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Discrete element modeling of powder spreading and flow for metal additive manufacturing

PRESENTED BY

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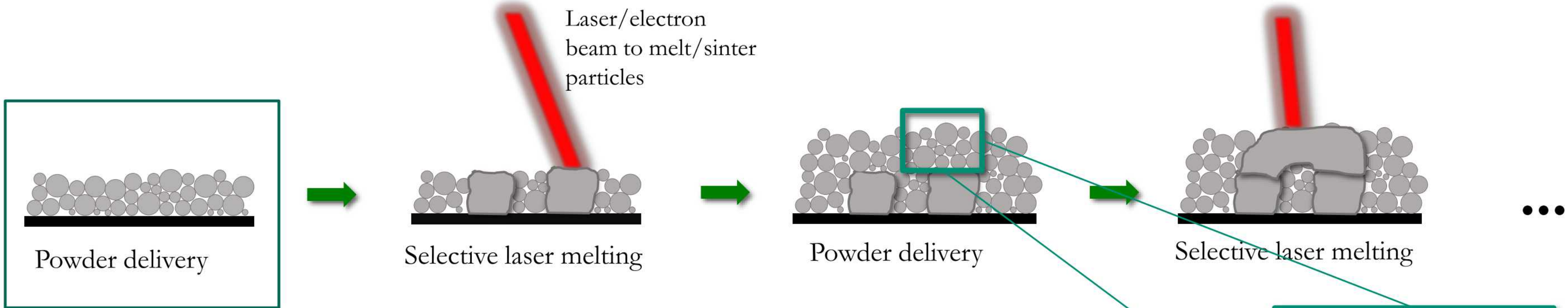
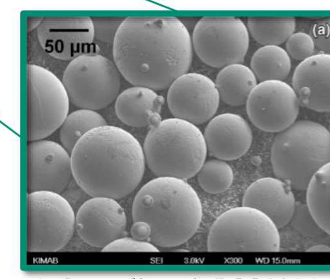
Motivation: powder bed fusion processes





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1. Strondl et al, *JoM* 2015.

Powder bed surface affects laser interaction

Powder bed bulk packing affects void formation, surface finish

Variability in powder properties due to e.g. vendor supply, powder recycling

Some key length scales:

- Layer thickness ~ 30-100 μm
- Laser spot size ~100-200 μm
- Particle diameter ~ 10-100 μm
- Material defects ~ 100 μm

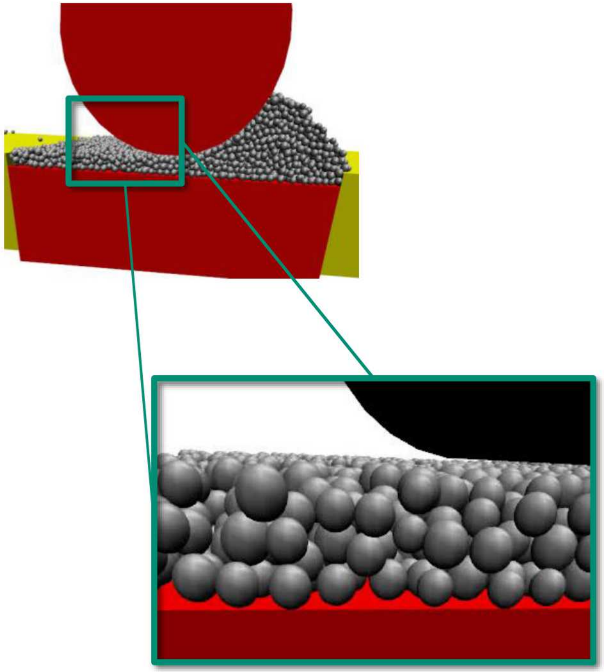
Understanding powder at scale of individual particles is important!

