SAND2022-8379C

LDRD
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Sandia National Laboratories

Exceptional service in the national interest

Beyond Beta: Modeling Plastic Heat Generation

US National Congress on Theoretical and Applied Mechanics, Austin, TX, June 24, 2022

B. T. Lester, B. Talamini, K. Karlson, T. Ivanoff, W. Hodges, L. Phinney, and A. Jones

Sandia National Laboratories

SAND2022-XXXXP

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

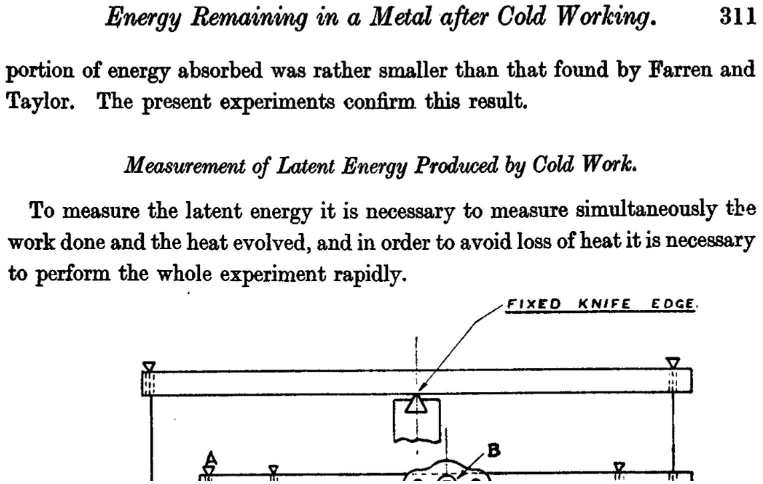
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

U.S. DEPARTMENT OF ENERGY
NNSA

Heat Generation via Plastic Work

- Heat generation during plastic work is a long studied problem
  - o Taylor and Quinney (1934) first measured ~90% of plastic work dissipated
  - o More recent studies show range of values

- Accurately capturing heating effects essential for mechanical prediction
  - o Thermal softening during failure
  - o Adiabatic shear banding



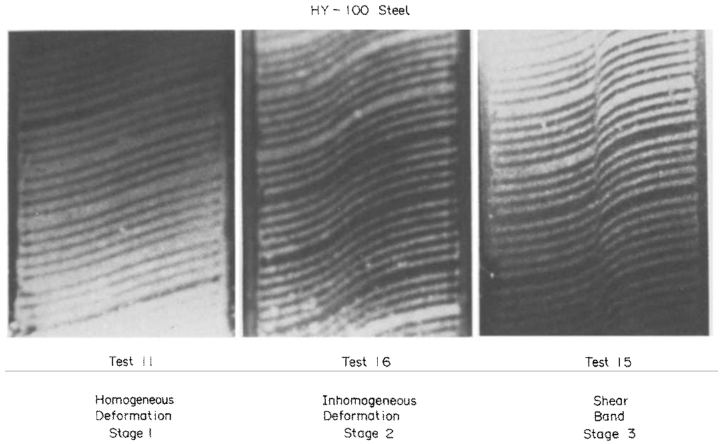
Energy Remaining in a Metal after Cold Working. 311

portion of energy absorbed was rather smaller than that found by Farren and Taylor. The present experiments confirm this result.

Measurement of Latent Energy Produced by Cold Work.

To measure the latent energy it is necessary to measure simultaneously the work done and the heat evolved, and in order to avoid loss of heat it is necessary to perform the whole experiment rapidly.

Taylor and Quinney, 1934, *PRSA*, 143(849), pp. 307-326



Marchand and Duffy, 1988, *JMPS*, 36(3), pp. 251-283

Characterization and Prediction of Plasticity Induced Heat Generation

- In their original work, Taylor and Quinney first proposed assuming a constant fraction of plastic work is converted to heat

- Subsequent experiments have shown large range of values depending on many things
  - Loading mode
  - Microstructure (grain size)
  - State variables (plastic strain, plastic strain rate, and temperature)

- A number of approaches have been proposed/investigated but improved modeling remains an open question

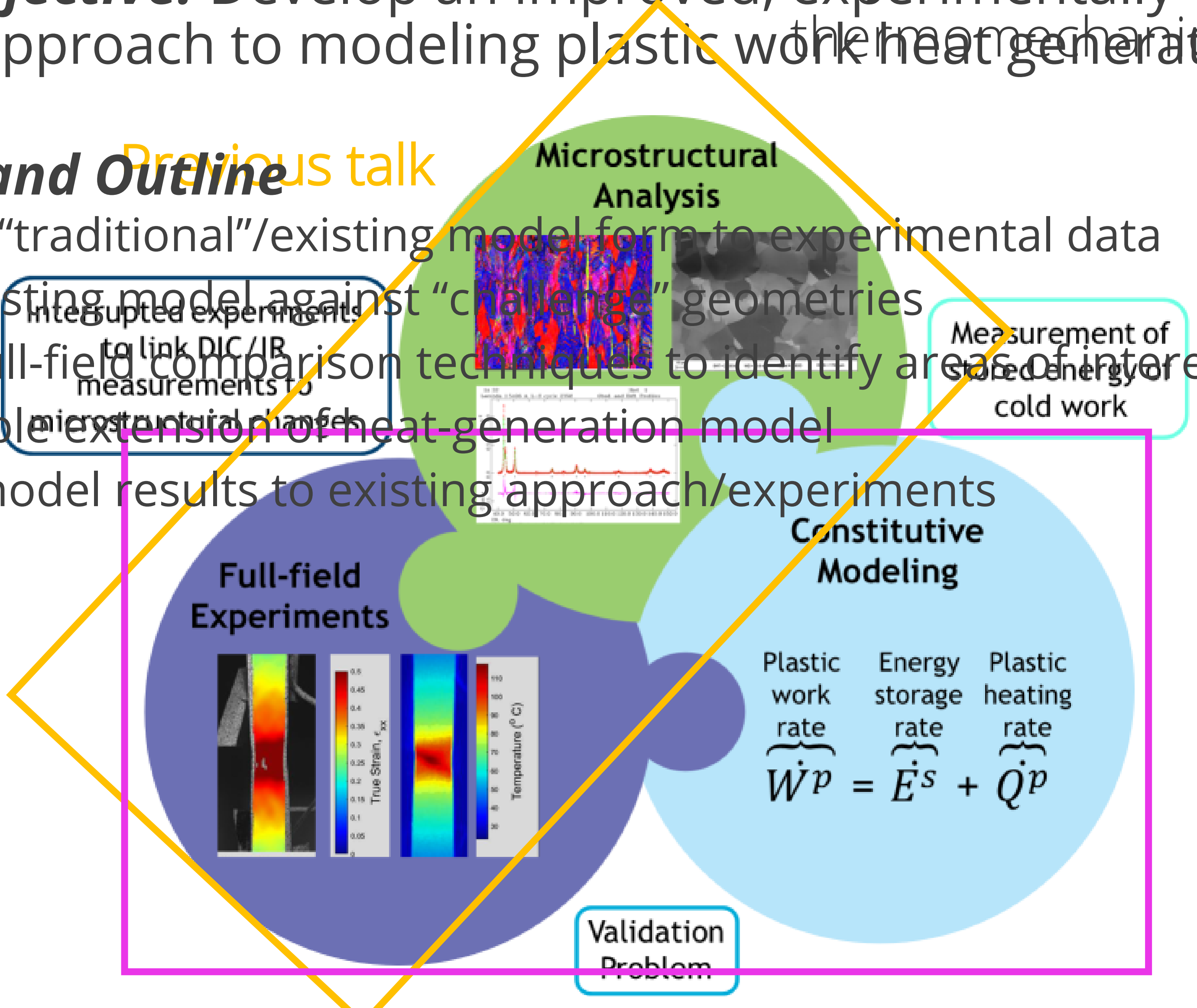
Objective

- ***Current Objective:*** Develop an improved, experimentally-informed approach to modeling plastic work heat generation

"*BeyondBeta*" – A full understanding of thermomechanical coupling

- ***Approach and Outline***
  - Calibrate a "traditional"/existing model form to experimental data
  - Validate existing model against "challenge" geometries
  - Leverage full-field comparison techniques to identify areas of interest
  - Create simple extension of heat-generation model
  - Compare model results to existing approach/experiments

