The Impact of Residual Stress on Hybrid Additive/Subtractive Manufacturing Processes

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National Institute of Standards and Technology

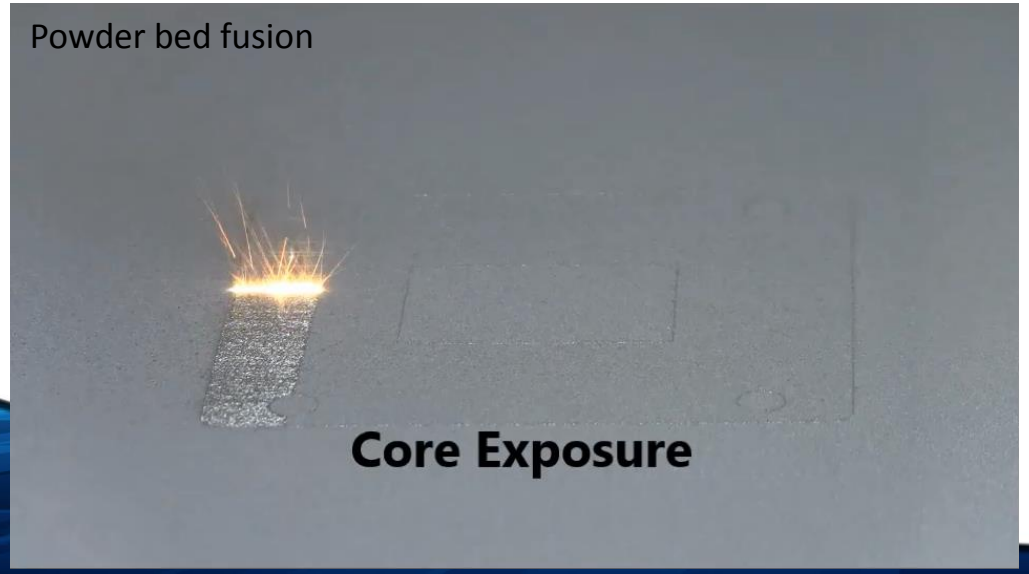
Certain commercial equipment, instruments, or materials are identified in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

Additive Manufacturing

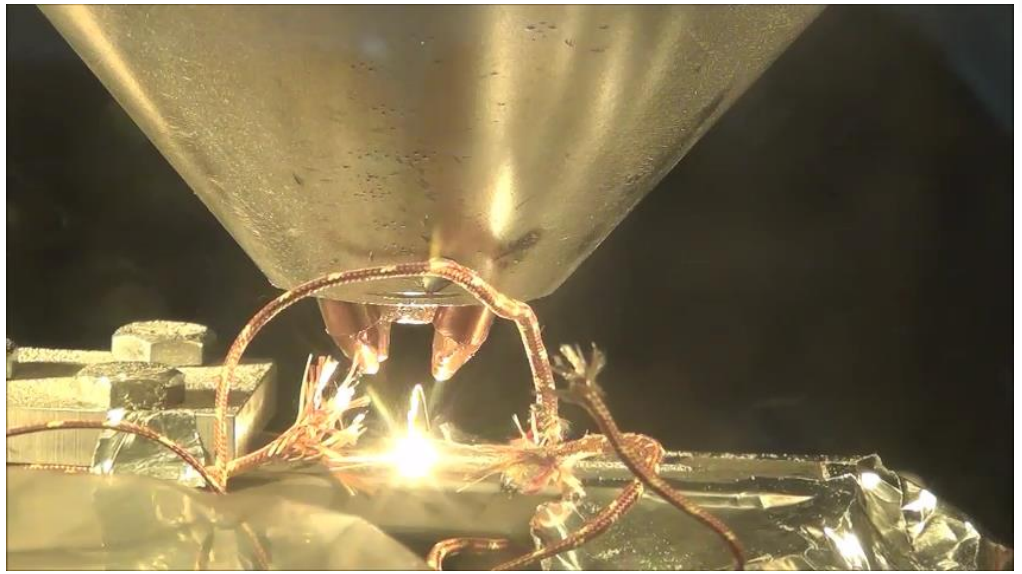
Additive manufacturing is the layer-by-layer addition of material to create parts.

Focusing on metal AM processes….

Powder bed fusion



Directed energy deposition

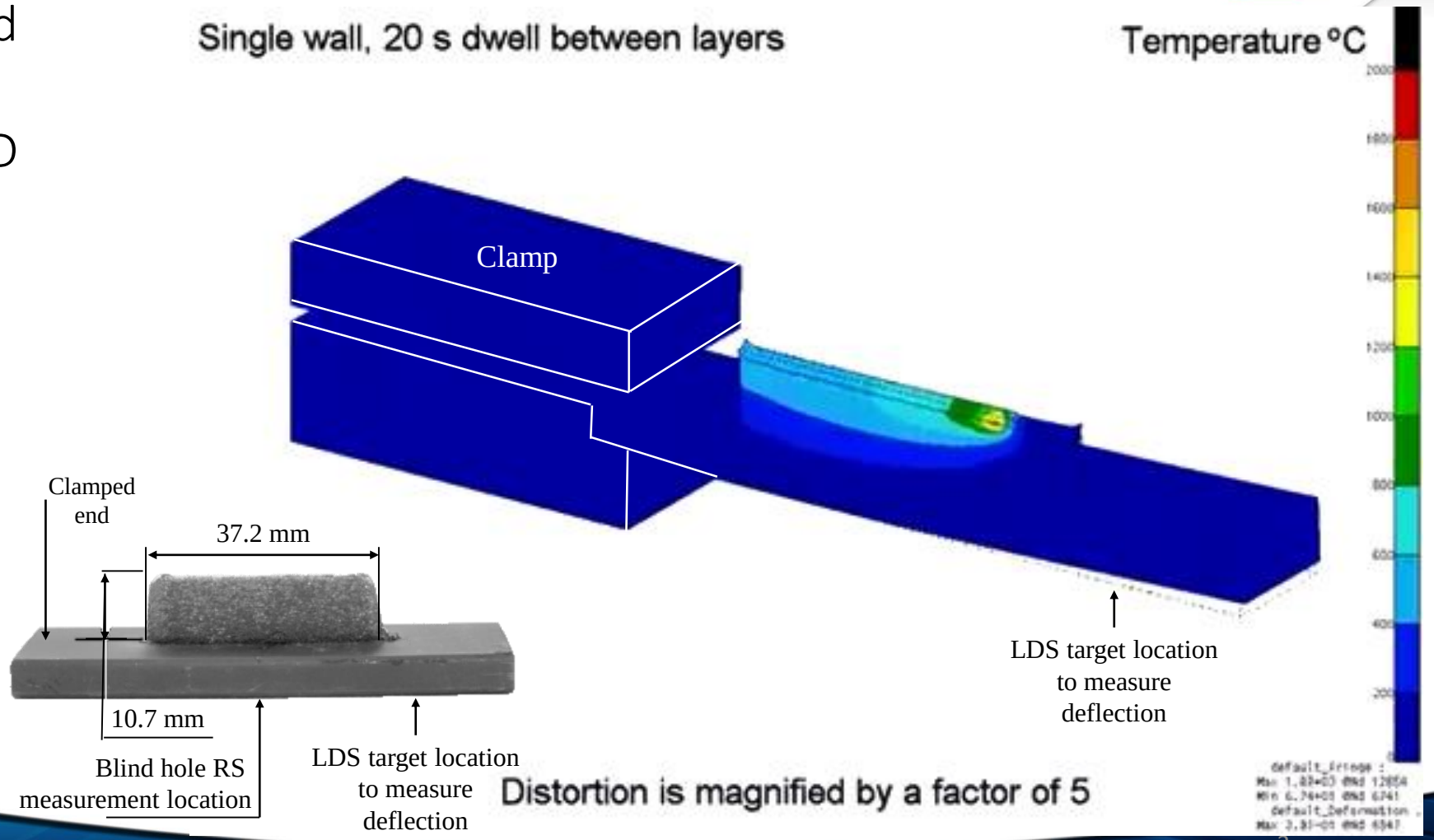


Both processes use a laser or electron beam, but the spot size in PBF is an order of magnitude smaller and moves much faster.

AM creates a lot of stress and distortion

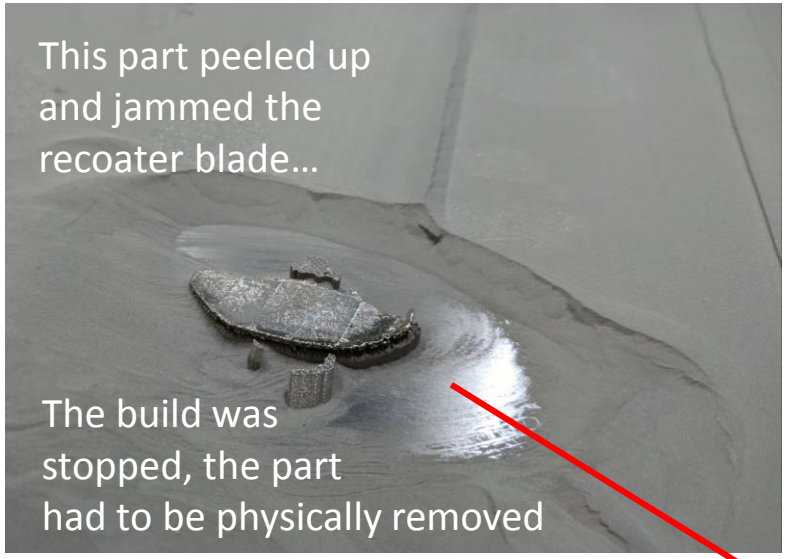
My graduate work focused on developing thermo-mechanical models of DED processes