Simulation method: **D**iscrete **E**lement **M**ethod (DEM)

- Molecular-dynamics like method, elements are rigid individual particles
- Explicitly integrate $\mathbf{F}_i = m_i\mathbf{a}_i$, $\tau_i = L_i\boldsymbol{\omega}_i$; $i = 1,\ldots,N$, $\mathbf{F}_i = \mathbf{F}_i(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_N)$

Advantages:
- Captures individual particle dynamics
- Can handle particle size, shape variations; complex geometries/boundary conditions
- Material/particle properties captured by **contact models** that include sliding/rolling/twisting friction, cohesion

Disadvantages:
- Computationally expensive
- **Difficult to parametrize**



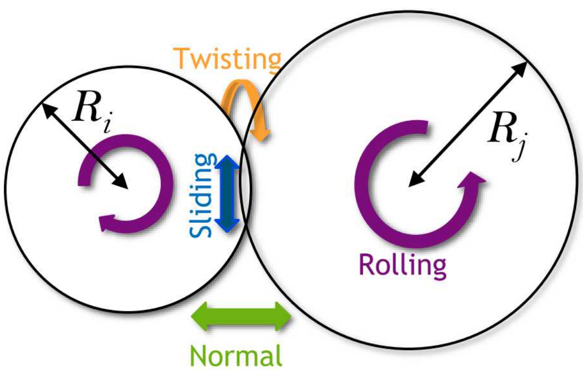
Layer thickness ~ particle diameter

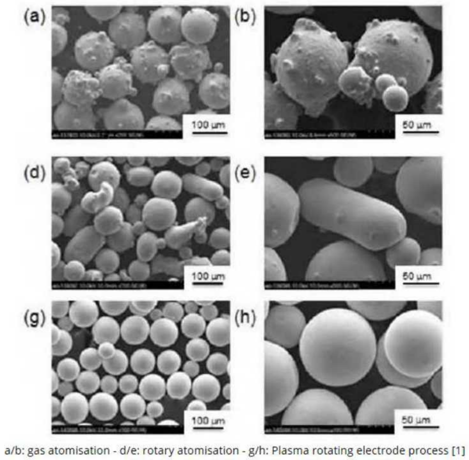
→ continuum models (e.g. μ(I) rheology) problematic

Simulation method: **D**iscrete **E**lement **M**ethod (DEM)

Contact model: determines pairwise force/torque as a function of position, velocity

Fine powders require more complex models that account for history-dependent friction, cohesion:





Strondl et al, *JoM* 2015.

Normal: $\boldsymbol{F}_n = \left(\frac{4Ea^3}{3R} - 4\pi\gamma R\right)\boldsymbol{n} - \eta_n \boldsymbol{v}_R \cdot \boldsymbol{n}$

Sliding: $\boldsymbol{F}_S = -k_S \int_{t0}^{t} \boldsymbol{v}_{tR}(\tau)\mathrm{d}\tau - \eta_T \boldsymbol{v}_{tR}$

$$\|\mathbf{F}_s\| \leq \mu_s \|\mathbf{F}_N\|$$

...

E: Particle Young's modulus

k_s: tangential stiffness (related to shear modulus)

γ : cohesion energy density

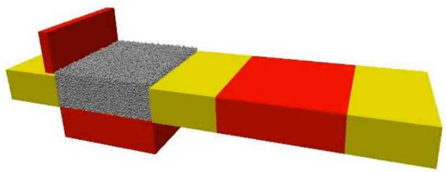
η_N, η_T: damping constants (related to restitution coeff.)

