Development and Experimental Validation of a Spin Forming Finite Element Model



Elizabeth Urig

Advanced Materials and Processing Branch (D307/AMA)

Research Review Forum

April 21, 2026

Overview

- **Motivation & Background**
  - Spin Forming Motivation
  - Computational Motivation
- **Finite Element Model**
  - Methodology
  - Need for Path-Dependence
- **Experimental Validation**
  - Forming Loads
  - Geometric Agreement
  - Hardness-Plastic Strain Correlation
- **What's Next?**
- **Acknowledgements**



Spin Forming Motivation

- **Integrally stiffened cylinders (ISCs) – Thin cylindrical skin with integrated longitudinal stiffeners**
- **Formation of cryogenic tanks, aircraft fuselage (domes, axisymmetric cylinders, rocket nozzles, etc)**
- **Significant schedule and cost savings predicted in both space and aeronautic applications**
  - Reduce manufacturing time, number of components, and stress concentrators
  - Cryogenic Tanks: 50% cost reduction, 40% schedule reduction, 10% mass savings
  - Aircraft Fuselage: 150 – 200% improvement in manufacturing process rate and reduced cost production, with potential for improved maintenance schedules





10-ft diameter, 5-ft tall ISC formed in 1.5 hours, January 2019

Close-up of stiffeners

"Session Matrix : NASA High-Rate Aerostructures Technology Plans." Accessed February 5, 2021. https://www.sae.org/techSession?EVT_NAME=ADS203&GROUP_CD=TSESS&SCHED_NUM=313029&tab=sessionDetails&REQUEST_TYPE=SESSION_DETAILS.

Stoner, Mary Cecilia, Austin R. Hehir, Marie L. Ivanco, and Marcia S. Domack. "Cost-Benefit Analysis for the Advanced Near Net Shape Technology (ANNST) Method for Fabricating Stiffened Cylinders," May 1, 2016. https://ntrs.nasa.gov/citations/20160006525.

Frederic, Peter. "Advanced Metallic Fuselage Cost Study," September 1, 2024. https://ntrs.nasa.gov/citations/20240011427.

Open Computational Questions

How to scale from 5” to 10’ diameter scale?

Alloy selection?

What drives the deformation mechanisms?

Effects of preform microstructure on final structure?

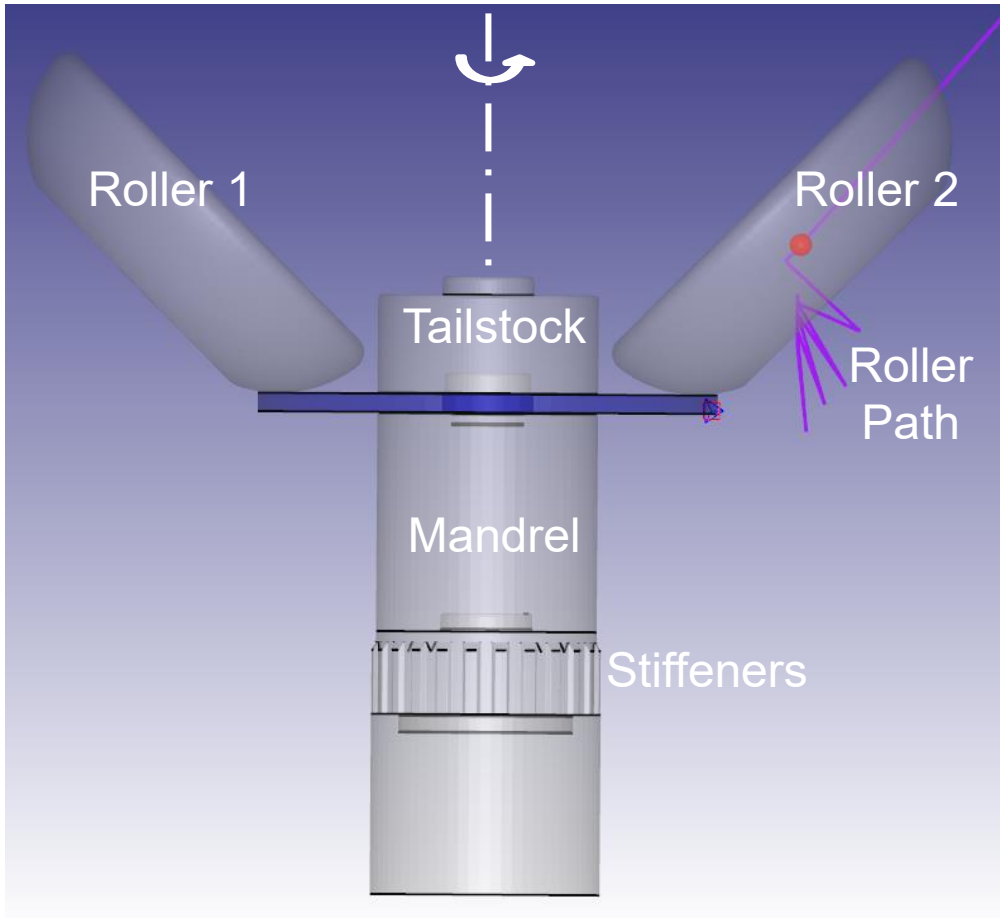
Processing limits, dislocation evolution, fracture mechanics?

Process-structure-property linkages

Methodology

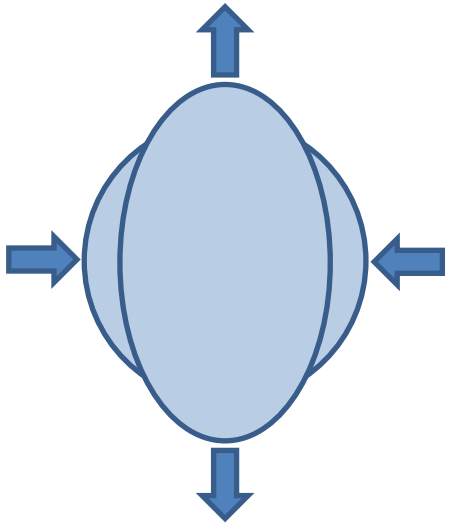
Large strain deformation finite element model: solves continuity, momentum, energy

Time Step	0.5 ms (0.0005 s)
Mandrel RPM	300 rpm – 400 rpm (6.67 rev/s)
Roller Translation Speed	800 mm/min – 3000 mm/min (13.3 mm/s – 50 mm/s)
Time Steps / Revolution	~300
Number of Elements	~220,000 tetrahedral, with 15° refinement wedge (1.55 mm edge length, 0.6 mm in refinement)
Computational Time	~43 seconds per time step (~3 weeks full simulation)
Solver	3D Implicit Augmented Eulerian–Lagrangian (ALE)



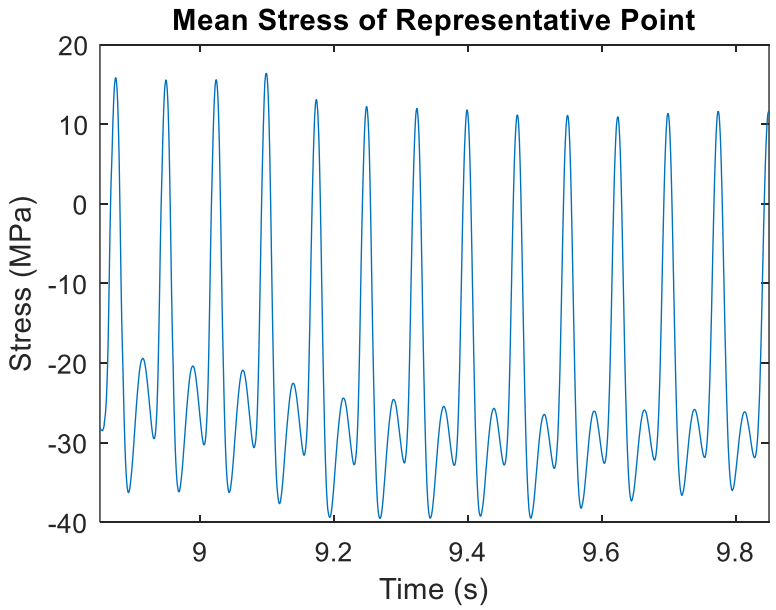
Elasto-Plastic Constitutive Law

- **How to describe the material response to a thermomechanical input over time**
  - Generally described through strain ϵ, strain rate $\dot{\epsilon}$, and temperature T
  - Path-independent $\sigma = f(\epsilon, \dot{\epsilon}, T)$
  - Path-dependent $\sigma = f(\hat{\sigma}, \dot{\epsilon}, T)$

