Additive Manufacturing Powder Material Supply Chain: Verification and Validation

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Project Background

- The quality and integrity of a part is determined by a combination of multiple factors.
- This project specifically addressed material supply and the impact it has on the quality of parts.
- Laser Beam Powder Bed Fusion (PBF-LB)
- AlSi10Mg 20-63 µm
- GSTP activity "Additive Manufacturing Powder Material Supply Chain: Verification and Validation (G61A-018QT)"
- Consortium partners:
  - European Space Agency (ESA)
  - Manufacturing Technology Centre (MTC)
  - Swerim AB
  - Swedish Space Corporation

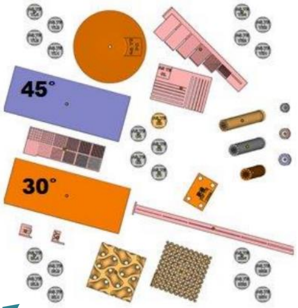
Aims & objectives

The aim of the project was to:

- Develop understanding of the relationship between powder properties and properties of parts manufacturing by AM, specifically Laser Beam Powder Bed Fusion (PBF-LB) systems

WP3000

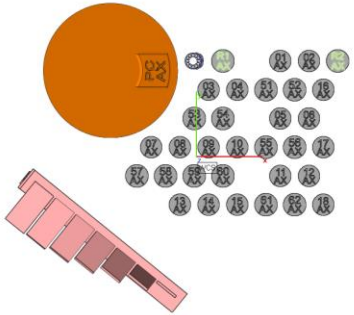
- 4 AlSi10Mg 20-63µm powders
- 3 AM bureaus
- 44 powder characterisation tests
- 39 AM parts built per powder batch
- 8 tests evaluating properties of AM parts



XY view of the position of the parts on the build plate

WP4000

- 2 AlSi10Mg 20-63µm powders
- 2 AM Bureaus
- 18 powder characterisation tests
- 35 AM parts built per powder batch
- 5 tests evaluating properties of AM parts



Project work breakdown

mtc

WP1000 Market review of powder suppliers and space part design

- Definition of initial powder procurement specification **PS1 (general and premium specification)**
- Selection of AM parts
- Downselection of AlSi10Mg suppliers for PBF-LB

WP2000 Selection of laboratories and AM service providers

- Survey powder characterisation laboratories
- Survey AM service providers
- Downselection of powder characterisation service providers and test methods
- Downselection of AM service providers (3 AM bureaus)
- Feedstock procurement

WP3000 1st powder material evaluation campaign

- Powder distribution
- 1st critical review of powder testing results
- 1st test and analysis campaign on AM artefacts
- 1st critical evaluation of test results generated by service providers **PS2 specification**

WP4000 2nd powder material evaluation campaign

- Feedstock procurement Selection of powder characterisation laboratories and AM service providers
- Powder distribution
- 2nd critical review of powder testing results
- 2nd test and analysis campaign on AM artefacts
- 2nd critical evaluation of test results generated by service providers **PS3 specification**

Powder characterisation campaign

Evolution of procurement specification

	Chemical composition (Inductively Coupled Plasma Emission Spectroscopy; O,N, H determined via Inert Gas Fusion)															
Element	Al	Si	Mg	Fe	Cu	Mn	Ni	Zn	Pb	Sn	Ti	N	O	H	Other (each)	Other (total)
PS1 General	Balance	9-11	0.20-0.45	< 0.55	< 0.05	< 0.45	< 0.05	< 0.10	< 0.05	< 0.05	< 0.15	None	None	None	< 0.05	< 0.15
PS1 Premium	Balance	9-11	0.25-0.45	< 0.25	<0.05	< 0.10	< 0.05	< 0.10	< 0.02	< 0.02	<0.15	< 0.20	< 0.08	None	< 0.05	< 0.15
PS2, PS3	Balance	9-11	0.25-0.45	< 0.25	< 0.05	< 0.10	< 0.05	< 0.10	< 0.02	< 0.02	< 0.15	< 0.20	< 0.03	< 0.003	< 0.05	< 0.15
Variation of PS2 and PS3 to ASTM F3318				(< 0.55) ✓		(< 0.45) ✓			(<0.05) ✓	(0.05) ✓				None ✓		

