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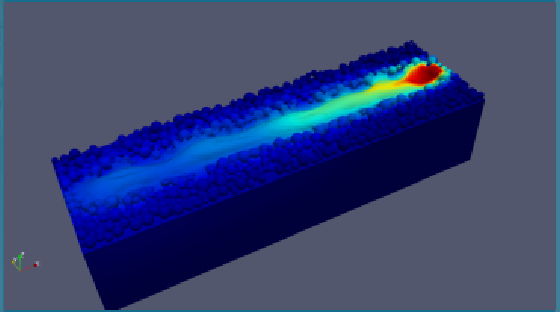
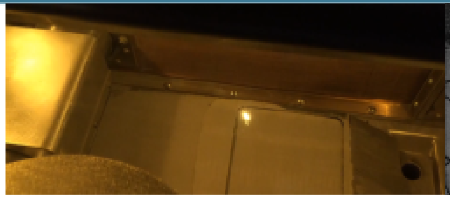
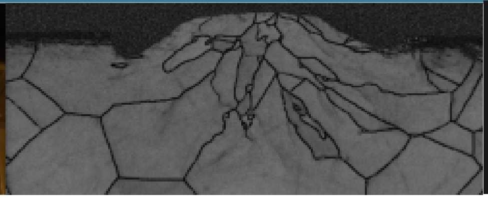
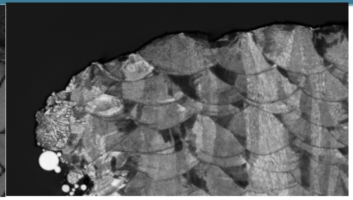
Model-based quantification of uncertainties in metal additive manufacturing









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Sandia National Laboratories

International Conference on Additive Manufacturing

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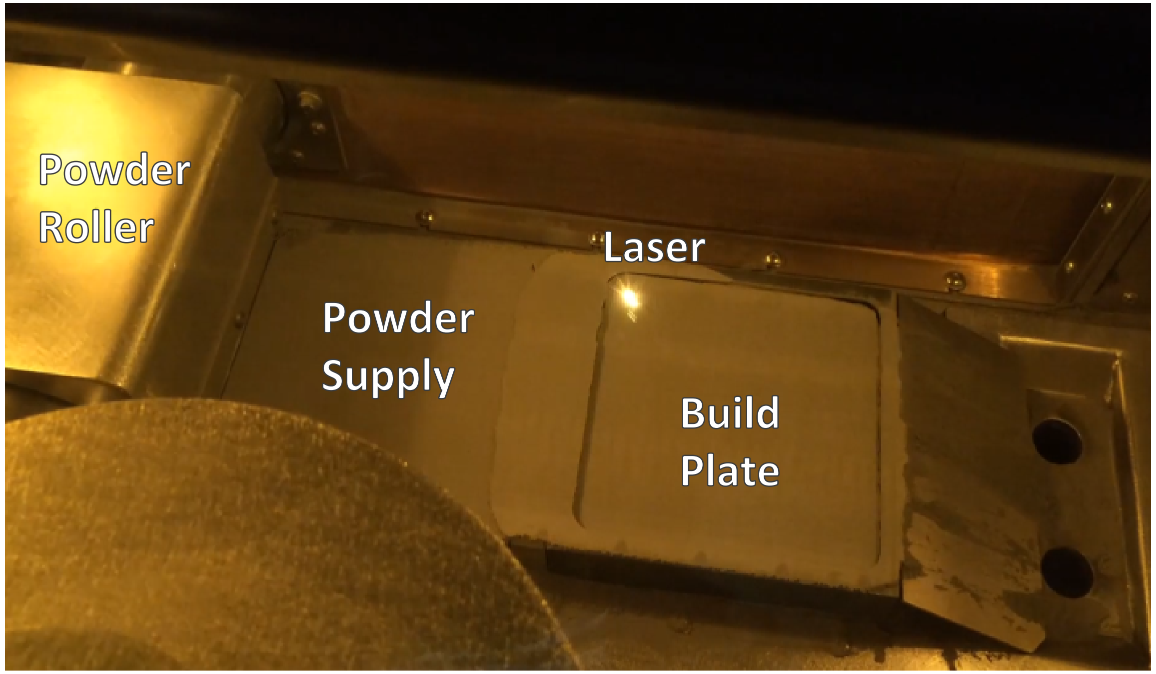
Laser Powder Bed Fusion Qualification Challenges