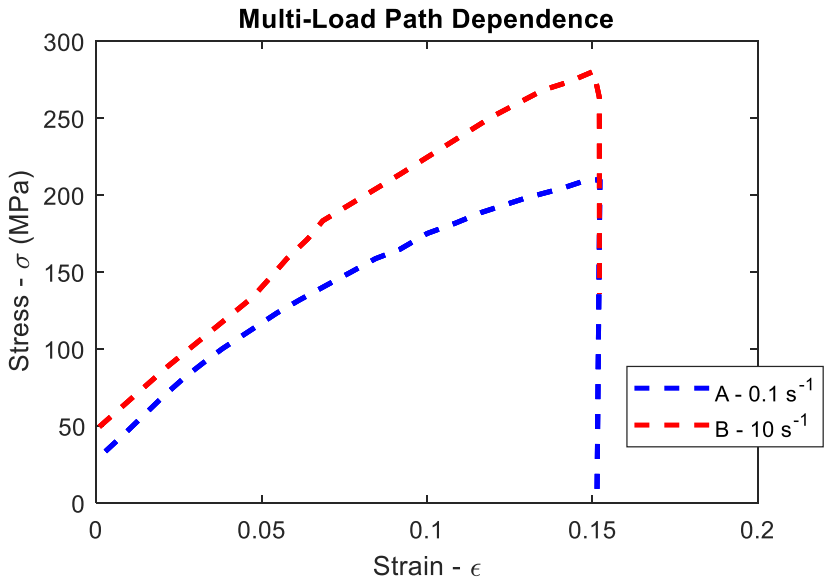


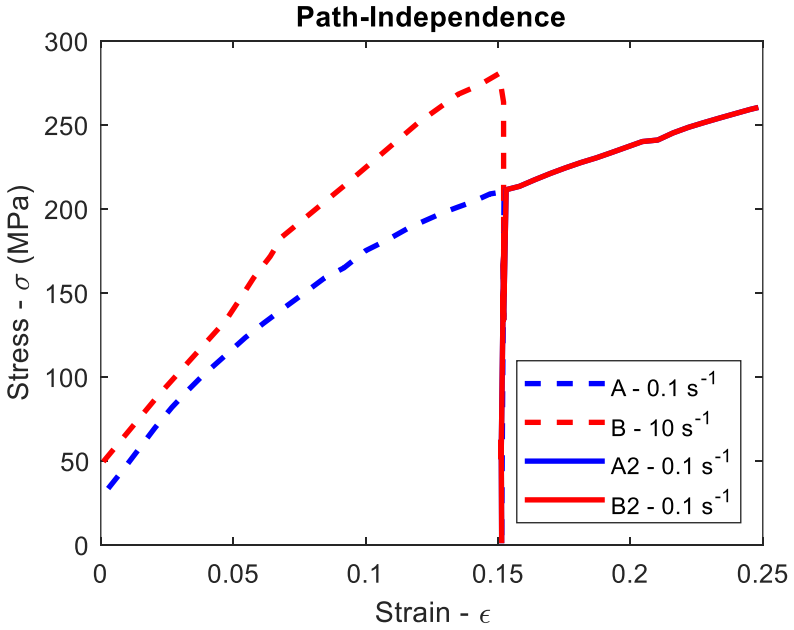
- **Since there's a significant amount of cyclic loading in spin forming, path-dependence must be included**
- **Mechanical Threshold Stress selected**
  - Physics-based model which captures material hardening through approximated dislocation density evolution through activation energy and tracked internal state variable $(\hat{\sigma})$

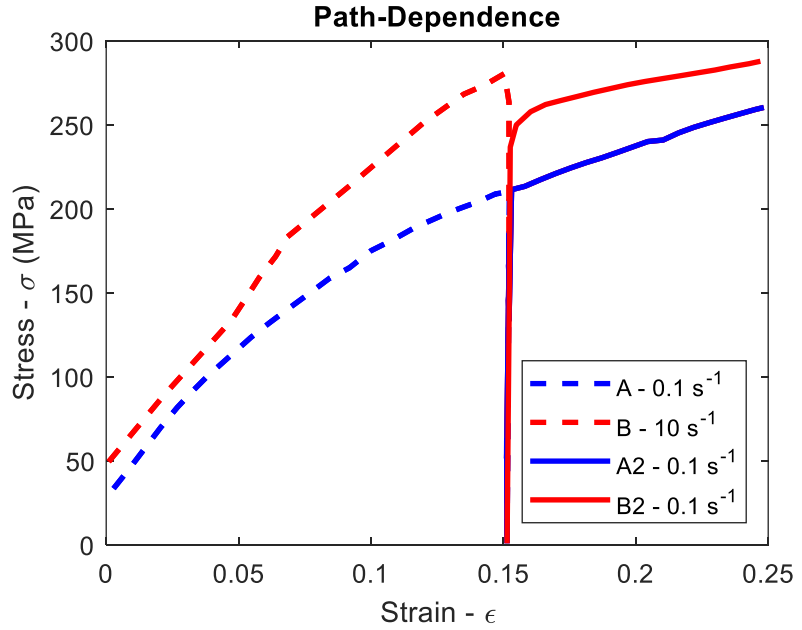
$$\sigma = \sigma_a + s(\dot{\epsilon}, T)\hat{\sigma} \qquad s(\dot{\epsilon}, T) = \left\{\left[1 - \frac{kT}{G}\ln\left(\frac{\dot{\epsilon}_0}{\dot{\epsilon}}\right)\right]^{\frac{1}{q}}\right\}^{\frac{1}{p}}$$