	Particle size (Laser diffraction)					Density		Flow rate		Particle density (Helium Pycnometry)	BET surface area	Morphology (Dynamic Image Analysis)	
Parameter	D10 (µm)	D50 (µm)	D90 (µm)	Volume % < 20 µm (%)	Volume % > 63 µm (%)	Apparent density (g/cm^3)	Tapped density (g/cm^3)	Hall flow (s/50g)	Carney flow (s/50g)	Average particle density (g/cm^3)	Surface area (m^2/g)	Aspect ratio: d50 (xc_min or x_area)	Sphericity: d50 (xc_min or x_area)
PS1 General	18-30	37-47	55-70	< 5%	< 7%	> 1.0	None	None	None	None	None	None	None
PS1 Premium	25-30	42-47	60-65	< 2%	< 5%	> 1.2	> 1.6	< 65	< 17	None	None	None	None
PS2	None	None	None	< 5%	< 10%	> 1.30	> 1.65	None	None	> 2.660	< 1.110	≥ 0.85	≥ 0.95
PS3	None	None	None	< 5%	< 10%	> 1.30	> 1.65	None	None	> 2.660	None	≥ 0.85	≥ 0.95

Powder characterisation laboratories and test selection (WP4000)

Consortium partners and external laboratories

WP3000:
44 tests

WP4000:
18 tests

Test	Test conducted in WP3000	Test conducted in WP4000	Laboratory conducting the test
Apparent, poured, tapped density; Hausner ratio	Yes	Yes	ESA, MTC
Automated Scanning Electron Microscopy (ASEM) and SEM	Yes	Yes	External test houses (ASEM-WP3000) ESA (ASEM-WP4000), MTC (SEM)
BET Surface area	Yes	Yes	External test house
Dynamic angle of repose (DAoR) (GranuDrum)	No	Yes	External test house (WP3000) ESA (WP4000)
Dynamic angle of repose (Revolution Powder Analyser)	Yes	Yes	MTC, Swerim
Dynamic Image Analysis (DIA) (Camsizer XT)	Yes	Yes	MTC, Swerim
Helium gas pycnometry	Yes	Yes	External test house
Inductively coupled plasma optical emission spectrometry (ICP-OES)	Yes	Yes	MTC
Inert Gas Fusion (IGF) O, N, H content	Yes	Yes	MTC
Laser absorptivity	No	Yes	External test house
Laser diffraction	Yes	Yes	ESA, MTC
Laser diffraction & DIA using Microtrac SYNC	No	Yes	External test house
Layer density	Yes	Yes	External test house
Moisture content via Karl Fischer	No	Yes	External test house

Summary of AlSi10Mg powders against PS2 specification

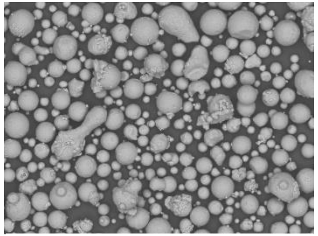
MTC characterisation results

Requirements	PS2 specification					
	P1	P2	P3	P4	P5	P6
Chemical composition – alloying elements	Passed	Passed	Passed	Passed	Passed	Passed
Chemical composition – interstitial elements	Failed	Failed	Failed	Failed	Passed	Passed
Particle size distribution – laser diffraction	Passed	Failed	Failed	Failed	Failed	Passed
BET surface area	Passed	Failed	Failed	Failed	Passed	Failed
Apparent density	Failed	Passed	Failed	Failed	Passed	Passed
Tapped density	Passed	Passed	Failed	Failed	Passed	Passed
Particle density	Failed	Passed	Failed	Failed	Passed	Passed
Particle morphology – dynamic image analysis	Failed	Passed	Failed	Failed	Passed	Passed

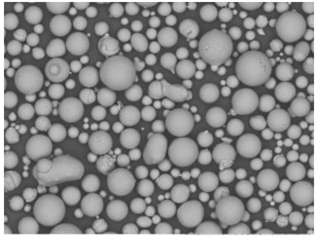
Electrode Induction Gas Atomisation (EIGA)
20-63 µm

Vacuum Induction Gas Atomisation (VIGA)
20-63 µm

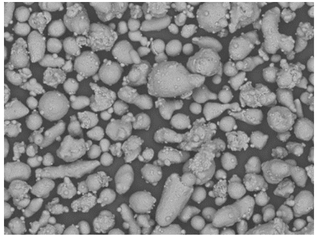
Plasma atomised
20-63 µm



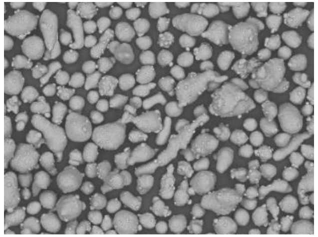
P1 (powder 1)



