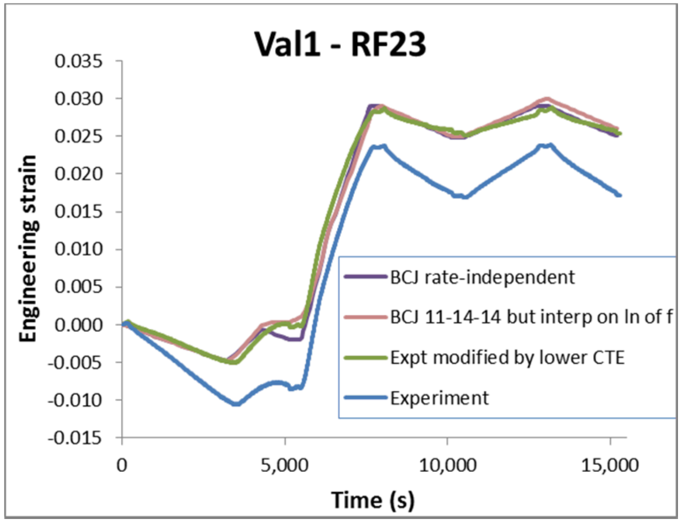


Antoun, Emery, Chambers

GTM

- Validation
  - Model performs well, but cannot model strain jumps
  - Effects of dynamic strain aging will be added to address this shortcoming





Summary

- Determining meaningful parameters for most ductile materials requires a temperature and rate dependent material constitutive model
    - We have demonstrated the major areas of concern, there are others
    - Temperature measurements (full-field) should be included on key experiment
- Substantial errors will be propagated throughout other simulations if parameters are not determined properly (model or method)
- Using a history dependent model is necessary for simulating complex events
    - Non-constant applied loading rates
    - Change in strain rate during deformation
    - Any variation in temperature
- Overuse of tensile test data is discouraged
    - Does it reflect the correct stress state to be simulated? Shear, compression, multi-axial loading
    - Triaxiality limited
    - Many more meaningful characterization experiments that are possible today that are much more efficient (material use and number of experiments) and can be tailored to extract data meaningful to the application of interest