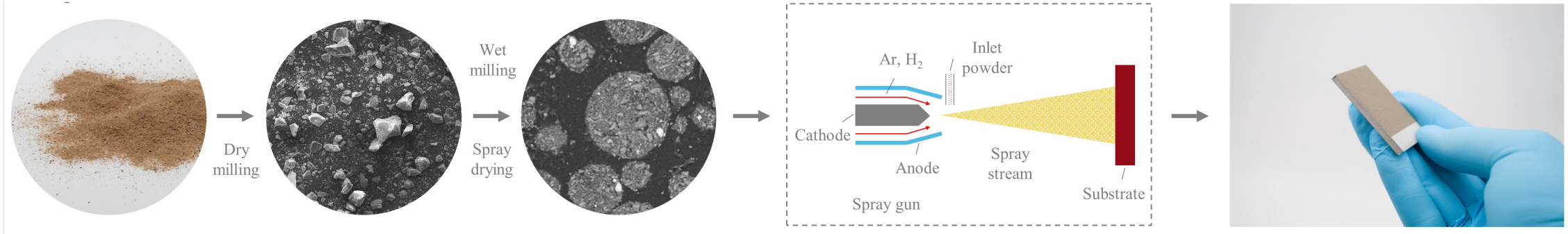
25th Space Resources Roundtable
Session 11 – Space Manufacturing – 5 June 2025, Thursday; 13:30-14:50



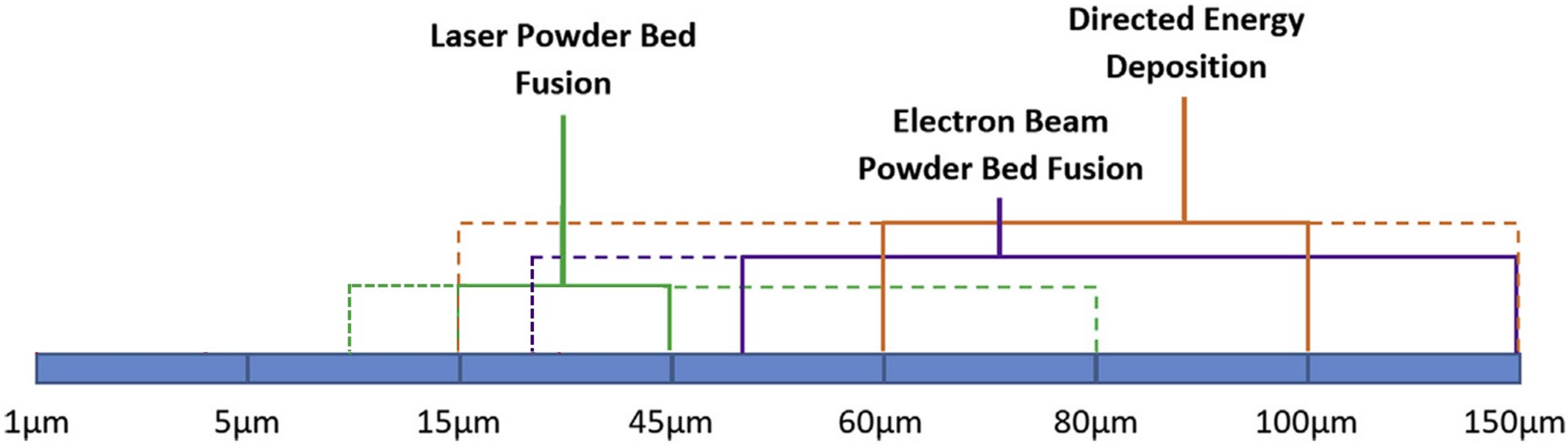

# Novel approach to increase flowability of regolith: Agglomeration of powder for thermal spraying

David Karl[1,3]*, Chenggui He[1], Paul Junge[3], Ruben Prause[1], Rafael Kleba-Ehrhardt[1], Christian Rupprecht[3] and Aleksander Gurlo[1]

[1] Chair of Advanced Ceramic Materials – Technische Universität Berlin, Germany.
[2] Chair of Coating Technologies – Technische Universität Berlin, Germany.
[3] Center for Space Resources – Colorado School of Mines, Golden, Colorado, USA

Correspondence: **karl@tu-berlin.de**

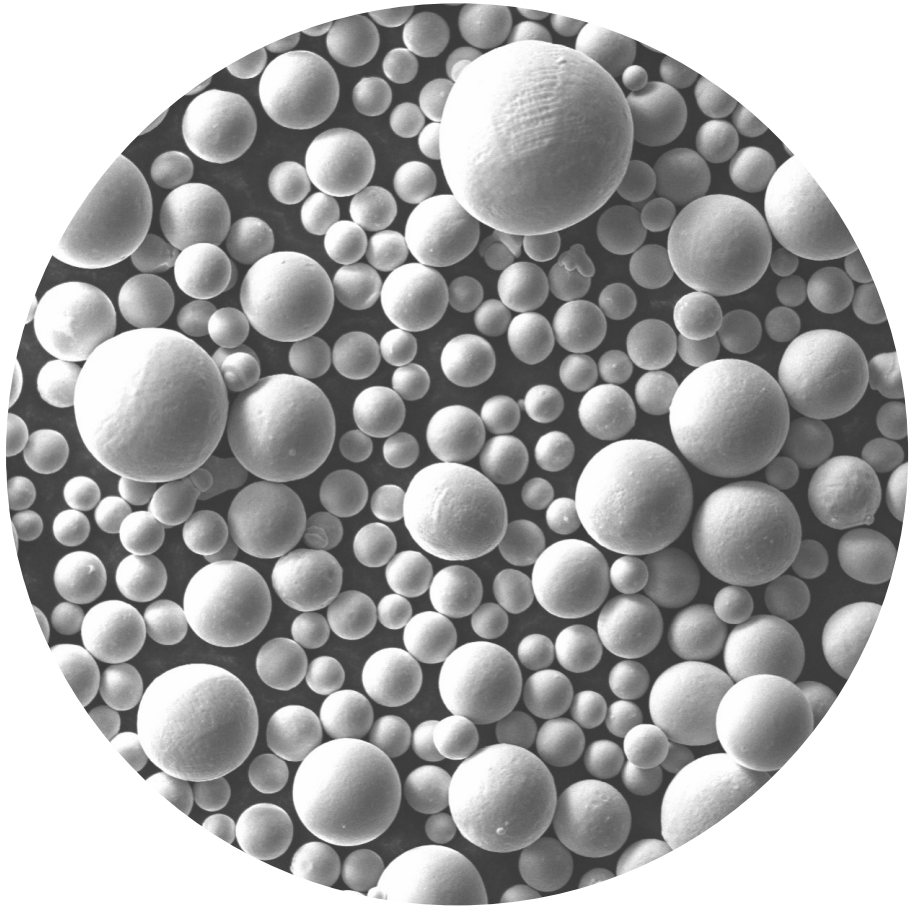
# Motivation: Homogeneous, well-flowing powders for manufacturing



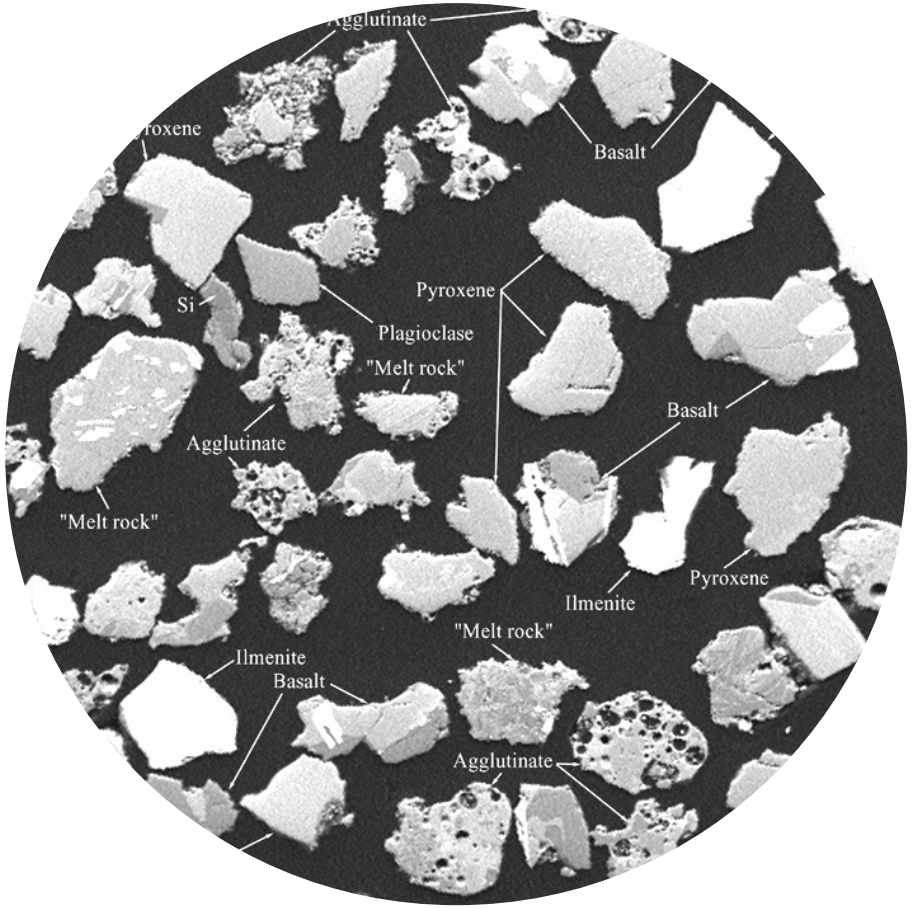

Ideal size range for metallic beam-based Additive Manufacturing (spherical particles).