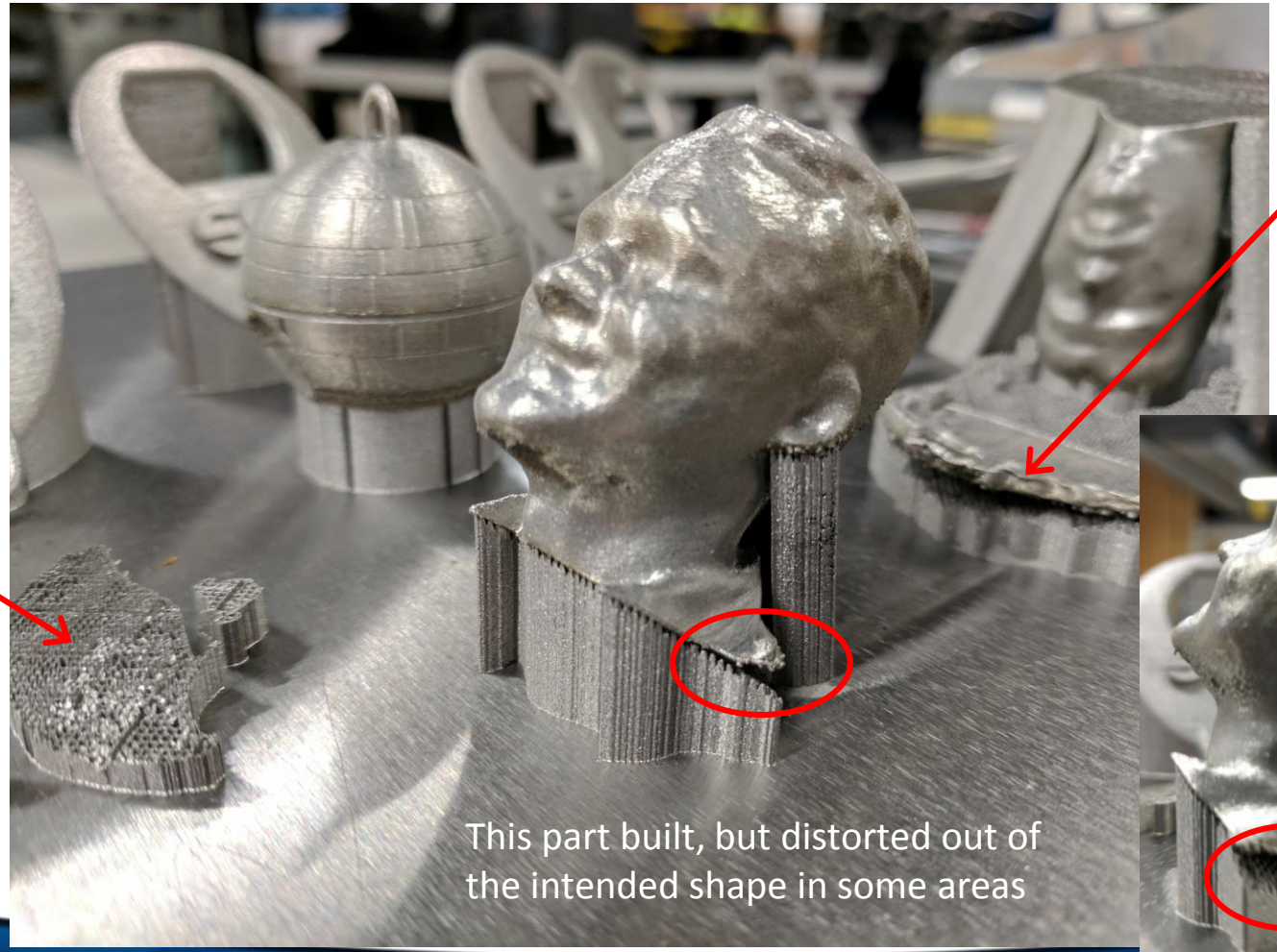
Mechanical models were validated by measuring in-situ distortion and post process stress through blind hole drilling



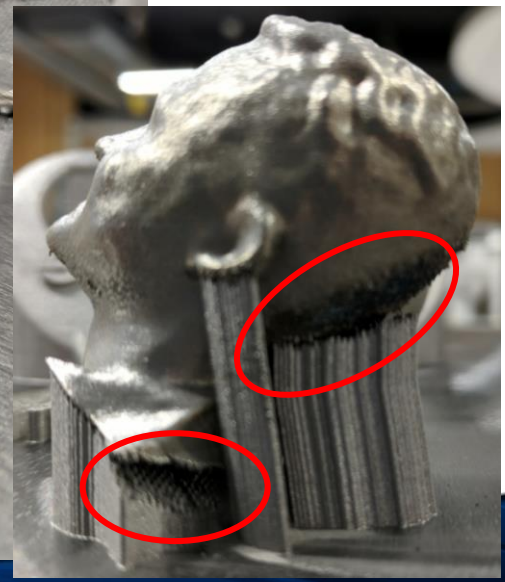
Heigel, J.C., Michaleris, P., & Reutzel, E.W. (2015). Thermo-mechanical model development and validation of directed energy deposition additive manufacturing of Ti–6Al-4V. *Additive manufacturing*, *5*, 9-19.

Distortion from high stress can cause the build to fail or not achieve the intended geometry





This part was peeling up as well, but it was noticed early and deleted from the build file



These challenges can be addressed in AM

- Thicker build plates can be used to prevent build plate warpage
- Stronger supports can hold the part to the build plate
- Modeling can be used to predict the distortion and compensate
  - Measurements are required for validation
- Heat treating can relieve the residual stress

Not all of these solutions can be implemented in hybrid additive/subtractive manufacturing

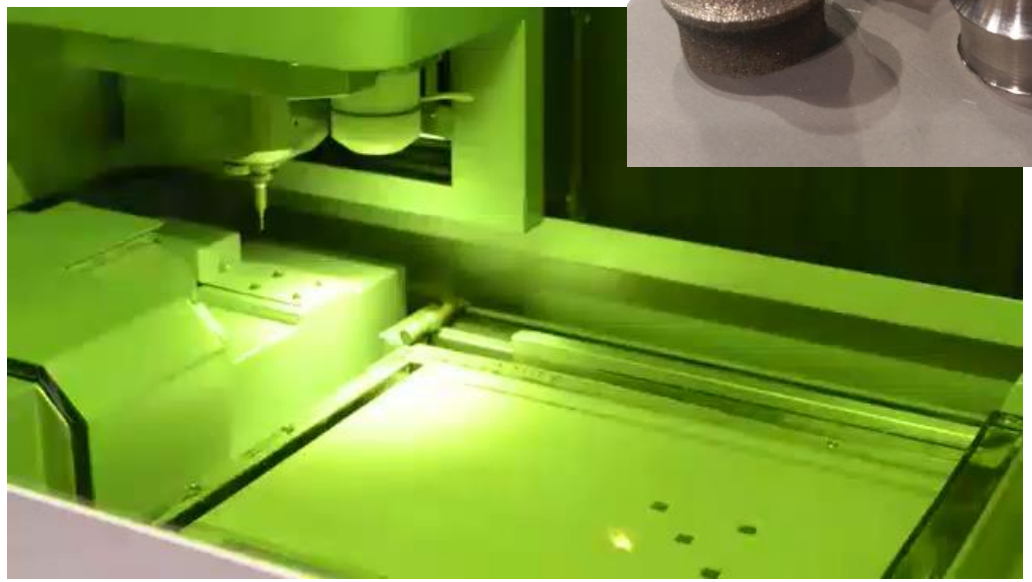
Hybrid Additive/Subtractive Manufacturing

Both additive and machining operations are performed

- In-envelope (all in the same machine)
- Out-of-envelope (two or more different machines)

Heat treatment cannot be used to remove stress. How does the high stress impact the accuracy of the machining process?

https://www.youtube.com/watch?v=Ttt3nMKr9Oo



Sodick https://www.youtube.com/watch?v=Zetn7fh6Whw

Exploratory project to investigate hybrid

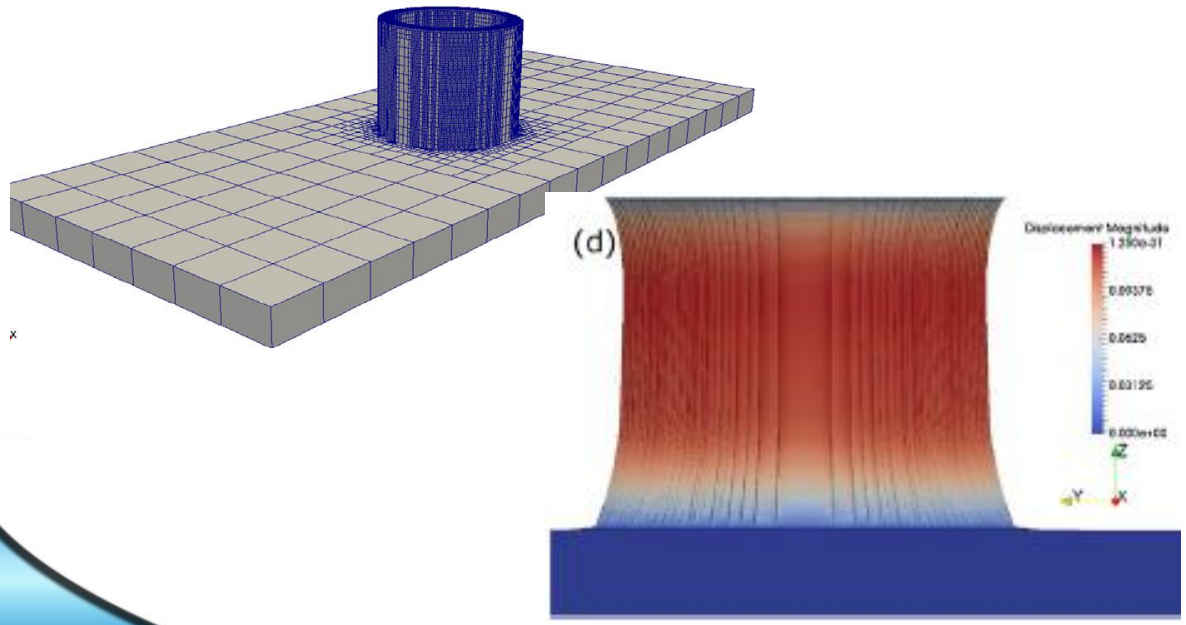
- Objective:
  - To measure the geometric errors in each phase of hybrid additive/subtractive manufacturing and to identify the impact of their propagation on the final dimensional accuracy of the part.

