MECHANICAL, THERMO-MECHANICAL, AND METALLURGICAL COMPARISON BETWEEN WAAM AND BULK SS316L

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Introduction to Wire and Arc Additive Manufacturing (WAAM)

- Regular welding machine and wire.
- Maneuvering the melt pool.
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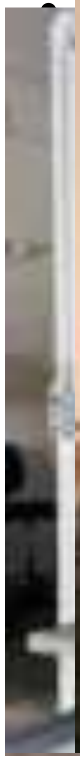
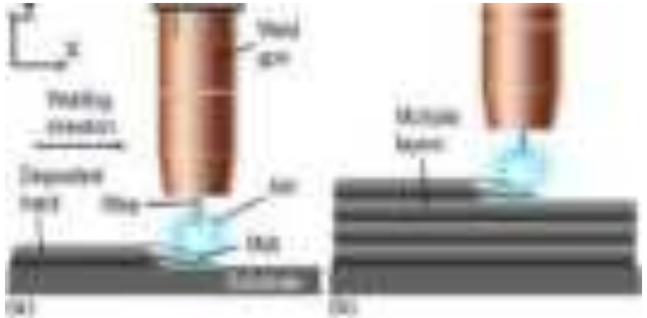
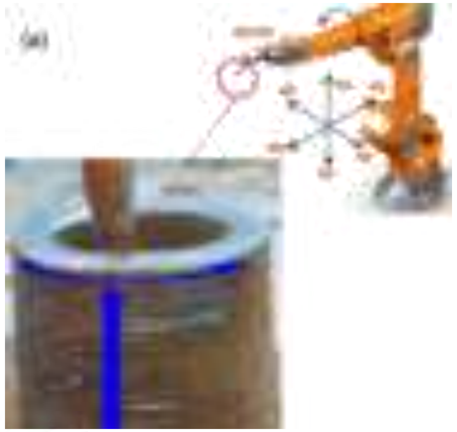




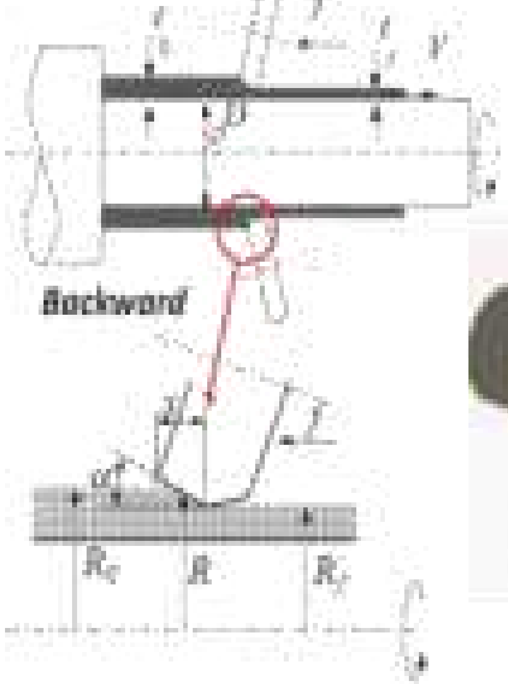
Starting point

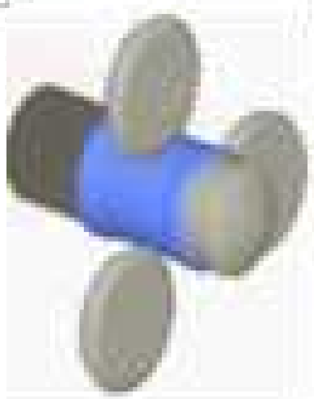
- Shirizly and Dolev in 2019: First plastic deformation of AM – flow forming



- Very high UTS

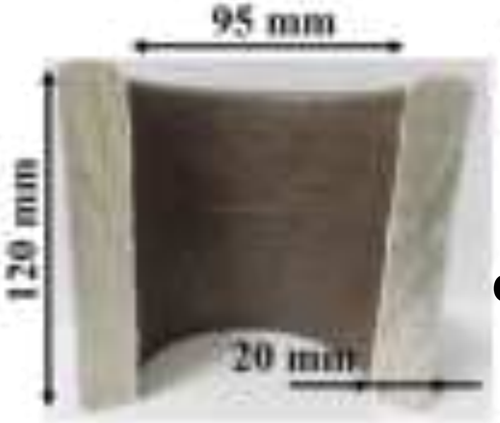
- **Many questions left open:** Loading, UTS, RS, anisotropy, TQC, bulk