# Regolith as feedstock: Rugged particles from diverse minerals

## Gas-atomized metallic AM powders



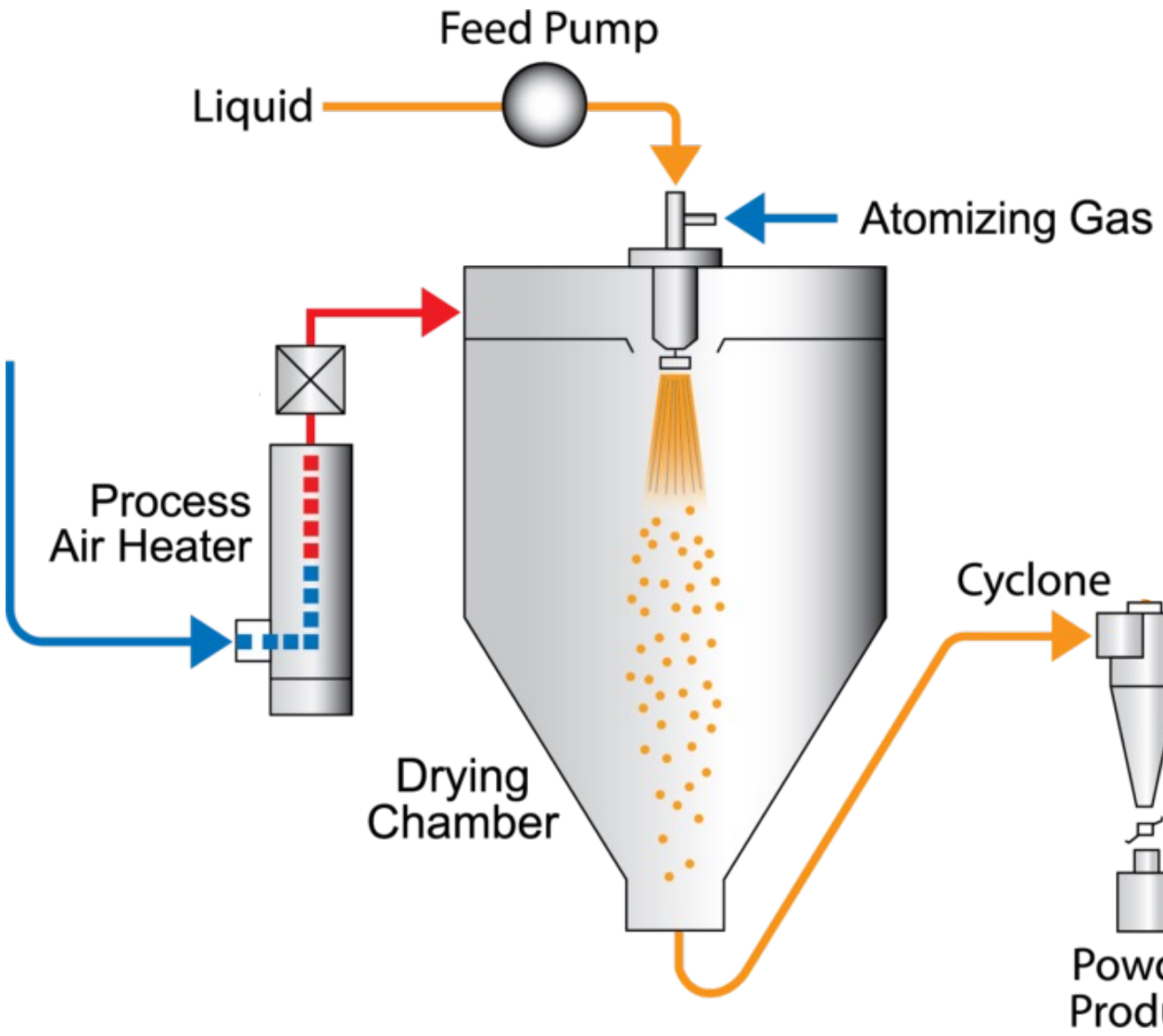
## Lunar regolith powders

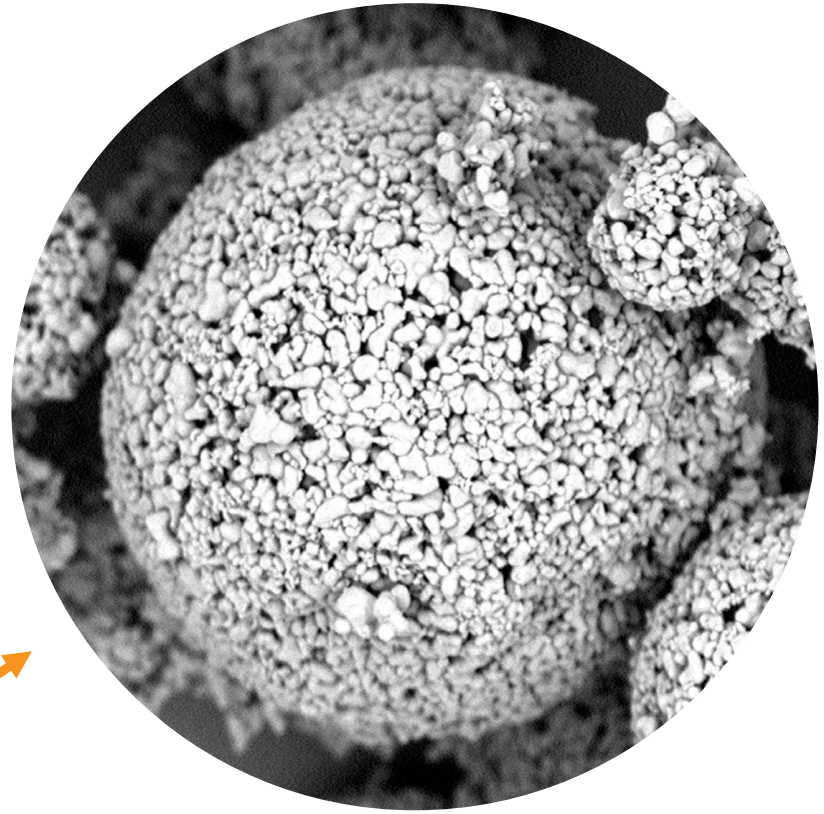


# Regolith feedstock improvement: Milling and granulation

## Powder granulation

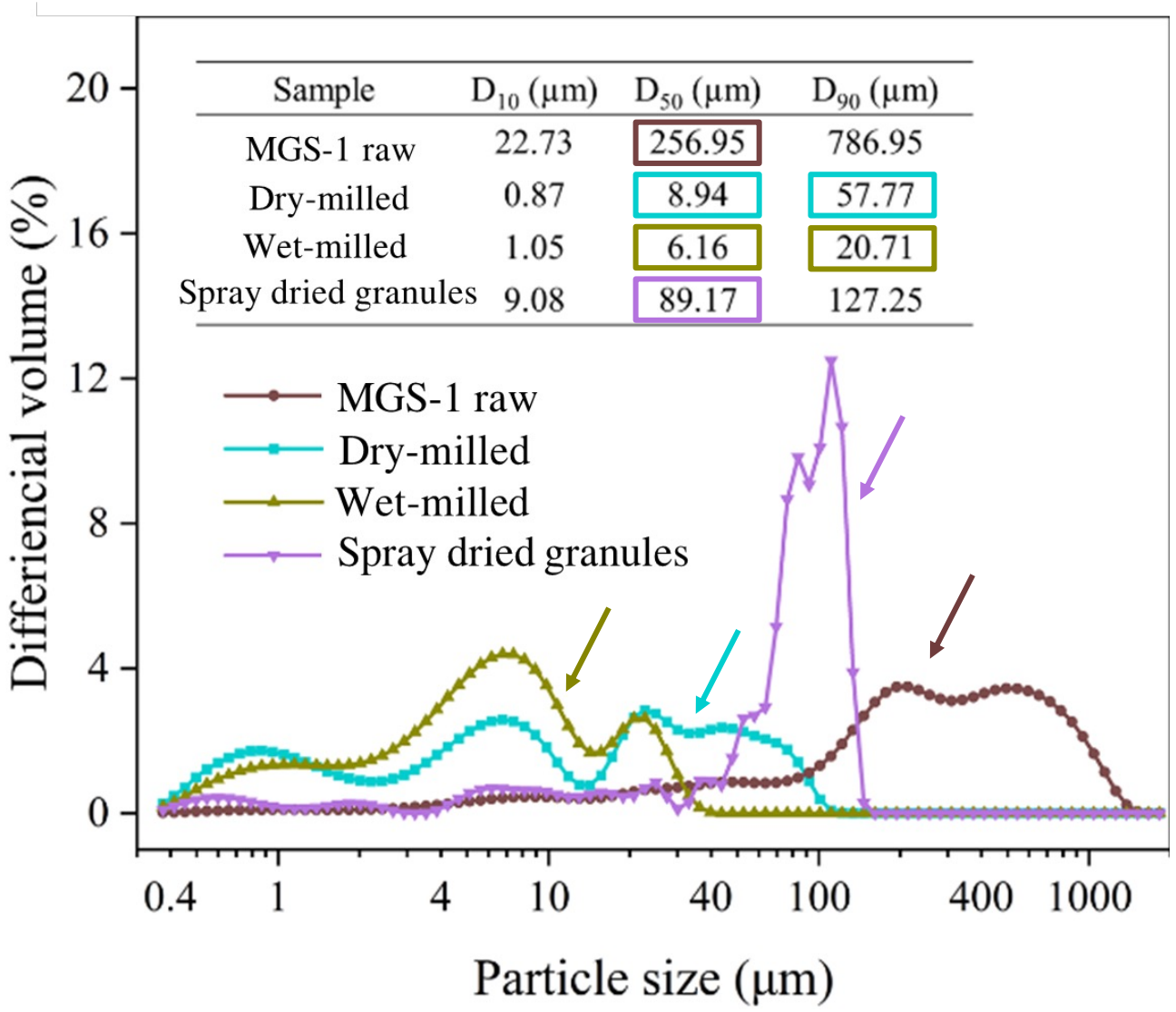
# Granulation: Spray-drying of colloids



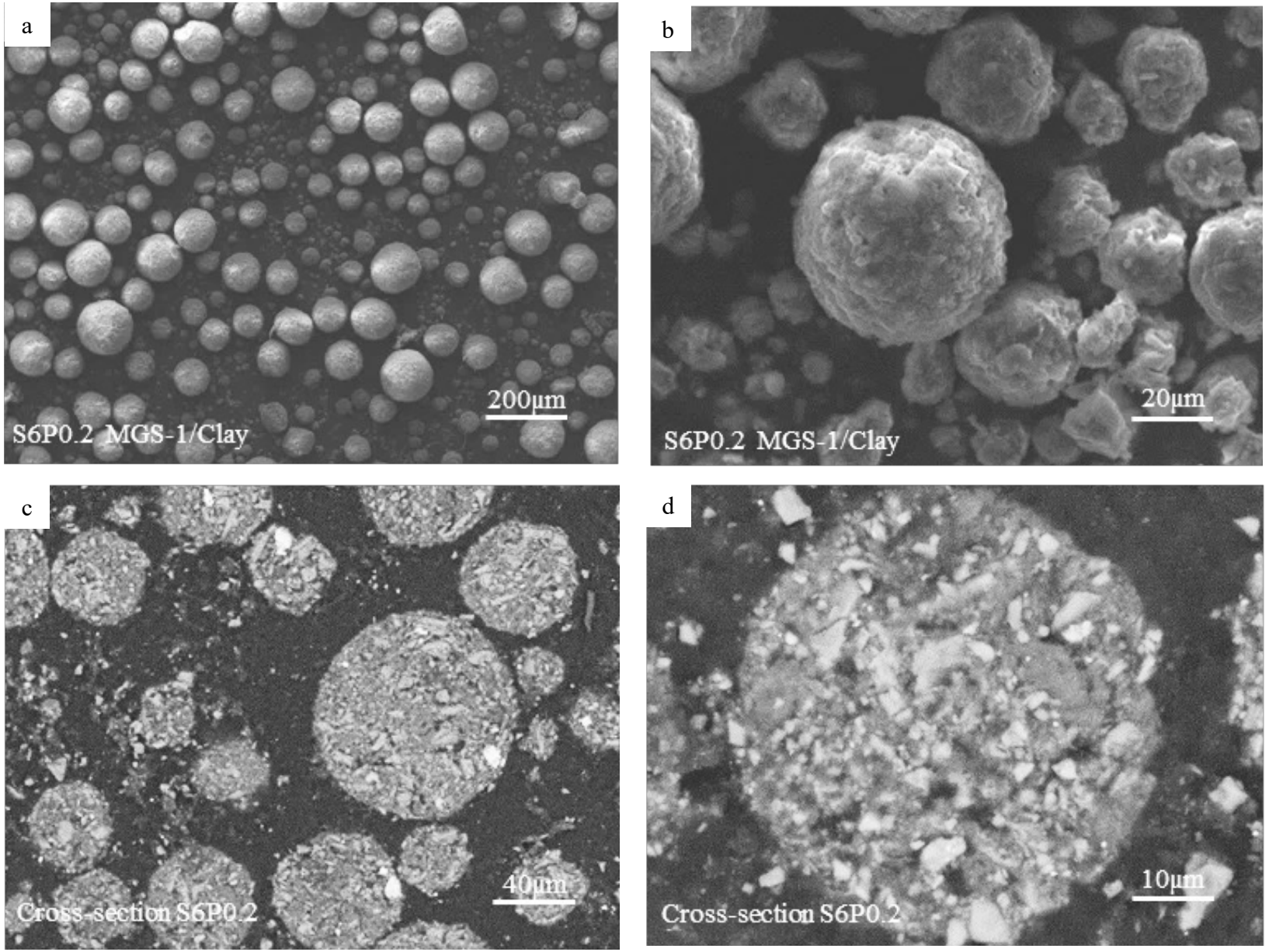



# Particle size distribution: Granulation of MGS-1 Martian Simulant

| Sample | $D_{10}$ (µm) | $D_{50}$ (µm) | $D_{90}$ (µm) |
|---|---|---|---|
| MGS-1 raw | 22.73 | 256.95 | 786.95 |
| Dry-milled | 0.87 | 8.94 | 57.77 |
| Wet-milled | 1.05 | 6.16 | 20.71 |
| Spray dried granules | 9.08 | 89.17 | 127.25 |



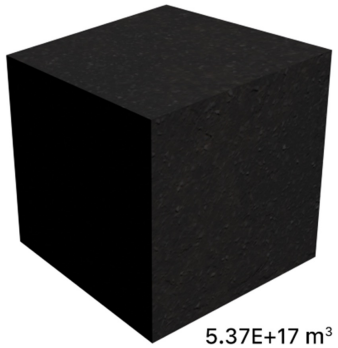
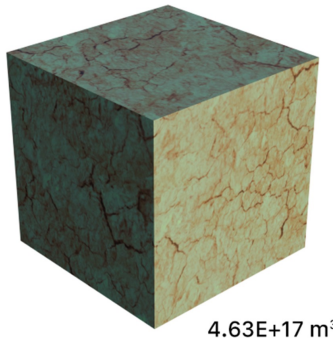
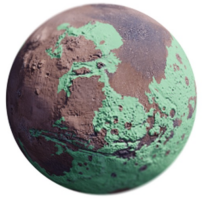
# Morphology: Granulation of MGS-1 Martian Simulant



# Granulation: Spray-drying colloids

Concept of using nanosized phyllosilicates (clay) as a binder:

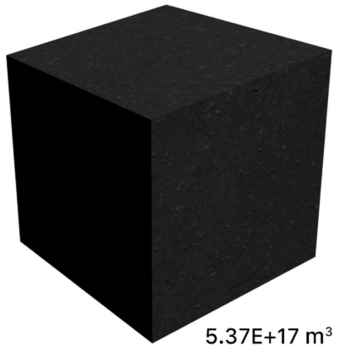
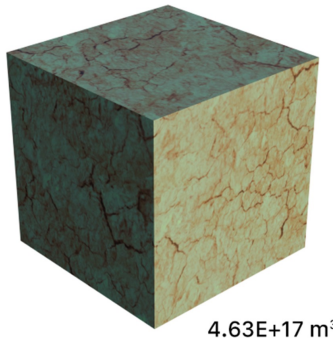
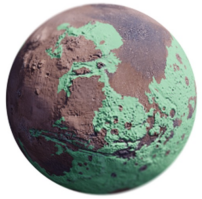
# SRU mining: Accessible phyllosilicate volume and Lunar clay

| Source | Material Volume | Phyllosilicate Volume |
|---|---|---|
| C-type MBAs  |  5.37E+17 m³ |  4.63E+17 m³ |
| Mars Noachian Crust  |  7.80E+16 m³ |  2.34E+15 m³ |
| Ceres Crust  |  3.37E+15 m³ |  3.04E+14 m³ |
| C-type NEAs  |  2.62E+12 m³ |  2.26E+12 m³ |



**Karl and Cannon**, Proposal of a Space Clay Economy (**2025**) Manuscript in preparation.

# SRU mining: Accessible phyllosilicate volume and Lunar clay

| Source | Material Volume | Phyllosilicate Volume |
|---|---|---|
| C-type MBAs  |  5.37E+17 m³ |  4.63E+17 m³ |
| Mars Noachian Crust  |  7.80E+16 m³ |  2.34E+15 m³ |
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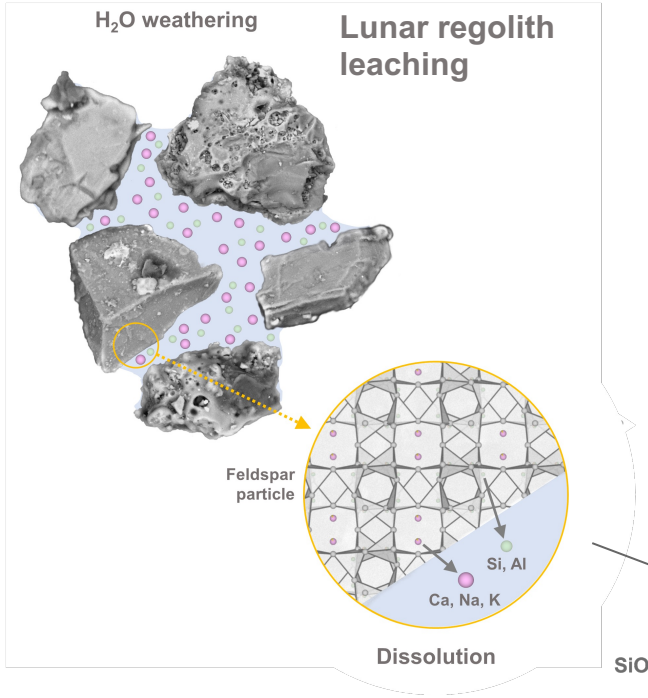
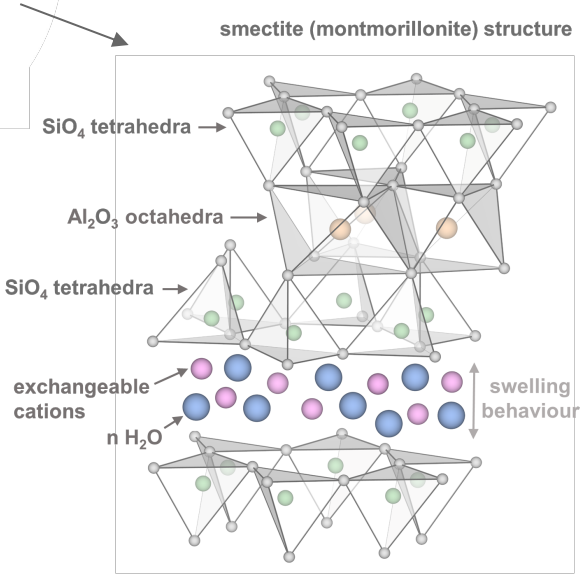





