COMSOL Heat Transfer Simulation for Reliability Estimation of Additive Manufacturing Process

Kai Wing Kelvin Leung, Azadeh Keshtgar, Nagaraja Iyyer
Technical Data Analysis, Inc., 3190 Fairview Park Drive, Suite 650,
Falls Church, VA 22042, USA

Presented by: ***Kai Wing Kelvin Leung***
Oct 6, 2016

COMSOL CONFERENCE
2016 BOSTON

Background

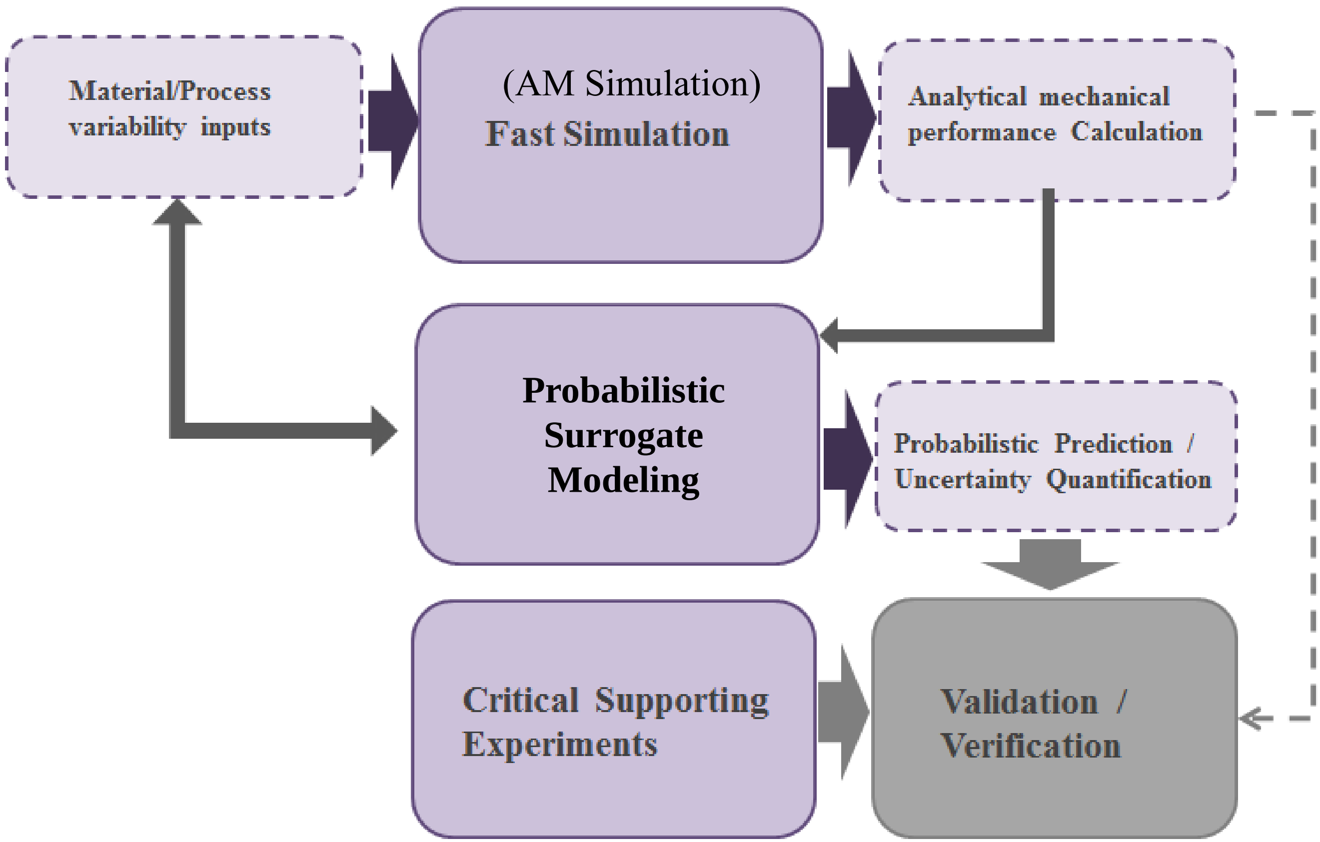
➢**Problem:**

- Selective laser melting (SLM) is a popular additive manufacturing (AM) process
- Difficult to certify AM part as its final quality can largely vary
- A quantitative computational approach for uncertainty analysis is needed
- Simulation of complete and complex AM processes are hampered by long run-times

