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Beyond Beta: Systemic Experimental Investigation of Plastic Heat Generation

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

A. Jones, ***T. Ivanoff*** , C. Loeffler, B. Song, and M. Rodriguez

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SAND2022-XXXXP

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An age-old solid mechanics problem

The Latent Energy Remaining in a Metal after Cold Working.

By G. I. Taylor, F.R.S., Yarrow Professor of the Royal Society, and H. Quinney, M.A.

(Received August 31, 1933.)

A common approach

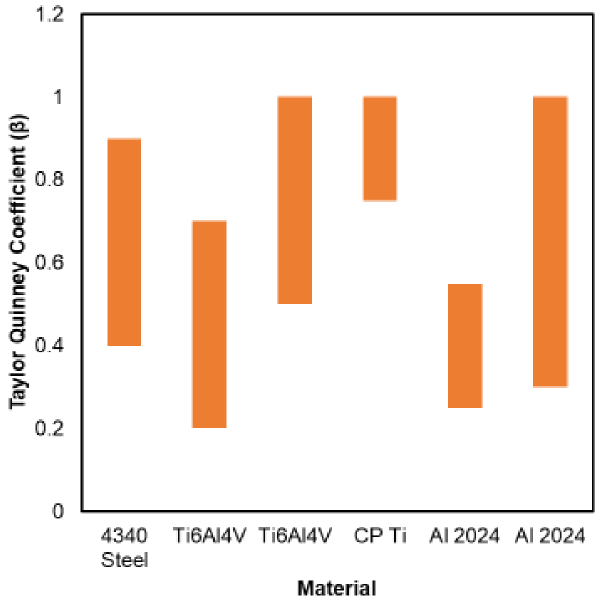
Under adiabatic conditions[1,2] →

$$\beta = \frac{\dot{Q}^p}{\dot{W}^p}$$

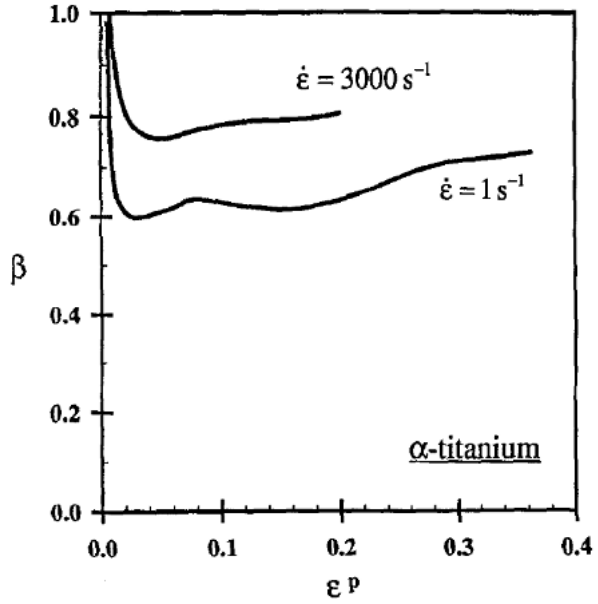
$\dot{Q}^p$=Rate of Heat Generation
$\dot{W}^p$ =Plastic Work Rate

→ Assume β is constant in thermomechanical model

Literature values for β for a range of materials adapted from Rittel, 2017 [3]



β as a function of plastic strain for titanium alloy [1]



[1]Hodowany et al., EM, 2001
[2]Rosiakis et al, JMPS, 2000
[3] Rittel et al, JMPS, 2017

An age-old solid mechanics problem

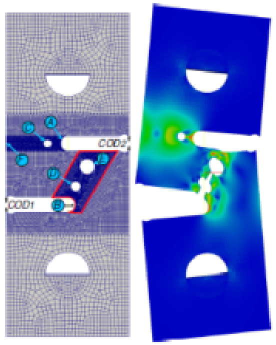
Key Scientific Question: Can we accurately predict thermomechanical behavior (beyond just calibrating the Taylor-Quinney coefficient, β) if we consider a range of strain rates, loading conditions, material classes, thermal environments as well as perform microstructural analysis?

Potential relevant problems include:

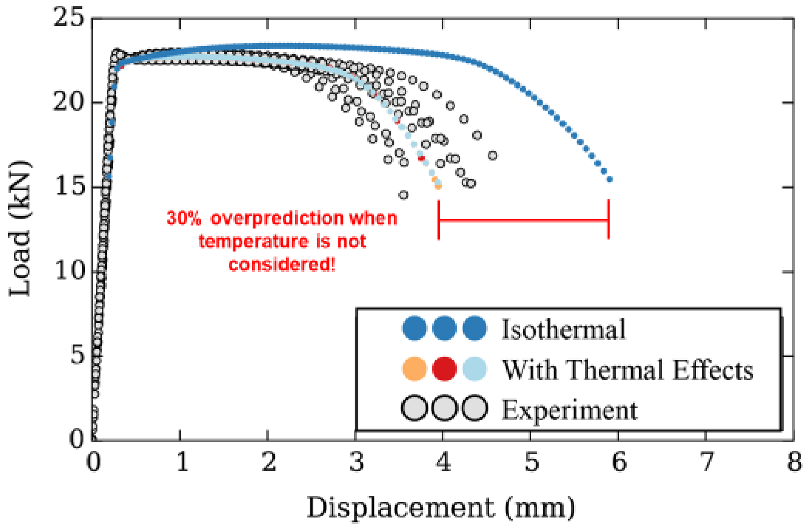
- thermal softening of materials
- understanding adiabatic shear bands
- puncture/ crush scenarios

Experimental challenges:

- synchronization of full-field data
- accounting for heat losses at quasi-static rates
- Microstructural changes
- Noise during data collection



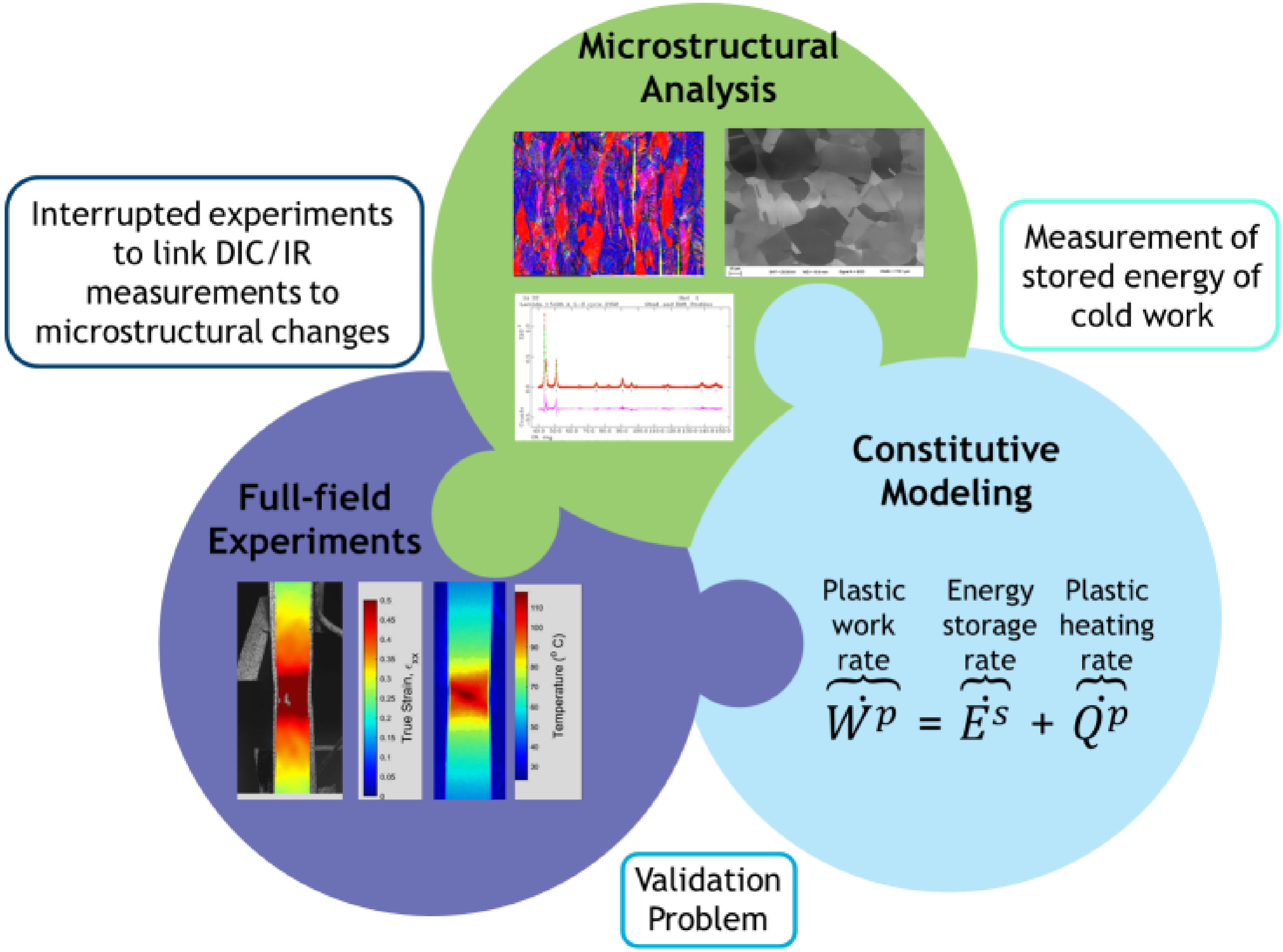
Comparison of Ti6-Al-4V load-displacement response to simulation results in the Second Sandia Fracture Challenge [4]



[4] Karlson et al., Int. J. Frac, 2016
[5] NHTSA, 2015 Honda Fit Report

Technical Approach

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



"Beyond Beta"
A full understanding of thermomechanical coupling

Technical Approach

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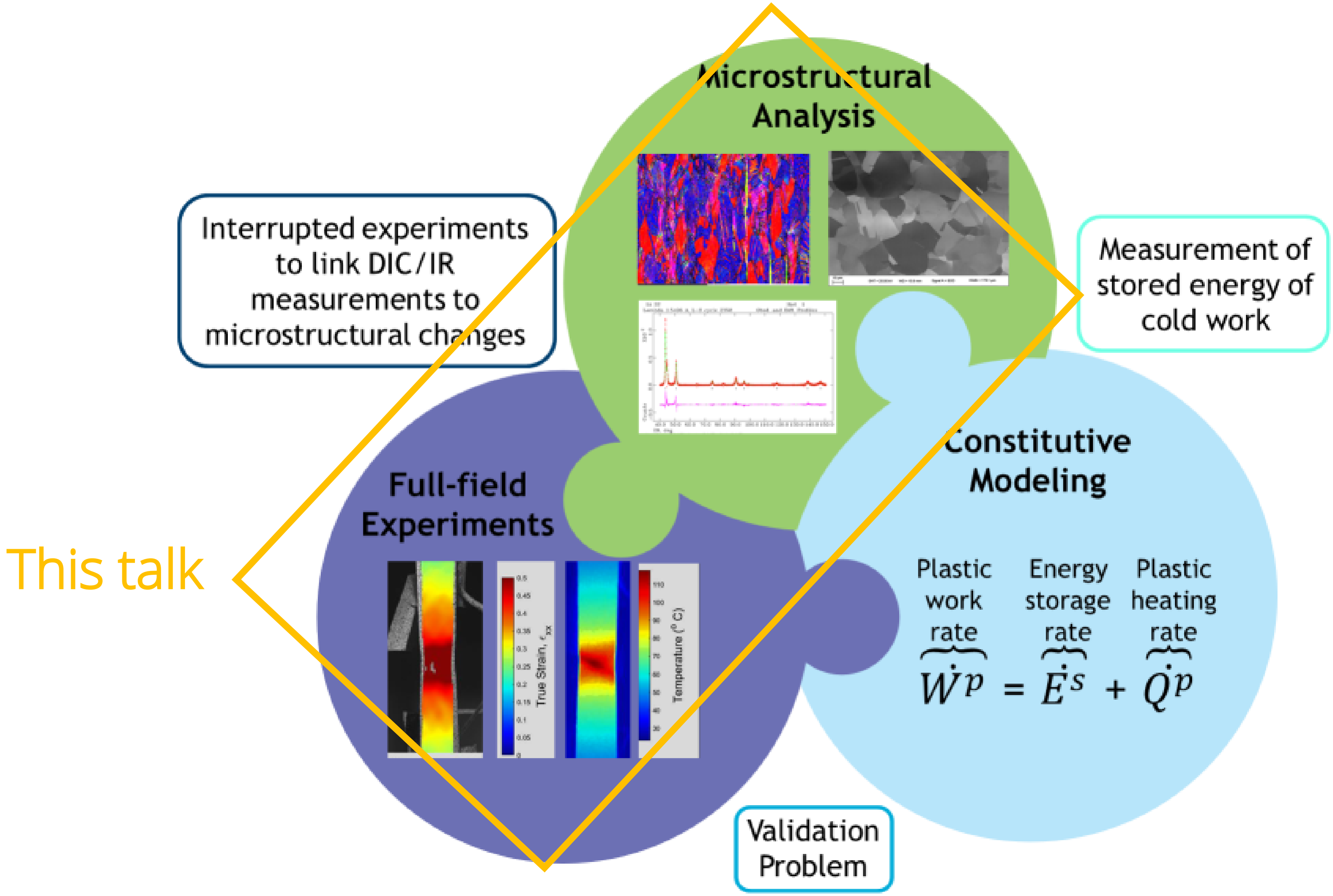