**Karl and Cannon**, Proposal of a Space Clay Economy (**2025**) Manuscript in preparation.

# Parameter development: Viscosity of spray-drying slurry

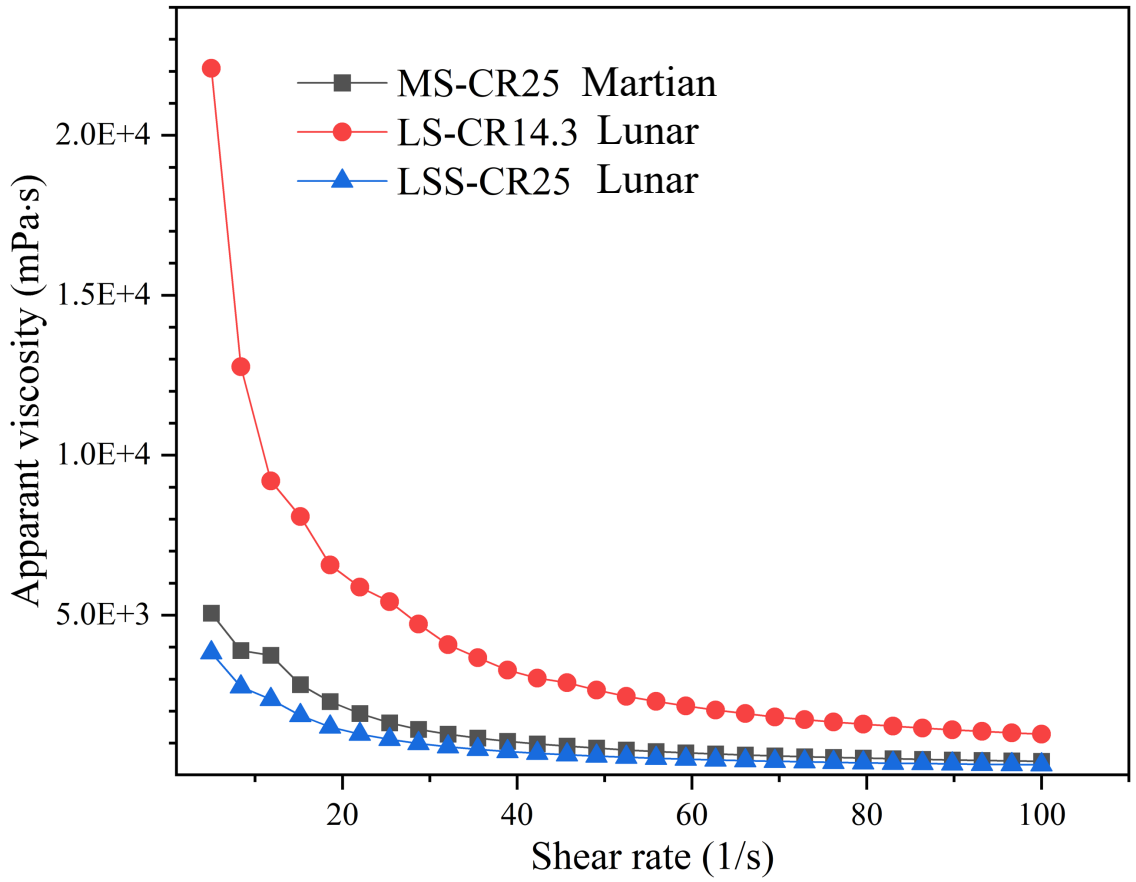
Composition of Martian and Lunar simulant slurries:

| Sample | Simulant | Clay ratio (wt.%) | Solids loading (wt.%) |
|---|---|---|---|
| MS-CR25 | MGS-1 (C) (4 wt.% Mg-$SO_4$) | 25 | 40 |
| LS-CR14.3 | CSM-LHT-1G | 14.3 | 40 |
| LSS-CR25 | CSM-LHT-1G + Mg-$SO_4$ (4 wt.%) | 25 | 40 |

Martian and Lunar slurries with identical clay amounts and Mg-sulfate exhibit similar rheological properties.

For Lunar slurries with lower clay amount and without Mg salts, higher viscosity and a steeper G' recovery curve are observed.

Viscosity of Mars and Lunar simulant slurries:



# Spray-drying: Parameter study

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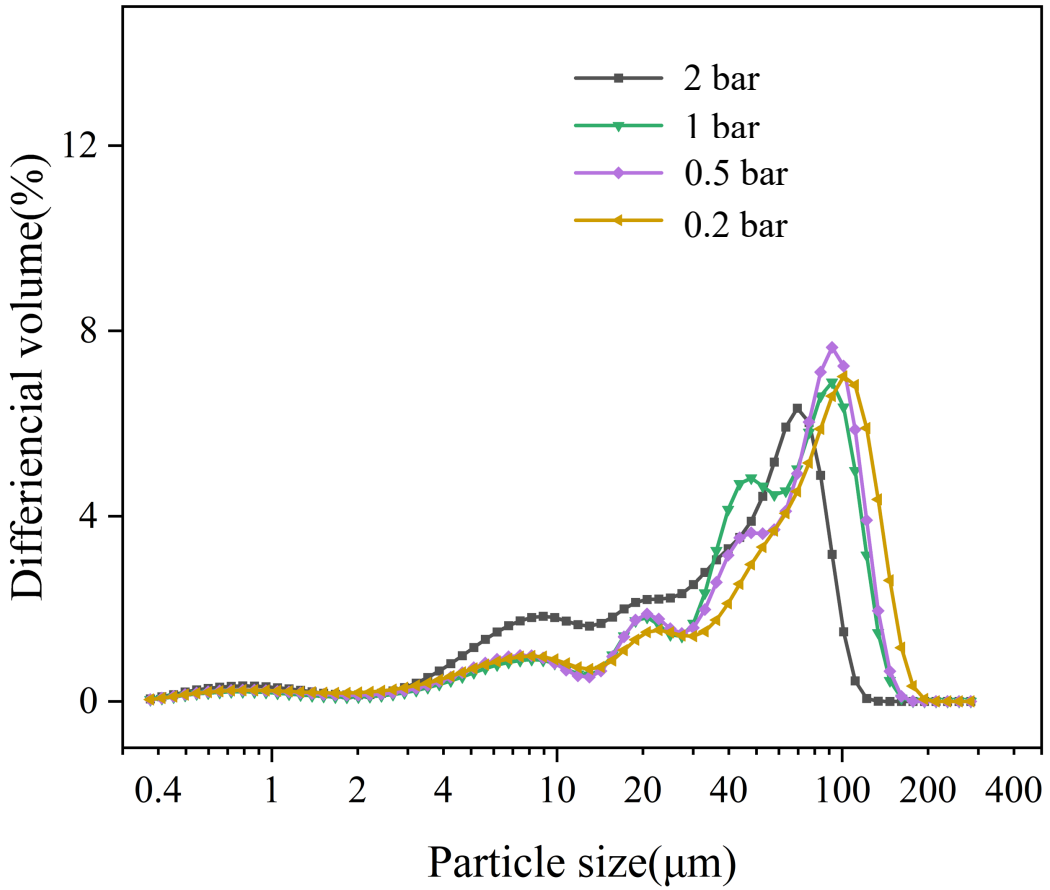
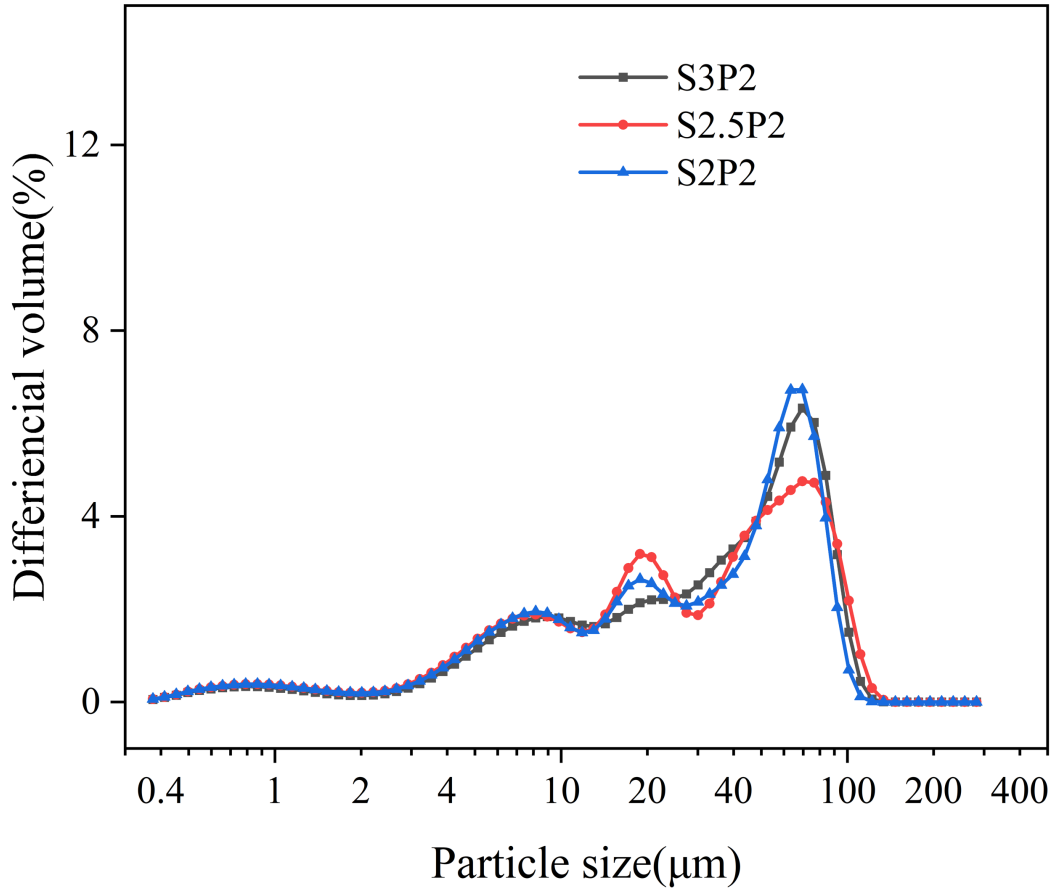
Variation of air pressure:




Variation of pumping speed (pressure 2 bar):



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# Morphology: Granulation of Martian and Lunar Simulants

