From granular rheology to 3D printing in space — and back

Olfa D’Angelo

Institute of Materials Physics in Space
German Aerospace Center, Cologne
From granular rheology
to 3D printing in space — and back

Olfa D’Angelo
Who is talking to you?

Olfa D’Angelo

Background
Materials science and engineering

Master thesis
ESA/EAC (Spaceship EAC)

PhD
German Aerospace Centre,
Institute for Material Physics in Space

Powder-based additive manufacturing for space
What is the near future of humans in space?

Planetary exploration
- Long endurance missions
- Low gravity
- *In-situ* resource utilisation: sandy planetary surface (regolith)

Continuous human presence in space
- Long duration missions
- Microgravity
- Versatile (metals, polymers, ceramics)
- Material recycling

→ AM in low- and microgravity: enabling technologies for future space missions
Additive manufacturing in space

Currently: filament-based (FDM) AM on board the ISS (since 2014)
Additive manufacturing in space

Currently: filament-based (FDM) AM on board the ISS (since 2014)

- Small, low constrains parts
  - < 200 functional parts over two years
- Limited size
  - Low quality parts (delamination, limited resolution)
  - Thermoplastics only

Additive manufacturing in space

- Higher resolution
- Higher dimensional accuracy
- Multimaterials fabrication:
  - Polymers, metals, ceramics

**Powder-bed based**

- Versatile (polymer, metal, ceramic powders)
- High resolution (~100µm)

**Diagram**

- Energy source
- Powder roller for homogenisation
- Powder bed
- Stock of virgin powder
- 3D printed object
- Printing platform
Additive manufacturing in space

**Powder-based AM for space:** Gas-flow assisted powder-bed stabilisation

First parts 3D p. in µg from powder
From ceramic and metal powders
High resolution (~100µm)

Deposition relies on powder flowability
(i.e. limited recycling / powder batch reusing)
Bed thickness limited by pump power
Powder without fines
Vertical walls thickness < 2 mm


Powder flow in microgravity
Video courtesy of Plasma Ben, available on https://www.youtube.com/watch?v=Q0kteyMDnwE
Handling powders in microgravity

How to explain behaviour change of granular materials in microgravity?

Material parameters (PS powder):
- mass density $\rho = 1460 \text{ kg.m}^{-2}$
- dielectric constant $\varepsilon = 3$
- surface tension $\gamma = 72 \text{ mN.m}^{-1}$
- liquid contact angle $\theta = 5^\circ$
- aperture angle of capillary liquid bridges $\phi = 20^\circ$
- Hamaker constant $A = 8 \times 10^{-19} \text{ J}$
- surface charge density $\sigma = 1.6 \times 10^{-5} \text{ C.m}^{-2}$

$r = 40 \mu\text{m}$

Distance $l$ between particles /m
Handling & 3D printing powders independently of gravity
A process for 3D printing powders independently of gravity

O. D’Angelo et al., A gravity-independent powder-based additive manufacturing process tailored for space applications, unpublished manuscript (2021) arXiv:2102.09815 [cond-mat.mtrl-sci]

Patent application DE 10 2020 123 753.7 (2020)

Apparatus and Method for Additive Manufacturing of Components in Environments with Various Gravitation-levels and with Materials of Different Flowability
A process for 3D printing powders independently of gravity

1. Screw conveyor rotation: blades rotation pushes material downwards

2. Force chains

3. Inner tube rotates: disruption of force chains by orthogonal force
Using rheology as a tool towards adaptability

material

"flowability"

process

process parameters

in-situ probing
Technology demonstration
Technology demonstration

- Use simulation
  - DEM simulation: number of particles limited by computational power
  - Continuum approach: no constitutive equations encompassing all states

- Experimental proof of concept
  1. Build prototype(s)
  2. Experiment on-ground (1g)
  3. Experiment in weightlessness (µg)
Technology demonstration

Parabolic flight as a microgravity experimental platform
Technology demonstration

*Parabolic flight as a microgravity experimental platform*

**ESA Education**

**FLY YOUR THESIS! 2019**
Technology demonstration
Results

Motivations & State of the Art

Powder flow in µg

AM in space

Technology demonstration

Results & Conclusion
Demonstrator powders: two typical powders (PS 80\(\mu\)m), very different flowability…

- Smooth surface powder
- Rough surface powder
Results: powder rheology vs. gravity

On-ground

In weightlessness

Shear stress $\sigma$ / kPa

Shear strain $\gamma$

Smooth surface powder

Rough surface powder

(a) SS, 1g (layer 3)

(b) RS, 1g (layer 5)

(c) SS, $\mu g$ (layer 7)

(d) RS, $\mu g$ (layer 4)

$\sigma$ span (all layers)
Results: powder-based 3D printing in weightlessness

Smooth surface powder

Rough surface powder
Results: powder-based 3D printing in weightlessness
Conclusion
Additive manufacturing for space applications

- AM: enabling technology for space exploration
- New processes are yet to be developed
  - 3D printing metals with high precision and minimal waste
  - Handling granular materials in extreme environments

Altered-gravity experimental platforms

- Need for altered-gravity experimental platforms:
  - To provide reliable proof of concept
  - To work with materials difficult to simulate (e.g. granular materials)
  - For technology demonstrations
Special acknowledgment to the Grain Power team:
Abeba Birhane, Tolga Bastürk, Merve Seçkin and Felix Kuthe

And to my supervisors:
Prof. Andreas Meyer, Prof. Thomas Voigtmann, Dr. Till Kranz

This project was supported by:
ESA/NPI nº4000122340: Physical Properties of Powder-Based 3D Printing in Space and On-Ground
DLR/DAAD Research Fellowship nº91647576
ESA Education Fly Your Thesis! 2019 flight opportunity