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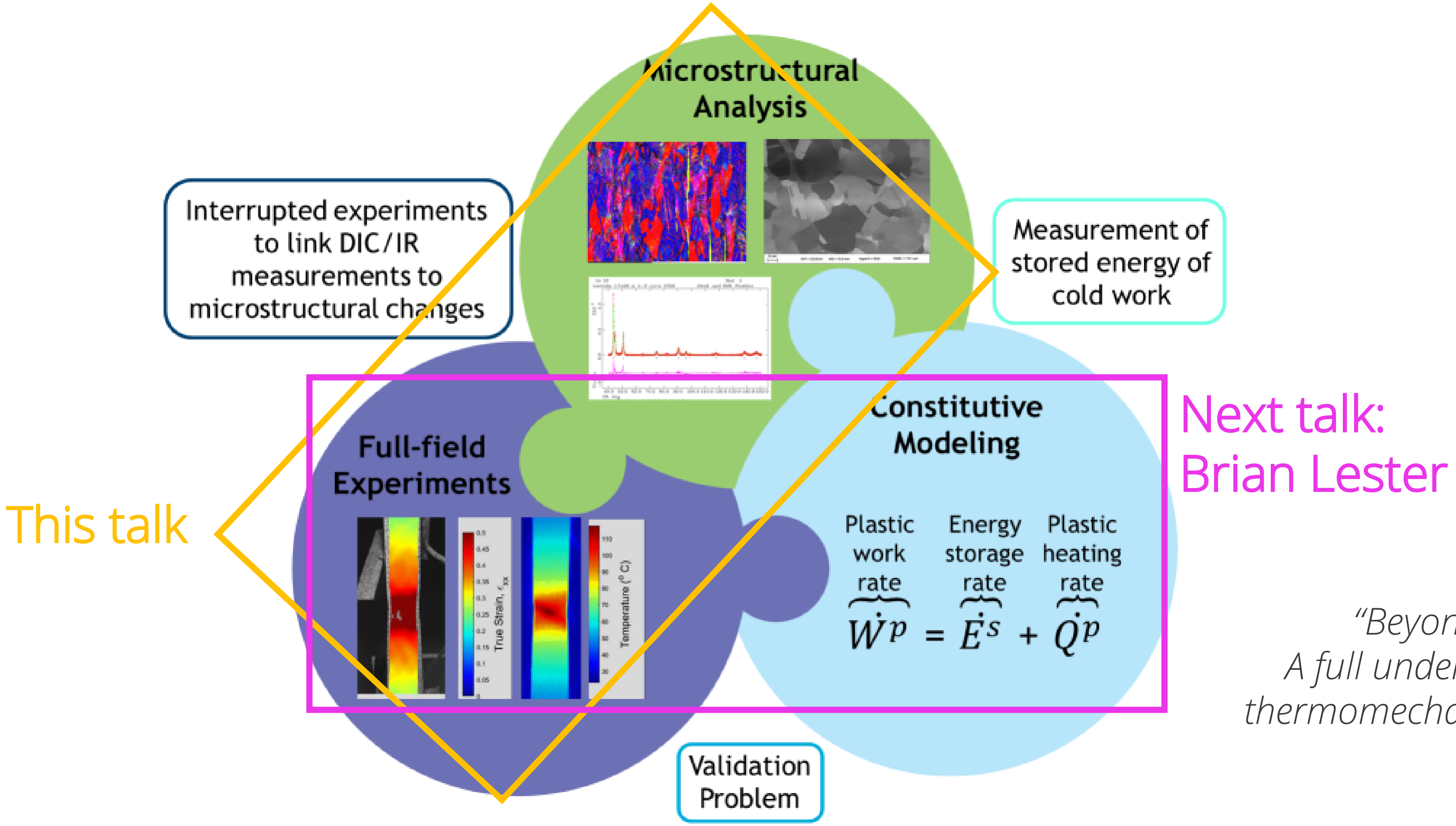
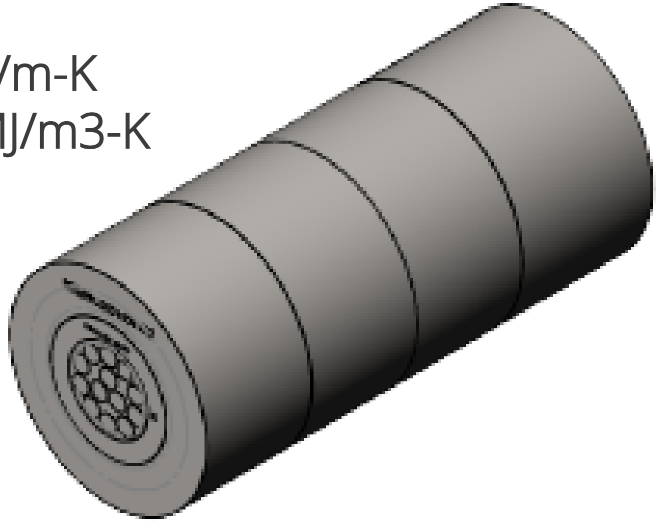


"Beyond Beta"
A full understanding of thermomechanical coupling

Selected two materials which vary in thermal properties and material performance

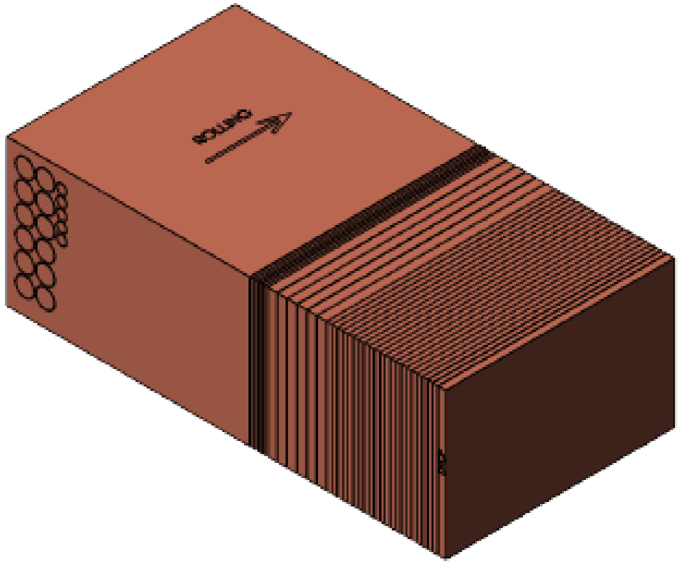
304L-VAR Stainless Steel
7.5” Round Bar Stock

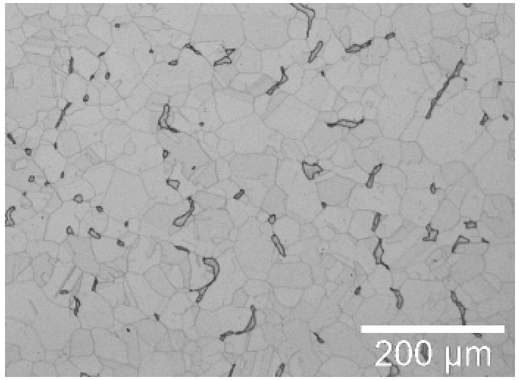
$k = 14.9$ W/m-K
$\rho\text{-}C_p = 3.77$ MJ/m3-K

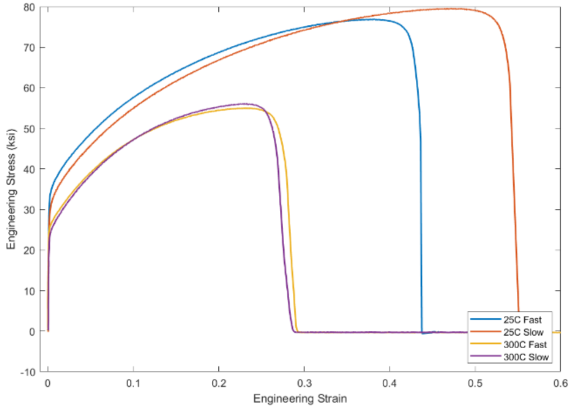


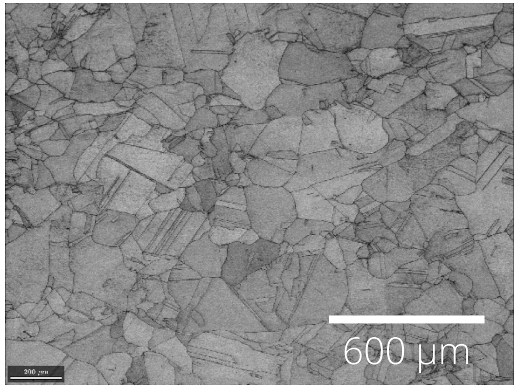
OFHC Copper
12” x 4” x 12” Thick Plate

$k = 401$ W/m-K
$\rho\text{-}C_p = 3.44$ MJ/m3-K









Selected two materials which vary in thermal properties and material performance

This talk

304L-VAR Stainless Steel
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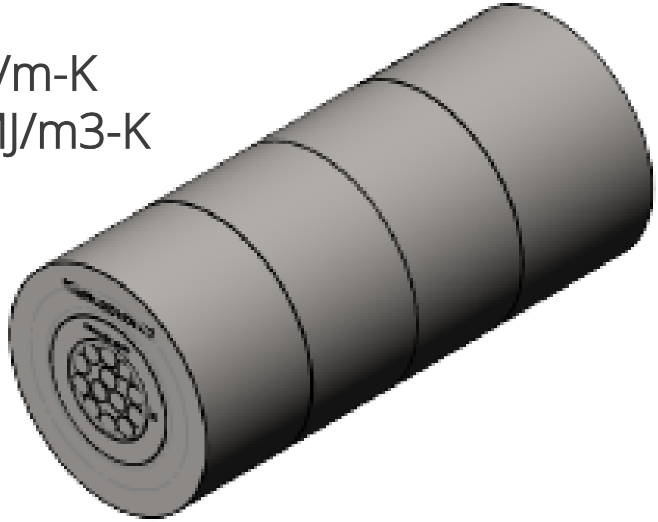

