INFN AM Workshop 2019

20th September 2019, Padova, Italy

The role of powder properties on Precision Additive Metal Manufacturing

Mirko Sinico

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PAM² | KU Leuven AM Research Group

Belgium

The PAM² project (https://pam2.eu/)

- **Precision Additive Metal Manufacturing**

MARIE CURIE ACTIONS

THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION

HORIZON 2020

European Commission

Horizon 2020
European Union funding
for Research & Innovation

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The PAM² project (https://pam2.eu/)

- **Precision Additive Metal Manufacturing**

- ➢ **with 6 Academic partners**
- ➢ **and 6 Industrial partners**

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Consortium

Full Network Participants (Beneficiaries)

Academic partners

- KU Leuven, Mechanical Engineering Department, Belgium
- Technical University of Denmark, Denmark
- University of Padua, Italy
- Karlsruhe Institute of Technology, Germany
- Delft University of Technology, The Netherlands
- The University of Nottingham, United Kingdom

Industrial partners

- 3D Systems Leuven, Belgium
- NP TEC (Nuovo Pignone Technologie s.r.l), Italy
- Alicona, Austria
- LEGO System A/S, Denmark

Associated Partners

- ASML, The Netherlands
- MAGMA GmbH, Germany

The PAM² project (https://pam2.eu/)

- **Precision Additive Metal Manufacturing**

- ➢ **with 6 Academic partners**
- ➢ **and 6 Industrial partners**

- ➢ **& 15 young researchers**

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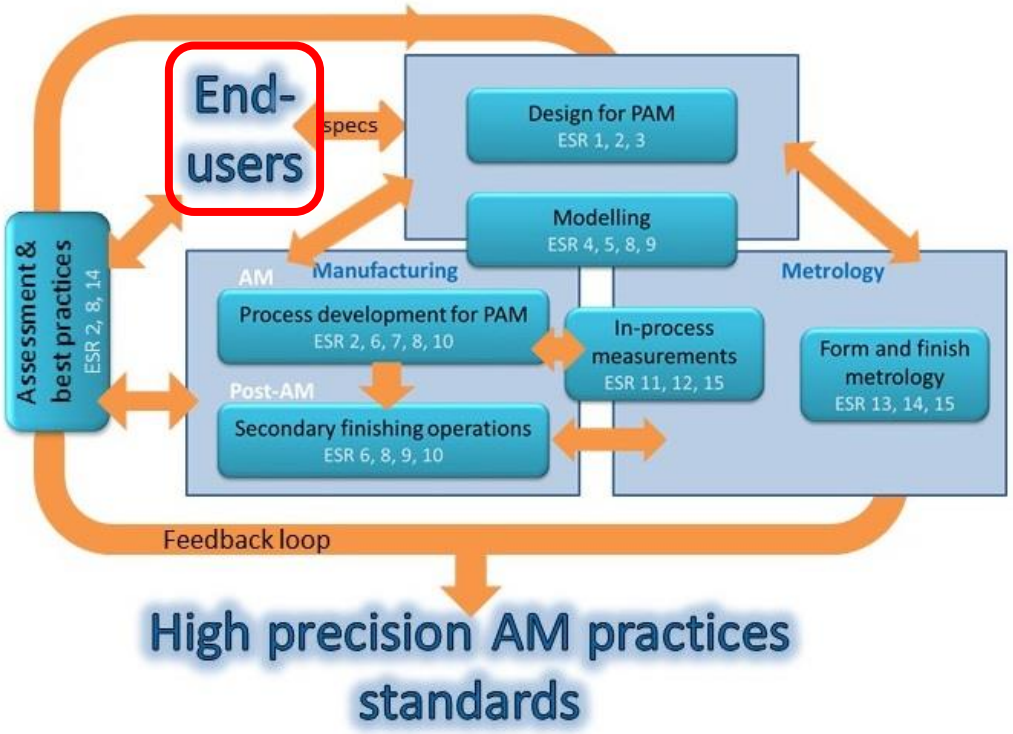
The PAM² project (https://pam2.eu/)

- **Precision Additive Metal Manufacturing**

➢ **with 6 Academic partners**
➢ **and 6 Industrial partners**

- Our goal is to **improve the precision of the LPBF process**, covering all the value chain of the AM manufacturing

  and…**test** our research **on end-users cases**



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The role of powder properties on PAM²

precision precision precision

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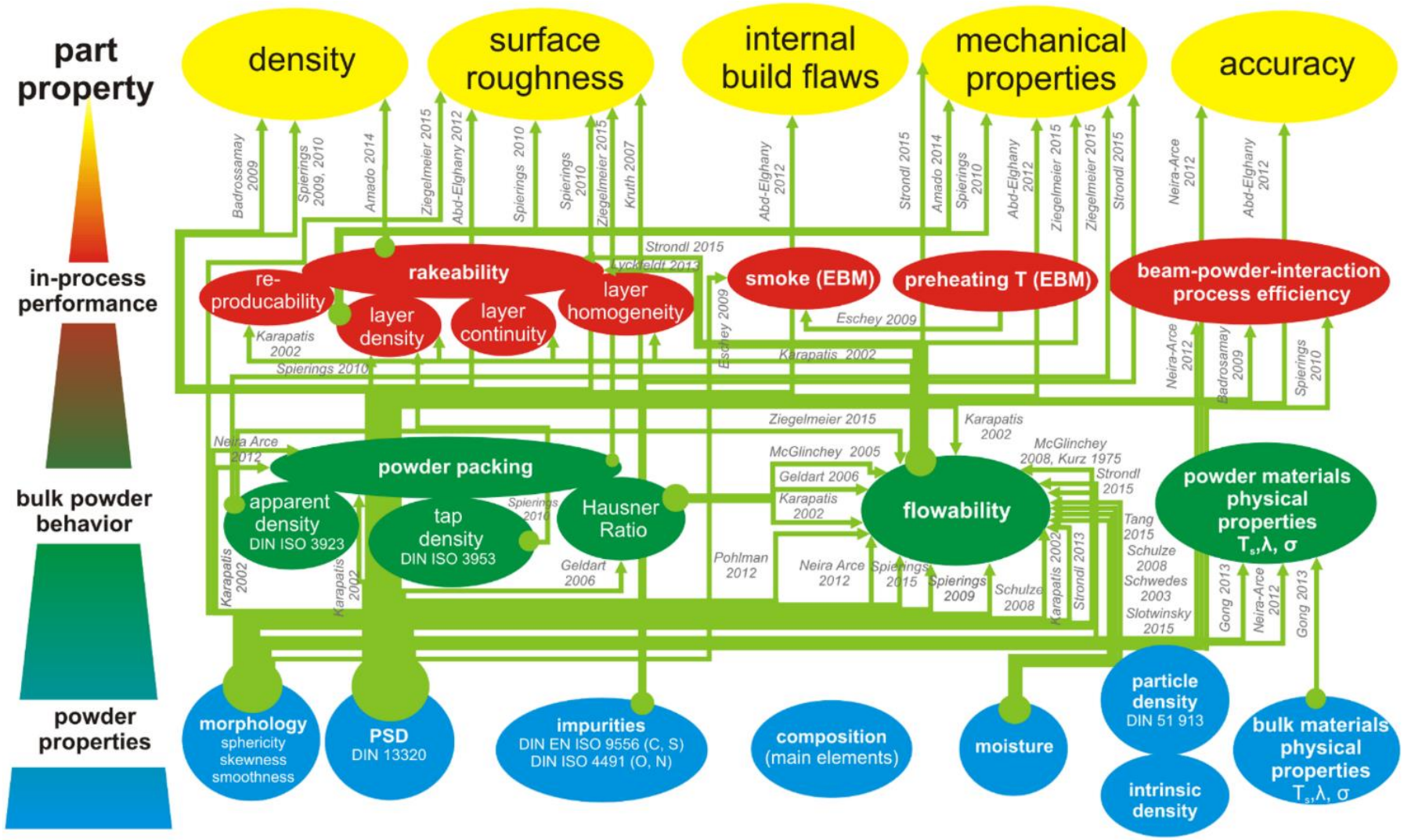
Powder properties influence LPBF part properties



from S. Vock, B. Klöden, A. Kirchner, T. Weißgärber, and B. Kieback, 'Powders for powder bed fusion: a review', *Progress in Additive Manufacturing*, Feb. 2019.

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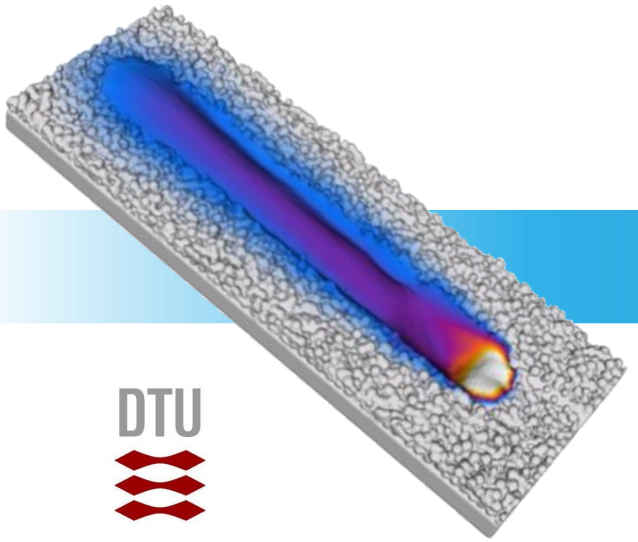
The role of powder properties on PAM²

Simulations

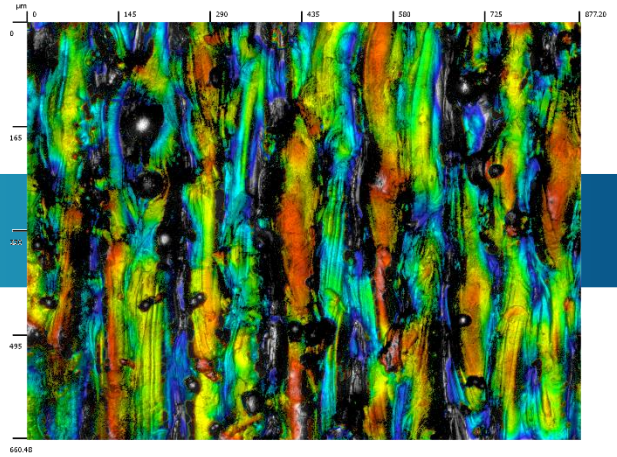


Novel full physical meso-scale numerical model

Characterization

Characterization of AM Metal Powder with an Industrial Microfocus CT

Processability



Influence of the Particle Size Distribution on surface quality

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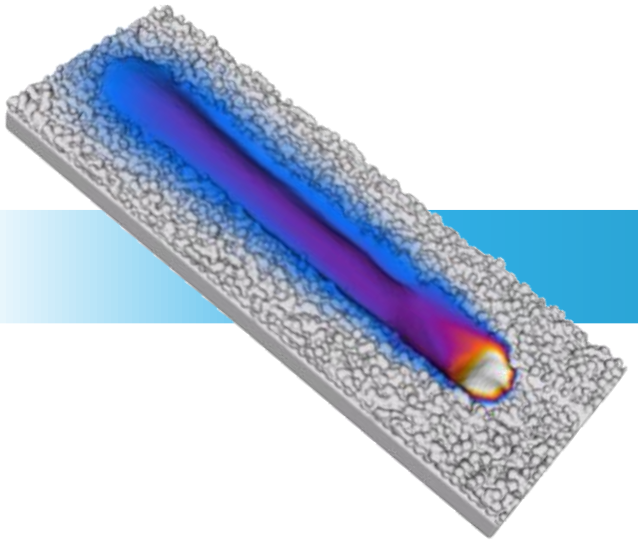
The role of powder properties on PAM²

Simulations



Novel full physical meso-scale numerical model

Mohamad Bayat

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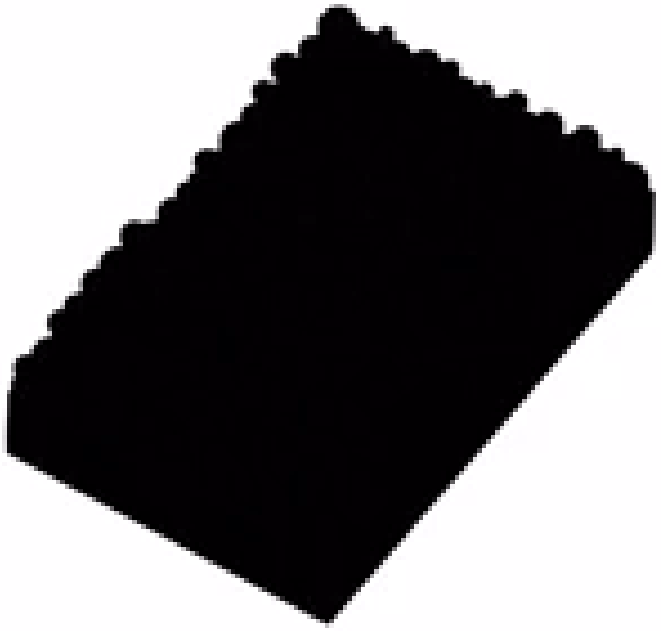
Novel full physical meso-scale numerical model



Novel full physical meso-scale model:

- Analyze thermal fields, cooling rates, formation of voids, surface porosities, **surface roughness**…
- Taking into account melting/solidification, evaporation, keyhole formation, radiation, ray-particle interactions, **particle distribution, powder deposition**….
- **BUT:** e.g. Maraging 300 no surface tension and viscosity parameters

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The role of powder properties on PAM²

Characterization

PAM²

Characterization of AM Metal Powder with an Industrial Microfocus CT

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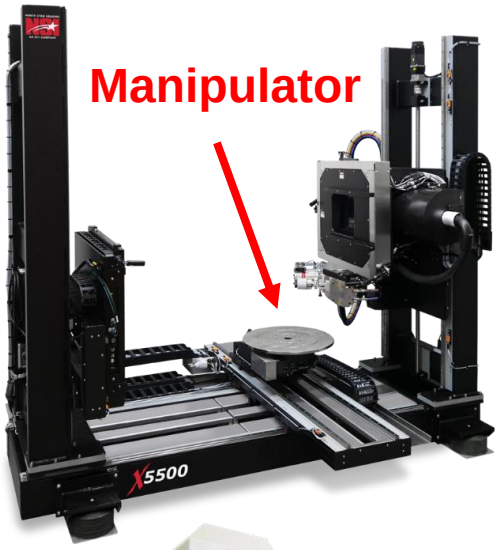
Medical vs. industrial CT scanners



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Influence factors

Software / data processing
- 3D reconstruction
- Threshold determination and surface generation
- Data reduction
- Data corrections (scale errors)

Hardware
- X-ray source (spectrum, focus properties, stability)
- Detector (stability/thermal drift, dynamics, scattering, contrast sensitivity, pixel variance, noise, lateral resolution)
- Mechanical axis (geometrical errors, mechanical stability

MEASUREMENT UNCERTAINTY

Measurement object
- Surface roughness
- Penetration depth (attenuation), dimension and geometry
- Beam hardening
- Scattered radiation
- Material composition

Environment
- Temperature
- Vibrations
- Humidity

Operator settings
- X-ray source current
- Acceleration voltage
- Magnification
- Object orientation
- Number of views
- Spatial resolution (relative distance between source, object and detector)
- Detector exposure time

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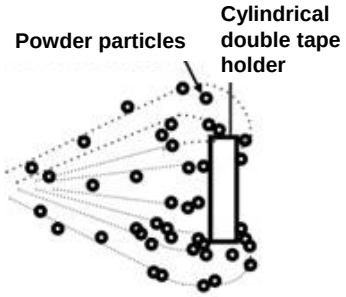
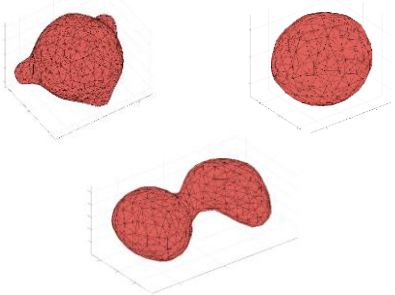
Characterization of metal AM powders with µ-CT



