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Thermal-Mechanical Modeling of Stainless Steel Forgings

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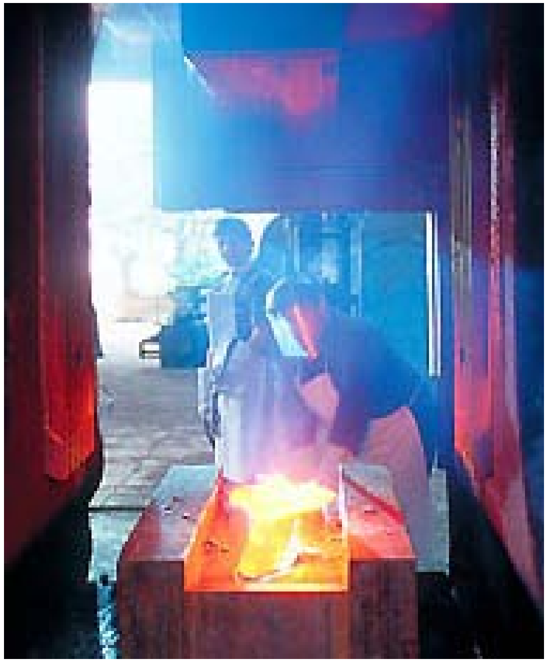
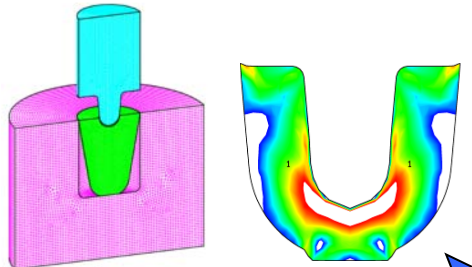
Overview

- High pressure gas reservoirs are 304L stainless steel vessels that contain hydrogen isotopes at high pressure. Reservoirs are required to have yield strengths in a tight range (55–75 ksi) to inhibit embrittlement.
- It can take 5 years to design and validate a forging process that meets Sandia's specifications
- Recent reservoir forging designs have experienced large amounts of recrystallization, resulting in inadequate material strength.
- In order to better predict material properties of forged components, work is being done to model the effects of recrystallization on the material strength and properties of the final forged product.

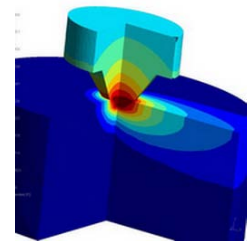


The modeling challenge is to predict the evolving state of a reservoir through its entire life cycle



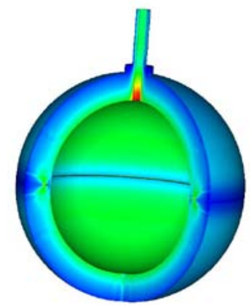
Forging

Welding



Heat affected zone of welded joint is prime location for cracking.

Residual Stresses



Tritium/Helium Diffusion

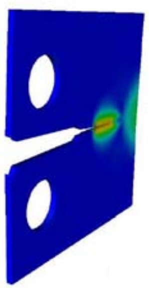
Diffusion is material, pressure, and temperature dependent.

Material Hardening → Embrittlement

Margin/Uncertainty → Reservoir Design Life

Reservoir Design Guide assures sufficient margin based on predictive uncertainties.

Crack Initiation and Growth



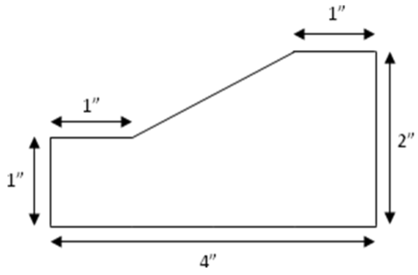
Failure

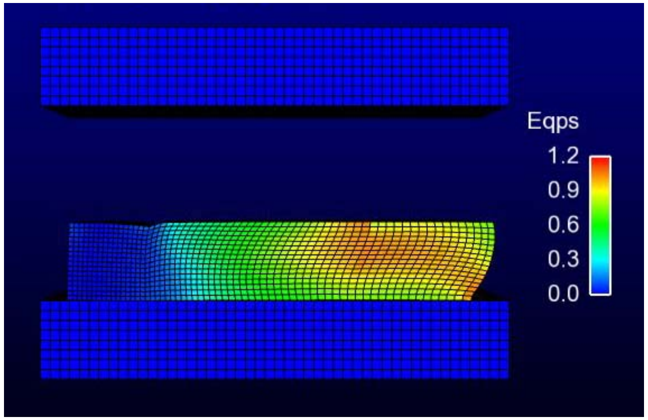
Transition from crack initiation to reservoir failure is not well characterized.

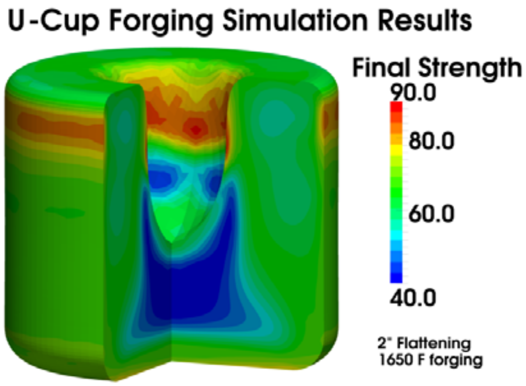
Predictive uncertainties result in large safety factors, reduced lifetimes, and increased costs.

Outline

- Overview of the forging process
- Recrystallization
- Constitutive model
- Model performance
  - OFHC copper
  - Stainless steel 304L (wedge and U-cup forgings)
- Summary





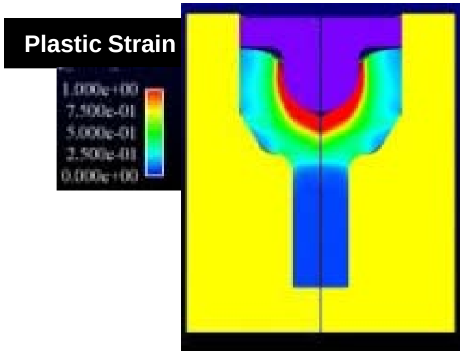


Each forging stage involves multiple processes

Heating in furnace
(~1 hour)

Transfer to die (~2 to 5 sec)

Conduction to die before compression (~3 to 5 sec)



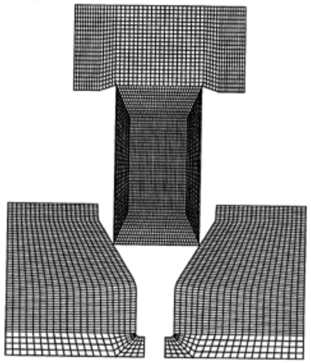
Compression (~0.01 sec)

Conduction to die before removal
(~5 to 60 sec)

Transfer to quench bath
(~3 to 5 sec)

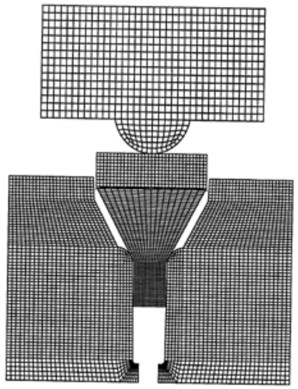
Pictures courtesy of Bonnie Antoun

Material properties for reservoirs are determined by the multi-stage forging process



First stage

1800° F

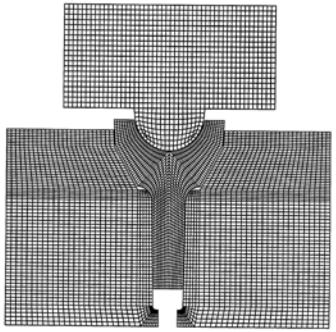


Second stage

1700° F

. . .

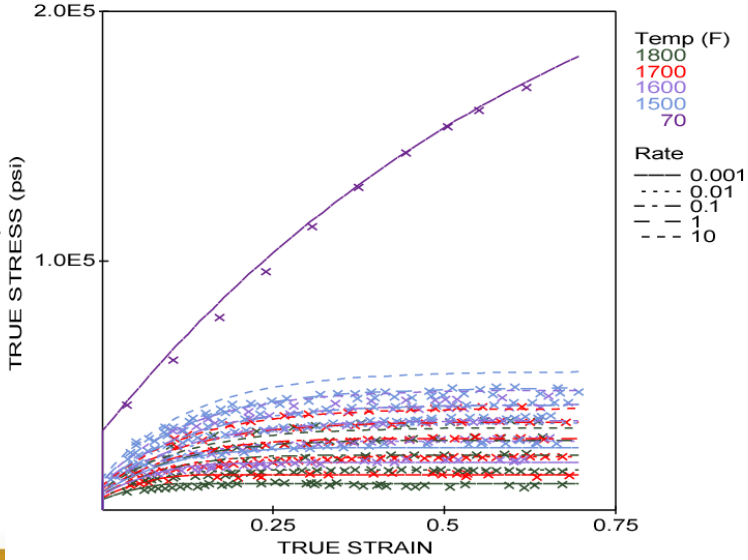
Annealing (1750F to 1800F)



Final stage

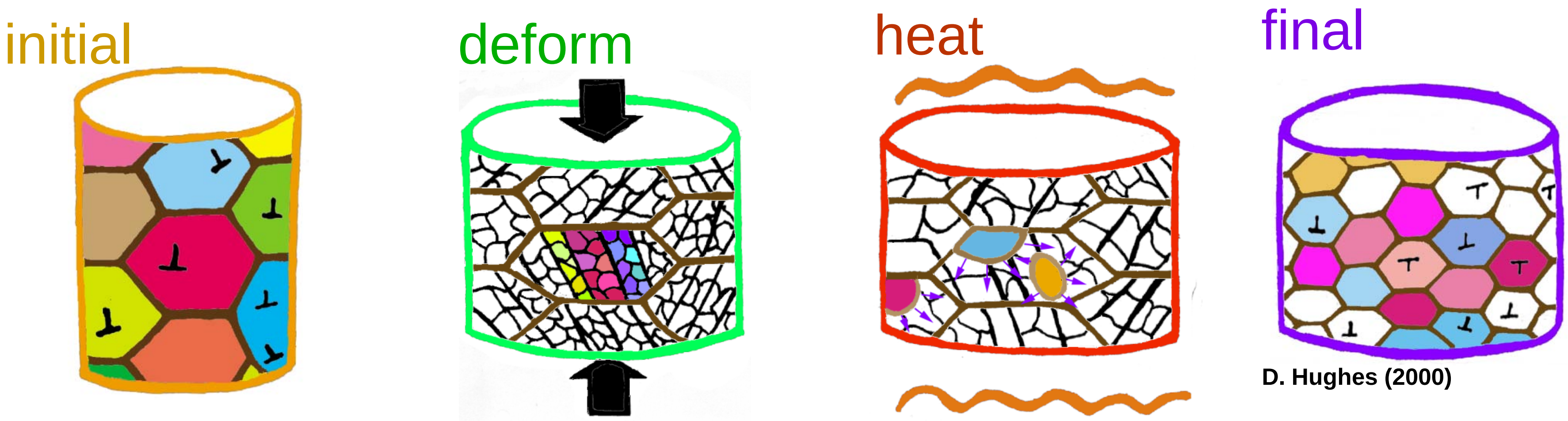
1600° F

- **For now, we are modeling the final stage, assuming the annealing removes dislocation structure from previous stages**
- **Requires a material model with temperature and rate dependence**