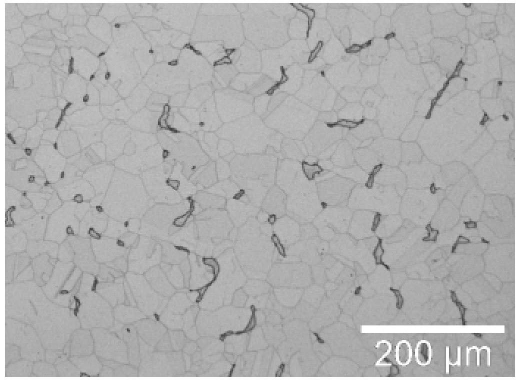

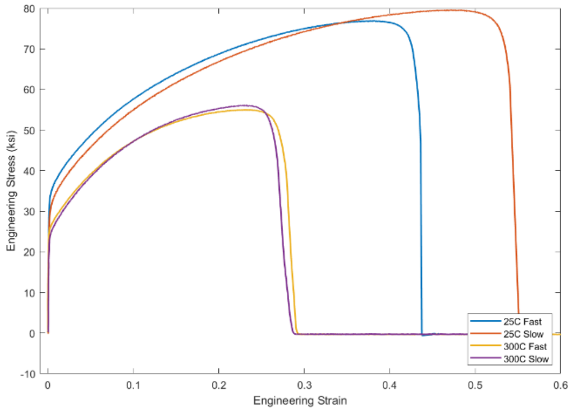

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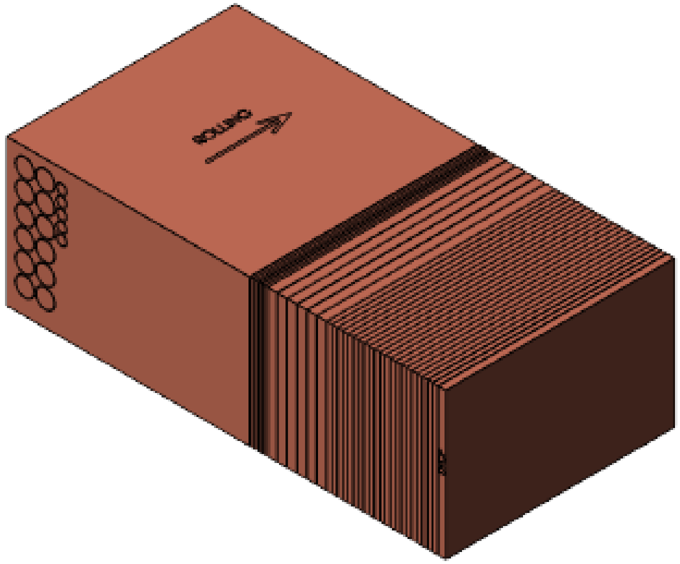
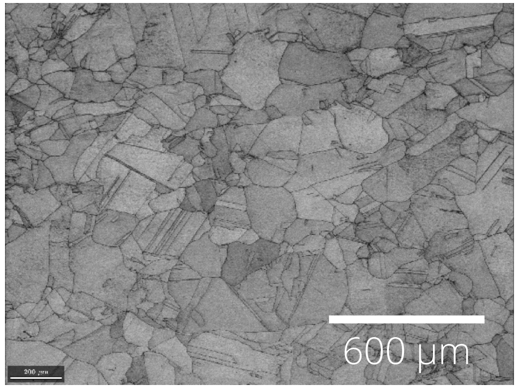




Experimental Setup- Quasi-static mechanical testing

Test Conditions

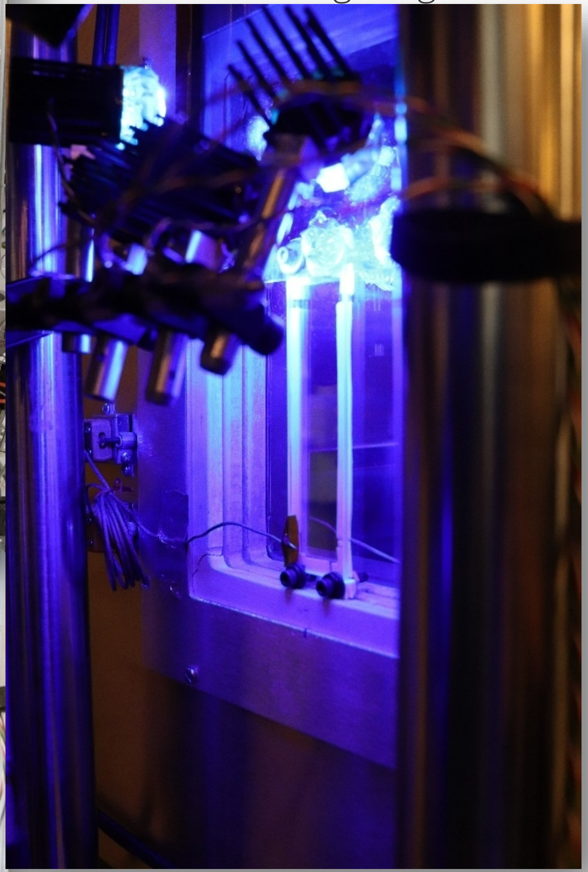
- Strain rates: 10^{-3}, 10^{-2}, 10^{-1} s^{-1}
- Temperatures: 25, 150, 300 C
- puncture/ crush scenarios

Metrology

- DIC for full-field strain
- IR camera for full-field thermography
- Thermocouples to capture heat transfer conditions
- Data synced with a single trigger

Convective furnace on MTS servo-hydraulic load frame

IR transparent window and lighting for DIC

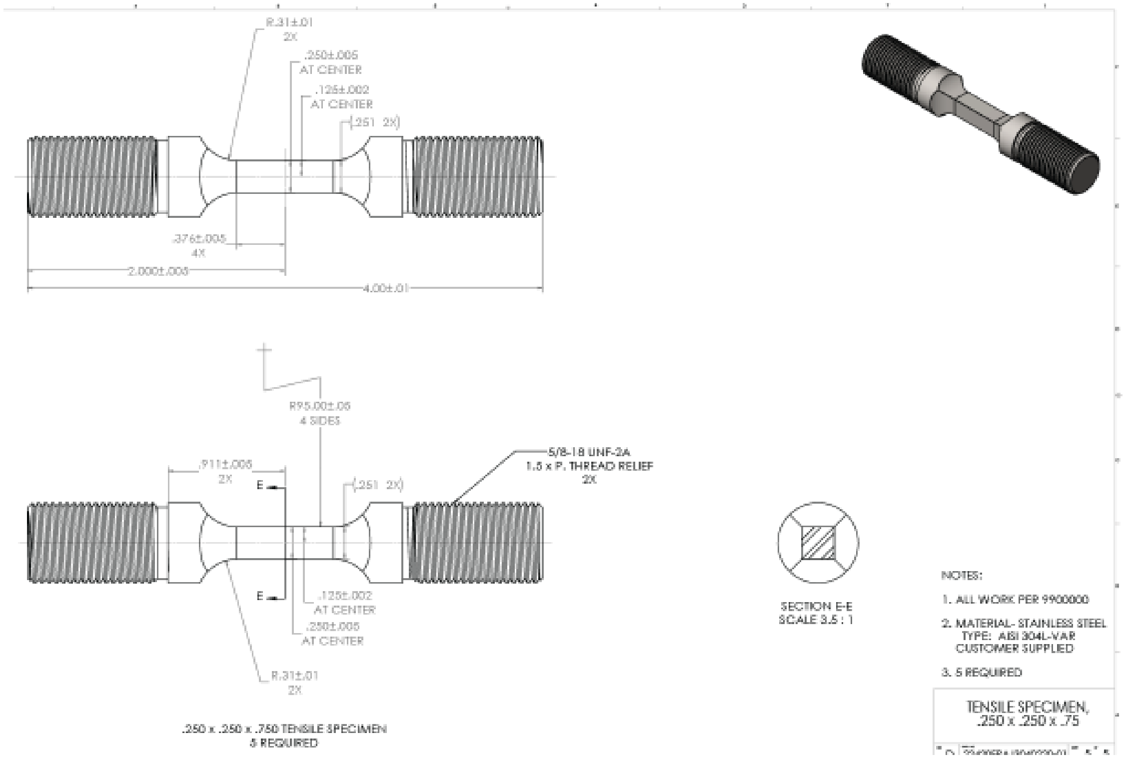


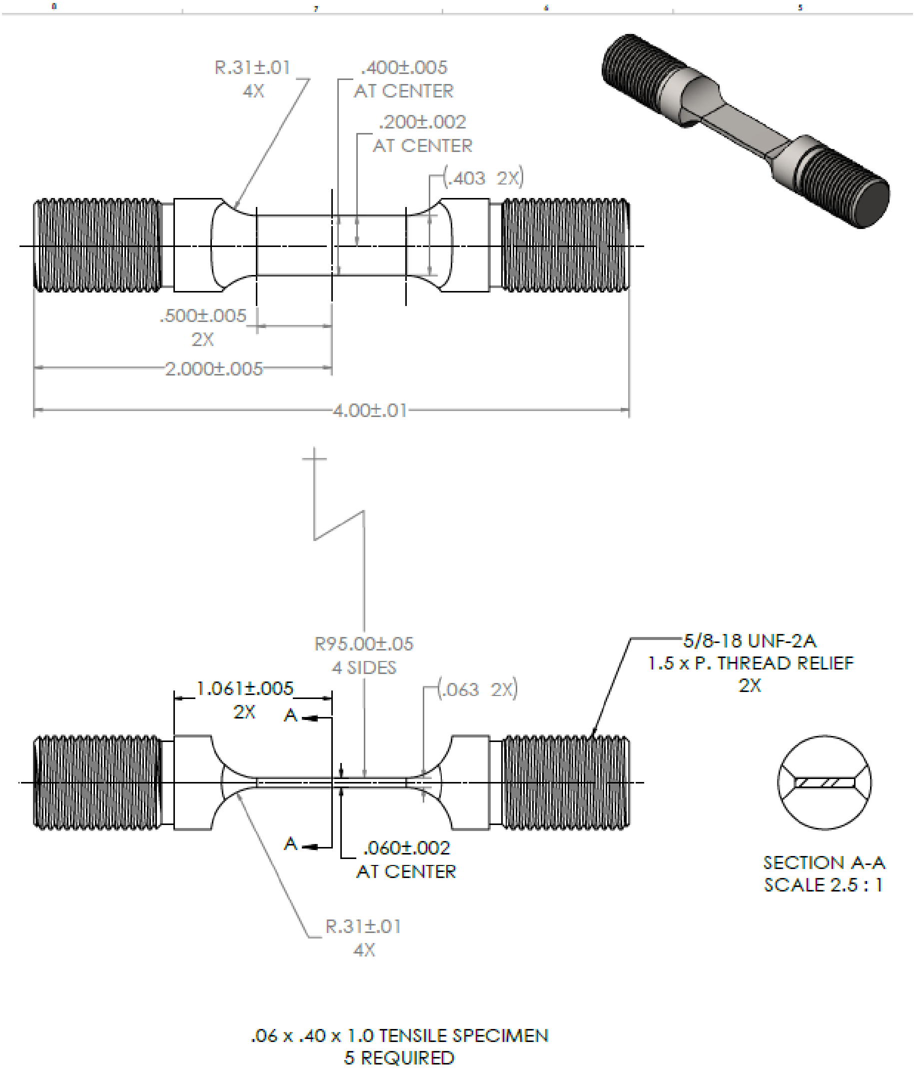
FLIR IR Camera

Experimental Setup- Quasi-static mechanical testing

Specimen Design

- Flat surfaces for metrology
- Different geometries to evaluate heat transfer/ size effects