VOLUME GRAPHICS
SOLUTIONS ABOUT VOXELS



Specimens preparation	µ-CT scan	Surface determination	MATLAB analysis
• Minimum specimen size to reach high mag. • Dispersion via dry spraying to avoid particles in contact • Powders from Al to W analyzed (various ρ)	• High mag. (69) • Low power (< 7 W) • Voxel rescaling via calibration artifact	• Global ISO 50% thres. • Our developed local thres. for comparison	• In-house developed code • Multiple outputs for particle size distribution • Multiple outputs for particle shape analysis

- Pushing to the limits our µ-CT Nikon XT H 225 ST by measuring metal powders from 10 µm of Ø
- The metrological traceability is maintained by referencing our measurements to Laser Diffraction analyses (both dry and wet) compliant with ISO 13320-1

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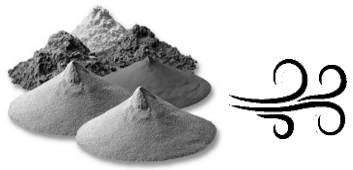
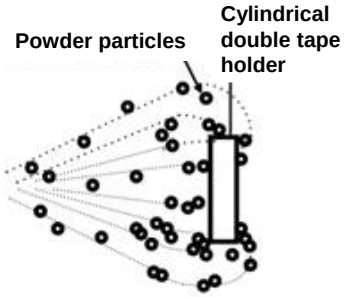
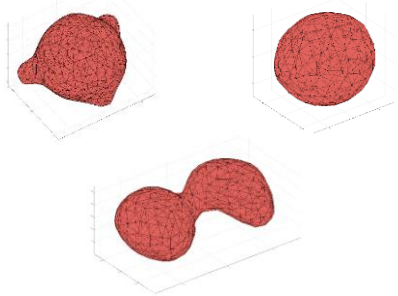
Characterization of metal AM powders with µ-CT







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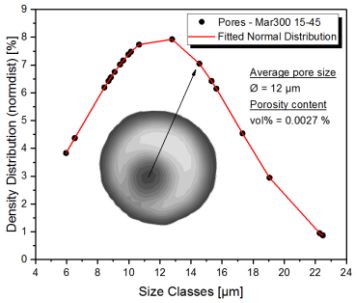
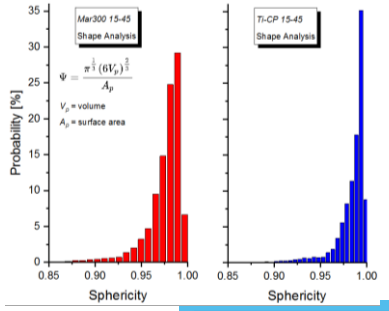
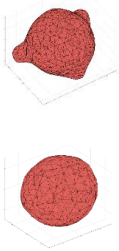
➢ Powder distribution, powder shape, powder porosity, and powder contamination can be analyzed

POROSITY



SHAPE





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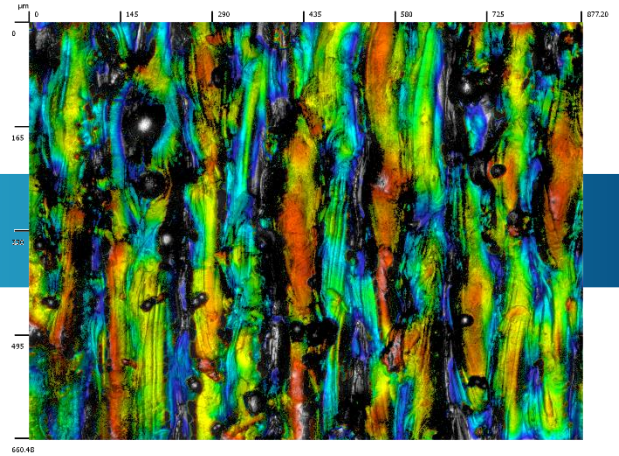
The role of powder properties on PAM²

Processability



Influence of the Particle Size Distribution on surface quality

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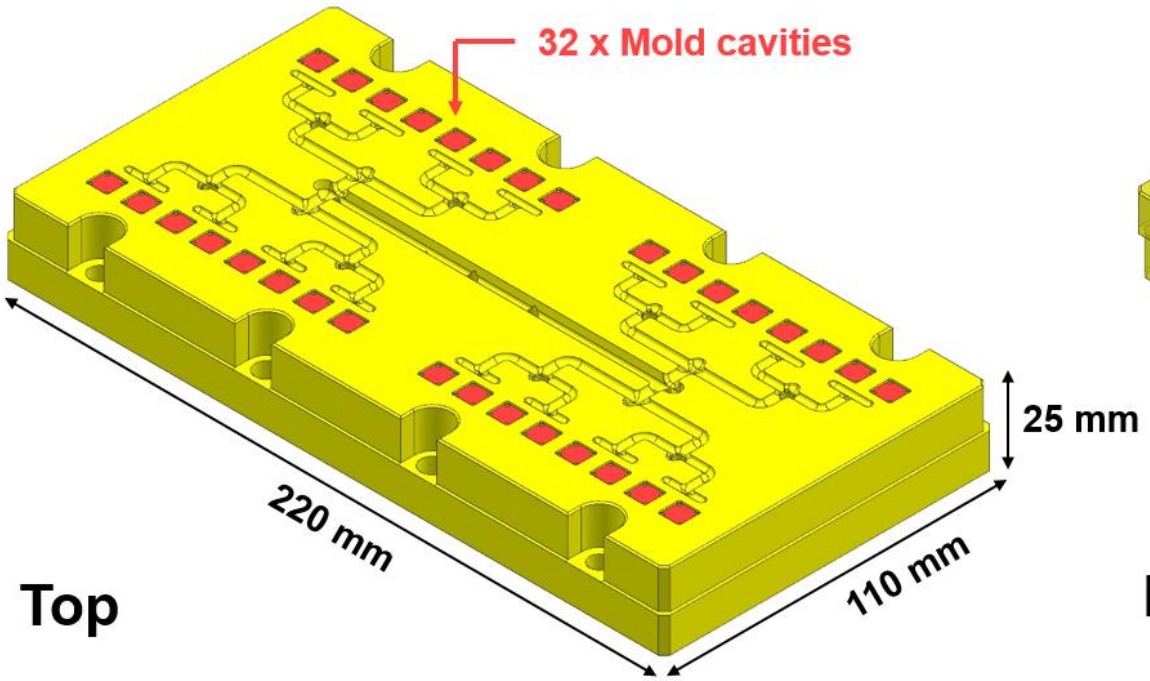
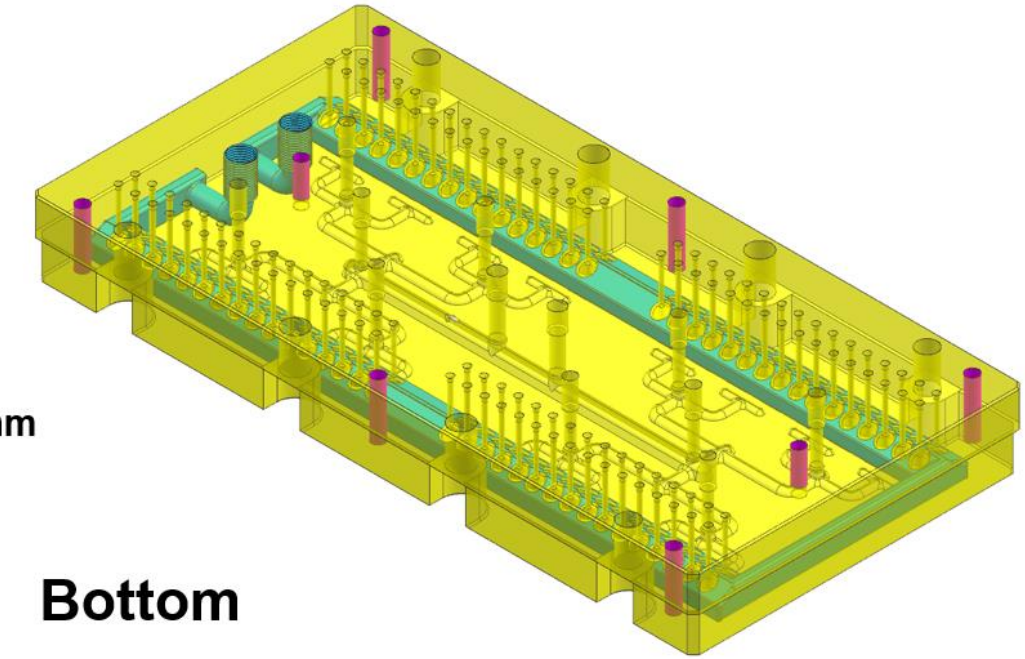
Starting backwards: an industrial user-case





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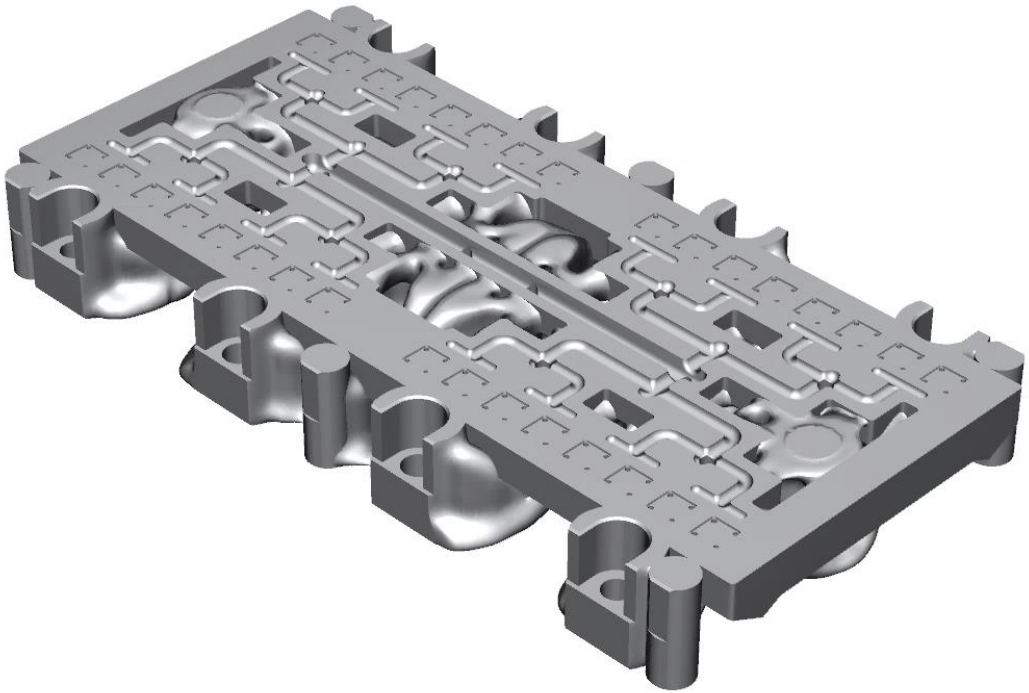

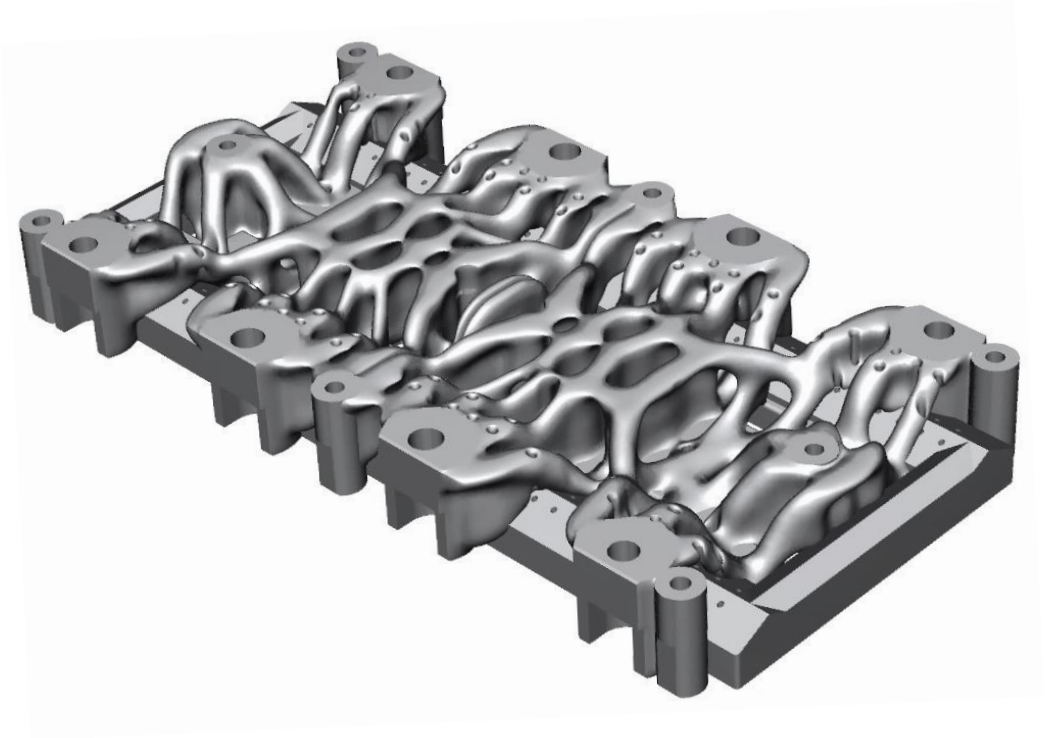

M. Sinico, R. Ranjan, M. Moshiri, C. Ayas, M. Langelaar, A. Witvrouw, F. van Keulen, and W. Dewulf,
A mold insert case study on Topology Optimized design for Additive Manufacturing,
Proceedings of the 2019 Annual International Solid Freeform Fabrication Symposium, 2019.