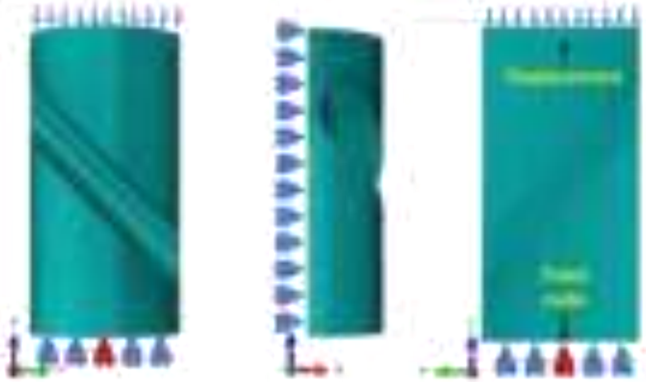




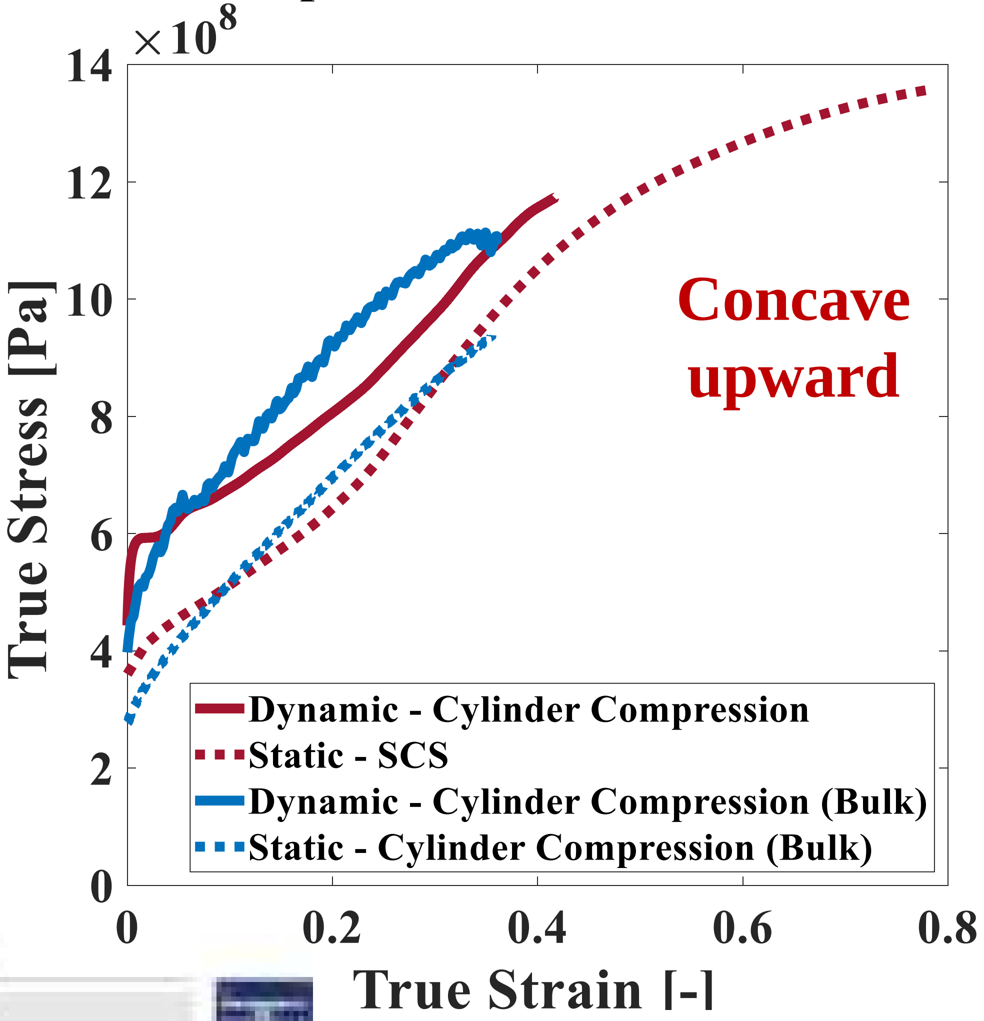
Preliminary mechanical properties

- Thick-walled WAAM cylinder made of SS316L.
- Static (10^{-3} 1/s) and dynamic ($\sim 10^{3}$ 1/s) conditions.
- Compared to bulk material.