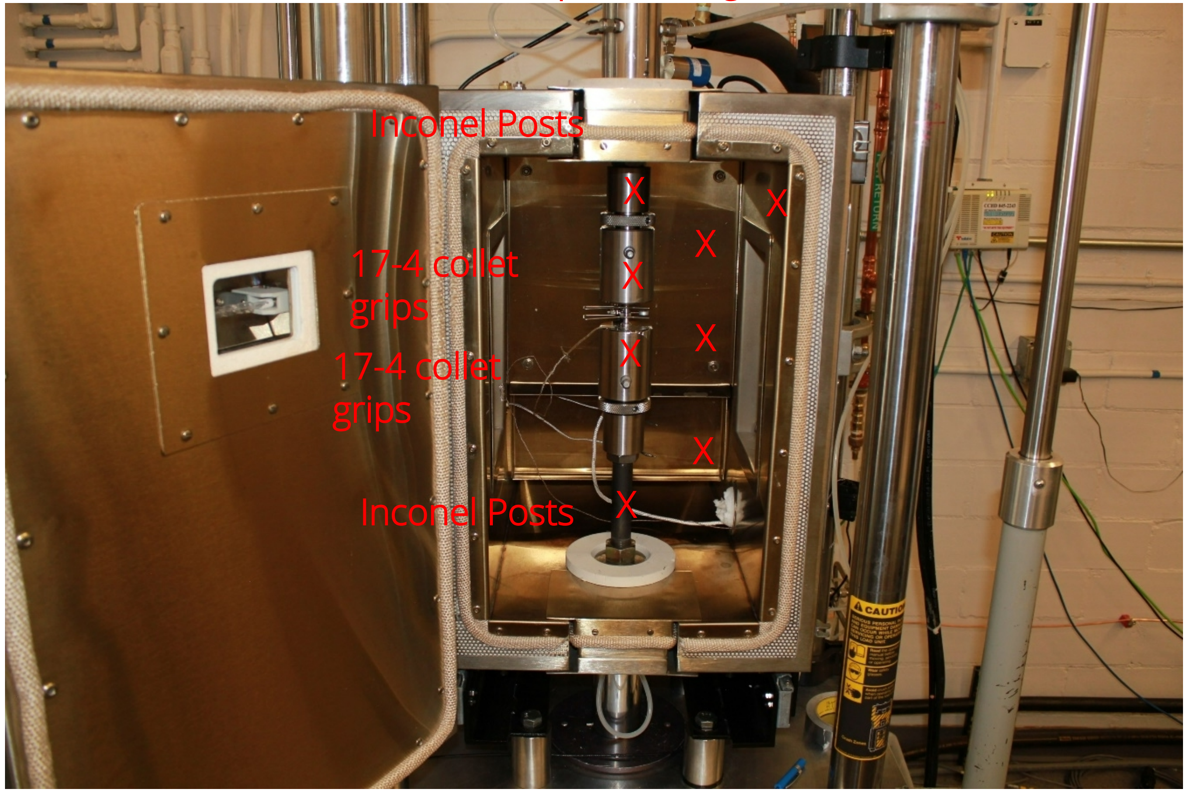


Experimental Setup- Quasi-static mechanical testing

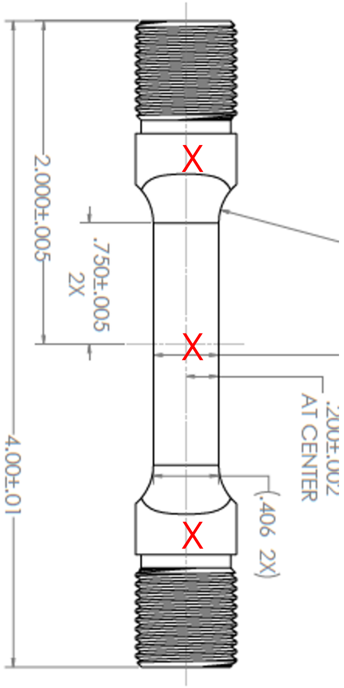
Thermocouples in the furnace

- Calibrate heat transfer conditions
- Compare to IR camera signal

Liquid cooling

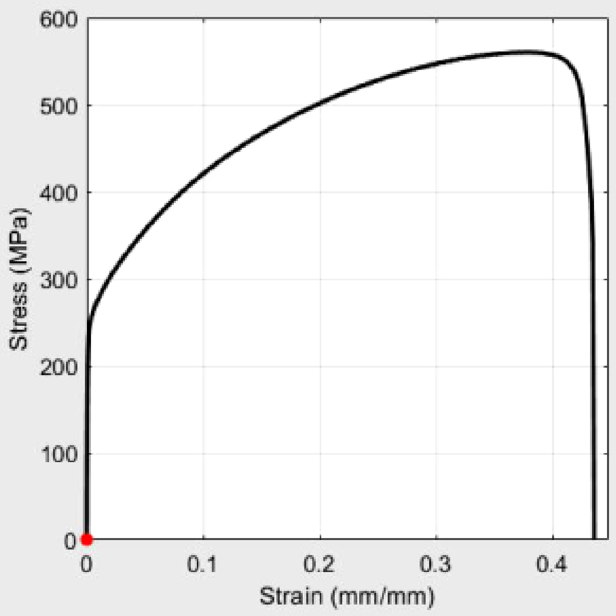


Liquid cooling

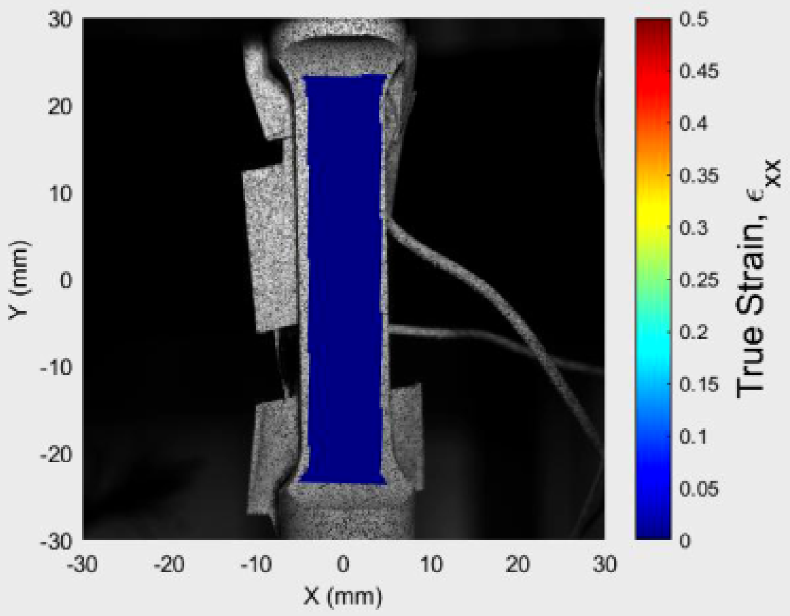


Synchronized Full-field data for model calibration- Quasi-static

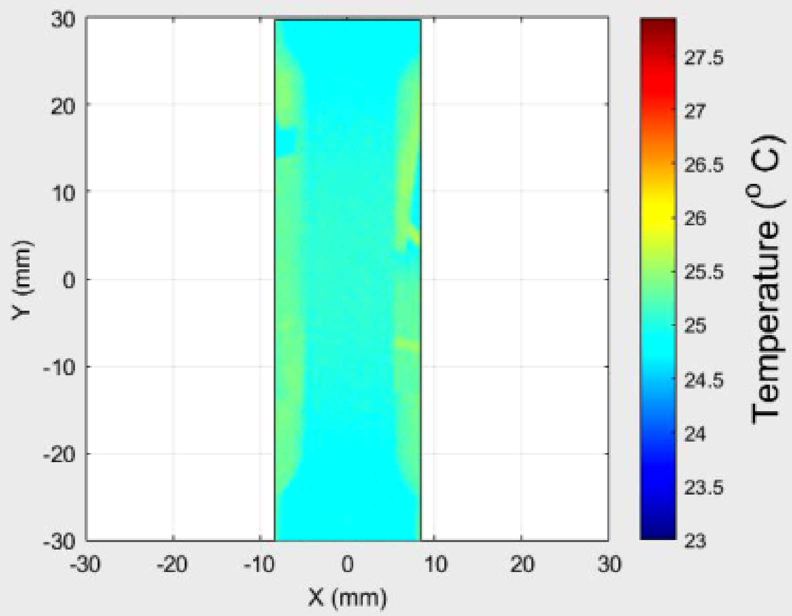
Stress- Strain Response



Full-field Strains from Digital Image Correlation (DIC)



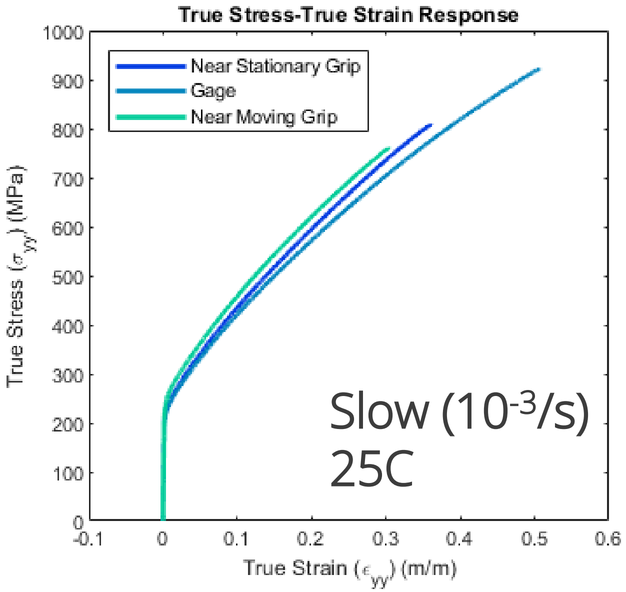
Full-field Temperatures from Infrared (IR)



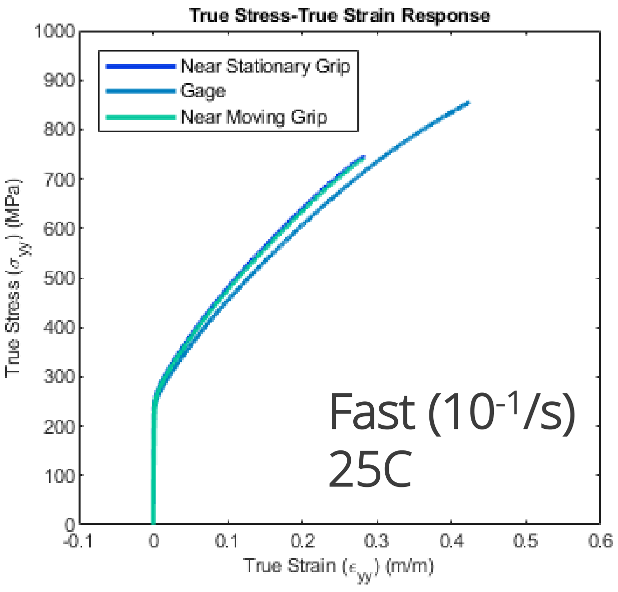
Full-field data:

- Reveals heterogeneity in thermomechanical response and localization phenomena
- Provides insight into uncertainty of point measurements

Results



True Stress-True Strain Response
Near Stationary Grip
Gage
Near Moving Grip
True Stress (σ_{yy}) (MPa)
True Strain (ϵ_{yy}) (m/m)
Slow (10^{-3}/s)
25C



True Stress-True Strain Response
Near Stationary Grip
Gage
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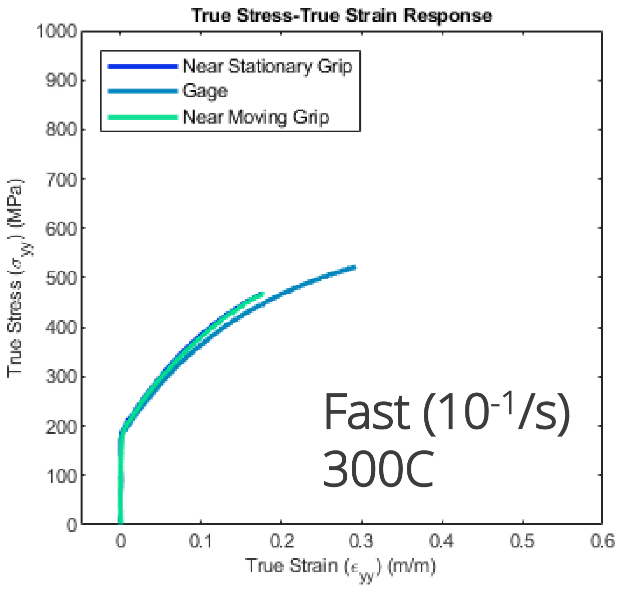
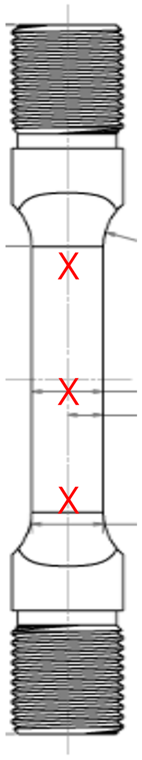
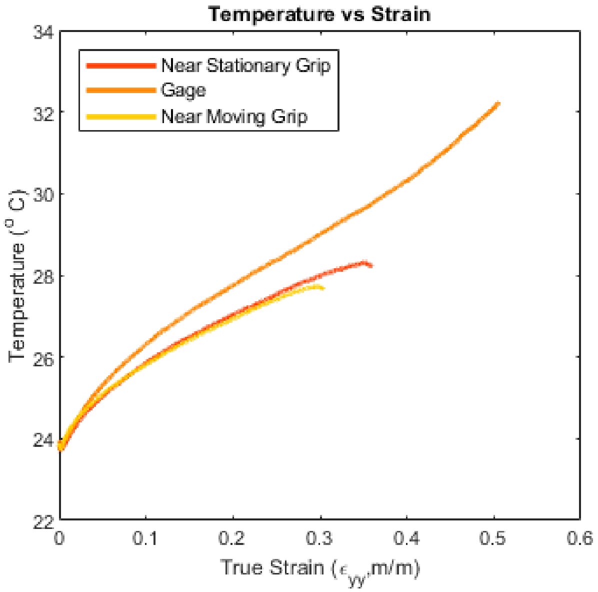
True Stress (σ_{yy}) (MPa)
True Strain (ϵ_{yy}) (m/m)
Fast (10^{-1}/s)
25C



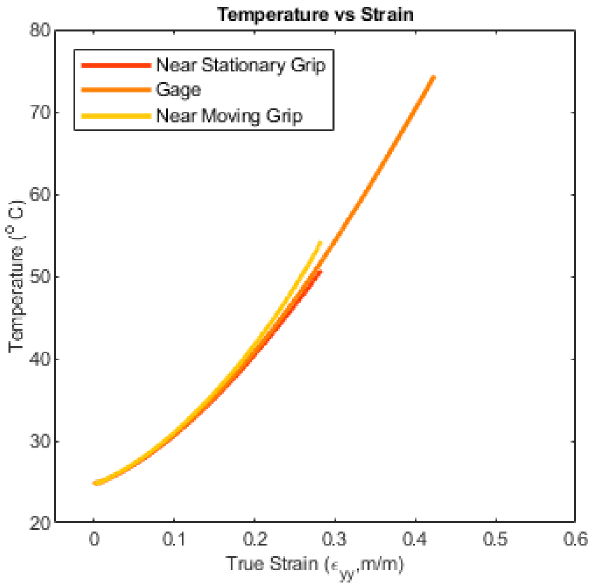
True Stress-True Strain Response
Near Stationary Grip
Gage
Near Moving Grip
True Stress (σ_{yy}) (MPa)
True Strain (ϵ_{yy}) (m/m)
Fast (10^{-1}/s)
300C