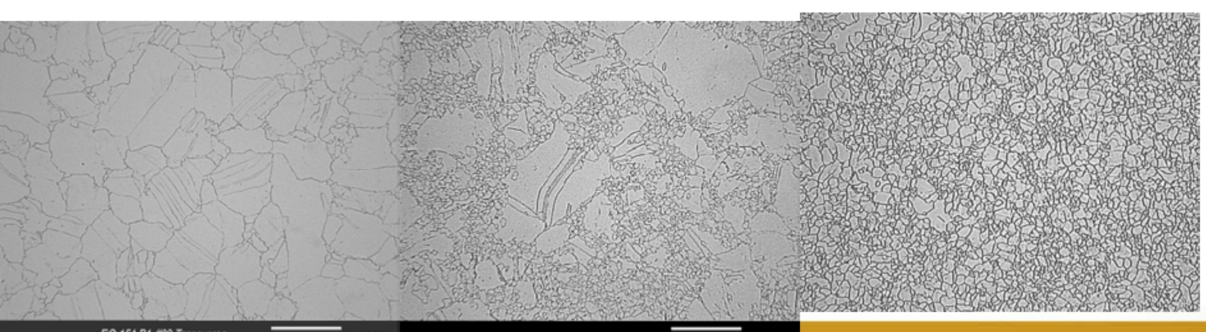


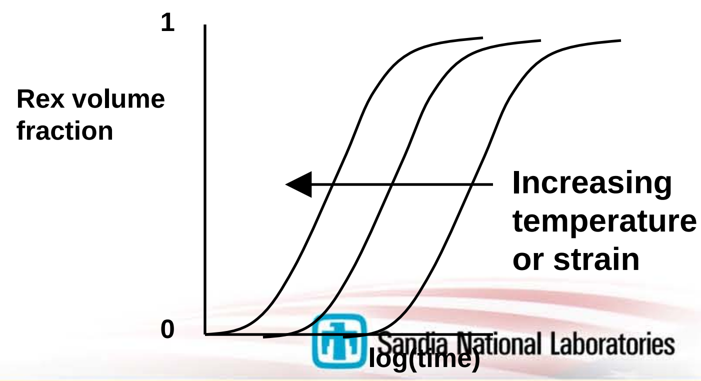
Recrystallization

- During deformation, subgrains form. At high temperatures, some will grow at the expense of their neighbors, forming the nuclei of new grains.
- *Recrystallization* is the process by which the dislocation structure in a worked material is wiped away by growth of nuclei that form a new, relatively dislocation-free set of grains



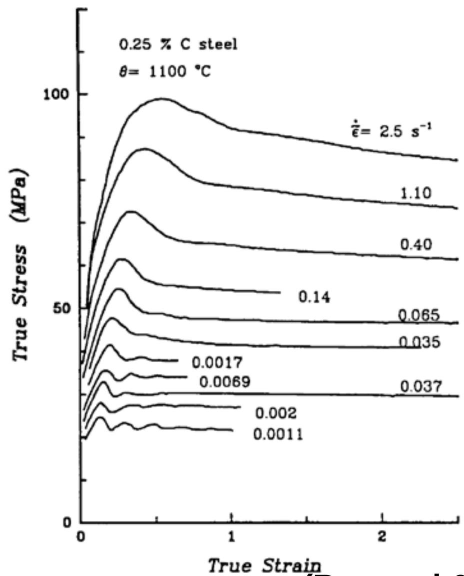
D. Hughes (2000)



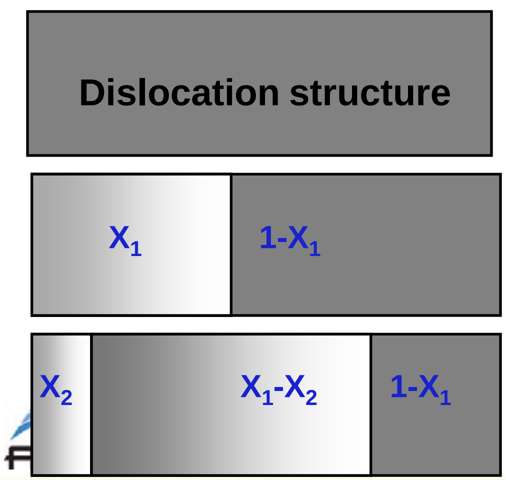


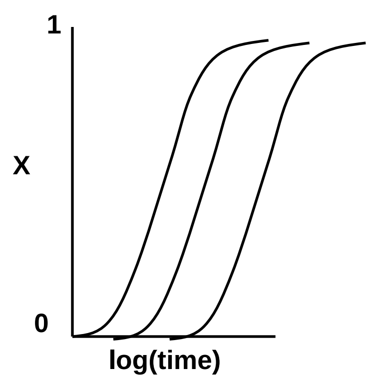
Recrystallization

Dynamic recrystallization



(Rossard & Blain, 1959)

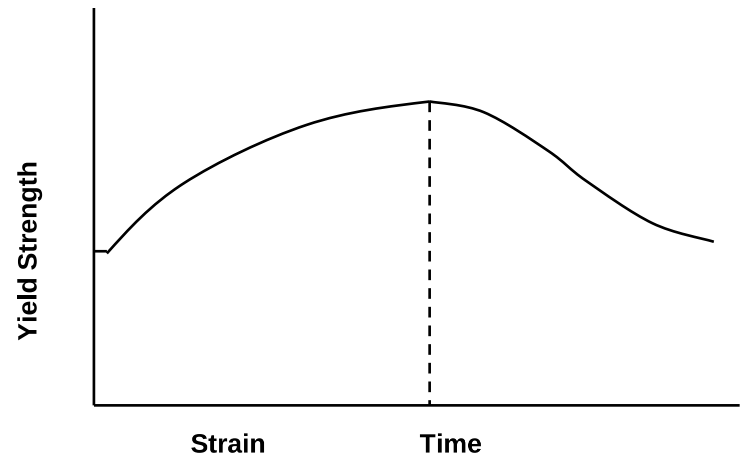


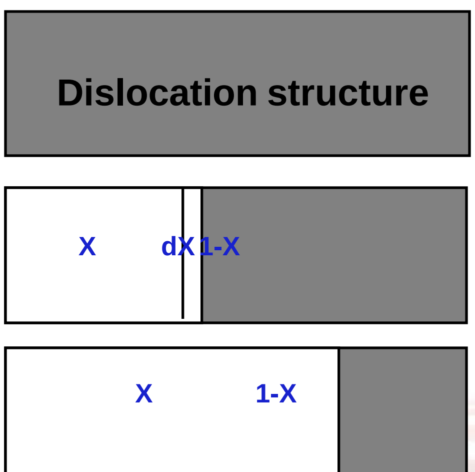


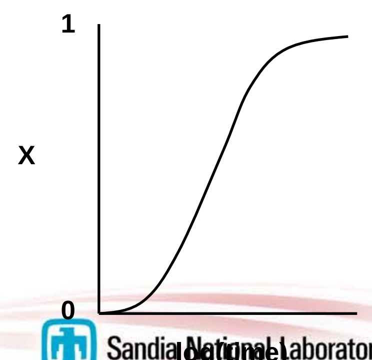
Static recrystallization

Occurs if deform at elevated temperature at high strain rate

Or if deform at low temperatures, then heat







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EMMI Elasto-Viscoplasticity Model
(simplified for uniaxial, isothermal loading)

σ = true stress, ε = true strain, θ = temperature

κ = isotropic hardening variable representing the density of statistically stored dislocations

$$\kappa = c_{\bar{\varepsilon}_{\mathrm{ssds}}} b \mu(\theta) \sqrt{\rho_{\mathrm{ssds}}}$$

Hypoelasticity

$$\dot{\sigma} = E(\dot{\varepsilon} - \dot{\varepsilon}^p)$$

Flow rule for plastic strain

$$\dot{\varepsilon}^p = f(\theta)\left(\sinh\left[\left\langle \frac{|\sigma|}{\kappa + Y(\theta)} - 1 \right\rangle\right]\right)^{\mathrm{n}}$$

Statistically stored dislocations

$$\dot{\kappa} = H(\theta)\left|\dot{\varepsilon}^p\right| - R_d(\theta)\kappa\left|\dot{\varepsilon}^p\right|$$

The flow rule can be inverted to solve for the rate- and temperature-dependent yield stress

$$\sigma = \left(\kappa + Y(\theta)\right)\left(1 + \sinh^{-1}\left(\frac{\dot{\varepsilon}^p}{f(\theta)}\right)^{1/n(\theta)}\right)$$

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EMMI Elasto-Viscoplasticity Model
(for uniaxial loading)

The model tracks multiple cycles of recrystallization simultaneously, as well as the state variables corresponding to each volume fraction

The energy drop that occurs as recrystallization nuclei grow is the driving force for recrystallization. The mobility of nuclei boundaries increases with misorientation angle.

Recrystallized volume fraction

$$\dot{X}_{i+1} = R_{rex}\left(\theta\right)Q_{rex}\left(\kappa_i, \zeta_i\right)g\left(X_i, X_{i+1}\right)$$

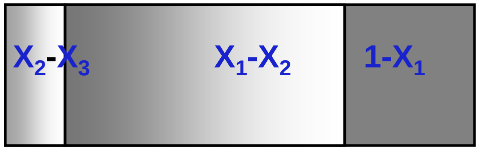
Isotropic hardening variable

$$\dot{\kappa}_{X_i - X_{i+1}} = \left(H - R_d \kappa_{X_i - X_{i+1}}\right)\left|\dot{\varepsilon}^p\right| - \kappa_{X_i - X_{i+1}} \frac{\dot{X}_i}{X_i - X_{i+1}}$$

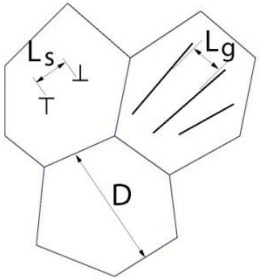
Misorientation variable

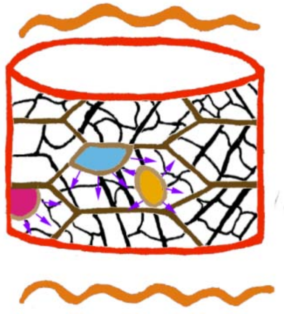
$$\dot{\zeta}_{X_i - X_{i+1}} = h\zeta_{X_i - X_{i+1}}^{1-1/r}\left|\dot{\varepsilon}^p\right| - \zeta_{X_i - X_{i+1}} \frac{\dot{X}_i}{X_i - X_{i+1}}$$

Misorientation variable is based on Kok & Beaudion (2002)



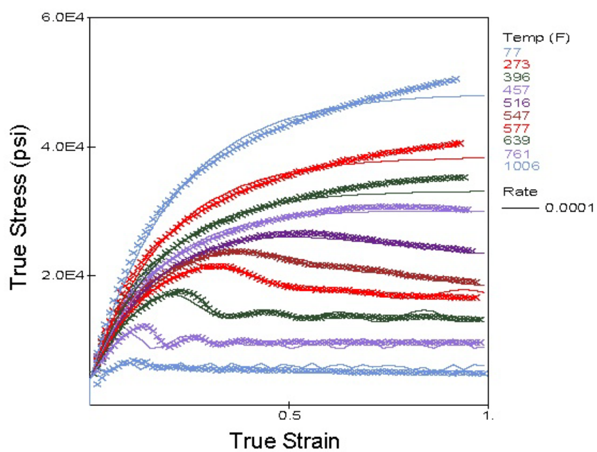
For now, we are neglecting static recovery