μ_s : sliding friction coefficient

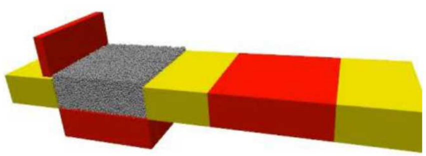
…

Overview of simulation-based approach

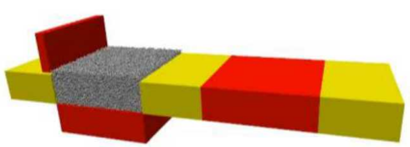
Small simulations: 10^5 particles



Omit sliding friction



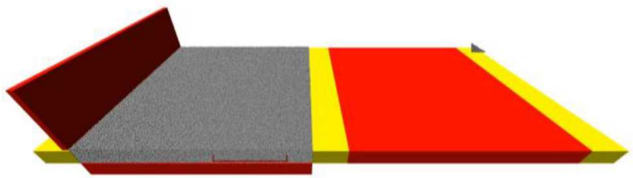
Typical contact parameters



Excessive cohesion

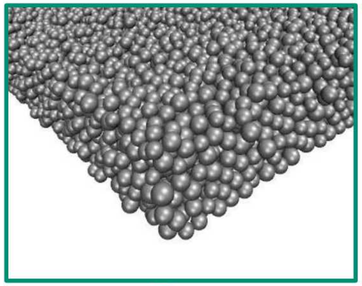
HPC simulations: 10^6-10^7 particles

Future possibility (Sequoia): 10^8-10^9 particles → approaching full scale!

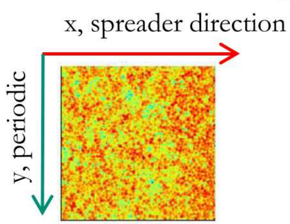


http://lammps.sandia.gov

Analysis of packed beds



Surface properties

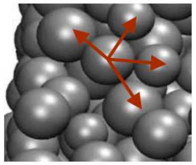


Powder bed height profile, **roughness**

→ Connection to laser interaction, melting

Local particle contact properties

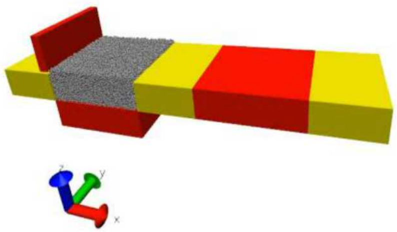
- Coordination number distribution
- Contact size distribution
- Fabric tensor

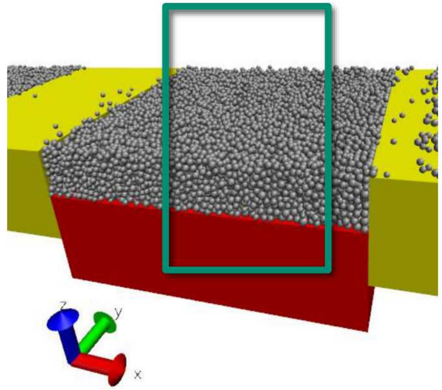


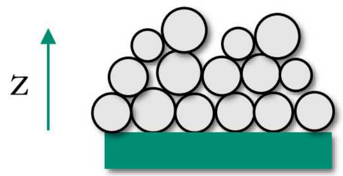
Powder bed bulk properties:

- **Porosity**, variations in different directions
- Generalized pore size distribution
- Spatial correlation functions
- . . .