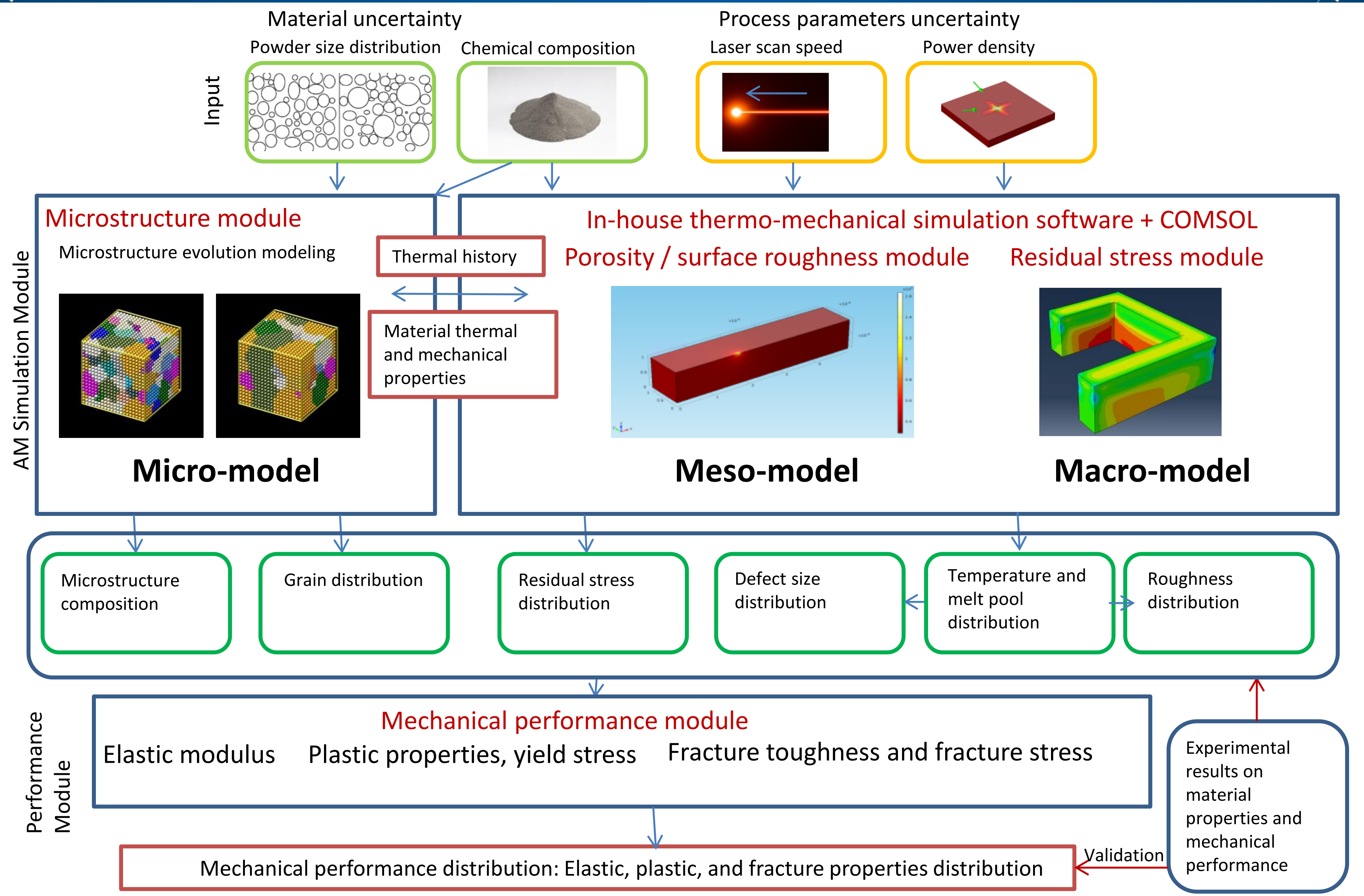
➢**Goal:**

- Develop a probabilistic physics-based numerical prediction approach to characterize the propagation of uncertainties due to material and process variabilities of SLM into the performance of manufactured components

Proposed Framework



AM Simulation Module



Surrogate Modeling

- **Approach:**

  - We propose to demonstrate use of novel surrogate modeling approach which will provide good approximate answers to predict uncertainty overcoming run-time problems.