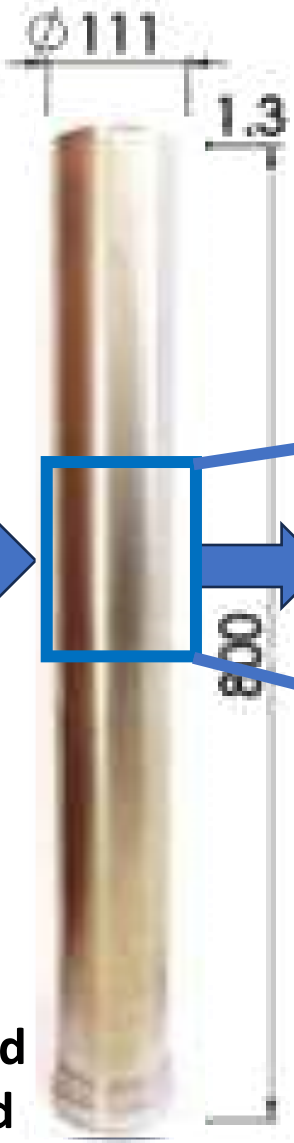


SS316L - WAAM and bulk : Concave upward Vs. annealed behavior

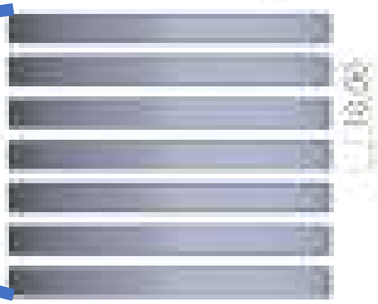


Application of WAAM material through case study – UTS and residual stresses

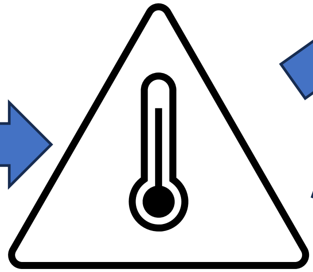
WAAM Thick-walled cylinder



Flow-formed Thin-walled tube



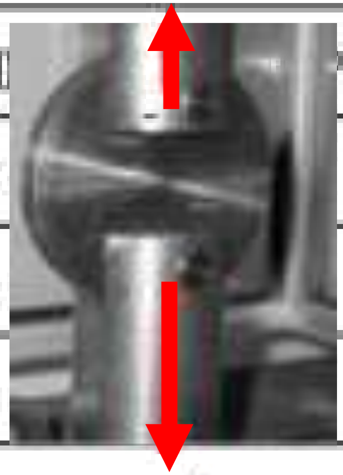
Sliced rings



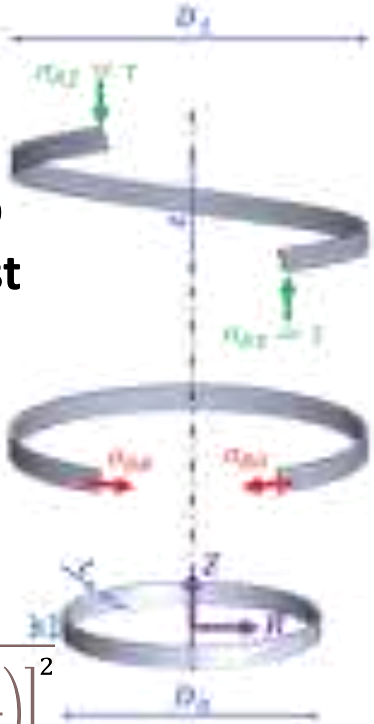
Heat treatments

Ring hoop tension test

Material	Furnace	No HT	400 °C	60… °C
Bulk	Air	✓		
WAAM	Vacuum	✓		
WAAM	Air	✓	X	

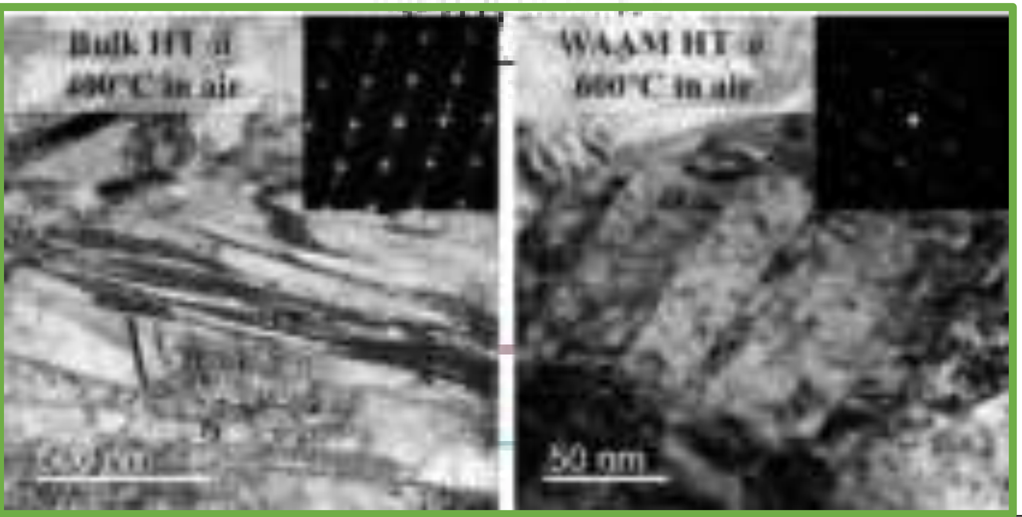


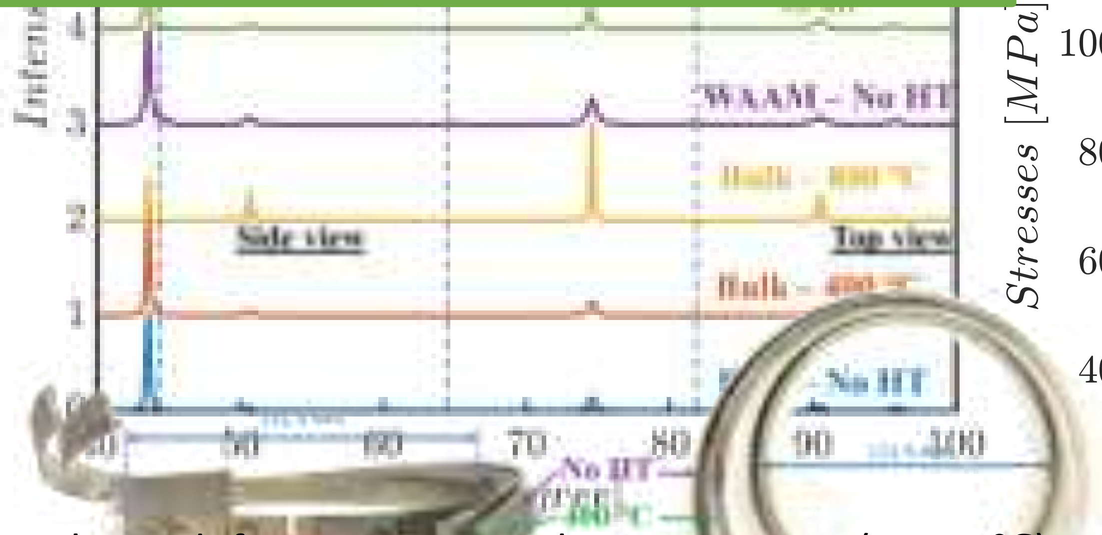
Ring hoop tension test

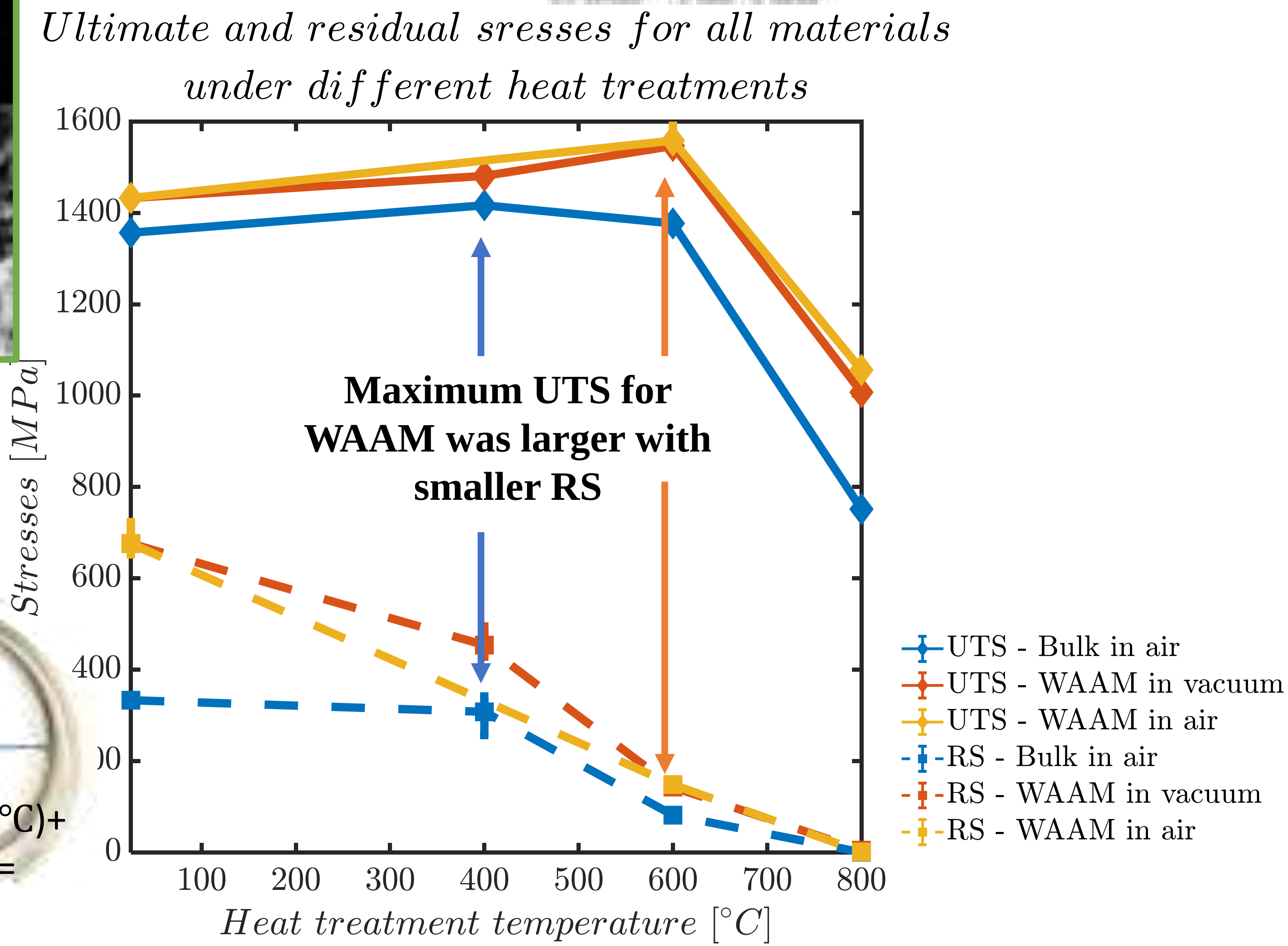


$$\sigma_e = \sqrt{\sigma_\theta^2 + 3\tau^2} = \sqrt{\left[\frac{E}{1-\nu^2}\left(\frac{1}{D_0} - \frac{1}{D_1}\right)\right]^2 + 3\left[\frac{FD_0(3t+1.8w)}{2t^2w^2}\left(1 + \frac{1.2}{c} + \frac{0.56}{c^2} + \frac{0.5}{c^3}\right)\right]^2}$$

