Prediction of Material Thermal Properties and Beam-Particle Interaction at Meso-Scale during Electron Beam Additive Manufacturing

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Background

- Additive manufacturing (AM) is an sophisticated process that involves many process variables (powder size, powder deposition rate, thickness of the powder layer, beam intensity, focal spot size, beam scanning speed, gas environment in chamber, etc.)
- Variation or inconsistency of these variables may lead to significant changes to material properties or defects such as porosity, cracking, unmelted powder, residue stress and excessive thermal deformation.
- The multi-scale physical phenomena associated with the AM process is not yet fully understood, and the control and optimization of AM processes with these variables usually takes tremendous efforts.
- Integrated computational materials engineering (ICME) models can provide a profound insights into the multi-physical phenomena and help to establish a fundamental correlation between the process variables and the performances of the final components.

This research aims at demonstrating ICME-based approach for controlling AM process parameters for optimal residual stress distribution in direct-metal AM

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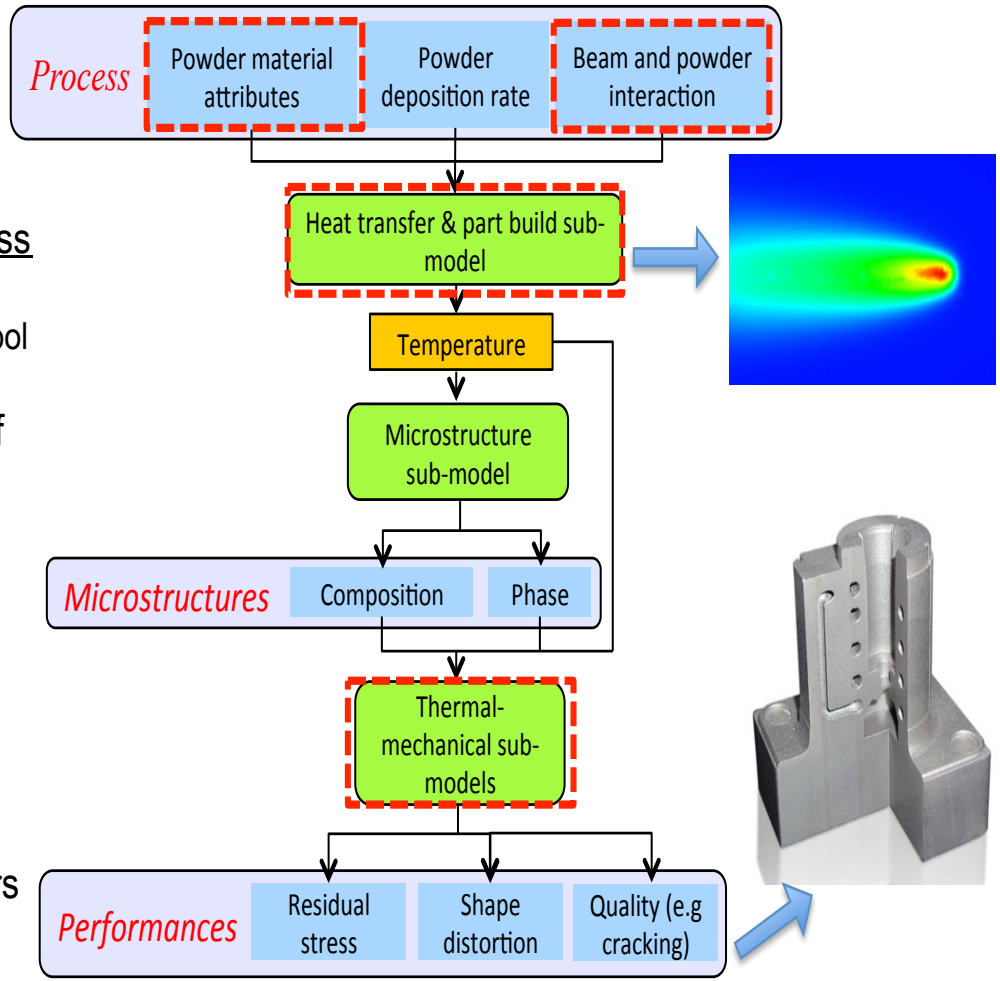
ICME Modeling Framework for AM

