SAND2019-12617C

Simultaneous IR/DIC Measurements for Thermomechanical Modeling

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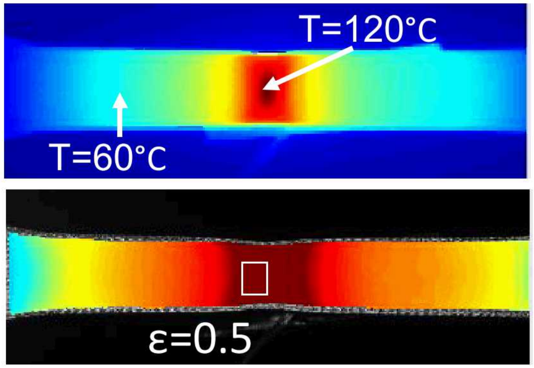
iDICs 2019- Oct 14-17



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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

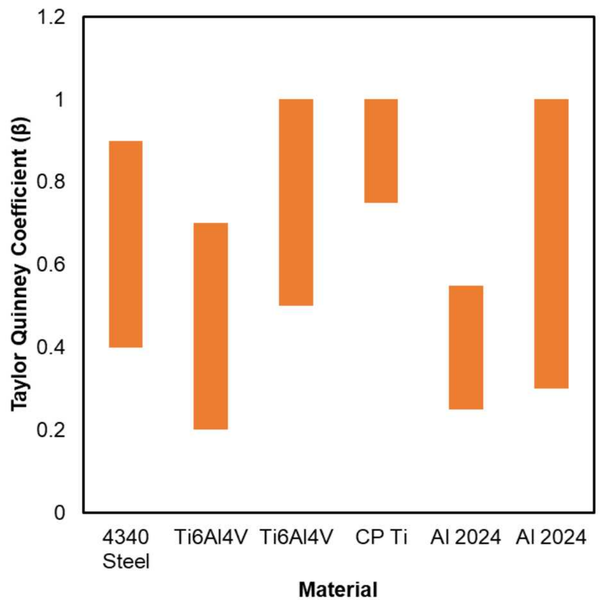
Under adiabatic conditions[1,2] →

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

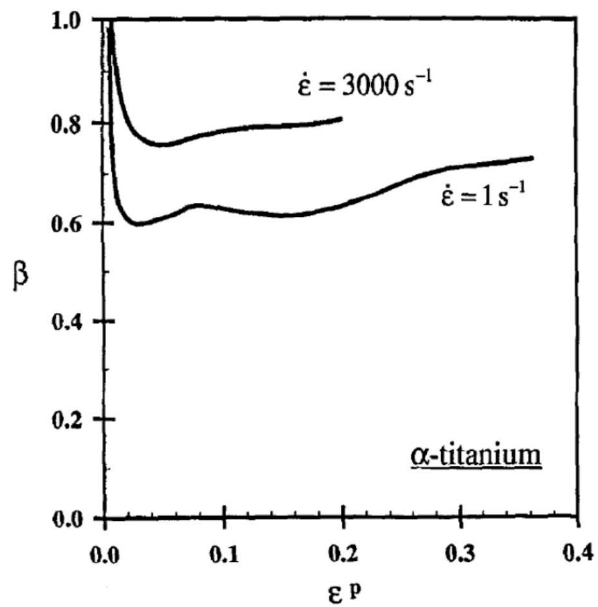
$\dot{Q}^p$=Rate of Heat Generation
$\dot{W}^p$ =Plastic Work Rate

→ Assume β is constant in thermomechanical model

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

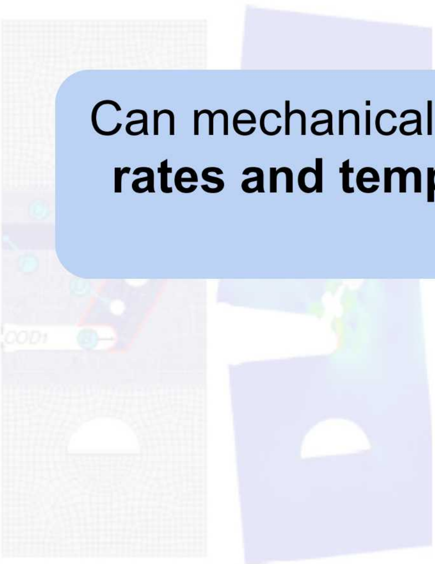


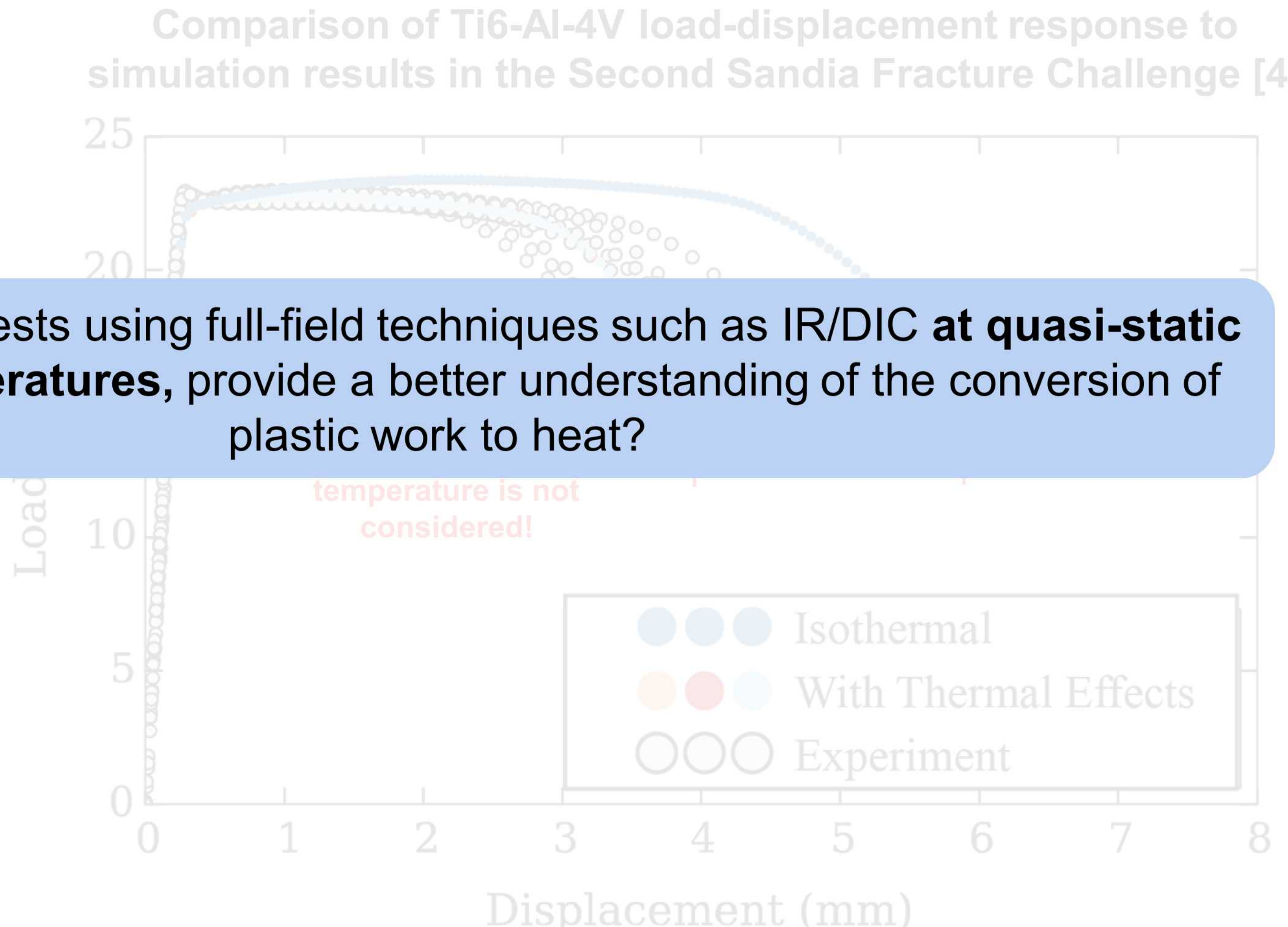
β as a function of plastic strain for titanium alloy [1]