Previous talk



This talk

Material and Model

- Material considered is SS 304L-VAR 7.5” bar stock
  - Rate and temperature dependent
  - (Relatively) poor conductor to emphasize impact of heating

- Modeled via isotropic hardening, isotropic yield, rate and temperature dependent plasticity

$$\sigma_{ij} = \mathbb{C}_{ijkl}(T)\left(\varepsilon_{kl} - \varepsilon^{\mathrm{p}}_{kl} - \varepsilon^{\mathrm{th}}_{kl}\right)$$

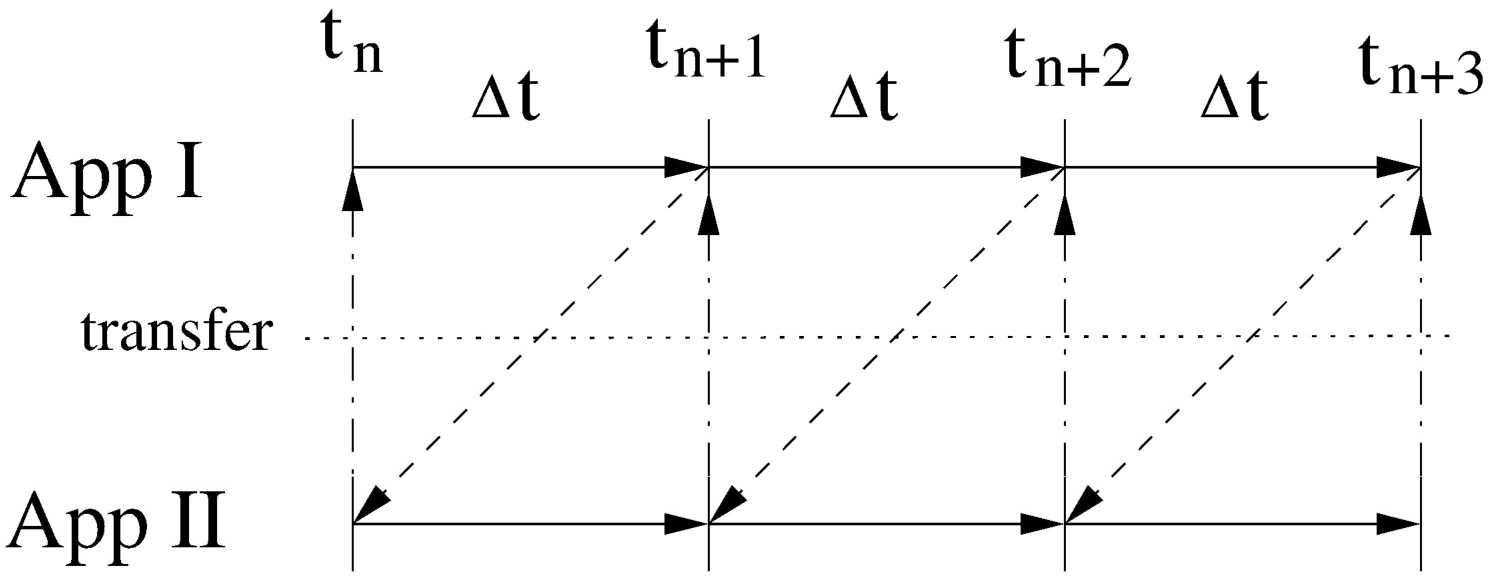
$$f\left(\sigma_{ij}, \bar{\varepsilon}^{\mathrm{p}}, \dot{\bar{\varepsilon}}^{\mathrm{p}}, T\right) = \phi\left(\sigma_{ij}\right) - \sigma_y\left(\bar{\varepsilon}^{\mathrm{p}}, \dot{\bar{\varepsilon}}^{\mathrm{p}}, T\right)$$

$$\sigma_y\left(\bar{\varepsilon}^{\mathrm{p}}, \dot{\bar{\varepsilon}}^{\mathrm{p}}, T\right) = \sigma^0_y \hat{\sigma}_y\left(\dot{\bar{\varepsilon}}^{\mathrm{p}}\right)\tilde{\sigma}_y(T) + A\left(1 - \exp\left(-n\bar{\varepsilon}^{\mathrm{p}}\right)\right)$$

$$r^{\mathrm{TQ}} = \beta \sigma_{ij} \dot{\varepsilon}^{\mathrm{p}}_{ij}$$

Finite Element Solution Strategy

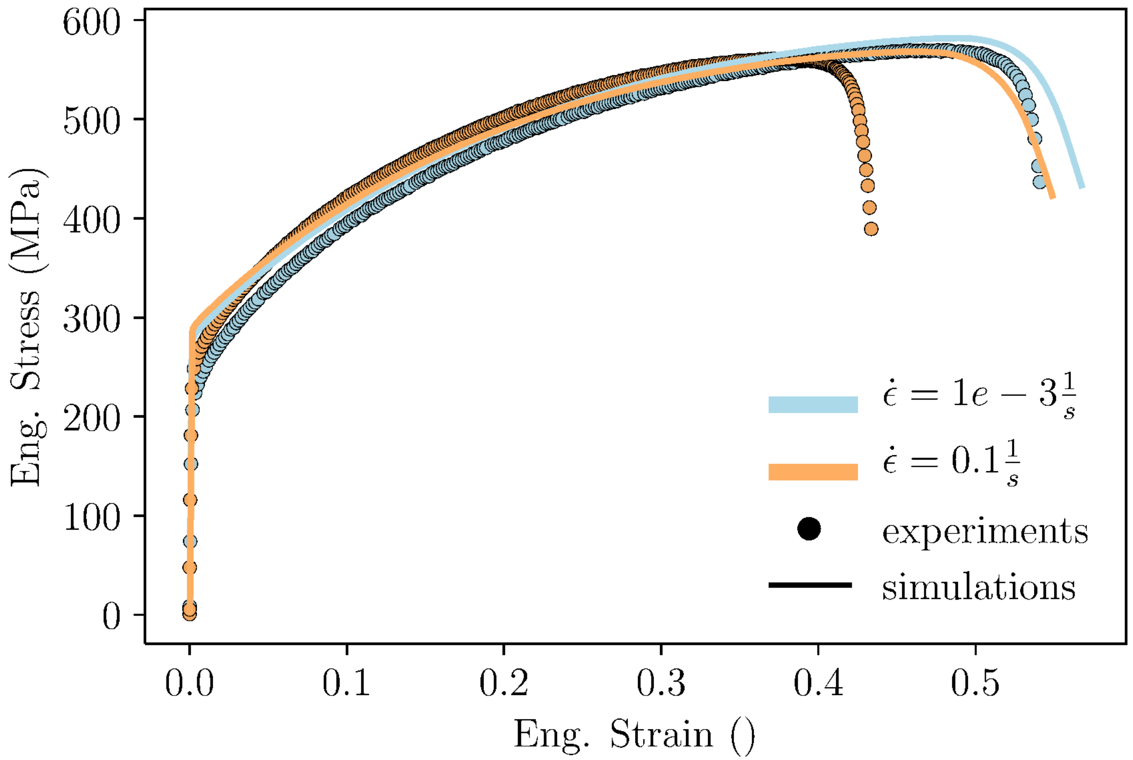
- Sierra/SolidMechanics code used for FE solves
  - Used for adiabatic simulations in which heat transfer is not allowed
- Thermomechanical solves via Arpeggio coupler
  - Coupling code leveraging Sierra/SolidMechanics and Sierra/ThermalFluids
  - "Loose"/Staggered coupling of mechanical and thermal solves