- Basic experimental approach:
  - Create parts using AM -> Measure geometry -> Machine -> Measure geometry

Residual stress will cause the part to distort during machining

Inspiration for this study came from 2 papers

- AM processes causes cylindrical parts to get an hourglass shape



Dunbar et al. (2016) "Experimental validation of finite element modeling for laser powder bed fusion deformation. Additiive Manufacturing V 12

- Basic simulations show that removing material through machining changes the stress balance

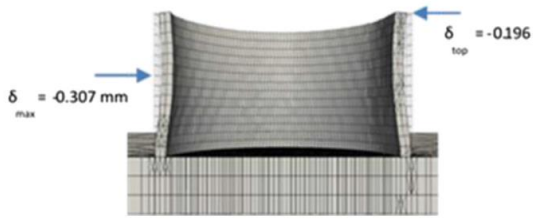


Fig. 11 Distortion of the tube after laser cladding with respect to the nominal geometry

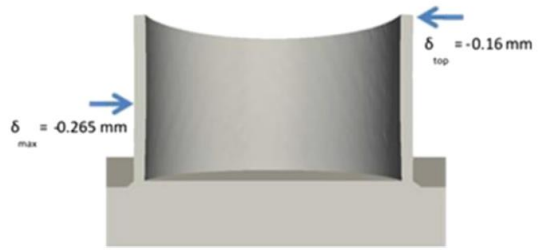


Fig. 13 Distortion of the tube with respect to nominal geometry after high speed machining

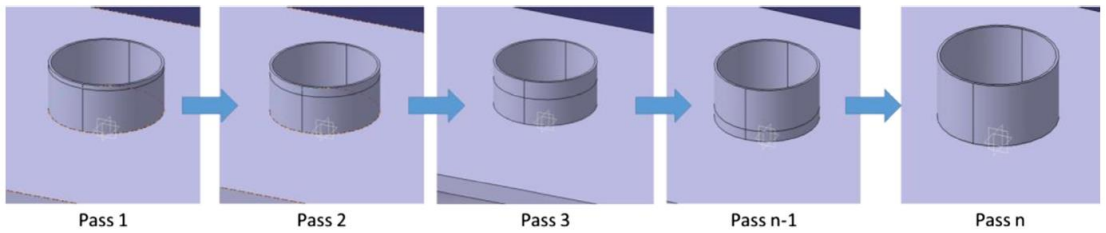
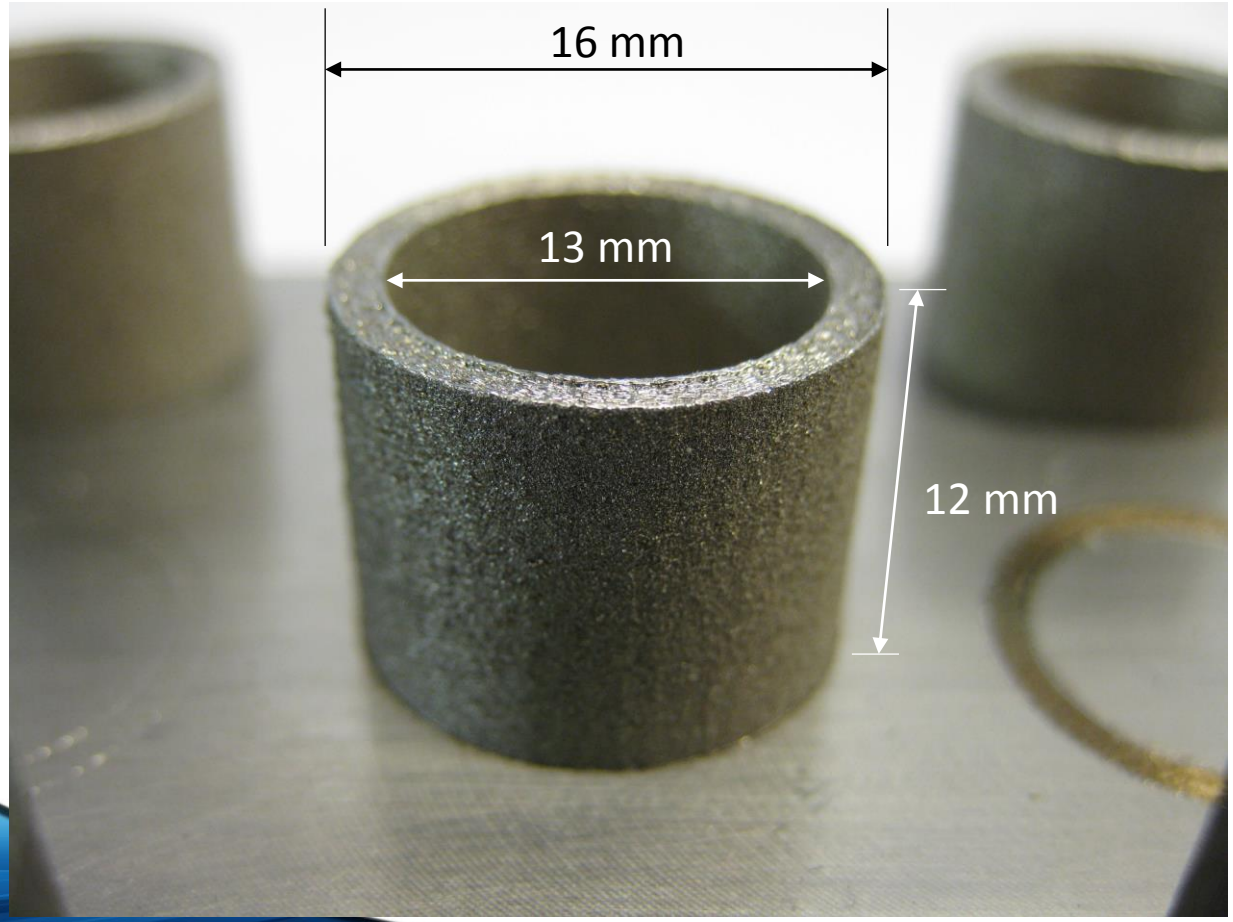
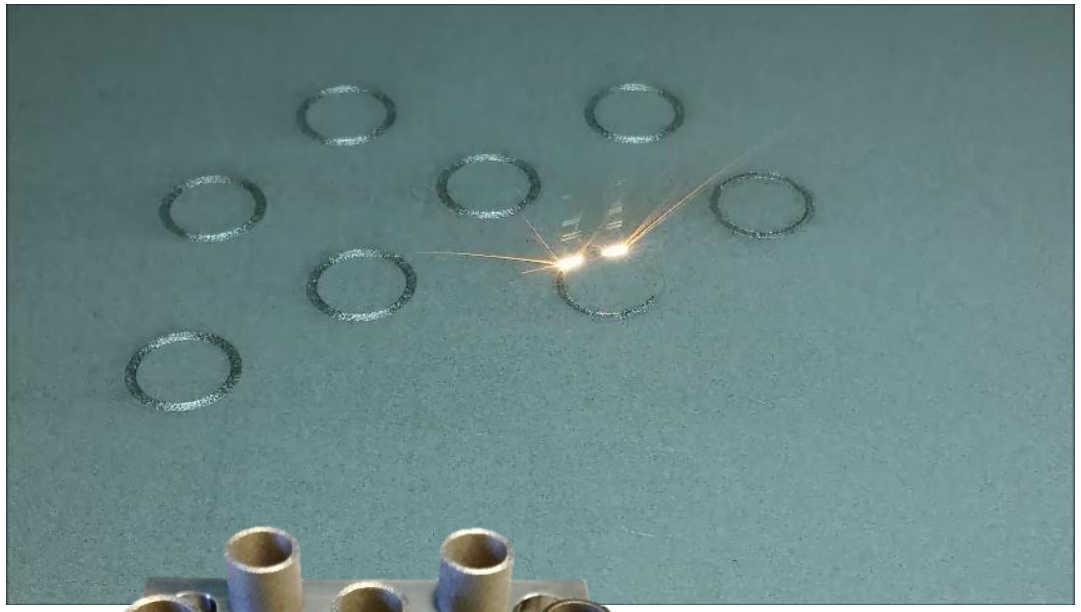


Fig. 9 Intermediate machined geometries

Salonitis, K., D'Alvise, L., Schoinochoritis, B., & Chantzis, D. (2015). Additive manufacturing and post-processing simulation: laser cladding followed by high speed machining. The International Journal of Advanced Manufacturing Technology, 1-11.