  - The methodology employs Kriging, which is most suitable for highly parameterized contexts as in AM, and has the advantage of taking into account the nature of the distribution functions of the uncertainties in the data and provides estimates of the uncertainty of the predictions using information in only a few areas/hot spots of the component.

- **Advantage:**

  - ✓ **Fast**
  - ✓ **Simple**
  - ✓ **Efficient**
  - ✓ **Acceptable accuracy**

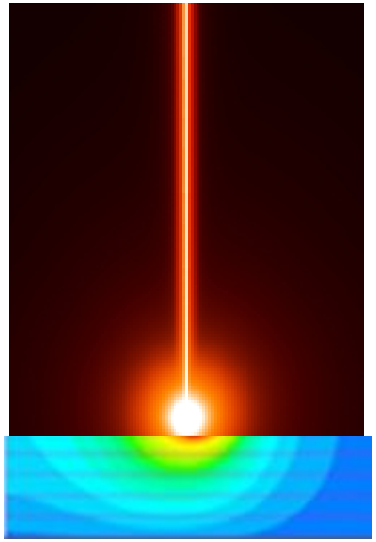
Thermo-mechanical Simulation

- The localized heating of powder is modeled by conductive heat transfer

$$\rho C_p \frac{dT}{dt} = k_{xx}\frac{d^2T}{dx^2} + k_{yy}\frac{d^2T}{dy^2} + k_{zz}\frac{d^2T}{dz^2} + \varphi$$

- T is the temperature, t is time, k_{xx}, k_{yy} and k_{zz} are thermal conductivities, ρ is the density, C_p is the specific heat and φ is the heat source term
- The thermal interaction between the domain and surroundings can be represented as

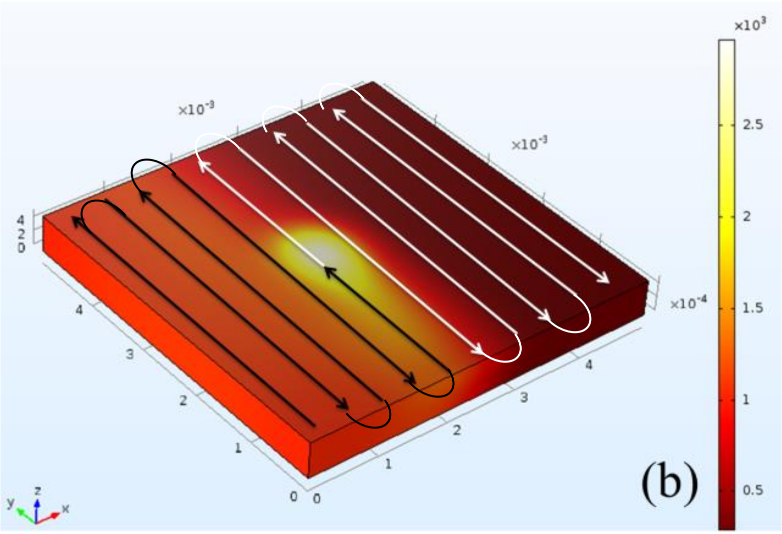
$$-k\frac{dT}{dn} = -\mathrm{h}(T_{amb} - T) + \sigma\varepsilon(T^4 - {T_{amb}}^4)$$