- Multi-physics based modeling approach
  - Integrated at appropriate levels
  - Purpose driven
- Specifics
  - Improve capabilities of existing models to Address AM-specific phenomena:
    - Interaction of energy source, powder and molten pool
    - Material addition (change in solution domain)
  - Generate key experimental data in supporting of the model
    - Thermo-physical Properties
  - Integrate the constituent models in a computationally-efficient manner
  - Experimental validation of key sub-models, and final residual stress
  - Demonstrate the capability of residual stress modeling
  - Apply the ICME model to find optimal parameters for controlling microstructure and properties



ICME framework

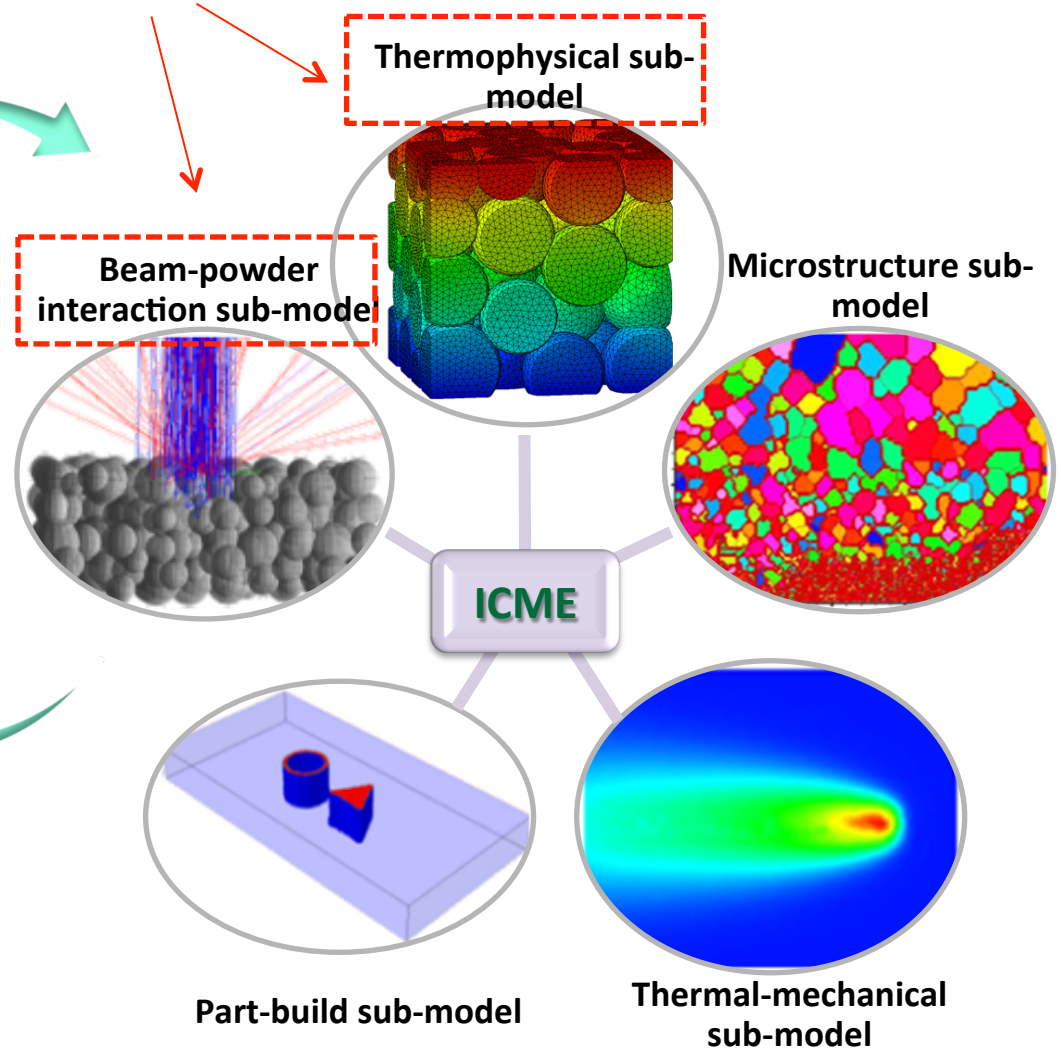
This presentation focuses on

Process parameters

- Powder attributes (size, density, porosity, etc.)
- Electron beam (intensity, speed, etc.)

Property and performance

- Residual stress
- Shape distortion
- Cracking



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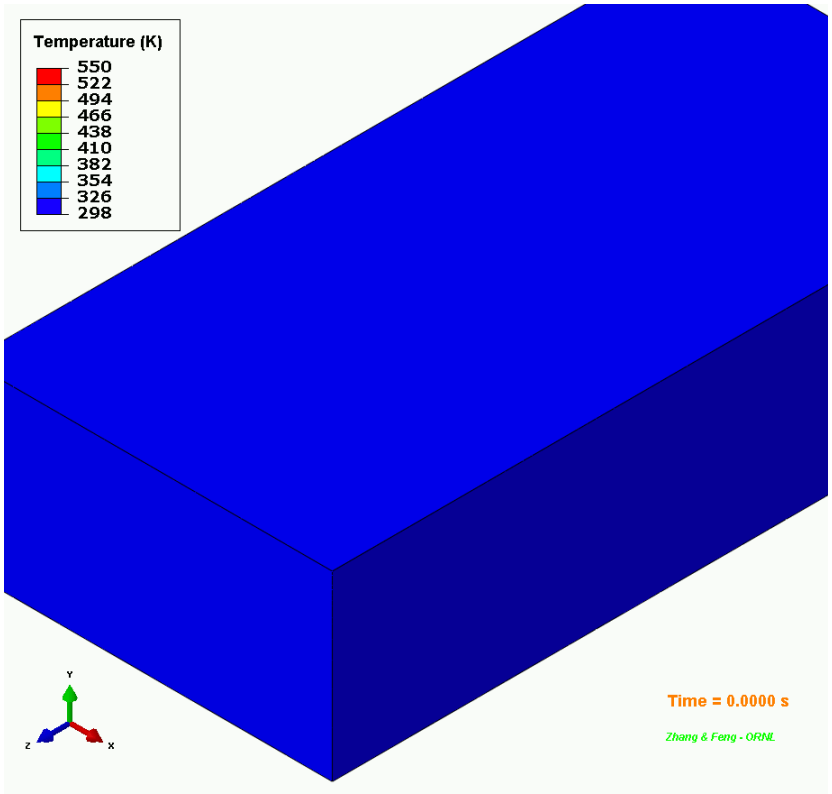
How to integrate micro-scale phenomena into heat transfer model?

- Globally, we solve conductive and convective heat transfer by energy conservation to obtain the temperature field in the build part

$$\rho\left(\frac{\partial\left(C_p T\right)}{\partial t}+\nabla\cdot\left(\vec{v}C_p T\right)\right)=\nabla\left(k\nabla T\right)$$