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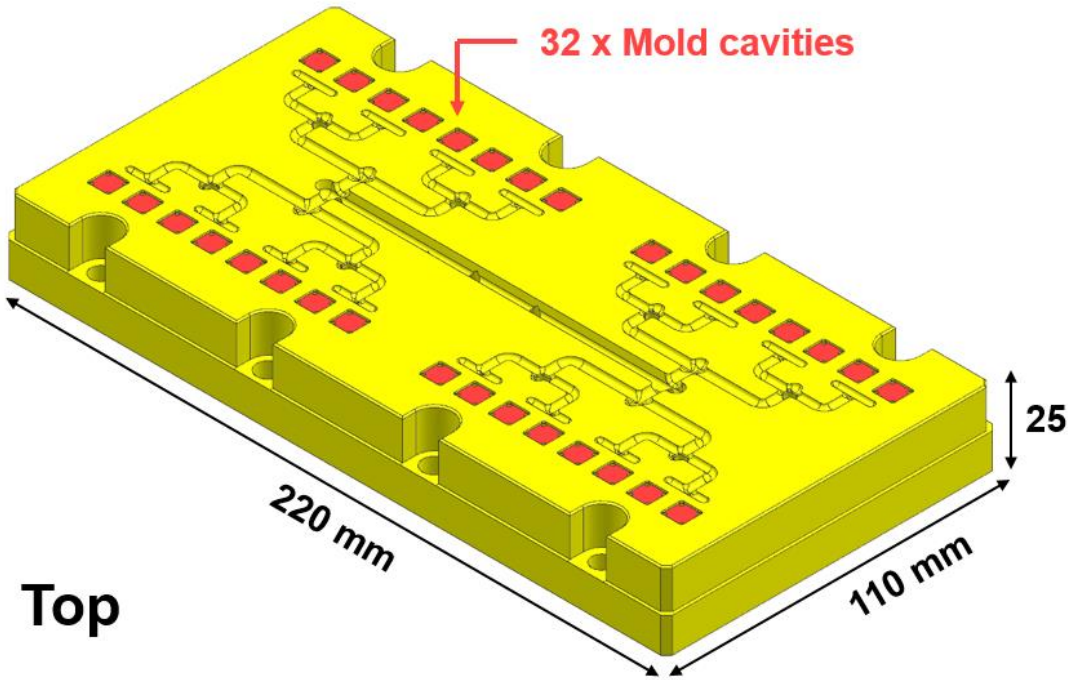
Industrial user-case requirements



Mold top surface by SPI standard
SPI, Society of Plastic Industry

- From **A-3**, **normal glossy finish**, **0.10 µm R_a** down to 0.05 µm R_a
- To **A-1**, **super high glossy finish**, 0.025 µm R_a down to 0.012 µm R_a

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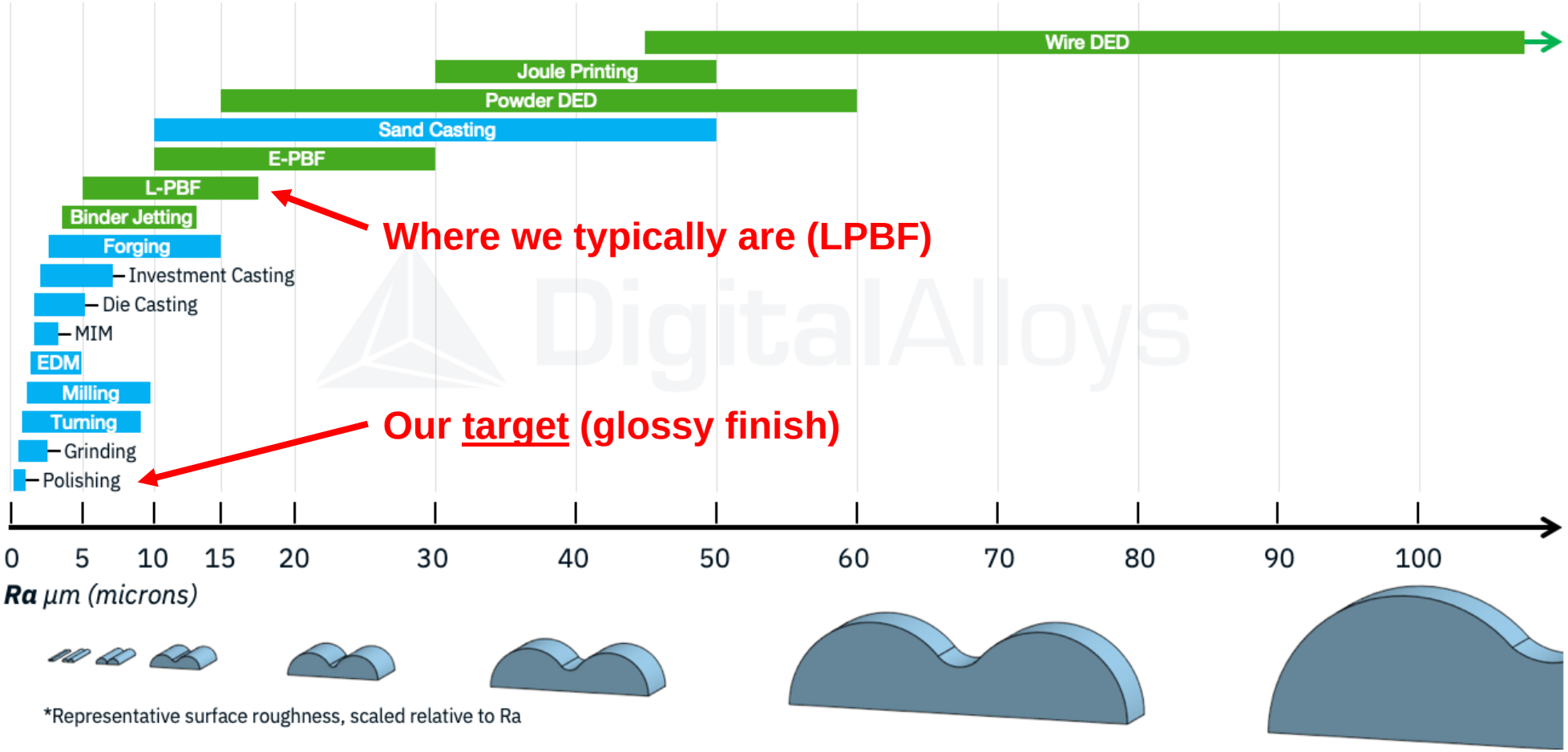
Typical surface roughness of metal AM



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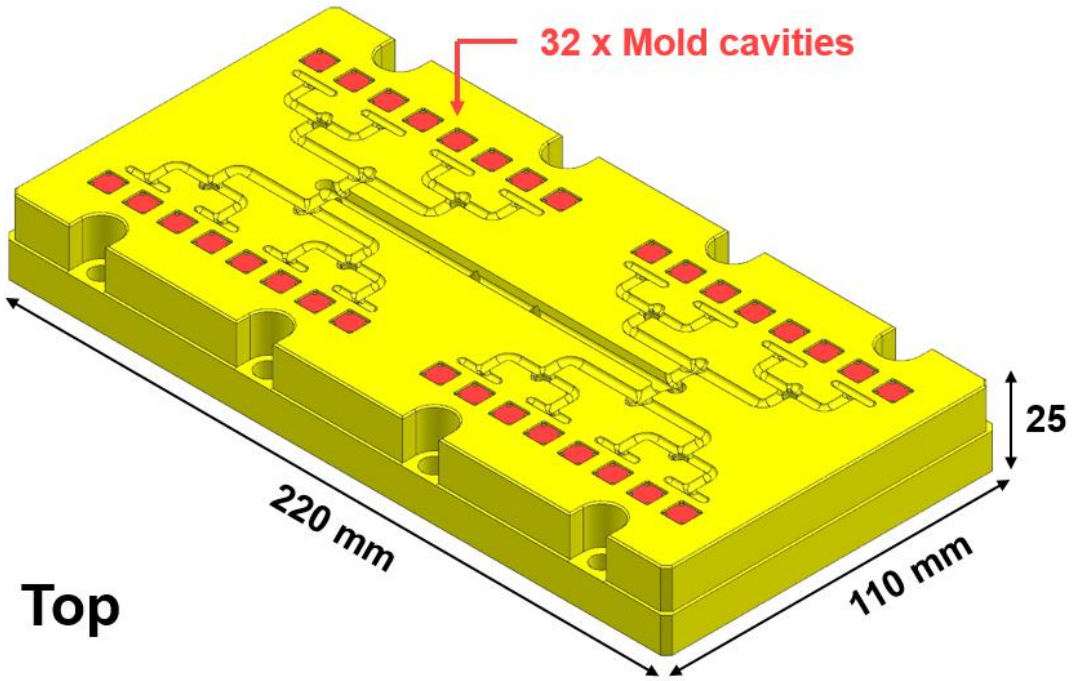
Industrial user-case requirements



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- From **A-3**, **normal glossy finish**, 0.10 µm R_a down to 0.05 µm R_a
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- **Several post-processing operations:** rough-milling, grinding, semi-finishing plus finishing and a final EDM/polishing

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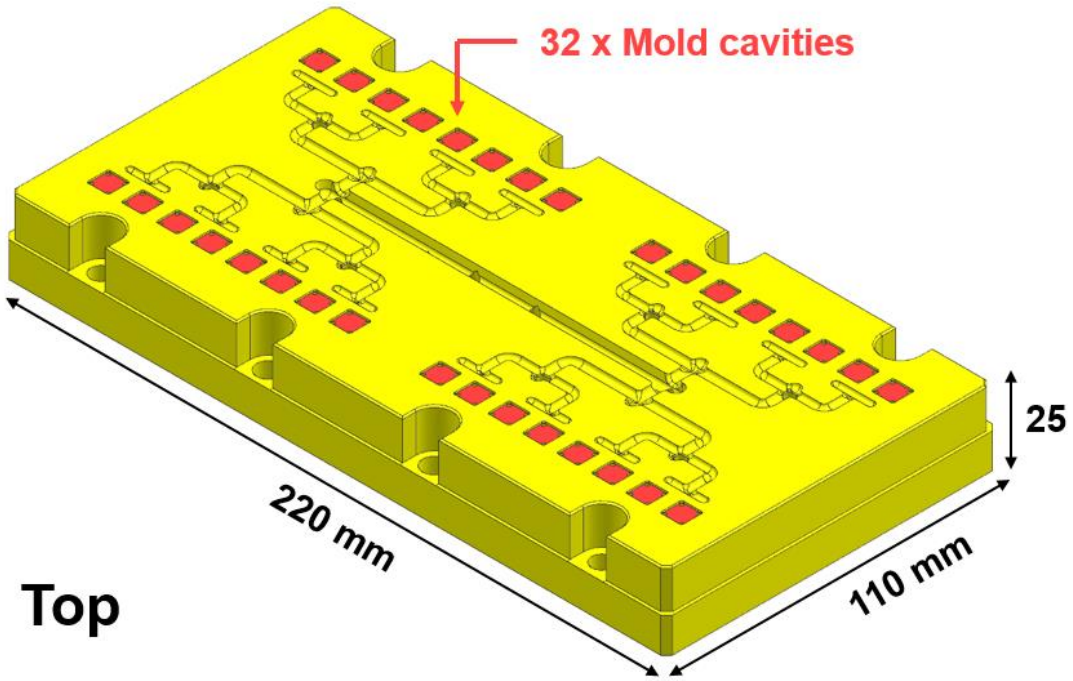
Industrial user-case requirements



Mold top surface by SPI standard
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- **Several post-processing operations:** rough-milling, grinding, semi-finishing plus finishing and a final EDM/polishing

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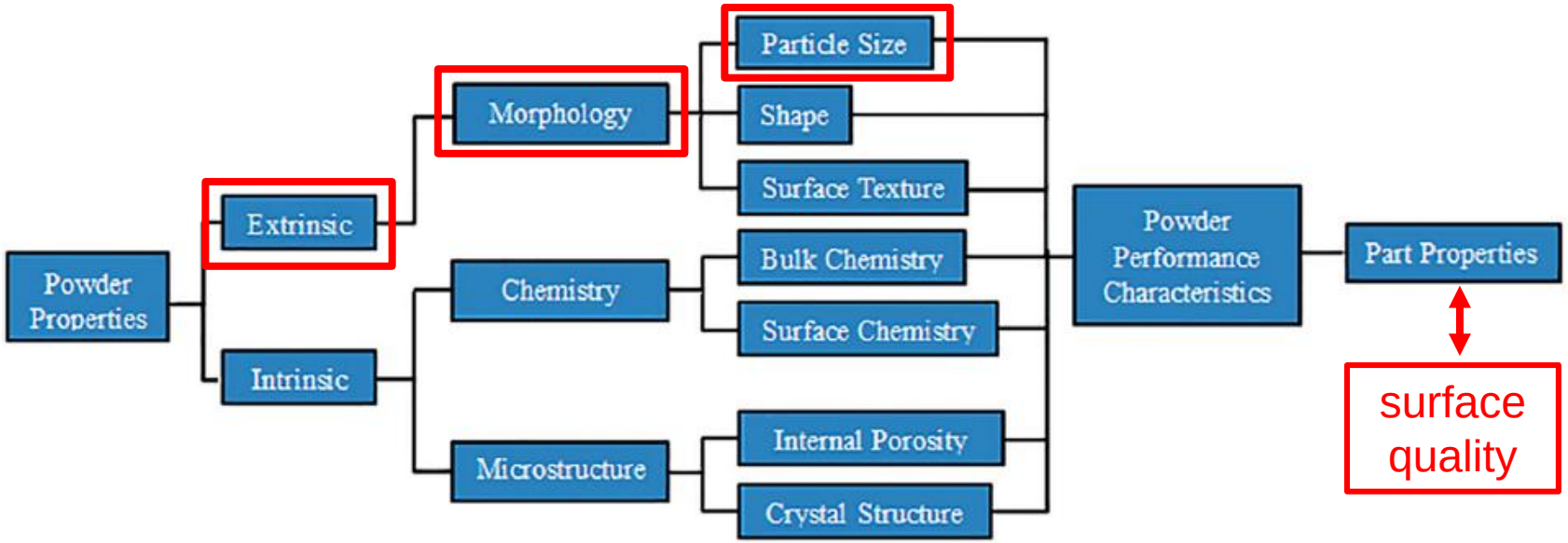
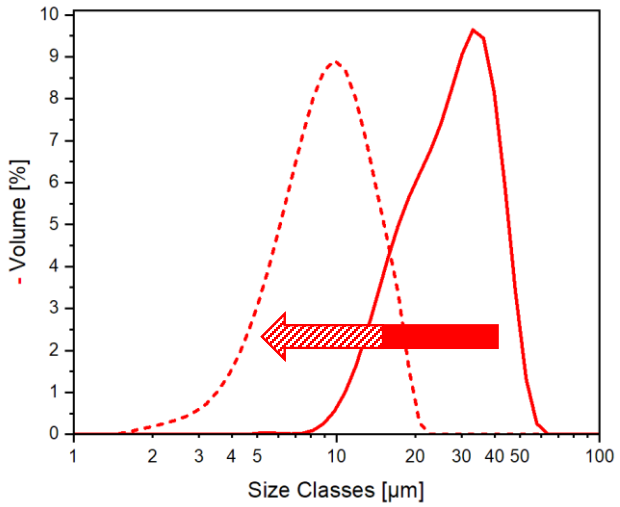
Powder properties influence LPBF part properties





If we ↓ decrease average particle size:

- ↑ Increase in purchase cost of the powder (typically)
- ↓ Decrease in flowability
- ↑ Increase in parts surface quality (lower R_a)

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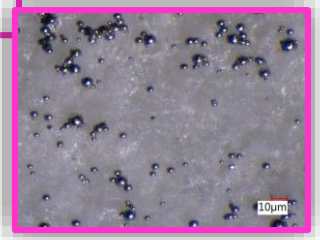
Research methodology

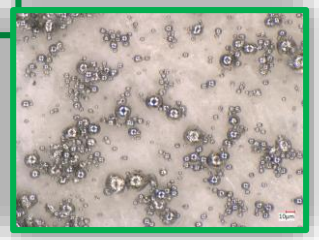
- **GOAL:**

  Test **3 different distributions** of **Maraging steel 300**

Mar 5-15

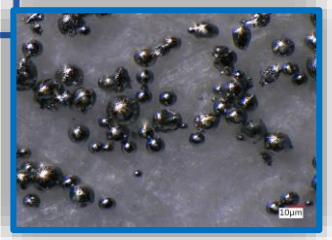


Mar 10-30



Mar 15-45

Standard



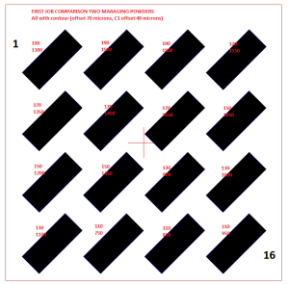
- **HOW:**

  Full **powder characterization** & **repeated build job DoE** on a ProX 320A machine