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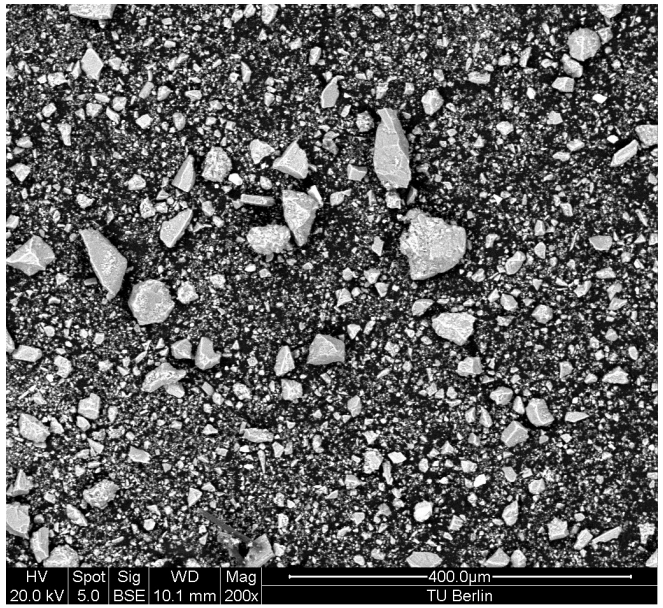
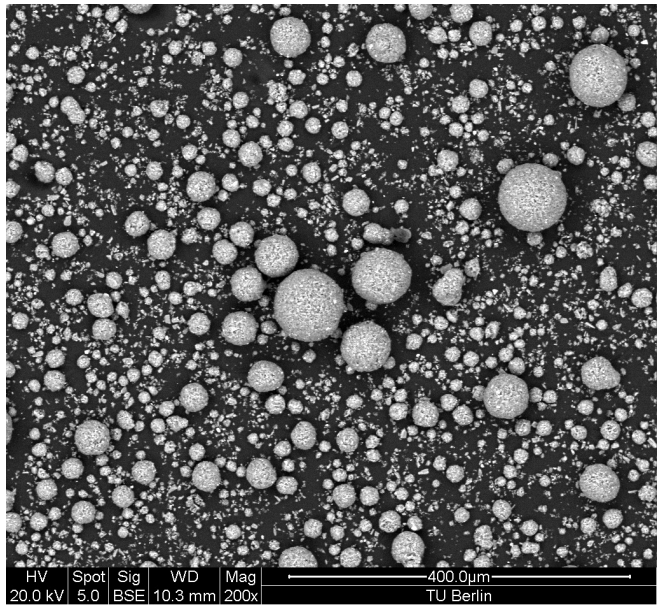
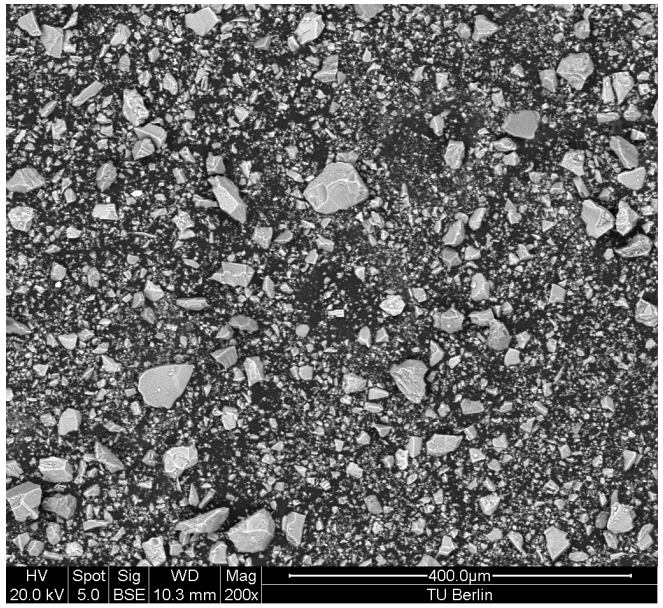
Dry-milled MGS-1C

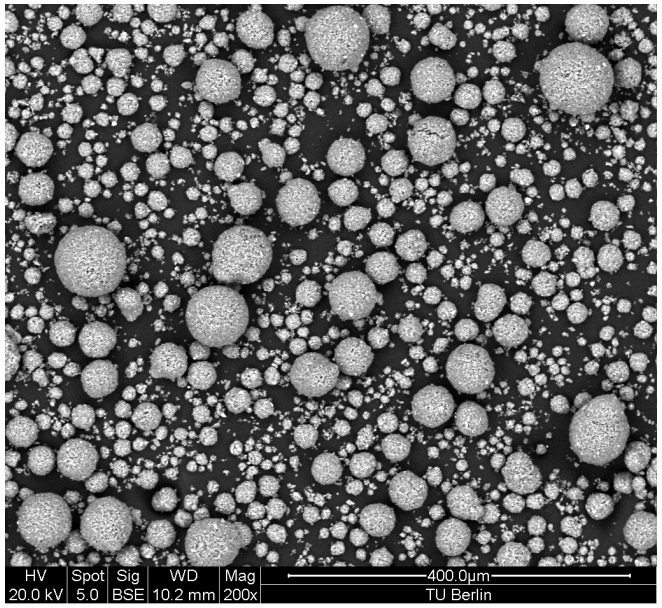



Spray-dried MGS-1C

Dry-milled CSM-LHT-1G




Spray-dried CSM-LHT-1G (C)



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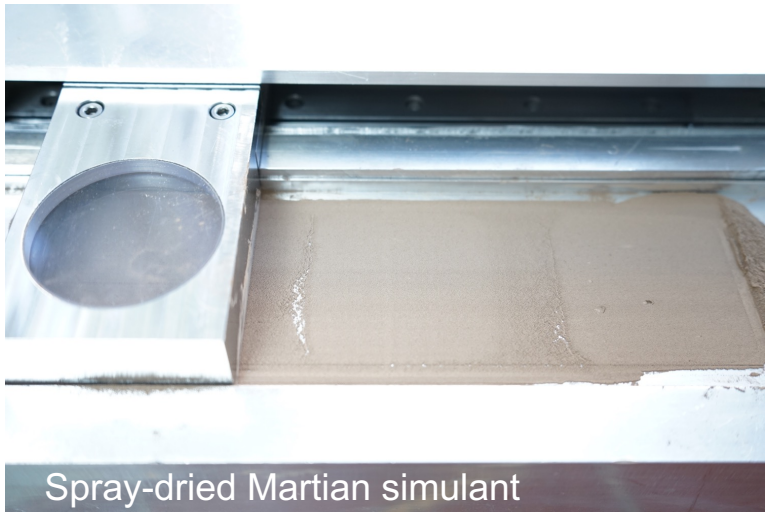
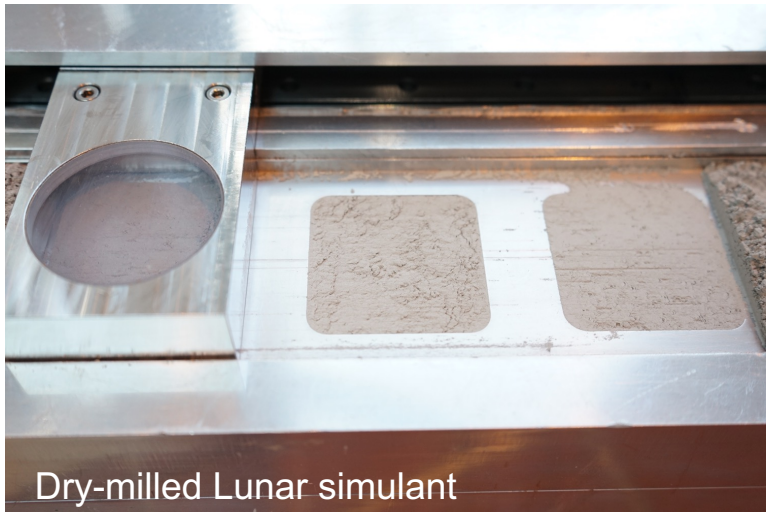
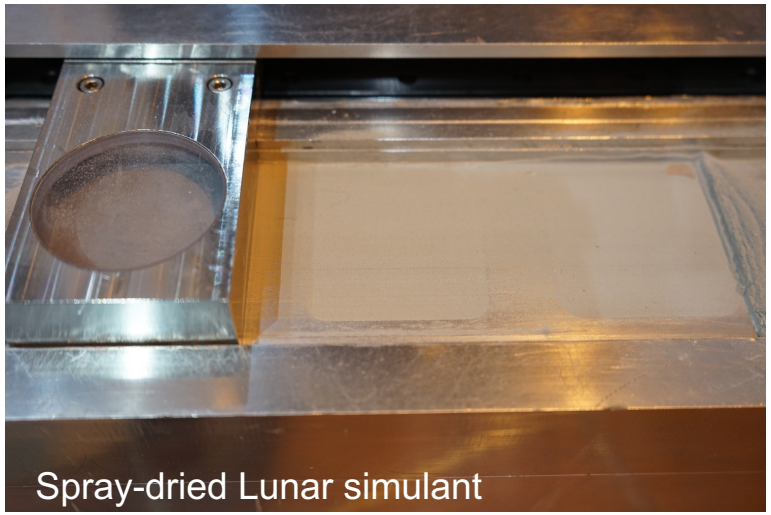
# Powder flow: Layer spreading for powder bed additive manufacturing


Spray-drying



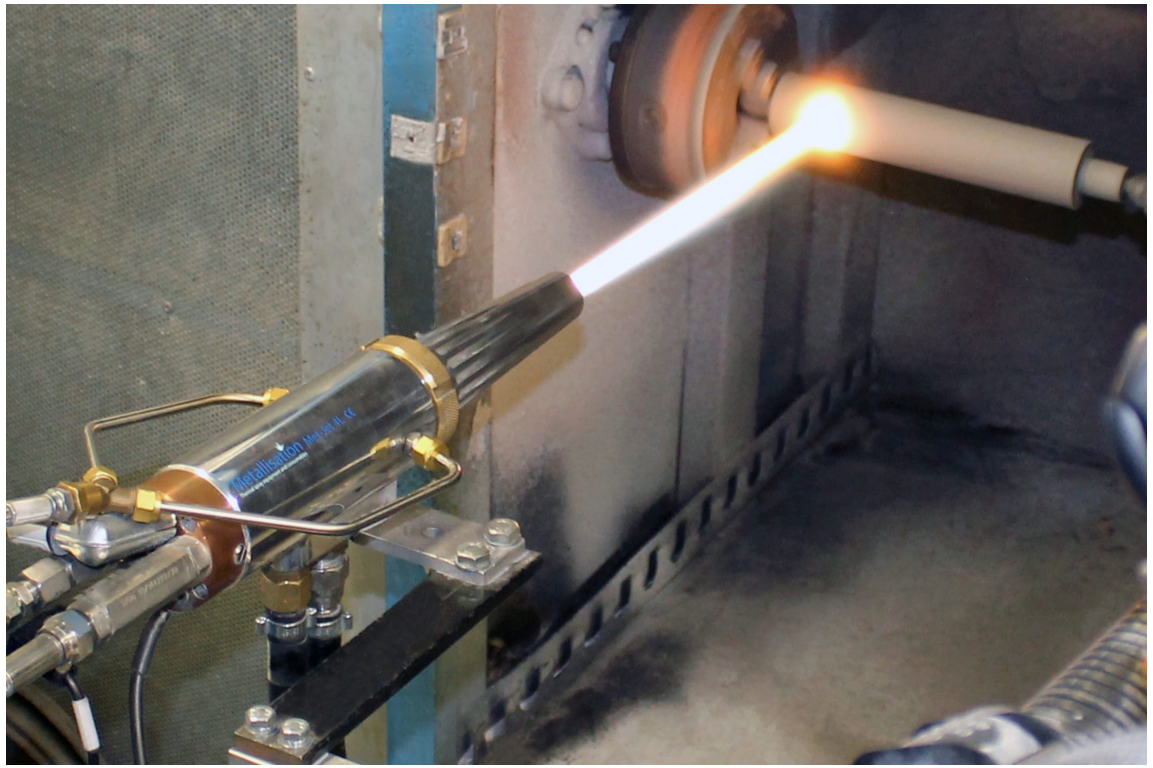




Spray-drying




| Sample | Compressibility | | |
|---|---|---|---|
| | Bulk density ($g/cm^3$) | Tapped density ($g/cm^3$) | Hausner ratio |
| Dry-milled Martian | 0.81 ± 0.02 | 1.75 ± 0.01 | 2.15 (very very poor) |
| Spray-dried Martian | 0.80 ± 0.01 | 1.09 ± 0.003 | 1.37 (poor) |
| Dry-milled Lunar | 0.53 ± 0.05 | 1.53 ± 0.01 | 2.91 (very very poor) |
| Spray-dried lunar | 0.79 ± 0.003 | 1.03 | 1.30 (passable) |