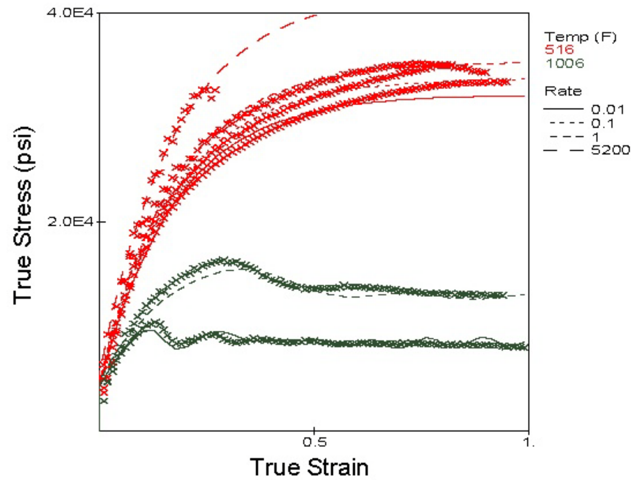




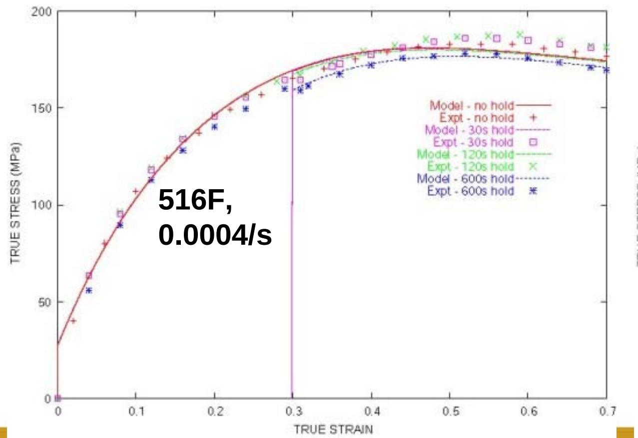
Validation for Static/Dynamic Recrystallization Modeling

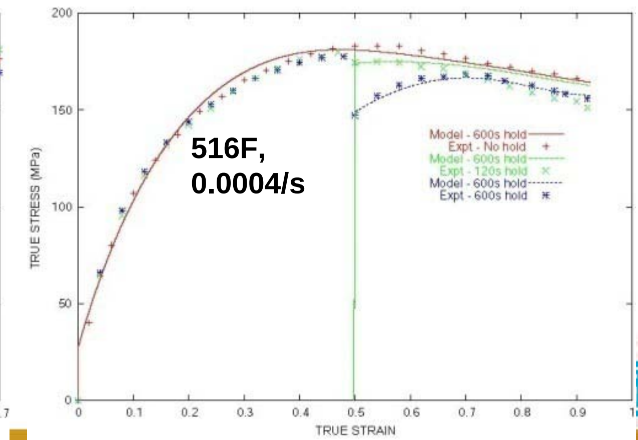
- 16 parameters were fit to copper data (Tanner et al.) using a modified version of Bfit (code by Lathrop)





- Then, predictions of compress/hold/compress experiments were made





Tanner (1999): OFHC copper

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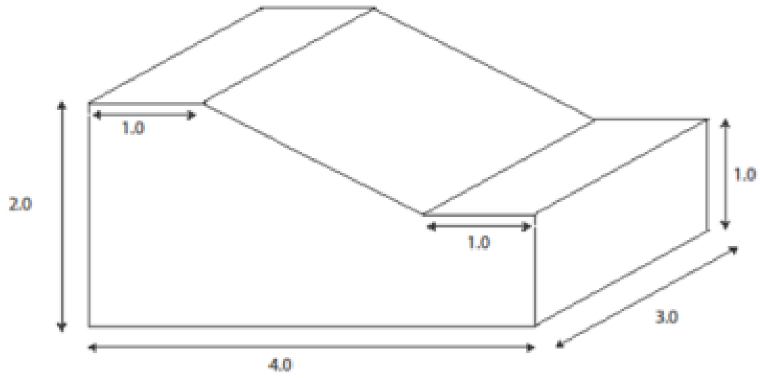
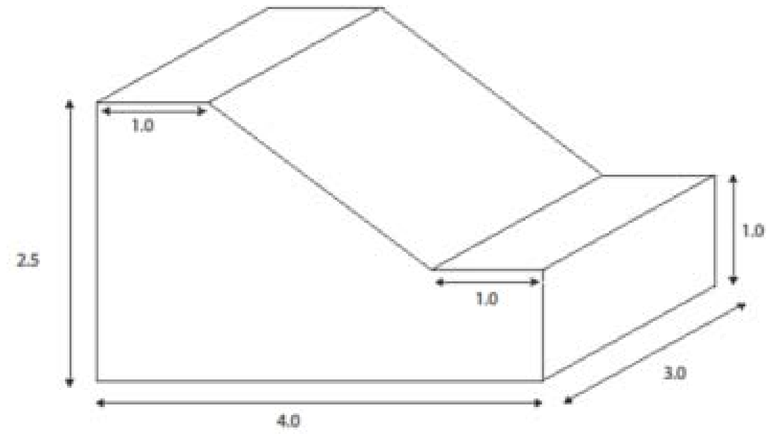
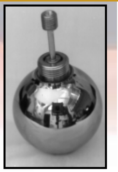
Wedge Forgings for Validation

- Two wedge geometries were forged by the HERF (High Energy Rate Forging) process
  - Three initial temperatures (1500F, 1600F, and 1700F)
- Tensile specimens were machined and tested to get quasistatic, room-temperature yield strength in six locations



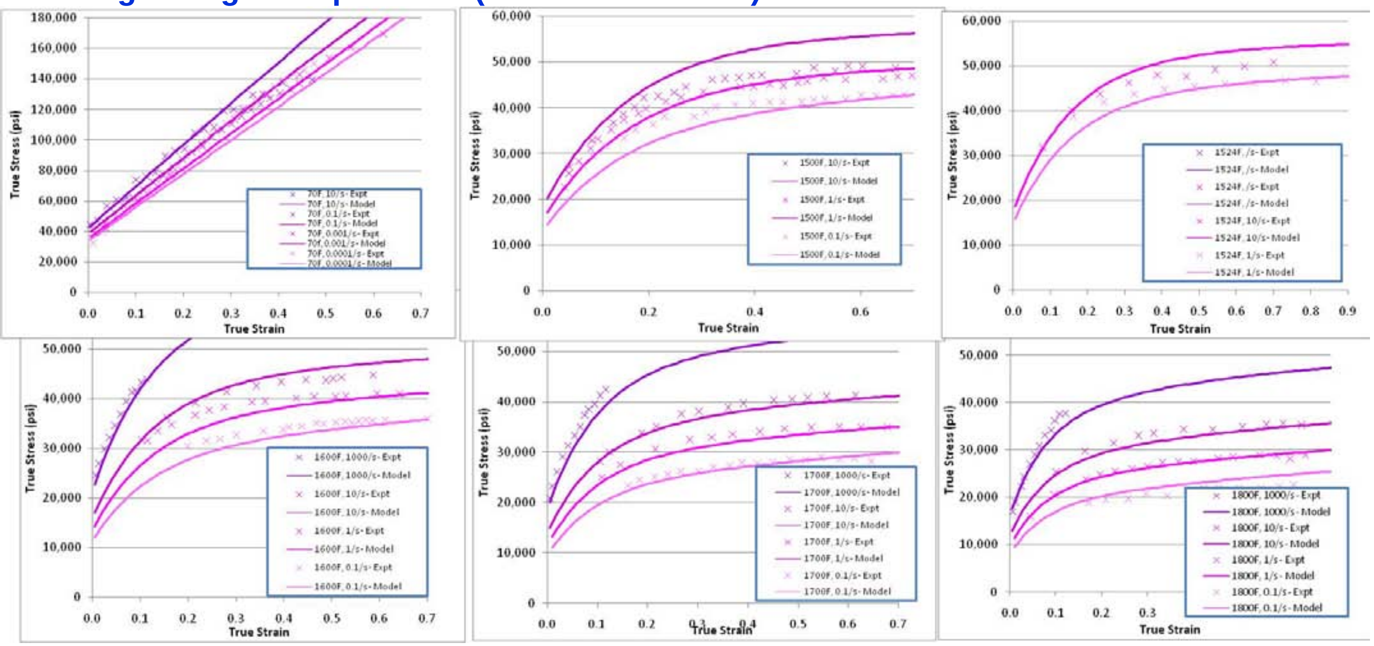




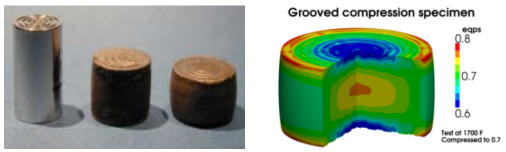
304L Parameter Optimization

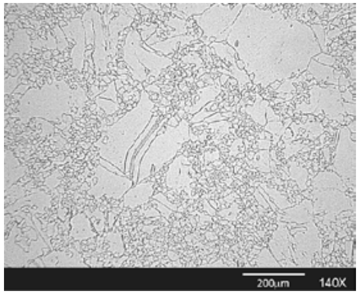
Rates ≥ 0.1/s

Single-stage compression (stress-strain data)

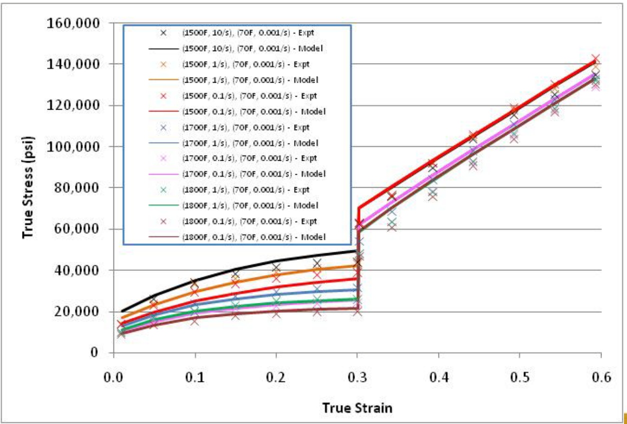


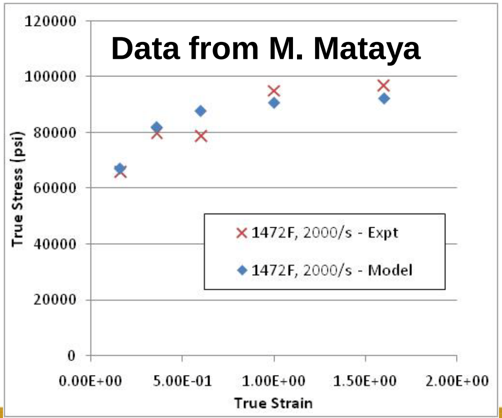
Data from B. Antoun



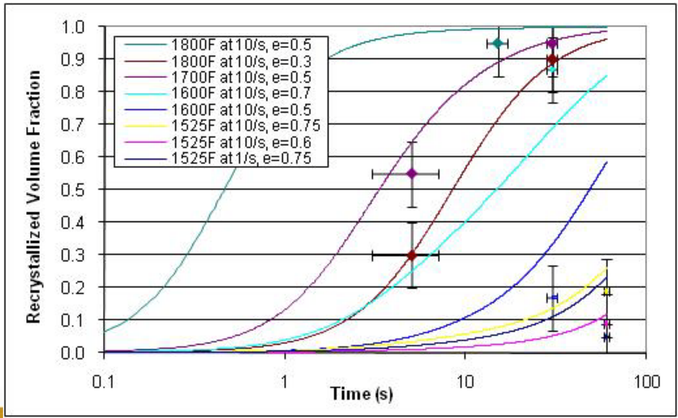


Two-stage compression (stress-strain data)