S. Subia et al., *SIERRA Code Coupling Module: Arpeggio User Manual – Version 4.54*, SAND2019-12294

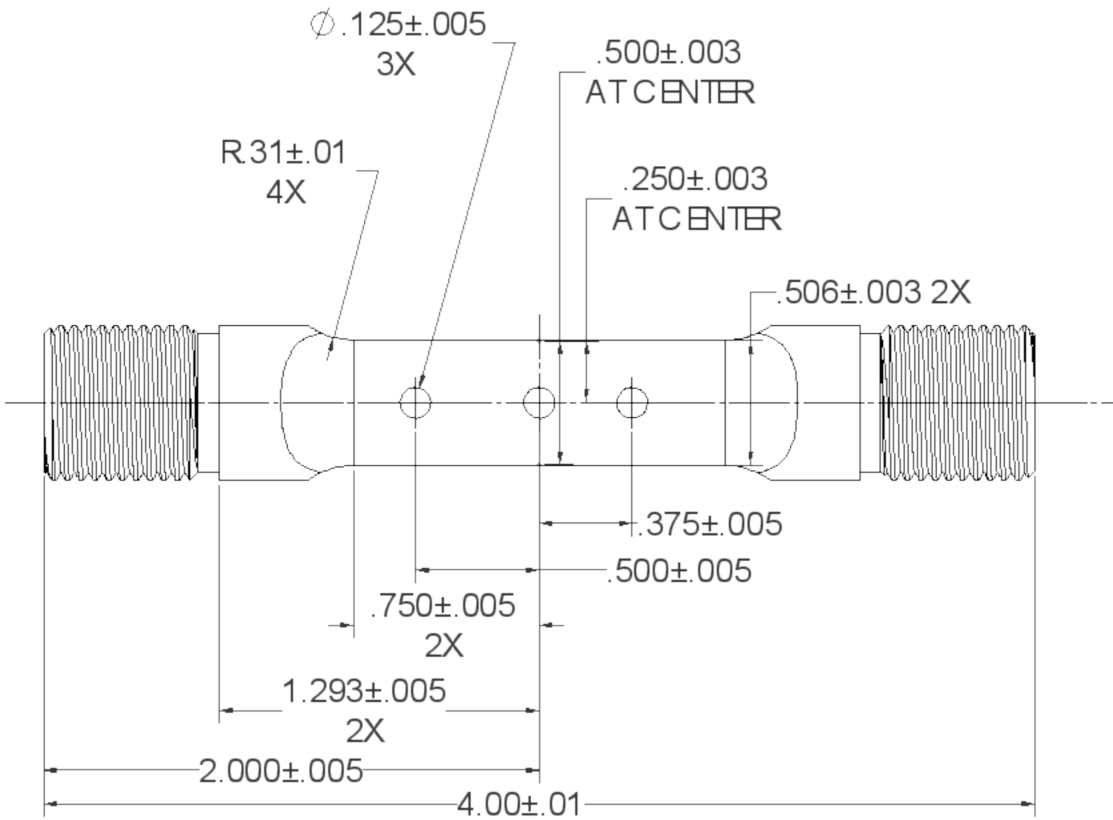
Model Calibration

- Calibration of material model done via FEMU approach
  - Internal tool “MatCal” used
  - Combines Sierra FE solver and Dakota UQ package
- Supplemental data from unrelated characterization of same material also used
- Thermal dependence found from literature
  - MMPDS data



Validation Problem & Geometry

- Investigate response with "Three-hole punch" specimens
- Uniaxial stress mechanical loading
  - All specimens initially at RT
  - Slow (1E-3 /s) and Fast (1E-1 /s) rates
  - Thermal BCs*
    - Interior surfaces adiabatic
    - Top and bottom via equivalent flux
    - Convection on rest of outer surfaces



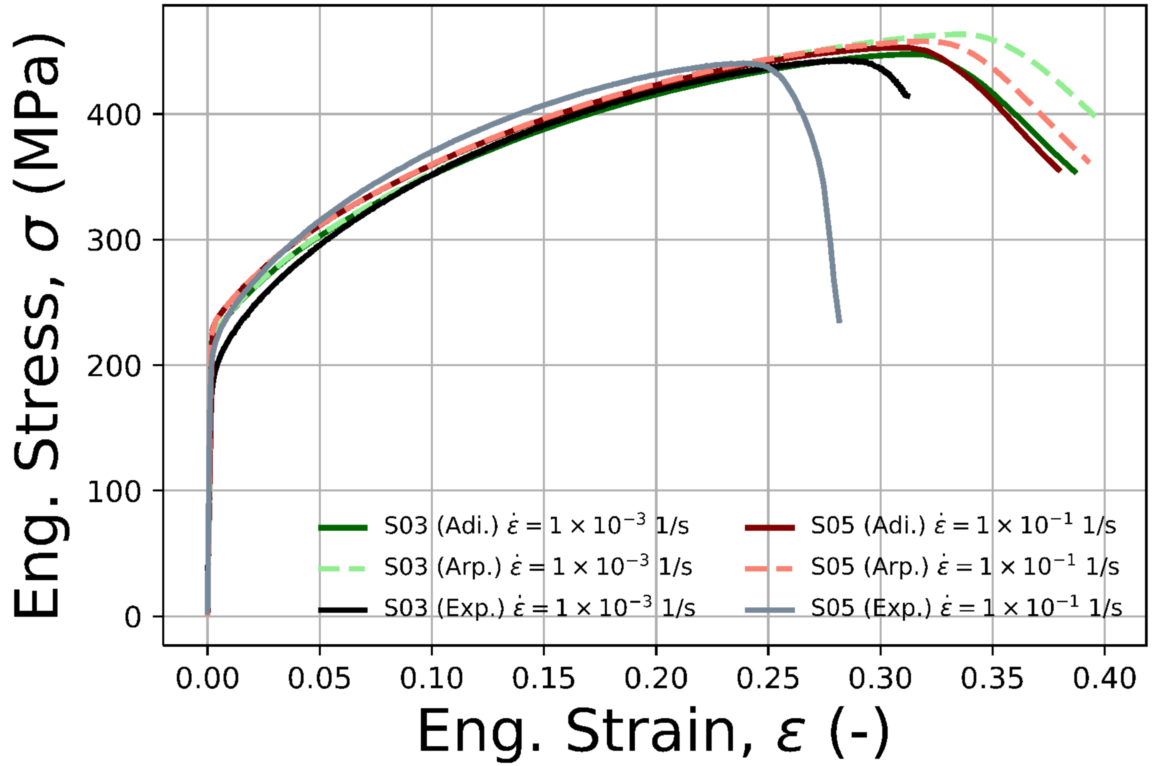
All dimensions in inches

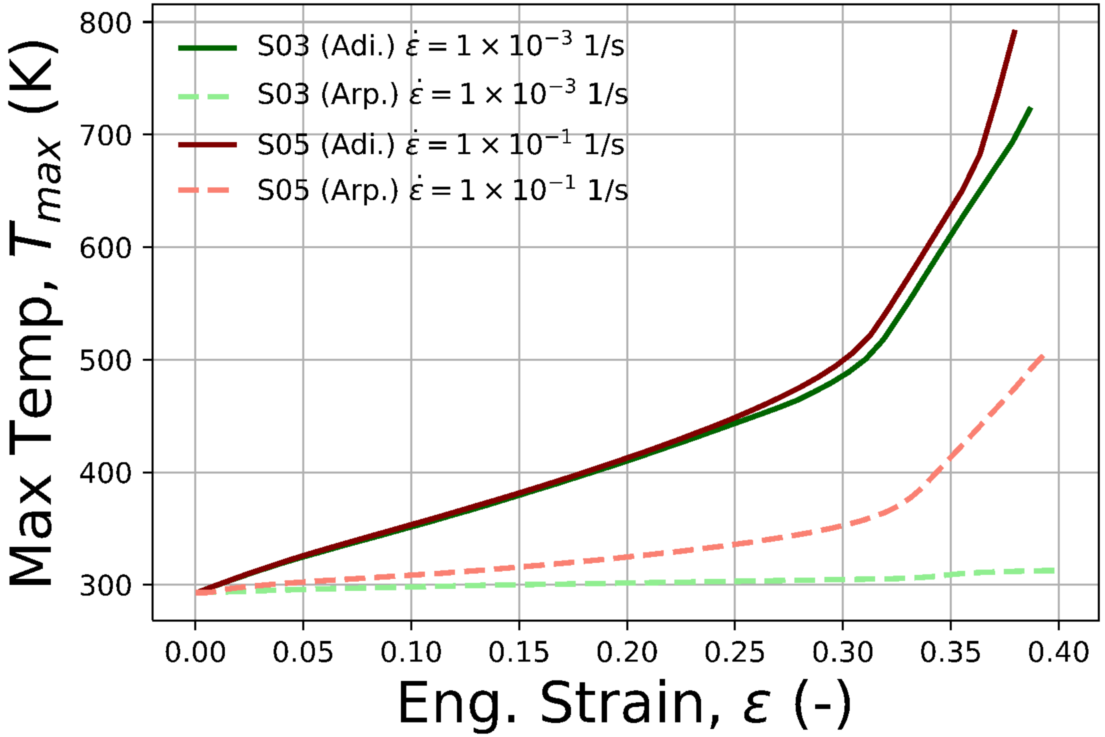
0.2" thick in center

*See W. Hodges et al. https://doi.org/10.1115/IMECE2021-68479

Global Metric Comparison

- Larger temperatures leader to smaller strain to failure
- Cases :
  - ”Adi.” -> adiabatic
  - “Arp.” -> coupled/Arpeggio