Path-Dependence Example





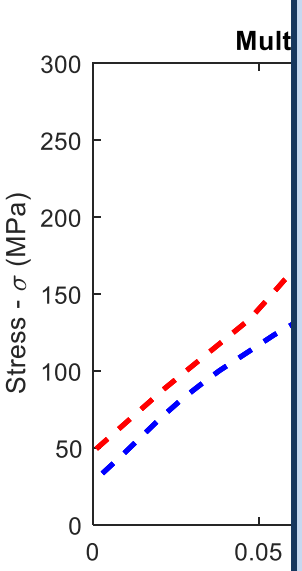


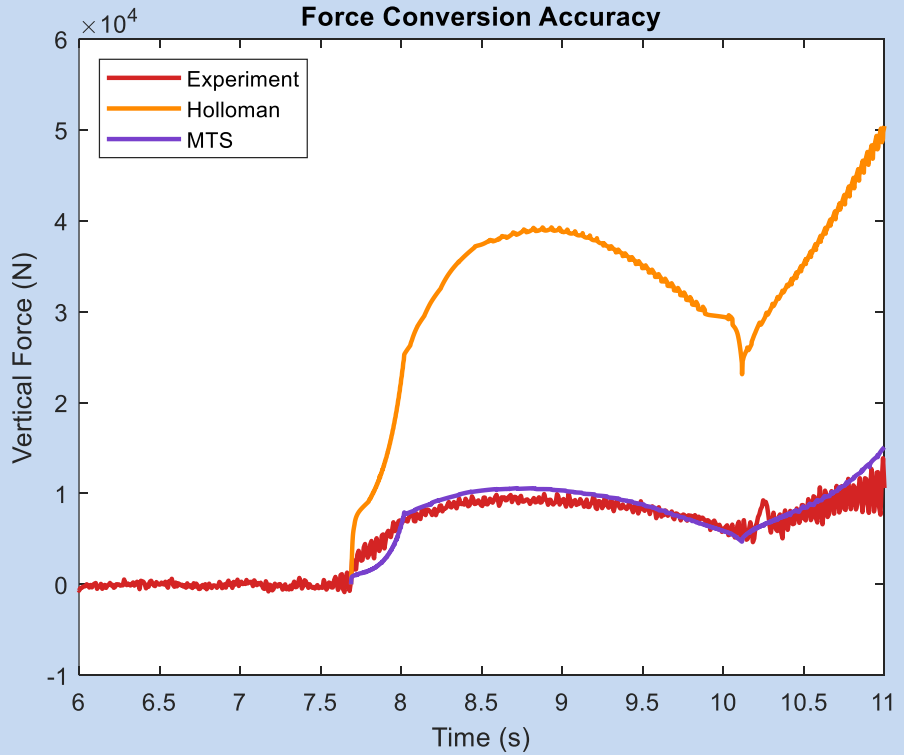
Follansbee, Paul S. “On the Definition of State Variables for an Internal State Variable Constitutive Model Describing Metal Deformation.” *Materials Sciences and Applications* 2014 (June 20, 2014). https://doi.org/10.4236/msa.2014.58062.

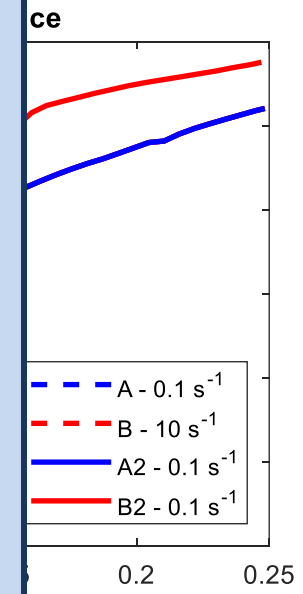
Kuykendall, Katherine Lynn. “An Evaluation of Constitutive Laws and Their Ability to Predict Flow Stress over Large Variations in Temperature, Strain, and Strain Rate Characteristic of Friction Stir Welding,” n.d.

Path-Dependence Example

Without path-dependence, even robust constitutive models (Hollomon with kinematic hardening, Johnson-Cook) overpredict forming loads and stress response for spin forming







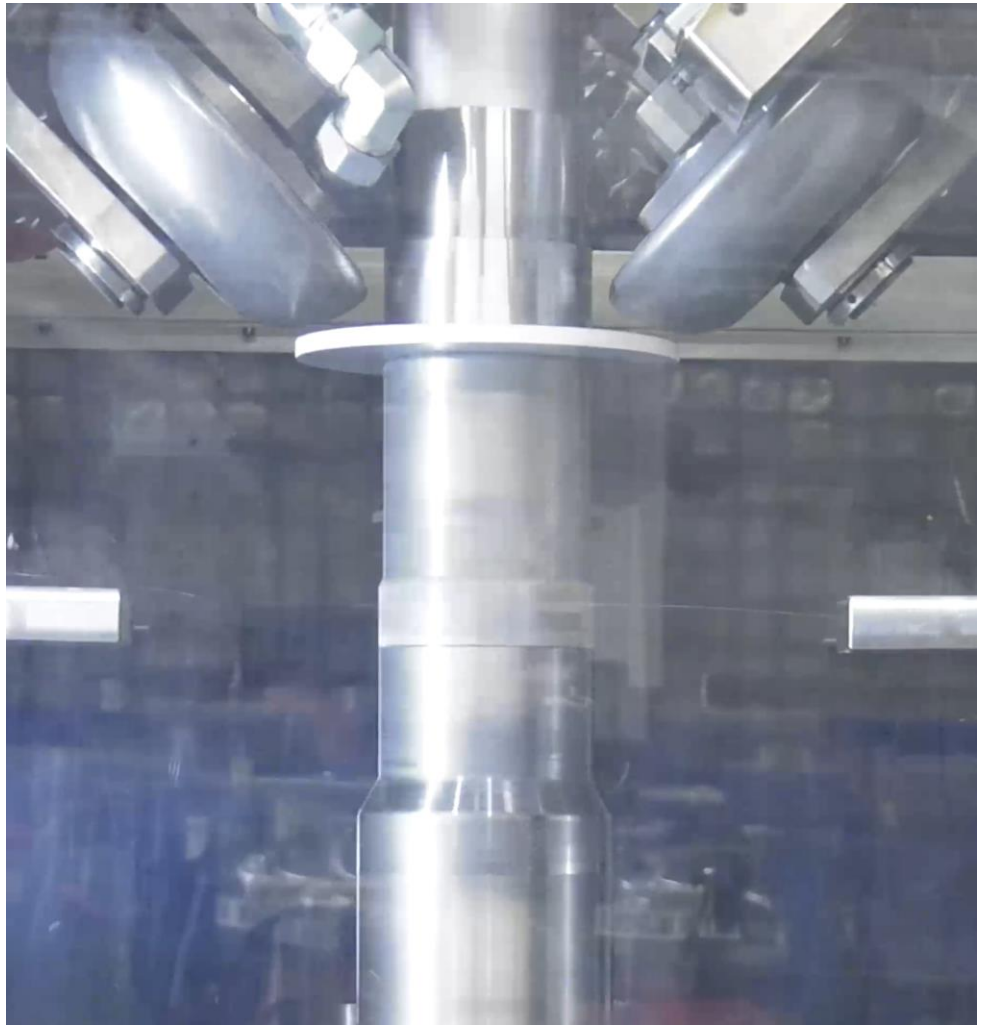
Follansbee, Paul S. "O
https://doi.org/10.4236/