X
X
X



Temperature vs Strain
Near Stationary Grip
Gage
Near Moving Grip
Temperature (^{o} C)
True Strain (ϵ_{yy},m/m)



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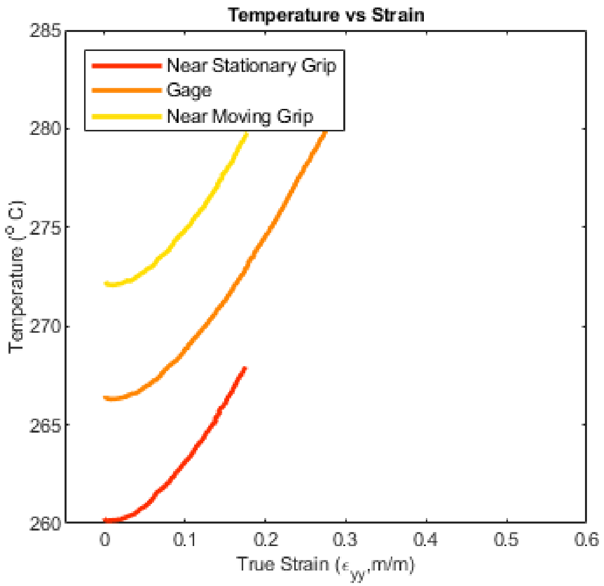

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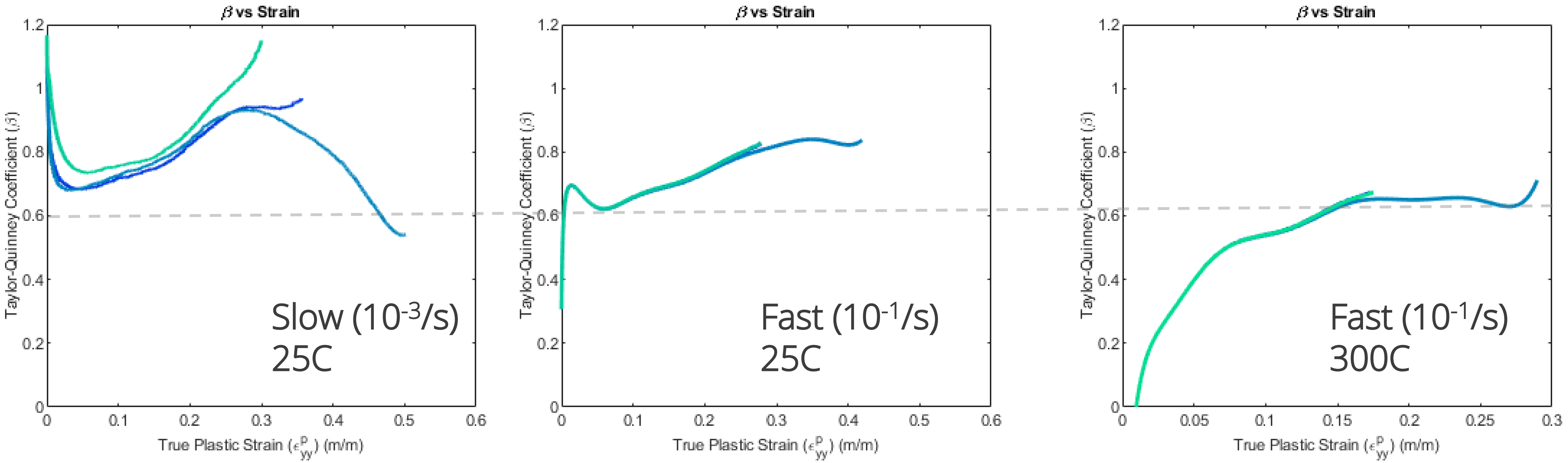


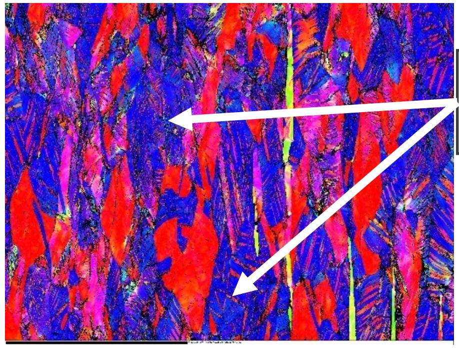
Taylor-Quinney Coefficients

- Varies with strain rate and temperature heat transfer conditions
- Non-uniform across deformation

Preliminary results show microstructural basis for mechanical behavior

Goal: *Understand the microstructural mechanisms that lead to differences in the conversion of plastic work to heat*

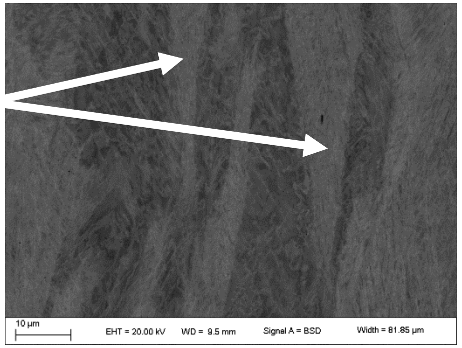
EBSD Inverse Pole Figure
(slow strain rate)



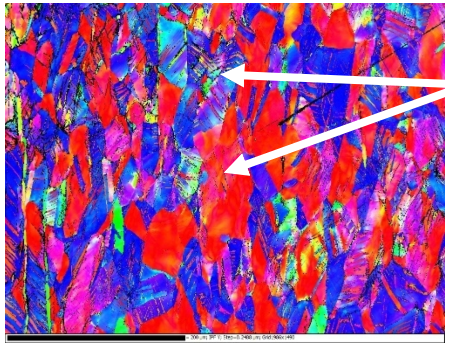
Defects

Defect Density:
10^9-10^8 cm^{-2} (blue)
10^7 cm^{-2} (red)

ECCI Analysis
(slow strain rate)



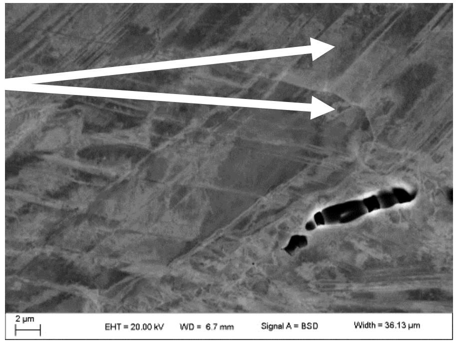
EBSD Inverse Pole Figure
(fast strain rate)

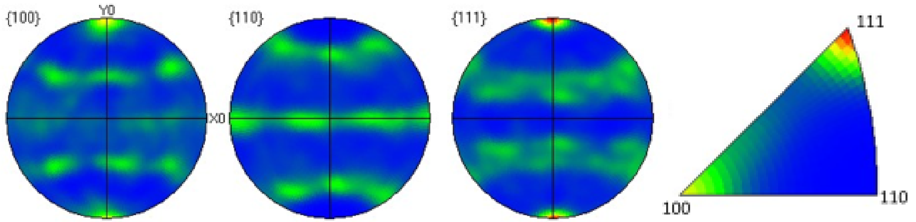


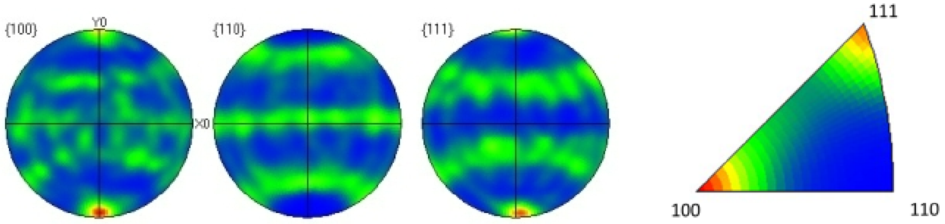
Defects

Defect Density:
10^9-10^8 cm^{-2} (all)

ECCI Analysis
(fast strain rate)

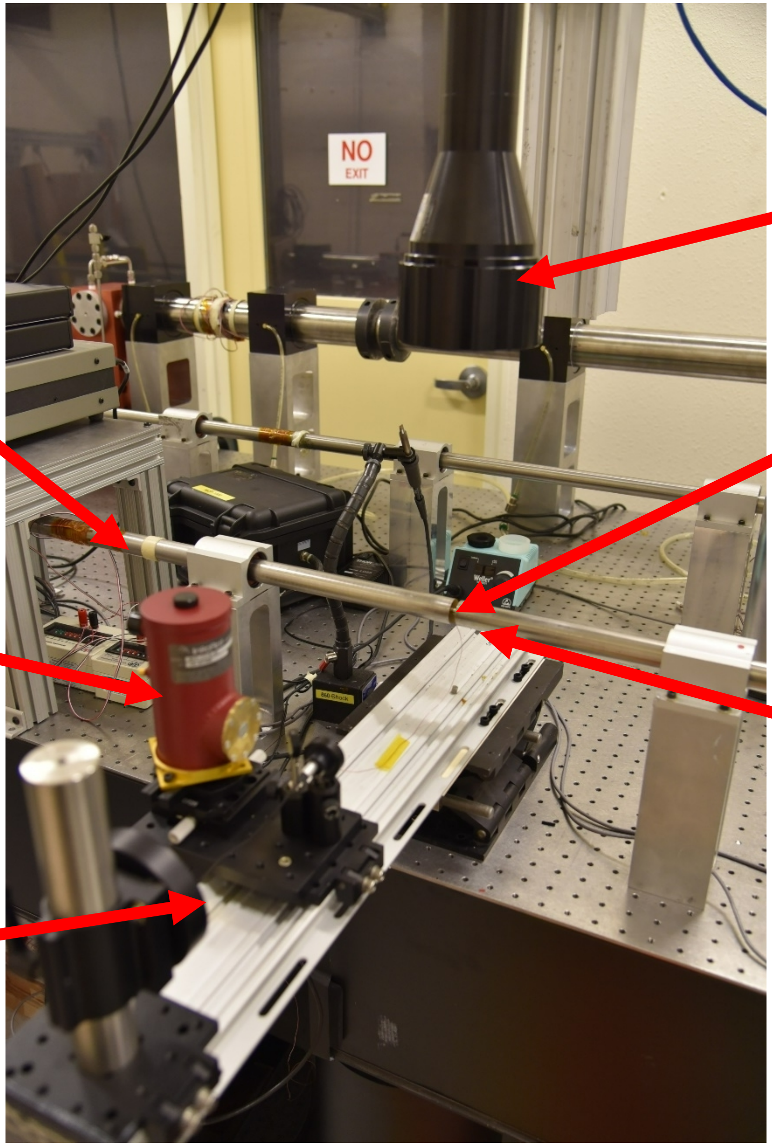






Key conclusions: (1) Without temperature rise, at very slow quasi-static rates, defect formation preferentially occurs in the 110 (blue) grains only, and 111/100 grains (red) preferentially reorient instead. At faster rates, all grains form defects (i.e. two main deformation mechanisms identified which vary with testing rate); (2) Electron Channel Contrast Imaging preliminary results are semi-quantitative