DoE at 3 different E_v

$$E_v = \frac{P}{v \times h \times t}$$

- ~ 50 J/mm^3
- ~ 60 J/mm^3
- ~ 70 J/mm^3



Array of specimens
~ 20x10x10 mm

t = 30 µm, h = 70 µm

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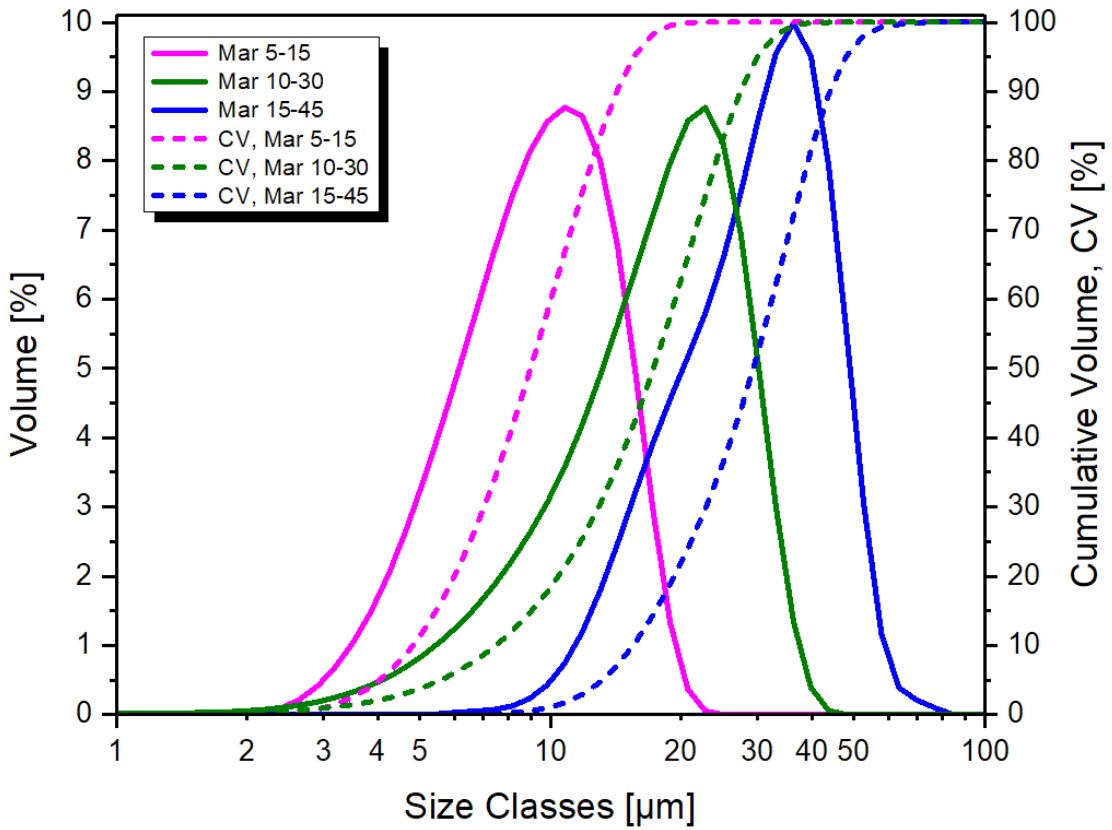
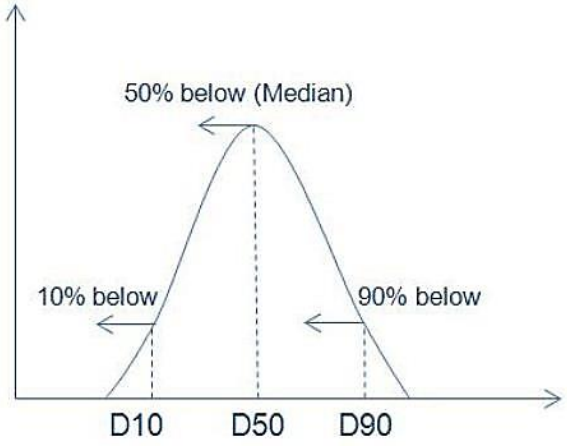
Powder characterization

Laser Diffraction



	D10 [µm]	D50 [µm]	D90 [µm]
Mar 15-45	15.50 ± 0.78	29.29 ± 0.88	44.04 ± 2.20
Mar 10-30	7.48 ± 0.37	17.26 ± 0.52	27.34 ± 1.37
Mar 5-15	4.82 ± 0.24	8.99 ± 0.27	14.20 ± 0.71



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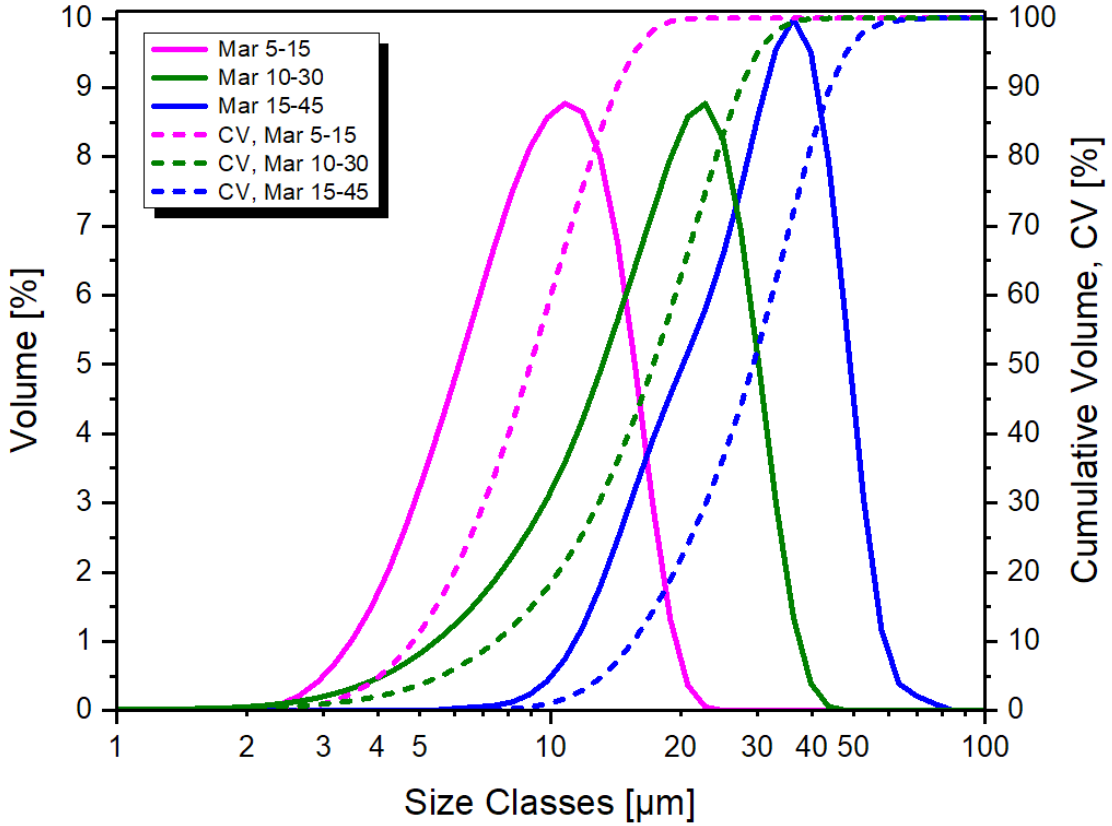
Powder characterization

Laser Diffraction



+ Optical microscope

$$C = \frac{4\pi A}{P^2}$$

	D10 [µm]	D50 [µm]	D90 [µm]	Circularity, mean [-]
Mar 15-45	15.50 ± 0.78	29.29 ± 0.88	44.04 ± 2.20	0.800 ± 0.100
Mar 10-30	7.48 ± 0.37	17.26 ± 0.52	27.34 ± 1.37	0.861 ± 0.098
Mar 5-15	4.82 ± 0.24	8.99 ± 0.27	14.20 ± 0.71	0.849 ± 0.087

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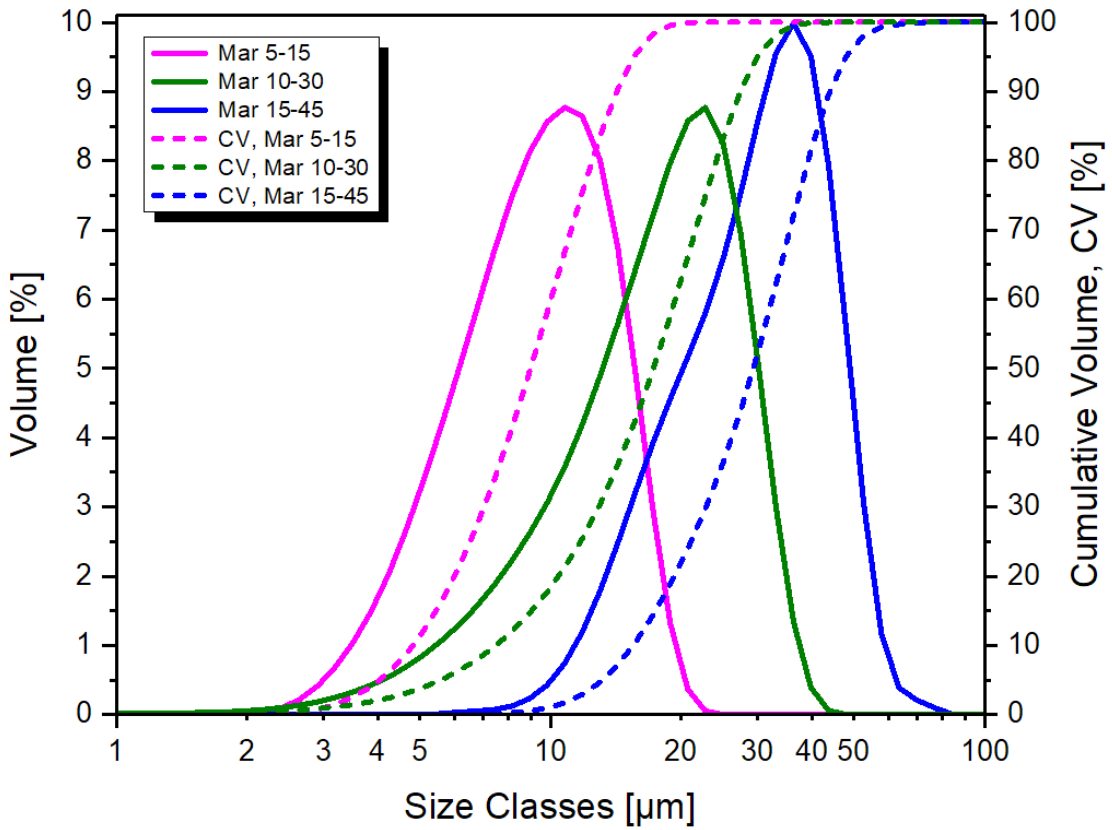
Powder characterization

Laser Diffraction + Optical microscope + Industrial µ-CT



$$S = \frac{\pi^{\frac{1}{3}}(6V)^{\frac{2}{3}}}{A}$$

	D10 [µm]	D50 [µm]	D90 [µm]	Circularity, mean [-]	Sphericity, mean [-]
Mar 15-45	**15.50** ± 0.78	29.29 ± 0.88	**44.04** ± 2.20	0.800 ± 0.100	0.958 ± 0.025
Mar 10-30	**7.48** ± 0.37	17.26 ± 0.52	**27.34** ± 1.37	0.861 ± 0.098	0.962 ± 0.025
Mar 5-15	**4.82** ± 0.24	8.99 ± 0.27	**14.20** ± 0.71	0.849 ± 0.087	0.951 ± 0.027

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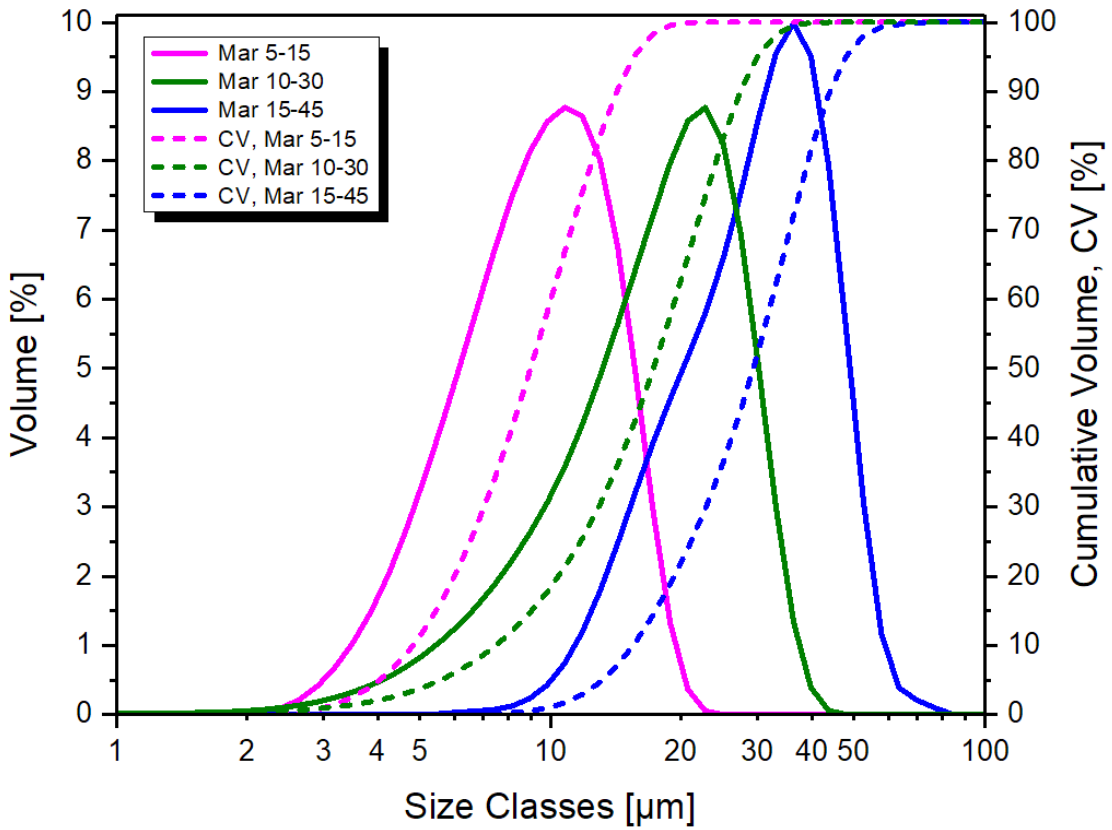
Powder characterization



+ ASTM B213, B212 and B527 testing

- For flowability (Hall Flow), apparent density ρ_{app} and tap density ρ_{tap}

	Hall Flow, 50 g [s]	ρ_{app} / ρ_{true} [%]	ρ_{tap} / ρ_{true} [%]	Hausner Ratio [-]
Mar 15-45	14.64 ± 0.23	52.3 ± 0.3	60.2 ± 0.1	1.15
Mar 10-30	No flow	48.9 ± 0.2	58.8 ± 0.1	1.20
~~**Mar 5-15**~~	No flow	39.7 ± 0.3	55.1 ± 0.1	1.39 **>> 1.25**