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

An age-old solid mechanics problem



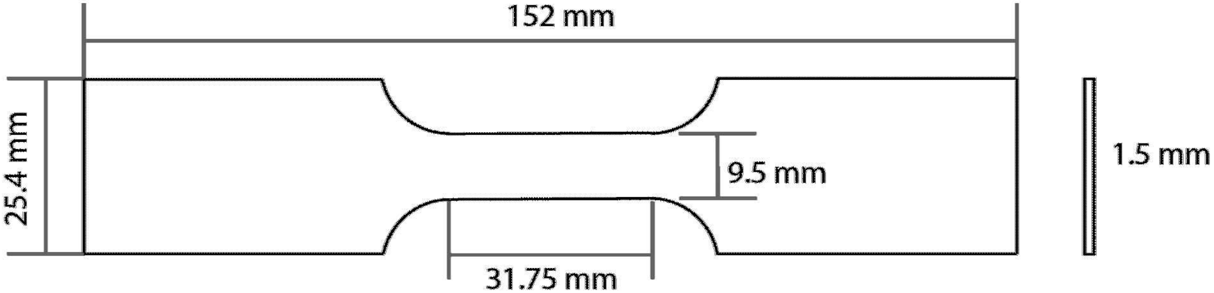


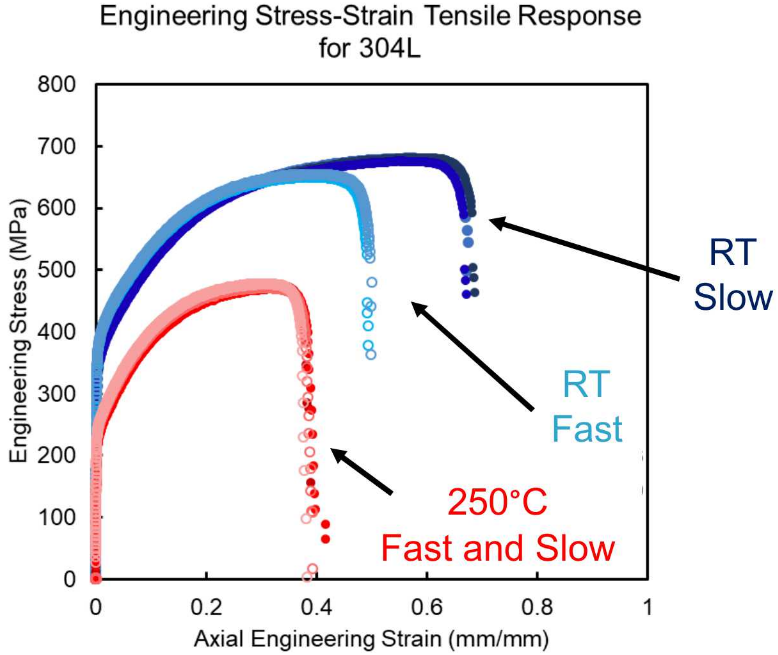
Can mechanical tests using full-field techniques such as IR/DIC **at quasi-static rates and temperatures,** provide a better understanding of the conversion of plastic work to heat?