Cylinders are used in this investigation

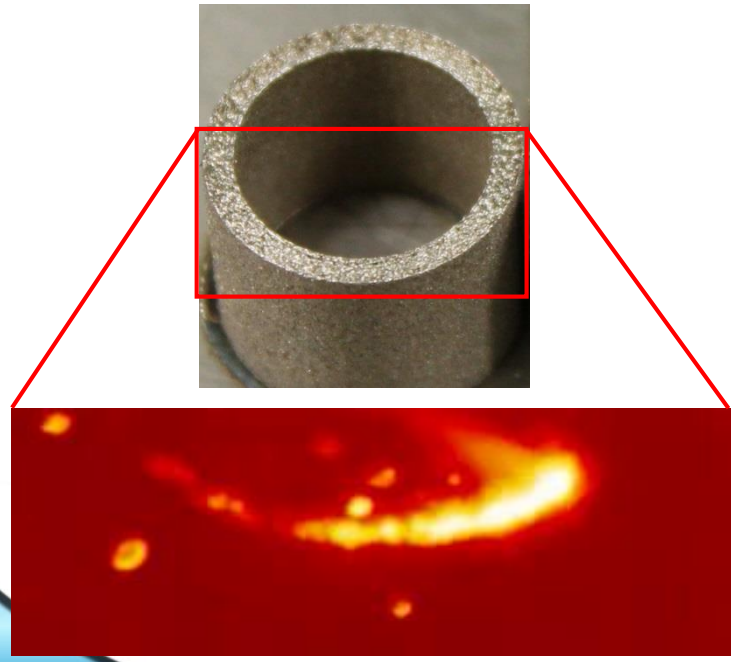


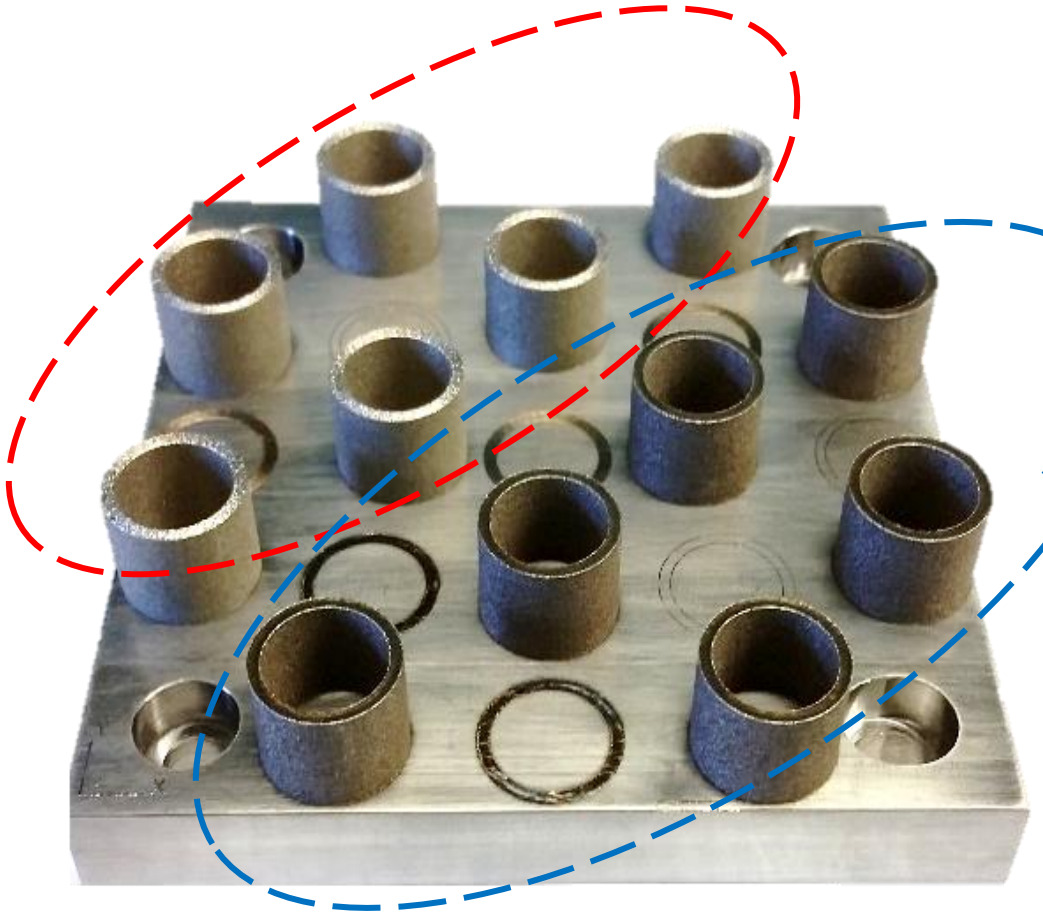


Different scan strategies result in different cooling rates. Visible oxidation difference.

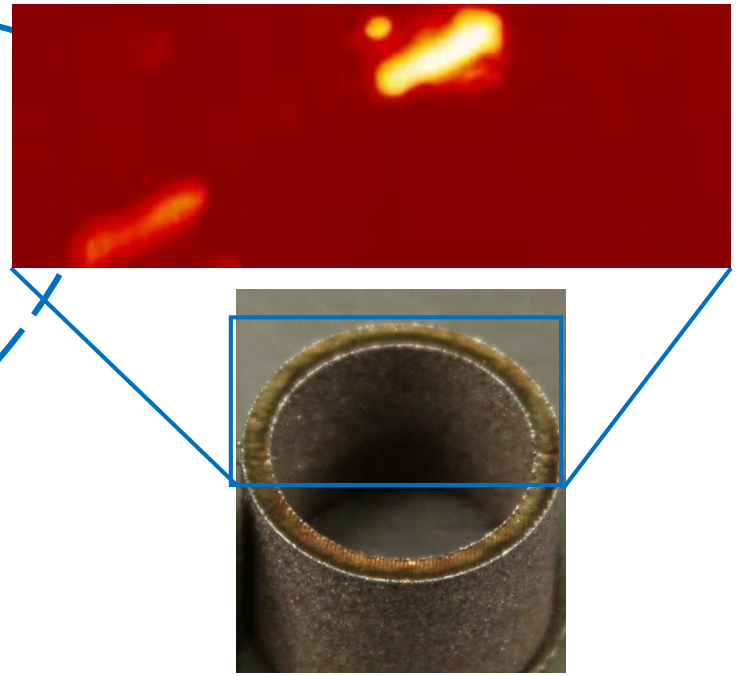
Temperature was measured

15 Concentric Circles





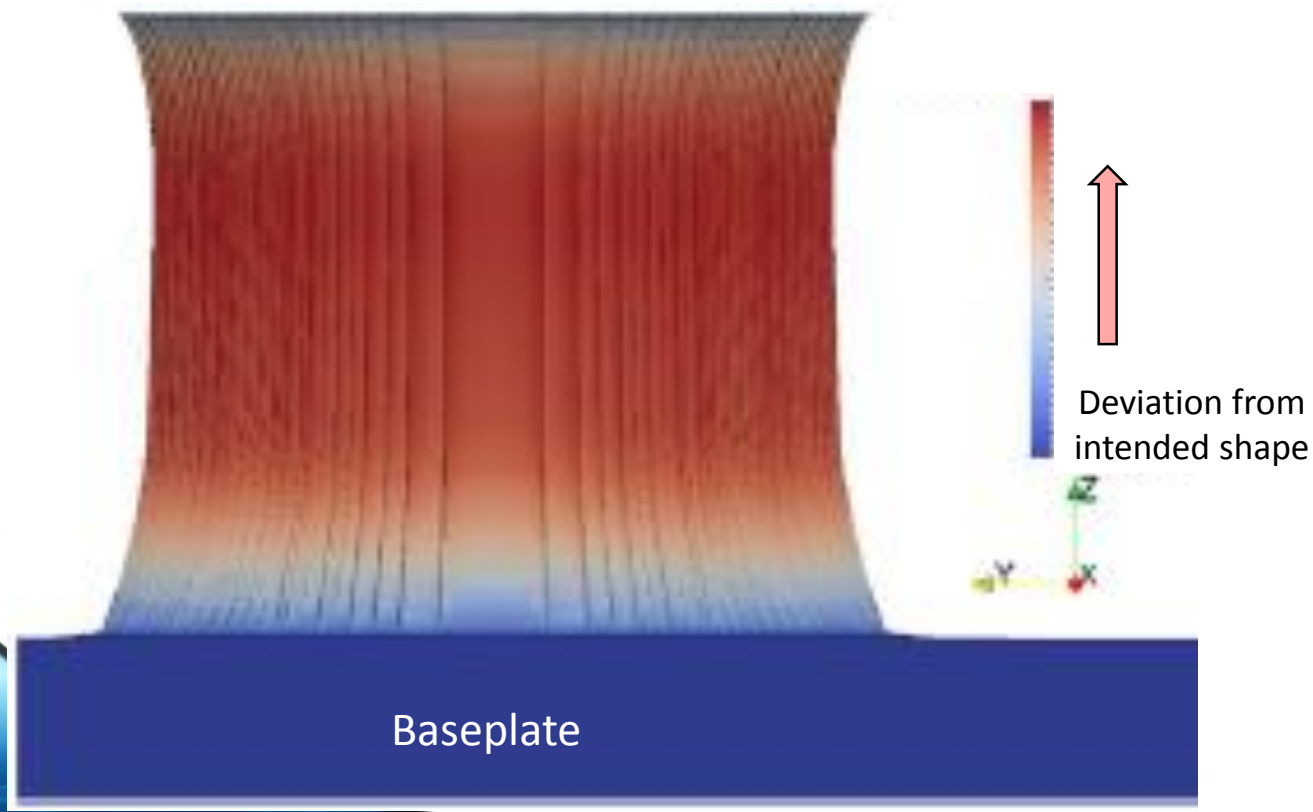
Standard scan strategy, rastering back and forth



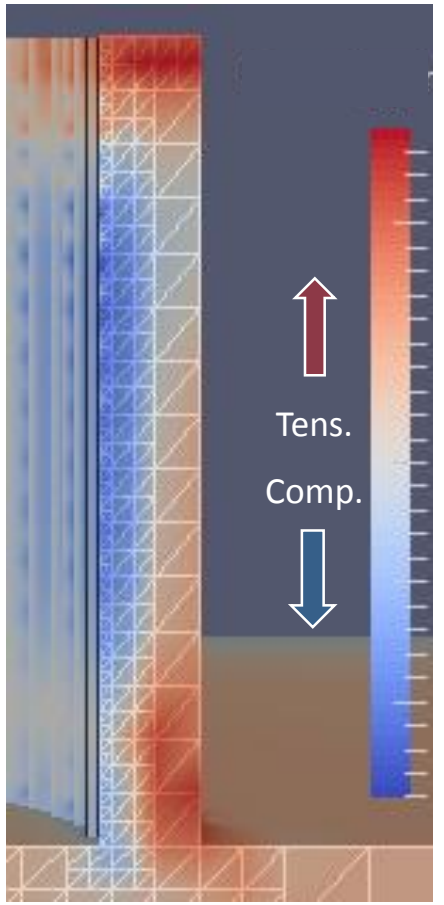
These videos are acquired using a high-speed infrared camera, acquiring images at 1800 frames per second. The raw camera signal is presented (brighter color is more signal). Temperature has not been calculated. These videos are solely intended to illustrate the process and scan pattern.

