Effects of Environmental Conditions on Powder Mechanics

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Outline

- History
- Current state of the art
- Emerging trends
- Research needs
What are environmental factors?

➢ Atmosphere:
  - Chemistry
  - Partial, total, and differential pressures
  - Relative humidity
  - Flow rate (magnitude, direction)
  - Temperature

➢ External forces:
  - Vibrations
  - Electro-static forces, magnetic forces

➢ Rake system:
  - Material
  - Shape, design
  - Speed, torque
History


State of the art


Emerging trends

Research needs
### History

**Does the flow rate of metal powders change as a function of ambient gas pressure?**


- Vacuum/pressure studies on powder flow in the context of the lunar landing in the 1960s. Low powder settlement/high cohesion was expected and confirmed at $10^{-7}$ Pa in Salisbury’s et al work.
- High cohesion was attributed to desorption of adsorbates, “clean” surfaces, also possible due to sun radiation.
- More recent work on metal powders did not reveal significant changes in Hall flow numbers across nine orders of magnitude difference in pressure.

Does the flow rate of metal powders change as a function of ambient gas pressure?


**Powder flow through Hall funnel**

- **Strong**
- **Light**
- **No lateral fluctuations**

**Differential pressure impacts flow, total pressure does not seem to influence flow.**
**Vibration effects on powder layers**


\[ \Gamma = 4\pi^2 f^2 A / g \]

- \( f \): frequency
- \( A \): peak to peak amplitude
- \( g \): gravitational constant
- \( \Gamma \): dimensionless acceleration

FIG. 1. Patterns in a 1.2 mm deep layer at \( f = 67 \) Hz: (a) \( f/2 \) stripes (\( \Gamma = 3.3 \)), (b) \( f/2 \) hexagons (\( \Gamma = 4.0 \)), (c) flat with kink (\( \Gamma = 5.8 \)), (d) competing \( f/4 \) squares and stripes (\( \Gamma = 6.0 \)), (e) \( f/4 \) hexagons (\( \Gamma = 7.4 \)), and (f) disorder (\( \Gamma = 8.5 \)).
Vibration effects on powder layers


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→ Build plate vibrations do not necessarily cause “settling” and powder bed densification, but can induce the opposite—patterns with extra space between particles.
### Historical or prior art in environmental effects on powder mechanics:

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<td>Pharmaceutical Industries</td>
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- **Food Industries**
- **Pharmaceutical Industries**
- **Powder injection molding**
State of the art in theory:


- Very limited results on pattern formation in vibrated granular systems.

- Extensive literature on differential pressure effects on flow in granular systems, limited relevance for AM.

- Limited knowledge on surface phase stability for common AM alloys as functions of partial pressures and temperature.
State of the art in **theory**:

- Limited knowledge on surface phase stability for common AM alloys as functions of partial pressures and temperature.

- Surface phase stability can be determined using first-principles calculations and yield equilibrium phases at surfaces as a function of temperature and partial pressure of gases, for example, the phases developing on titanium surfaces in contact with an oxygen-containing atmosphere.
State of the art in measurements:

- Laboratory-level set-ups to examine flow and environmental effects (e.g., at NIST, UConn,…).

Image shows UConn lab set up: raking with original rakes over build plates in controlled atmosphere (moisture content).
State of the art in measurements:

- 50 g of Ti-6Al-4V powder was used for Hall flow test in 62 % r.h. conditions.
- Same powder was then dried in oven, re-tested.
- Reduction in flow time after drying, strong variations in flow time over the first ~ 3 min after removal from oven.
State of the art in measurements:

- Raking of powder over build plate.
- Atmosphere control possible.
- How is powder bed analyzed?
  - Here we remove powder from different locations on build plate, analyze size distribution.
State of the art in measurements:

- Ti-6Al-4V powder was used for rake test in 62 % r.h. conditions and after oven drying.
- Oven drying at 106 C for 30 min, powder was then transferred to rake chamber within ~ 10 s and raked.
- Main observation: no significant differences appear for the size distribution before and after drying or across the build plate.
State of the art in machine designs:

- Most commercial laser machines specify argon or nitrogen as shield gas; no further information or powder pre-heating/vibration to modify powder coating.

- Some machines (Renishaw, 3DSystems, AddUp Solutions,… offer internal recycling, including vibration sieving. Impact on powder coating unclear.

- Experimental machines become increasingly available with potential to evaluate environmental impact on powder mechanics, e.g., at UConn: Controlled atmosphere (vacuum, gas mixtures, etc), Controlled gas flow, heating, potential for vibrating powder feeds, plates.
Emerging trends in flow characterization

1. New powder flow measurement approaches to better characterize powder raking

Example: X-ray CT scans of powder beds
Emerging trends in **flow characterization**

2. New powder flow measurement techniques with better scientific meaning than Hall flow

(Courtesy of Anton Paar)
Emerging trends in **flow characterization**

3. Atomic force microscopy to detect interparticle forces with environmental control.

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**Emerging trends in machine designs**

Focus on atmospheres in machines, design of machines with environment in mind:

- Gas chemistry, partial pressures: influence on powder particle surface phases, powder particle interactions.
- Flow pattern of gas in chamber: influence of flow pattern, flow, on powder bed.
- Powder flow toward build plate
Emerging trends in **material development**

- Surface modifications of metal powders to modify flow behavior

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**United States Patent**

Johnson et al.

**Metal Powders with Improved Flowability**

| Inventors: | Curtis E. Johnson, Ridgecrest, CA (US); Kelvin T. Higa, Ridgecrest, CA (US); Roger M. Sullivan, Raleigh, NC (US) |
| Assignee: | The United States of America as represented by the Secretary of the Navy, Washington, DC (US) |
| Notice: | Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 173 days. |

**Patent No.:** US 8,894,739 B1  
**Date of Patent:** Nov. 25, 2014

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**Authors:** Johnson, C. E.; Harris, D. C.; Nelson, J. G.; Kline, C. F.; Corley, B. L.

**Title:** "Strengthening of Glass and Pyroceram with Hydrophobic Coatings"

**Source:** NAWCWD TP 8536, Apr. 2003
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**Research needs at the material/atomic level**

- Formation and stability of hydroxides, hydrated oxides, etc. on alloy (powder) surfaces as a function of temperature, atmosphere conditions.
- Contact forces between powder particles as a function of surface layer (hence temperature, atmosphere conditions).
- Kinematics of relative particle motion as a function of surface phases (hence temperature, atmosphere conditions).
- Characterization approaches for surface phases specific to AM conditions.
Research needs at the \textit{material/mesoscale level}

- Pattern formation during powder vibrations, implications on “inter-agglomerate” distances, etc.

\textit{Questions to be addressed:}

- Under what conditions (vibrations, substrate) do patterns develop?
- What characteristic pattern length-scales develop (e.g., the distance ‘d’ in the left cartoon)?
### Engineering development needs in physical simulations of raking

Raking or rolling rigs with full environmental control and characterization capabilities:

- Control of temperature, humidity, gas flow and direction, gas type and partial pressures
- In-situ characterization capability without powder bed disturbance (tomography)
**Engineering development needs in machine designs**

Science and physical simulation input should be applied to machines to identify impact of powder delivery designs, machine atmosphere and gas flow patterns on powder bed characteristics.

Step toward real machines involves sieves, shakers, etc, need to be included in research, analysis.
Concluding remark

Several open and potential research directions for environmental effects on powder flow,

BUT

What is the influence and sensitivity on melting, solidification?