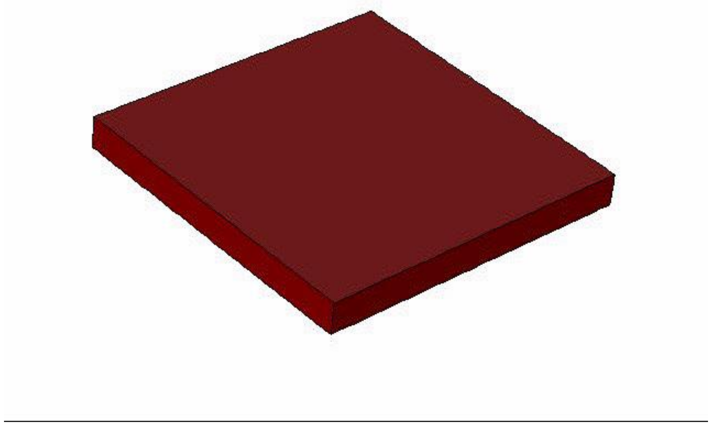


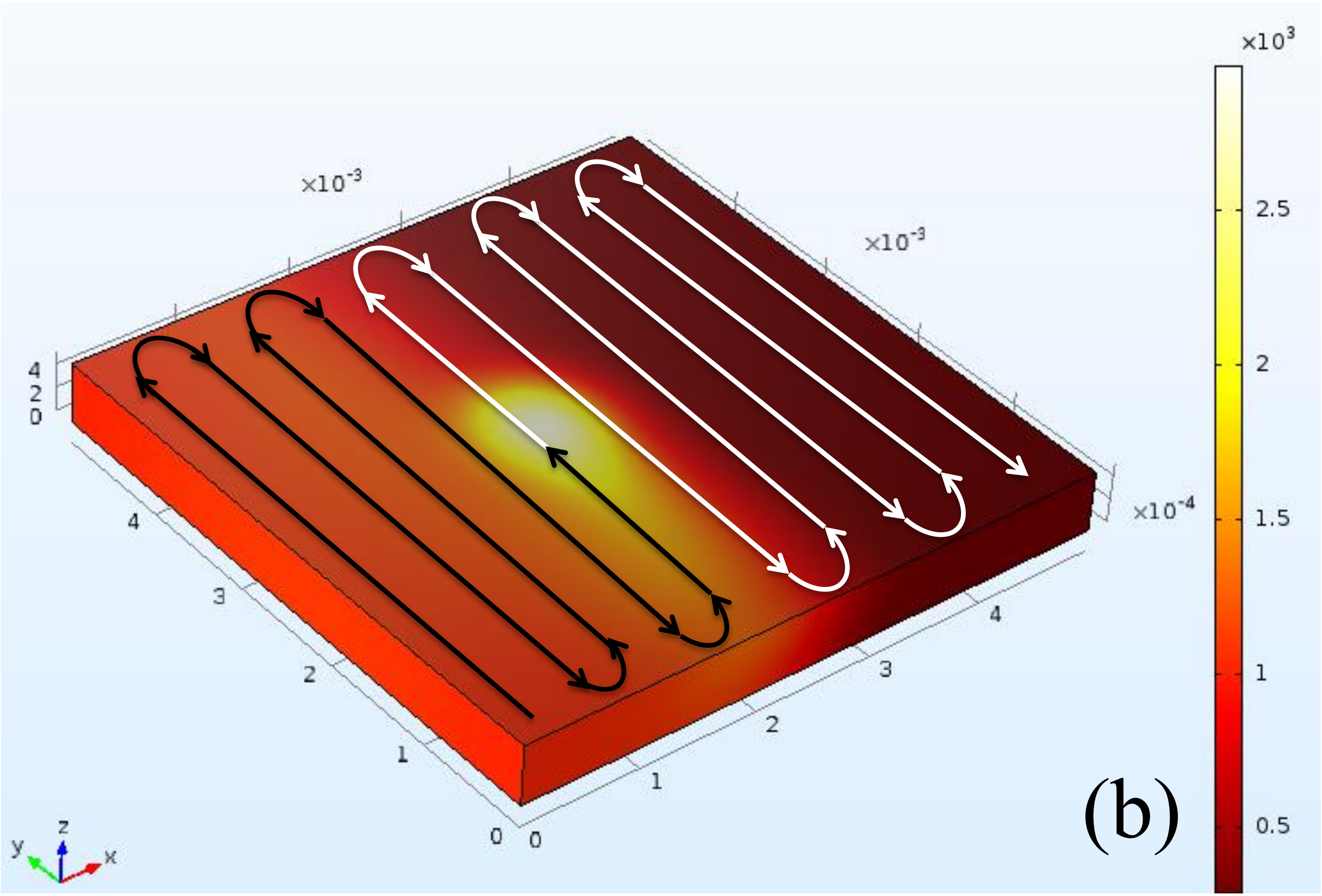
- h is the heat transfer coefficient, T_{amb} is the temperature of the environment, ε is the emissivity of the material and σ is the Stefan-Boltzman constant
- Thermal properties of material are dependent on temperature and the porosity of the randomly packed powder bed