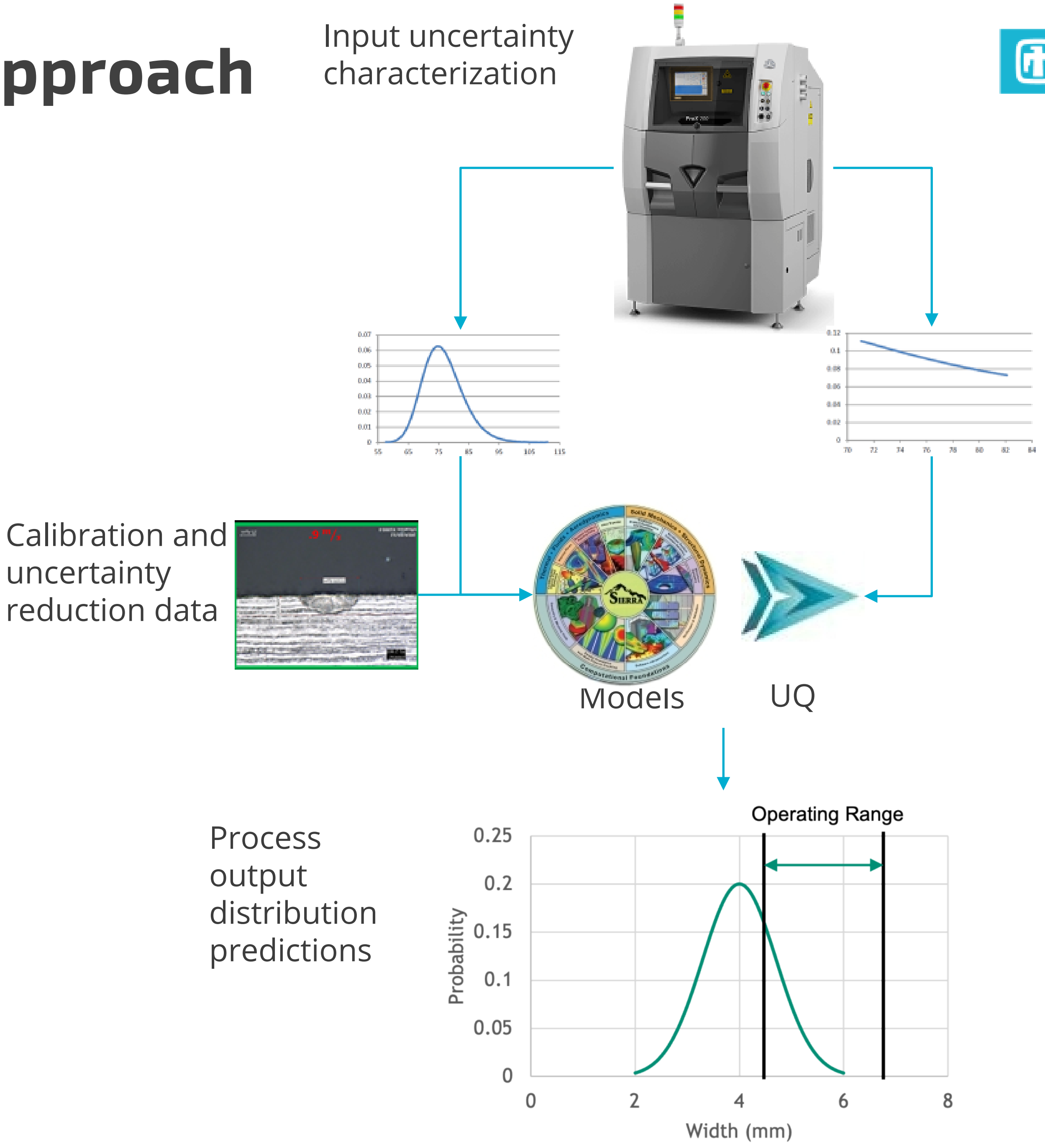
- Laser Powder Bed Fusion (LPBF) is a leading additive technology for producing functional metal parts for critical applications
- Part qualification remains an expensive, time-consuming, often ill-defined process
- Process physics of laser-induced melting and re-solidification produces difficult to predict, often unrepeatable outcomes
  - Anisotropic microstructures
  - Thermally-induced residual stresses and distortions
- Mod-Sim and UQ possible path forward to reduce cost of part qualification
- Model-based evidence to support process qualification