Hopkinson bar tests



Hopkinson Bar Strain-Gages

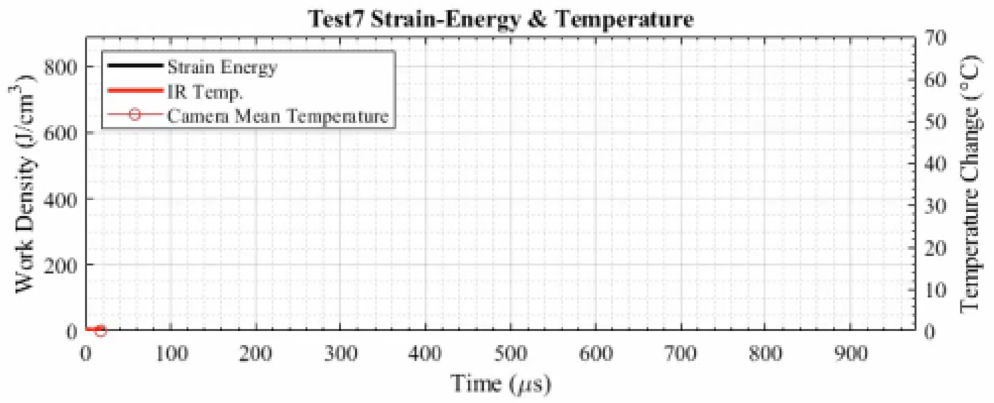
High-Speed Infrared-Detector

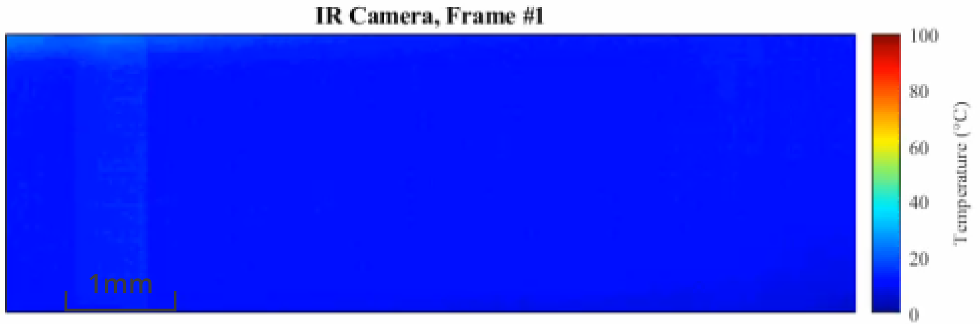
IR collection optics

High-Speed Infrared-Camera

Sample

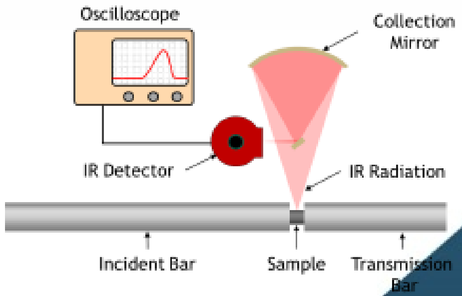
Thermocouple





IR Camera Telops M3K

IR Thermography

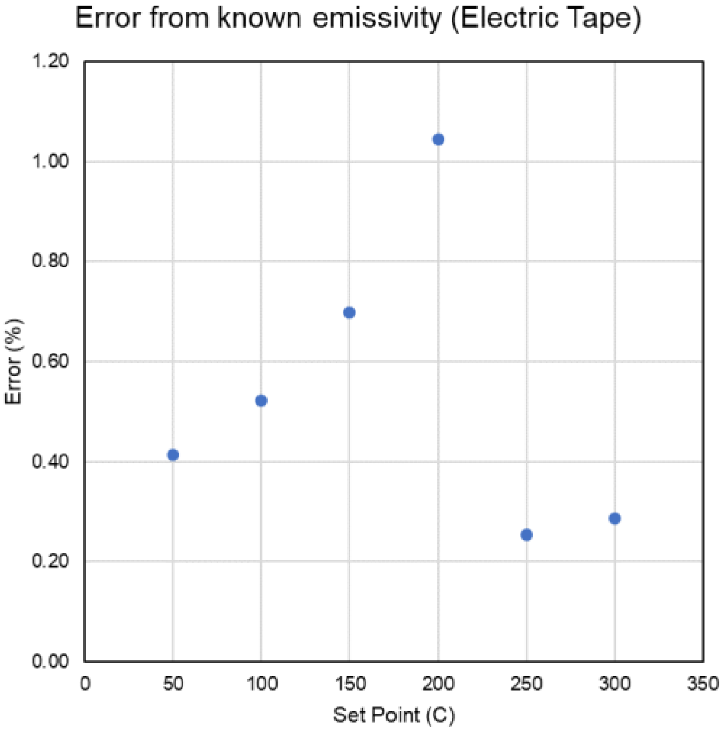


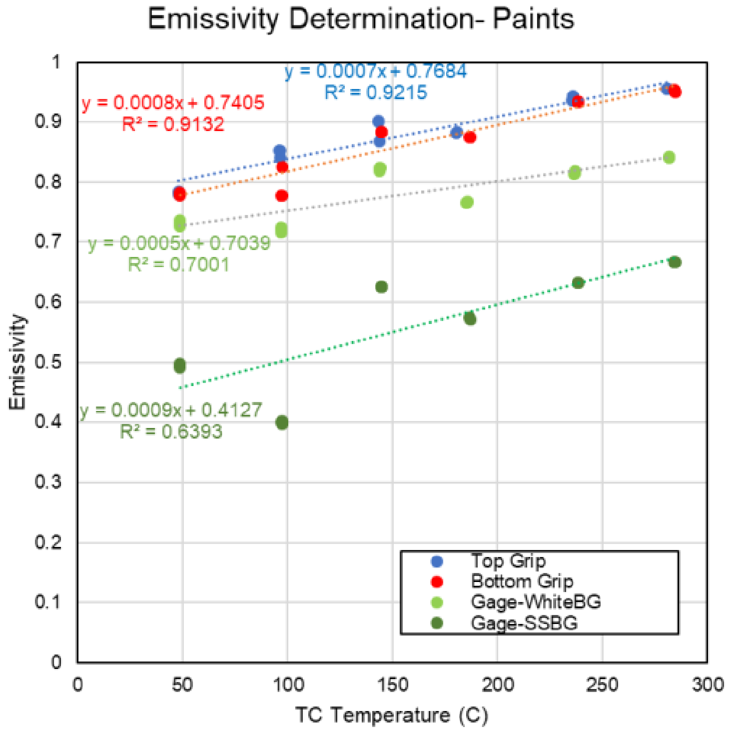
Experimental Uncertainty

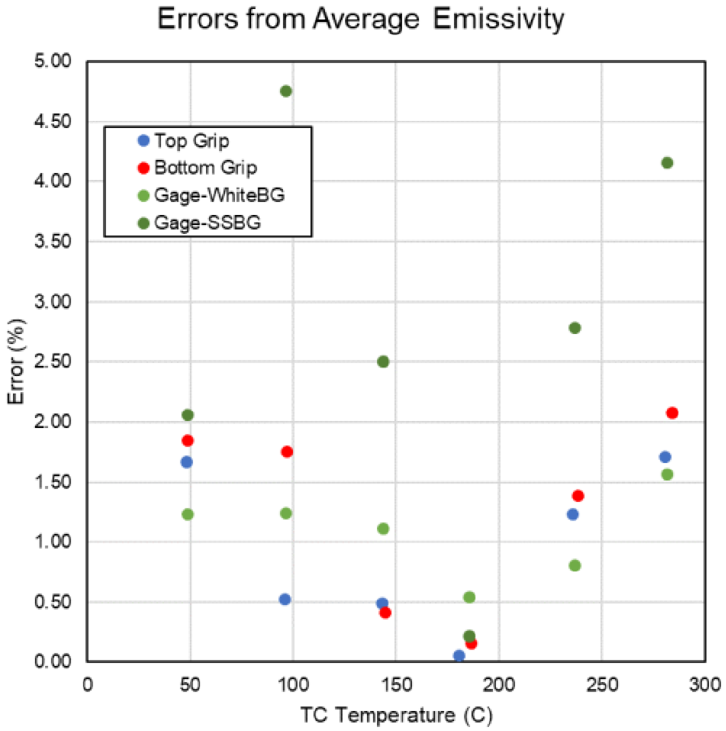
DIC Noise Floor

Temperature	U (µm)	V (µm)	W (µm)	ε_{xx} (µε)	ε_{yy} (µε)	ε_{xy} (µε)
25C	0.59	0.56	2.57	91.52	170.20	104.71
300C	2.87	3.54	15.24	722.40	599.71	518.23

IR Camera







Summary and Future Work

- Acquired full-field strain and temperature measurements for two materials
  - Strain rates spanning 3 orders of magnitude
  - Temperatures from 25 to 300 C

- Characterized microstructure before and after deformation
  - Identified local grain and dislocation structures

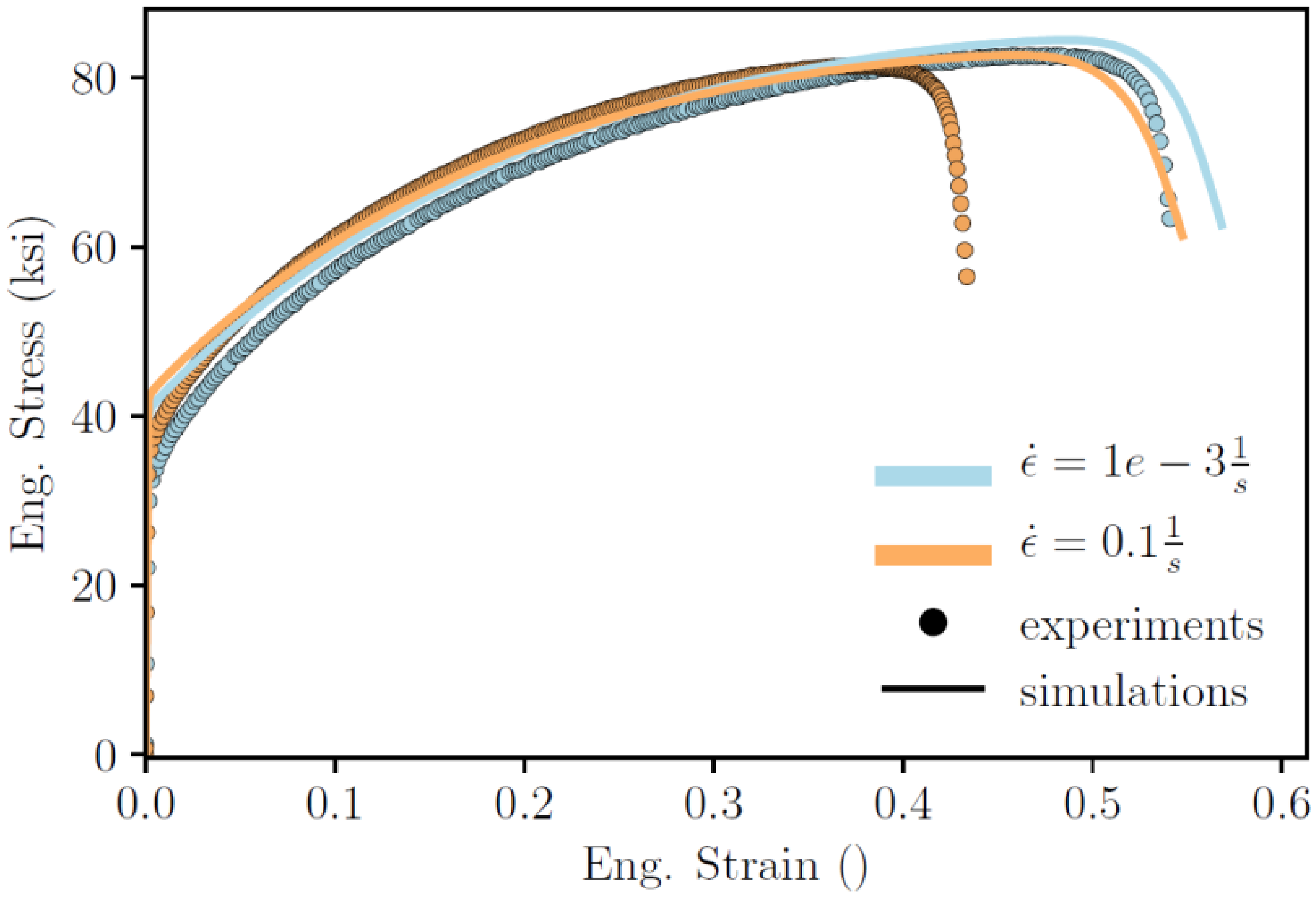
- Incorporate microstructure, strain rate, and temperature dependence into a new model beyond beta

- Propagate uncertainty in experimental measurements into calculations and thermomechanical models

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

Material Calibration



0.95 for beta

Thermal BCs (from Wyatt)

Goal: *Determine if we can successfully mitigate error from heat loss measurements and/or determine the slowest quasi-static rate attainable with reasonable error*

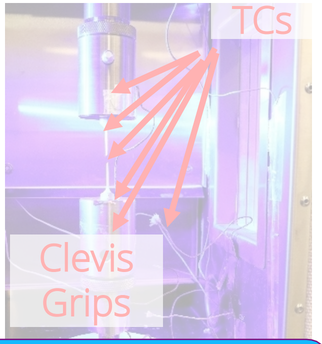
Convection coefficient plays large role in measured ΔT

Using data from Exploratory Express

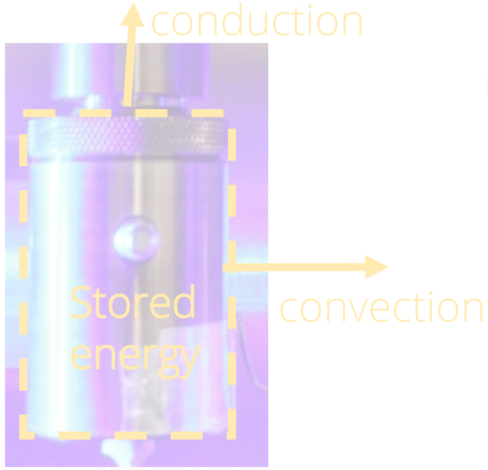
Convection Coefficient – W/ (m^2K)	Maximum Temperature - °C	Maximum Delta T- °C
2	109	82
5	99	72
10	88	61
25	68	41

Large change in predicted ΔT with increasing convection coefficient!