Single-layer Multi-track Simulation

- The heat transfer analysis of a single-layer multi-track AM process is modeled with and solved by COMSOL Multiphsysics
- The material under consideration is Ti-6Al-4V
- We use COMSOL Livelink with Matlab to read a laser scan path input file and create the motion of the laser source
- COMSOL and Livelink with Matlab for analyzing the large database of temperature history results

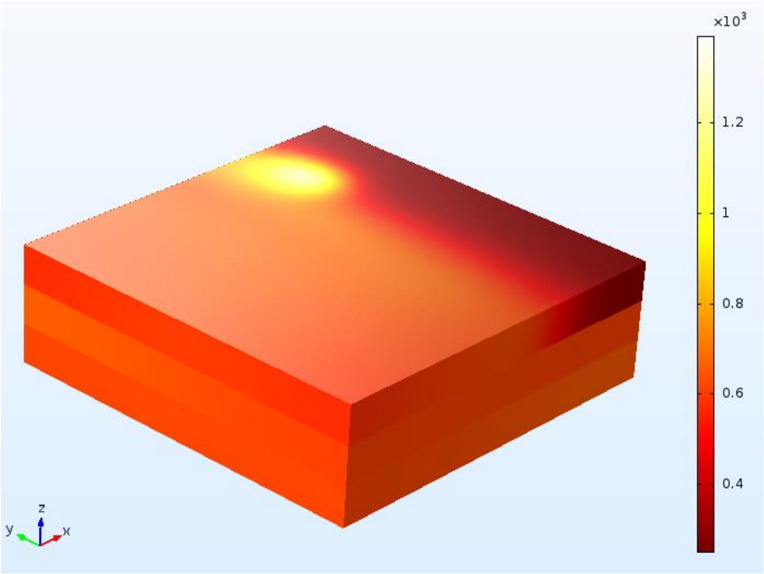


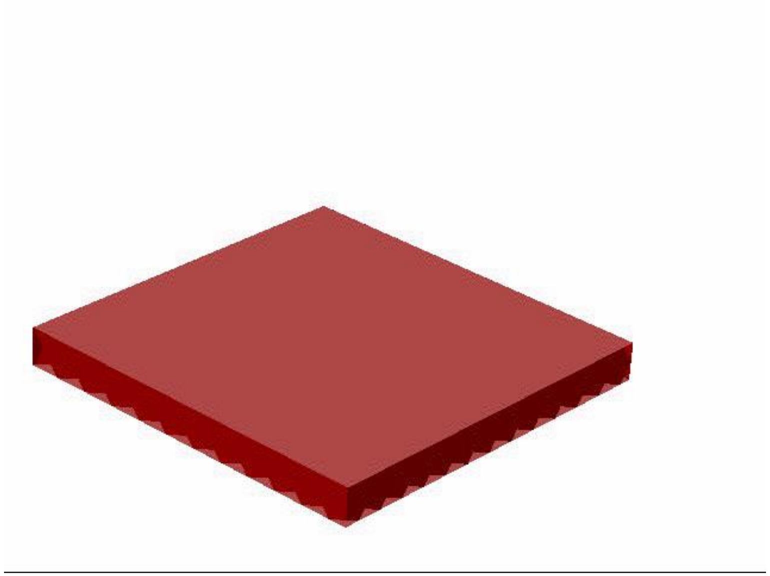



×10⁻³
×10⁻³
×10⁻⁴
×10³
2.5
2
1.5
1
0.5
4
2
0
4
3
2
1
0
0
1
2
3
4
z
y
x
(b)

Multi-layer Multi-track Simulation

- The heat transfer process is modeled with COMSOL Multiphsysics
- The material under consideration is Ti-6Al-4V
- We use COMSOL Livelink with Matlab to read a laser scan path input file and create the motion of the laser source
- The temperature history of the lower layers can affect the heat transfer process of the upper layers





Uncertainty Quantification

Monte Carlo Simulation (MCS):

- Sampling based method
- Well known and popular
- dealing with complex limit states

Kriging method :

- An efficient Surrogate modeling to incorporate measures of error and uncertainty when determining estimations.
- Dealing with computationally demanding models.
- Taking into account the nature of the distribution functions of the uncertainties in the data and provides estimates of the uncertainty of the predictions.