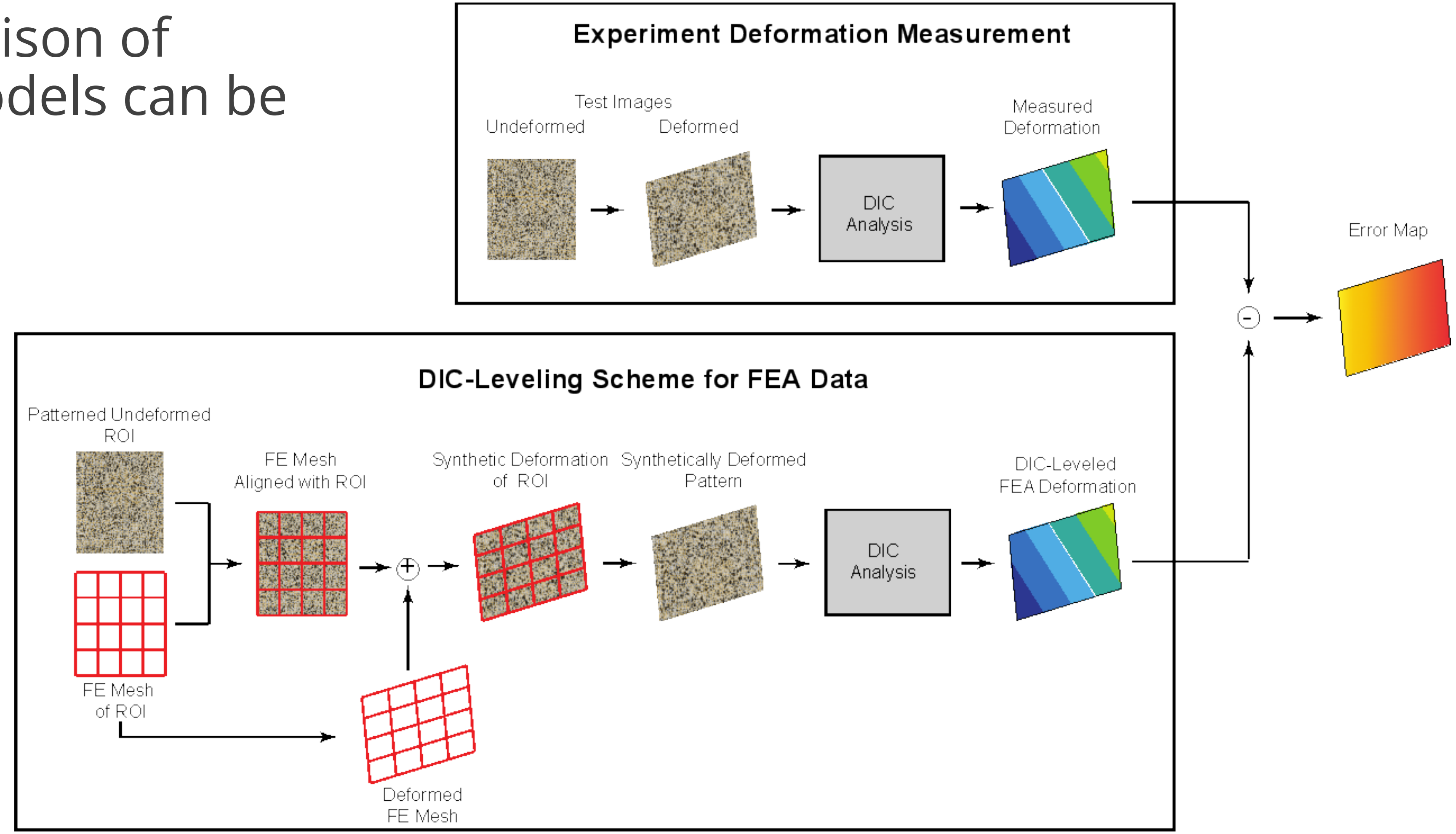




Leveling Approach Explained

- Quantitative comparison of experiments and models can be challenging

MatchID
Metrology beyond colors

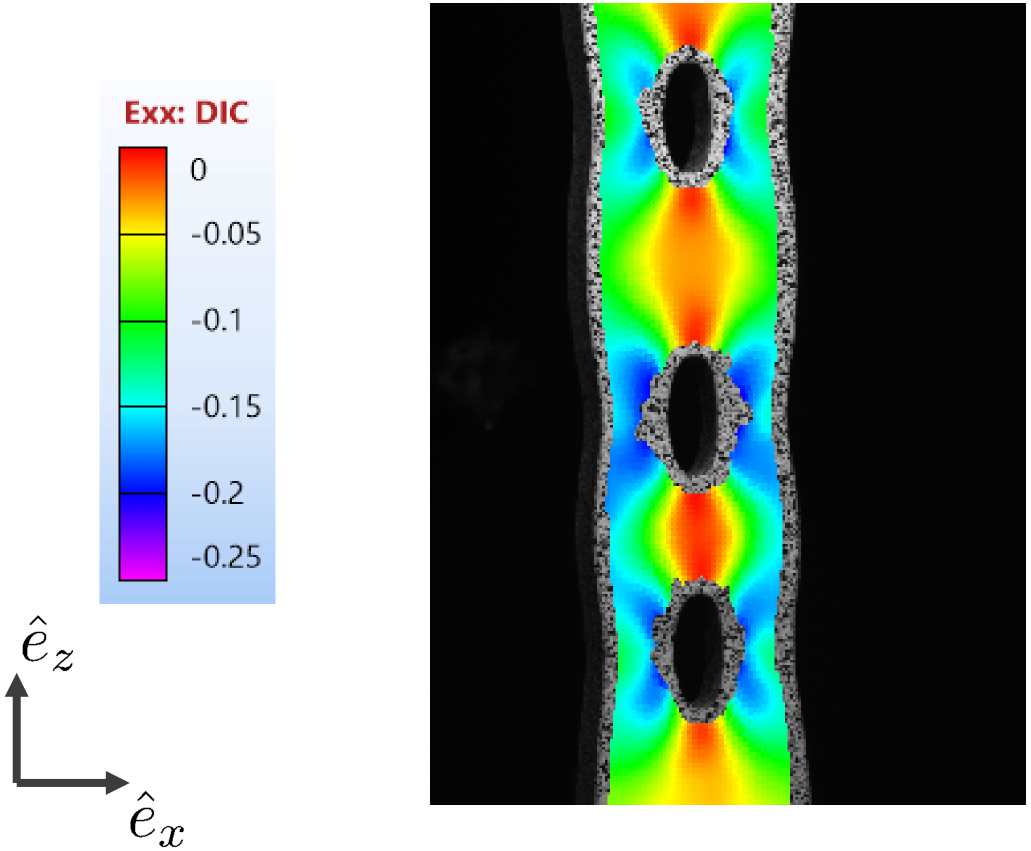


E. Jones et al., 2021, *IJSS*, 213, pp. 148--166

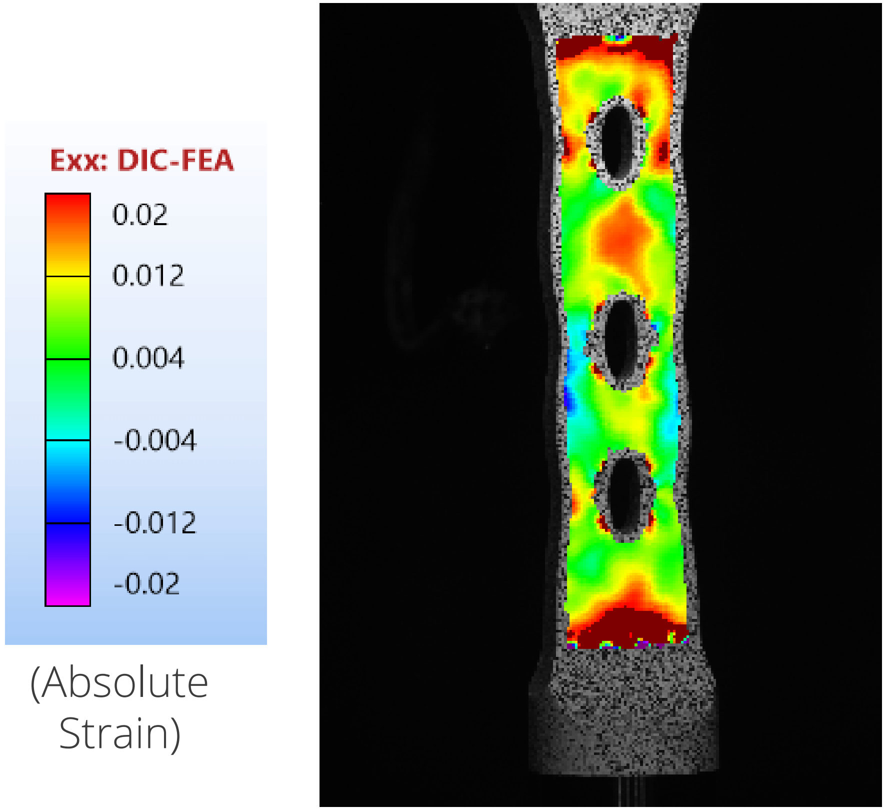
S03 Field/Leveling Comparison (Slow Rate)

- Generally reasonable agreement between results
- Differences more pronounced between “top” holes than bottom

Experimental Results



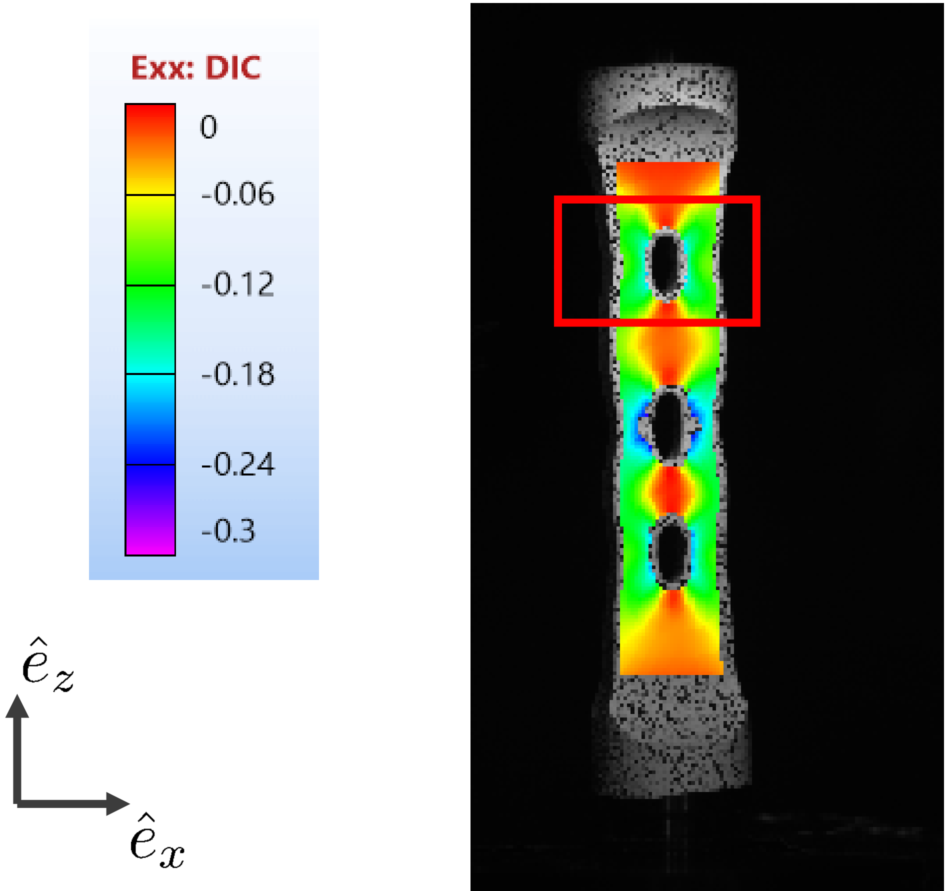
Difference Fields (Exp. – Sim.)



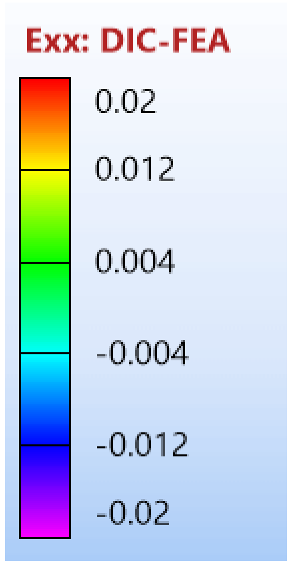
S05 Field/Leveling Comparison (Fast Rate)

- Fast rates seem to show higher differences than slow
- Still same asymmetry in the feature gaps

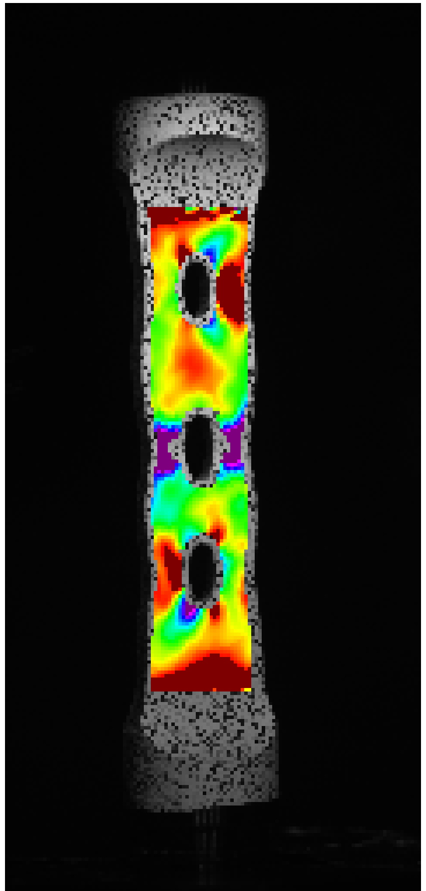
Experimental Results



Difference Fields (Exp. – Sim.)



(Absolute Strain)



Extension of TQ Factor

- With data, now need to consider how to use and improve descriptions
  - Develop tools for quantitative analysis of experiments
  - New theory basis

- To address first, going to assume functional form of TQ coefficient