Experimental Setup

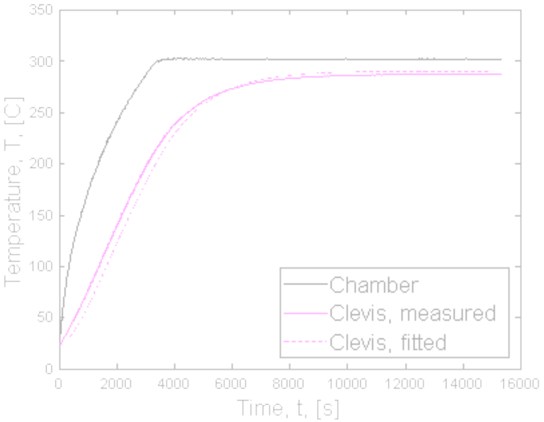


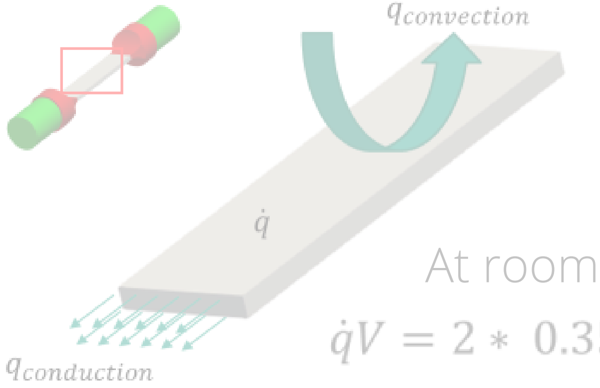
Key conclusions: (1) We have high confidence in our thermal loss metric from thermal modeling; (2) We are now using thermal model to inform boundary conditions for the coupled thermomechanical simulation



$$\dot{E}_{st} = q_{conduction} + q_{convection}$$

h = 21.7 ± 0.9 W/m2/K produces best fit across 4 datasets



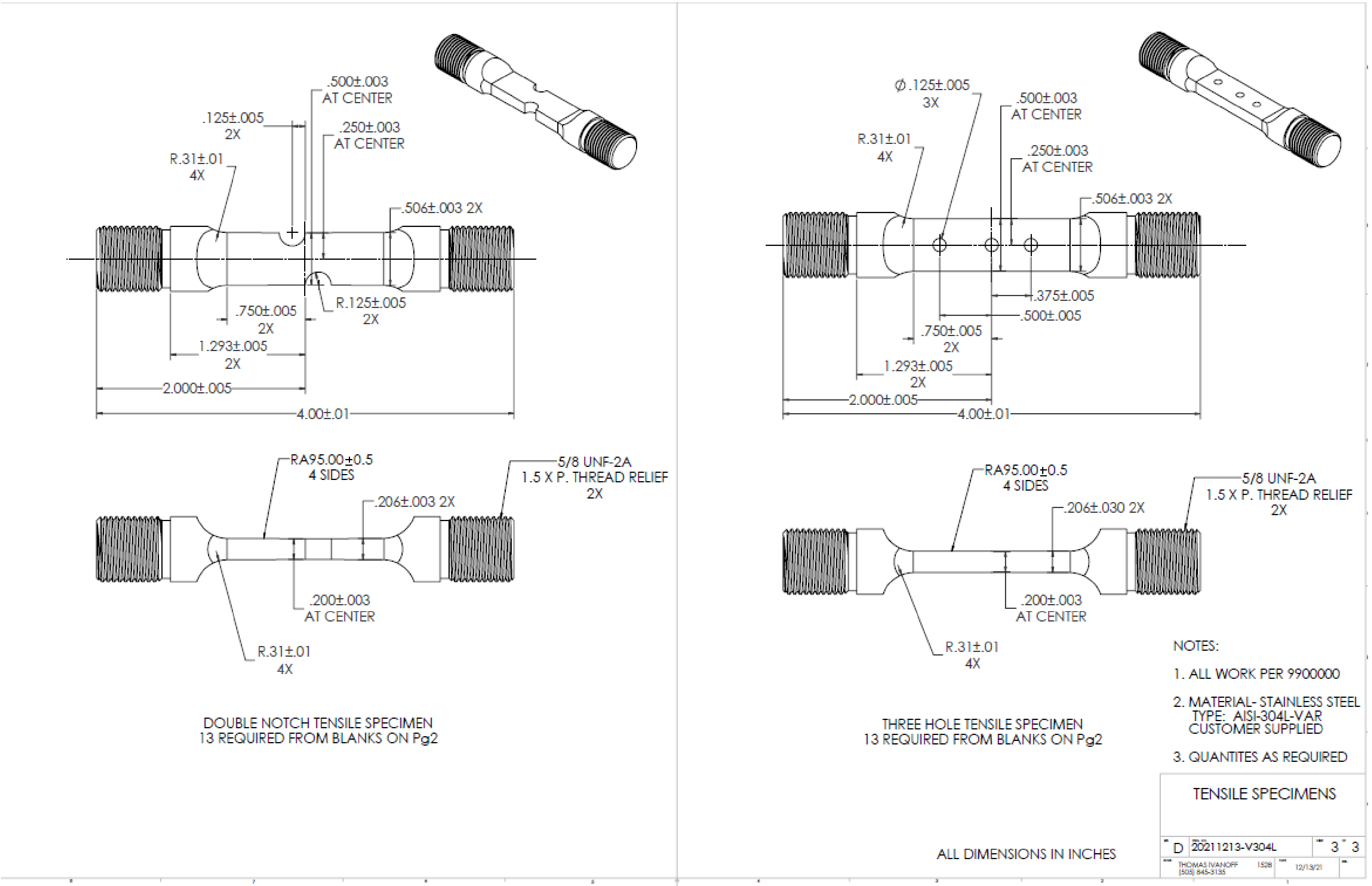


$$\dot{q}V = q_{conduction} + q_{convection}$$

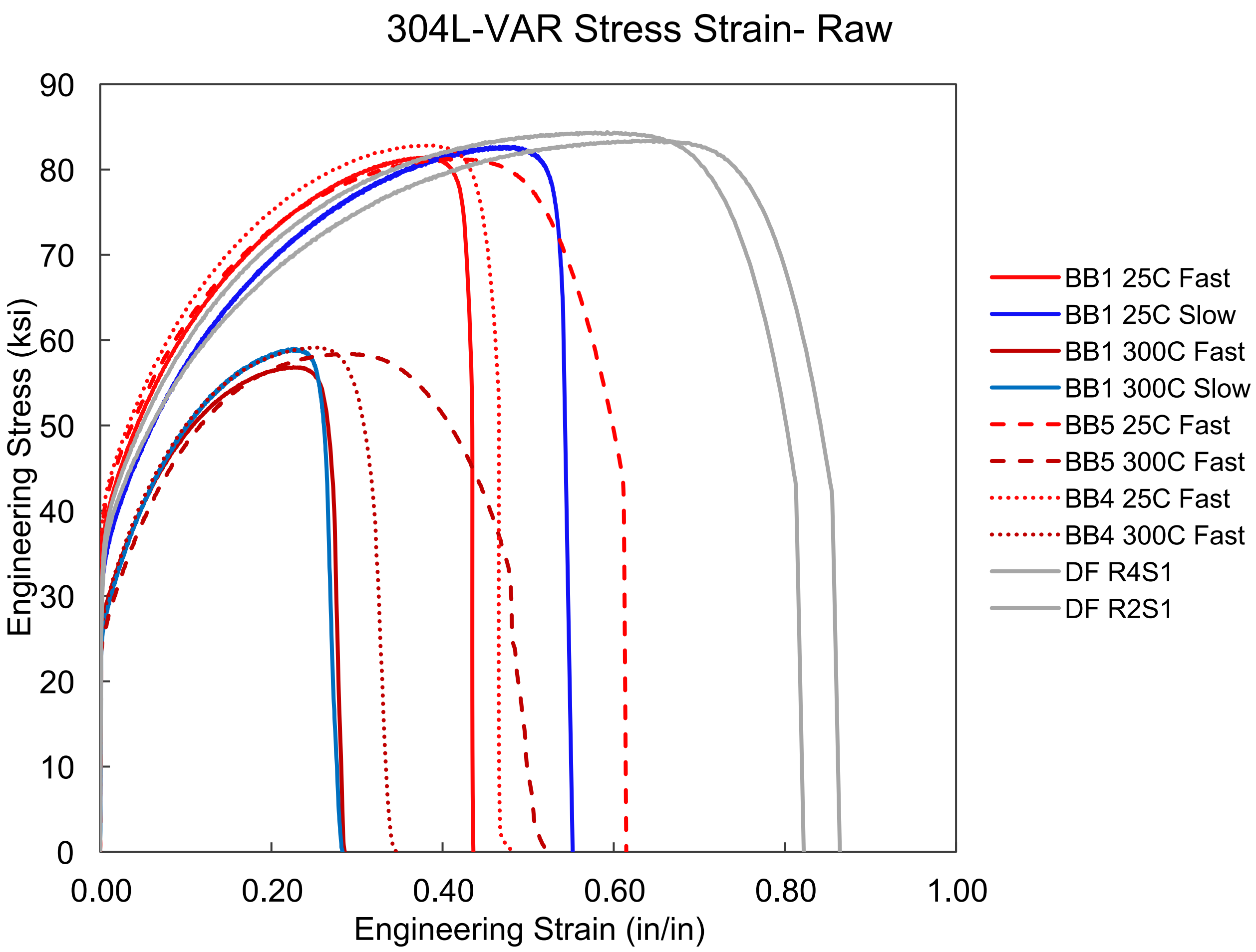
At room temperature:

$$\dot{q}V = 2 * 0.355\,\dot{q}V + 0.29\,\dot{q}V$$

Validation Specimen Geometries



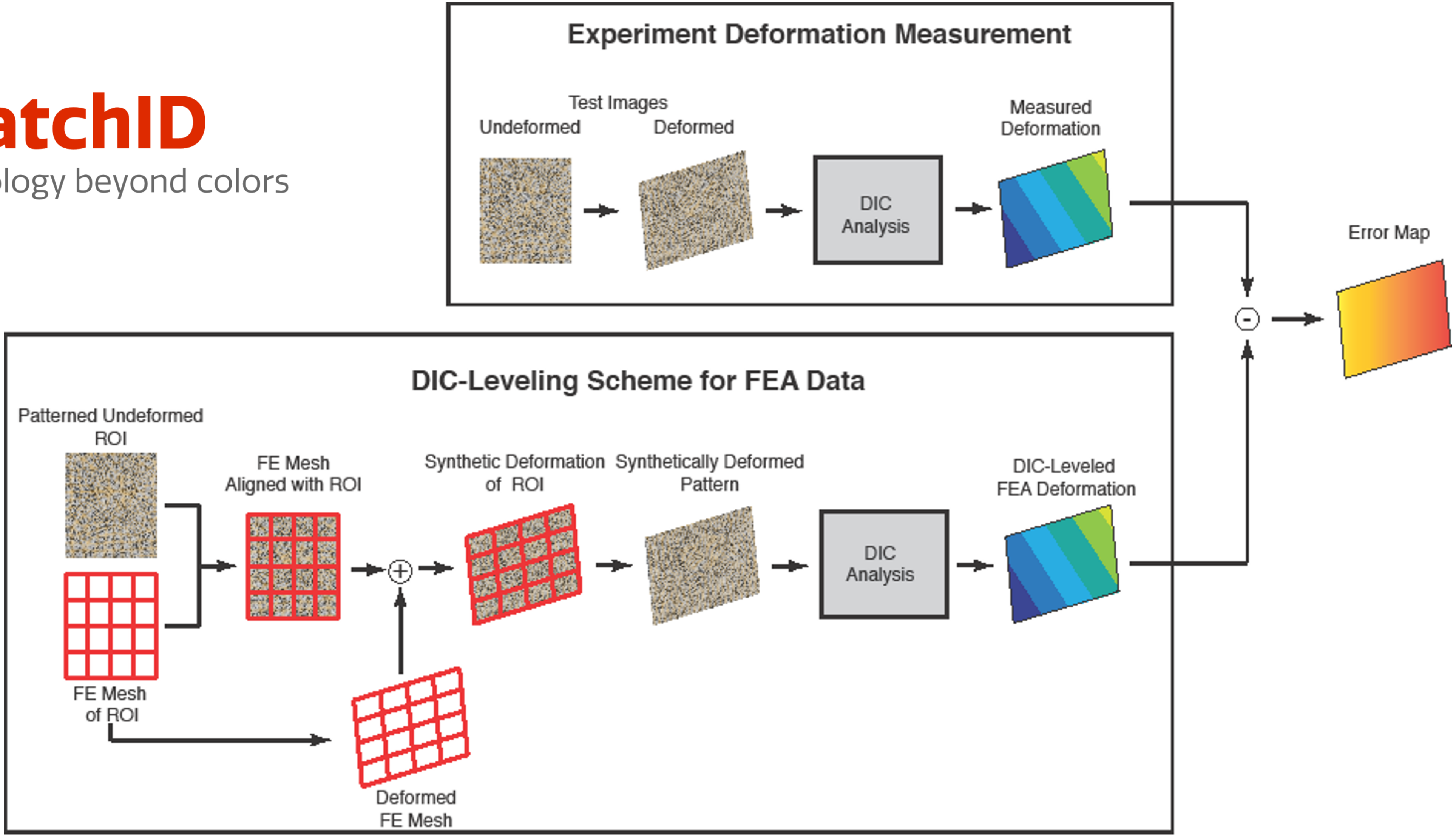
Calibration Data (BB and DF)