[4] Karlson et al., Int. J. Frac, 2016

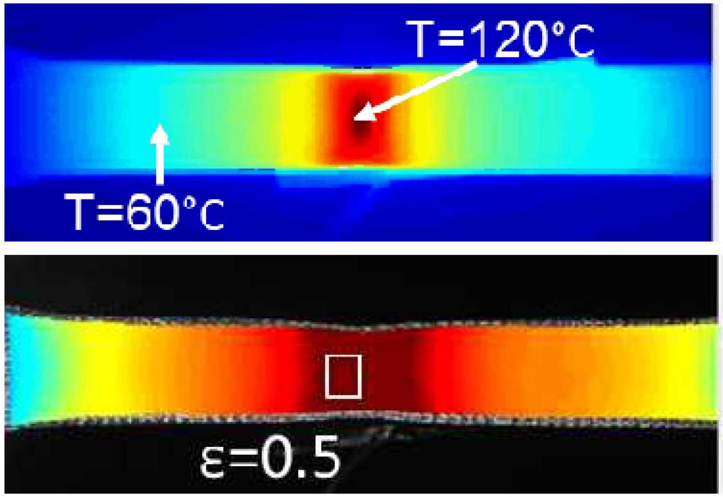
Specimen Design and Material Properties

304L Stainless Steel Tensile Flat Sheet Dogbone



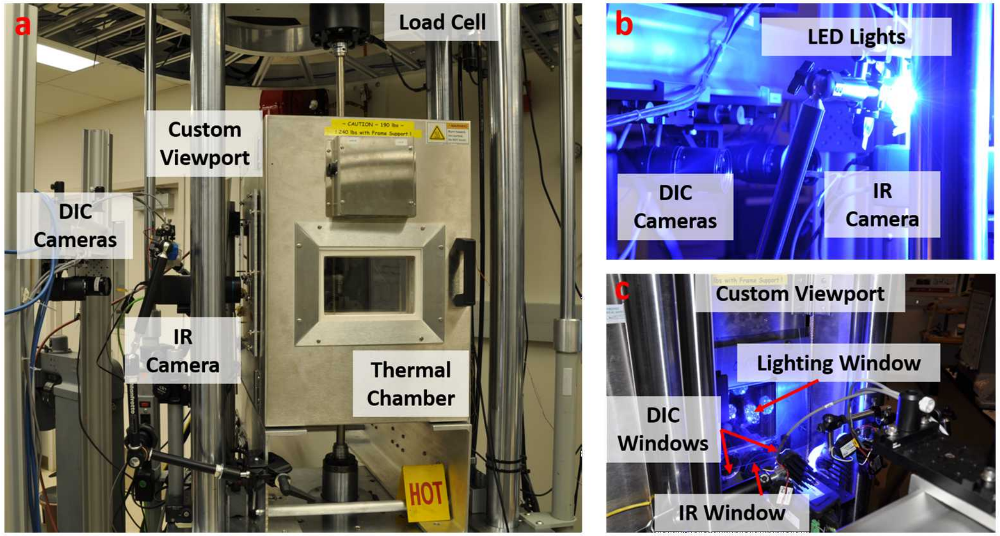


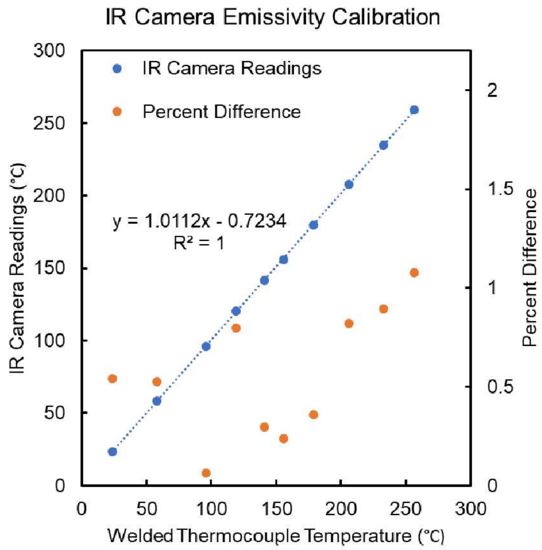
304L SS is ideal material from a signal to noise perspective



Experimental Approach

Tensile tests were performed on 304L SS with synchronized **digital image correlation (DIC)** and **infrared (IR)** thermography measurements at two strain rates, **0.002 s^{-1} and 0. 08 s^{-1}**, and two temperatures, **room temperature and 250°C**

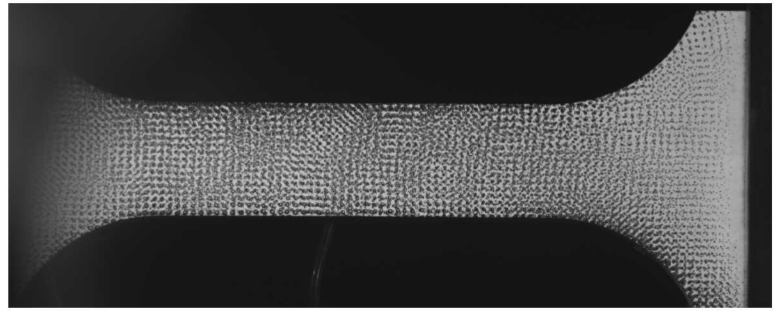




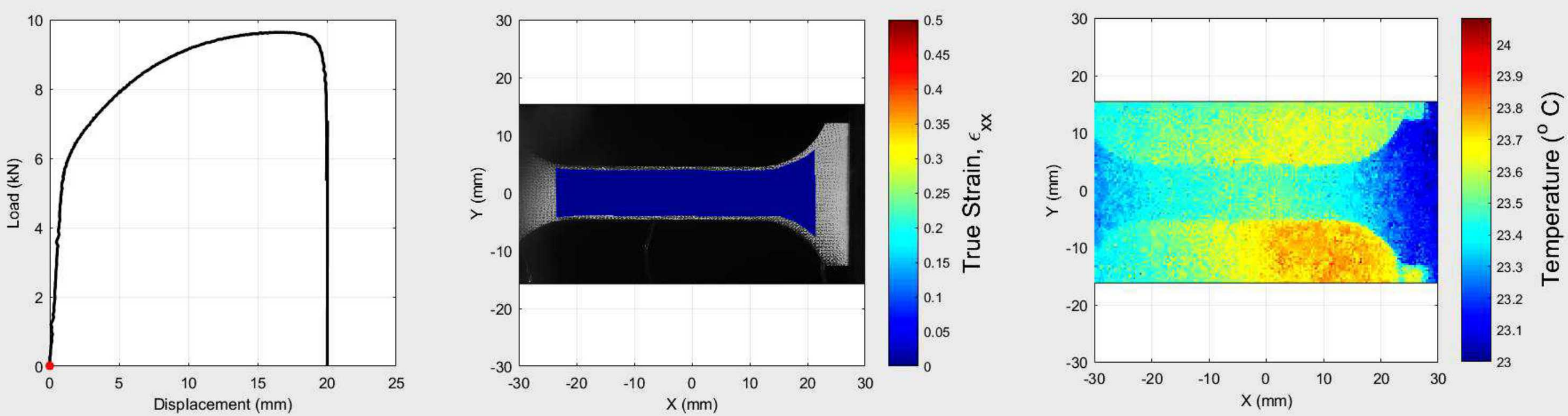
Specimen Temperature	FOV (pix/mm)	Noise Floor					
		U (mm)	V (mm)	W (mm)	$\varepsilon_{xx}(\mu\varepsilon)$	$\varepsilon_{yy}(\mu\varepsilon)$	$\varepsilon_{xy}(\mu\varepsilon)$
RT	20.92	0.0040	0.0009	0.0056	214	190	141
250^oC	20.92	0.0058	0.0053	0.0222	1275	1063	705

Simultaneous IR/DIC Results

DIC and IR both on the front surface



Representative data for a RT, fast strain rate (0. 08 s^{-1}) tensile test of 304L stainless steel



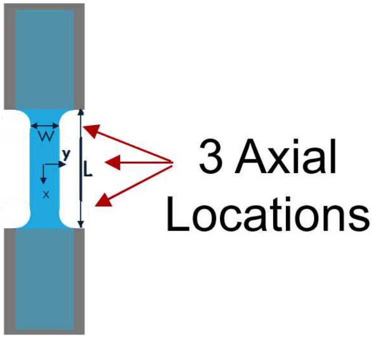
Application of Simultaneous IR/DIC full-field data