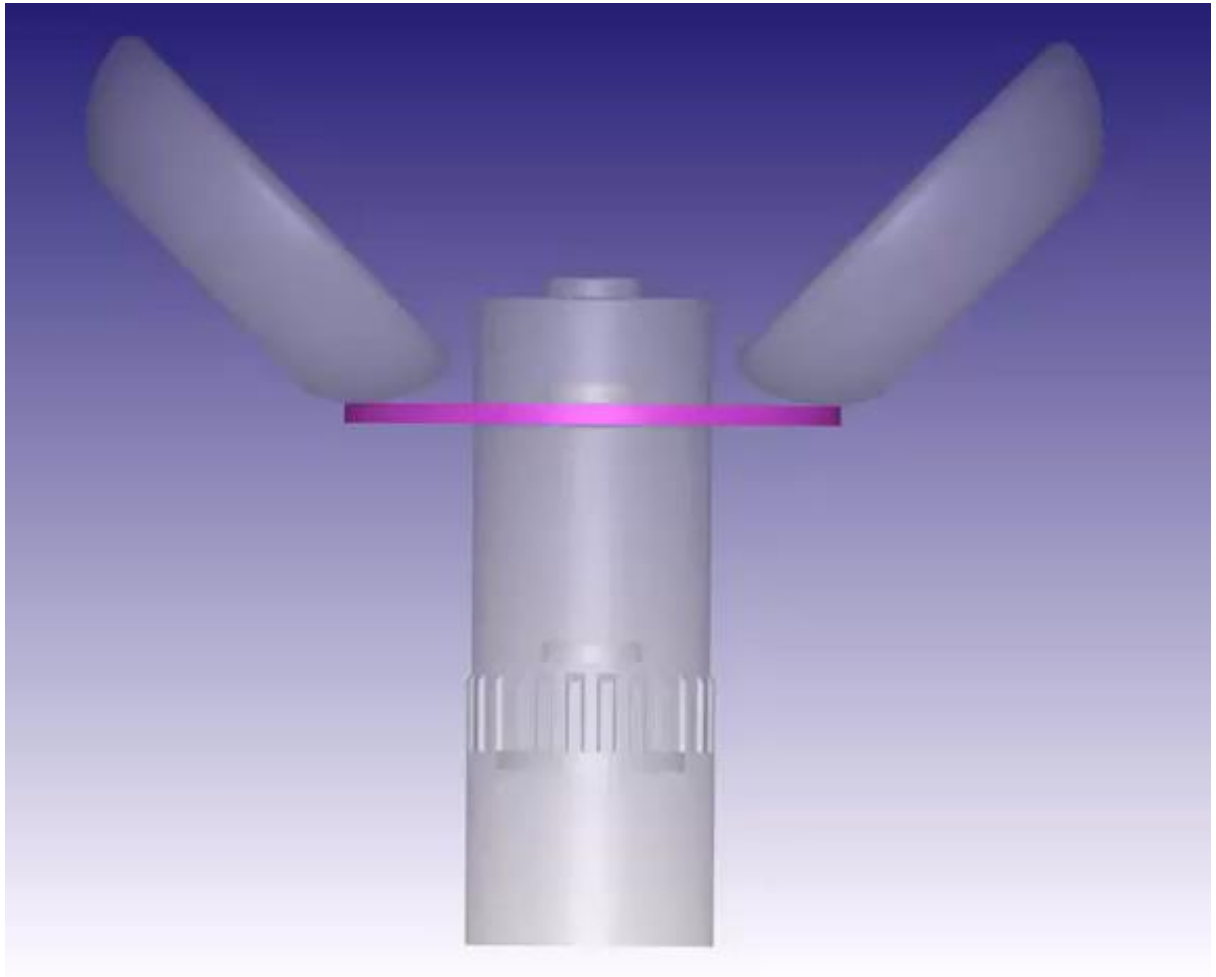
Urig, E. Stegall, D., Zhigilei, L. (2024) Constitutive Law Selection for Finite Element Modeling of Incremental Rotary Forming. TMS Specialty Congress 2024. Minerals Metals and Materials Society. Cleveland, OH

ns 2014 (June 20, 2014).

Kuykendall, Katherine Lynn. "An Evaluation of Constitutive Laws and Their Ability to Predict Flow Stress over Large Variations in Temperature, Strain, and Strain Rate Characteristic of Friction Stir Welding," n.d.

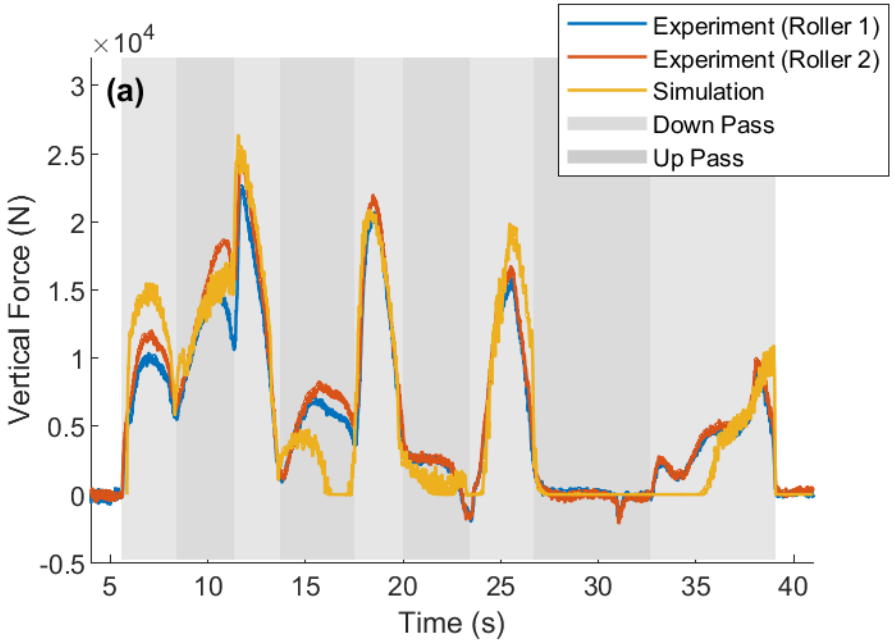
Results: Video Comparison

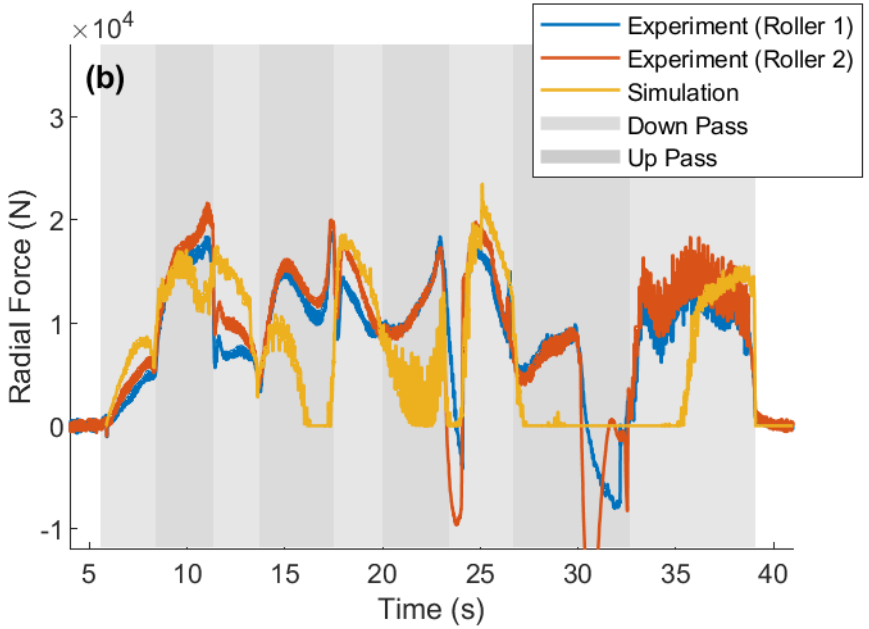


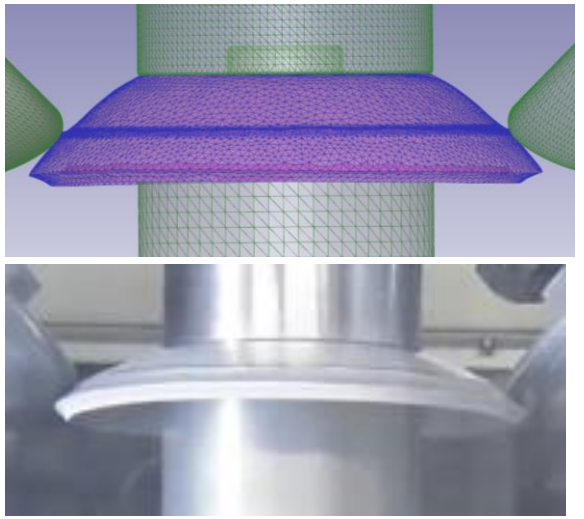


Validation: Forming Loads

- **The model predicts peak roller loads within 11-18% of experiment during down passes,**
  - Indicating a good metric for predicting maximum forming loads
  - While the up passes exhibit more deviation, experiment generates a small bow wave which drives the reaction forces, but is below the 0.6 mm mesh resolution and computationally impractical