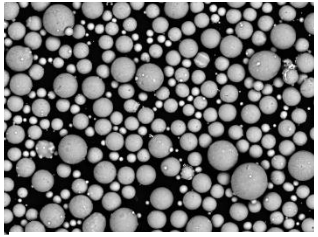
P2 (powder 2)



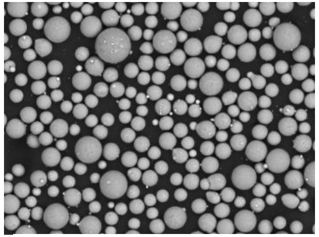
P3 (powder 3)



P4 (powder 4)



P5 (powder 5)



P6 (powder 6)

Repeatability analysis

Reproducibility analysis conducted in the WP4000 (P5 and P6 powders)

Repeatability refers to the variability of test results when a test is conducted using the same machine and the operator in the same laboratory

Chemical property tests	Repeatability	Laboratories
Bulk alloy chemistry (ICP-OES)	Passed	MTC
Trace element chemistry (ICP-OES)	Passed	MTC
Interstitial chemical analysis (IGF)	Failed	MTC

Physical property tests	Repeatability	Laboratories
Apparent density	Passed	ESA, MTC
Poured density	Passed	ESA, MTC
Tapped density	Passed	ESA, MTC

Rheological property tests		Repeatability	Laboratories
Hausner ratio		Passed	ESA, MTC
Dynamic angle of repose:	Avalanche angle	Passed	MTC, Swerim
	Avalanche energy	Failed	MTC, Swerim
	Surface fractal	Failed	MTC, Swerim
	Thickness cohesion	Failed	MTC
GranuDrum:	Dynamic angle	Passed	ESA
	Dynamic cohesion index	Failed	ESA

Geometric property tests		Repeatability	Laboratories
Distribution descriptor		d10 d50 d90	
Particle size:	Laser Diffraction	Passed	ESA, MTC
	DIA (x_area)	Passed	MTC, Swerim
	DIA (xc_min)	Passed	MTC Swerim
Aspect ratio:	DIA (x_area)	Passed	MTC, Swerim
	DIA (xc_min)	Passed	MTC, Swerim
Sphericity:	(x_area)	Passed	MTC, Swerim
	(xc_min)	Passed	MTC, Swerim

Reproducibility analysis

Reproducibility analysis conducted in the WP4000 (P5 and P6 powders)

Property	Test	Variable	Reproducibility	Laboratories
Geometric	Laser diffraction	d10	Failed	MTC + ESA + MIC (Microtrac)
		d50	Passed	
		d90	Passed	
	DIA Particle size (x_area + xc_min)	d10	Passed	MTC + Swerim
		d50	Passed	
		d90	Passed	
		Mean	Passed	
	DIA Aspect Ratio (x_area + xc_min)	d10	Failed	MTC + Swerim + MIC
		d50	Failed	
		d90	High	
		Mean	Failed	
	DIA Sphericity (x_area + xc_min)	d10	Passed	MTC + Swerim
		d50	Passed	
		d90	Passed	
		Mean	Passed	
Physical	Apparent density	Apparent density	Passed	MTC + ESA
Rheological	Hausner ratio	Hausner ratio	Passed	MTC + Swerim
	Dynamic angle of repose	Avalanche Angle	Failed	MTC + Swerim
		Avalanche Energy	Failed	
		Surface Fractal	Failed	