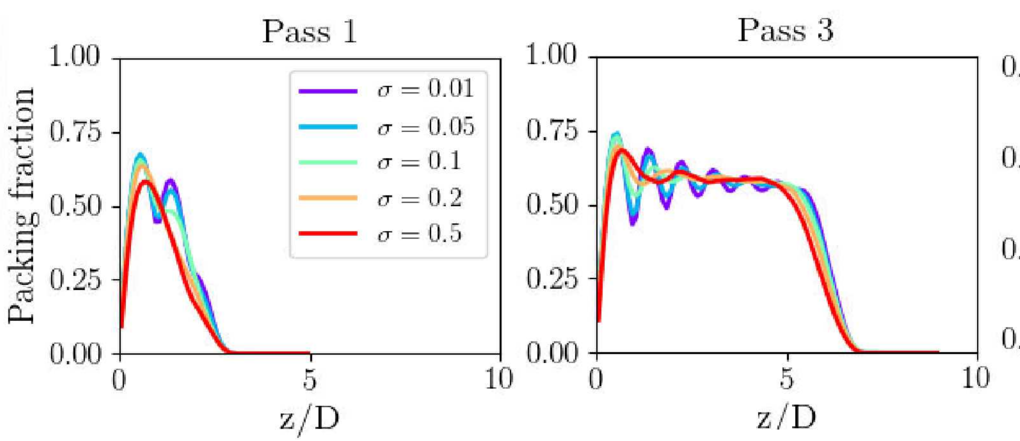
Example simulations





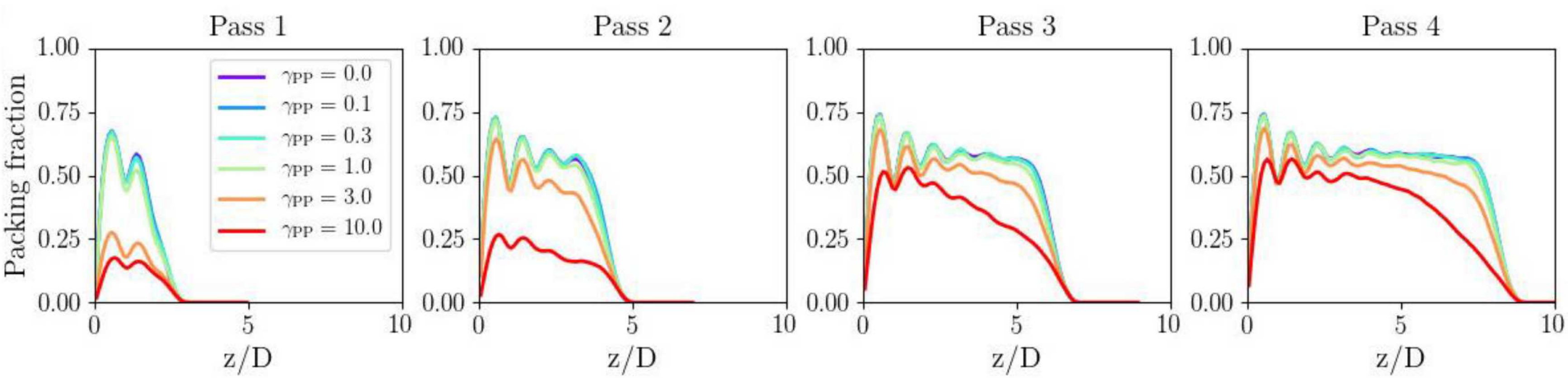


Effect of particle size polydispersity σ:

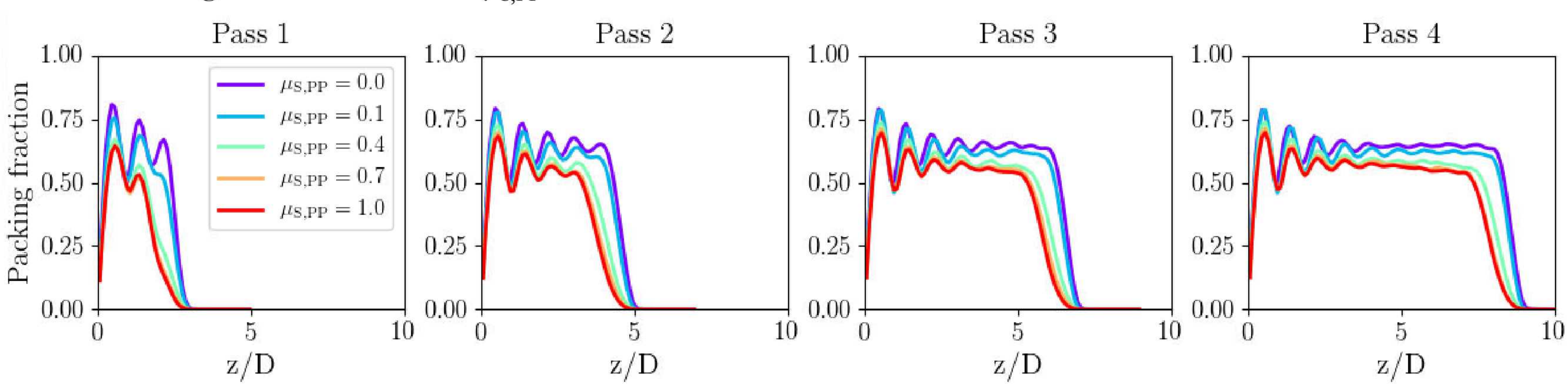


Example simulations

Effect of particle-particle cohesion γ_{PP}:

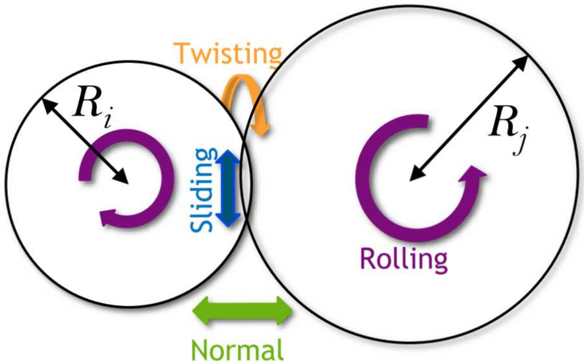


Effect of sliding friction coefficient $\mu_{S,PP}$:



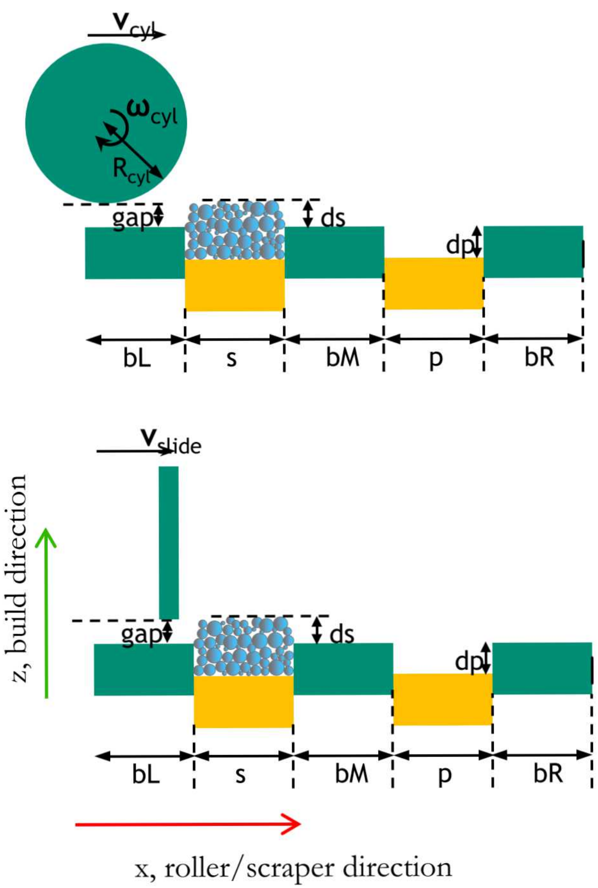
Challenge: large parameter space

Particle-related



- Particle size distribution
- Contact model form
- Stiffness, damping
- **Friction** (sliding, rolling, twisting) → relates to particle surface morphology
- **Cohesion** → particle surface morphology, chemistry
- Different for particle/particle, particle/wall contact?

Process-related



Powder Spreading Sensitivity Analysis

Goal: Identify parameters that have most effect on spreading (results shown for single layer on flat substrate)

Parameters Considered:

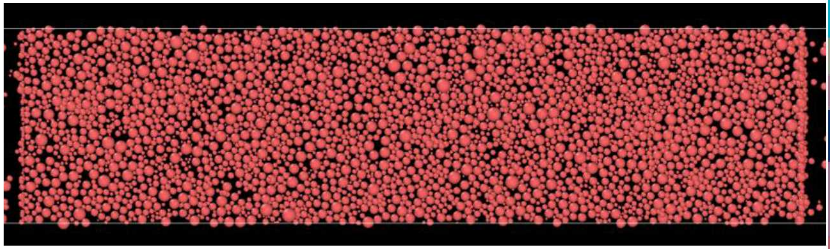
- Sliding Friction (P-P, P-W)
- Rolling Friction (P-P, P-W)
- Cohesion (P-P, P-W)