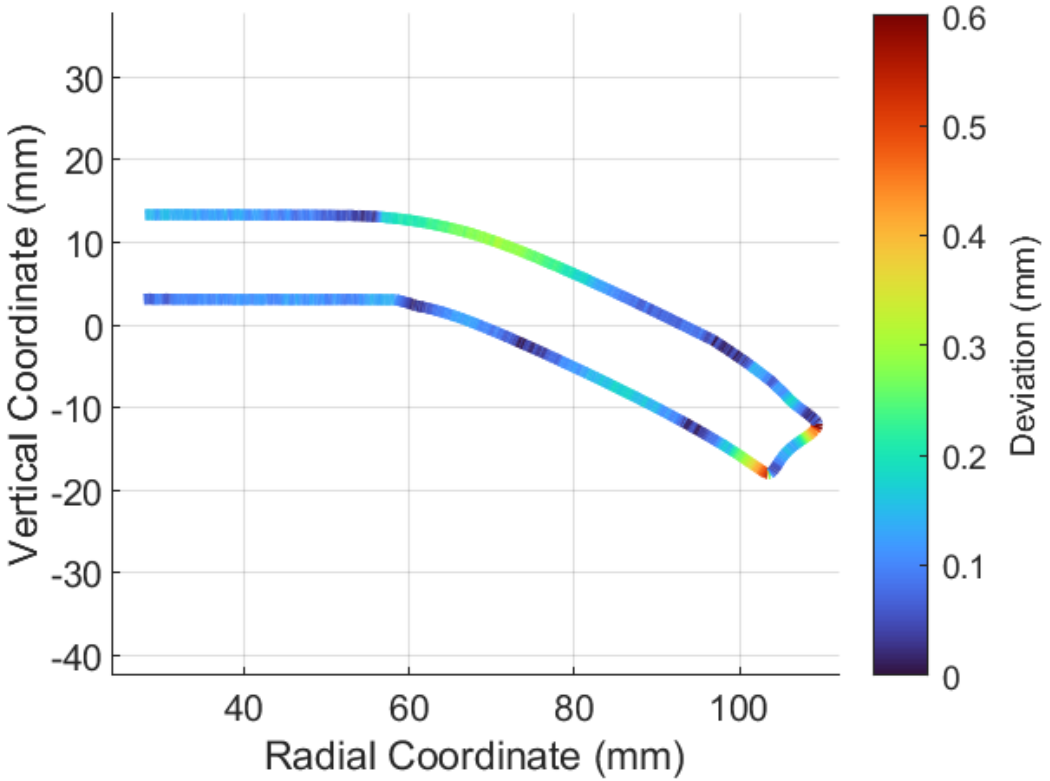




Validation: Geometric Tolerances

- **Structured light scans (resolution of 50 μm) of experimental parts**
- **Secondary elastic simulation run**
  - Captures inter-pass behaviors/match experimental light scans
  - After Pass 1, modeled 0.3 mm vertical movement, demonstrating the springback
- **Maximum deviation was 0.6 mm**
  - Outer edge effects where simulation had idealized right angles, and experimental has more rounded edges
- **Average deviation was 0.1 – 0.3 mm**
  - Half of the mesh edge length
  - Demonstrates model captures elastic and plastic deformation and material flow

Pass 1 Geometric Deviation from Experiment



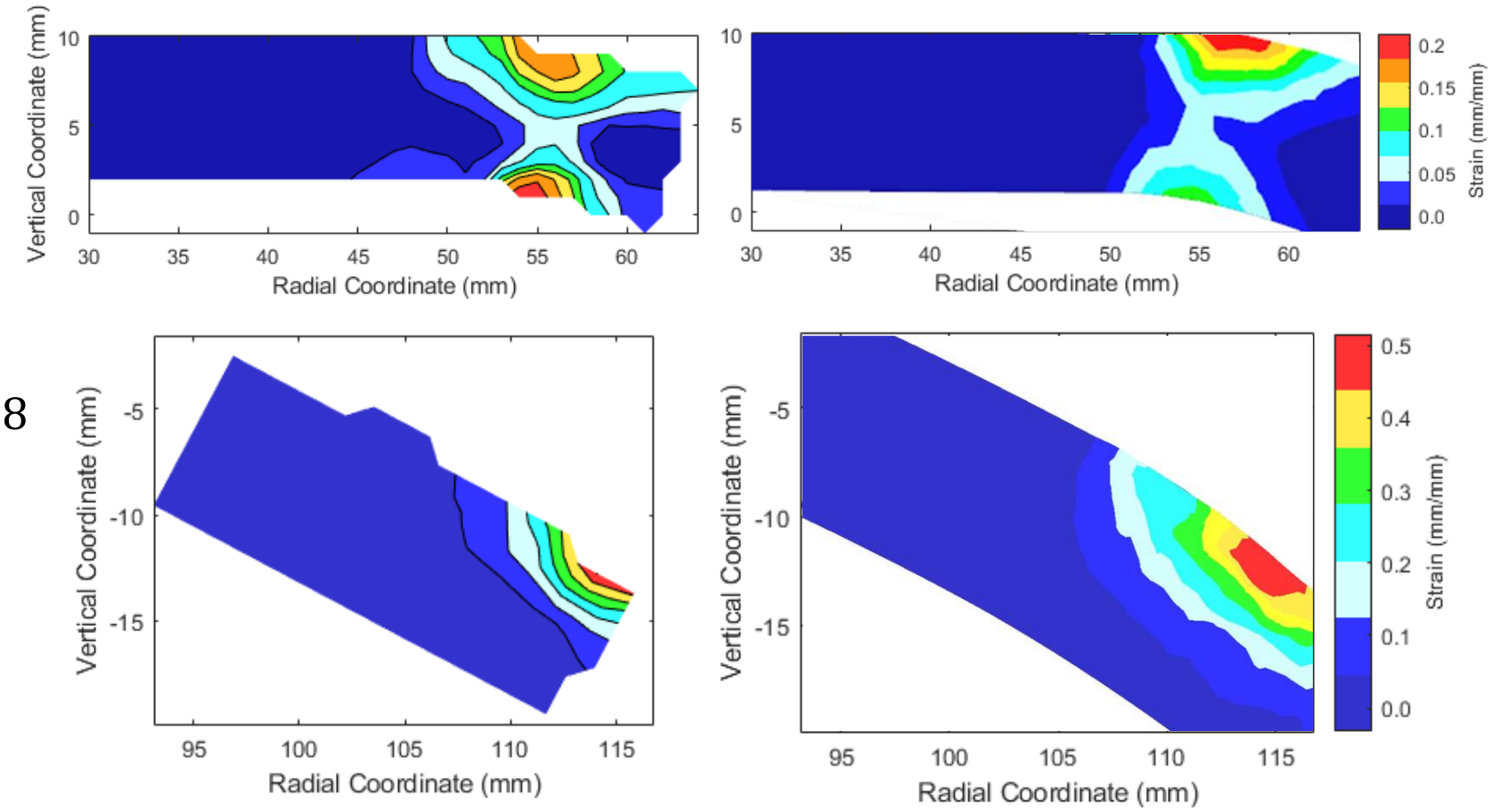
Validation: Plastic Strain Maps

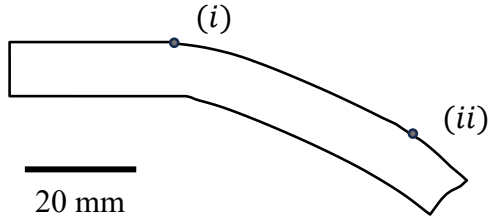
- **Developed empirical relationship between Vickers hardness measurements and plastic strain maps**

$$H(\epsilon_p) = A(\epsilon_p + \epsilon_{ind})^B$$

$$\epsilon_p(H)_{6061-O} = 4.4836(H)^{6.3161} - 0.08$$

- **Effective plastic strain matches empirical hardness measurements**
  - **Clamped zone (i):** 0.219 mm/mm (exp.), 0.208 mm/mm (sim.)
  - **Roller contact (ii):** 0.439 mm/mm (exp.), 0.495 mm/mm (sim.)