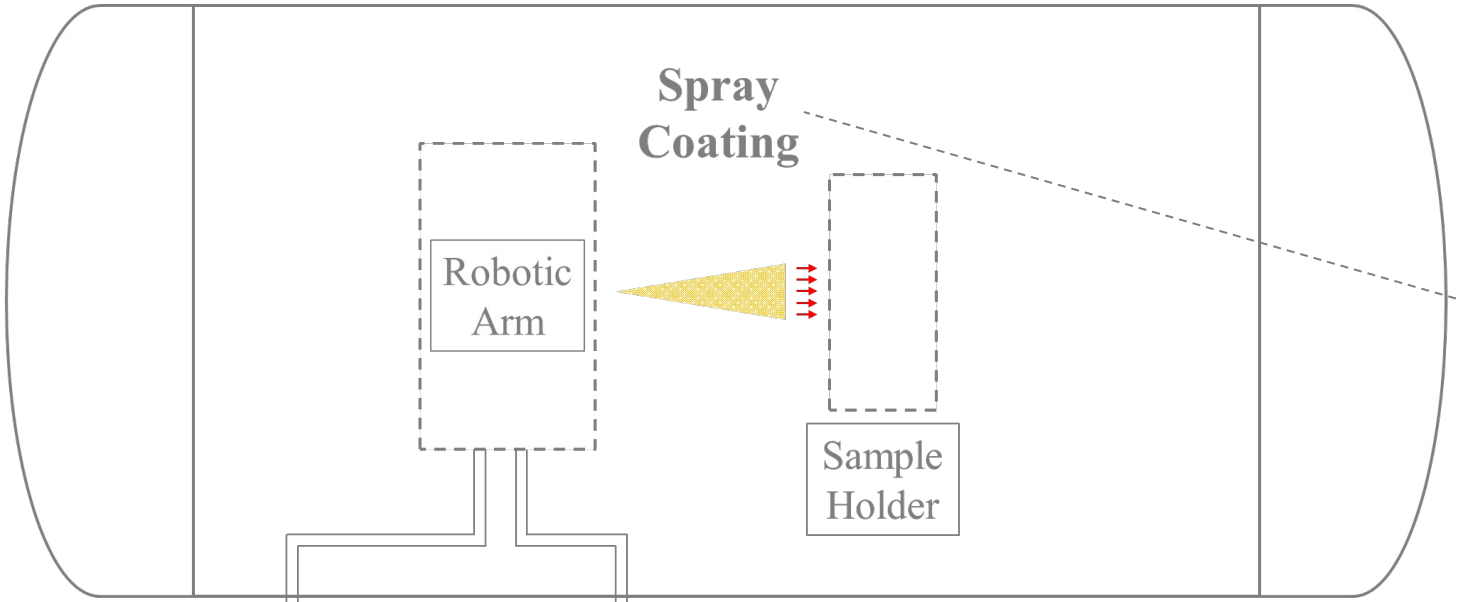
# Thermal spraying: Ceramic coatings on metallic substrates

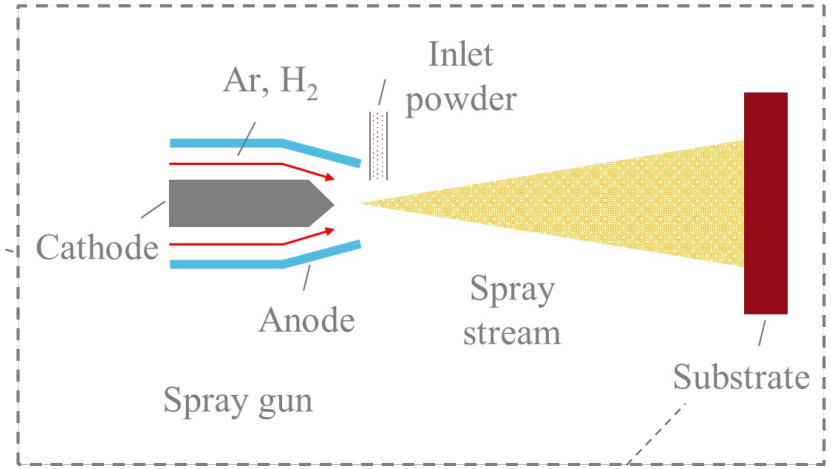


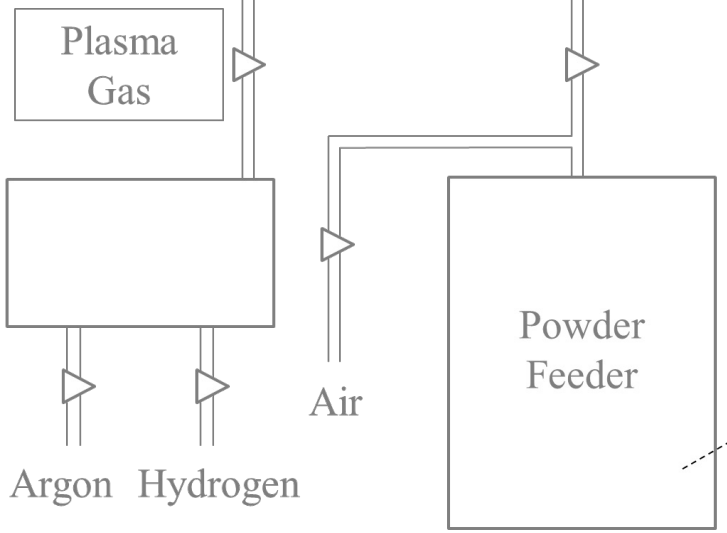
Ceramic thermal barrier coating (TBC)
on turbine guide vane.

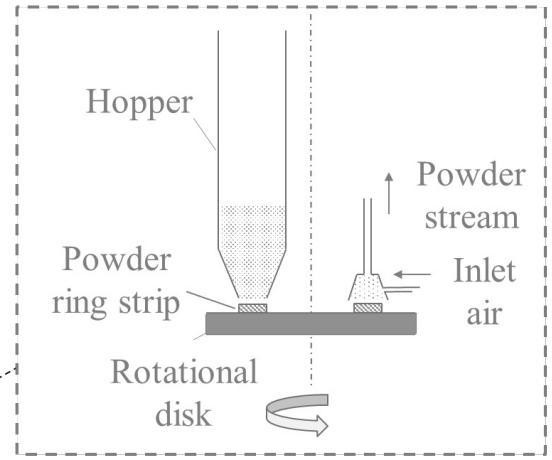
# Thermal spraying: Ceramic regolith coatings on metallic substrates