Initial Results

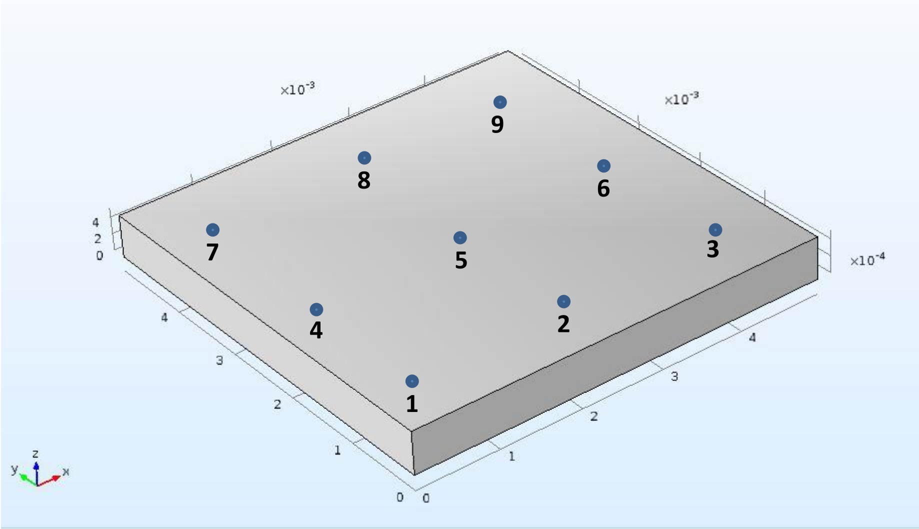
Probability distribution functions were assumed for all random variables and five percent uncertainty was introduced to each parameter.

The training points were generated using the input distributions:

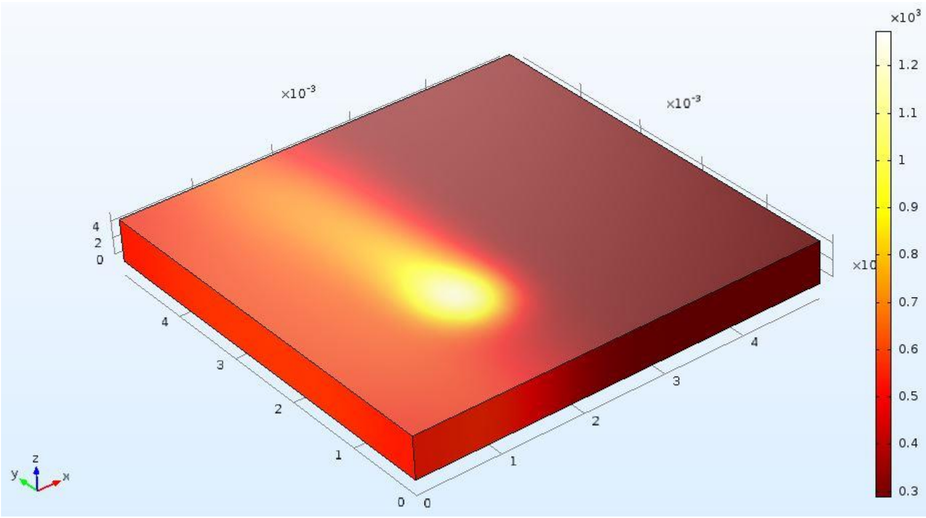
Random Variable	Probability Distribution	Mean value	Standard deviation
Laser Power	Normal	120 (W)	6 (W)
Laser Beam Width	Normal	*0.4 (mm)*	0.02 (mm)
Chamber temperature	Normal	293.15 (K)	14.6 (K)