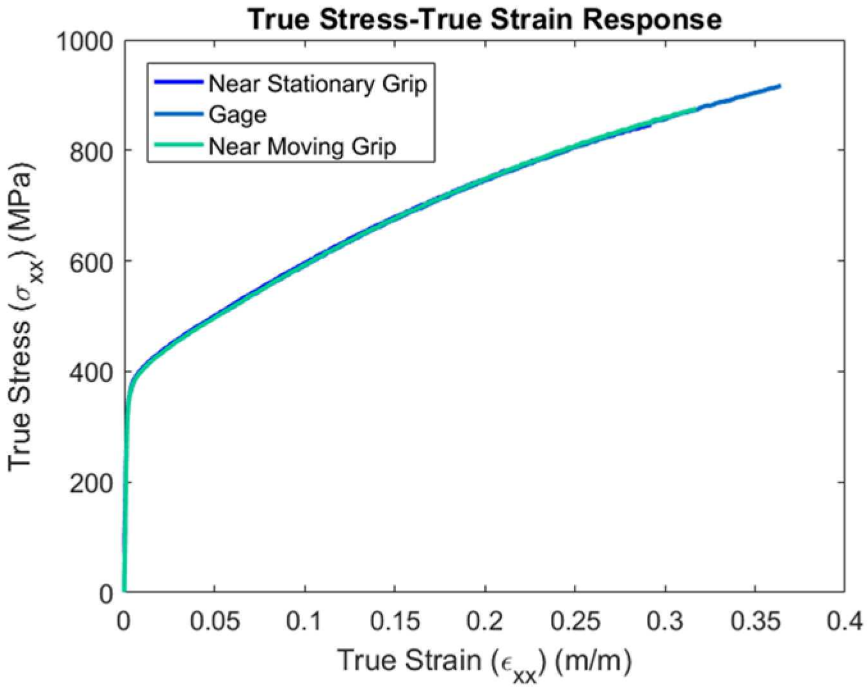
1-D Lagrangian Formulation

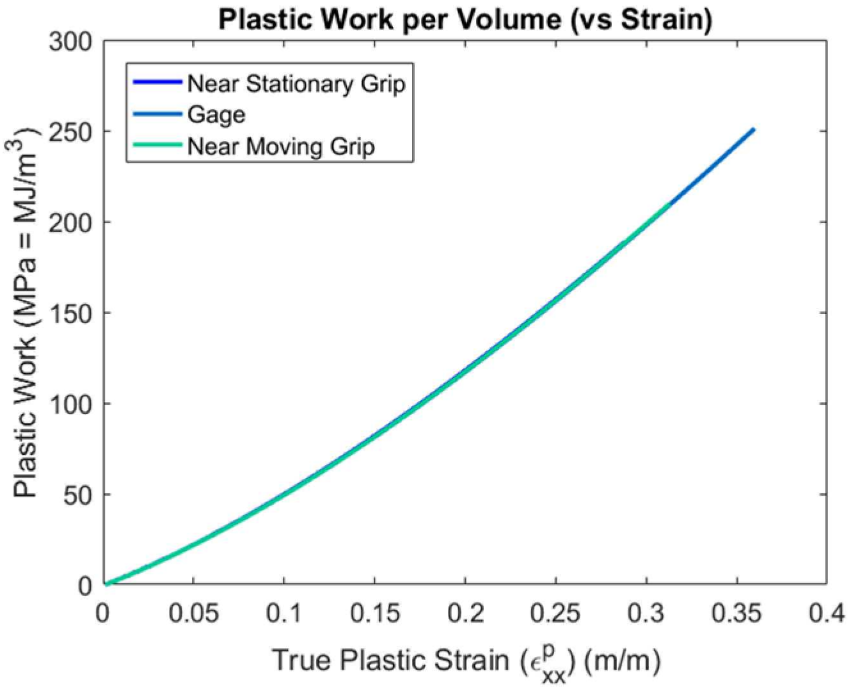
$$\beta = \frac{\dot{Q}^p}{\dot{W}^p}$$

Plastic Work

$$\dot{W}^p = \frac{\partial}{\partial t}\int_0^{\varepsilon^p} \sigma \partial \varepsilon^p$$







Assumes 1D state of stress; data truncated after peak stress

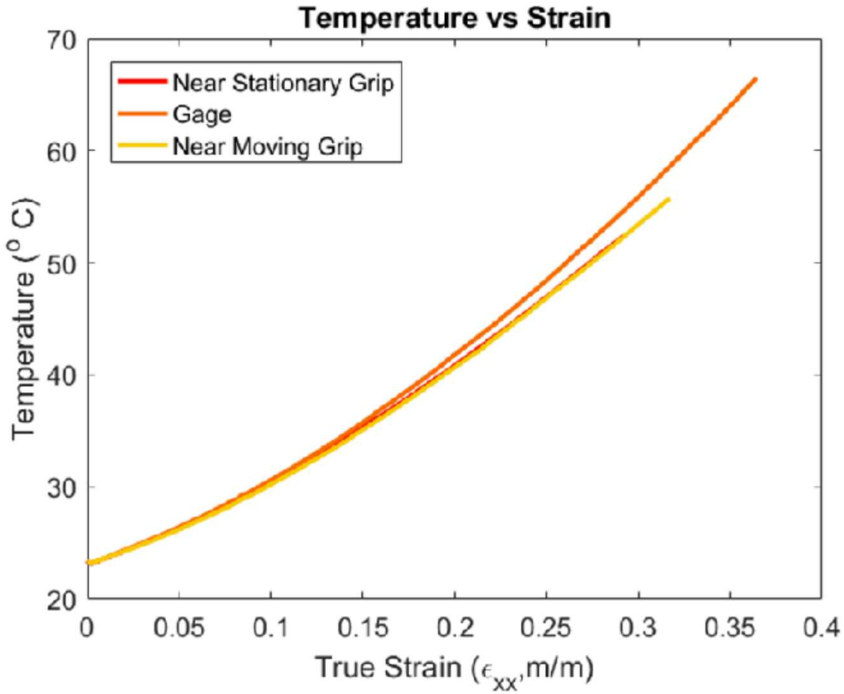
Acknowledge Elizabeth Jones for code development

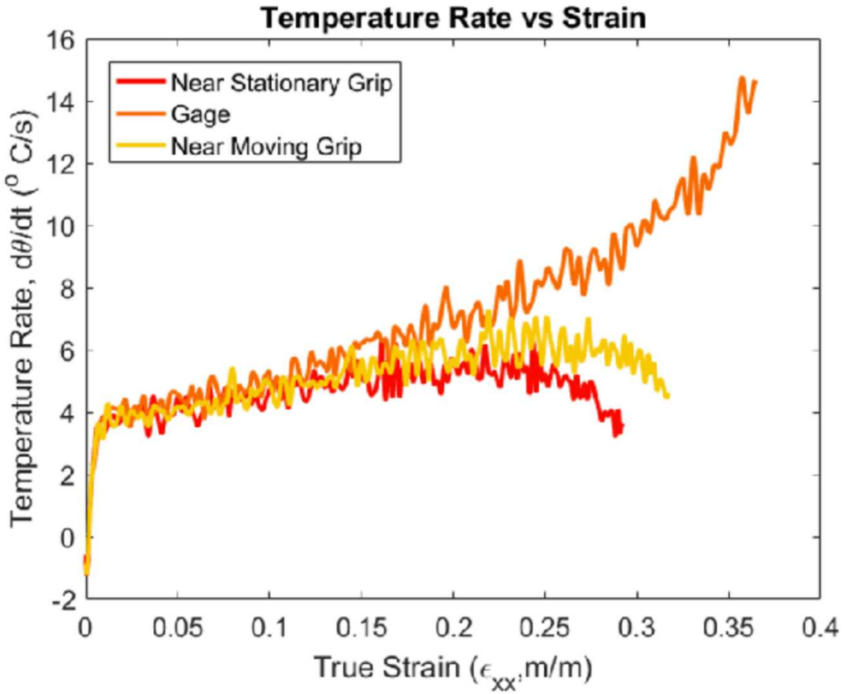
Application of Simultaneous IR/DIC full-field data