The expected stress and distortion trends

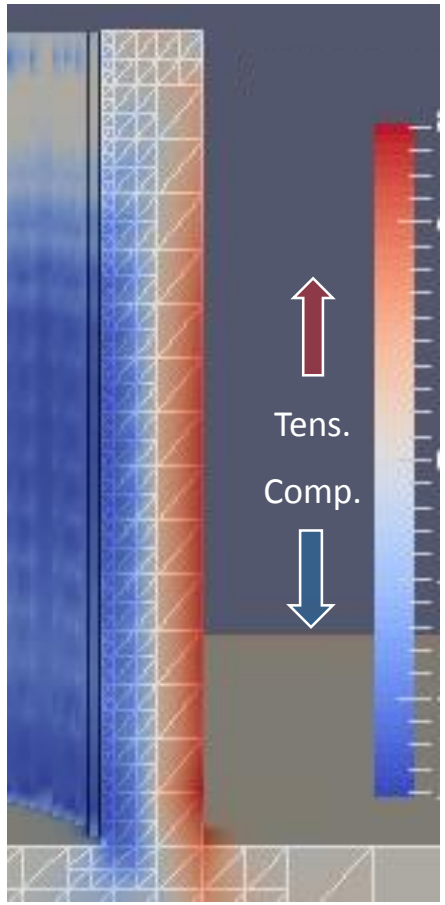
Distortion (magnified)



Hoop Stress



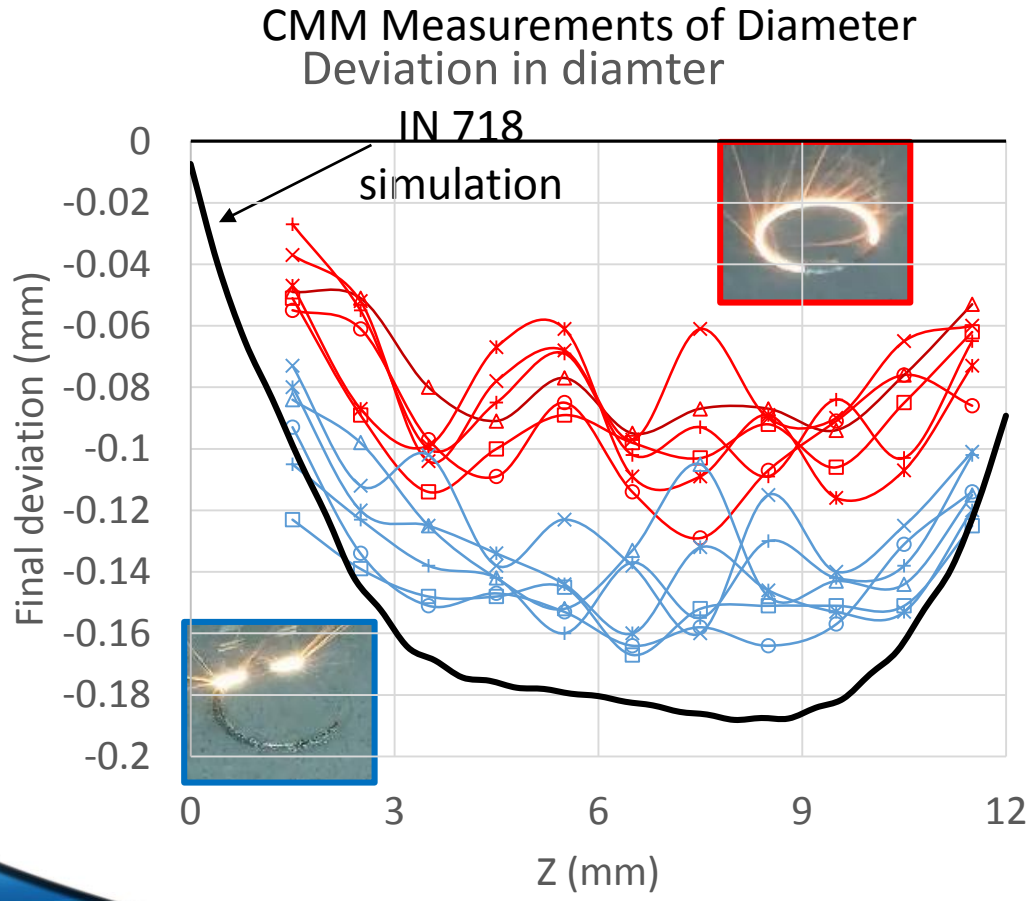
Axial Stress



Dunbar et al. (2016) "Experimental validation of finite element modeling for laser powder bed fusion deformation. Additive Manufacturing V 12

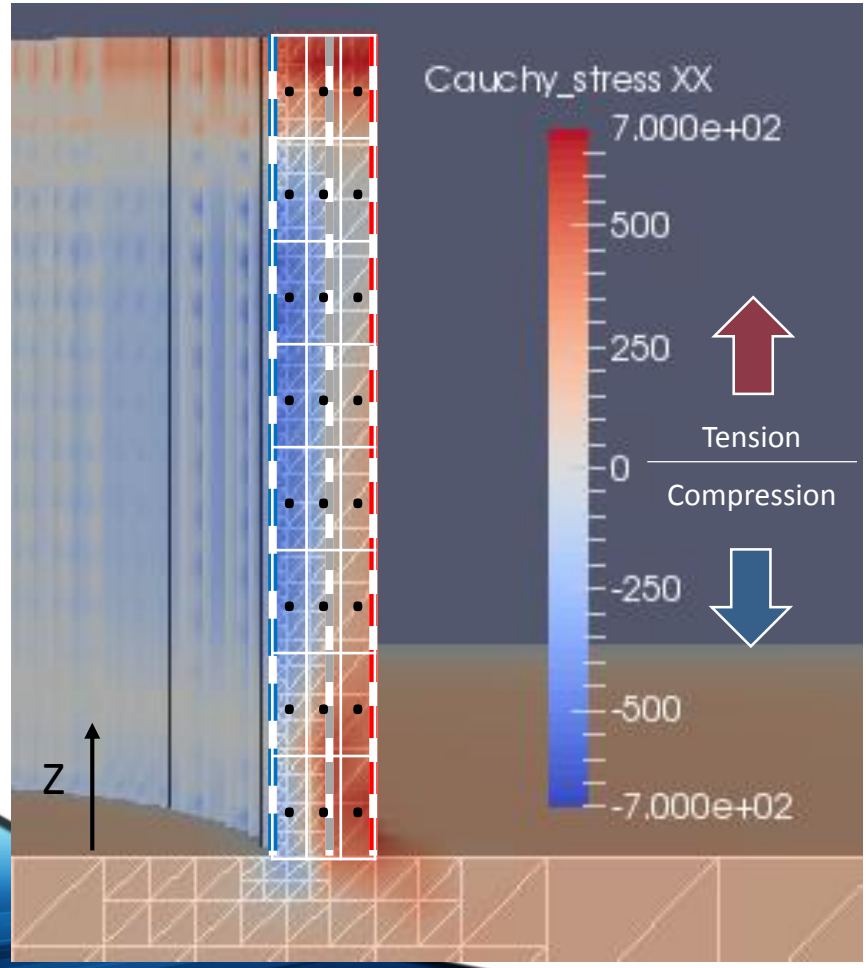
Stress modeling courtesy of Autodesk.
Simulation performed on IN 718

Measured distortion follows the anticipated trend



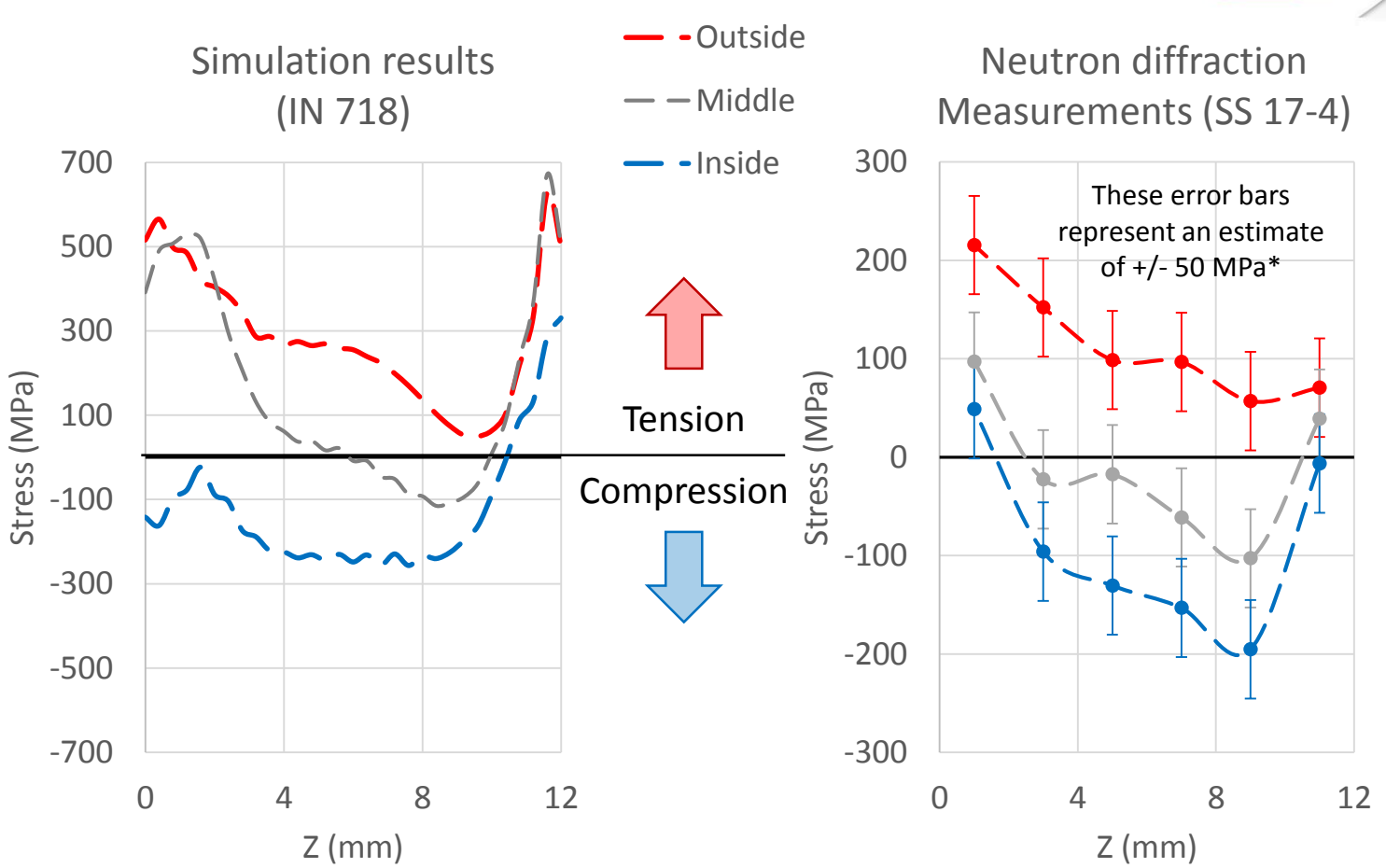
- Diameter is measured using 8 measurement points at each height
- Each of these lines represents individual samples on 1 plate
  - 6 samples of each method per plate
- Trends follow the simulation well
  - Even though different materials
- A clear difference between strategies
  - Need to investigate further
- Measuring geometric error in additive is difficult due to the surface texture
  - Diameter measurement variance is approximately of 50 µm due to the rough surfaces