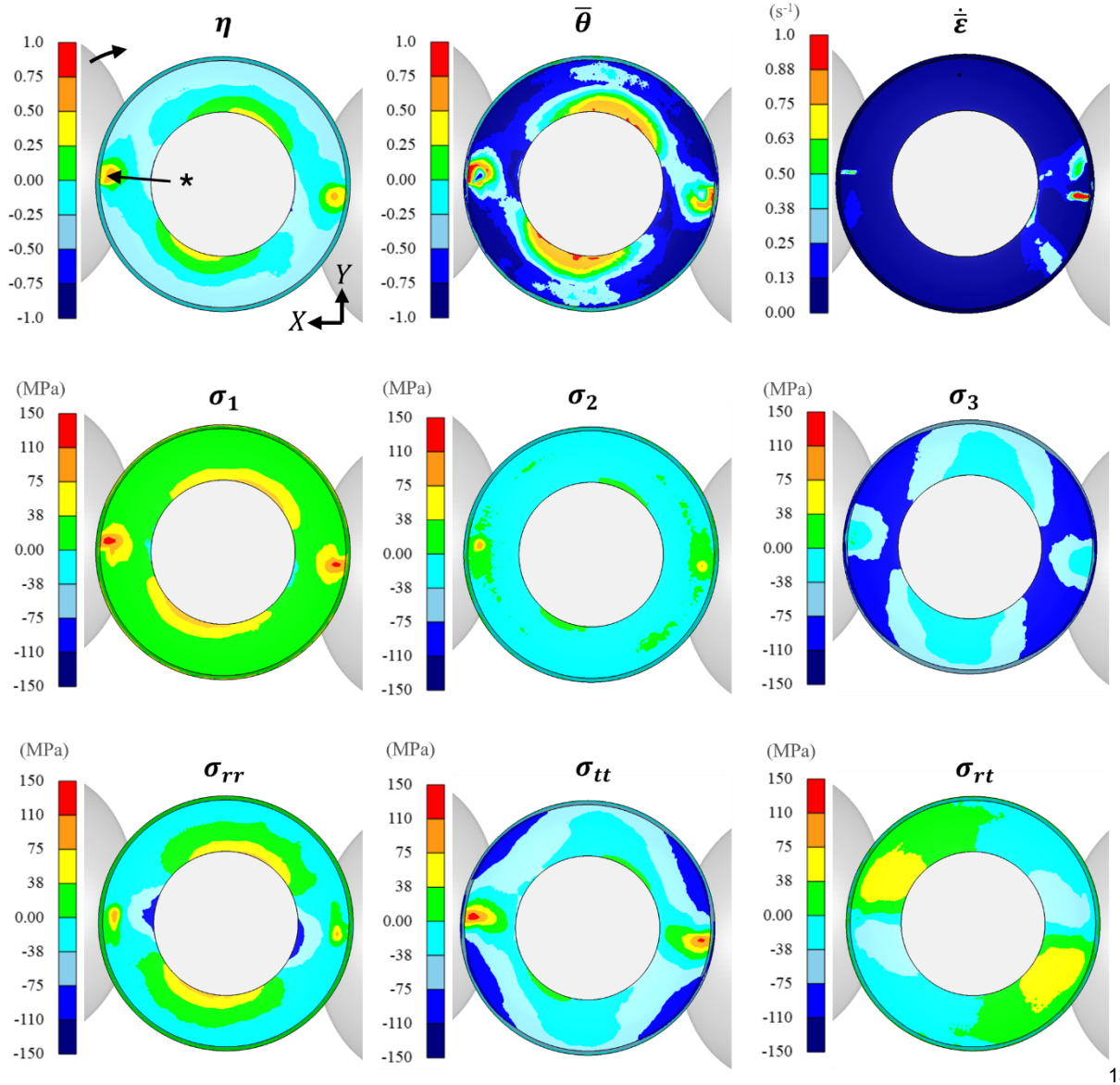


Urig E, Stegall D (2025) Hardness-strain correlation for rolled Al 6061-O plate validated by finite element modeling. NTRS - NASA Technical Reports Server, NASA Langley Research Center.

Haghshenas M, Wood JT, Klassen RJ (2012) Investigation of strain-hardening rate on splined mandrel flow forming of 5052 and 6061 aluminum alloys. Mater. Sci. Eng. A. 532: 287–294. https://doi.org/10.1016/j.msea.2011.10.094

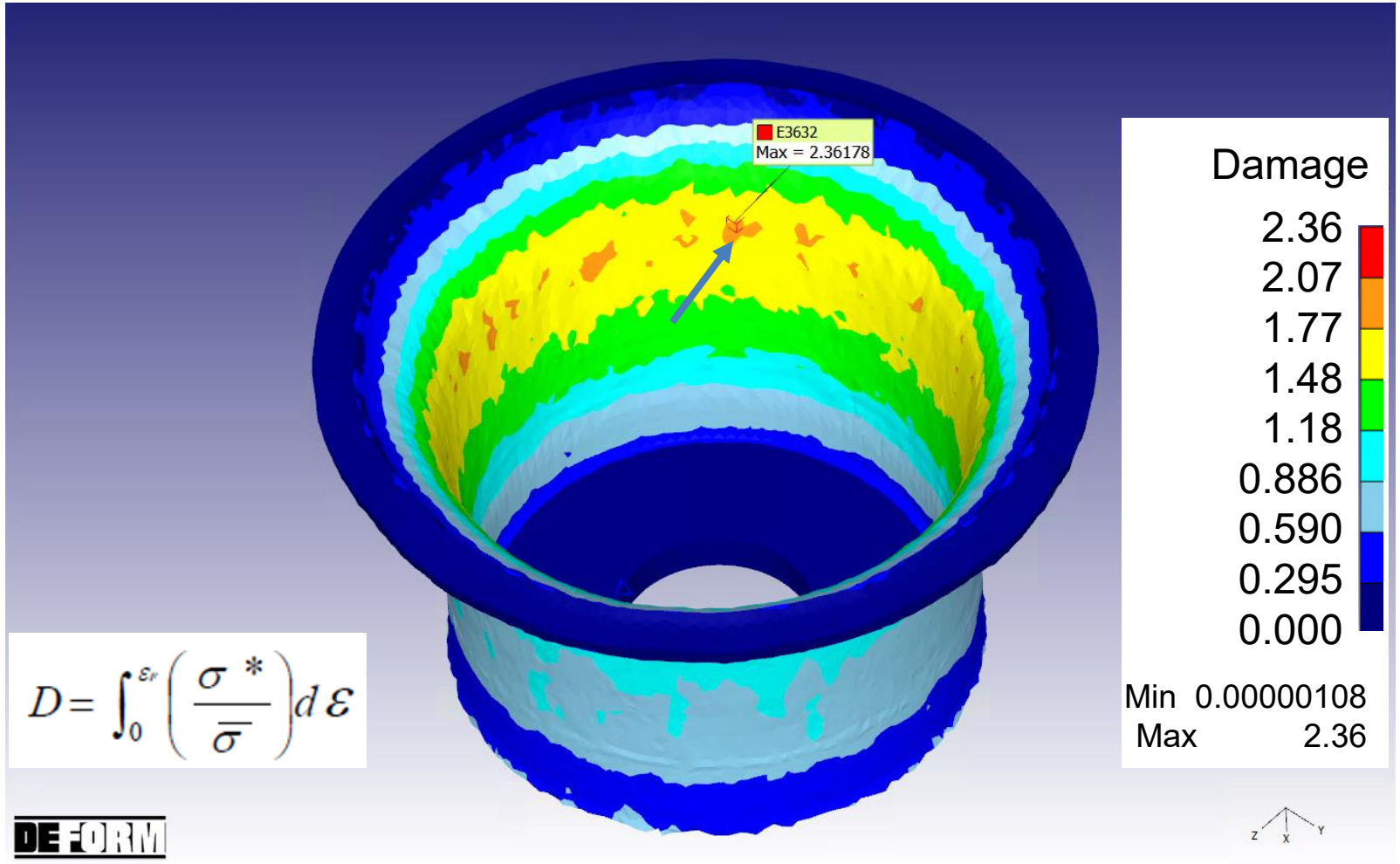
Where do we go from here?