Output Quantities of Interest:

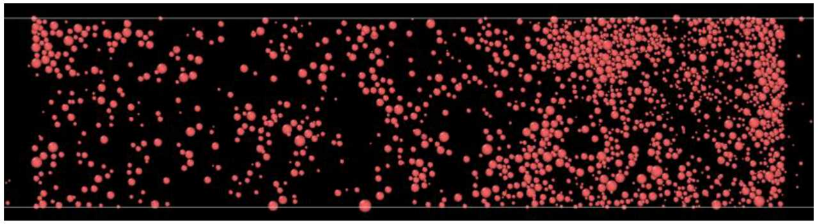
- Average Porosity
- Average Pore Size
- Powder bed surface roughness

Orthogonal Array Sampling used to isolate impacts of specific parameters

Desirable spread



Undesirable spread

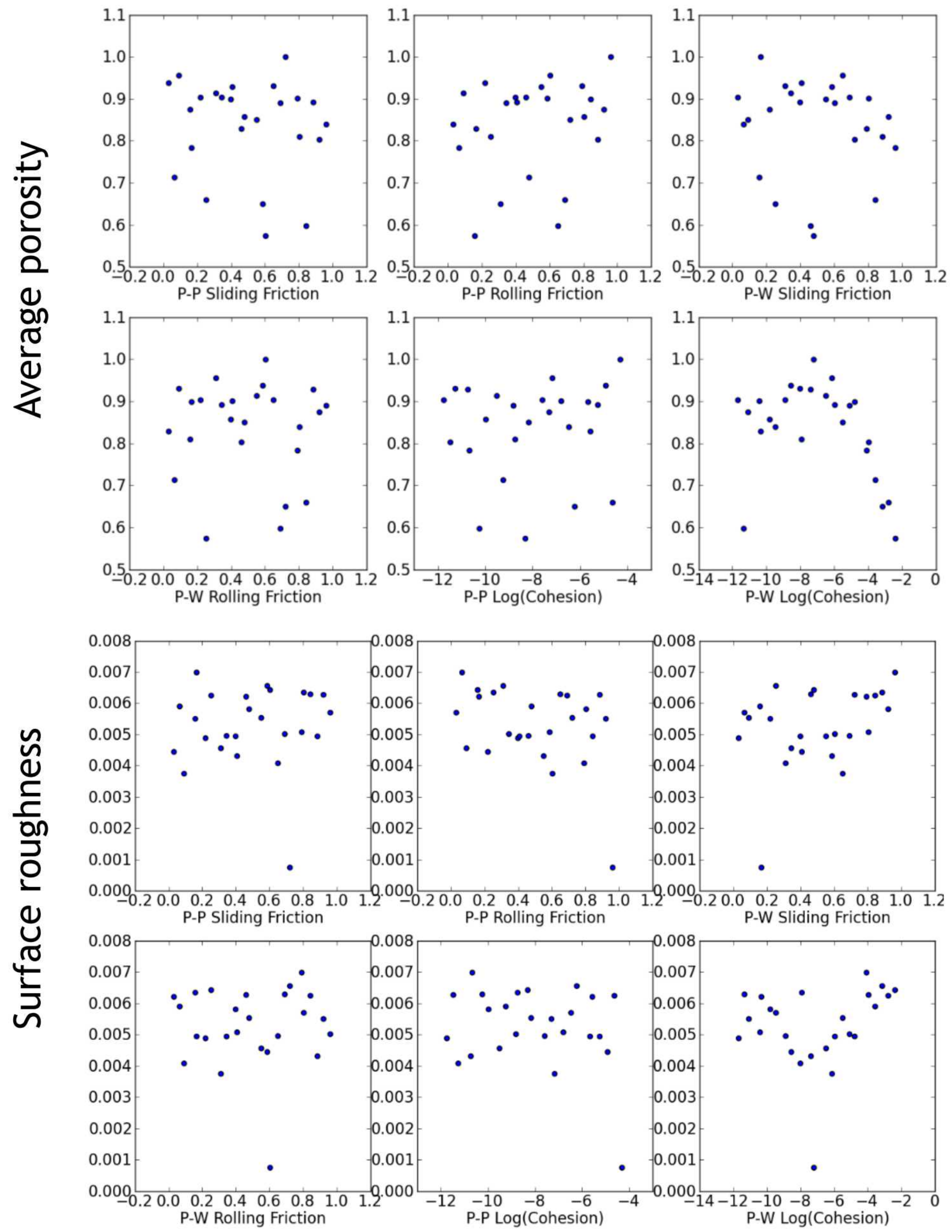


Sensitivity Results: Porosity Scatter Plots