Results – UTS and residual stresses





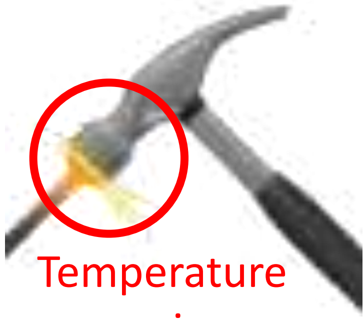


Plastic deformation + no phase transition (≤ 600 ℃)+ moderate HT temperature → **anneal-hardening** = Additional increase in UTS (~$\mathbf{1600}\boldsymbol{MPa}$)

Thermo-mechanical coupling: the Taylor-Quinney coefficient (TQC)

- Under dynamic loading - adiabatic conditions

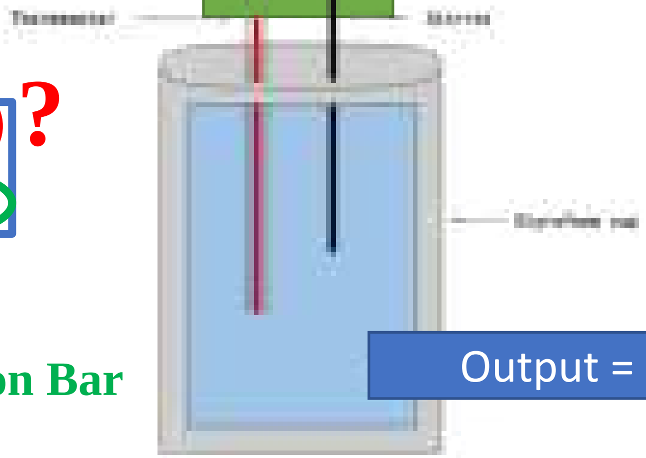
- Integral Taylor-Quinney coefficient (TQC or β_{int}).



Temperature rise

Impact /twist= plastic work

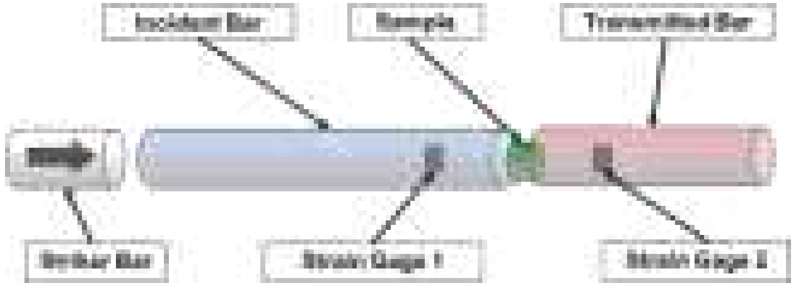
Deformed shape



$$\beta_{int} = \frac{generated\ heat\ (output)}{plastic\ work\ (input)} = \frac{\rho C_p \Delta T}{\int \sigma d\varepsilon^p}$$

?