1-D Lagrangian Formulation

$$\beta = \frac{\dot{Q}}{\dot{W}^p} = \frac{1}{\dot{W}^p}\left[\rho c\dot{\theta} - k\theta_{xx} + \frac{A_s}{V}\left[h(\theta - \theta_\infty) + \hat{\sigma}\tilde{\varepsilon}(\theta^4 - \theta_\infty^4)\right]\right]$$

Plastic Work **Heat Storage**



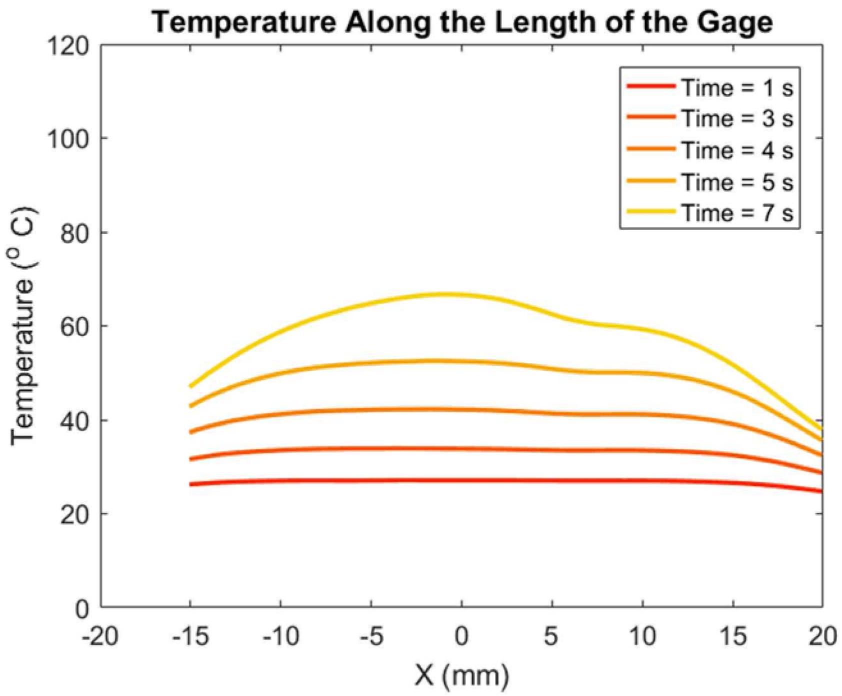


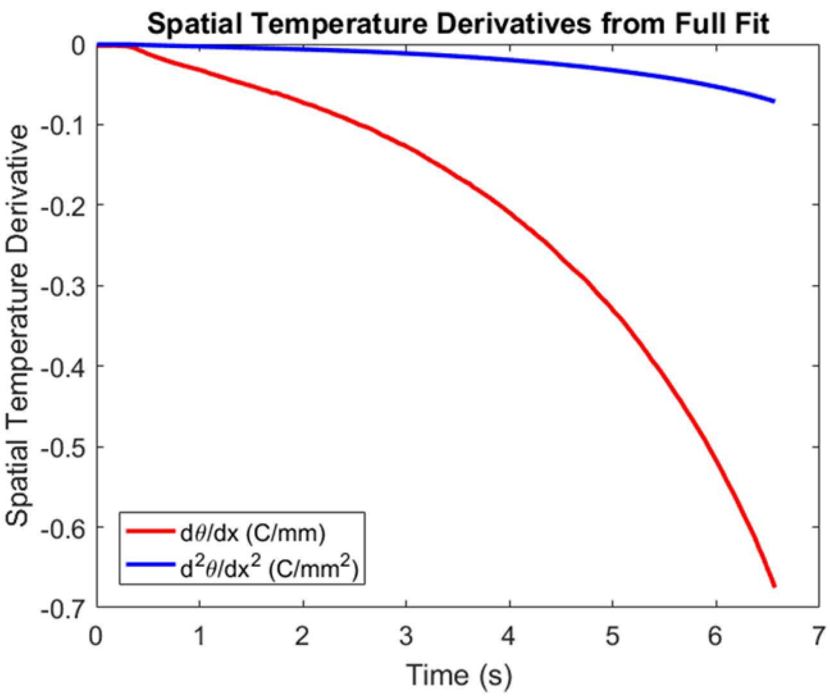
Application of Simultaneous IR/DIC full-field data

1-D Lagrangian Formulation

$$\beta = \frac{\dot{Q}}{\dot{W}^p} = \frac{1}{\dot{W}^p}\left[\rho c\dot{\theta} - k\theta_{xx} + \frac{A_s}{V}\left[h(\theta - \theta_\infty) + \hat{\sigma}\tilde{\varepsilon}(\theta^4 - \theta_\infty^4)\right]\right]$$

Plastic Work **Heat Storage** **Conduction**



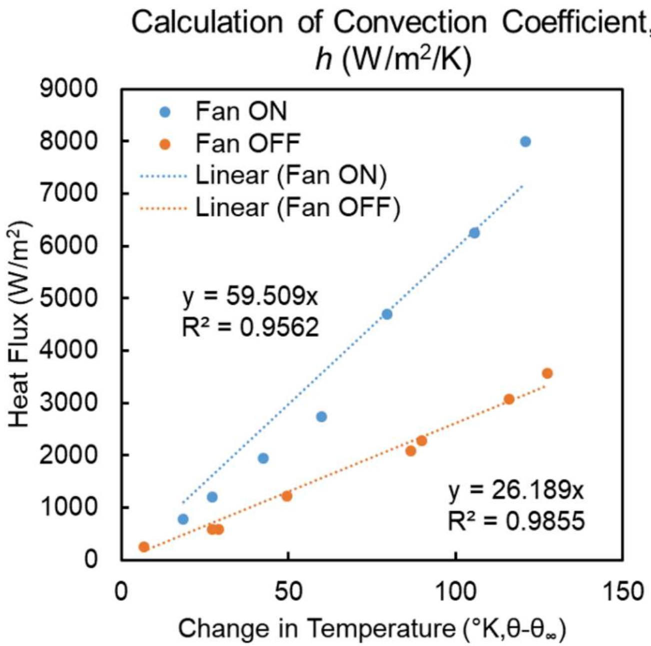


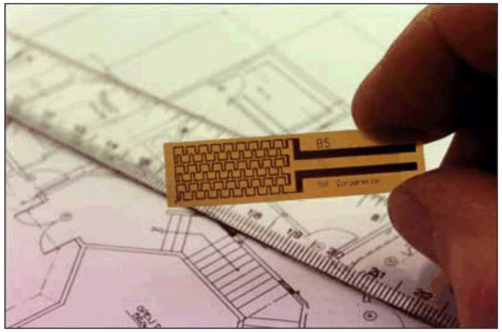
Application of Simultaneous IR/DIC full-field data