Measured hoop stress follows the anticipated trends



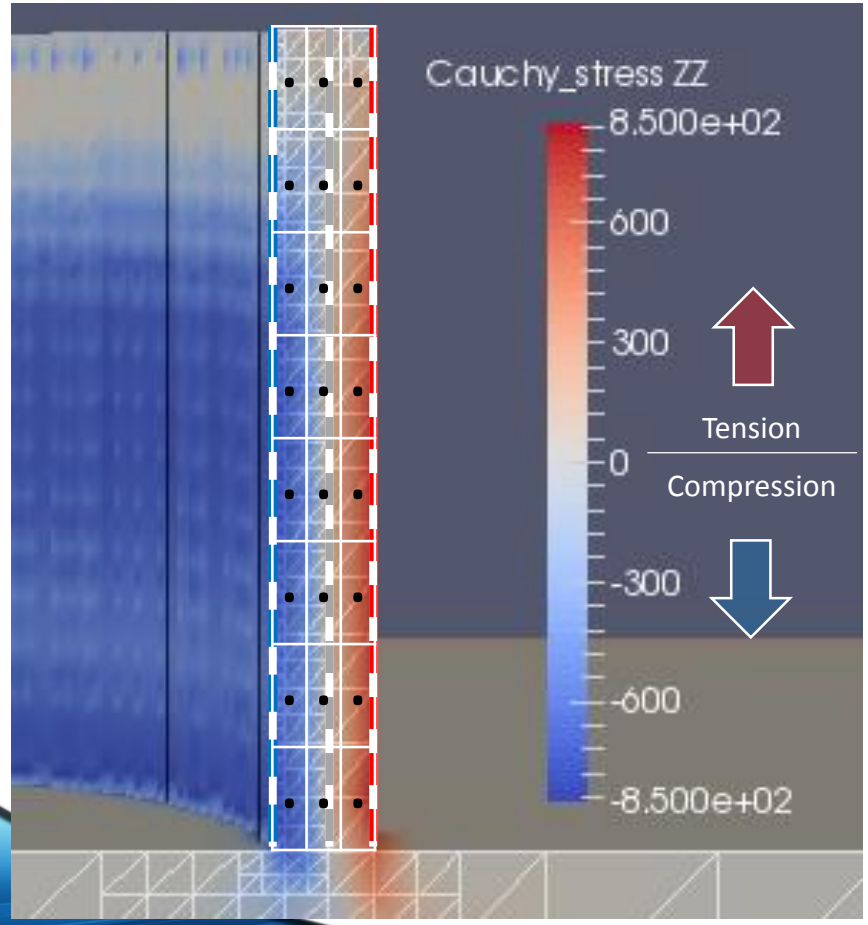
FEA AM simulation courtesy of a collaboration with Autodesk

Note the different materials and scales



* Brown, D. W., Holden, T. M., Clausen, B., Prime, M. B., Sisneros, T. A., Swenson, H., & Vaja, J. (2011). Critical comparison of two independent measurements of residual stress in an electron-beam welded uranium cylinder: neutron diffraction and the contour method. *Acta Materialia*, *59*(3), 864-873.

As well as the axial stress



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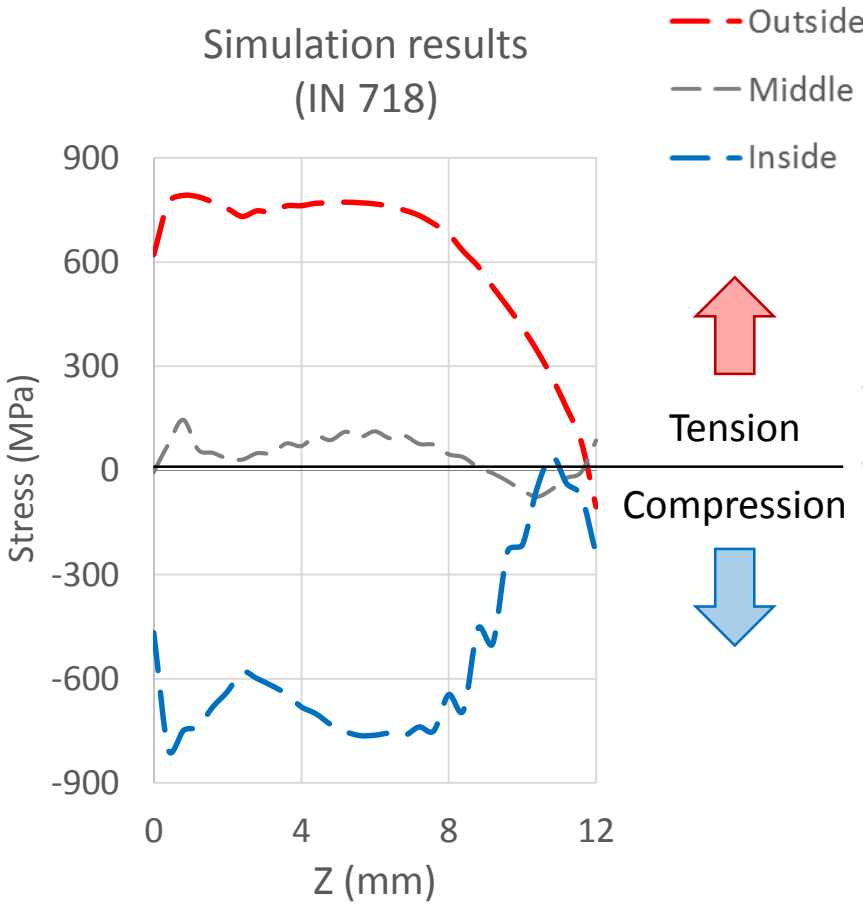
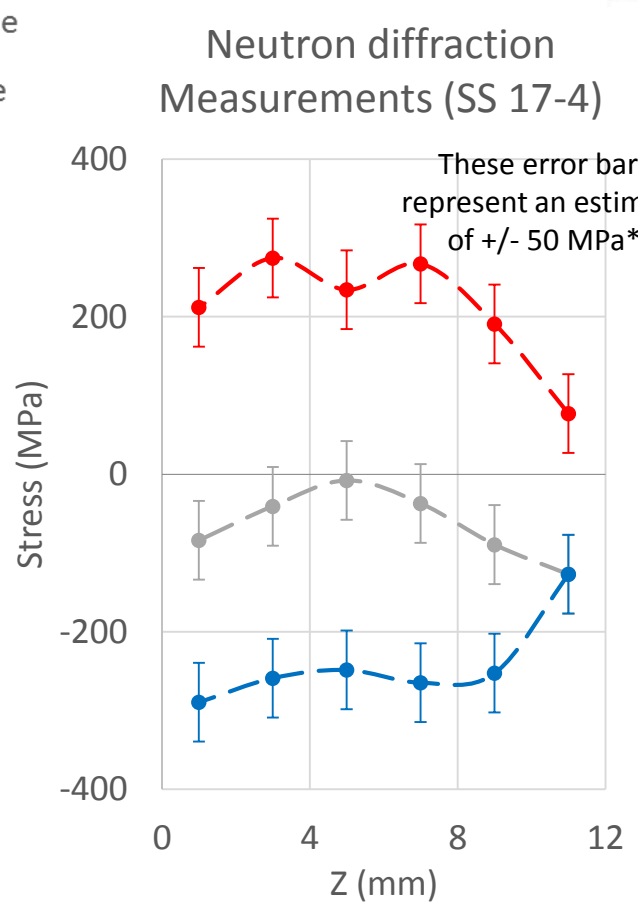
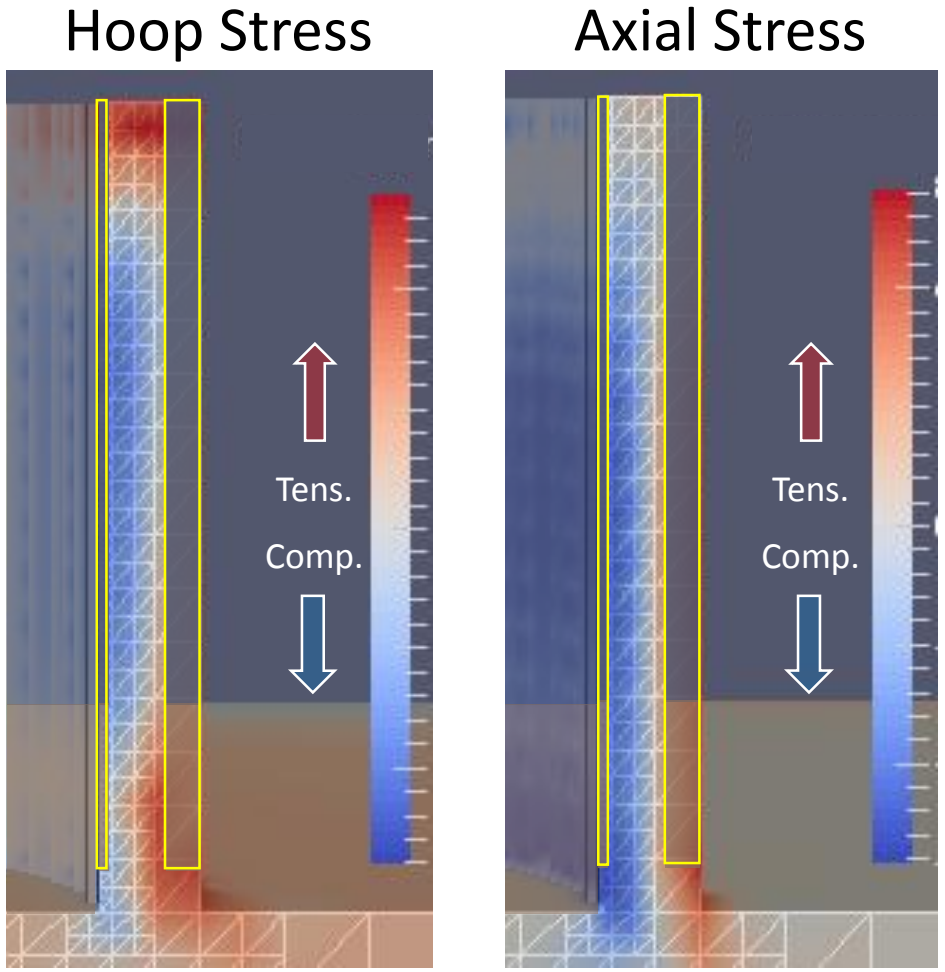