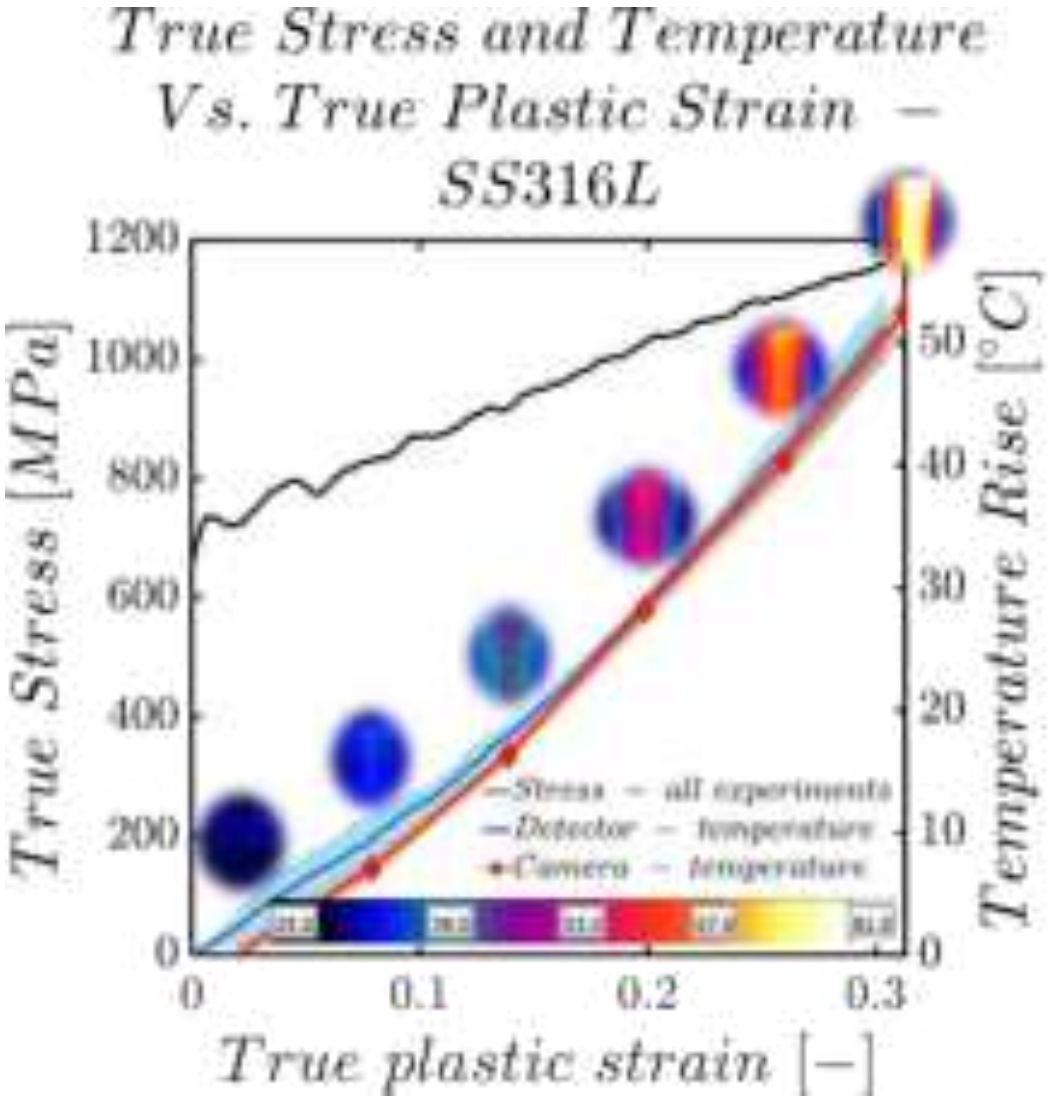
Split Hopkinson Bar



Output = heat

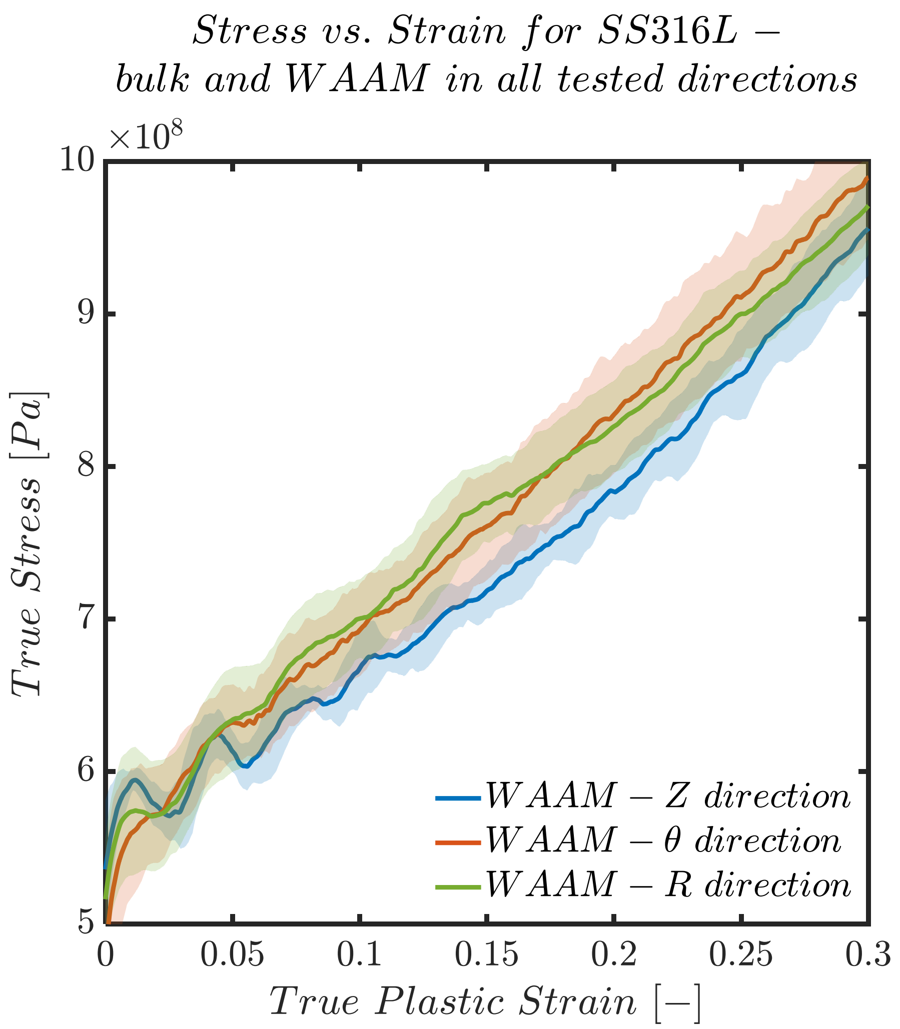
Introduction to thermo-mechanical coupling by TQC