$$\bar{\beta} = \beta \breve{f}\left(\bar{\varepsilon}^{\mathrm{p}}\right) \hat{f}\left(\dot{\bar{\varepsilon}}^{\mathrm{p}}\right) \tilde{f}\left(T\right)$$

- Going to assume forms and values from simple theory approximations
  - Allow for quantitative comparisons to start isolating functional dependencies
  - Literature reports different qualitative behaviors
  - Possible forms are material specific

State Dependence Theory

- Assume relationships aligned with calibrated model
  - Isotropic hardening w/ temperature dependent thermoelasticity

$$\psi\left(\varepsilon_{ij}, T, \varepsilon_{ij}^{\mathrm{p}}, \bar{\varepsilon}^{\mathrm{p}}\right) = \psi^{\mathrm{te}}\left(\varepsilon_{ij}, \varepsilon_{ij}^{\mathrm{p}}, T\right) + \psi^{\mathrm{p}}\left(\bar{\varepsilon}^{\mathrm{p}}\right)$$

  - Yield surface

$$f\left(\sigma_{ij}, \bar{\varepsilon}^{\mathrm{p}}, \dot{\bar{\varepsilon}}^{\mathrm{p}}, T\right) = \phi\left(\sigma_{ij}\right) - \left(\sigma_y^0 \hat{\sigma}_y\left(\dot{\bar{\varepsilon}}^{\mathrm{p}}\right) \tilde{\sigma}_y\left(T\right) + A\left(1 - \exp\left(-n\bar{\varepsilon}^{\mathrm{p}}\right)\right)\right)$$