- **Ability to understand the in-situ evolution of stress, strain and temperature**
- **Gives predictions and estimations beyond experiment**
- **Guides our understanding of failure mechanisms, alloy selection, and processing parameters**
- **Already leveraged to improve formability through process changes in 5xxx and 2xxx series alloys!**



Mulvaney, Mary Cecilia. Towards an Understanding of Spin Formability In Aerospace Aluminum Alloys. University of Virginia, Materials Science - School of Engineering and Applied Science, PHD (Doctor of Philosophy), 2025, 2025, doi.org/10.18130/bhcs-sv86.

Damage Accumulation and Fracture Prediction



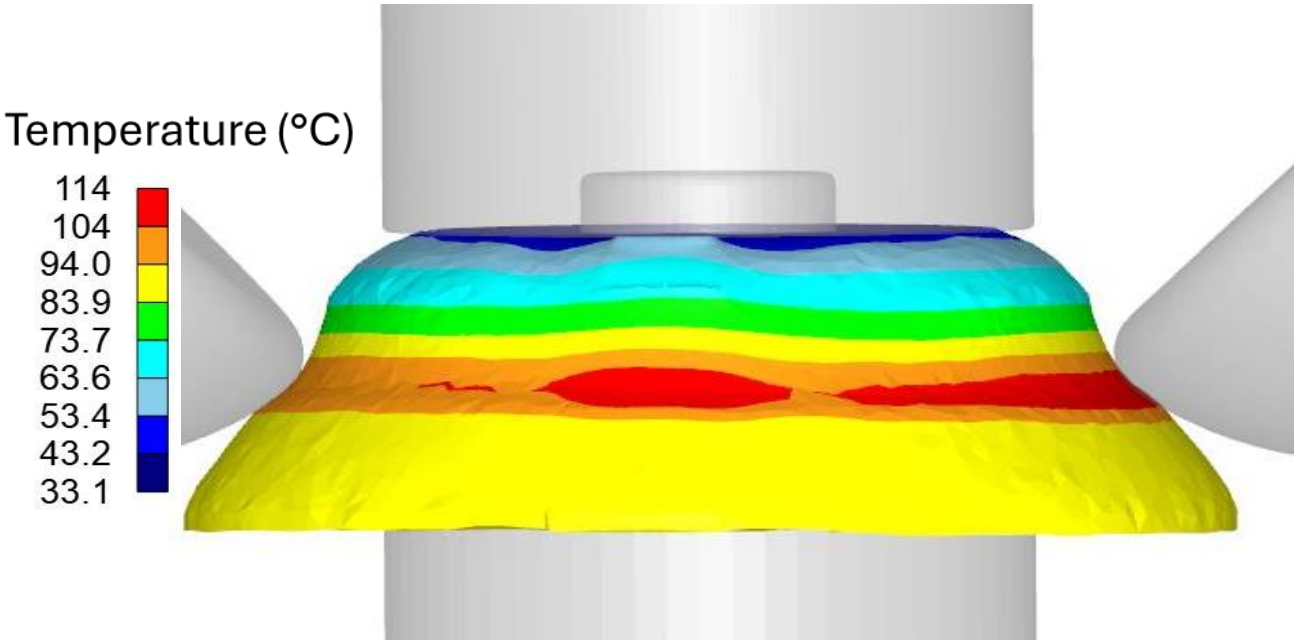


Highest damage (Cockcroft & Lantham) accumulation shown on the inside of the part, correlating with the “orange peel” effect and crack initiations observed experimentally

Thermal Estimations

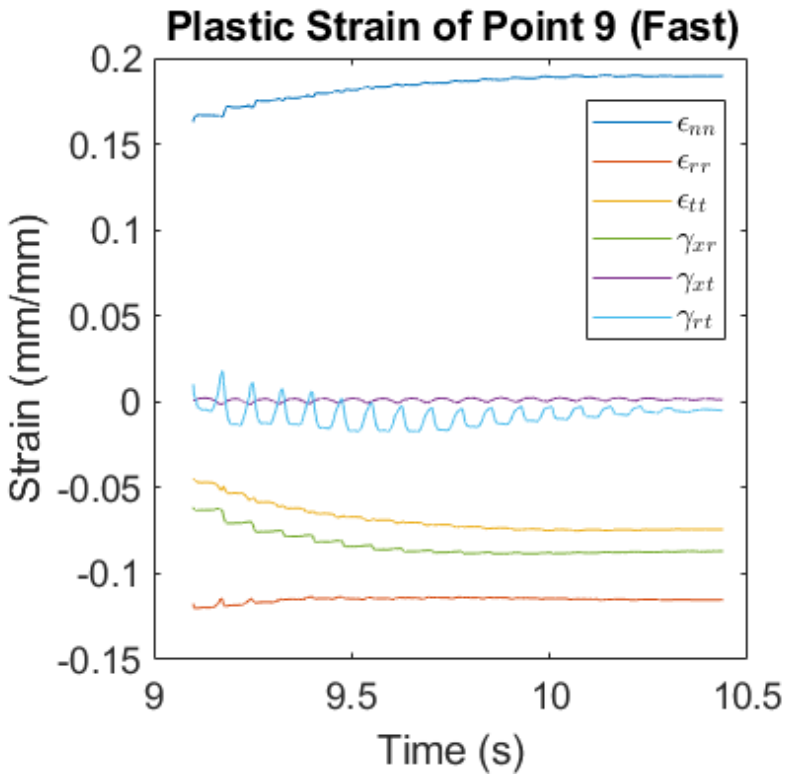
- **Provides more accurate temperature measurements**
  - Wired thermocouples cannot be effectively placed (rotary equipment)
  - Similarly, IR thermal cameras are subject to the high reflectivity of the formed surface and low emissivity of aluminum
- **Current observations show consistent steam generation under roller contact at ~14 seconds, which is when the model consistently predicts above 100 ° C**