* Brown, D. W., Holden, T. M., Clausen, B., Prime, M. B., Sisneros, T. A., Swenson, H., & Vaja, J. (2011). Critical comparison of two independent measurements of residual stress in an electron-beam welded uranium cylinder: neutron diffraction and the contour method. *Acta Materialia*, *59*(3), 864-873.

The next steps are to machine and re-measure

1. Lightly machine the inner diameter to create a smooth reference surface
2. Measure the ID using a CMM
3. Machine the OD to 15 mm
   - Removing approximately 1/3 of the wall thickness
4. Measure the ID again
   - The ID should shift outward as the stresses rebalance



Stress modeling courtesy of Autodesk.
Simulation performed on IN 718

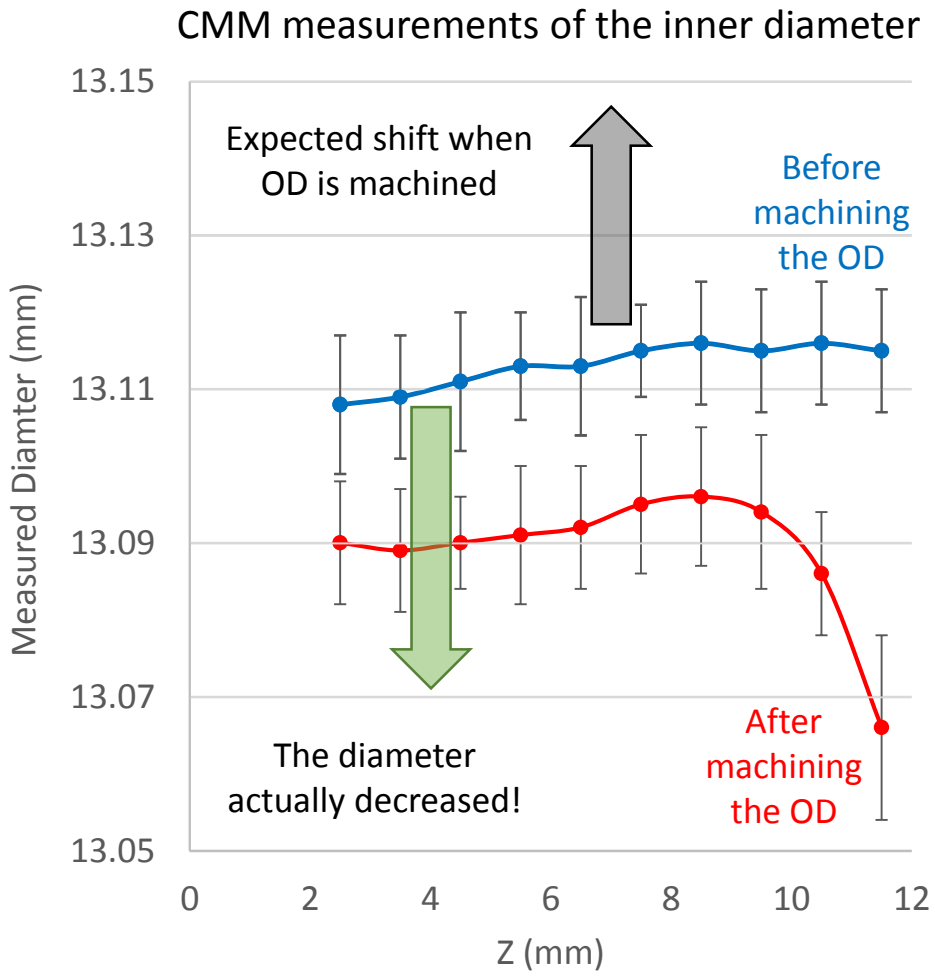
A significant amount of material in tension is removed…

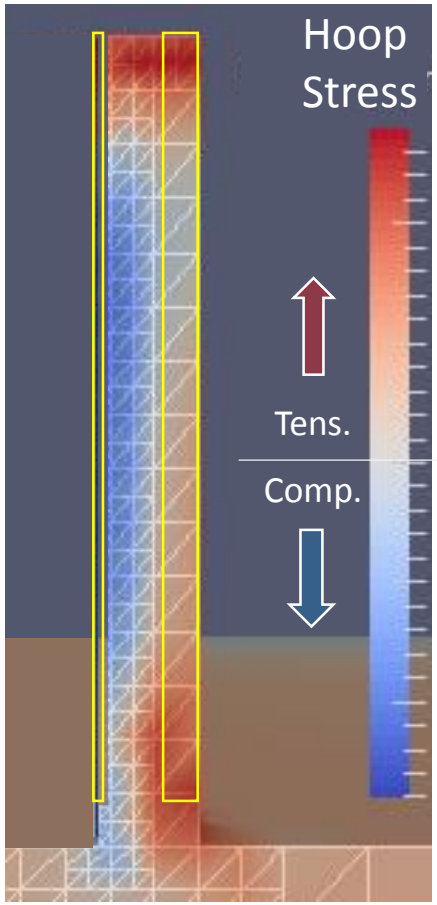
the part should distort outward and the diameter should increase

Stresses lead to more distortion during machining

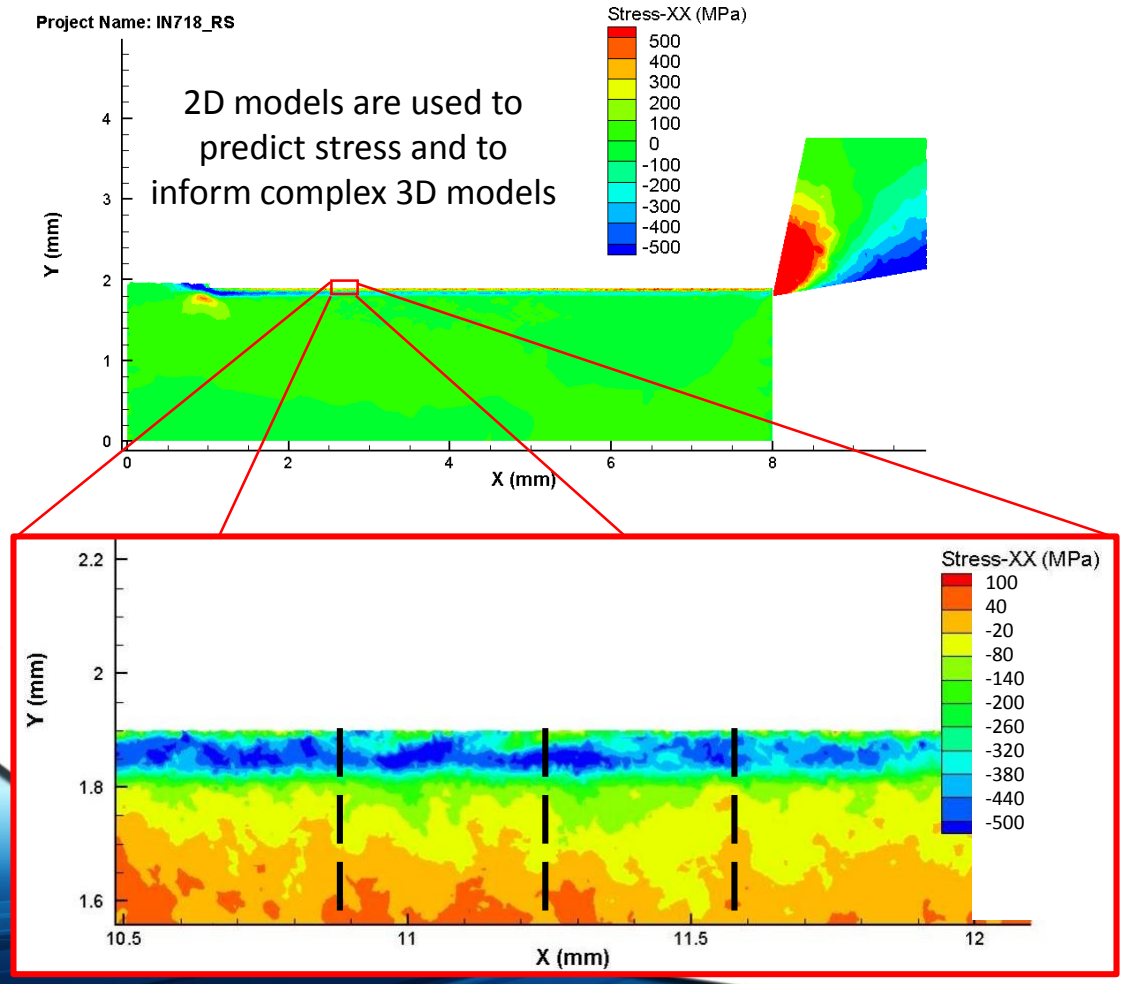
First, machine the ID to create a good surface to measure and compare

