What is needed *from* models for powder spreading?

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Modeling of Power Dynamics in Metal Additive Manufacturing meeting
Hilton Austin
August 9-10, 2017
Overview

- Introduction and History
- Powder rheometry
- Current state-of-the-art
- Emerging trends
- Research needs
- Finale: What is needed *from* models for powder spreading?
# Additive Manufacturing @Rice University

<table>
<thead>
<tr>
<th>Faculty</th>
<th>Research Areas</th>
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</table>
| Ed Akin, MECH | - Orthopedic AM  
- AM in drilling  
- FEM analysis |
| Matt Brake, MECH | - AM to minimize qualification testing  
- Optimization |
| Andrew Colopy, ARCH | - AM processes in design of urban space & architecture |
| Zack Cordero, MSNE | - Microstructure control  
- Sintering  
- AM of metals |
| B.J. Fregly, MECH | - Cancer patient-specific AM prostheses  
- Biomech (Knee/Walking) |
| Fred Higgs, MECH | - Powder mechanics,  
- Powder AM modeling,  
- Tribology  
- AM finishing |
| Jordan Miller, BioE | - AM of bio-tissue  
- Anatomical architectures  
- AM printer development |
| Pol Spanos, MECH | - Dynamics analysis of AM drilling |
| Jim Tour, CHEM | - AM of graphene and novel materials  
- Novel AM process design |
Powder tribology and rheology enable you to characterize, model, experimentally interpret the powder spreading and interfacial behavior in situ.
Key elements in powder spreading studies...

Real spreader

SEM image of AM powder

Contact model in normal and tangent directions

Layer i powder shown as a collection of exaggerated spheres over fused powder from previous layers

Unfused powder  Fused powder  Fresh powder of layer i

Before spreading layer i

After spreading layer i

Direction of spreading

Optical image of printed surface in Arcam

Striations due to electron beam path
History of particle media in sliding contacts: akin to spreading

Powder particulates

Theory
Lancaster (1967)
Heshmat et al. (1989)
Heshmat (1991)
Allam (1991)
Godet (1984)
Mathia & Louis (1984)
Heshmat et al. (1989)
Heshmat (1991)

Experiment
Heshmat & Walton (1993)
Higes (1999)
Klausner et al. (2000)
Heshmat (2000, 2002)
Kaur et al. (2001)
Bocquet et al. (2001)
Chen et al. (2002)
Iordanoff et al. (2002)
Tardos et al. (2002)

Numerical Sim.
Mei et al. (2000)
Tardos et al. (2002)
Fillot et al. (2005)

Granular particulates

Theory
Bagnold (1954)
Savage & Jeffrey (1981)
Haff (1983)
Lun (1984)
Godet (1984)
Jenkins and Richman (1985)
Johnson and Jackson (1987)
Jenkins, J (1987)
Elrod (1988)
Edwards (1990)??
Dai et al. (1994)
Yu et al. (1994)
Chen and Ling (1996)
Lun (1996)
Khonsari (1997)??
Tardos et al. (1998)??
Zhou & Khonsari (2000)??
Sawyer & Tichy (2001)
Massoudi & Mehrabadi (2001)
Tsai & Jeng (2002)
Srinivasa et al. (2002)
Pappur & Khonsari (2003)??
Higgs & Tichy (2004)
Massoudi & Phouc (2005)

Experiment
Bocquet et al. (2002)
MiDi (2004)
Higgs et al (2007)

Numerical Sim.
Campbell and Brennen (1985)
Walton (1986)
Elrod (1988)
Babic et al. (1990)
Louge et al. (1990)
Hopkins and Louge (1991)
Thompson and Grest (1991)
Yi and Campbell (1992)
Kim and Rosato (1992)
Savage and Dai (1993)
Louge (1994)
Rosato and Kim (1994)
Lun (1996)
Schwarz et al. (1998)
Schollmann (1999)
Latzel et al. (2000)
Karion and Hunt (2000)
Sawyer and Tichy (2001)
Aharonov and Sparks (2002)
Jasti and Higgs (2005)

Wornyoh, E., Jasti V.K. and Higgs III, C., 2006, ASME J. of Tribology
Some history on AM powder spreading ...