1-D Lagrangian Formulation

$$\beta = \frac{\dot{Q}}{\dot{W}^p} = \frac{1}{\dot{W}^p}\left[\rho c\dot{\theta} - k\theta_{xx} + \frac{A_s}{V}\left[h(\theta - \theta_\infty) + \hat{\sigma}\tilde{\varepsilon}(\theta^4 - \theta_\infty^4)\right]\right]$$

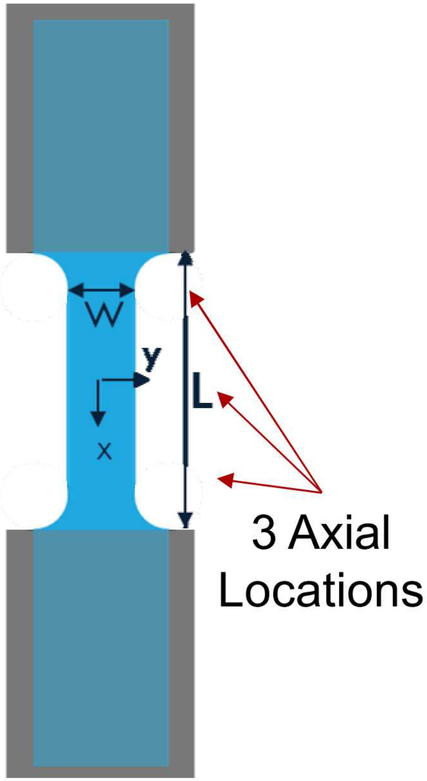
Plastic Work **Heat Storage** **Conduction** **Convection** **Radiation**