Optical image of LPBF machine in operation

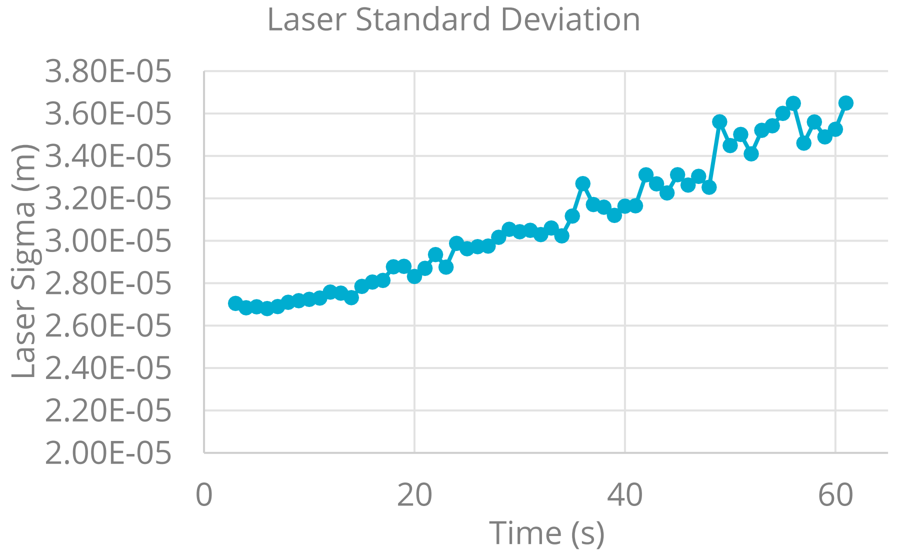
Uncertainty Quantification Approach

- Uncertainty quantification techniques allow uncertainties in model inputs to be propagated to model predictions
- Allows prediction of probability distributions for quantities of interest
- Goal is to take what we know about the uncertainties in machine operation and propagate them through physics models to predict distributions of as-built:
  - Dimensional accuracy
  - Residual stress
  - Microstructural features

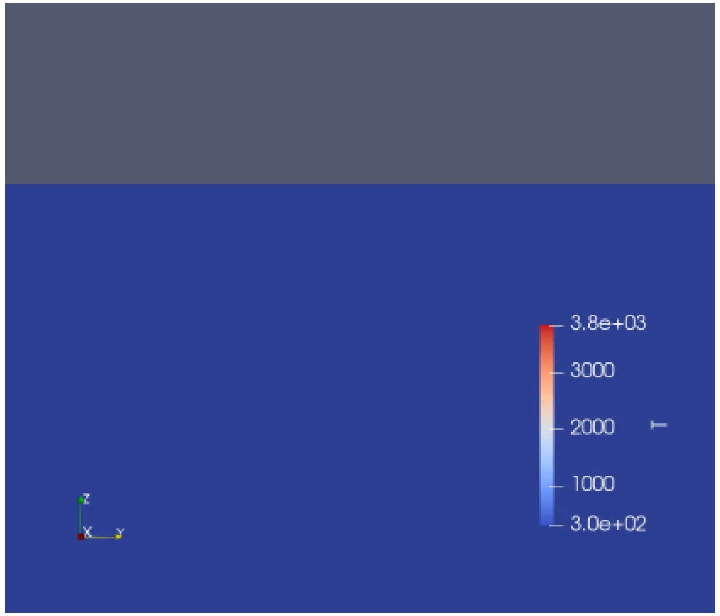


Input Uncertainty Estimates

- High fidelity melt pool model sensitivity analysis used to screen for process sensitivities to uncertain parameters
  - Ambient chamber temperature
  - Material sulfur content (impacts surface tension)
  - Index of refraction
  - Laser power
  - Gaussian laser standard deviation
- Probability distributions estimated using literature review, beam characterization, and integrating sphere data



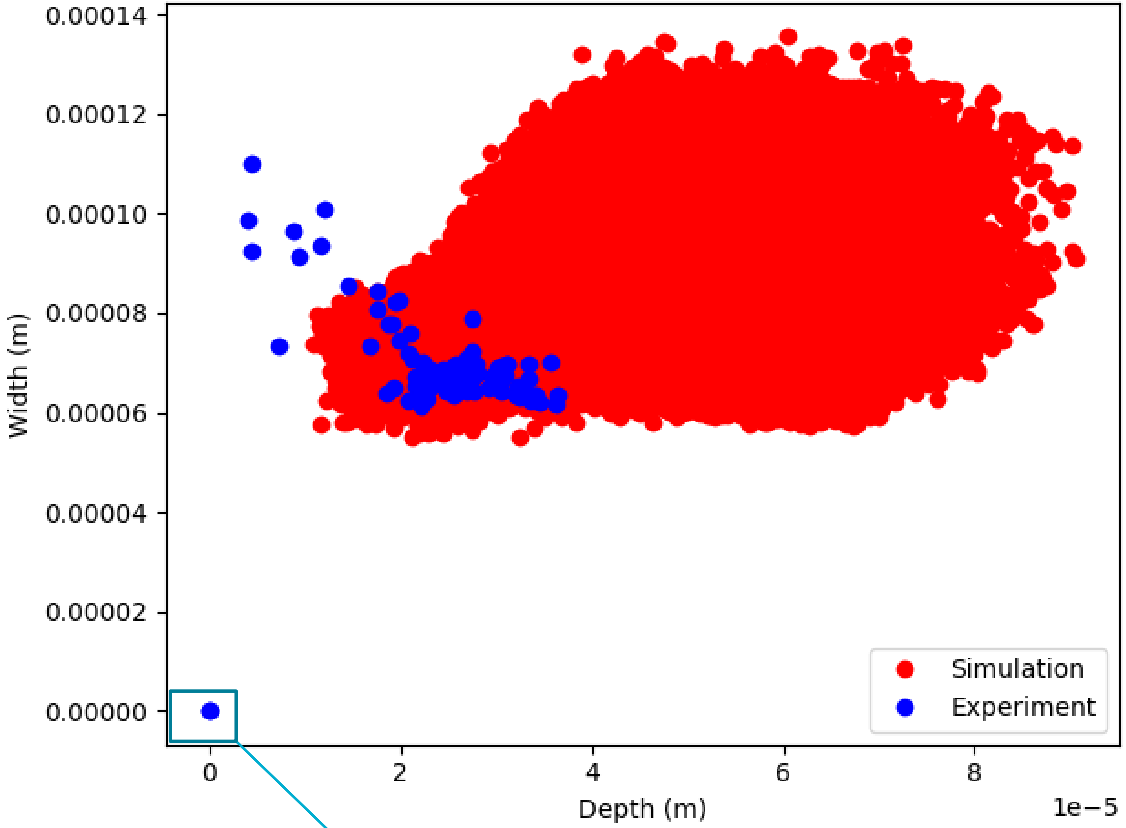
Measured evolution of laser spot size over time