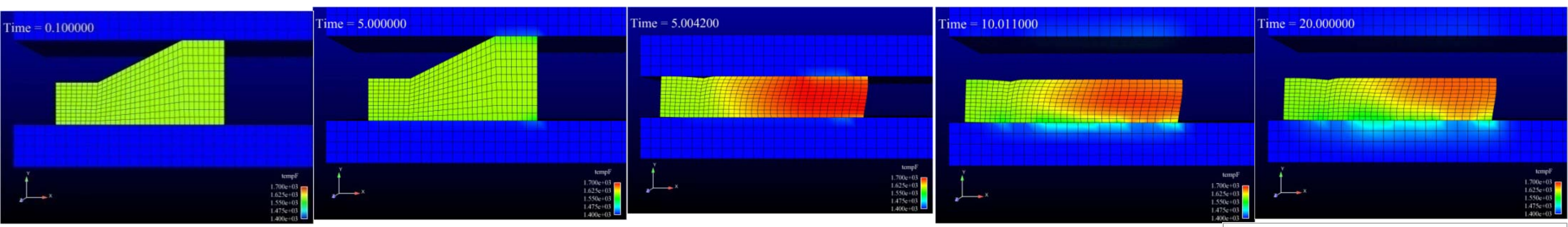
Compress/hold (Rexed volume fraction)

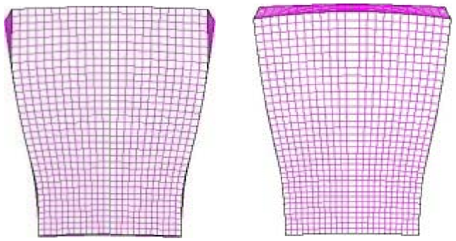


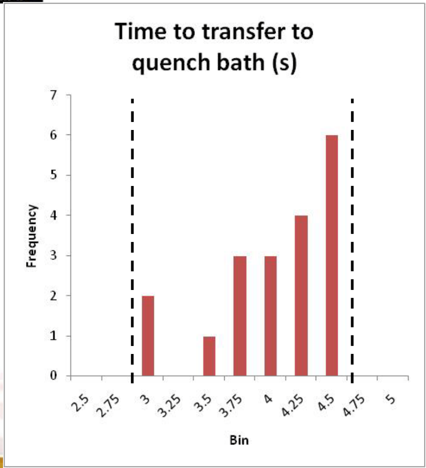
Wedge Assumptions

- Conduction, convection, heat generation, and radiation are modeled
- Tightly coupled thermal-mechanical solution
- Dimension variation from sample to sample has negligible effect
- Transfer times to die and to quench bath were based on measurements taken by Bonnie Antoun for other forgings at PMP (Precision Metal Products)
- Since die is flat, we assume 0.5 to 2s to remove ingot from die

Initial Temperatures | Conduction | Heating due to Plastic Dissipation | Conduction before transferred to quench bath

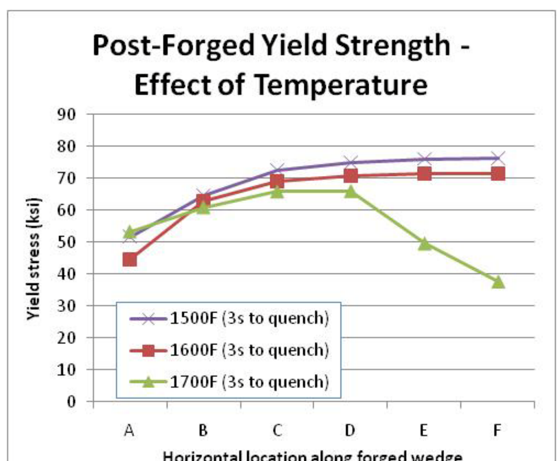


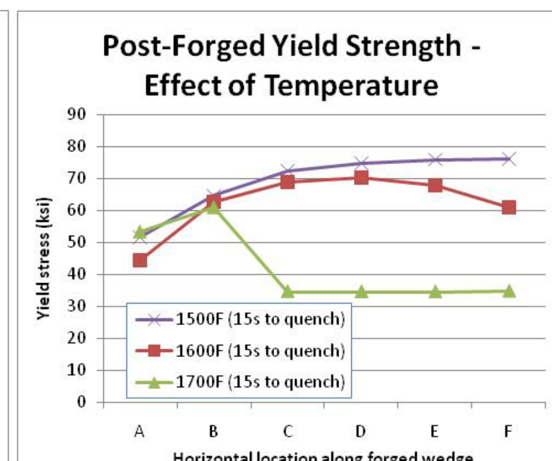




Coupled Thermal-Mechanical Simulations

- Final strength can be influenced by many factors:
  - Initial ingot, punch, and die temperatures
  - Times (between furnace to compression, time before quenching, etc)
  - Velocity
  - Dimensions
  - Lubrication
- For uncertainty quantification, we reduce the number of parameters through engineering judgement and sensitivity analysis

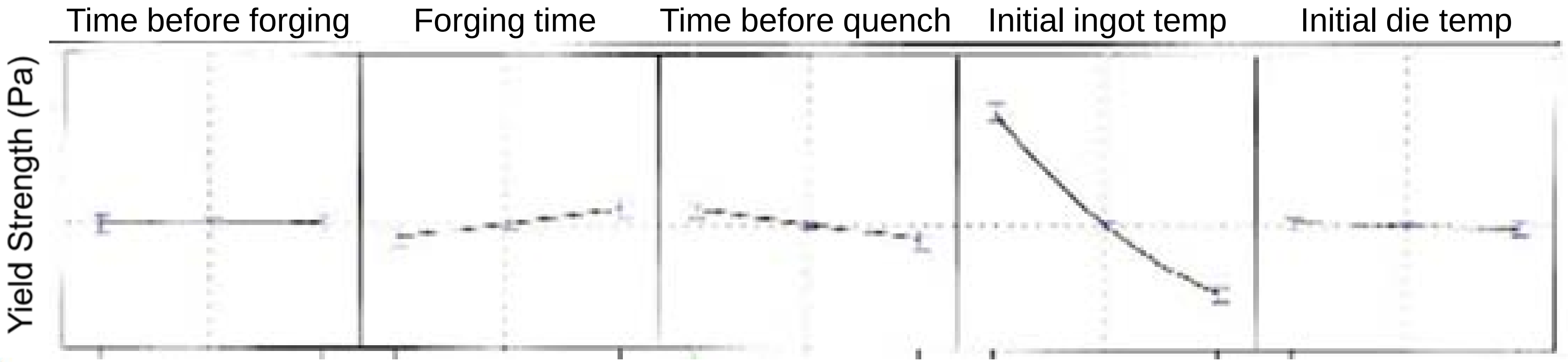




Sensitivity analysis

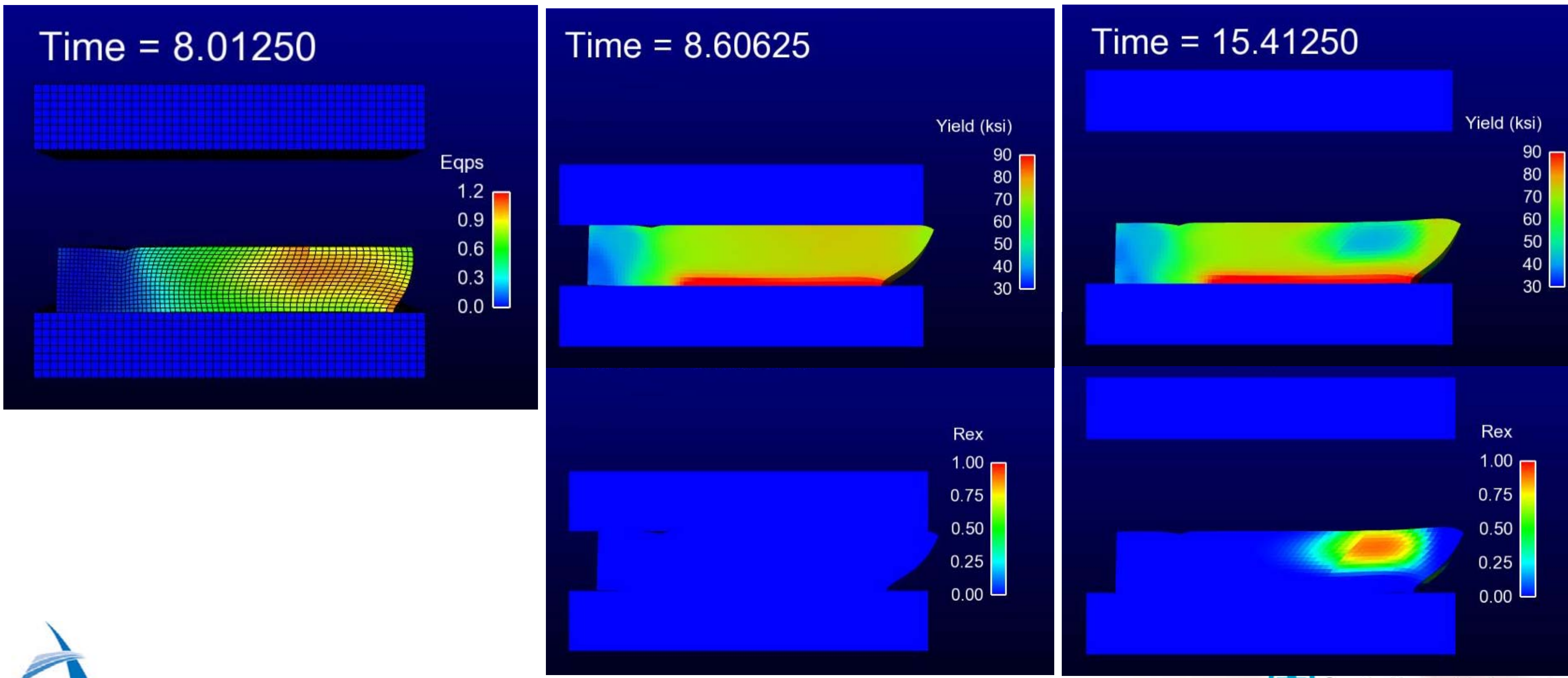
- Goals
  - To determine the most important input parameters to your model
  - To reduce the number of parameters that you need to be concerned with in performing uncertainty quantification
- Methods
  - Vary one input parameter at a time to see impact on response
  - Generate ensembles of simulations in which the input parameters are varied over specified ranges