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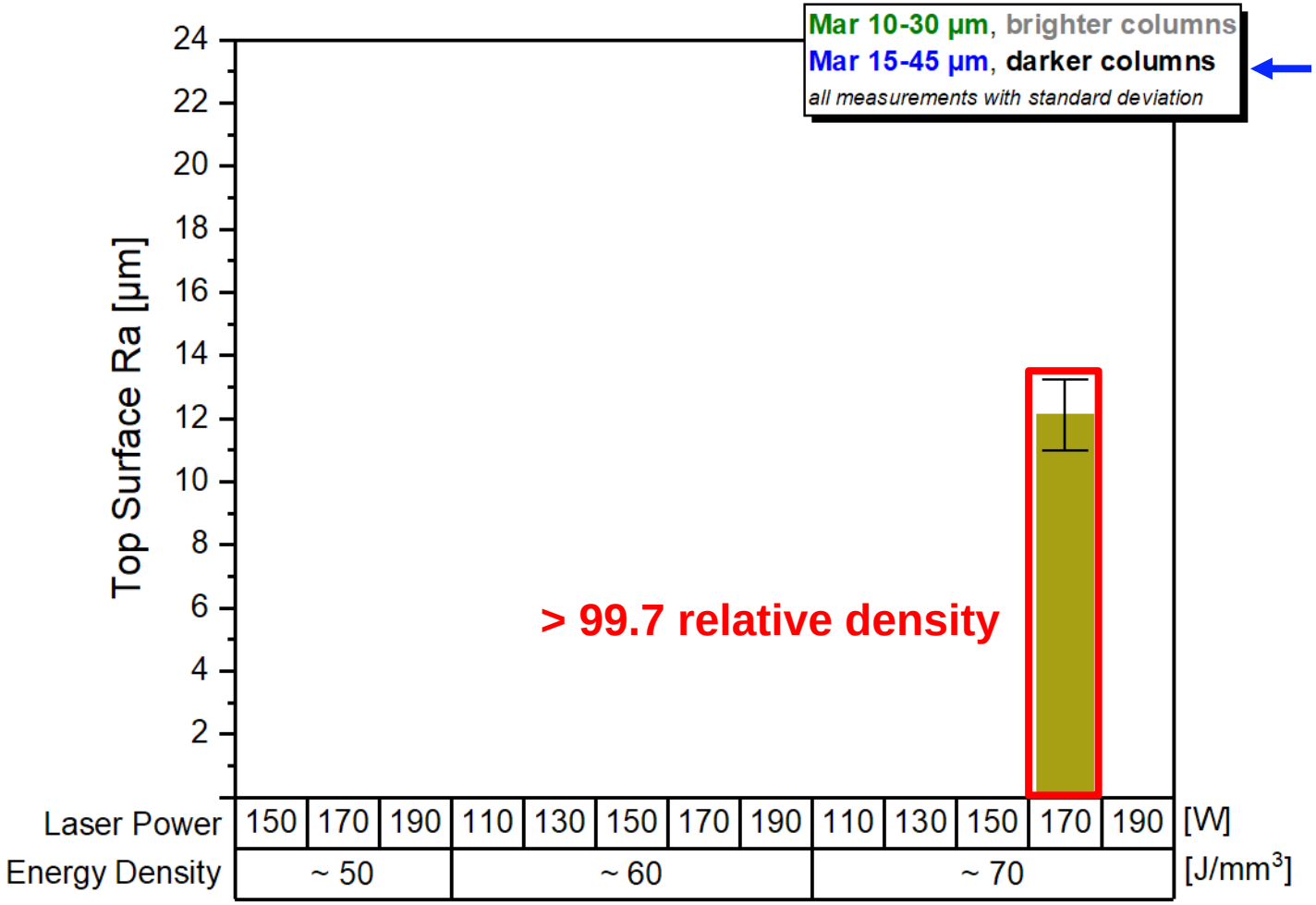
Top surface roughness



- **Mar 15-45, optimum** parameter set R_a = 12.12 µm
- **Optimum** at **170 W, ~70 J/mm³** E_v (1150 mm/s scan speed)

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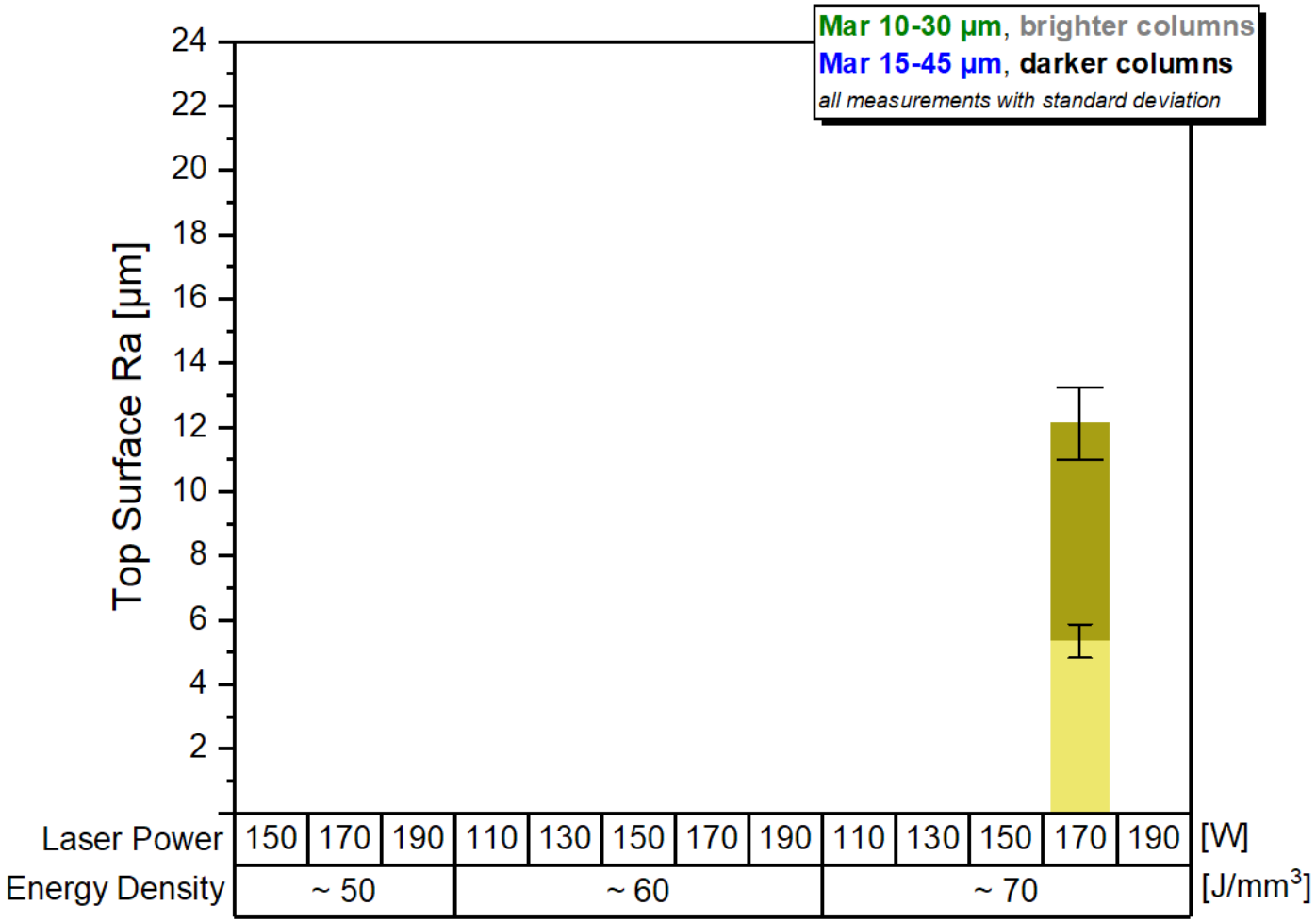
Top surface roughness



- **Mar 15-45, optimum** parameter set R_a = 12.12 µm
- **Mar 10-30, optimum** parameter set R_a = 5.34 µm, **56 % reduction**

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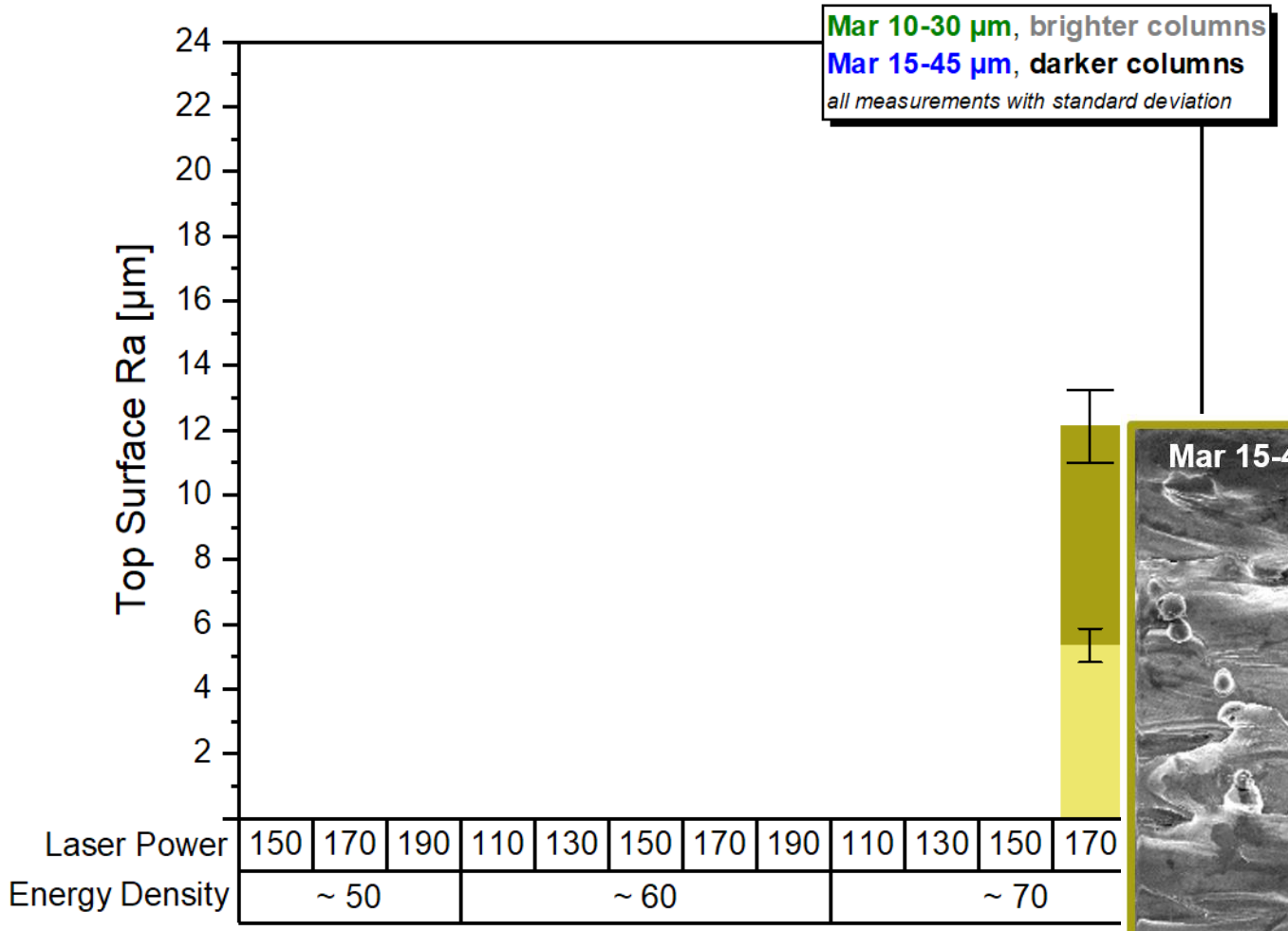
Top surface roughness



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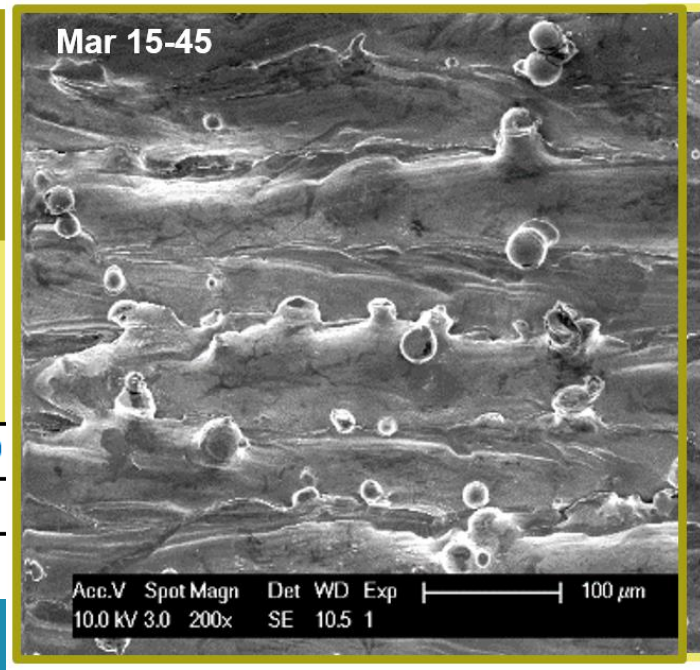
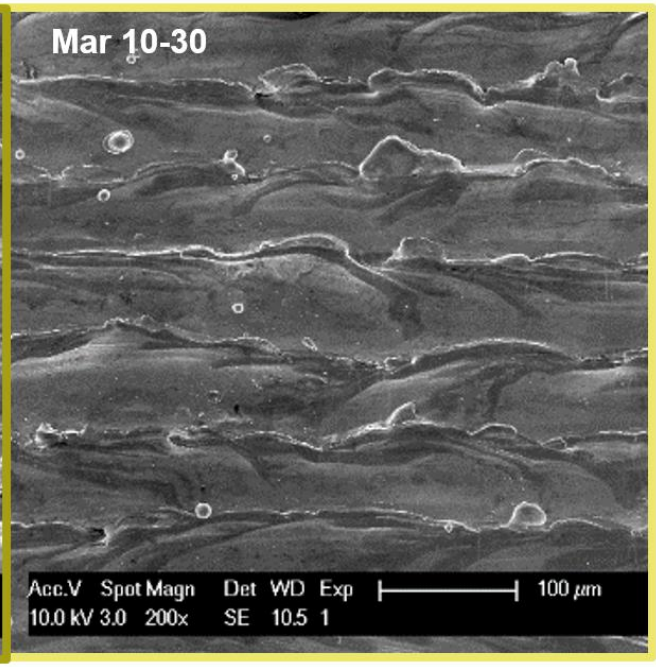
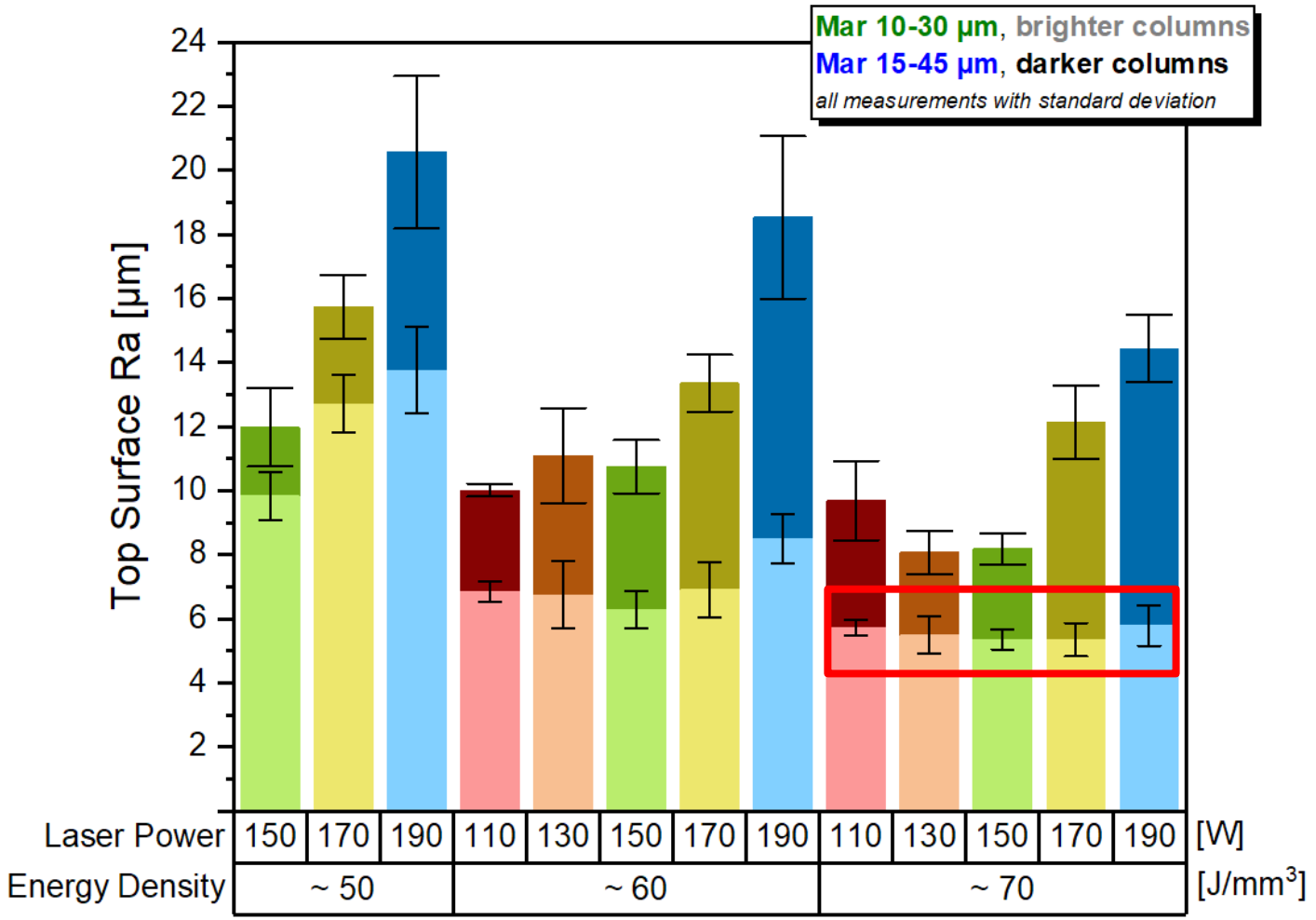