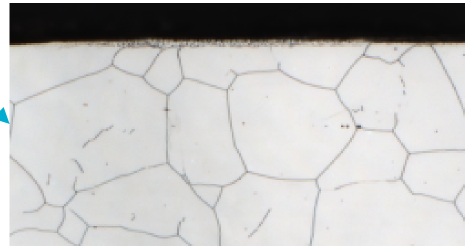
Example of high fidelity model used to predict spot weld behavior

Low Level Validation: Bead on Plate Dimensions

- Uncertain parameters are propagated through high fidelity thermal/fluid models using Gaussian Process Surrogates and Latin Hypercube Sampling
- Results compared to 100 experimental bead -on-plate dimensional measurements from cross section metallography
- Predicted distribution bounds the observed results for 91/100 cases
  - Investigating cause of what appear to be laser misfires
- At this point, **model has seen no calibration data**, just estimates of uncertain inputs

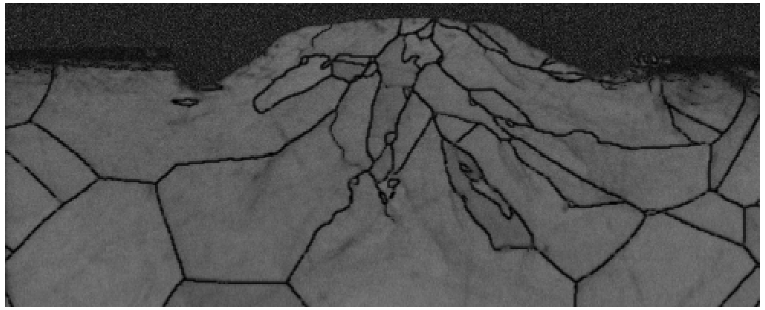


Distributions of predicted and measured melt pool widths and depths

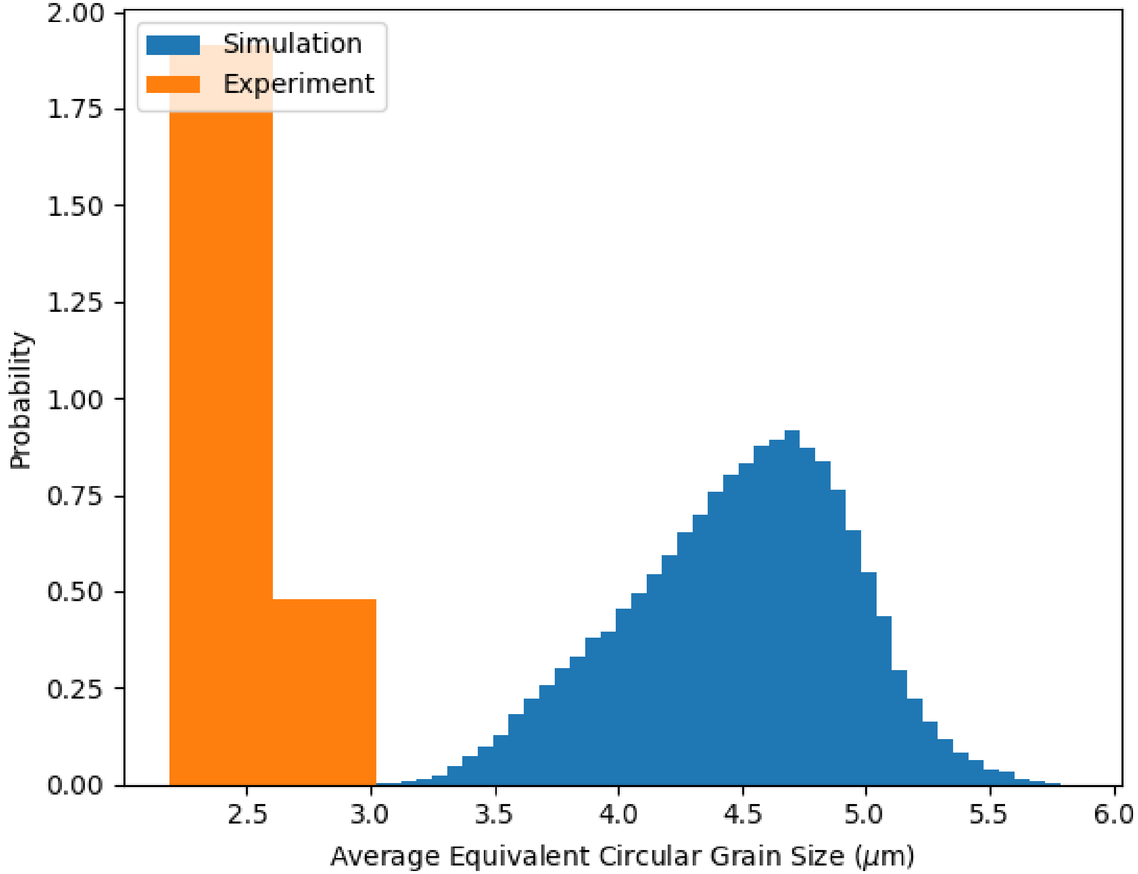


Low Level Validation: Bead on Plate Microstructure

- Thermal results used in undercooling-based microstructure prediction routine to build and sample Gaussian Process Surrogate for average grain size