Plots of average porosity as function of each parameter

Random scatter indicates low sensitivity

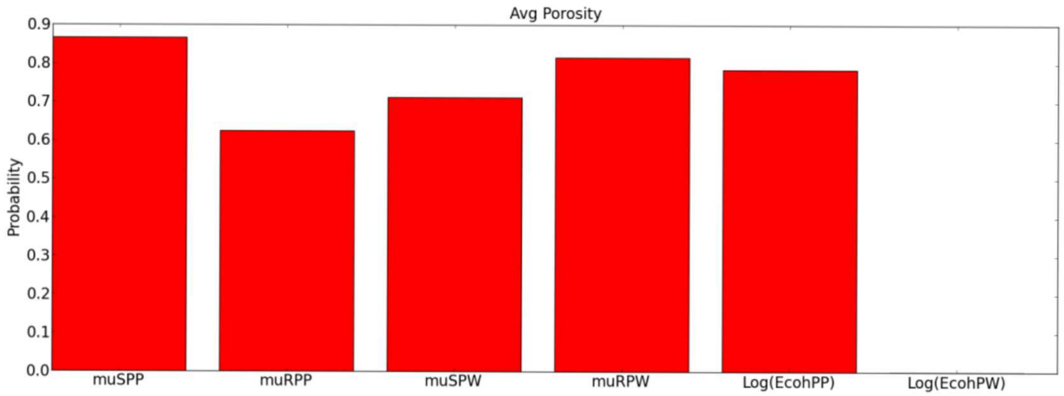
Trends indicate high sensitivity

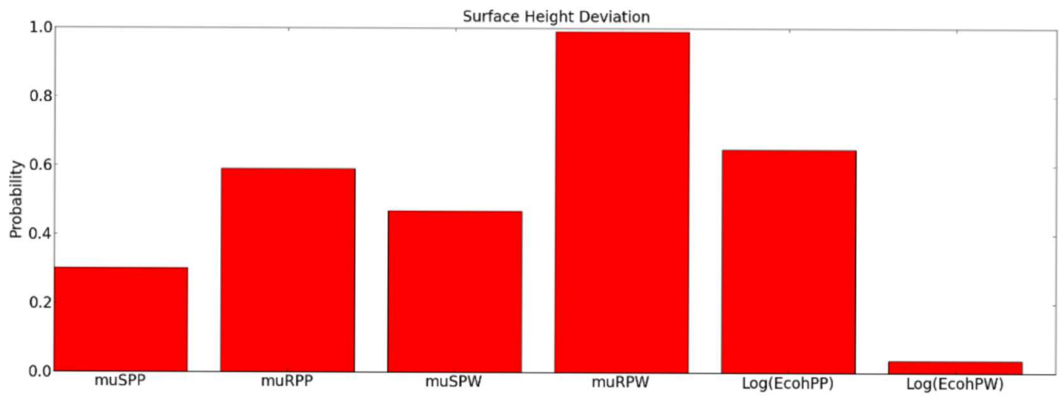


Analysis of variance

Probability of recovering variability in data if parameter is excluded (or insensitive)