Top surface roughness



- **Surface roughness** is **inversely** proportional to E_v, **directly** proportional to the **laser power**, at the same E_v
- On average, **~40 % R_a reduction** with **Mar 10-30**
- **Stability zone** seems **wider** for the **Mar 10-30** distribution

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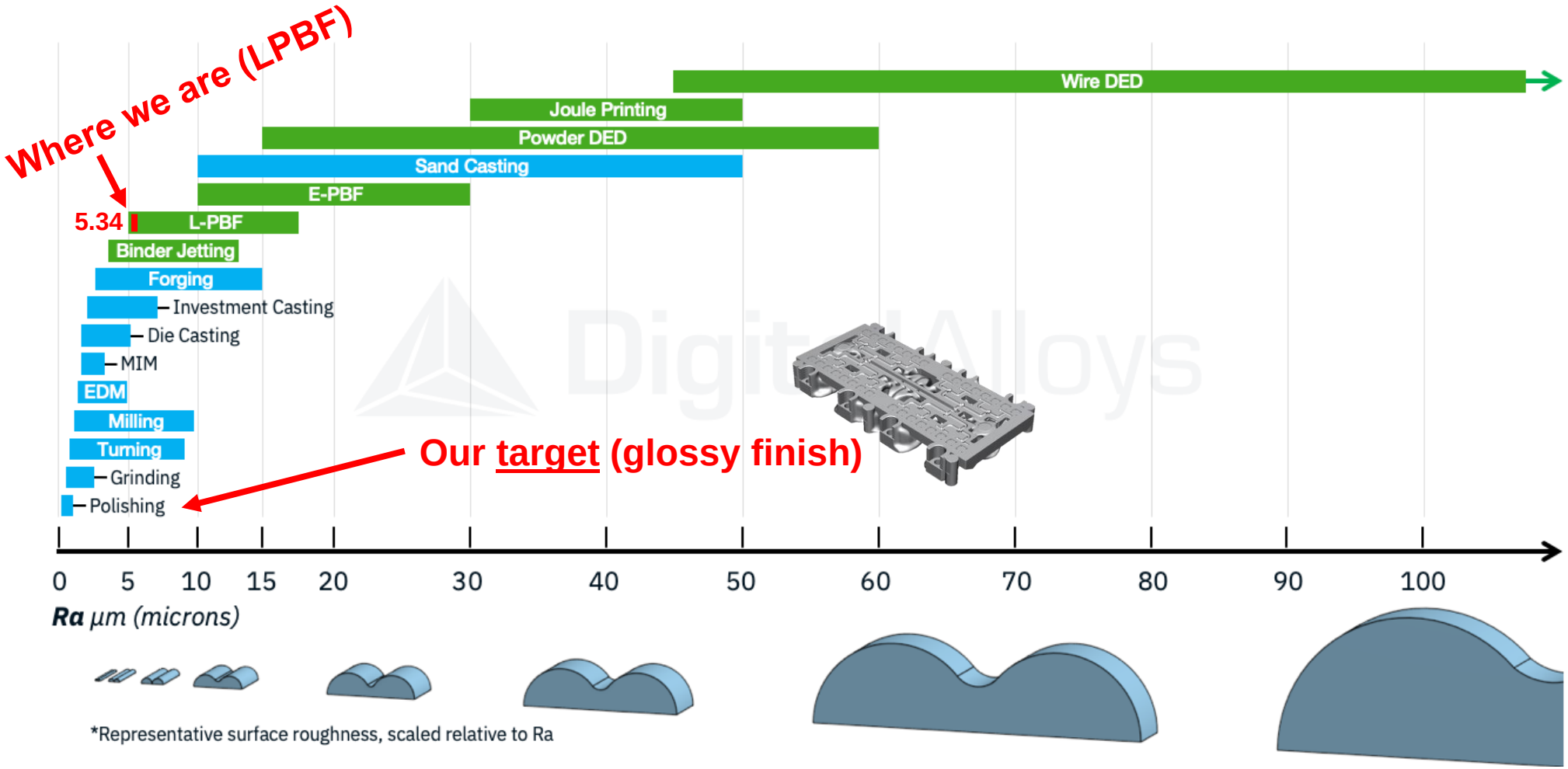
Typical surface roughness of metal AM



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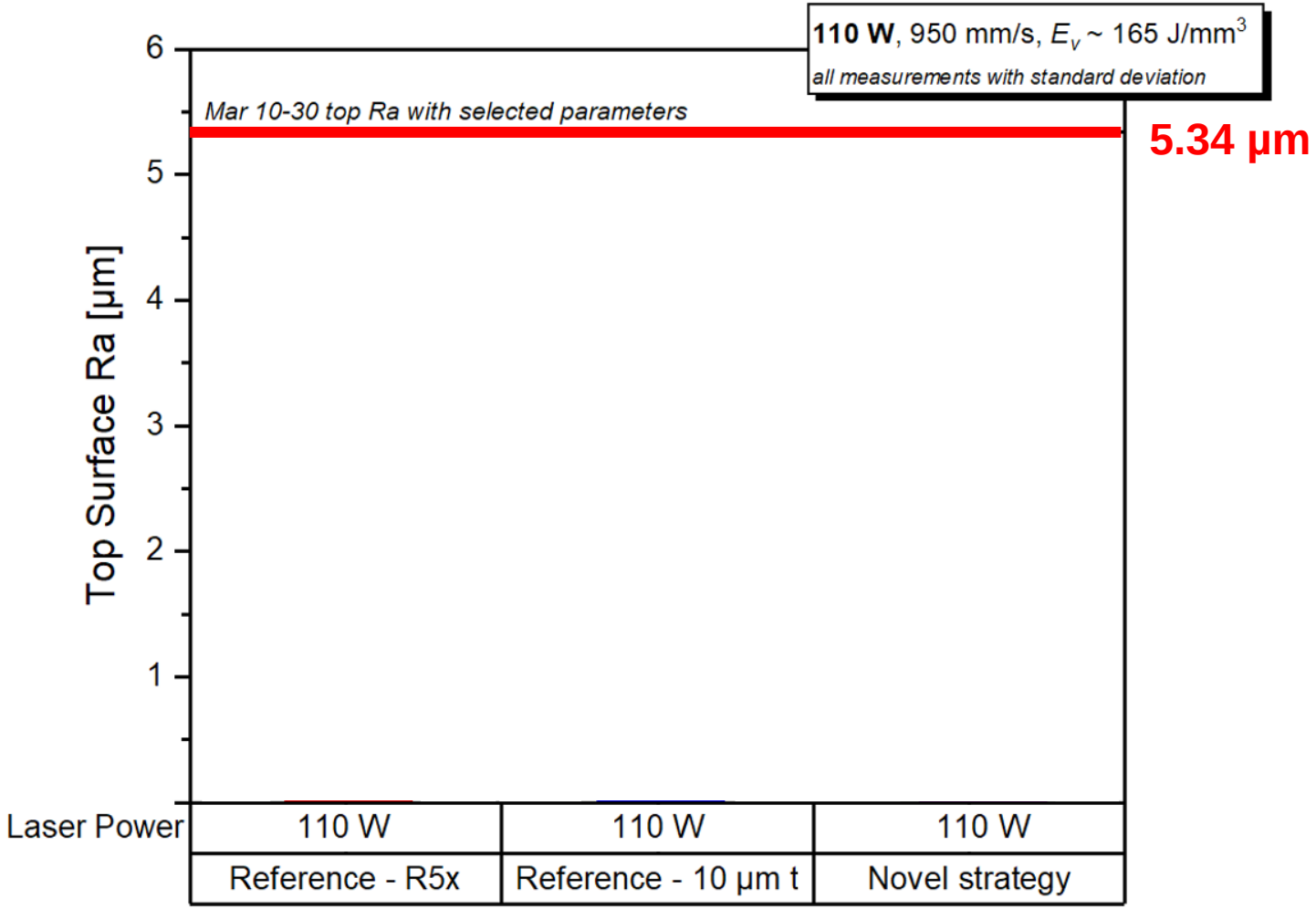
(extra) Novel remelting strategy



- Exploit **fine powder possibilities** combined **with remelting**

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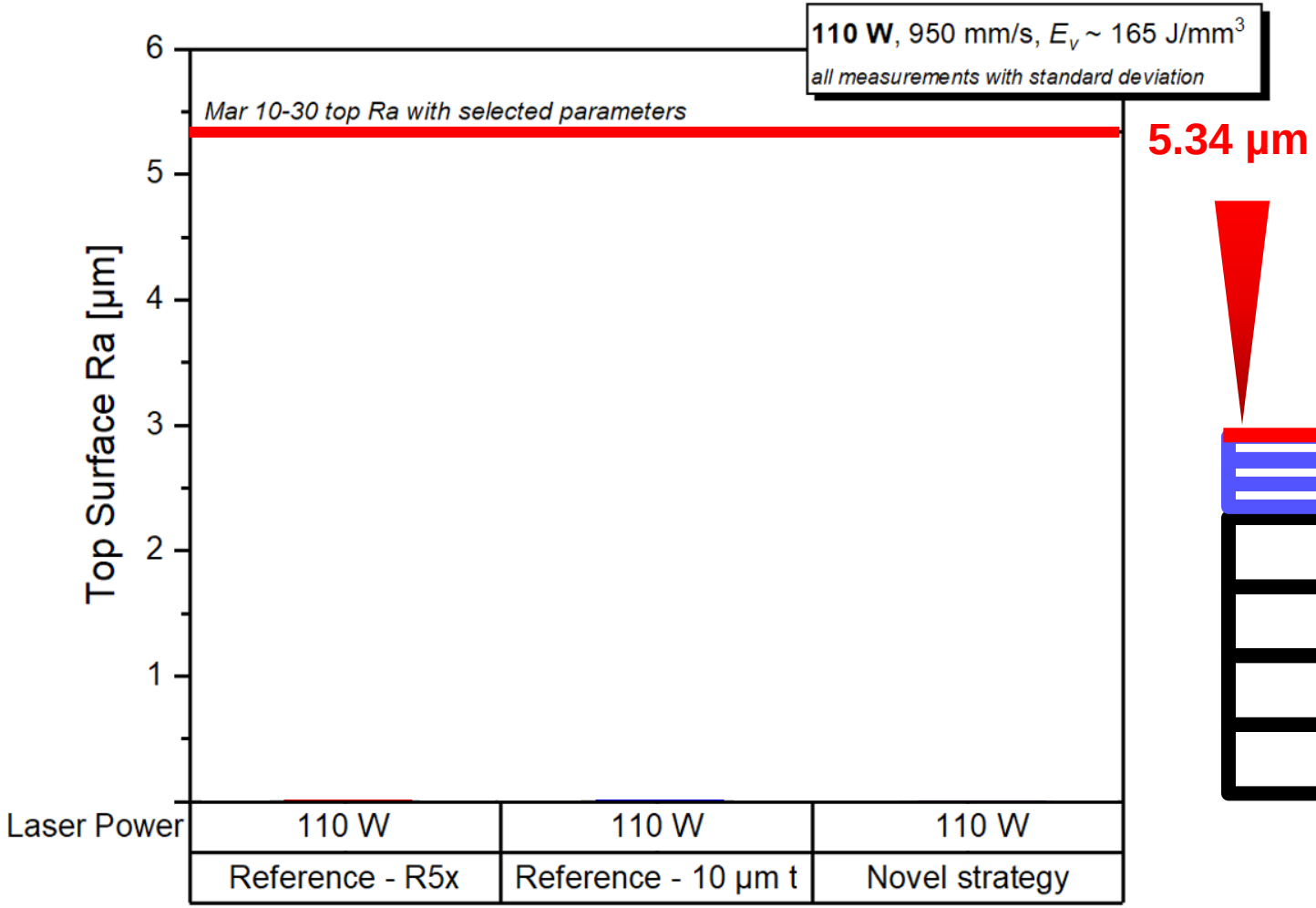
(extra) Novel remelting strategy



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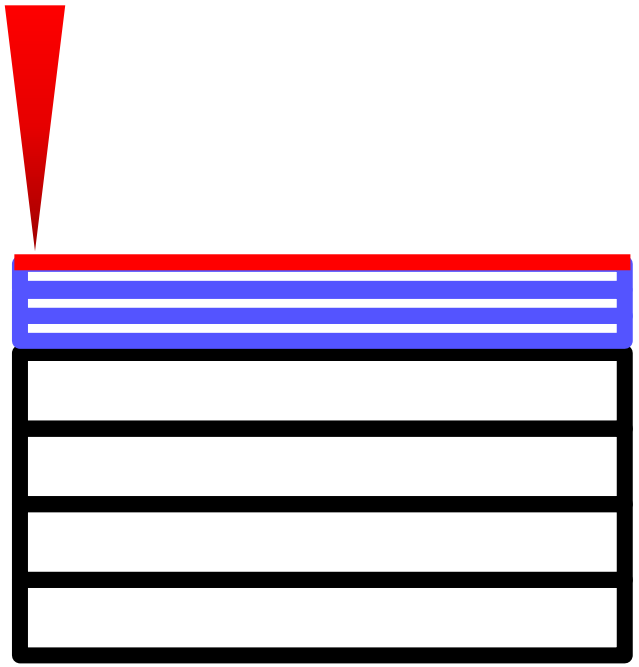