Sensitivities of response to various inputs



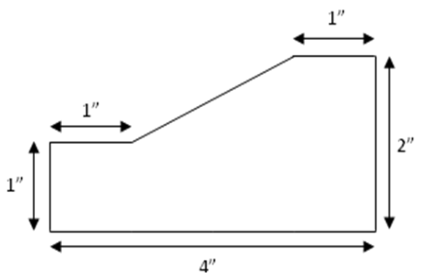
Short Wedge Forging

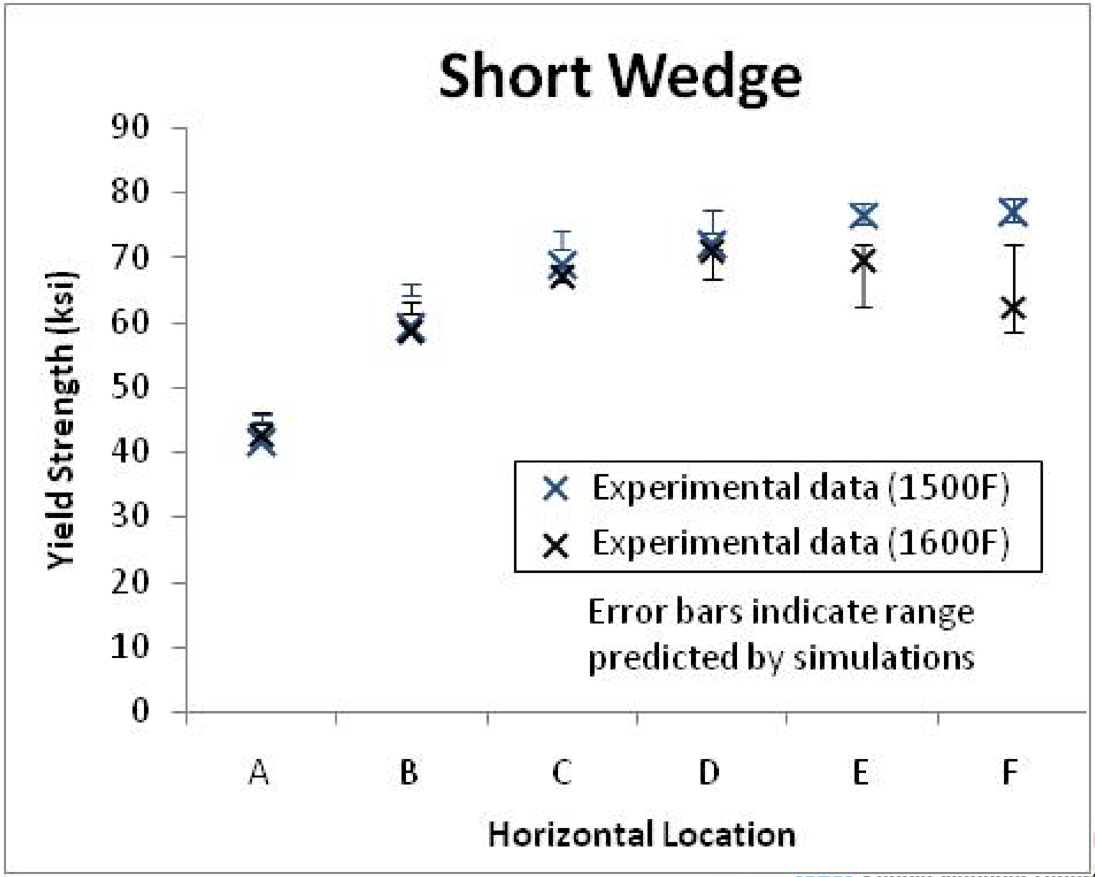
- Plastic strain increases from left to right
- Initially, yield stress increases with plastic strain due to work hardening
- As recrystallization develops, yield strength drops in regions with highest strain levels



Short Wedge Forging

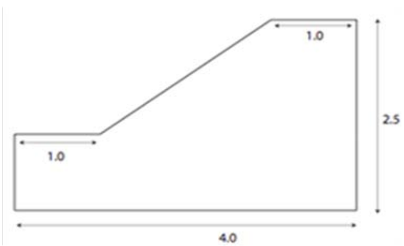
- Experimental values depicted by “x” symbols
- Simulations represented by error bars to account for the uncertainty in the predicted values based on simulations of upper and lower bound conditions for each nominal case

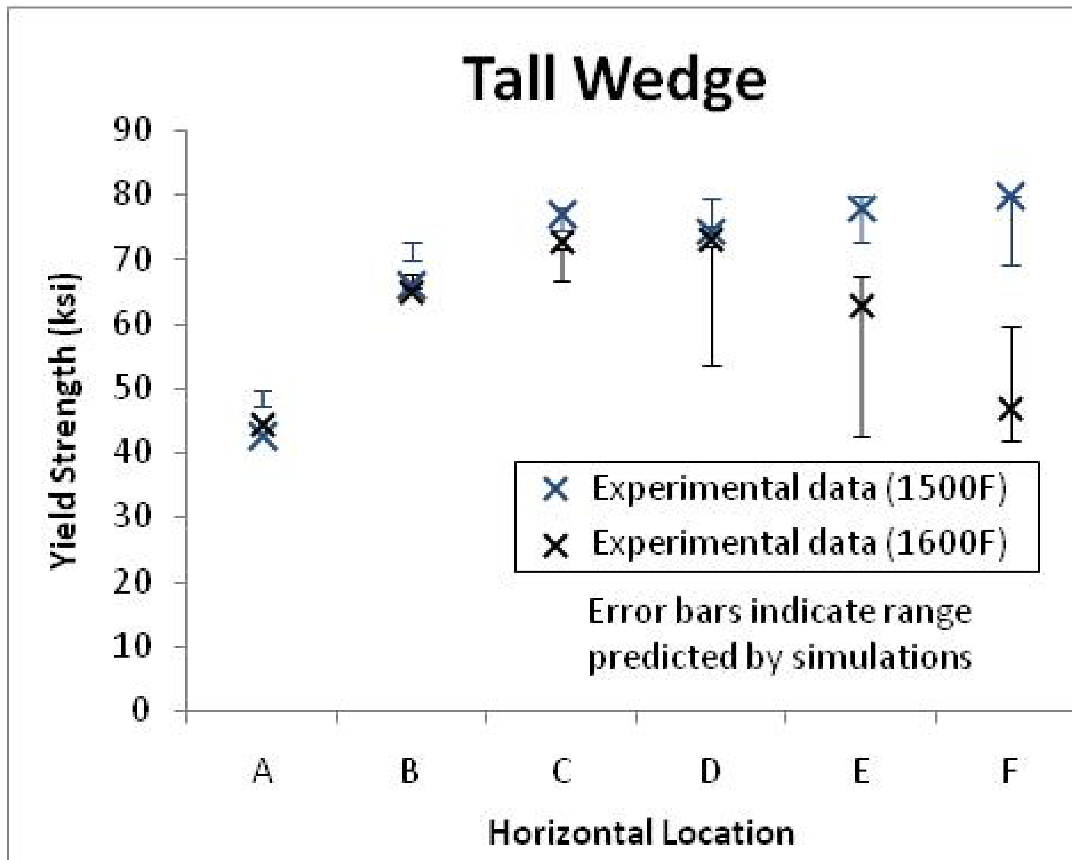




Tall Wedge Forging

- Uncertainty is highest at higher temperature in locations of higher strains
  - Due to high rate of recrystallization





Tall Wedge Forging

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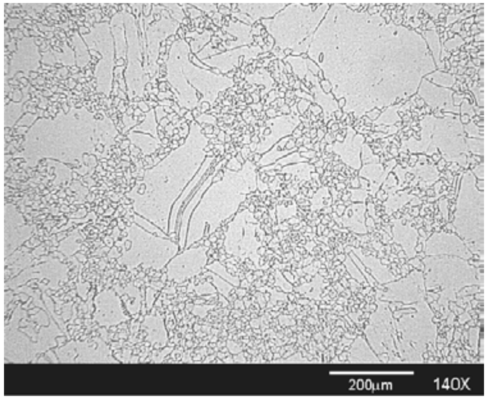
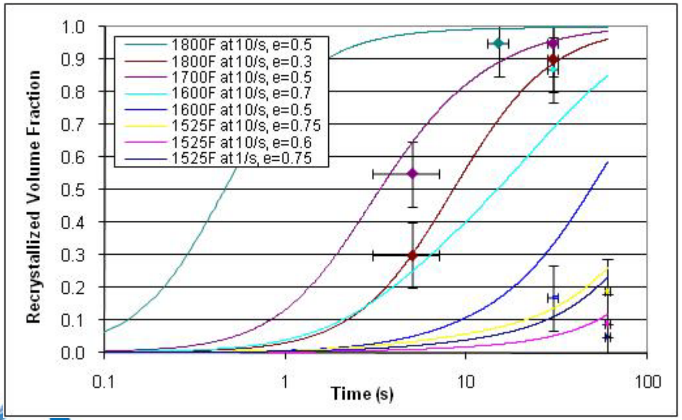
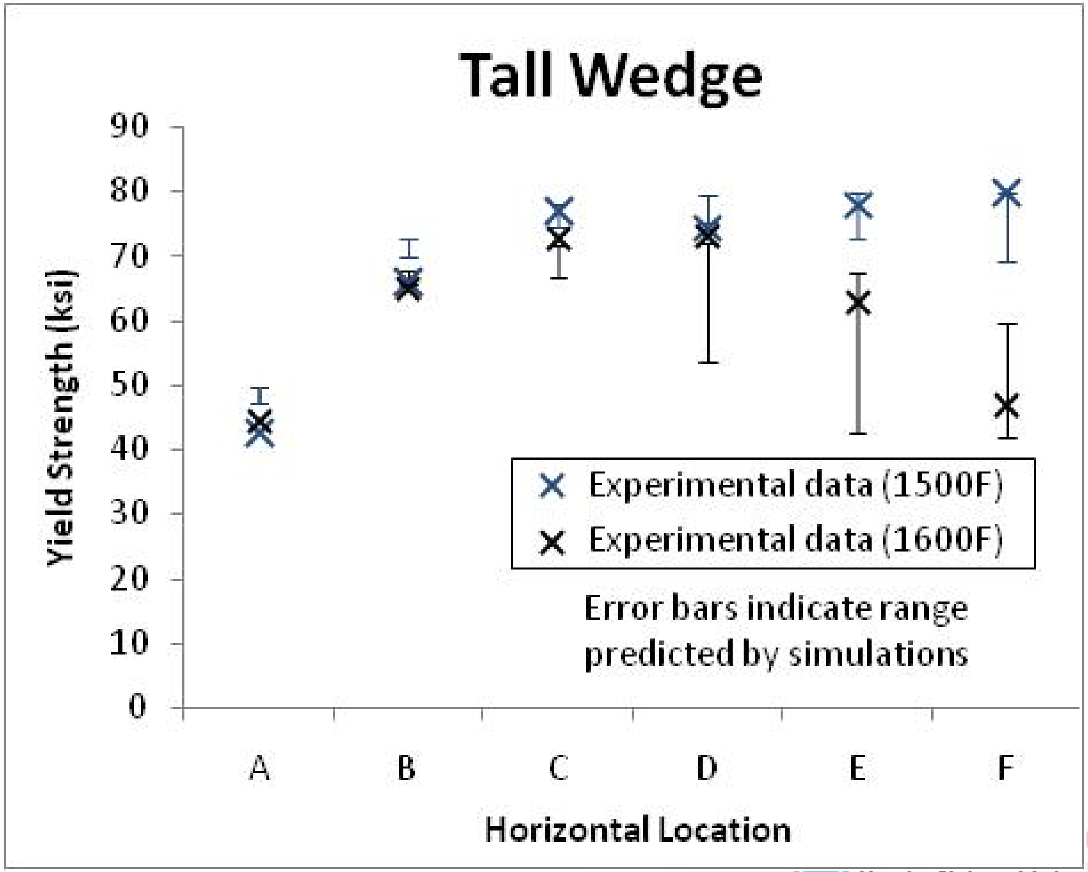


Compress/hold
(Rexed volume fraction)

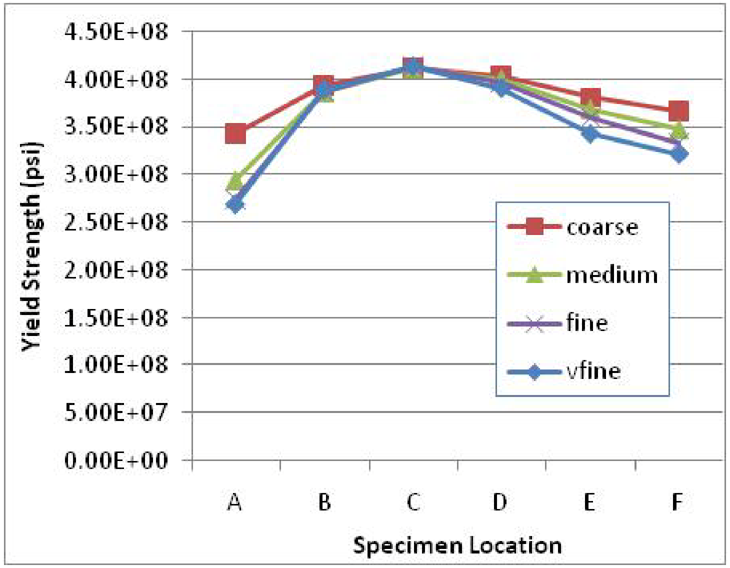




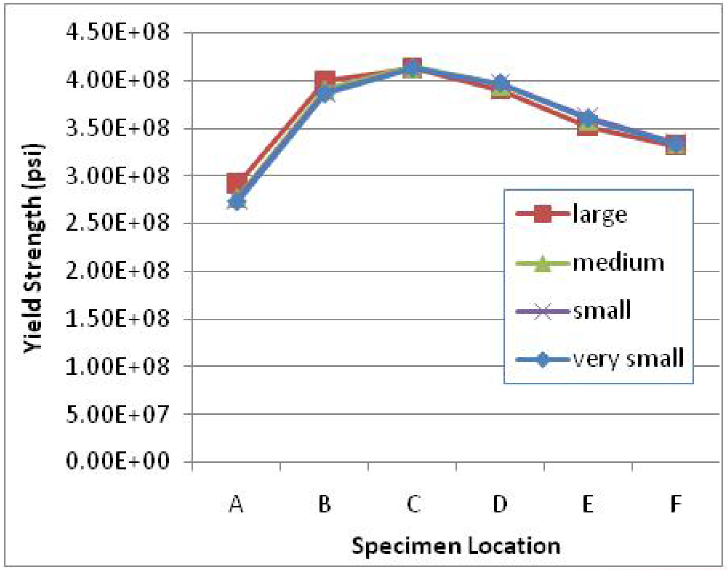
Checking mesh and timestep convergence for wedge simulations