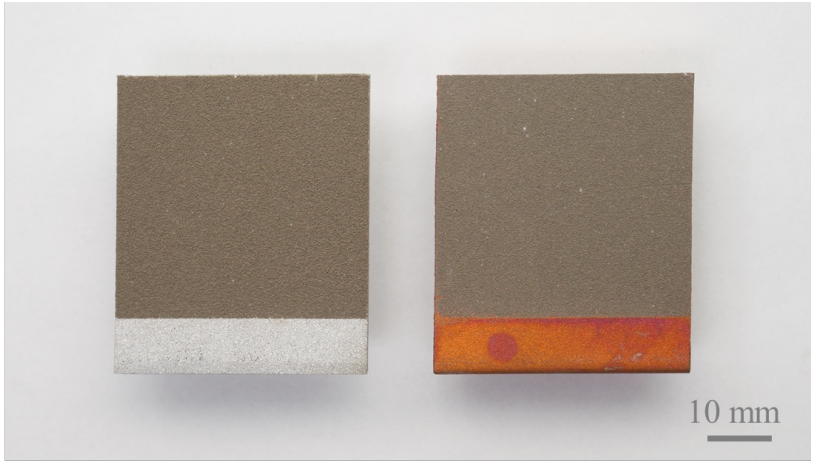
# Thermal spraying: Flowchart image



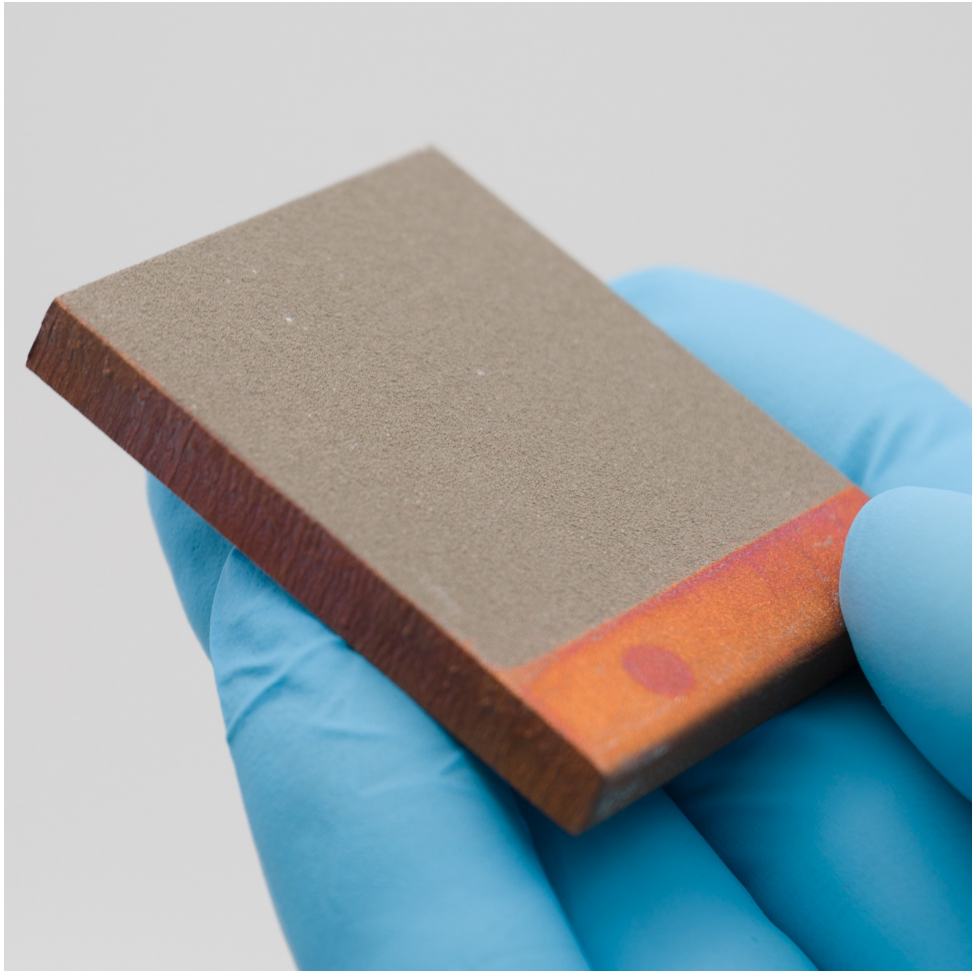



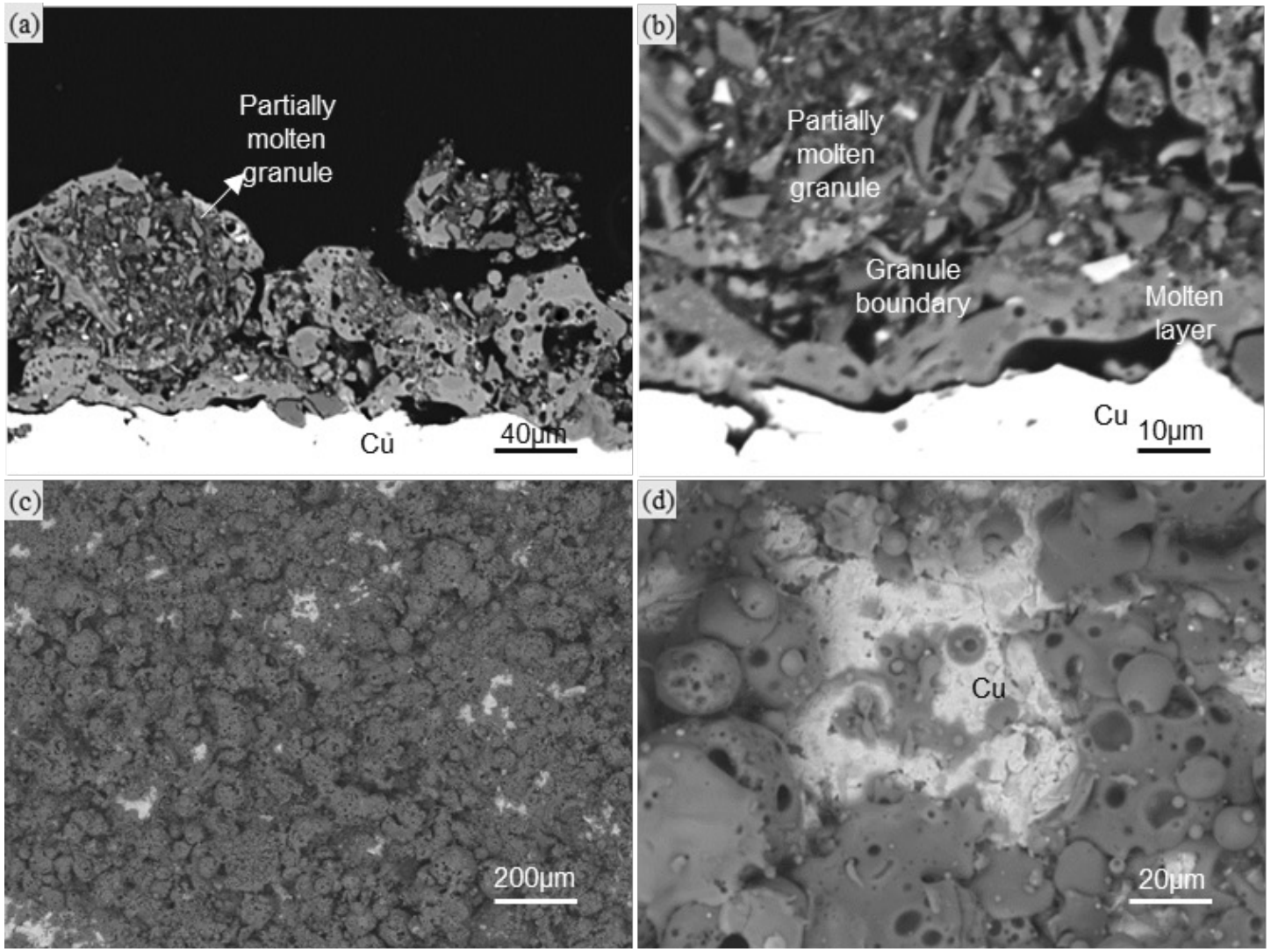



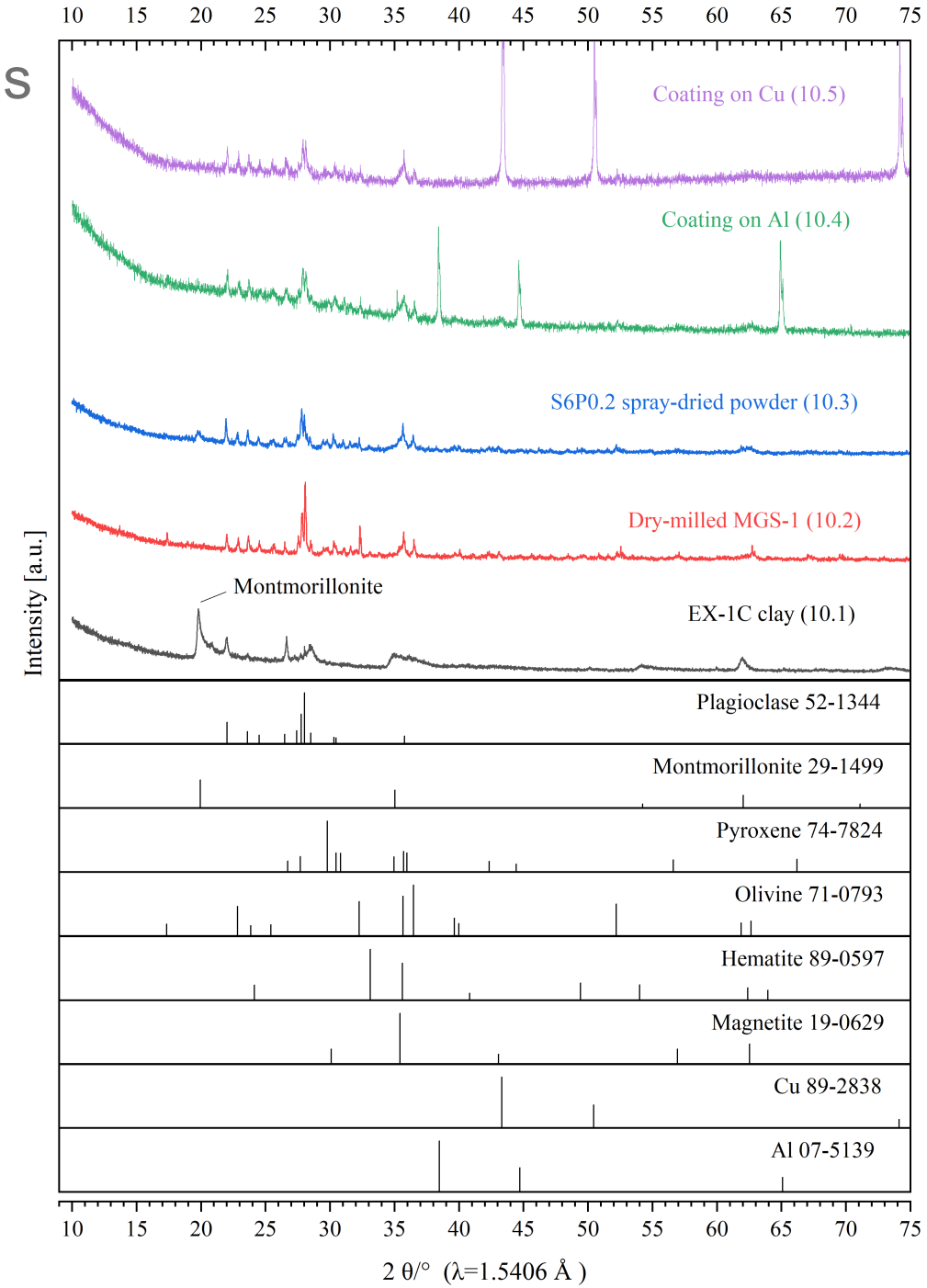



# Thermal spraying: Ceramic regolith coatings on metallic substrates



# Regolith coatings: Microstructure and phase analysis



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*Thank you very much*

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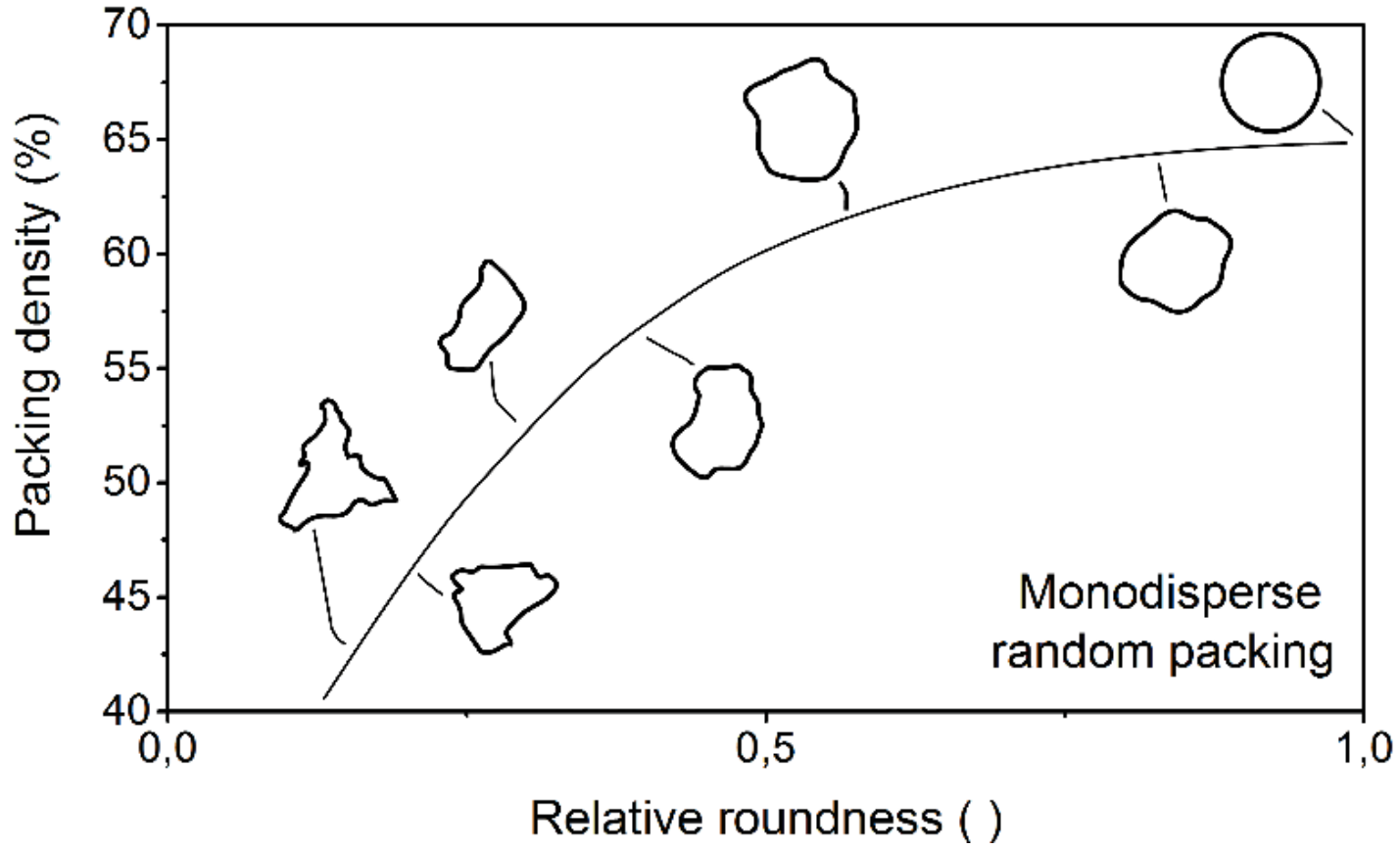
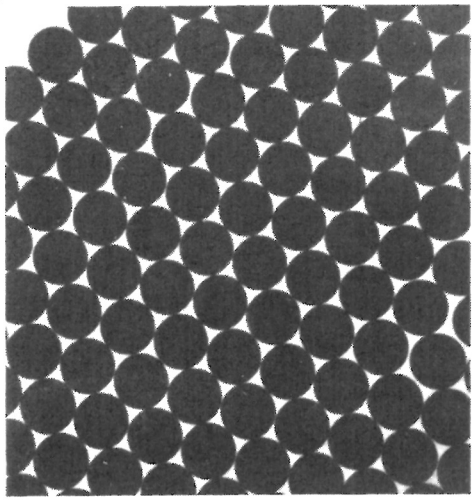
# Particle shape/roundness

Monodisperse **random** packing

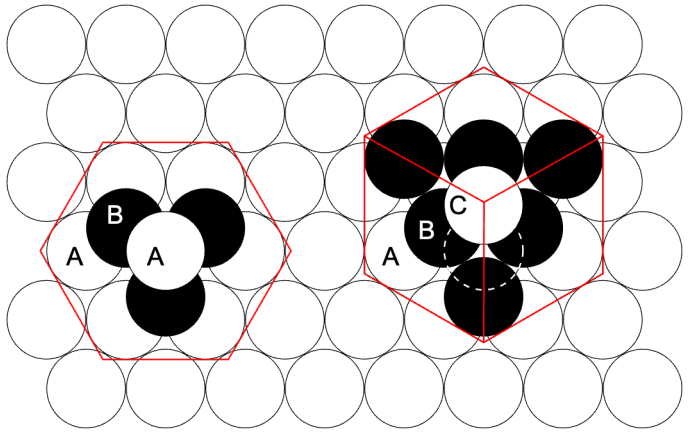



**German.** Particle packing characteristics. Princeton NJ: Metal Powder Industries Federation; **1989.**

# Packing density of powder beds



ordered




Comparison between hexagonal close-packed (**hcp**) and face-centred cubic (**fcc**).

| Packing form ordered / random | Packing density vol.% |
|---|---|
| hcp and fcc | 74.04 |
| bcc | 68.04 |
| Random (max) | ~ 64.1 |
| Metal powder bed | ~ 54-60 |
| Polymer powder bed | ~ 43-44 (PA12) |
| Ceramic powder bed | ~25-(50) |
| Lunar Regolith | ~35-60 |