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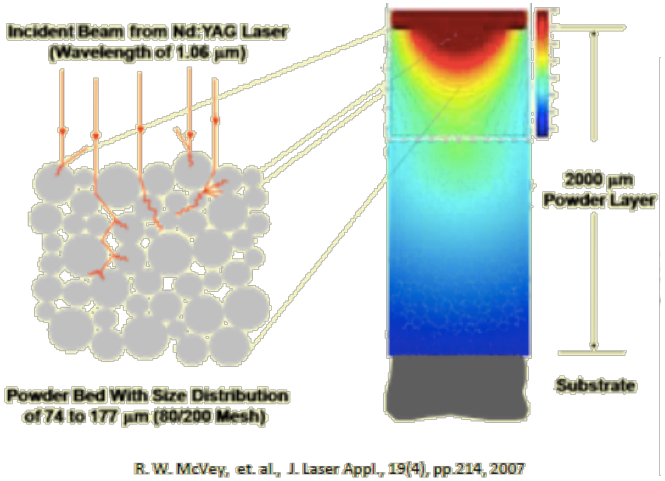
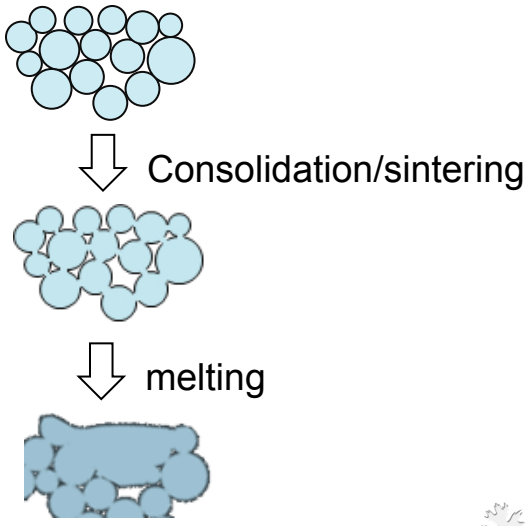


- We will need
  - The energy input from electron beam
    - Electron beam – powder particle interactions
  - Changes in thermo-physical properties (density, specific heat, and conductivity) as function of the material state
    - Effective thermo-physical properties to incorporate the change in materials states: loosely packed particles -> partial sintered particles -> melting and solidified solid bulk solid

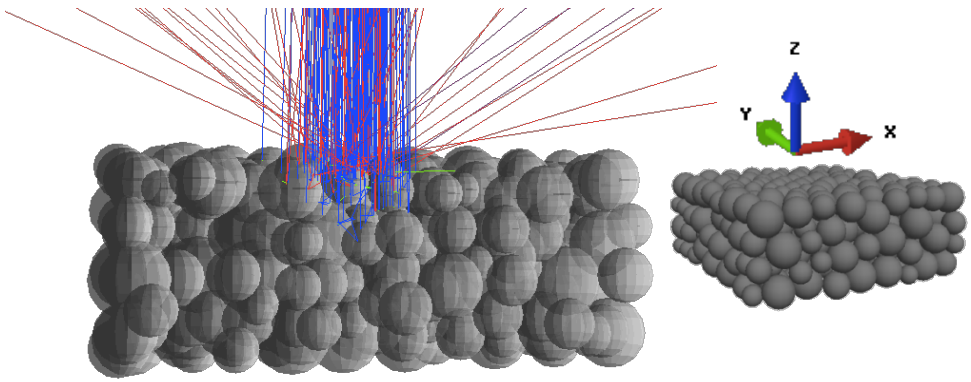


Electron-Particle Interaction Sub-model

Goal: Obtain the energy input required in the heat transfer model

Theory: (Rutherford & Mott)

- Primary electrons
- Secondary electrons
- Back-scattered primary electrons
- Back-scattered secondary electrons