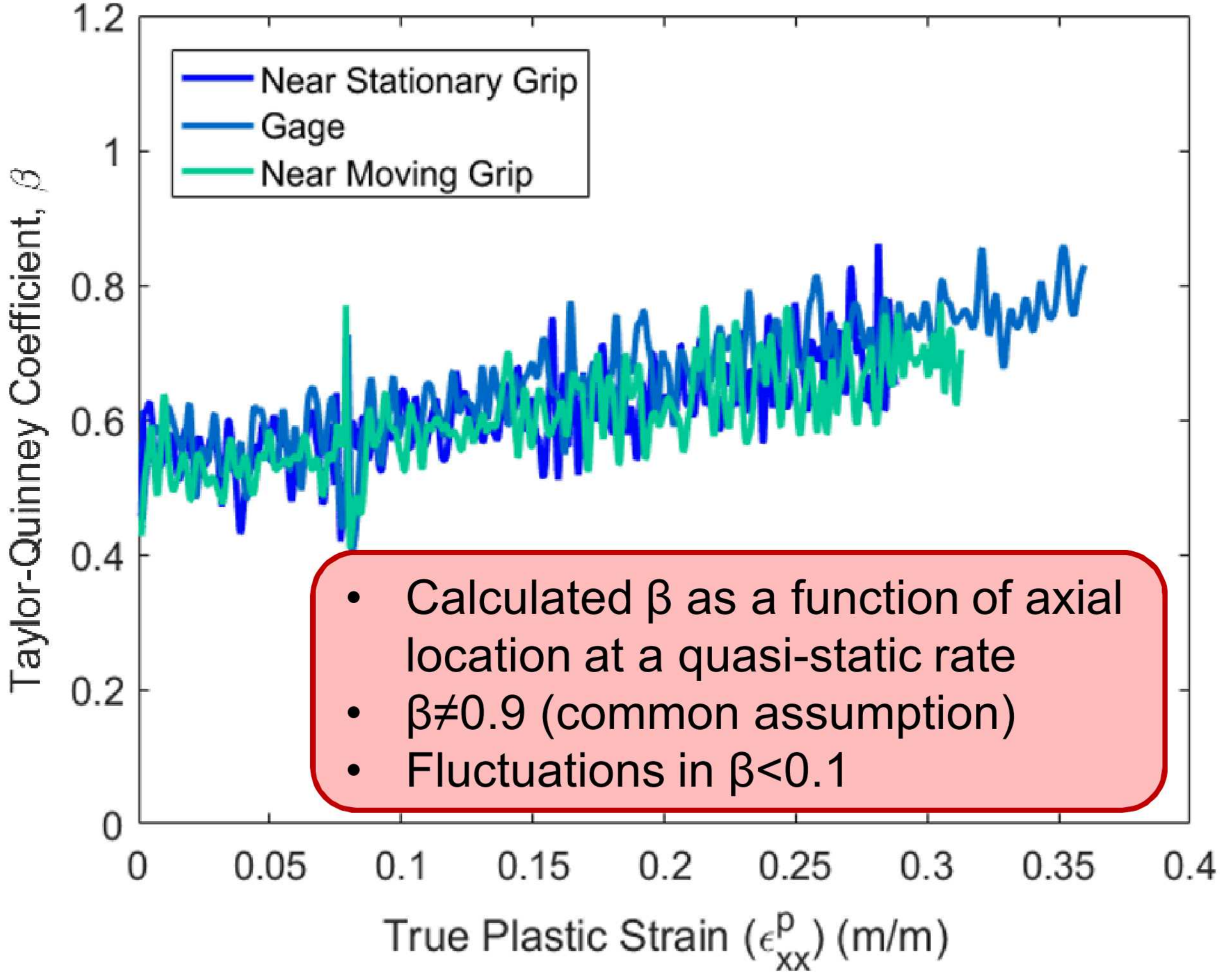


Heat flux sensor- RdF corp

β as a function of Plastic Strain

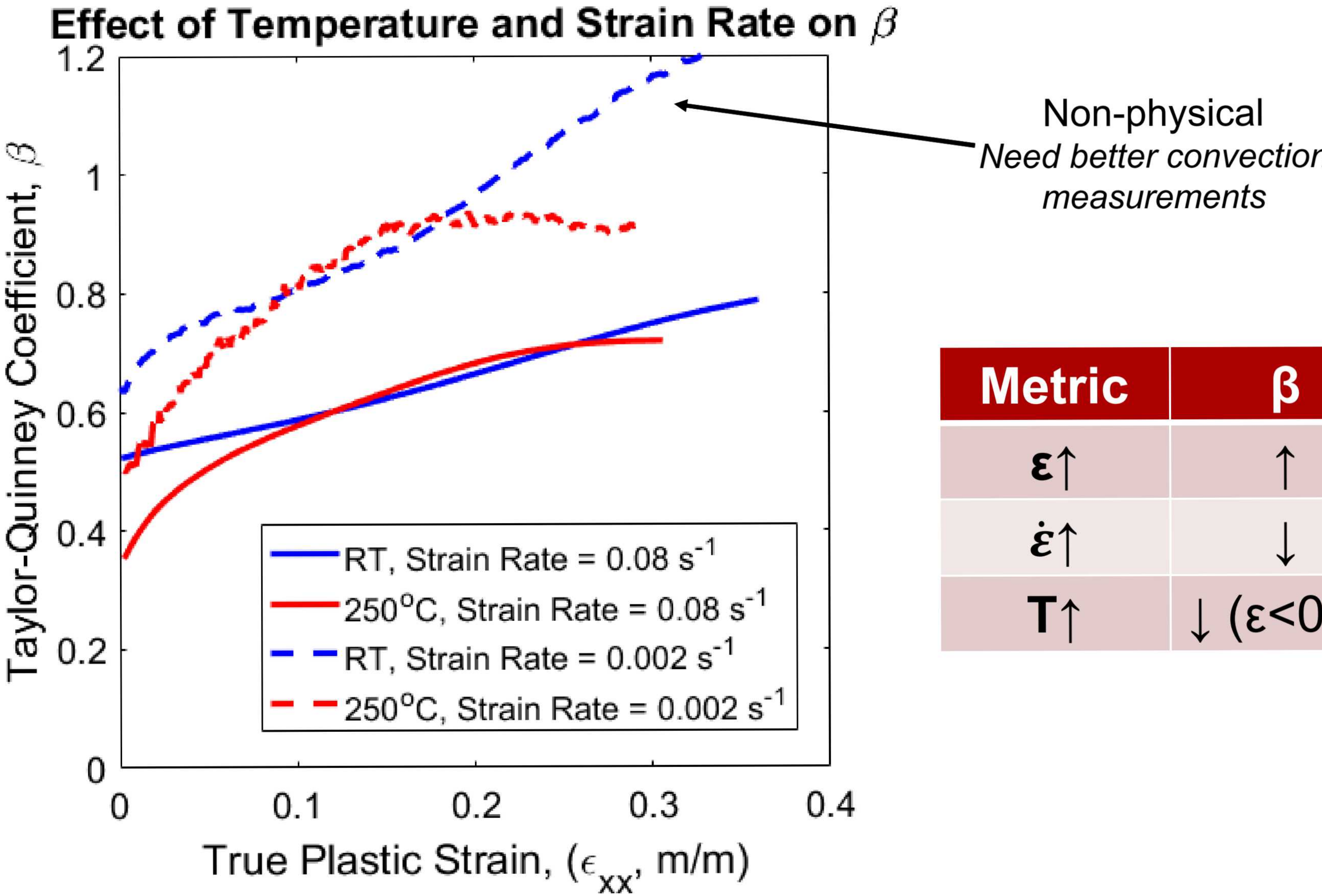


Calculation of β for 304L at room temperature and a strain rate of 0.08 s^{-1}



- Calculated β as a function of axial location at a quasi-static rate
- β≠0.9 (common assumption)
- Fluctuations in β<0.1

Effect of ϵ, $\dot{\epsilon}$, and T on β



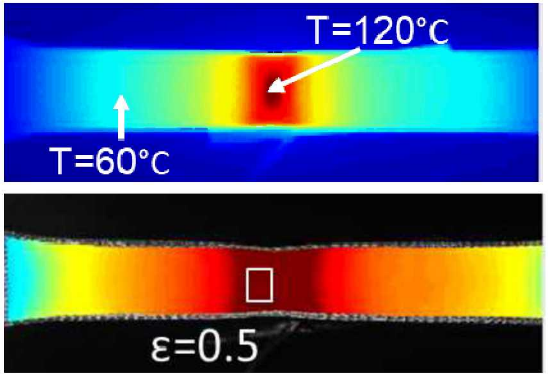
Metric	β
ε↑	↑
$\dot{\varepsilon}$↑	↓
T↑	↓ (ε<0.1)

Areas for Improvement

- Experimental design
  - Minimize heat losses to environment ~ minimize surface area *or* maximize signal to noise ratio
  - Use of a convection oven→ heat waves and complex convection environment
  - Used paint to apply DIC speckle pattern and provide high emissivity for IR camera
- Application of results
  - "Slow quasi-static" rate selected still had issues with heat losses to environment
  - IR camera resolution was worse than DIC cameras; interpolation required
  - Only had 1-D force measurements
    - Averaged through the width
    - Assumed constant through the thickness to get to volumetric quantities

Summary

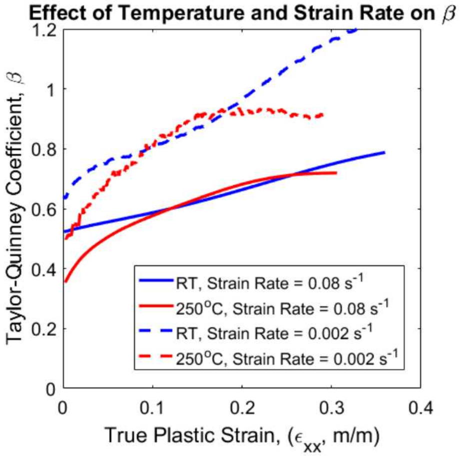
- Quasi-static thermomechanical tests were conducted with DIC/IR which was mapped to the same coordinate system



- Full-field data was utilized to estimate β, a parameter describing the conversion of plastic work to heat, which is important for thermomechanical modeling

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

- Results showed β varied with strain, strain rate, and environmental temperature, which is consistent with literature results