**German.** Particle packing characteristics. Princeton NJ: Metal Powder Industries Federation; **1989.**

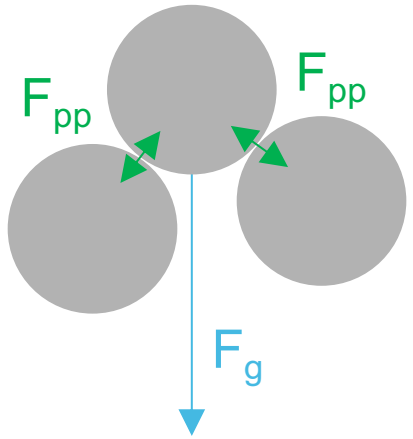
**Jacob**, et al. Effects of powder recycling on stainless steel powder and built material properties in metal powder bed fusion processes. NIST, **2017**.

**Tian**, et al. Int. Journal of Heat and Mass Transfer 120 (**2018**): 379-386.

# Interparticle forces and gravity

Perquisite for good powder flow with gravity:

$$F_g > F_{pp}$$




$F_g = \rho V g$ (Gravitational force)

ρ = density

$V = \frac{4}{3} \pi R^3$ (volume)

g = gravitational constant

$F_{pp} = \frac{AR}{12z^2}$ (Van der Waals forces)

A = Hamaker constant

R = radius

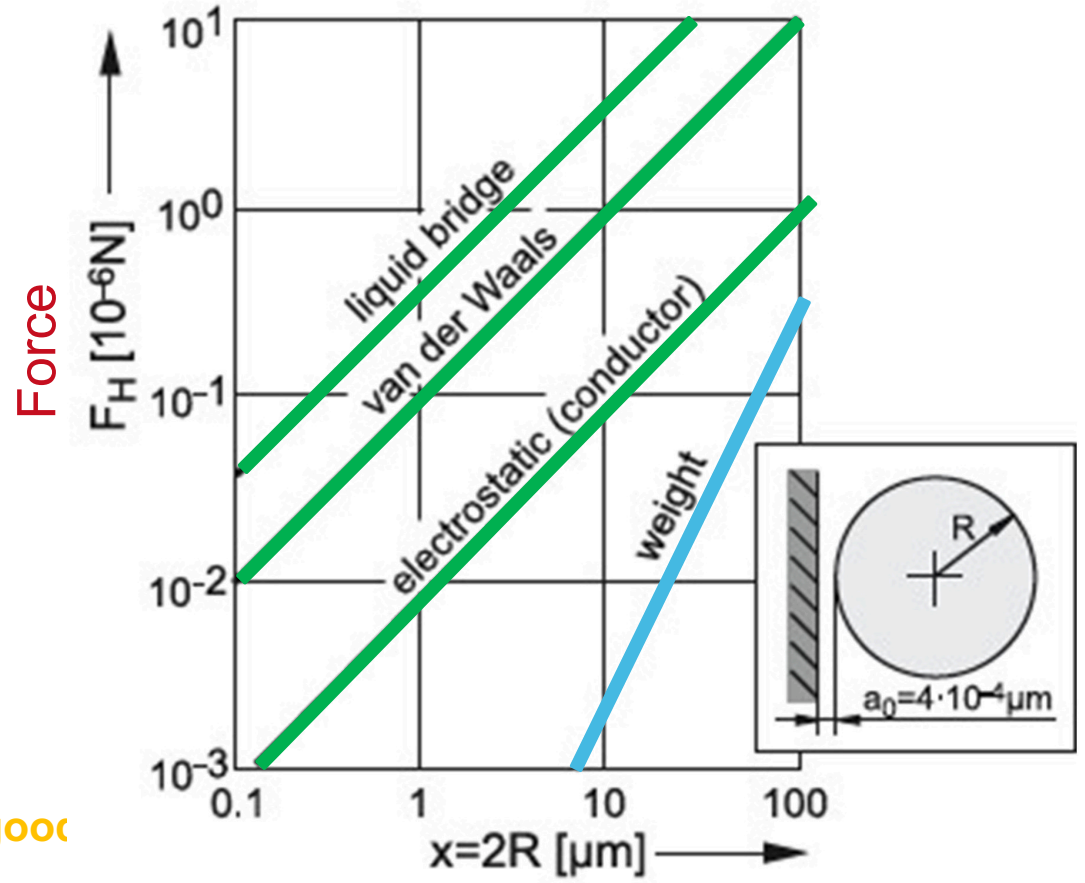
z = distance between particles

(assumed **0.4 nm for particles in contact**)

$$\rho \frac{4}{3} \pi R^3 g > \frac{AR}{12z^2}$$

**Particle properties for good powder flow on Earth**

- Diameter: ~10 -100 µm




Interparticle forces $F_H$ dependence on the particle size.


**Diener, Zocca and Günster** *Literature review: Methods for achieving high powder bed densities in ceramic powder bed based additive manufacturing;* Open Ceramics, **2021**, 8, 100191.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