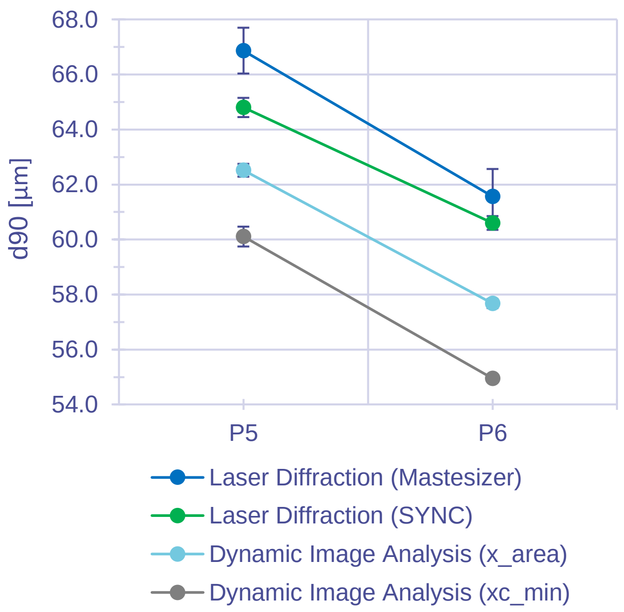
- Where one test evaluated multiple variables, if an RSD of > 5% was recorded between the mean values of the laboratories, for more than 10% of the results, then the test was said to fail the reproducibility analysis.
- Tests considered to be repeatable:
  - Particle size
  - Sphericity
  - Density
- Aspect ratio and rheological evaluations are considered to exhibit low reproducibility

Consistency analysis

Based on the reproducibility analysis conducted in the second round of the project (results for P5 and P6 powders)

- A dataset with an RSD value lower than 5% was deemed to have an acceptable level of consistency, whilst one with an RSD greater than 5% was believed to have poor consistency.

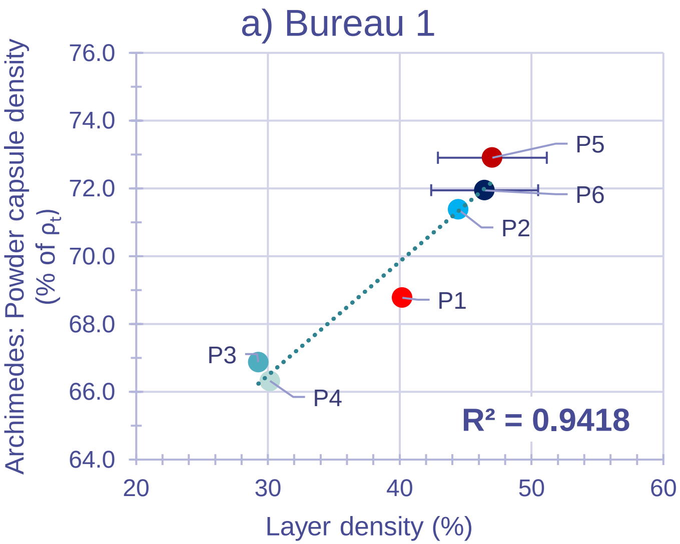
	Descriptor	d10		d50		D90	
	Powder batch	P5	P6	P5	P6	P5	P6
Geometric property	Test methods included within the evaluation	RSD (%)					
Particle size	• Laser diffraction (Mastersizer) • Laser diffraction (SYNC) • DIA (Camsizer, x_area) • DIA (Camsizer, xc_min)	2.36	2.79	2.31	2.26	4.58	5.11
Morphology: Aspect ratio	• DIA (Camsizer, x_area) • DIA (Camsizer, xc_min) • DIA (SYNC, Feret diameter)	0.16	0.33	0.04	0.07	0.04	0.04
Morphology: Sphericity	• DIA (Camsizer, x_area) • DIA (Camsizer, xc_min) • DIA (SYNC)	0.04	0.02	0.31	0.02	0.02	0.02

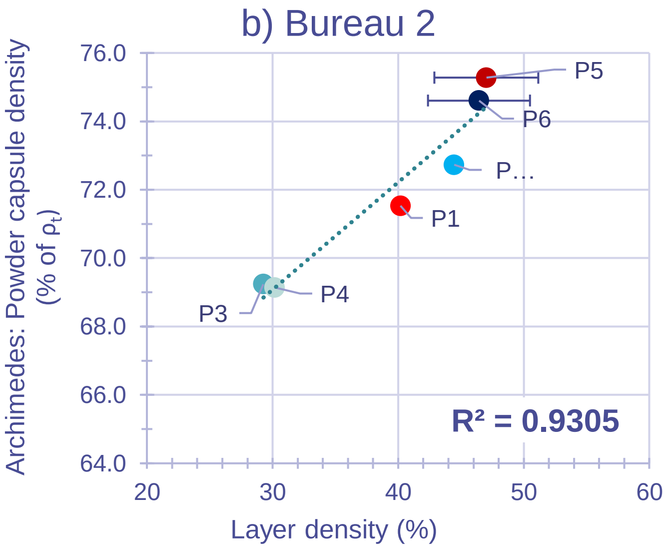


- d10 and d50 size evaluations prove to be consistent across test techniques
- Shape evaluations prove to be highly consistent across different definitions used for shape parameters calculations and across different equipment (Camsizer and SYNC) based on the same methodology (DIA)