Remelting step

Top at t = 10 µm

Base at optimum parameter set, t = 30 µm

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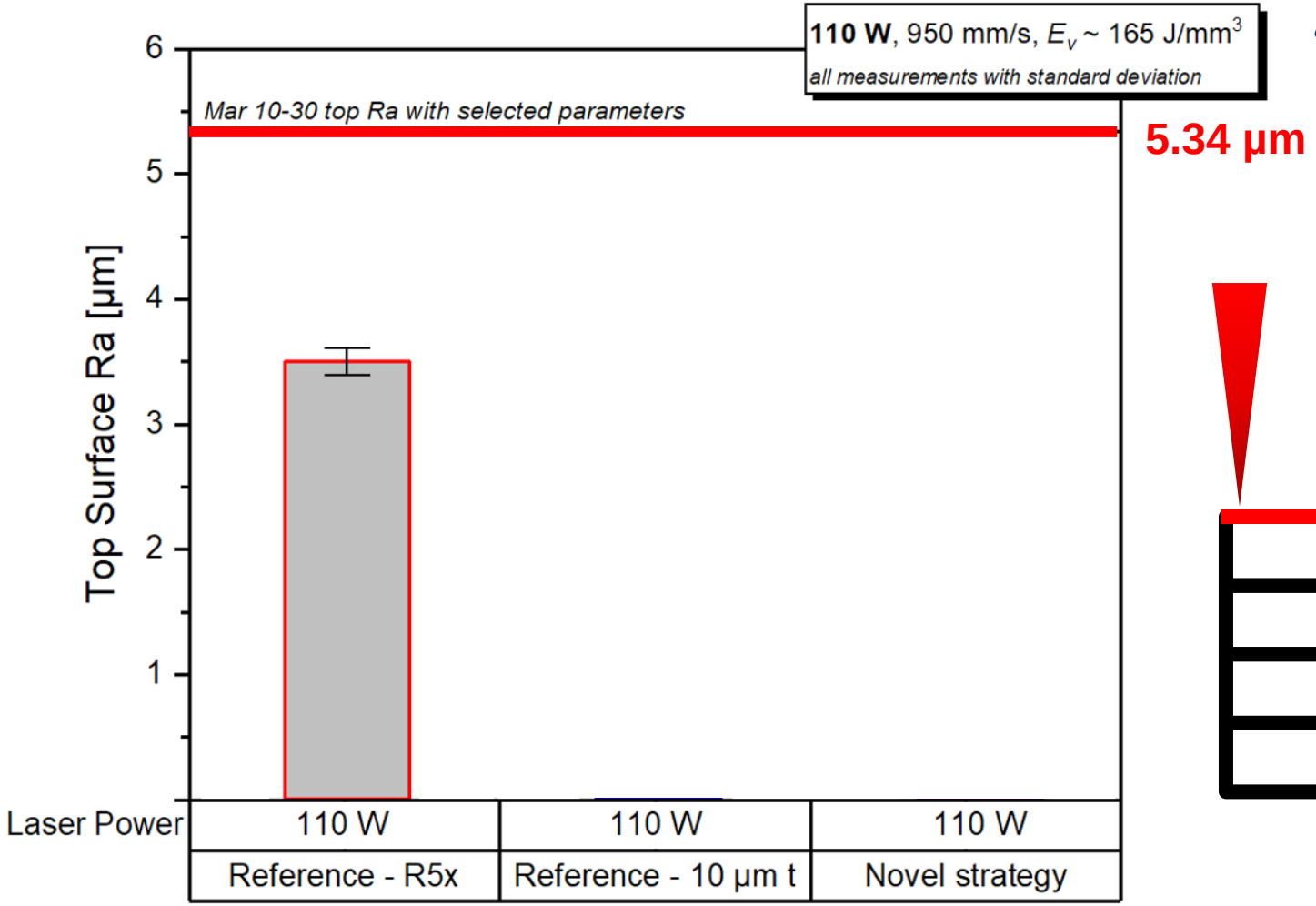
(extra) Novel remelting strategy



- Exploit **fine powder possibilities** combined **with remelting**

Remelting step

<u>Base</u> at optimum parameter set, t = 30 µm

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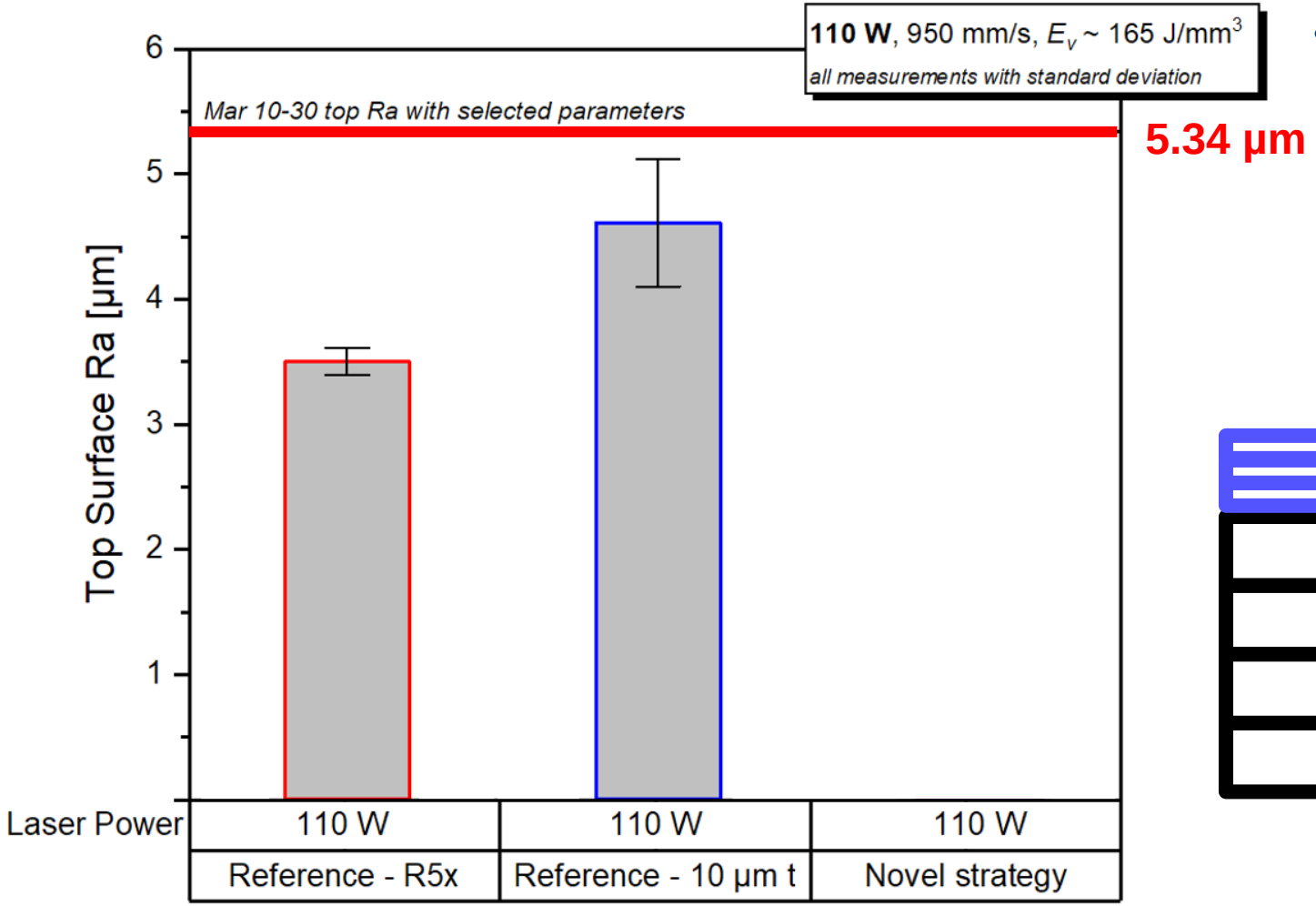
(extra) Novel remelting strategy



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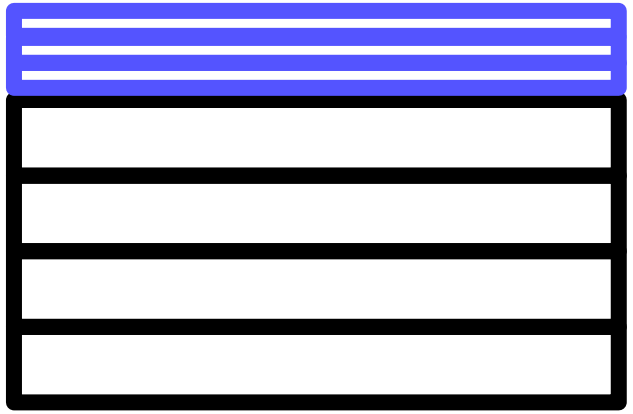

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Base at optimum parameter set, t = 30 µm

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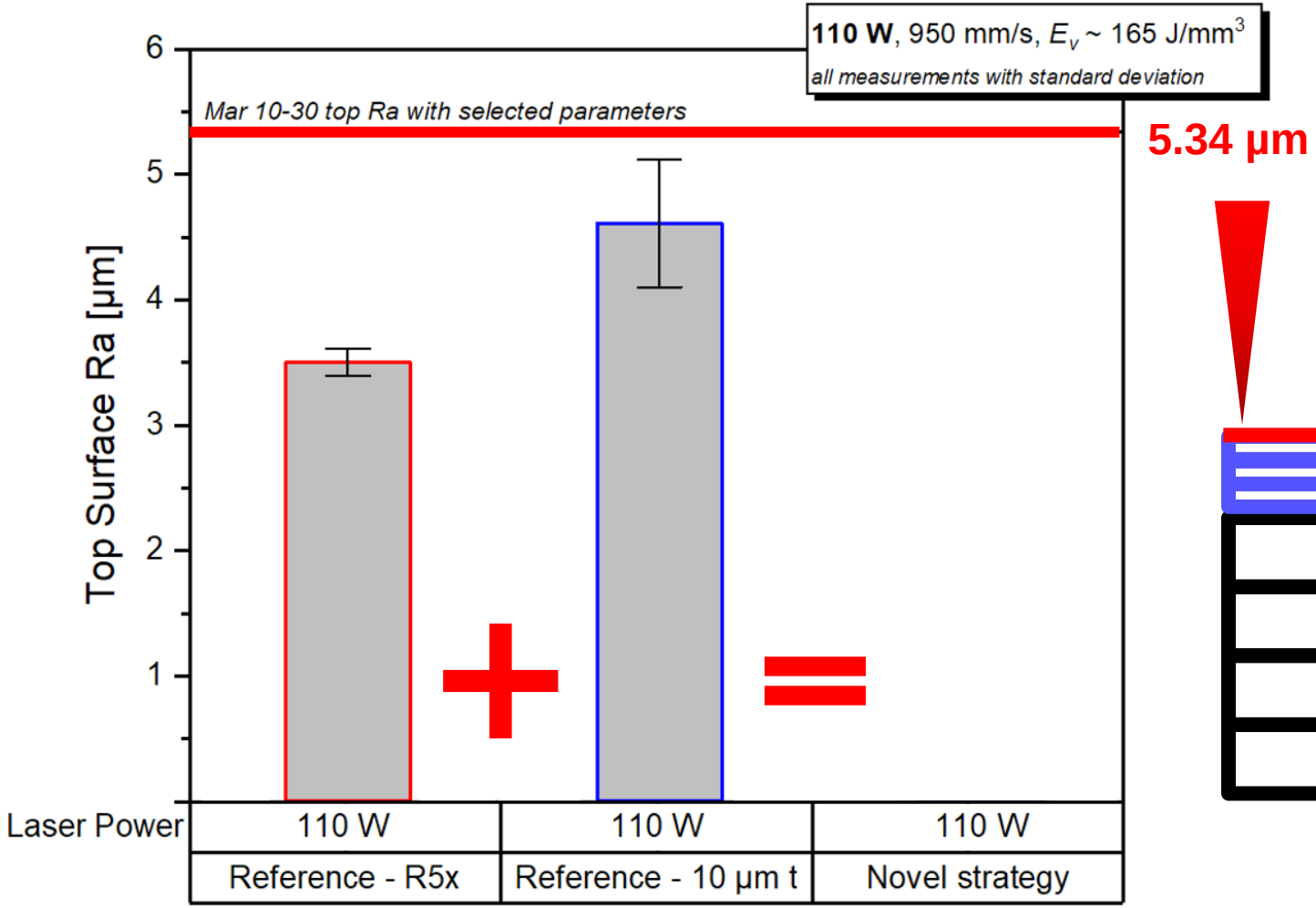
(extra) Novel remelting strategy



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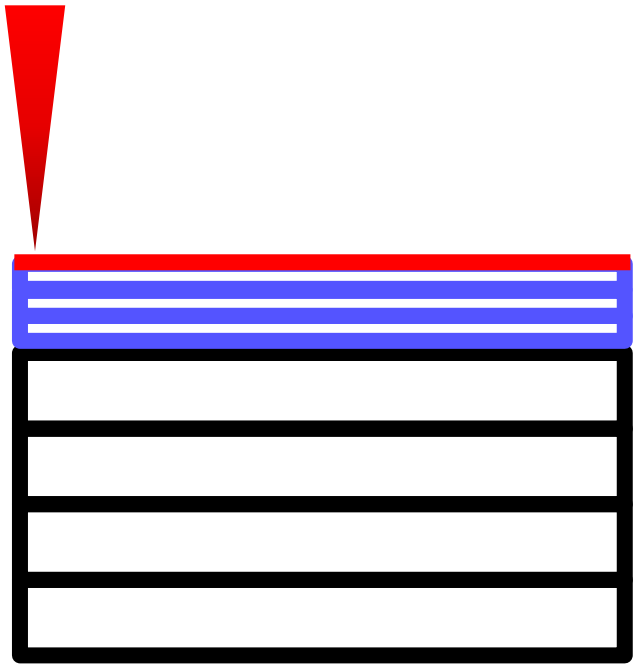

Remelting step

Top at t = 10 µm

Base at optimum parameter set, t = 30 µm

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Future steps: acquisition of surface topographies

- **Through a Sensofar S neox 3D surface profiler**

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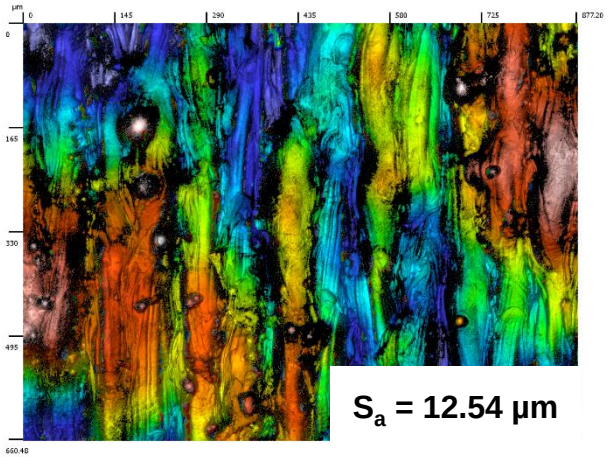
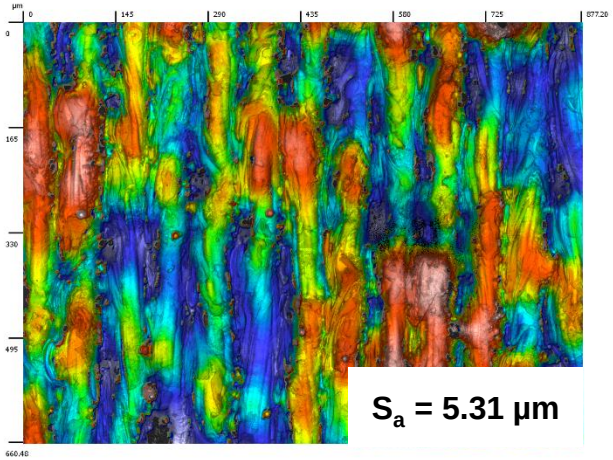
Future steps: acquisition of surface topographies

- Through a Sensofar S neox 3D surface profiler
- **Step 1: Acquisition (CLSM) and F-operator (form removal, plane)**

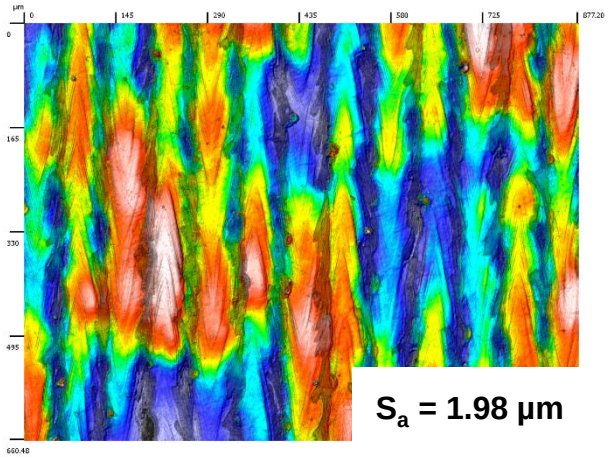
Mar 15-45 specimen



Mar 10-30 specimen



Novel RM specimen



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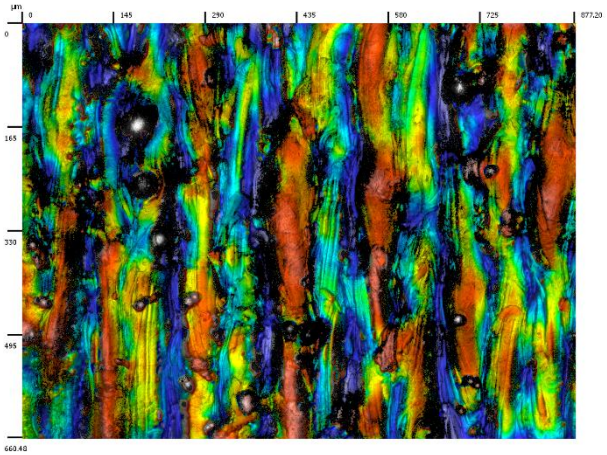
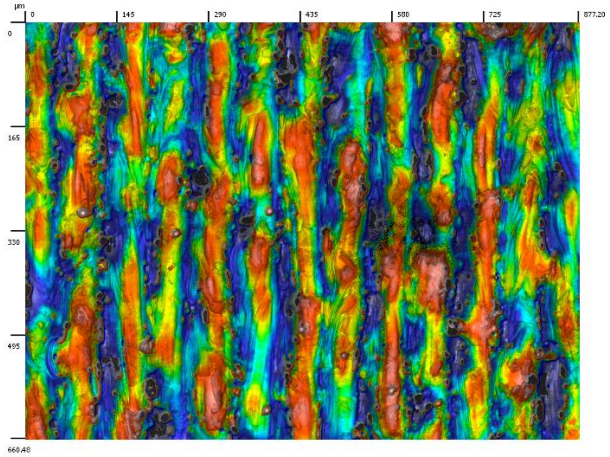
Future steps: acquisition of surface topographies