- Assume maximum dissipation

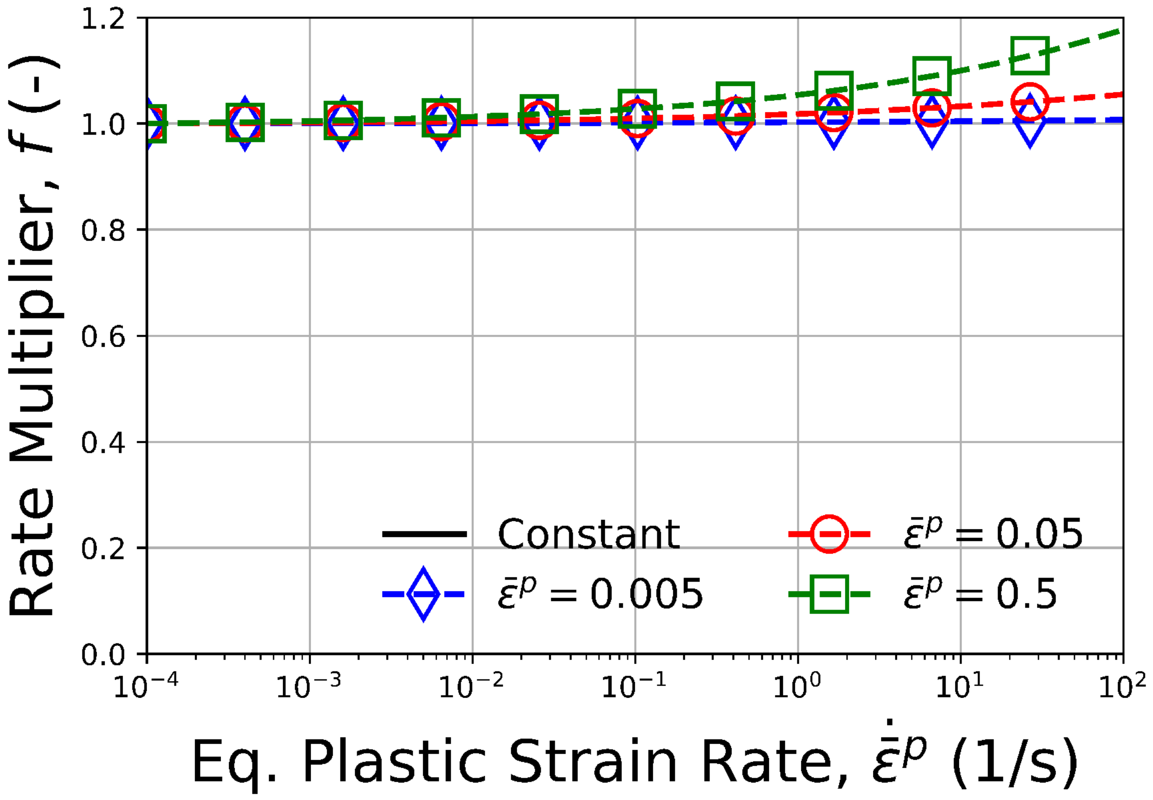
$$\mathcal{D} = \sigma_y^0 \hat{\sigma}_y\left(\dot{\bar{\varepsilon}}^{\mathrm{p}}\right) \tilde{\sigma}_y\left(T\right) \dot{\bar{\varepsilon}}^{\mathrm{p}}$$

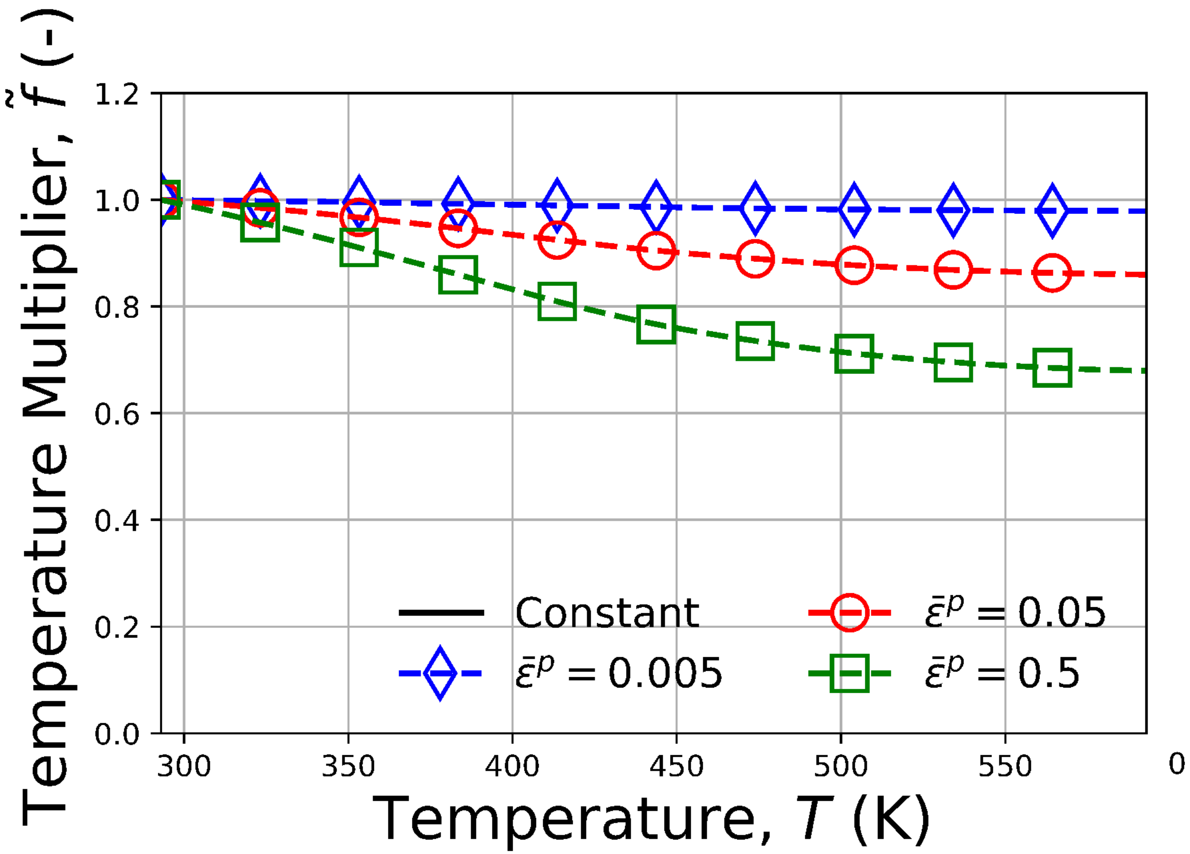
$$\bar{\beta} \approx \frac{\mathcal{D}}{\sigma_{ij}\dot{\varepsilon}_{ij}^{\mathrm{p}}} = \frac{\sigma_y^0 \hat{\sigma}_y \tilde{\sigma}_y}{\sigma_y^0 \hat{\sigma}_y \tilde{\sigma}_y + A\left(1 - \exp\left(-n\bar{\varepsilon}^{\mathrm{p}}\right)\right)}$$

These forms and results highly dependent on assumptions

Dependence Determination

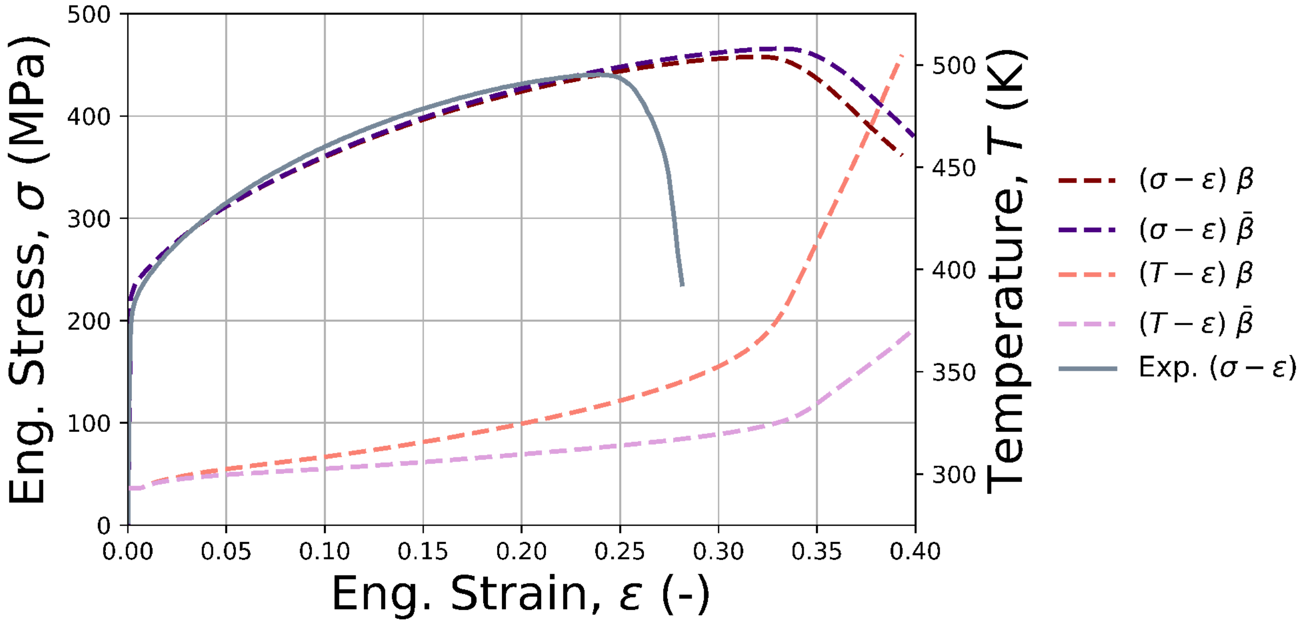
- Directly evaluate $\bar{\beta}$ and fit functions to results