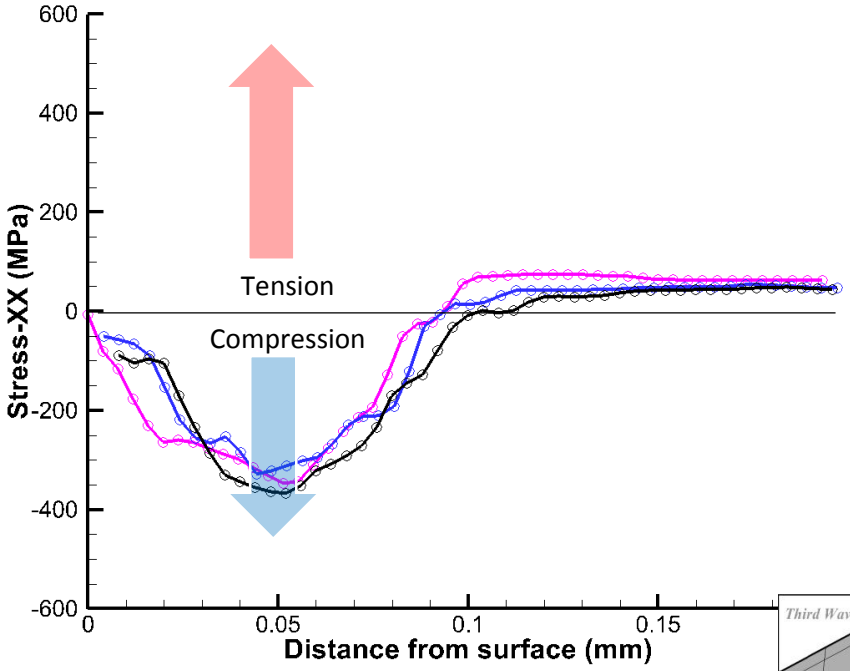
Then, cut the OD and remeasure the ID to see how it changes





The machining process imposes its own stresses

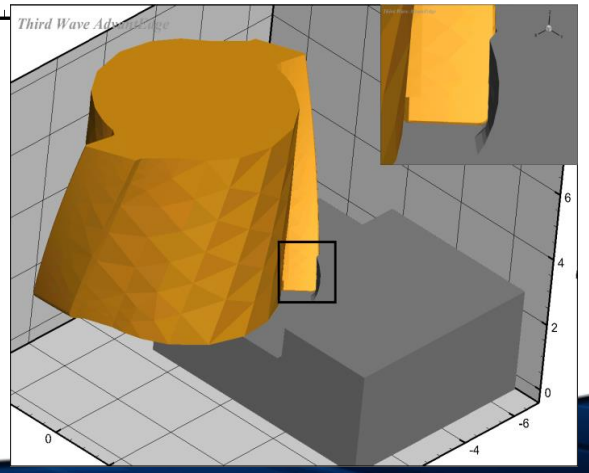




For this material, the cutting process generates a significant amount of stress near the surface.

Could this have caused the cylinders to deform inward after the final machining process?

When both AM and machining models are developed and able to pass information, they can be used to predict stress and distortion of the entire process



Modeling performed by Third Wave Systems

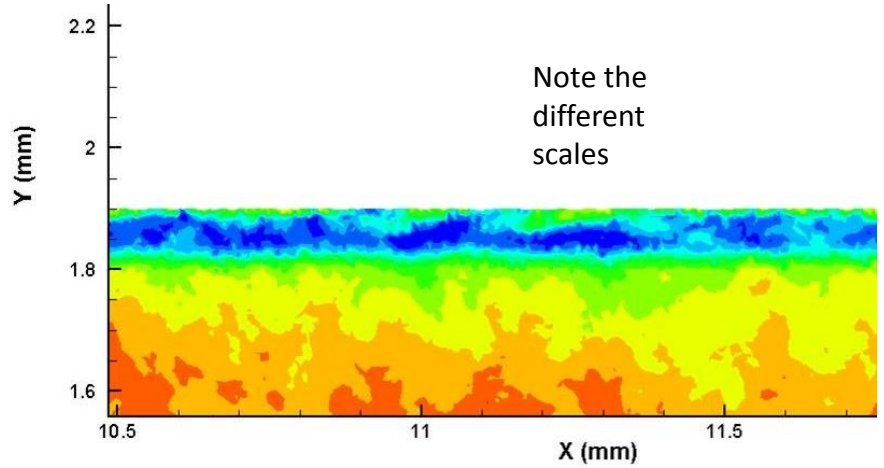
Material challenges experienced during the project

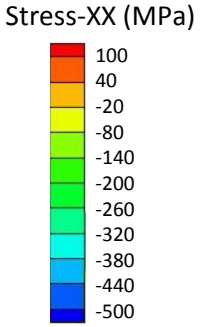
- Stainless steel 17-4 was chosen for the study because it is relatively easy to machine and failures during the final stage of the experiments could not be tolerated
  - 1 year project
- AM and machining modelers do not necessarily have validated material models for the same materials
  - Inconel 718 was a common material to use as a proof-of-concept
- Material has a big impact on stress
  - At least in machining…

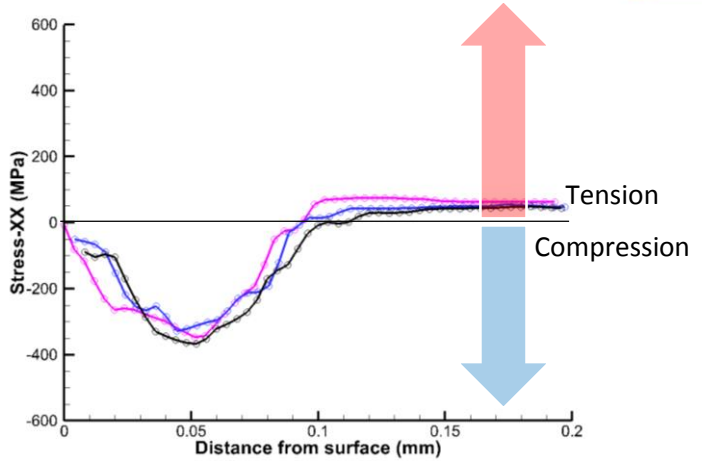
Material greatly affects stress in machining simulations

* Not all materials have validated models

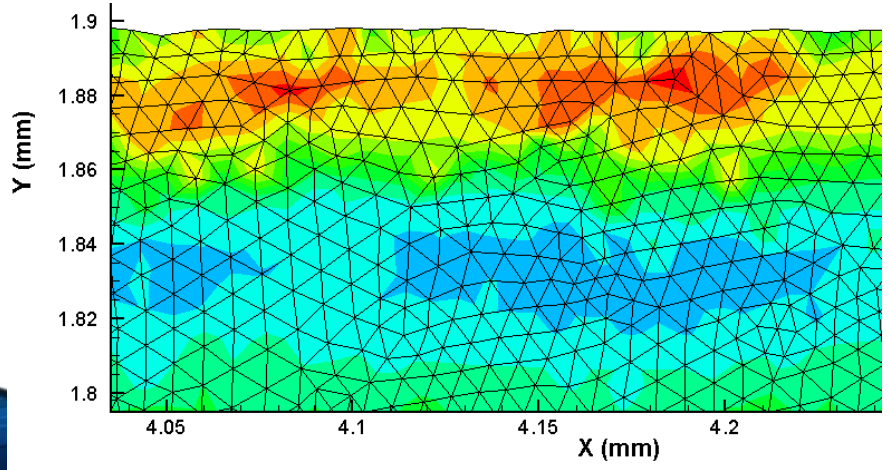
SS 17-4:

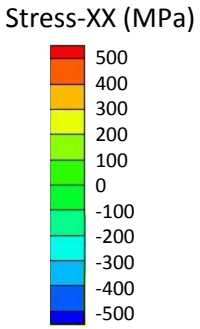


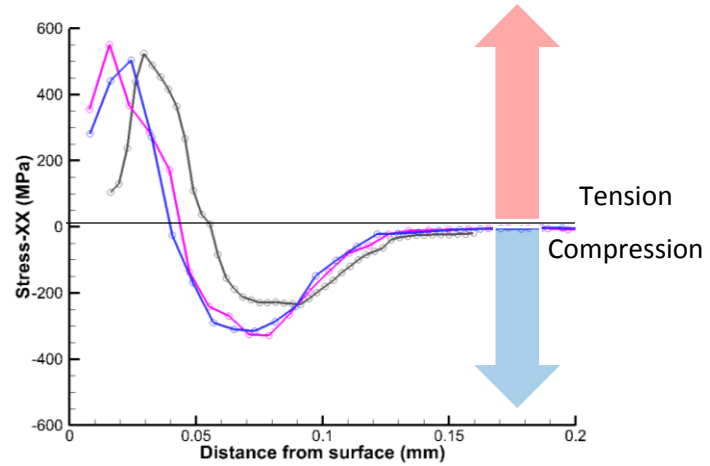




Inconel 718:







Modeling performed by Third Wave Systems

Conclusions

- AM processes create significant, measurable distortion and stress
- Residual stresses and those imposed by machining create additional distortion
- Not yet clear if/how AM material and stresses affect machining
- Measurement science advances needed to further the field
  - Form error
  - Residual stress / strain
  - In situ methods for in-envelope processes

Thank you for your attention

I'd also like to thank my collaborators:

- NIST
  - Jason Fox, Alkan Donmez, Thien Phan, Jay Nanninga, Tyler Gervasio, Kil-Won Moon, Jared Tarr
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- Third Wave Systems
  - Brian Becker, Cory Arthur
- UNC – Charlotte
  - Tony Schmitz, Andrew Honeycutt, Michael Gomez
- UC-Davis
  - Mike Hill, Chris D'Elia