- Results compared to 5 EBSD cross section images from bead-on-plate builds
- Predicted distribution has larger average grain sizes than experimentally observed
- Only thermal model parameters considered here. Study needs to be expanded to include additional uncertainties in microstructure model

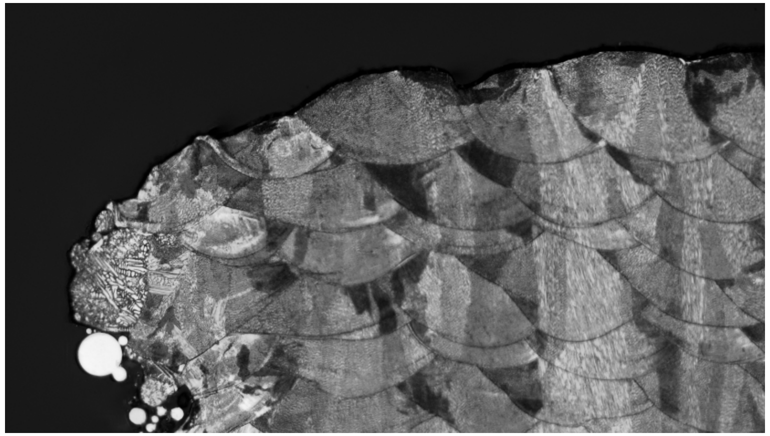


Melt Pool EBSD image with grain boundaries

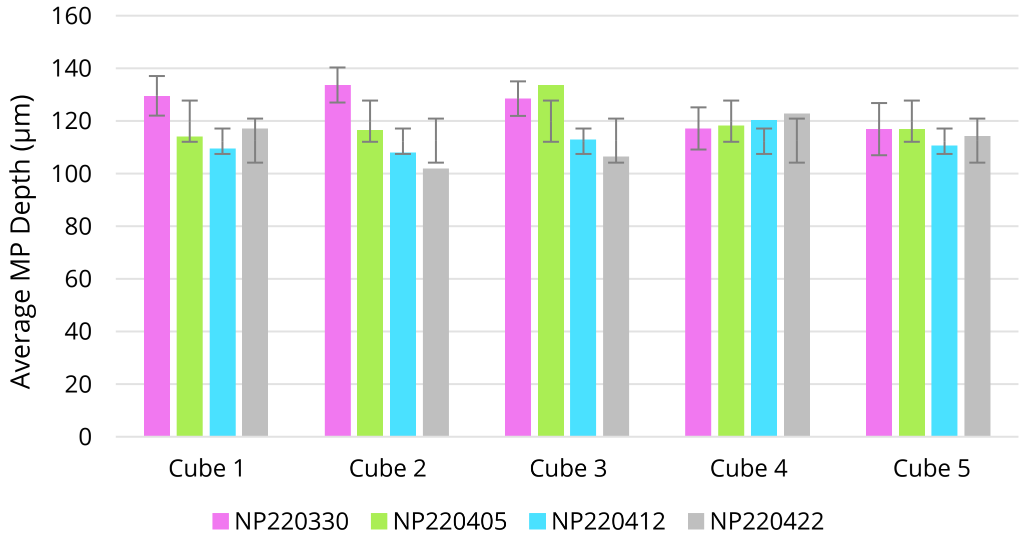


Part Scale Predictions

- Faster, reduced fidelity models needed to make predictions of cm-scale parts
- Conduction only model neglects fluid flow and simplifies laser interaction to ellipsoidal gaussian volumetric source
  - Heat source parameters require calibration
- Bayesian calibration of conduction-only model performed to metallography melt pool measurements of 2cm cubes
- Calculates probability distributions of calibrated parameters based on knowledge gained from observed data