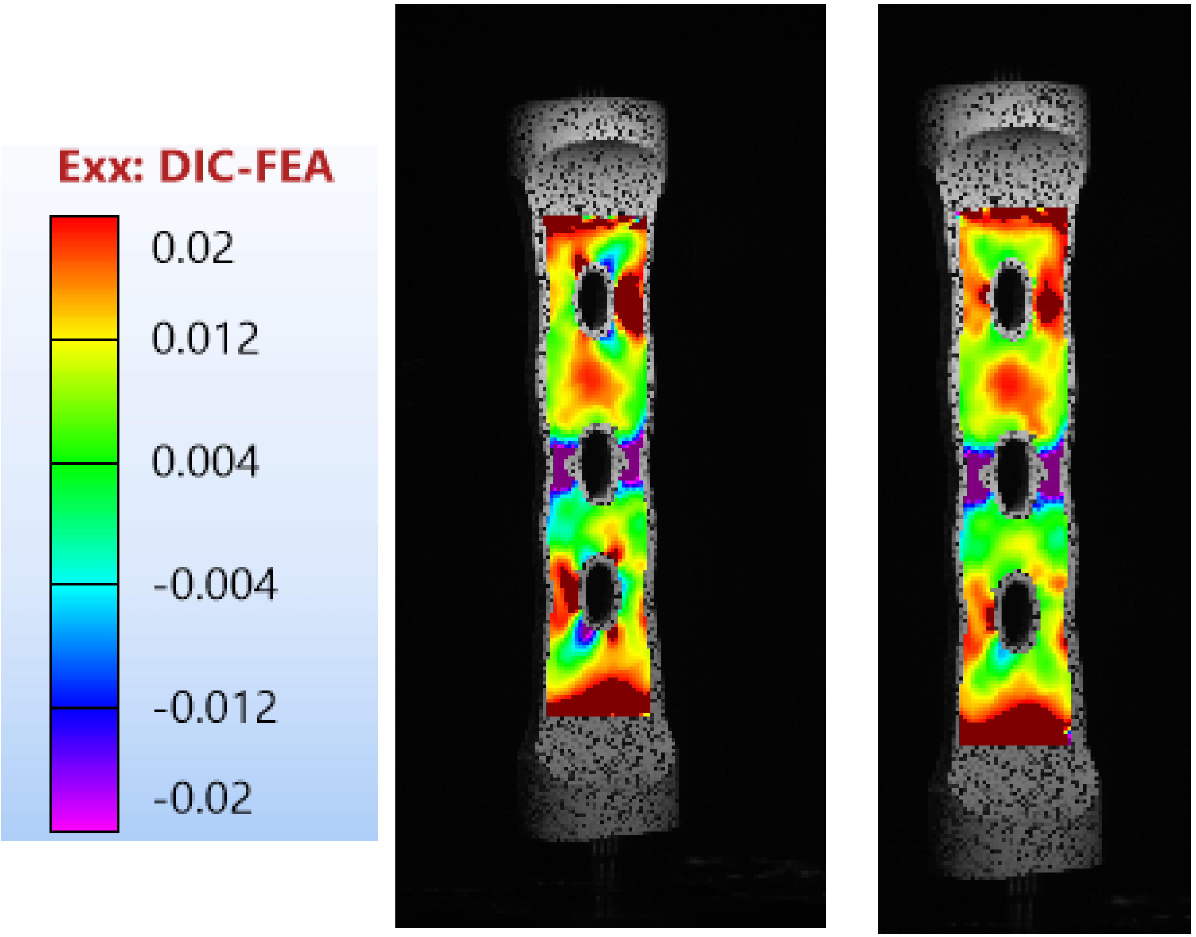
Impact of Constant vs. Variable Coefficient

- Noticeable global and local differences arising from use of variable coefficient



Difference Fields (Exp. – Sim.)

Constant β Variable $\bar{\beta}$



Summary and Conclusions

- Developed thermomechanical models of new experiments with thermal and mechanical models

- Investigating best approaches of direct comparison of results
    - Enables considering model agreement against wider set of states
    - Beginning to probe different functional relationships to identify dependence of coupling coefficient on different state variables

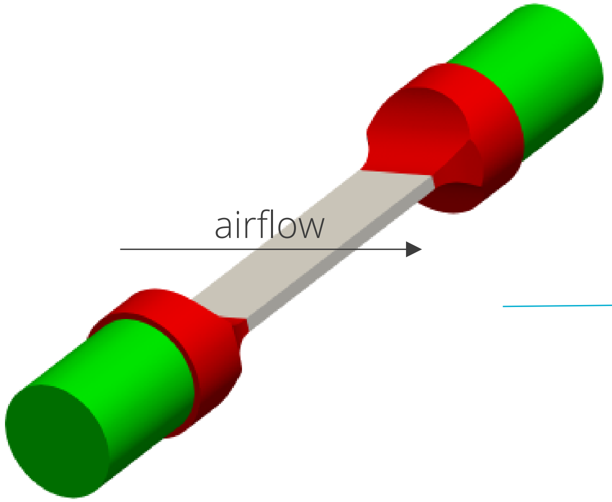
- Working on leveraging results to provide improved modeling capabilities
    - Considering simplified extensions of existing forms
    - Developing new constitutive forms leveraging more concrete thermomechanical bases (in-development)