Low probabilities = high sensitivity





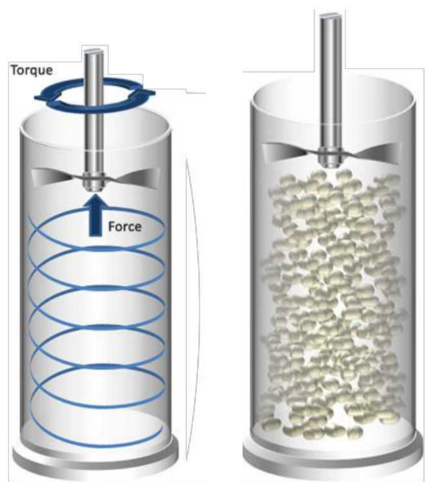
Toward experimental calibration and validation

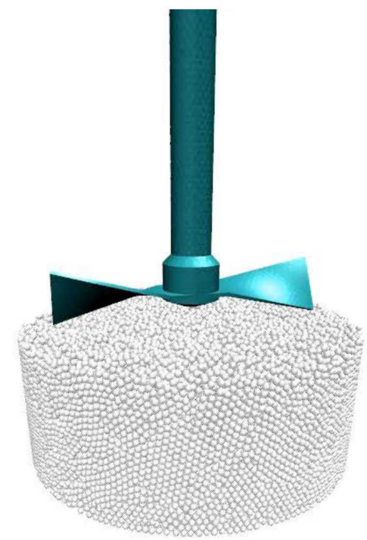
Direct measurement of particle-scale parameters extremely difficult

Goal: calibrate DEM parameters based on bulk powder dynamics experiments

Example bulk experiments :

- Angle of repose
- Hall flow
- Powder rheometry: measure force/torque for various impeller motions/depths [Lechman, “”]

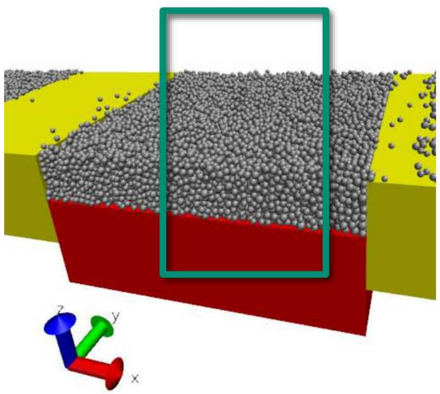


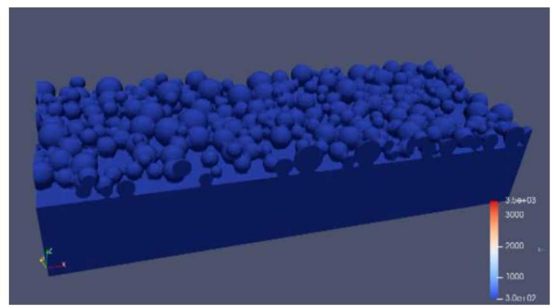


Future applications

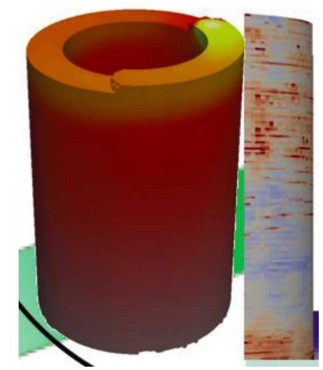
Couple to mesoscale melting and solidification models (Moser & Martinez)

- Connect powder properties, spreading conditions, laser and melting parameters → single track characteristics





Courtesy Dan Moser, Mario Martinez (SNL)



K. Johnson, K. Ford & J. Bishop (SNL)

Connect bulk powder characterization to powder bed quality

+ spreading parameters → Powder bed characteristics

QUESTIONS?