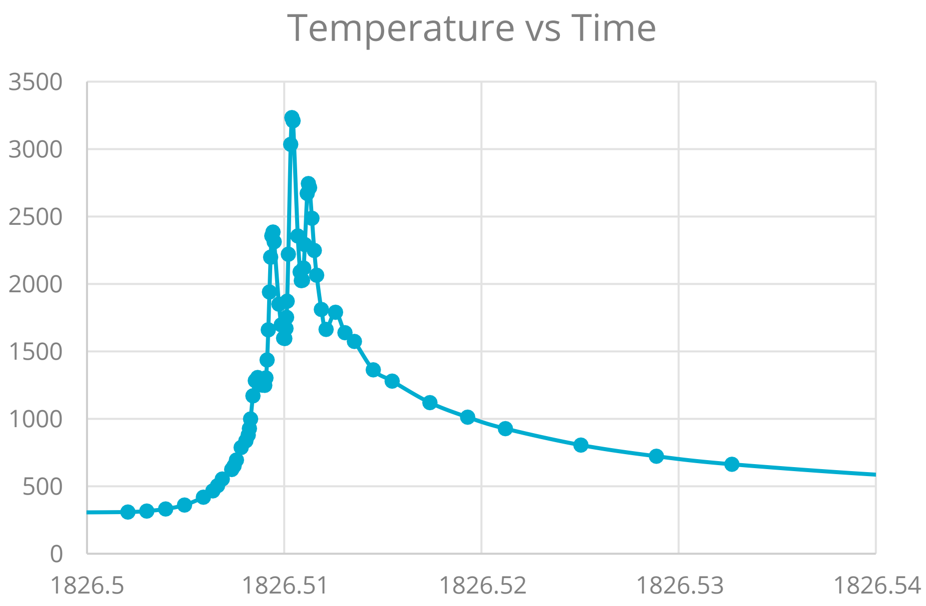
Metallography image of built cube showing overlapping melt pools



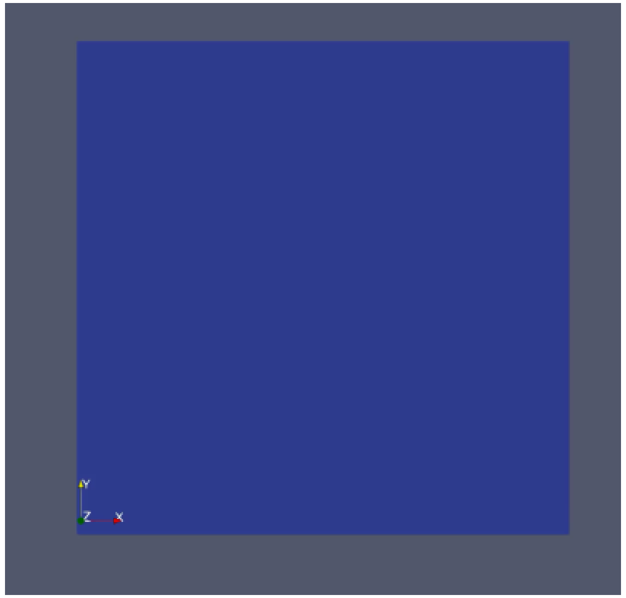
Average melt pool depths measured from metallography images

Part Scale Predictions

- Even simplified conduction model can be intractable at scale due to time stepping requirements
- Green's function analytical solutions enable rapid computation of time-temperature traces for a part
- Requires linearity assumption. Additional source of uncertainty due to unmodeled temperature dependence of material properties
    - Laser source parameters (depth, width, travel)
    - Thermal conductivity
    - Specific heat
- Distributions from 100 Latin Hypercube samples