- Through a Sensofar S neox 3D surface profiler
- **Step 1:** Acquisition (CLSM) and F-operator (form removal, plane)
- **Step 2: S-filter (8 µm) and L-filter (140 µm) to highlight scanning tracks**

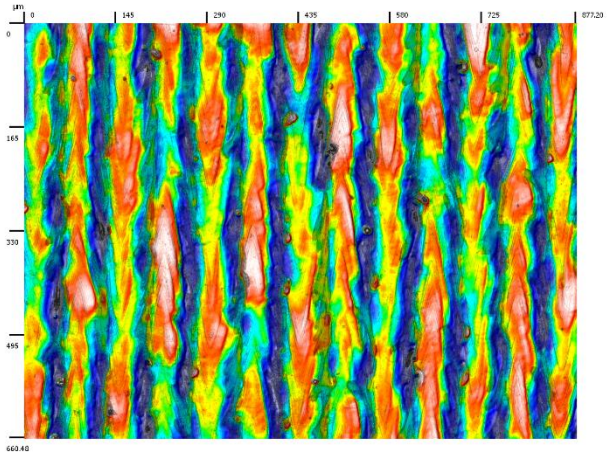
Mar 15-45 specimen



Mar 10-30 specimen



Novel RM specimen



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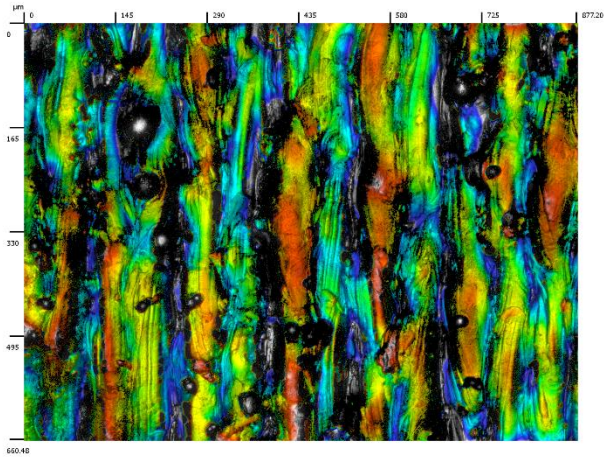
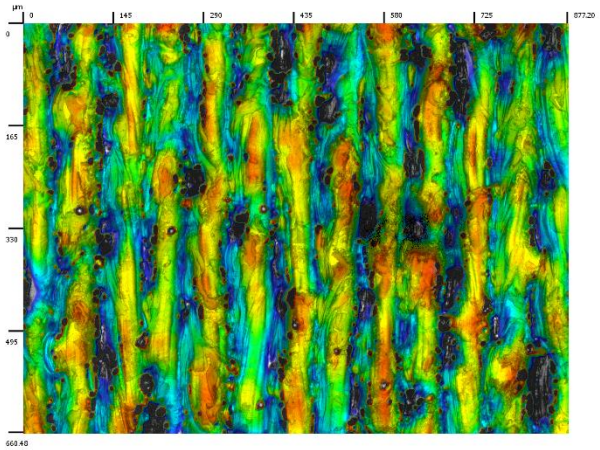
Future steps: acquisition of surface topographies

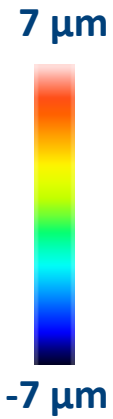
- Through a Sensofar S neox 3D surface profiler
- **Step 1:** Acquisition (CLSM) and F-operator (form removal, plane)
- **Step 2:** S-filter (8 µm) and L-filter (140 µm) to highlight scanning tracks
- **Step 3: Rescaling to the same Z range**

Mar 15-45 specimen

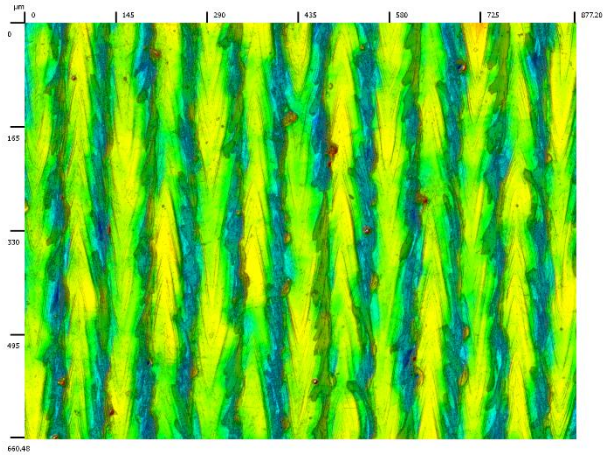


Mar 10-30 specimen





Novel RM specimen



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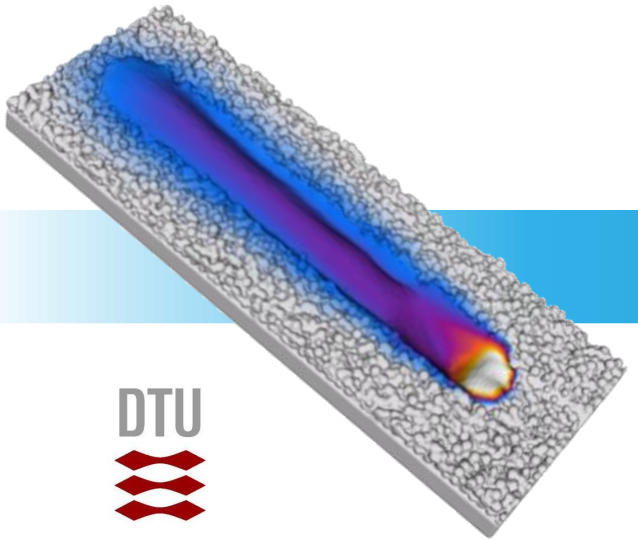
The role of powder properties on PAM²

Simulations

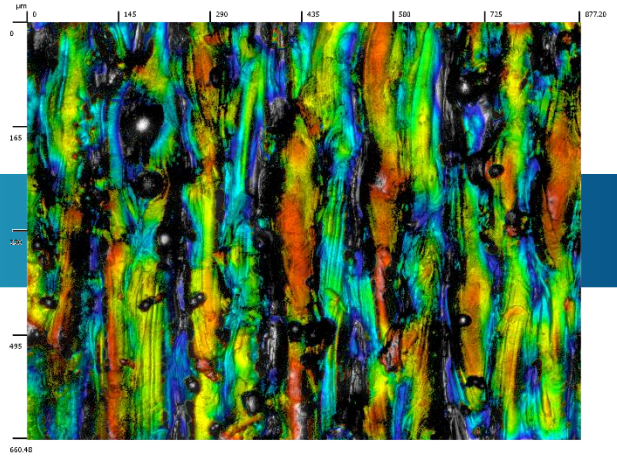


Novel full physical meso-scale numerical model

Characterization

Characterization of AM Metal Powder with an Industrial Microfocus CT

Processability



Influence of the Particle Size Distribution on surface quality

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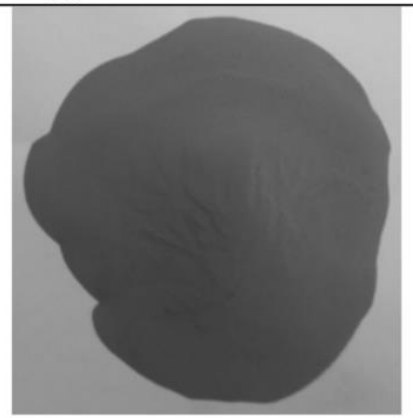
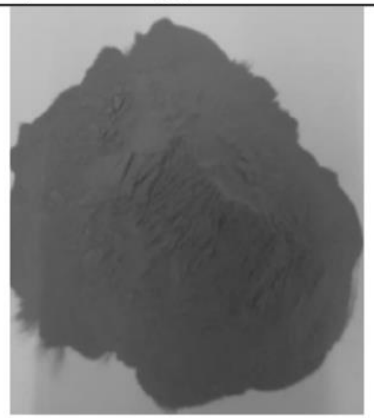
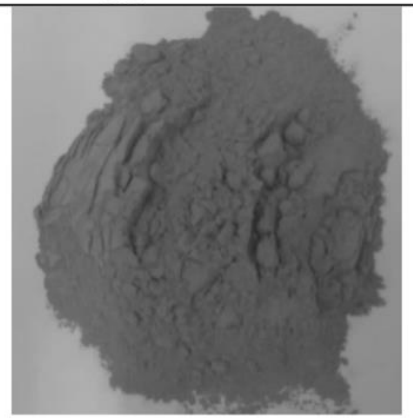
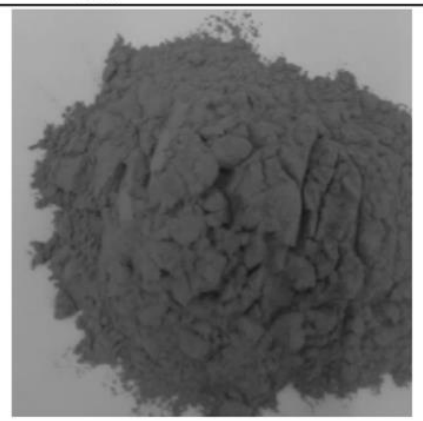
Thank you!

Mirko Sinico[1,2], Wim Dewulf[1], and Ann Witvrouw[1,2]

[1] Department of Mechanical Engineering, KU Leuven, 3001 Leuven, BE
[2] Member of Flanders Make - Core lab PMA-P, KU Leuven, 3001 Leuven, BE

Any question?

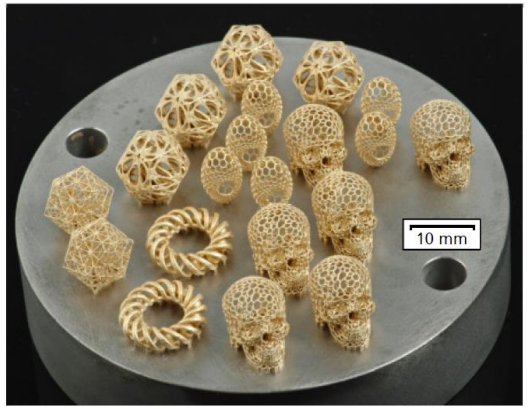
A digression in the decrease of flowability

φ = 1 – very good flowability no agglomerations	φ = 2 – sufficient flowability Very loose agglomerations	φ = 3 – critical flowability loose agglomerations	φ = 4 – unsufficient flowability severe agglomerations
			

from A. B. Spierings, M. Voegtlin, T. Bauer, and K. Wegener, 'Powder flowability characterisation methodology for powder-bed-based metal additive manufacturing', *Prog Addit Manuf*, vol. 1, no. 1–2, pp. 9–20, Jun. 2016.

3D micro PRINT

Powder with particle sizes < 5 µm



Fraunhofer ILT

µ-PBF, modified SLM-50 machine from Realizer

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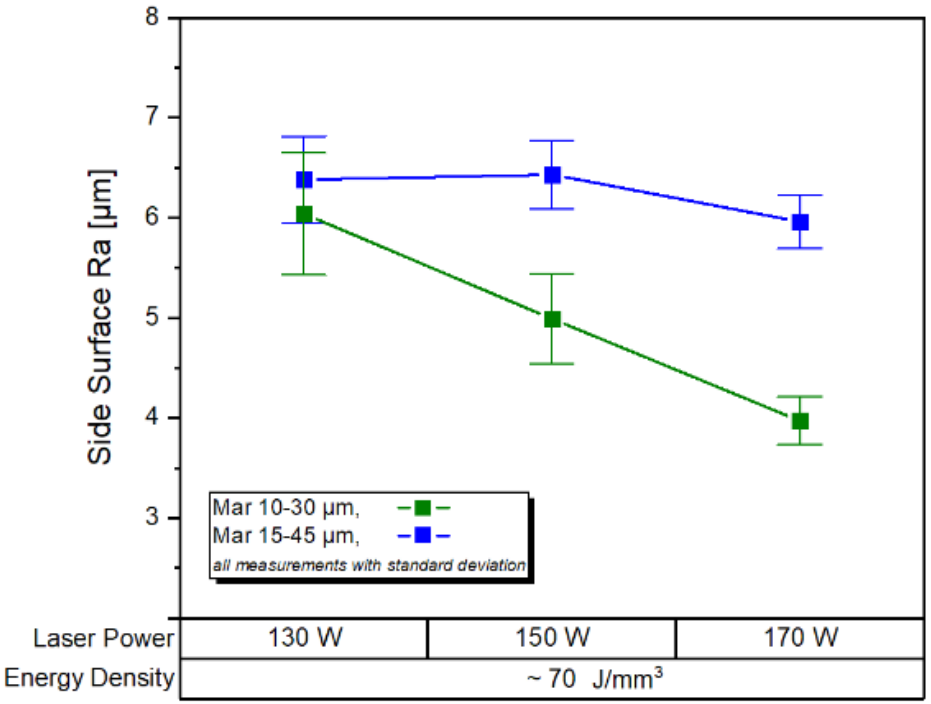
Future steps

- Complete powders characterization (SEM, rotatory drum flowability test)
- Establish **the evolution of surface quality for angled surfaces**, and downfacing surfaces



Example for vertical surfaces (90º)

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Future steps

- Complete powders characterization (SEM, rotatory drum flowability test)
- Establish **the evolution of surface quality for angled surfaces**, and downfacing surfaces
- Establish melt pool variability through the analysis of cross-section micrographs
- Understand the development of surface texture through full **3D topographic measurements**

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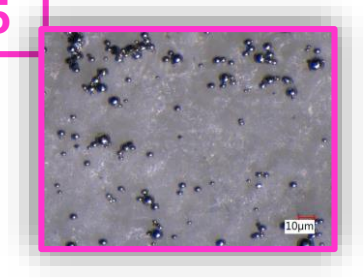
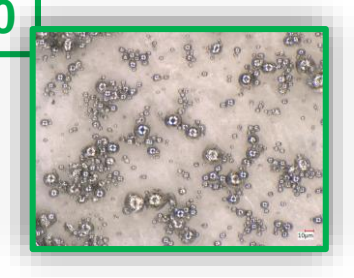
Conclusions

- Three Maraging 300 powders with different PSDs where tested

Mar 5-15



Mar 10-30



Mar 15-45

Standard

- The Mar 5-15 was deemed unsuitable for the ProX 320A recoating system
- A decrease > 50 % of top surface R_a was obtained for the Mar 10-30 distribution
- A novel remelting strategy was developed, resulting in top surface R_a of 1.5 µm

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(extra) Novel remelting strategy