Comparing performance

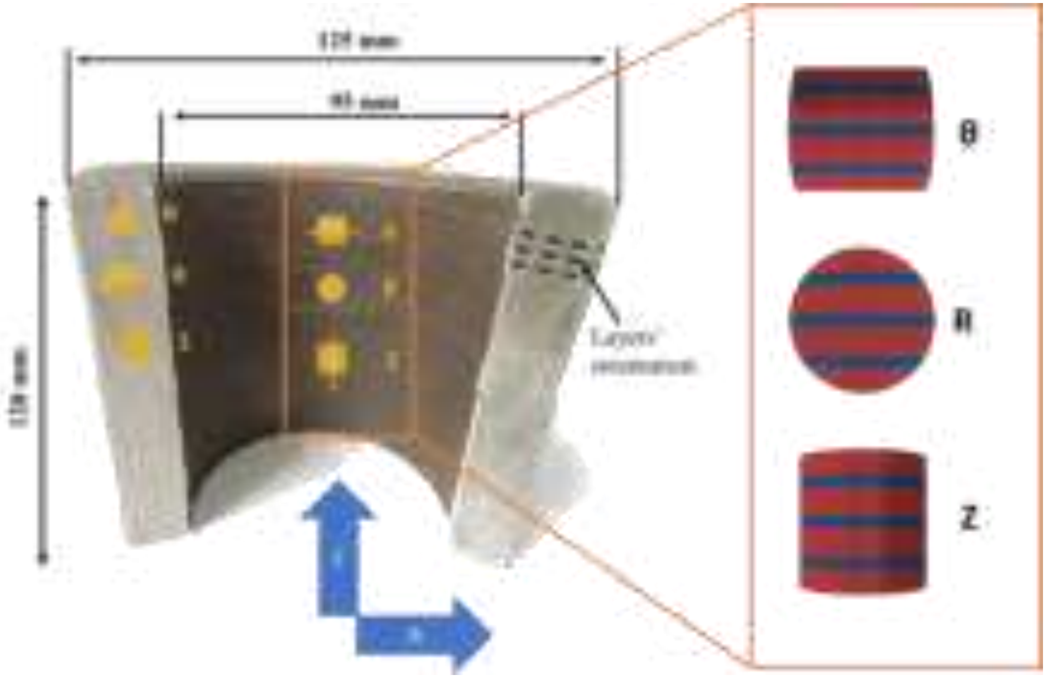


Investigation of an anisotropic material's TQC

Results



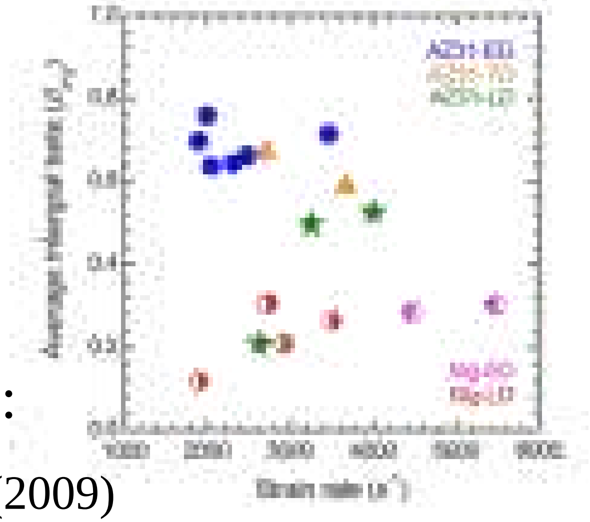
- A thick-walled cylinder was made of SS316L by WAAM.
- Dynamic loading (~10^3 1/s) conditions.



Investigation of an anisotropic material's TQC

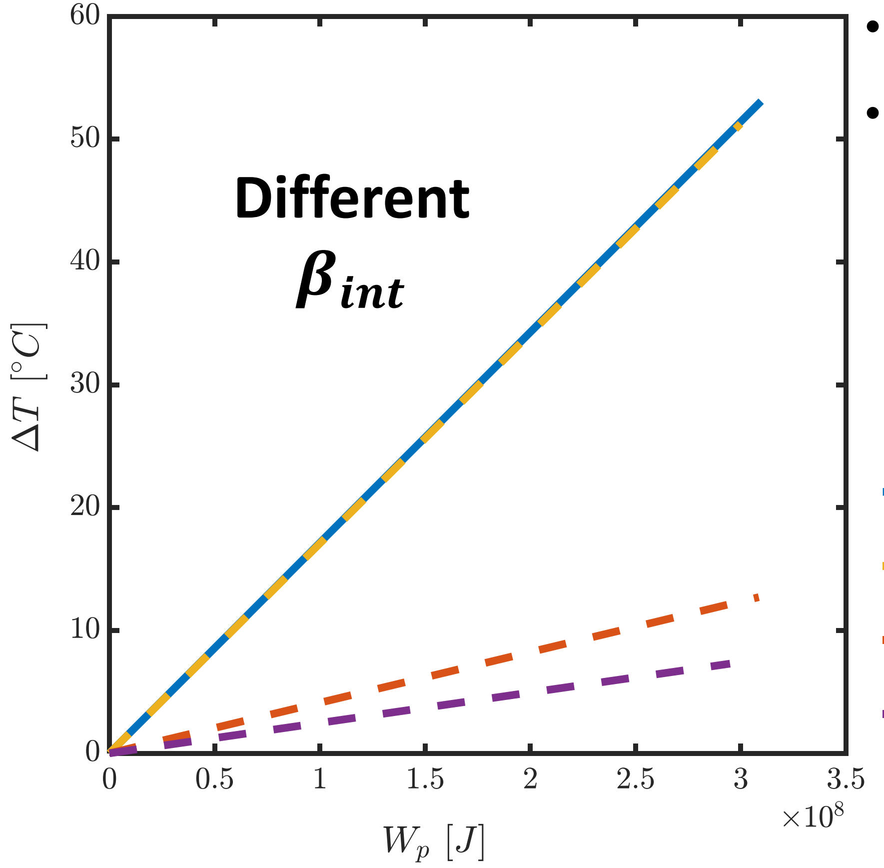
Results

- TQC using ***average*** stress-strain – scattering values
- This calculation method was used on anisotropic materials in previous studies:

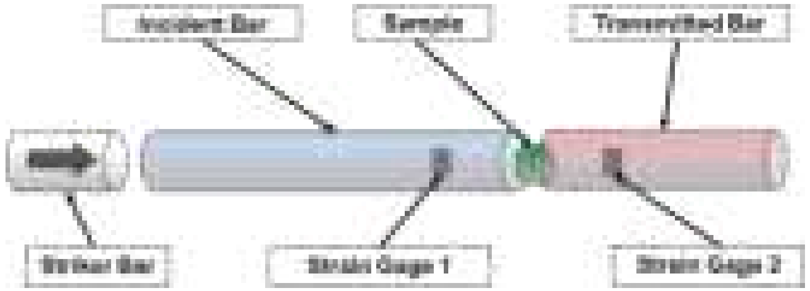


- Rittel, D., Silva, M. L., Poon, B., & Ravichandran, G. (2009)
- Ghosh, D., Kingstedt, O. T., & Ravichandran, G. (2017)
- Kingstedt, O. T., & Lloyd, J. T. (2019).

Linear interpolation for ΔT vs. Plastic work



- Major #1 - β_{int}=0.69, R^2=1.00
- Major # 2 - β_{int}=0.68, R^2=0.99
- Minor #1 - β_{int}=0.16, R^2=0.98
- Minor # 2 - β_{int}=0.10, R^2=0.96



$$\varepsilon = -2\frac{C_B}{L_S}\int_0^t \varepsilon_R\, dt \qquad \sigma = \frac{A_B}{A_S}E_B\varepsilon_T$$

$$\boxed{\beta_{int} = \frac{generated\ heat\ (output)}{plastic\ work\ (input)} = \frac{\rho C_p \Delta T}{\int \sigma d\varepsilon^p}}$$

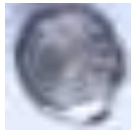
Investigation of an anisotropic material’s TQC

Results

- One overlooked point – major and minor diameters deform differently, hence use ***local*** instead of ***average*** stress-strain