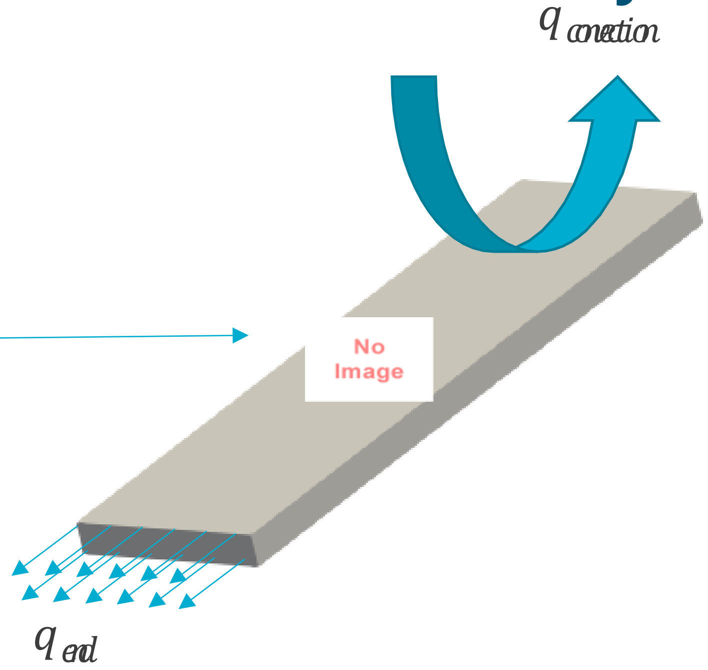
Acknowledgements

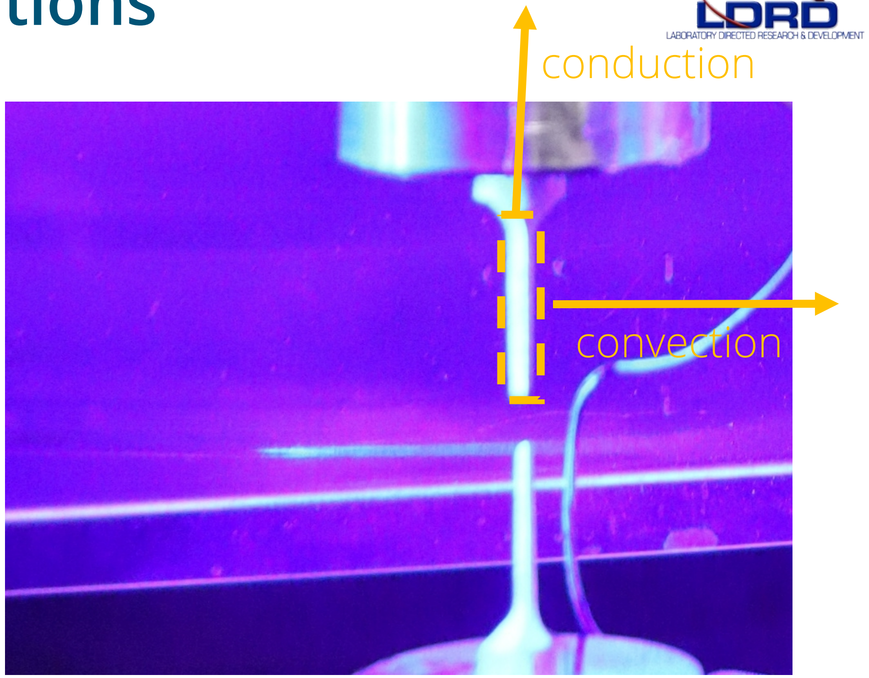
- The work is supported by the Laboratory Directed Research and Development program at Sandia National Laboratories, a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government

APPENDIX

Determination of Thermal Boundary Conditions



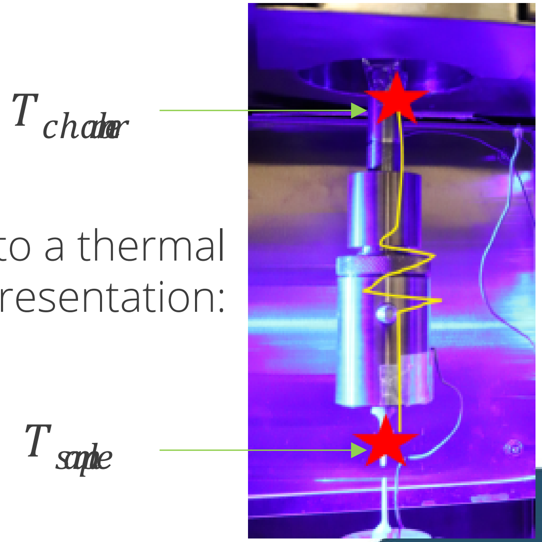




Clamped ends approximated as a convection boundary condition, represents all the heat flowing out the end (by conduction)

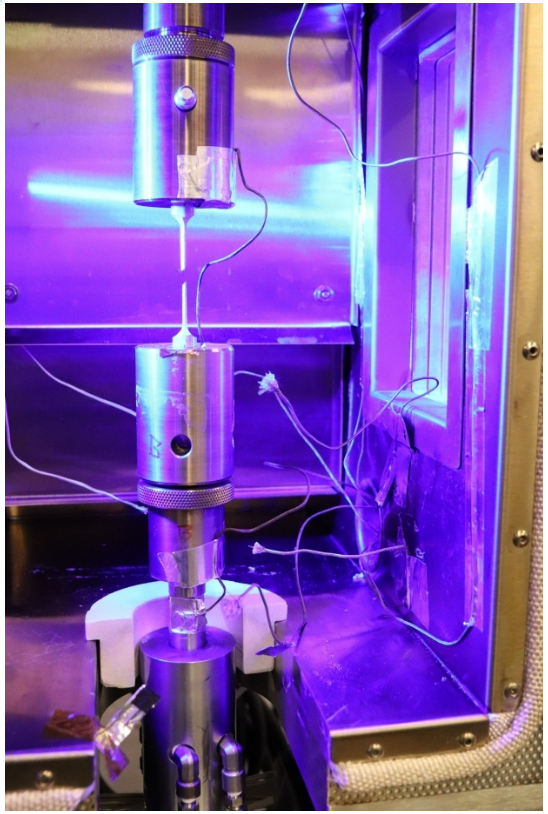
Calculated values from chamber heating data:

This is equivalent to a thermal resistance representation:

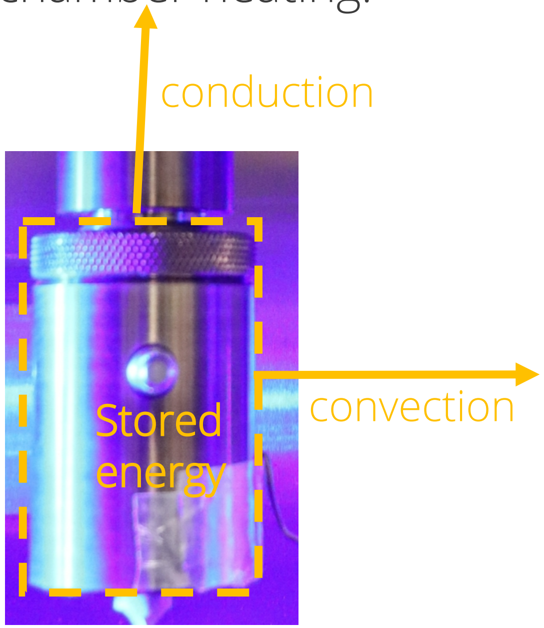


Convection coefficient of chamber

Test chamber:

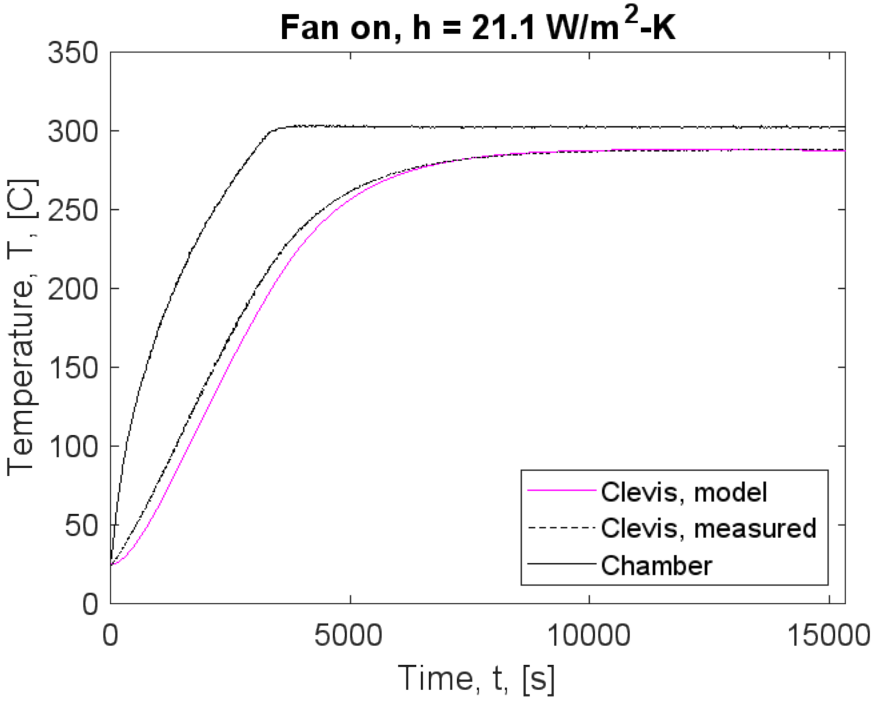


Energy balance on clevis during chamber heating:



Conduction has relatively little importance, convection dominates chamber heating response

Best fit:



Clevis is used due to large thermal mass and reliable data during chamber heating tests.

These results are detailed in Effects of Convection on Experimental Investigation of Heat Generation During Plastic Deformation, by W. Hodges, LM Phinney, B Lester, B Talamini, and A Jones. Presented at ASME IMECE in 2021