- Solution verification
  - Spacial and temporal convergence study
    - Three meshes, uniform refinement
    - Three timesteps, successive time scales halved
  - Solution does not seem to be mesh convergent

Mesh convergence

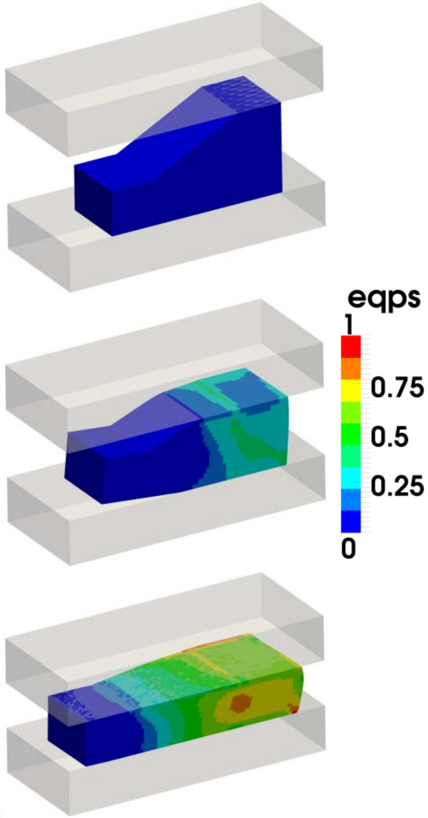


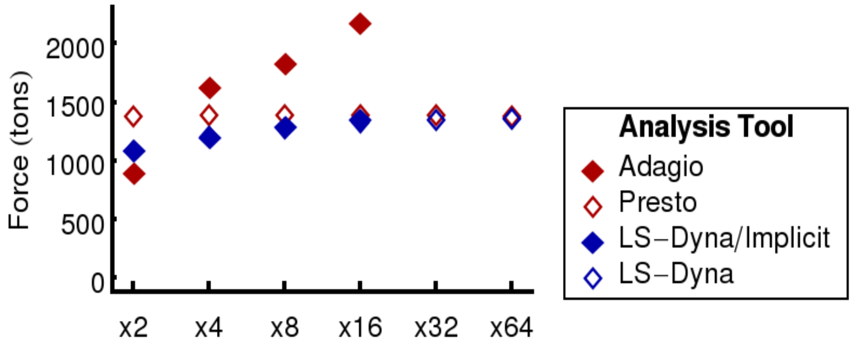
Time step convergence

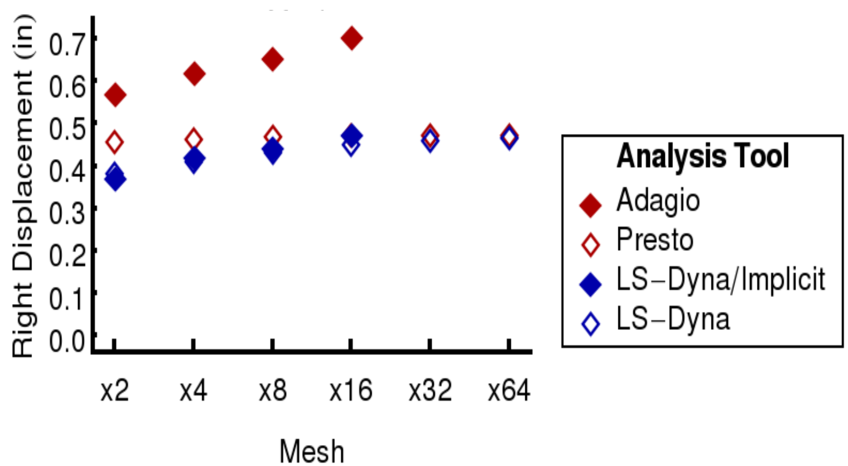


Mesh Convergence Study

- Sierra/SM Explicit results are very consistent from one mesh to another
- LS-Dyna converges to the Sierra/SM Explicit solution
- Sierra/SM Implicit diverges (analysis used early contact algorithm still in development)



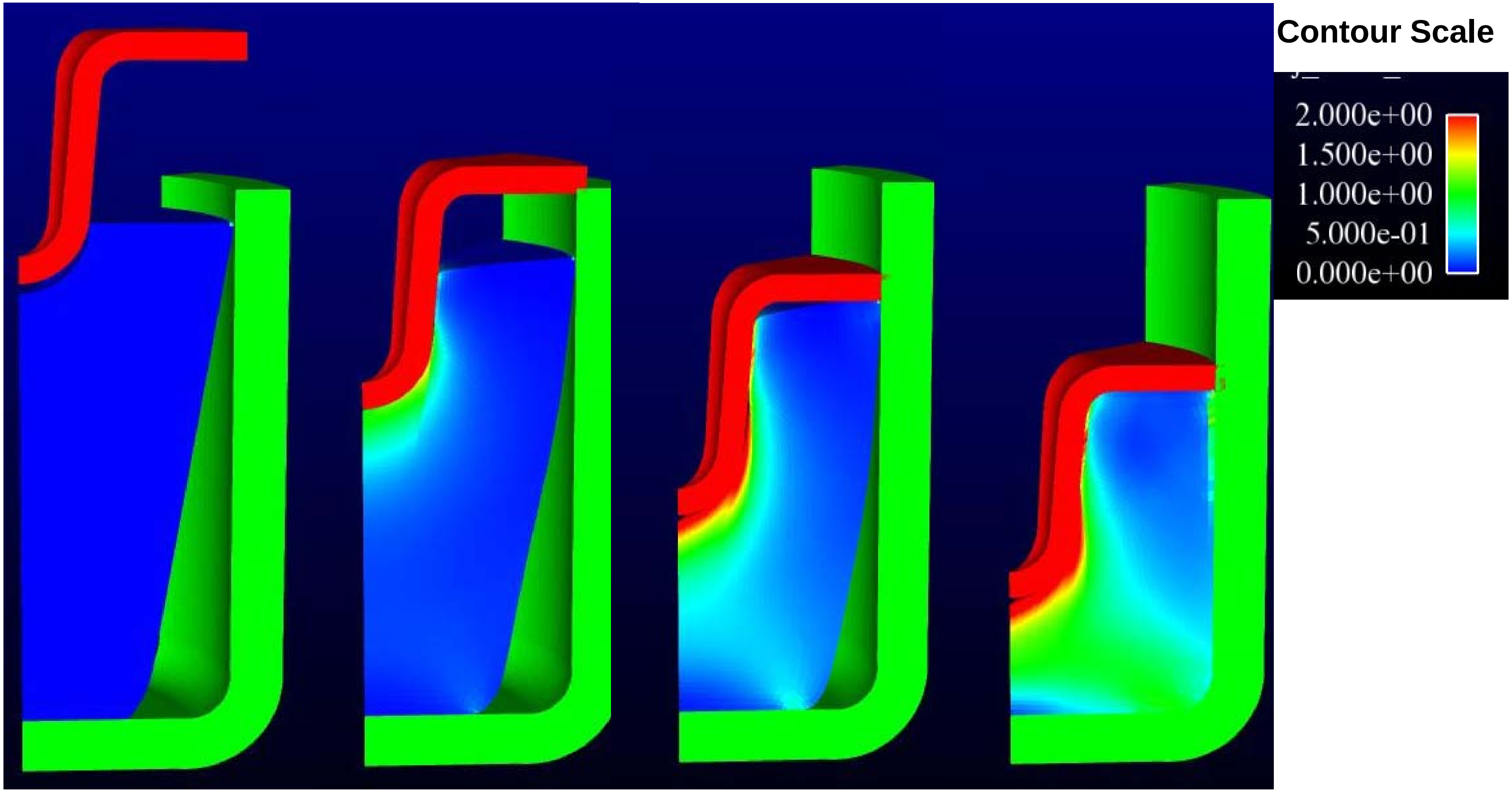




Mesh	Elements
x2	48
x4	408
x8	3,168
x16	25,344
x32	202,752
x64	1,622,016

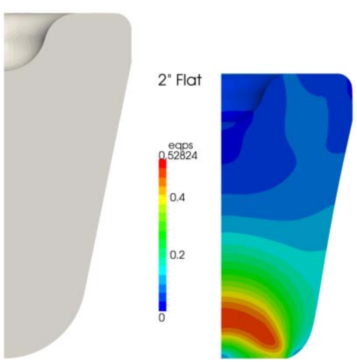
Results from a draft SAND report by Tim Kostka and Arthur Brown

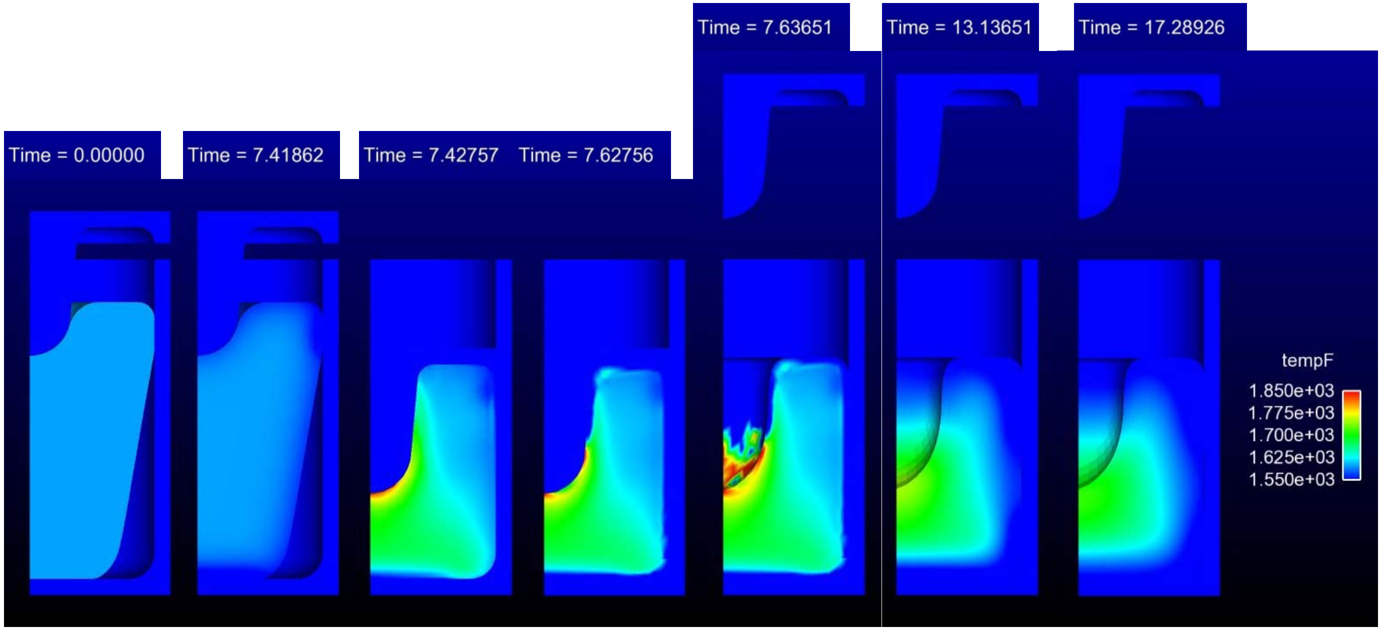
Plastic Strain Evolution During Forging



U-Cup Simulations

- **Coupled thermal-mechanical simulations**
  - Flattening stage is modeled first
    - Top is constrained in radial direction by a die to avoid expansion beyond diameter of final die
  - Output is remeshed for final forging simulation
  - For the final forging stage, convection, radiation, and conduction are modeled