Leveling Approach Explained

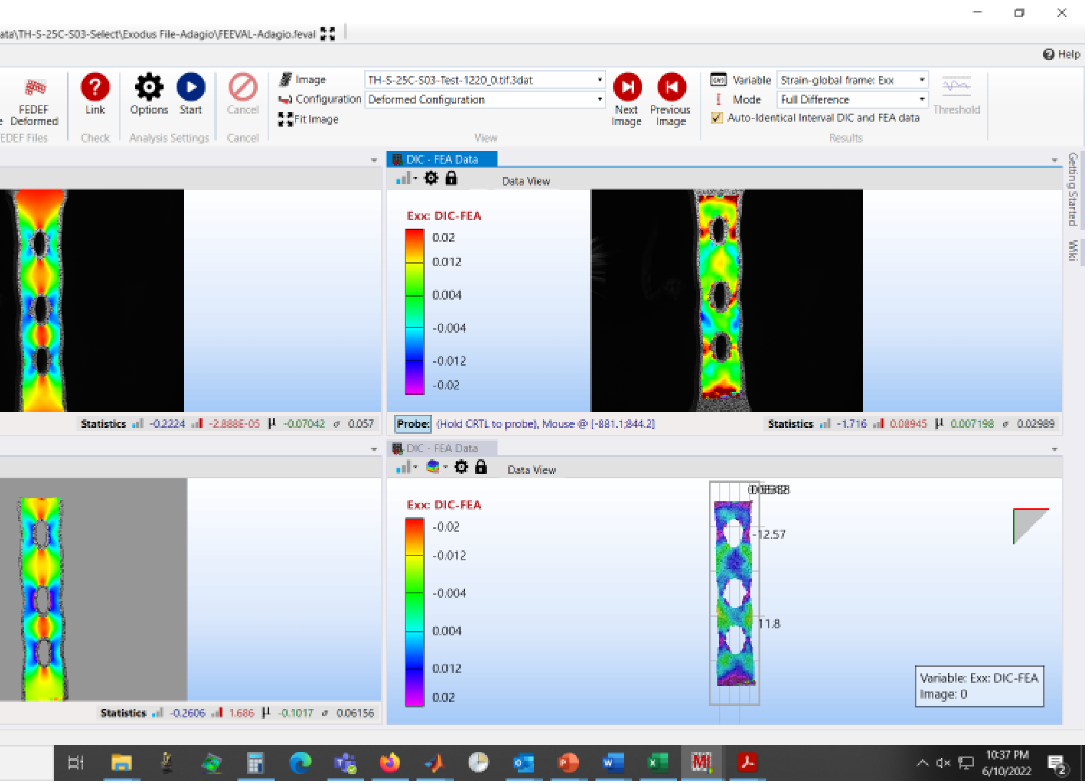
MatchID

Metrology beyond colors

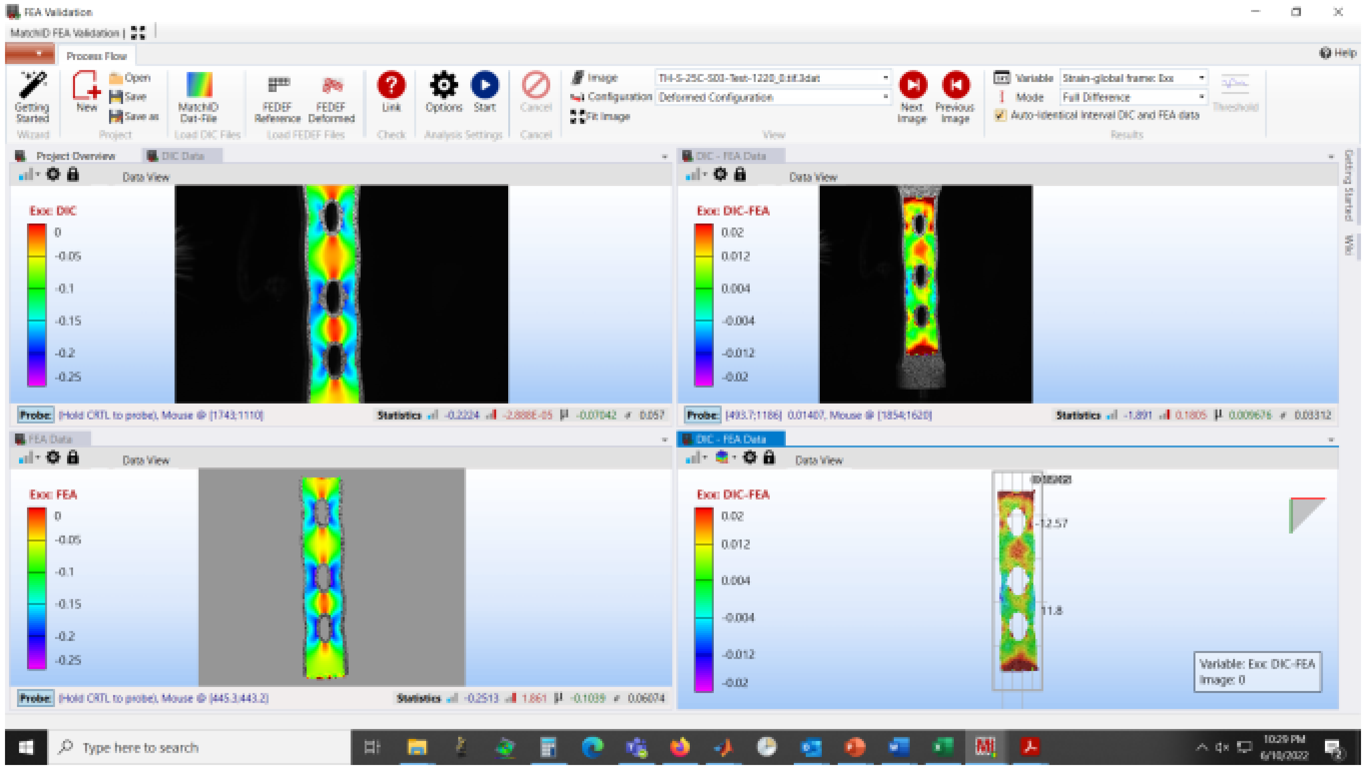


S03 Field/Leveling Comparison

Adagio



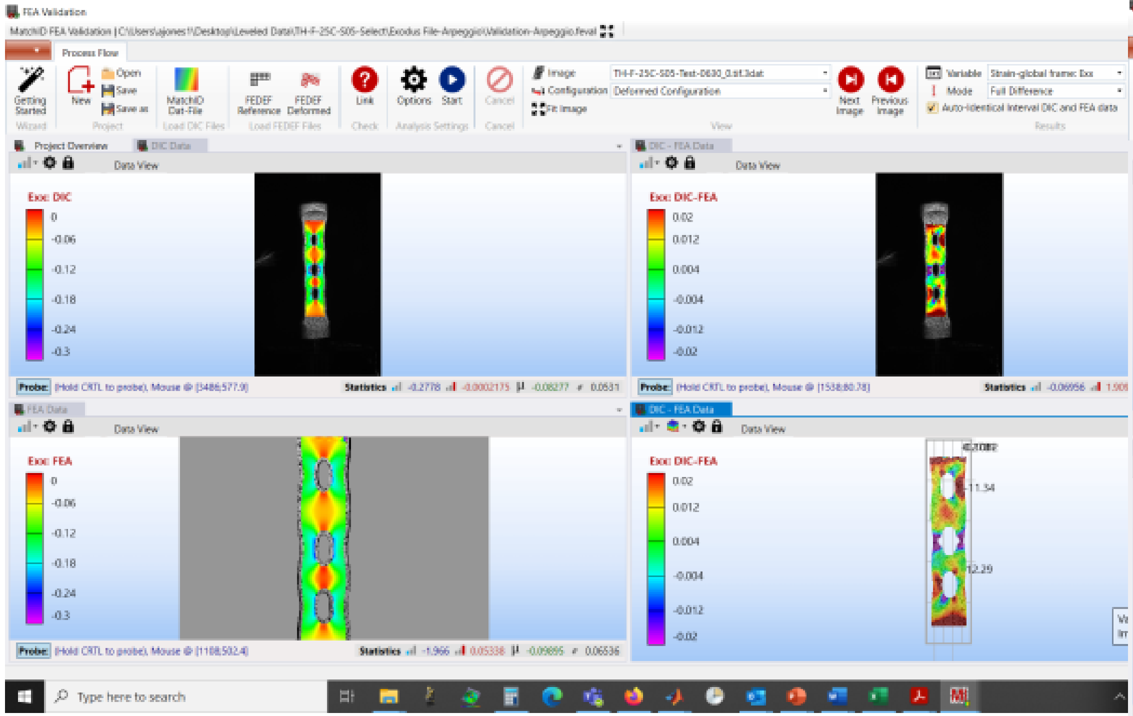
Arpeggio



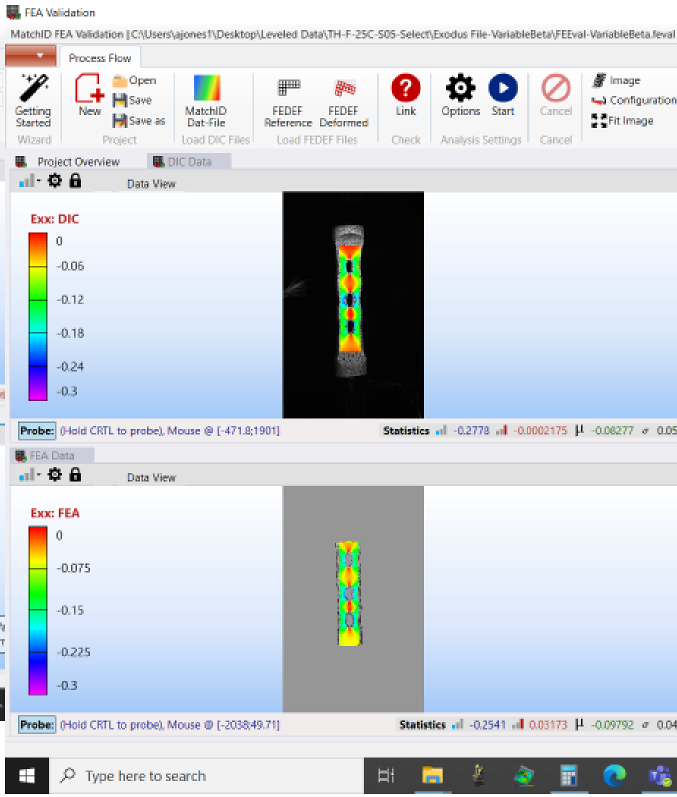
S05 Field/Leveling Comparision

Adagio

Arpeggio



VariableBeta



Copper Texture