Approach: 3D Monte Carlo simulation

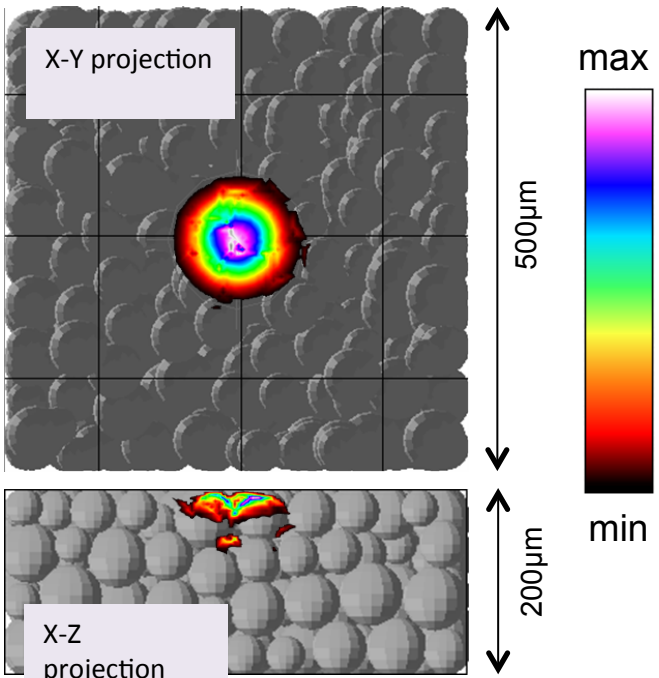
Input:

- Particle amount: 354
- Particle diameter: 40-70 μm randomly distributed
- Pack density ≈ 65~85%
- Electron beam diameter = 150 μm
- Electron energy = 20 KeV
- Amount of simulated primary electron = 5×10^6

Output:

Pack density	65%	75%	85%
Predicted absorption coefficient	77.67%	77.41%	77.02%

Energy distribution



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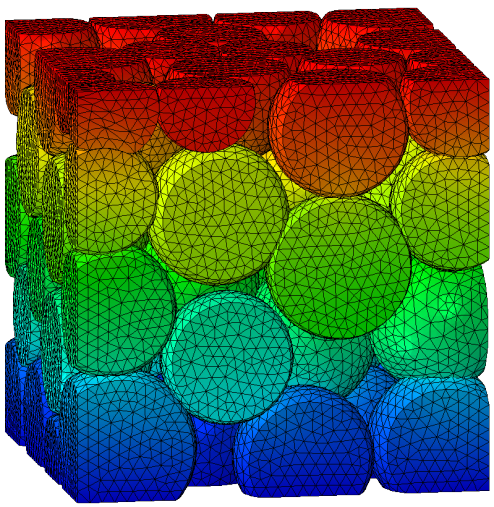
Effective Thermal Conductivity

Goal: Determine thermophysical properties as a function of material state changes in AM

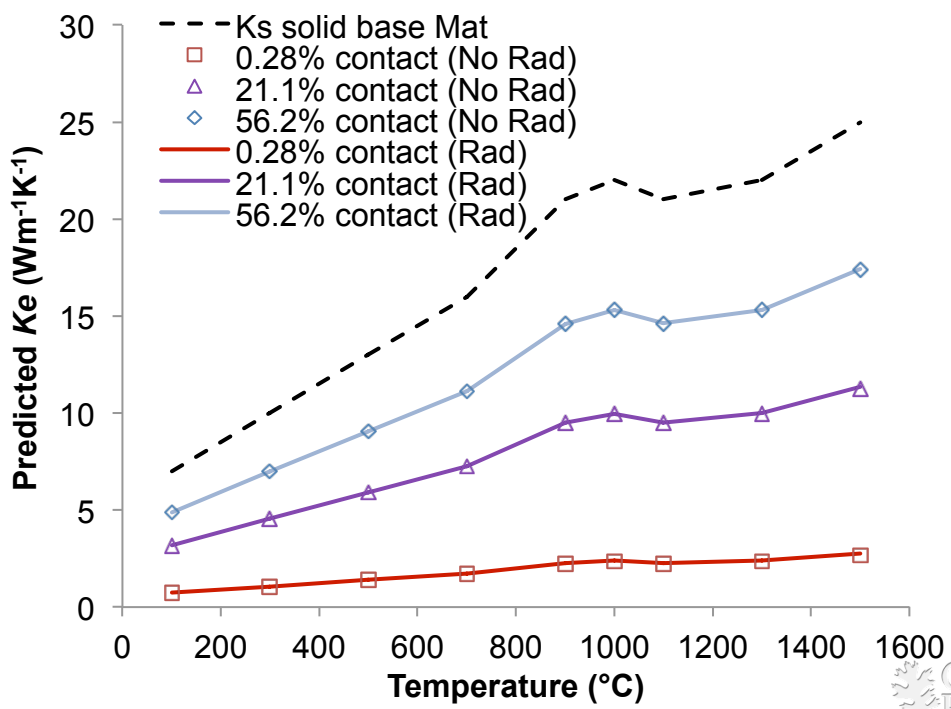
Approach: Multi-particle FEA heat transfer model