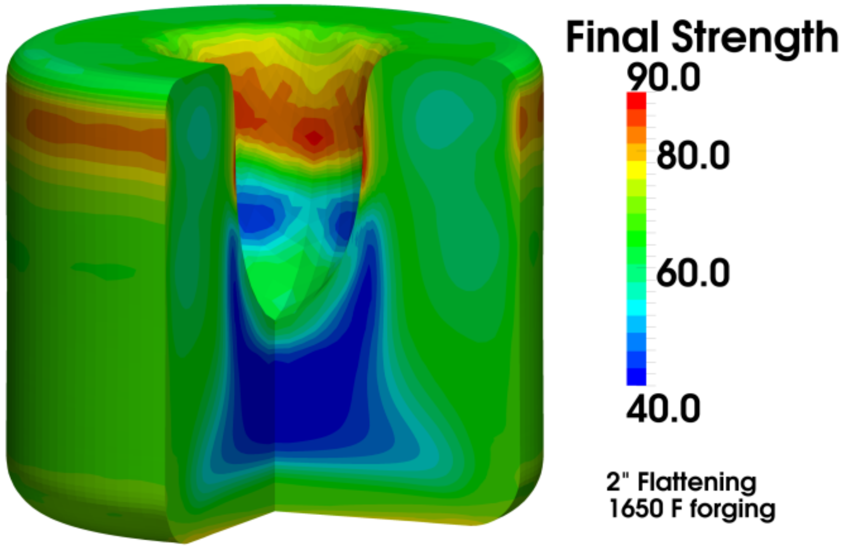




U-Cup Assumptions

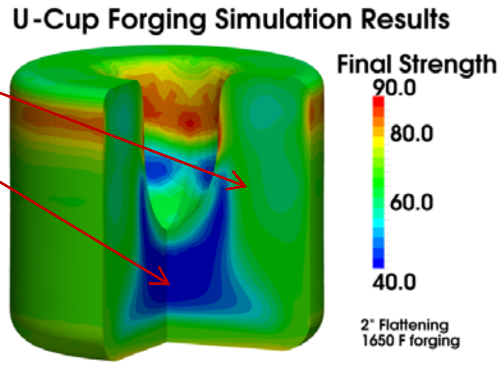
- Dimension variation from sample to sample has negligible effect
- Partial anneal before final stage is assumed to remove all effects from prior temperature/deformation history
- Epistemic uncertainty of 0.5 to 5.5s to remove ingot from die
- Modified corner geometry (used to help with contact) does not impact final strengths at key locations

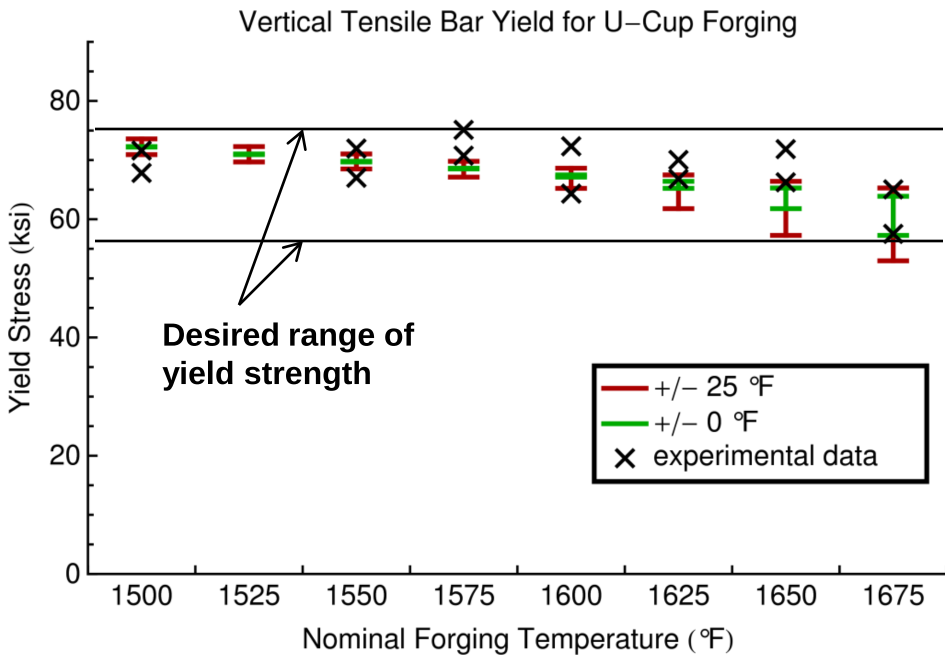
U-Cup Forging Simulation Results

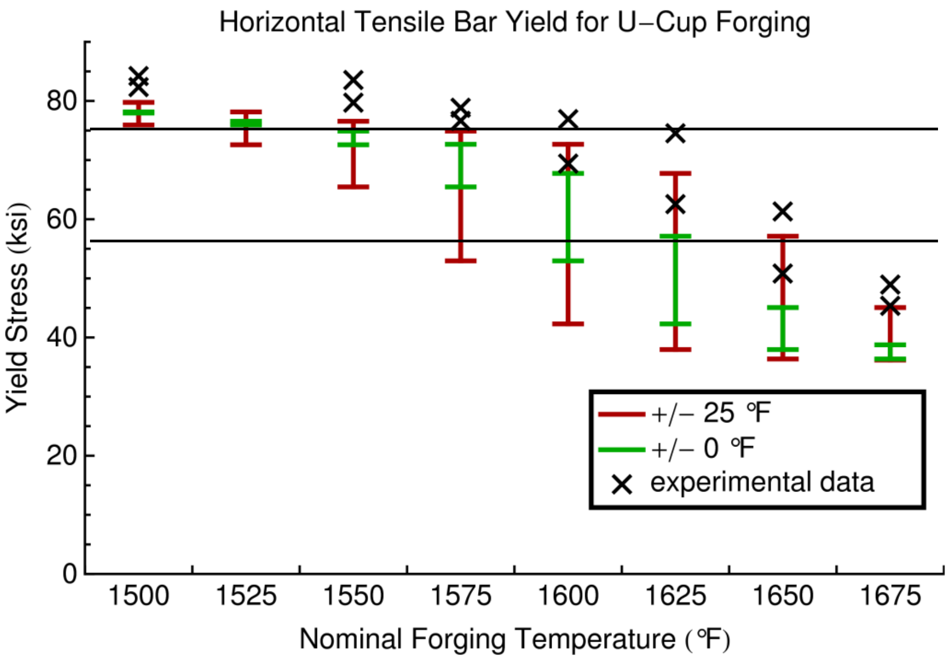


Ucup Forging

- Simulations compared to experimental results in two locations
  - Vertical tensile specimens cut in sidewall
  - Horizontal tensile specimens cut under punch
- Uncertainty largest in high-strain location
  - Due to high rate of recrystallization

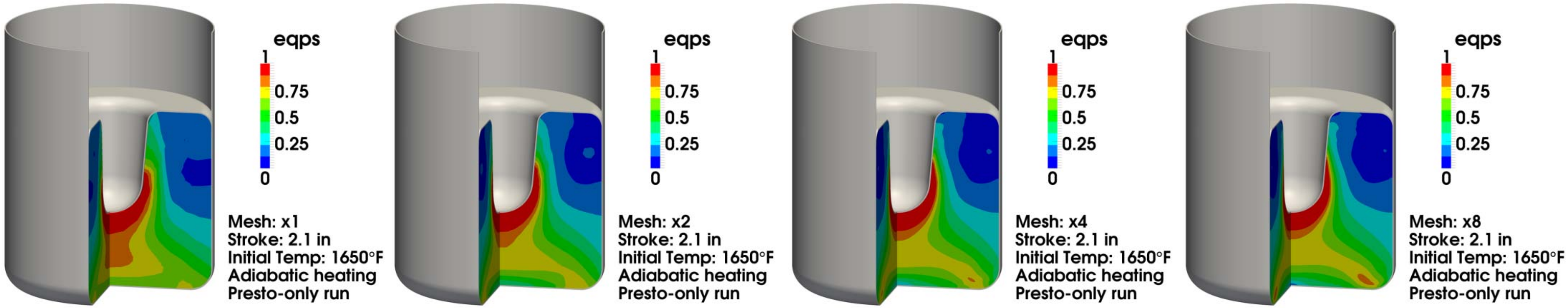




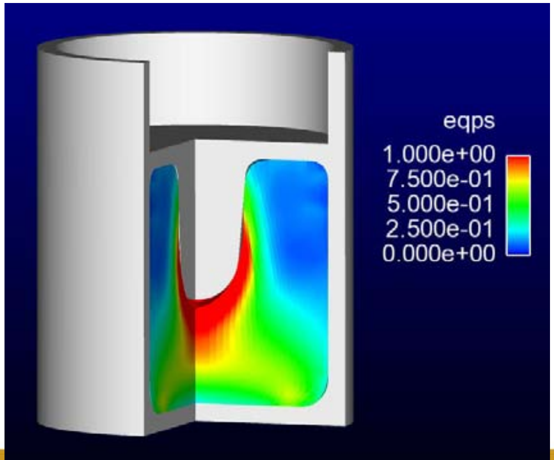


Mesh convergence achieved with Sierra/SM Explicit

Sierra/SM Explicit prediction



Sierra/TFA – Sierra/SM Implicit prediction

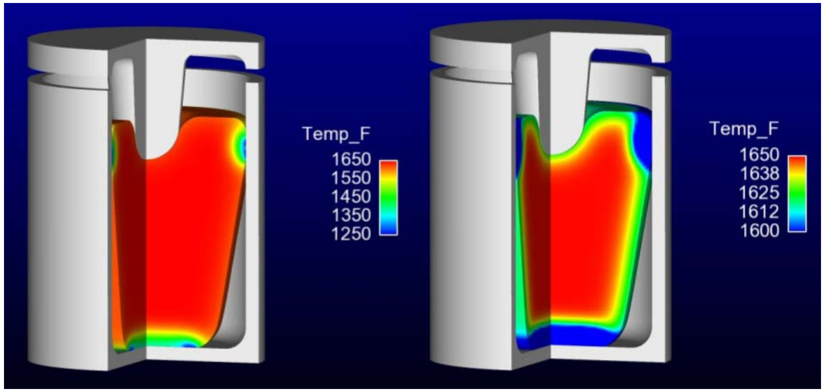


Solutions using refined meshes were not obtained in Sierra/SM Implicit-Sierra/TFA due to solver issues (failed to converge)