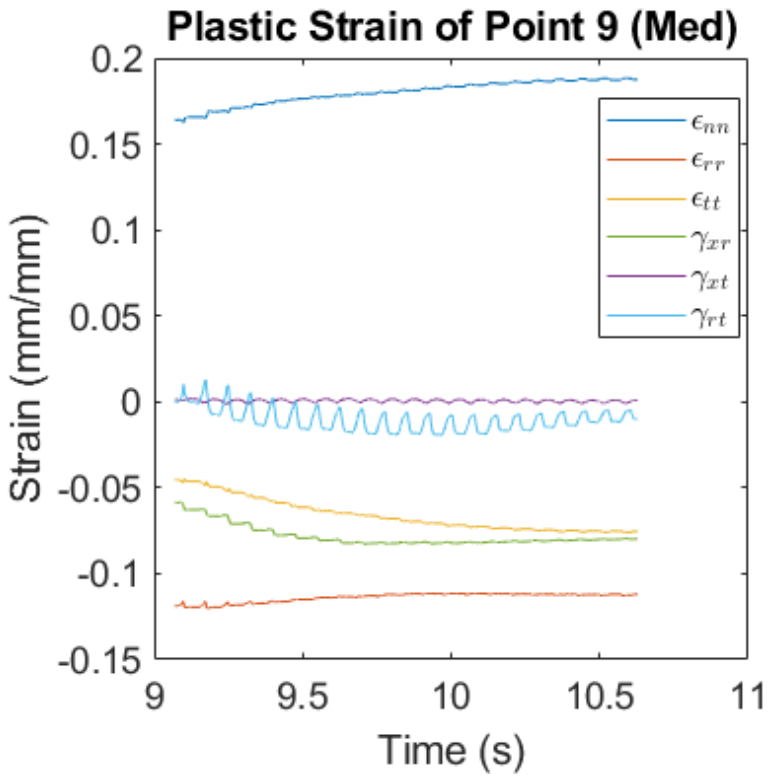


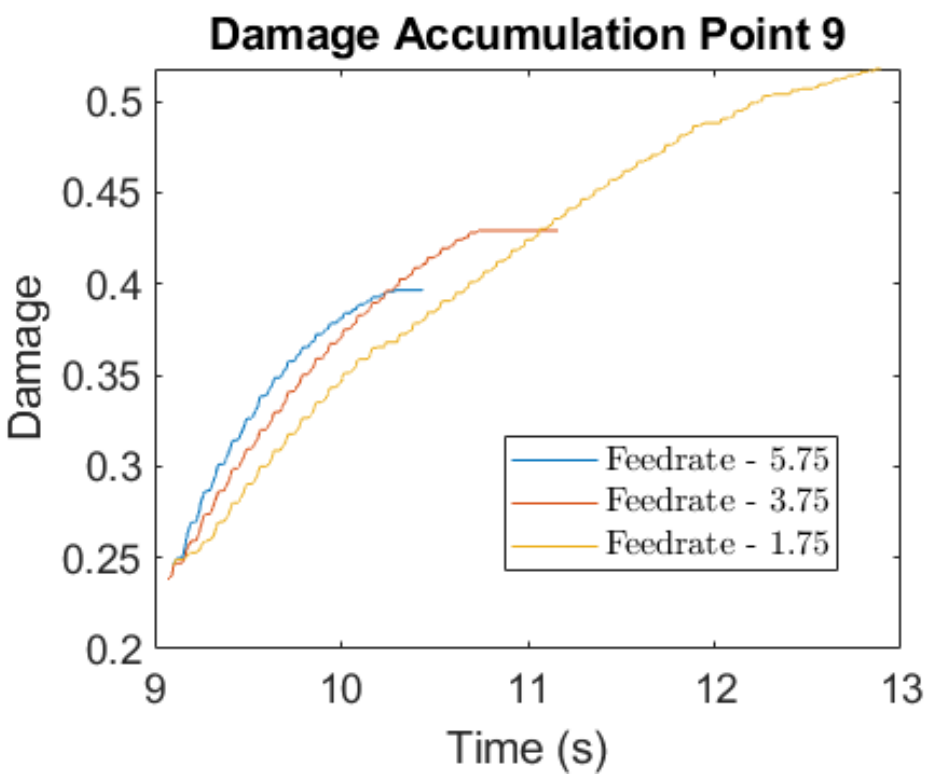


Extension to Varied Processing Parameters

- **How does the variation of mandrel rotation speed and roller linear speed impact in-situ forming as well as final part properties?**
  - Preliminary results show strong tie to more redundant straining and more damage accumulation with slower feedrates

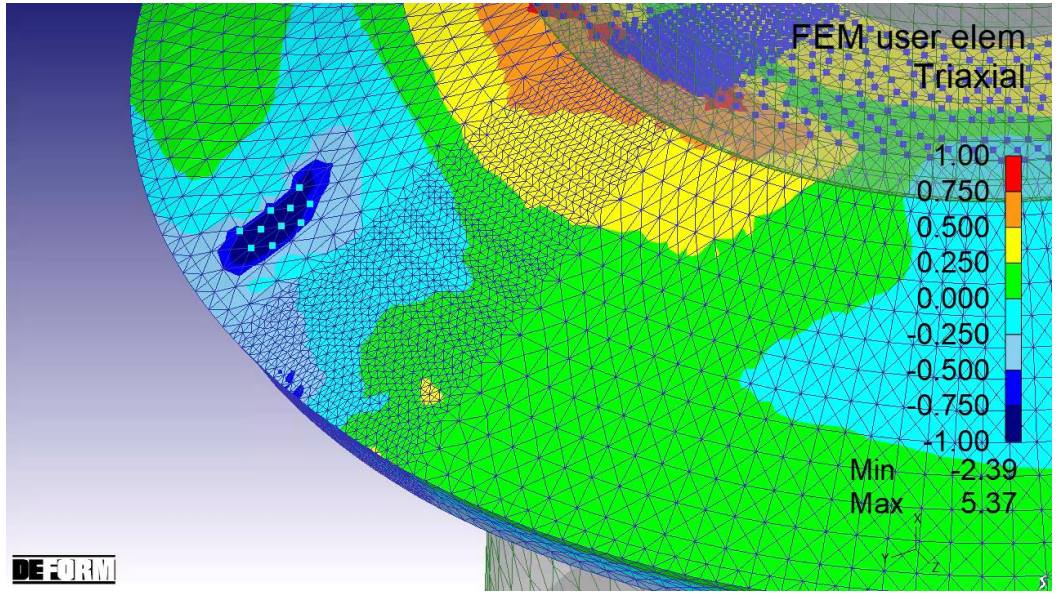


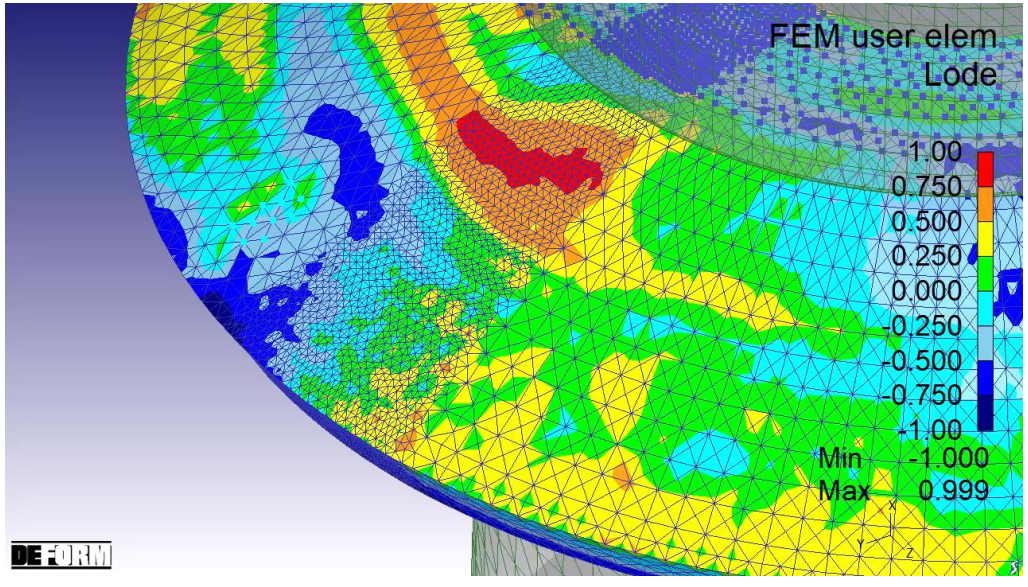




Summary and Ongoing Efforts

- **Spin and flow forming work at LaRC provides the potential for significant manufacturing advancements in both aerospace and aeronautics applications**
- **Computational modeling of the spin forming allows augmentation and extension of the experimental work**
- **Path-dependent modeling has been validated against multimodal experimental measurements**
  - Forming loads within 11-18%
  - Geometric tolerances within 3%
  - Plastic strain distributions within 10%
- **Future work**
  - Cryogenic dome manufacturing
  - Microstructural predictions
  - Improved alloy processing parameters





Acknowledgments

- Dr. Cecilia Mulvaney, D307
- Dr. David Stegall, D307
- Dr. Andrew Boddorff, D307
- Dr. Wesley Tayon, D307
- Karen Taminger, D307
- Harold Claytor, D307/AMA
- Joel Alexa, D307/AMA
- Marcia Domack, D307 (retired)
- Prof. Leonid Zhigilei, UVA
- Prof. Jim Fitz-Gerald, UVA

This work is supported by:

Advanced Air Transport Technology (AATT)

Subsonic Vehicle Technologies and Tools (SVTT)

Virginia Space Grant Consortium (VSGC)