K_e – effective thermal conductivity
q - heat flux
$(T_2-T_1)/d$ – temperature gradient

What are considered/included ?

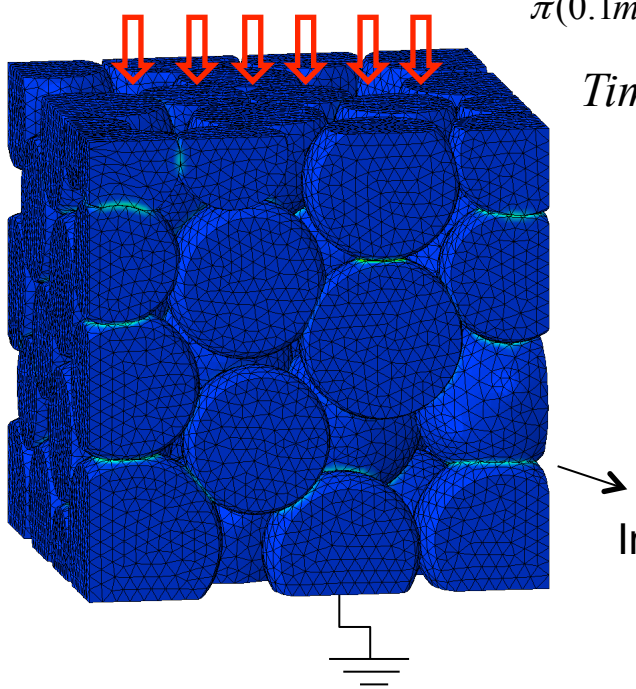
- Heat conduction through particle interfaces
- Inter-particle thermal radiation
- Percentage of contact area at different sintering stage
- Temperature dependent thermophysical properties of base solid material



Negligible Effects of Joule Heat

Approach: Multi-particle FEA electrical-thermal model

current density $J = \frac{0.02A}{\pi(0.1mm)^2} \approx 0.6A/mm^2$



Time = 1e-4 s

Max temperature rise due to *joule heat* at interfaces ≈ 10^{-2} °C

Inter-particle contact electrical resistance

Assume the electron kinetic energy is converted to temperature increase within the cubic region (adiabatic condition):

- electron energy = 20 KeV
- Energy absorption coefficient ≈ 0.77

Cubic temperature rise due to *electron kinetic impact* is estimated to be about 10^3 °C. Thus, joule heat is way smaller than electron impact energy.

Summary

- An ICME framework has been developed for AM process to establish the fundamental correlation among material properties, process parameters and thermal and mechanical performances of the final components.
  - Beam-particle interaction sub-model predicts the absorption coefficient and E-beam energy distribution over the powder bed.
  - Multi-particle heat transfer sub-model predicts the effective thermal properties of the powder bed as a function of temperature and powder consolidation stage.
  - Multi-particle electrical-thermal sub-model shows that the joule heating at inter-particle surfaces is negligible.
- These results provide the necessary input conditions to the macroscopic heat transfer and mechanical model for predicting the property and performance of the final component.

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