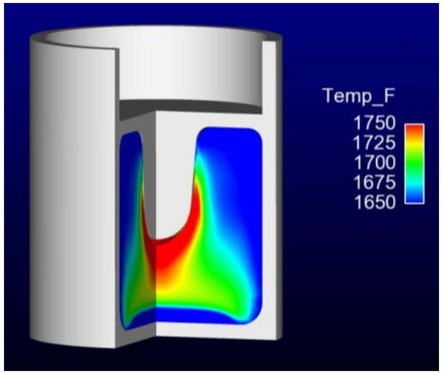
Temperature states in Sierra/SM (Implicit and Explicit)

- Initial temperature before forging is different, since Sierra/SM Explicit runs neglect the effects of die chill
- Previous sensitivity studies showed that die chill played a minimal role in determining the final strength

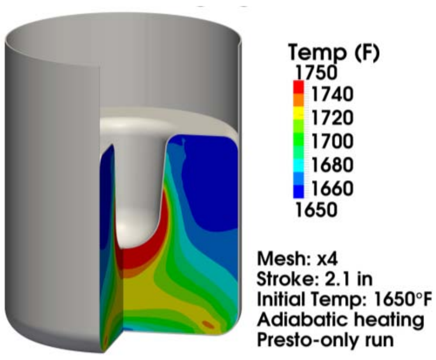
Initial temperatures right before forging in Sierra/SM (Implicit) – Sierra/TFA



Temperatures right after forging in Sierra/SM (Implicit) – Sierra/TFA

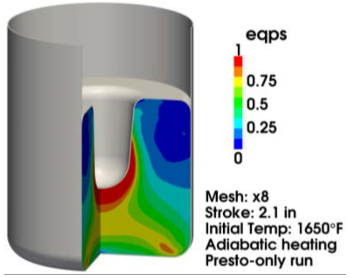


Temperatures right after forging in Sierra/SM Explicit

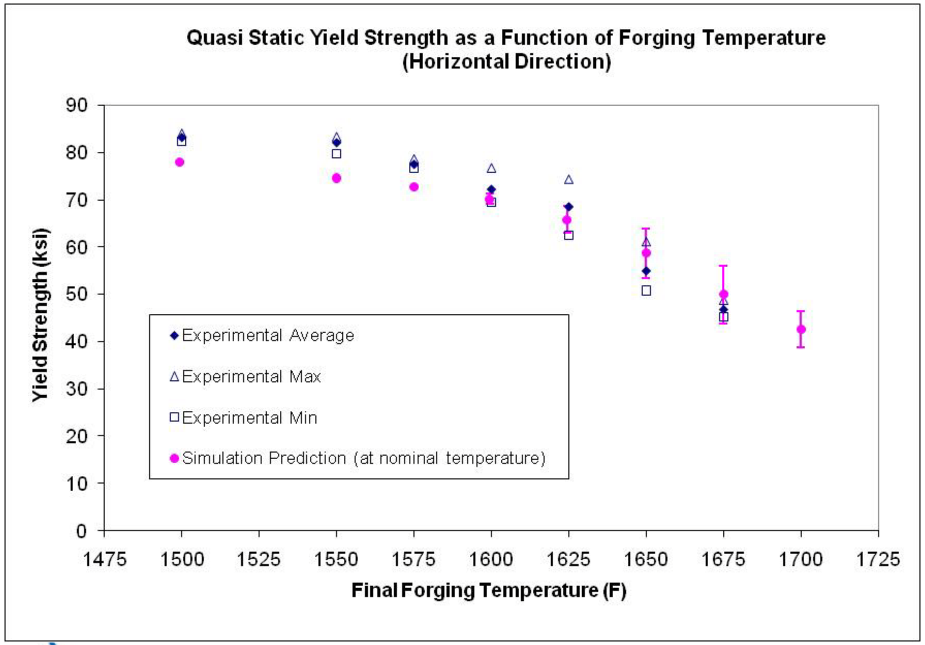


Sierra/SM Explicit Results

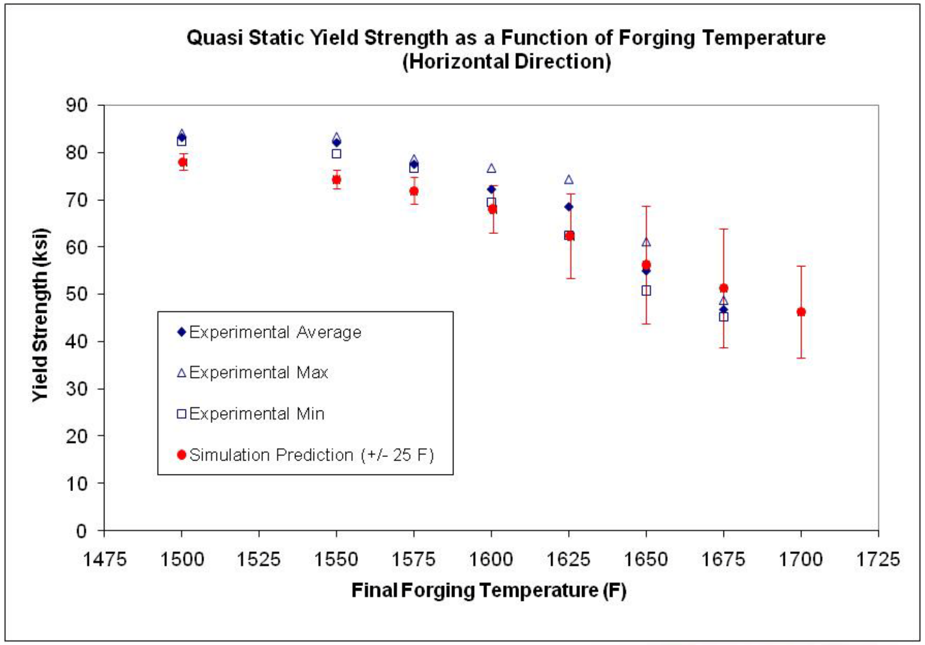
- **Ucup final strengths look much better using Sierra/SM Explicit strains**
- **When Sierra/TFA – Sierra/SM Explicit coupling is functional, these will be rerun to increase accuracy**



Uncertainties in times for each portion of ingot history

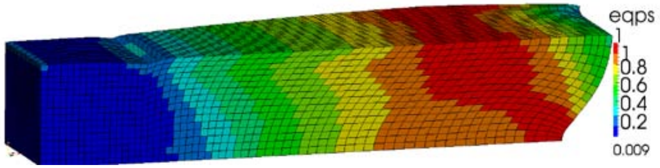


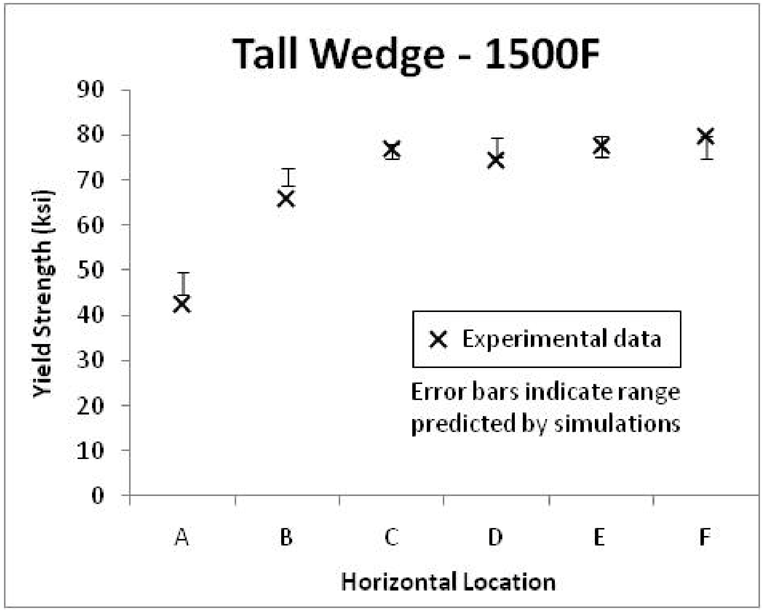
Here, the error bars also include an uncertainty in forging temperature of +/- 25 degrees Fahrenheit

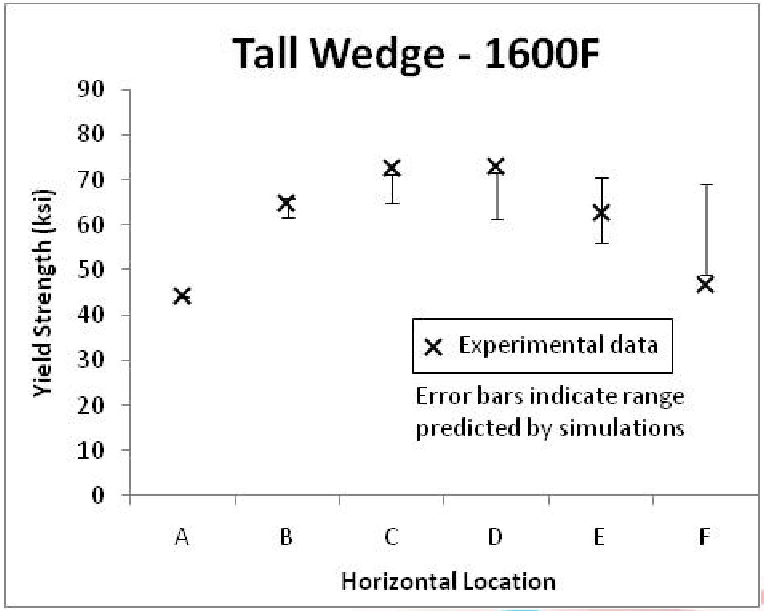


Sierra/SM Explicit Wedge Results

- **Wedge results also differ by using Sierra/SM Explicit**
- **When Sierra/TFA – Sierra/SM Explicit coupling is functional, these will be rerun to increase accuracy**

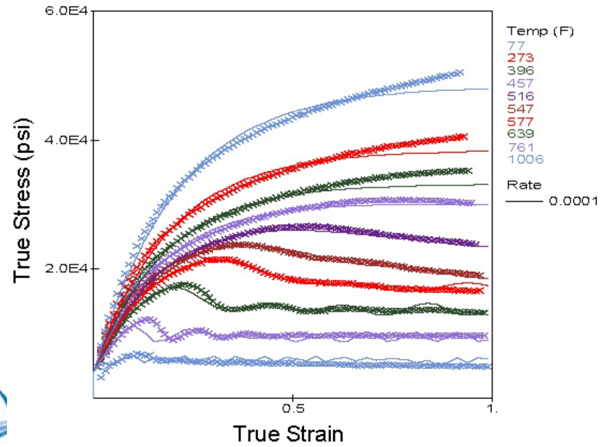


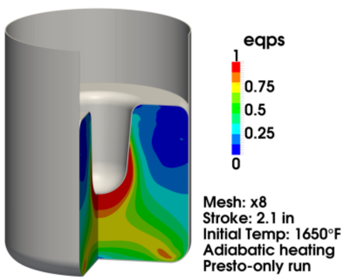


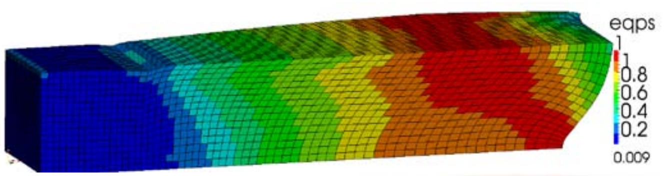


Summary

- Project is a good example of tight integration between P&EM, V&V, IC, C6, and DSW
- A constitutive model for recrystallization has been presented
- It is shown to predict both static and dynamic recrystallization with fairly good accuracy over a range of temperatures and strain rates
- Simulations need to be rerun with recent fixes to implicit contact
- Sierra/TFA – Sierra/SM Explicit for will be used for thermal-mechanical simulations with contact once it is functional until new contact formulation is completed in Sierra/SM Implicit







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