<u>Temperature map for isotropic ductile material:</u>

Bulk
Annealed

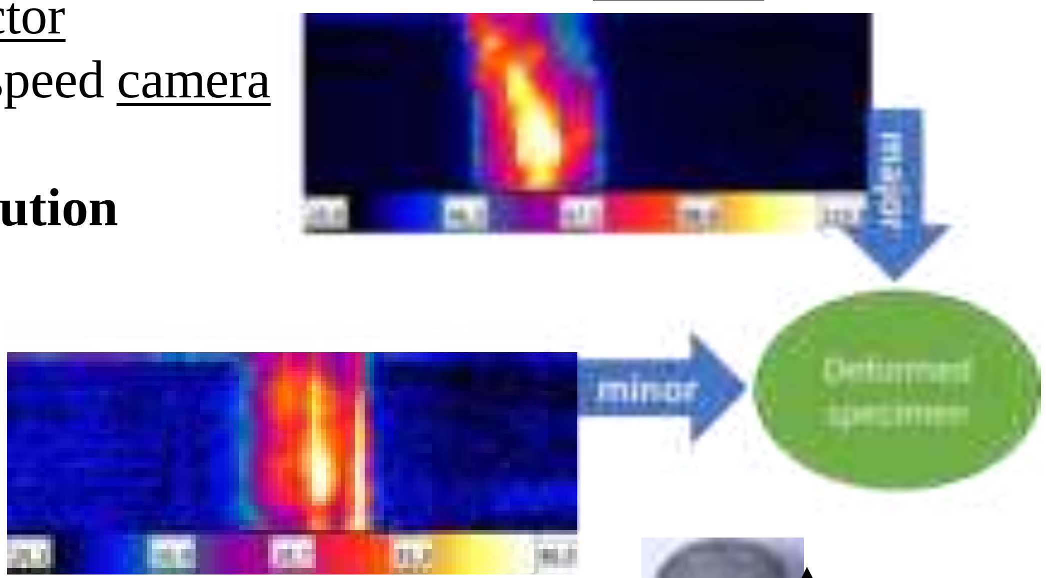


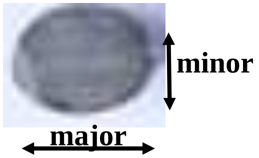
WAAM
Z direction

Previously: IR <u>detector</u>
Currently: IR high-speed <u>camera</u>

Better spatial resolution

<u>Temperature map for anisotropic material:</u>





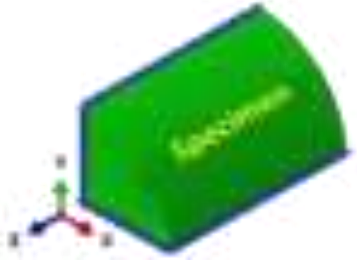
WAAM
R direction

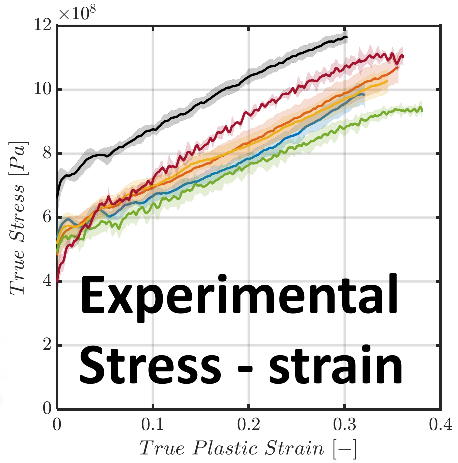
WAAM
θ direction

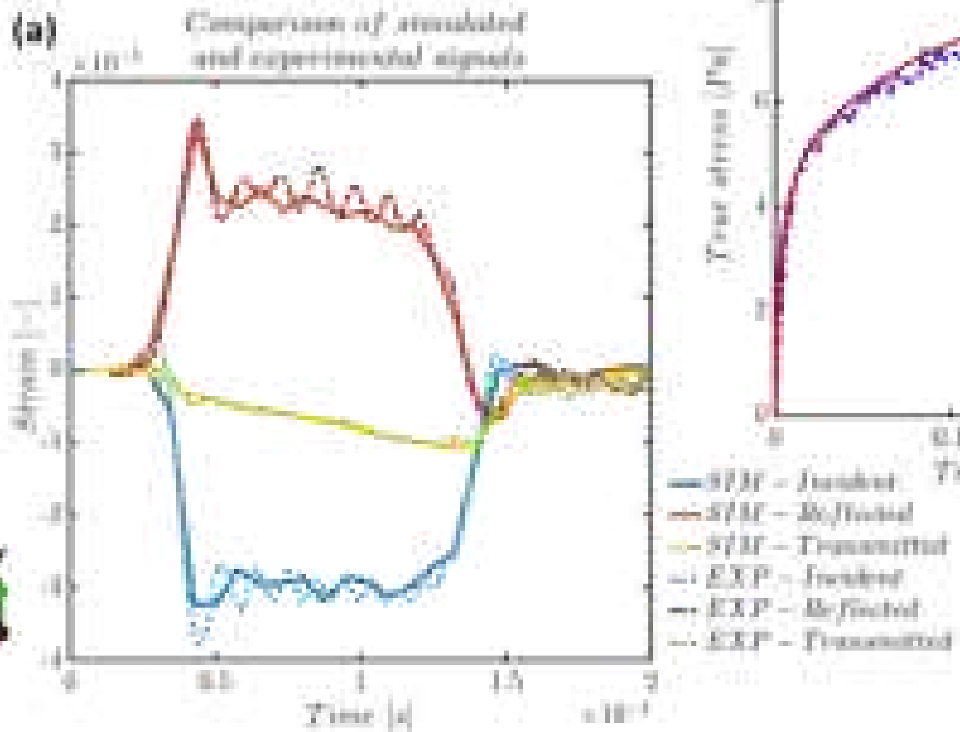
$$\beta_{int} = \frac{generated\ heat\ (output)}{plastic\ work\ (input)} = \frac{\rho C_p \Delta T}{\int \sigma d\varepsilon^p}$$

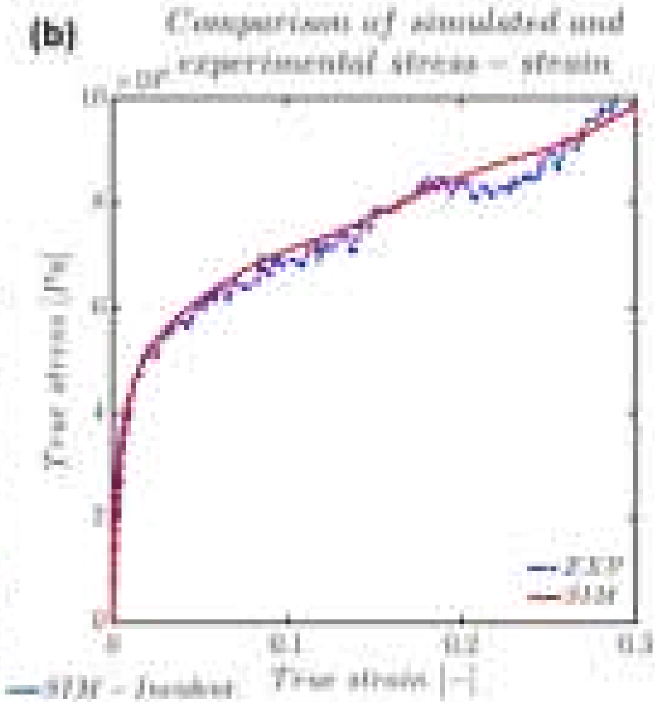
Investigation of an anisotropic material’s TQC
Numerical simulations

- Material’s deformation based on Hill’s plasticity model for anisotropic materials.
- Correlation to the experimental data was verified.