Initial Results

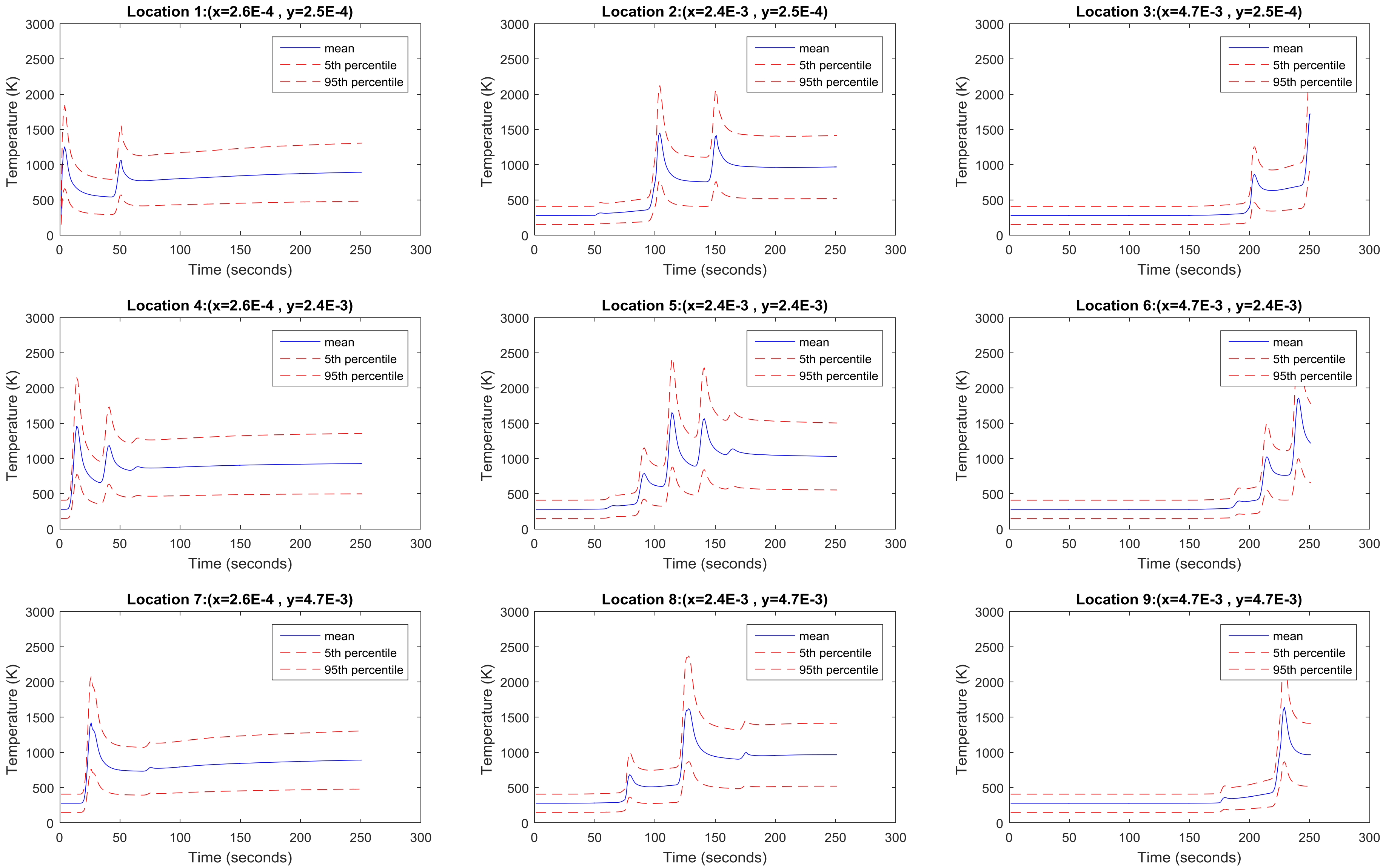
Simple geometry and selected locations



Temperature history – COMSOL results



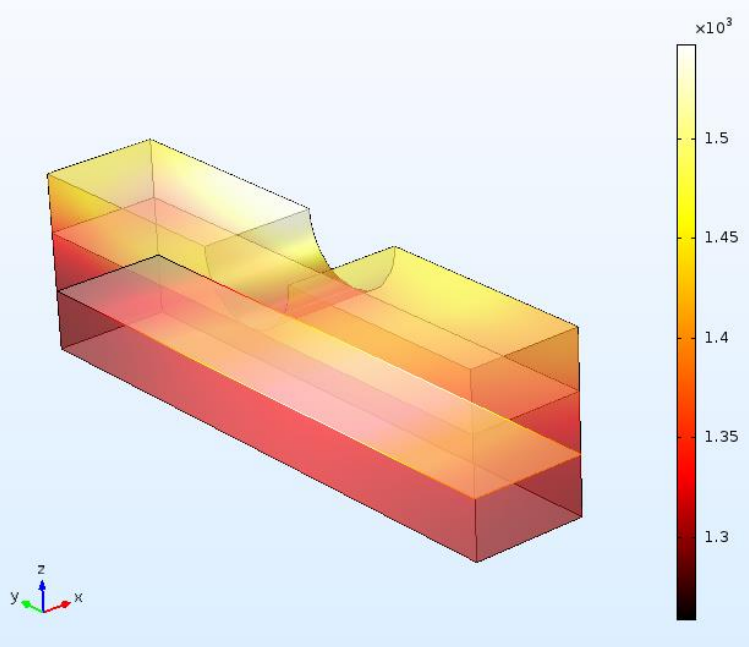
Prediction Results with MCS

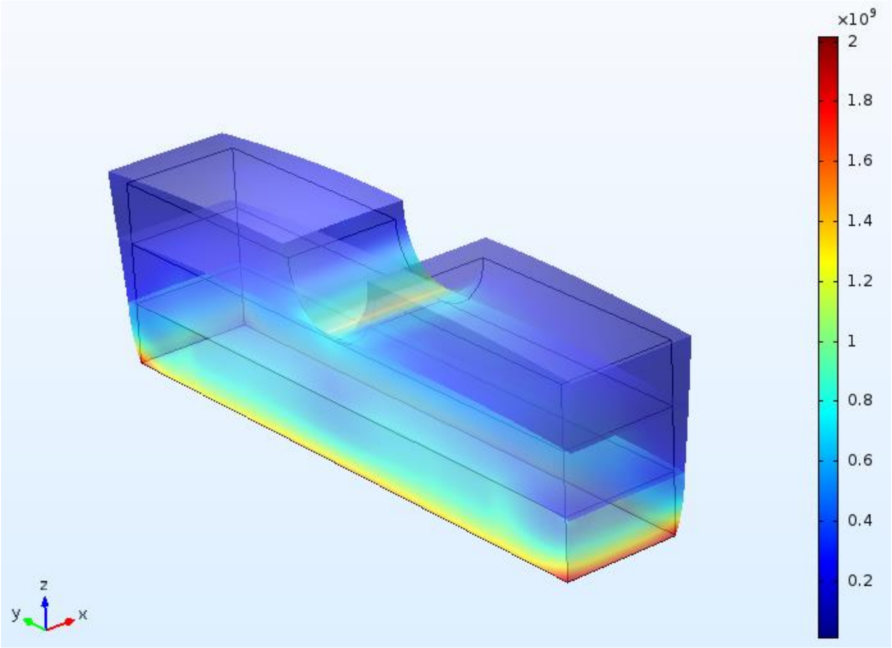


Residual Stress Prediction

- The temperature history can have significant effects on part's distortion and residual stresses
- Stresses and strains are induced by thermal loads
- The governing stress equation can be expressed

  $\nabla \cdot \sigma + f = 0$
- σ is the stress tensor and f is the internal forces
- Elastic, plastic, and thermal strains are considered





Concluding Remarks

- A quantitative computational approach for uncertainty analysis
- Combined physics-based and statistical-based modeling framework

- Heat transfer analysis of single- / multi-layer multi-track SLM AM process with COMSOL Multiphysics 5.2
- Monte-Carlo simulations for accessing uncertainty

- Temperature history and distribution useful for predict microstructure and mechanical properties
- Future works include prediction of residual stress for SLM AM process

- Any questions?