Experiments: Particulate Flows

AM powders
- Cooke & Slotwinski 2012
- Gu et al. 2012
- Huang 2013
- Clayton 2014
- Qian 2015
- Strondl 2015
- Tang et al. 2015
- Dougherty 2016

Physics-based modeling: Computational Particle Dynamics

AM spreading
- Herbold et al. 2015
- Parteli & Pöschel 2016
- Mindt et al. 2016
- Steuben et al. 2016

Machine Learning Predictions

Spreading Process Maps
- Jiang et al. 2014
- Chen & Zhao 2015
- Asadi-Eydivand 2016
- Tourloukis 2016
- Wilkinson 2017

None
Overview

- Introduction and History
- **Powder rheometry**
  - Relevant particle parameters
  - Flow energy measurements
- Current state-of-the-art
- Emerging trends
- Research needs
- **Finale:** What is needed *from* models for powder spreading?
Relevant particle parameters

- Moisture
- Particle Shape
- Particle-cohesion
- Aeration and Specific Energy
- Confined loading like BFE
- Electro-magnetic forces
- Particle Size Distribution
- Partial coverage (layer porosity)
- Top view of layer i powder shown as a collection of exaggerated spheres
- Side view of layer i powder shown as a collection of exaggerated spheres
- Partial coverage (layer porosity)

Diagram showing the scanning arrangement, hopper, spreader, before and after spreading layers, and top view of the powder as a collection of exaggerated spheres.
Characterizing Powders: Flowability vs. Spreadability

START:
New or Recycled powder

AM Assessment
Print parts using output

Hall Flow Meter
Powder Rheometer

Rheometry experiments

<table>
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<tr>
<th>State of the Powder</th>
<th>Rheometry Parameter</th>
<th>Relevance to AM</th>
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<tbody>
<tr>
<td>Confined Compressive Flow</td>
<td>Basic Flowability Energy (BFE)</td>
<td>Similar to spreader zone Low BFE -&gt; Free-Flowing</td>
</tr>
<tr>
<td>Unconfined Flow</td>
<td>Specific Energy (SE)</td>
<td>At spreader’s leading edge and hoppers Low SE -&gt; Free Flowing</td>
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Methodology:
Characterize powder candidates to determine flow properties, print layers to assess spreading quality, quantify which parameters govern 'Spreadability'.
SEM images (courtesy O. Harryson and A. Rollet groups at NCSU/CMU)
Effect of Particle Size and Shape on BFE for Different Ti64 Powders

- Increase in size and sphericity leads to large decrease in flow energy and Specific Energy
- EOS Ti64 found to have the most “fines”
- Ametek and Starmet had similar values
- Suggests a threshold for reducing energy based on particle size

**Ti64 Study**
- Increase in size and sphericity leads to large decrease in flow energy and Specific Energy
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- EOS: 40 µm**
- Arcam: 50 µm
- Ametek: 70 µm
- Starmet: 160 µm
Overview

- Introduction
- Powder rheometry
- **Current state-of-the-art DEM**
  - GPU modeling
  - Accurate representation of solid boundaries
  - Model calibration and validation
  - Virtual spreading
- Emerging trends
- Research needs
Powder Modeling Approach: DEM

- **Discrete Element Method (DEM)**
  - Simulates motion of discrete particles
  - Best suited to capture the spreading process
  - Contact forces:
    \[ F_n = K_n \Delta_n - \beta_n \dot{\Delta}_n \]
    \[ F_t = -\mu_s |F_n| e_t \]

- **GPU parallel processing**
  - GPUs have highly parallel computer architecture with thousands of 'slower' cores
  - DEM involves lots of 'simpler' calculations
  - GPUs can be used to accelerate DEM calculations

\[ K_n = \frac{f^2 m_{eq} V^2_{max}}{\phi^2}; \quad f = \frac{\phi}{\Delta_{max}} \]
\[ \beta_n = -2 \ln(e) \left[ \frac{K_n m_{eq}}{\pi^2 + (\ln(e))^2} \right]^{1/2} \]
Solid surface is represented in .STL format as a set of triangles. All Particle-Structure interactions can be resolved as Triangle-Sphere Contacts. Accuracy of the representation of the solid can be controlled by varying the number of triangles.
Powder rheometry: Calibrated DEM model for entire fill height