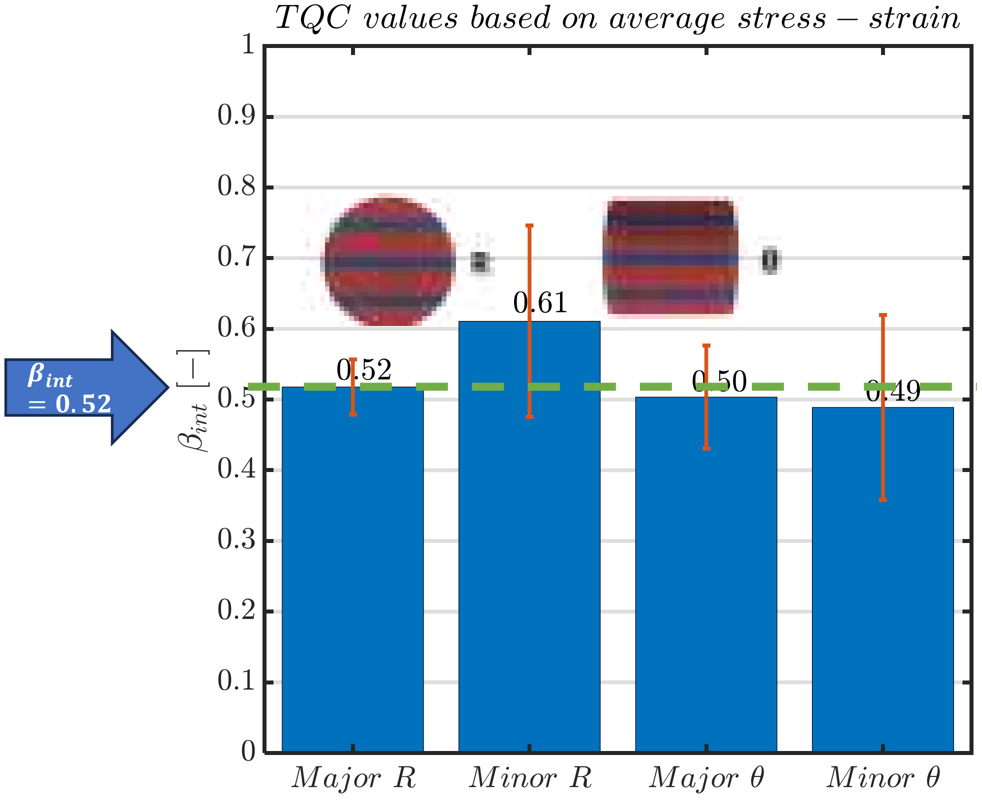




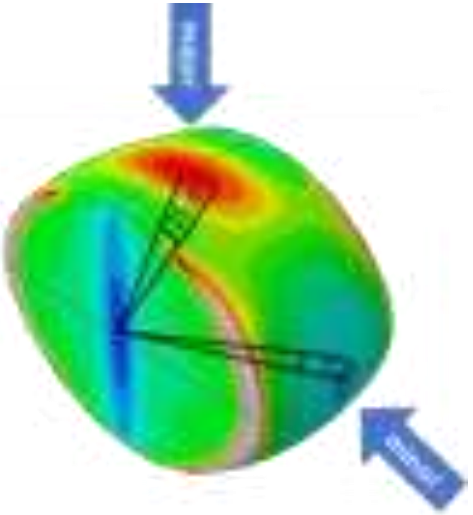


Investigation of an anisotropic material's TQC
Numerical simulations – evaluation of *local* TQC

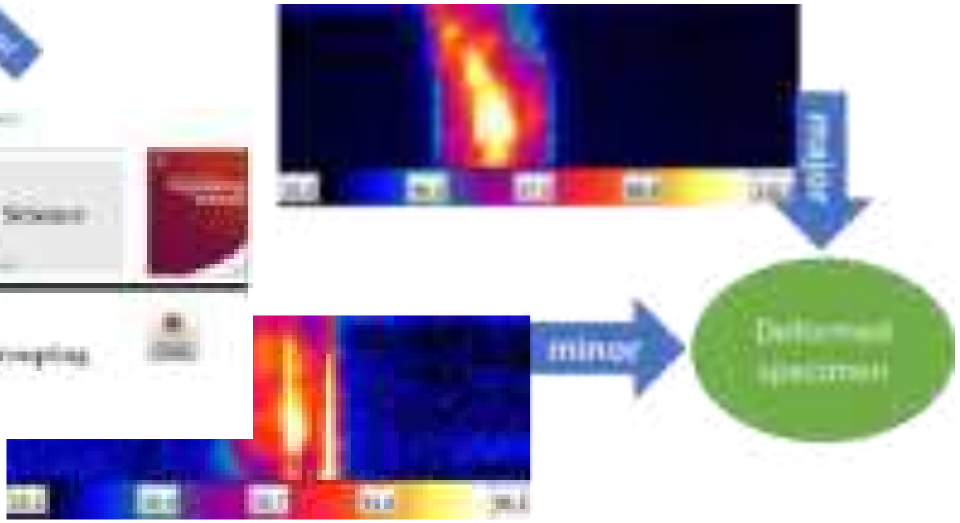
- The ***local*** plastic work and temperature, led to a single TQC for all cases.
- **Simulating $\boldsymbol{\beta_{int} = 0.52}$ reproduces the experimental heat map on the specimen.**



$$\beta_{int} = \frac{generated\ heat\ (output)}{plastic\ work\ (input)} = \frac{\rho C_p \Delta T}{\int \sigma d\varepsilon^p}$$



<u>Conclusion:</u>
<u>The TQC is isotropic even if the material is anisotropic and is a material property</u>



Summary and Conclusions

- Static and dynamic **mechanical properties** were tested, under different loading and in different principal directions
- Activating **nano-twins** deformation mechanism with **anneal-hardening** of WAAM material led to ultra-high ultimate strength ($\boldsymbol{\sigma_{UTS} \approx 1600\ MPa}$) in SS316L material.
- Comparison of high-speed IR **camera** with IR **detectors** presented resemblance in the TQC.
- TQC was found to be **isotropic** regardless of material's **mechanical anisotropy**.

Thank you for listening…

Questions?