Reporting Requirements

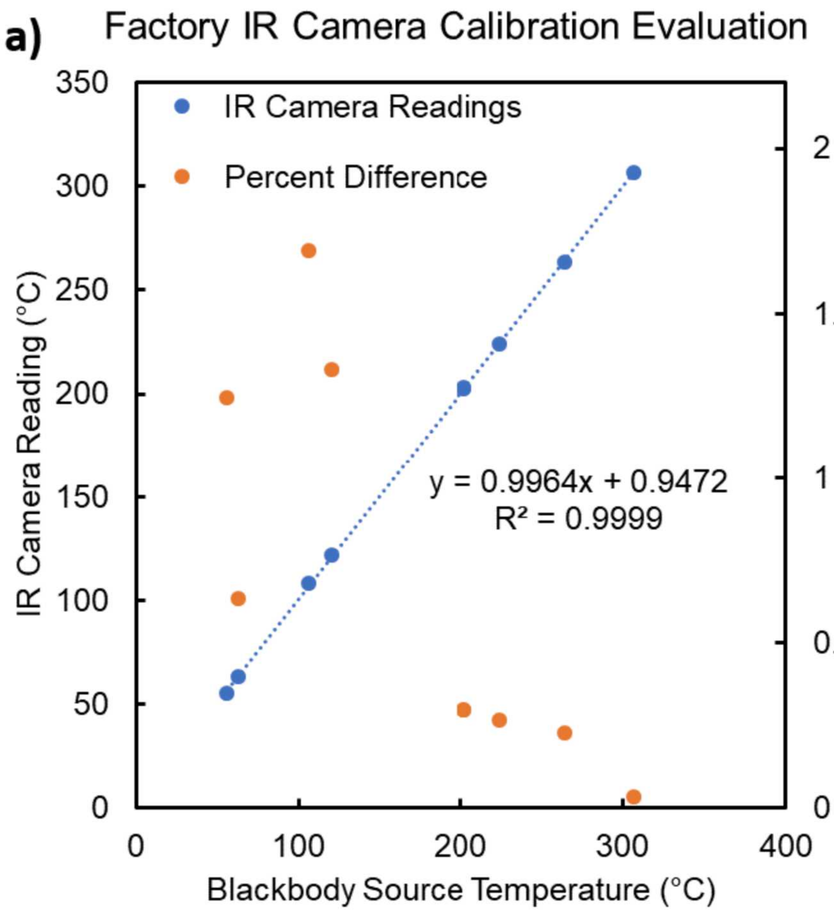
Parameter	Value
Camera Manufacturer and Model	2.5MP Grasshhopper USB3.0
Lens	Edmund Optics 75mm
FOV	90 mm x 57 mm
Image Scale	20.9 pix/mm
Stereo Angle	22 degrees
SOD	60 cm
Image Aq Rate	60 fps
Patterning technique	White paint background with black spray paint speckles (elevated temp) or stamp speckles (RT)
Pattern Size	0.19 mm

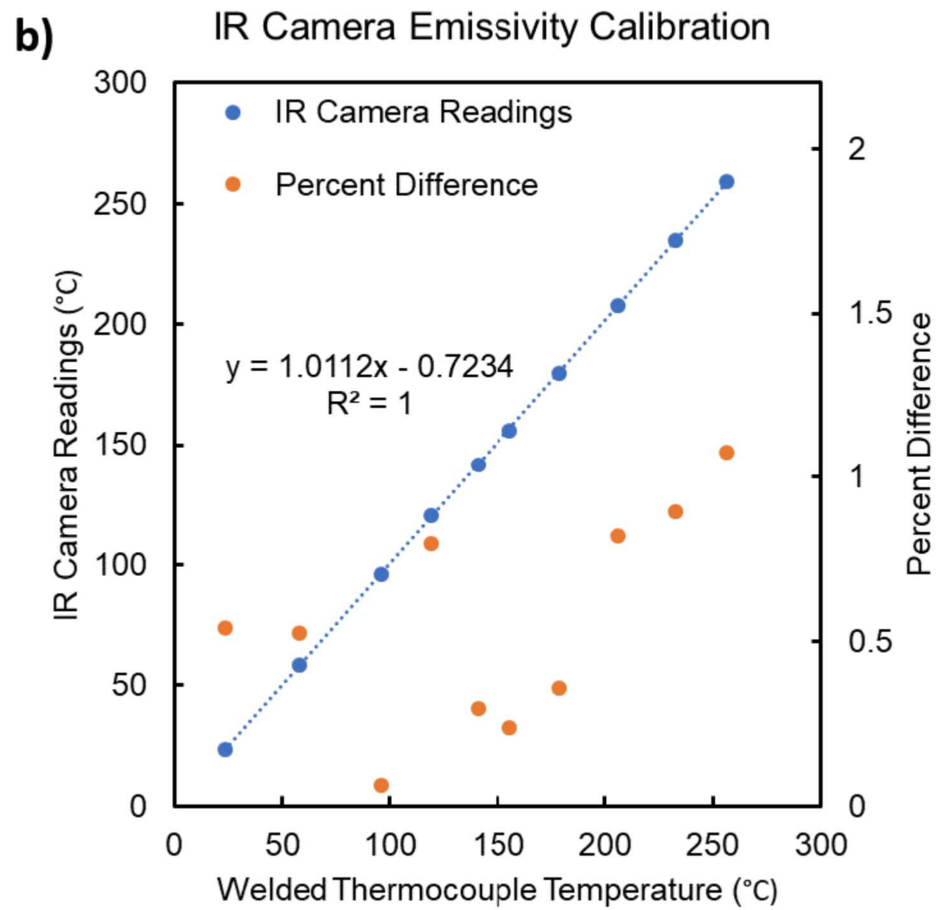
Reporting Requirements

Post-processing Parameter	Setting
DIC Type	3D
Analysis Code	VIC-3D 8
Incremental Analysis?	None
Subset Weights	Gaussian
Correlation Interpolation Type	Optimized 8-tap
Correlation Criterion	ZNSSD
Subset Size (pixels)	25
Step Size (pixels)	3
Strain Type	Hencky
Strain Window	7

*Low-pass filtering was applied

IR Calibration





Summary of Mechanical Properties

Specimen	Displacement Rate (mm/sec)	Nominal Eng. Strain Rate (ε/sec)	Oven Temperature (^oC)	Peak Stress (MPa)	Strain at Peak (mm/mm)	Strain at Failure (mm/mm)	Max. Temperature (^oC)
Beta-S8	0.0635	0.002	*RT*	788.5	0.57	0.67	76.2
Beta-S9	0.0635	0.002	*RT*	786.6	0.57	0.69	69.7
Beta-S12	0.0635	0.002	*RT*	789.7	0.55	0.67	64.8
Beta-s10	2.54	0.08	*RT*	781.4	0.38	0.49	> 150
Beta-S24	2.54	0.08	*RT*	786.3	0.40	0.50	> 150
Beta-S16	0.0635	0.002	250	475.3	0.31	0.39	259.2
Beta-S20	0.0635	0.002	250	470.1	0.31	0.40	266.3
Beta-S18	2.54	0.08	250	472.2	0.31	0.39	303.8
Beta-S22	2.54	0.08	250	477.6	0.31	0.38	294.5

Summary of QOI