In-house experiment
Blade tip speed = 100 mm/s

Rice’s
GPU P-STAC with 1.2 M particles

Rice University
Particle Flow & Tribology Laboratory
Virtual spreading on real surfaces

Now let’s perform virtual spreading on ‘real surfaces’ with spreader speeds in the range where virtual powder is validated for rheometry i.e. 40 to 100 mm/s

Blade tip speed = 70 mm/s
Blade tip speed = 40 mm/s
Metrology of real surfaces*

Rq = 46.5 microns

Striations due to electron beam path

Direction of spreading

Surface Metrology
Optical, non-contact roughness measurement rig

Arcam build

* Carried out by Recep from Prof. Ozdonglar’s lab
Incorporating real surface in P-STAC

Real surface

Gaussian surface used in P-STAC

\[ Rq \text{ of substrate} = 46 \, \mu m \]

\[ U = 100 \text{mm/s}; \ \omega = 20 \text{rad/s} \]

\[ U = 100 \text{mm/s}; \ \omega = 0 \text{rad/s} \]

\[ U = 100 \text{mm/s}; \ \omega = -20 \text{rad/s} \]
Incorporating real surface in P-STAC

- Gaussian surface used in P-STAC

Distribution of heights, $R_q$ (46 microns)

$R_q$ of substrate = 46 µm

$U = 100\text{mm/s}; \omega = 20\text{rad/s}$

$U = 100\text{mm/s}; \omega = 0\text{rad/s}$

$U = 100\text{mm/s}; \omega = -20\text{rad/s}$
Spread layer properties

- Quantity of spread:
  \[ M = \frac{\text{Vol. of powder spread per unit time}}{\text{per unit width of spreader}} \]
  This is indicative of spreading efficiency.
- Quality of spread:
  Roughness of the layer,
  \[ V_s = Ra \times U \]
Which software: the great philosophical debate

- Introduction
- Powder rheometry
- Current state-of-the-art DEM
  - GPU modeling
  - Accurate representation of solid boundaries
  - Model calibration and validation
  - Virtual spreading
- Software: Commercial (EDEM, ANSYS, LSDyna, etc.) vs. Open-source (LIGGGHTS, MFiX, etc.) vs. Academia (in-house code: P-STAC @Rice, others)
Overview

- Introduction
- Powder rheometry
- Current state-of-the-art
- Emerging trends
  - Machine Learning enables:
    - Spreading process maps
    - Direct path?: experiments-to-blackbox model
- Research needs
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Machine Learning (ML): Generating 3D printer recipes

Multiphysics model of 3D printing (slow)

3D printer spreading process map\(^1\): Tells 3D printer how to improve spreading

Machine learning generates extra data (fast)

\(^1\)Provisional patent, 2017 (Higgs)
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Research needs

- A validated, high-fidelity spreading model...
  - Incorporates CAD geometries, real surfaces (e.g., topography), and layer-to-layer heterogeneity
  - Incorporates particle size distribution
  - Incorporates particle shapes (likely more important than asphericity)
  - Incorporates all relevant forces (e.g., solid contact, cohesive and adhesive forces)
  - Has realistic particle counts (30-100 millions) in realistic times
  - Is experimentally validated

- ‘Spreading-aware’ 3D printers:
  - *In situ* metrology (e.g., friction, and optical, thermal, surface monitoring and metrology)
  - More spreading features and control
Research needs

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Ongoing work @Rice: Experimental validation of S-maps

Stl file → 3D Printer → Green Part → Profilometry of top surface

- Large deformations: $R_q = 36$ microns
- Medium deformations: $R_q = 35$ microns
- No deformations: $R_q = 25$ microns
Finale: What is needed from models for powder spreading?

Get fast, actionable information to printer’s spreading controls!

- Smart hardware, algorithm, and expert-insight gains needed (e.g., GPUs, Machine learning, Sensitive parameters only please)
- Rapid quantification of powder’s spreadability (e.g., BFE?, ‘Spreadability FOM’)
- Robust characterization of powder’s rheology (e.g., Powder rheometry tackled, ‘Powder avatar’ or ‘Virtual twin’)
- Powder spreading model reduced to ‘spreading process maps’ (or just the model)
- Spreading process map feeds ‘spread recipe’ to 3D printer
Acknowledgements

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  - Rice University School of Engineering

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