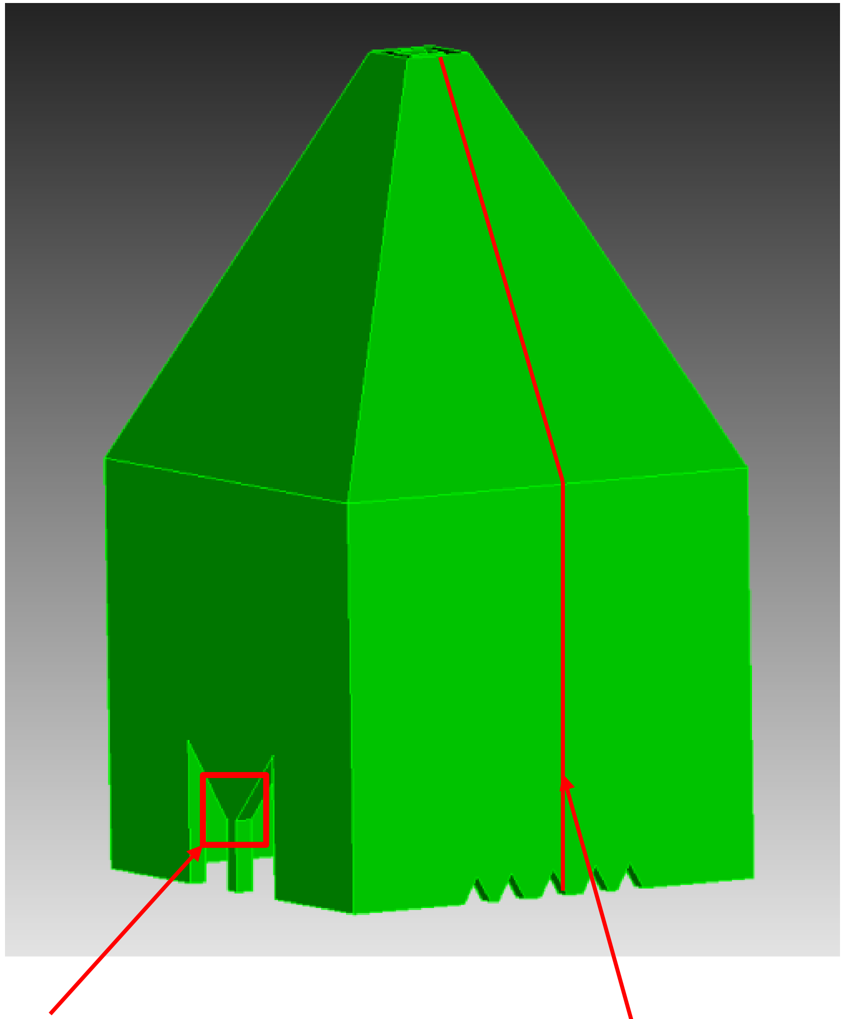
Example time-temperature trace for point in part build simulation



Full layer thermal history computed with analytical model

Part Scale Measurements

- 2cm 'house' geometry builds performed. EBSD and blue light coordinate measurements collected
- Various features added to create areas of microstructural/mechanical interest
- Cut for EBSD in "arch" section of geometry
- Deflections compared along outer wall in the middle

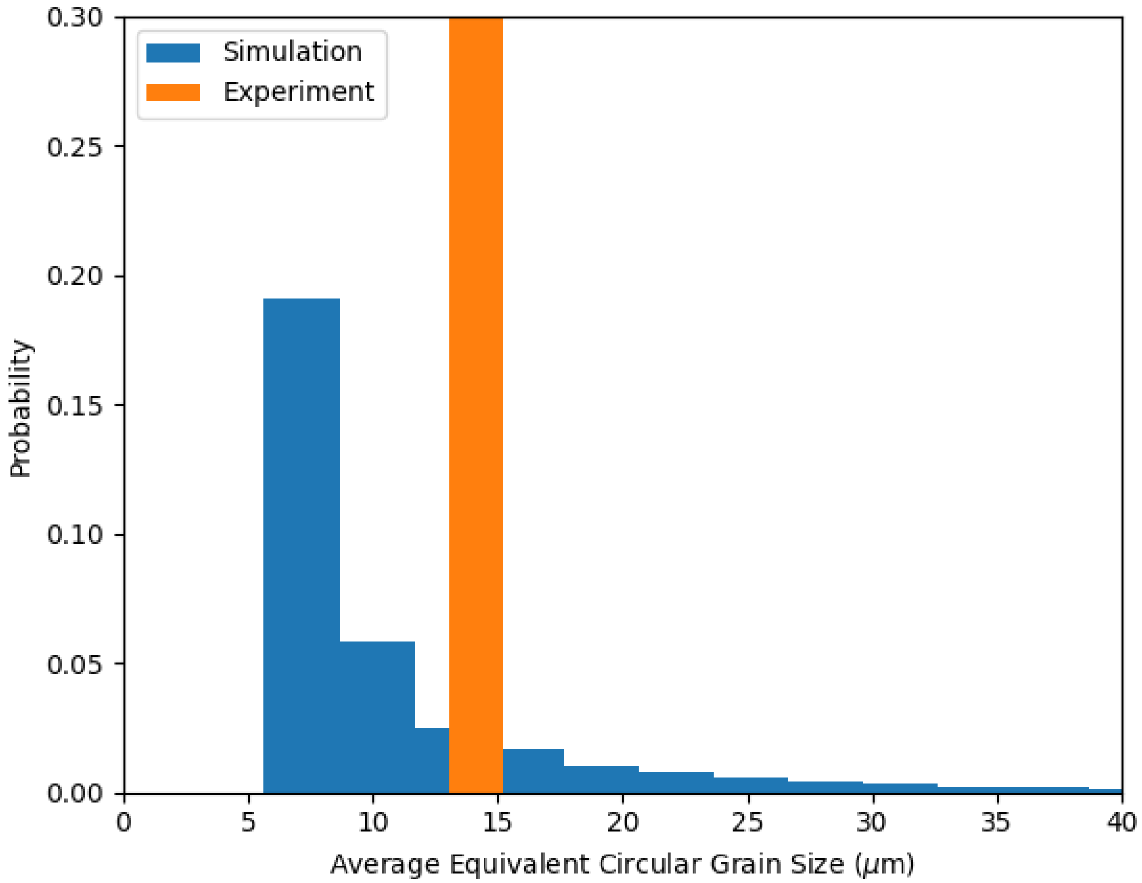


Cut location for EBSD measurements

Deflection comparison location

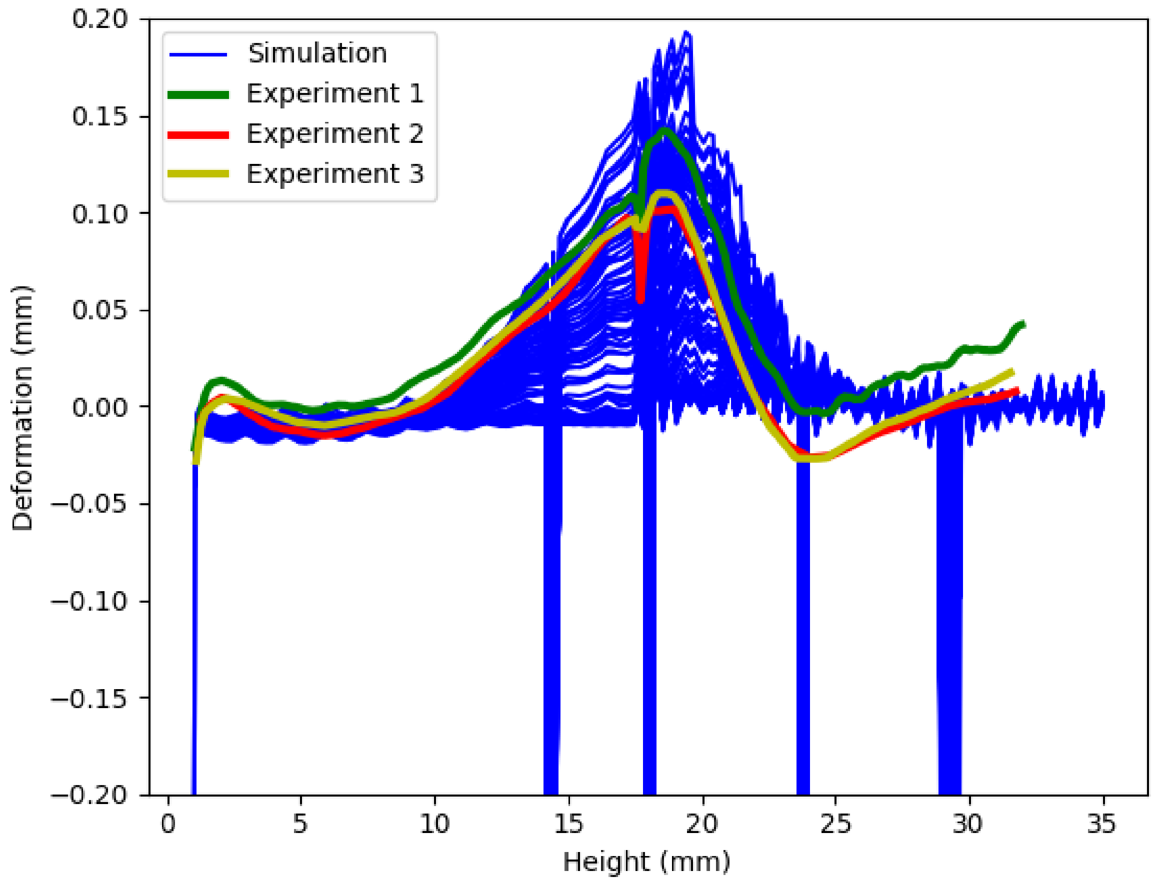
Part Scale Microstructure

- Using same undercooling based microstructure model as bead-on-plate predictions
- Simulations performed on small “window” of the part to allow for faster evaluations
- Predicted grain sizes do bound the experimentally observed grain sizes. Predicted distribution is much broader and predicts some population of very large grains
- Still only considering thermal model uncertainties. Results may be less sensitive to microstructure model parameters in larger build
- Next step is propagating uncertainties in microstructural features through to bulk material properties



Part Scale Deflection

- Enhanced inherent strain method employed, making use of time/temperature traces calculated from analytical thermal model
- Imposed plastic strains are scaled by the max thermal gradient seen at each point
- Mechanical model less sensitive to thermal model uncertainties than microstructure
- Model form uncertainty estimation for mechanical model is needed



Conclusions and future work

- Uncertainty quantification techniques have shown promise in bounding laser powder bed fusion build outcomes
- Future work is planned to fully propagate uncertainties from process physics to part distortion, residual stress, and material properties
- Model form uncertainty quantification is an outstanding challenge in reduced fidelity conduction models and rapid solid mechanics models
- Final goal is to predict outcome distributions for part performance that can be used to assist with process qualification