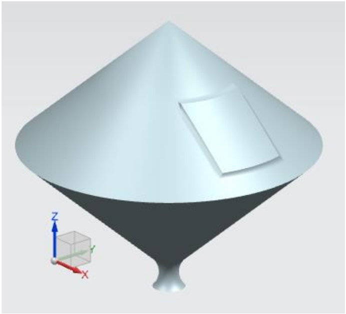
Correlations between flow measurements

- Layer density measurements were found to correlate well with the powder capsule density





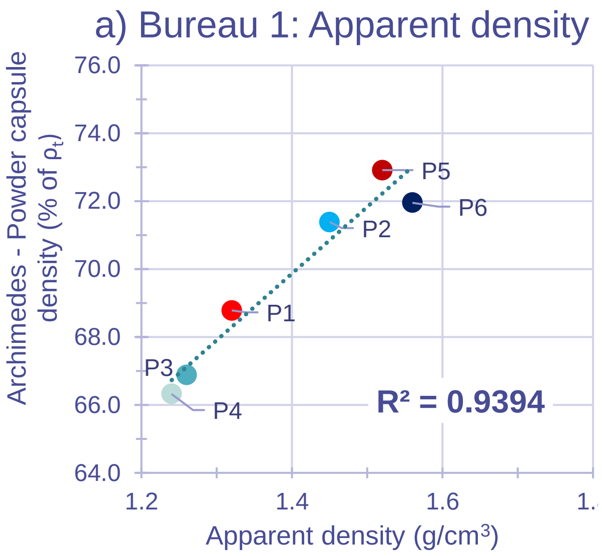
Powder spreading testbed (Lab-based test)

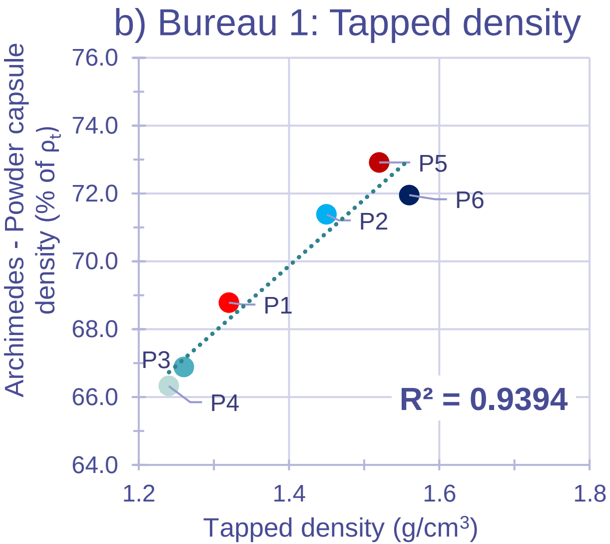


Powder capsule (In-process powder bed density)

Correlations Comparison of lab-based and in-process density evaluations

- In-process powder capsule density evaluations correlate well with lab-based density evaluations (poured density, apparent density, tapped density, Hausner ratio)





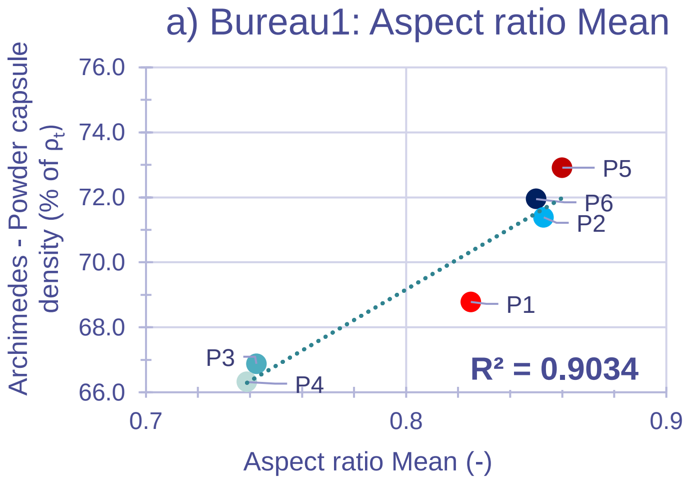
Apparent density using Hall flowmeter

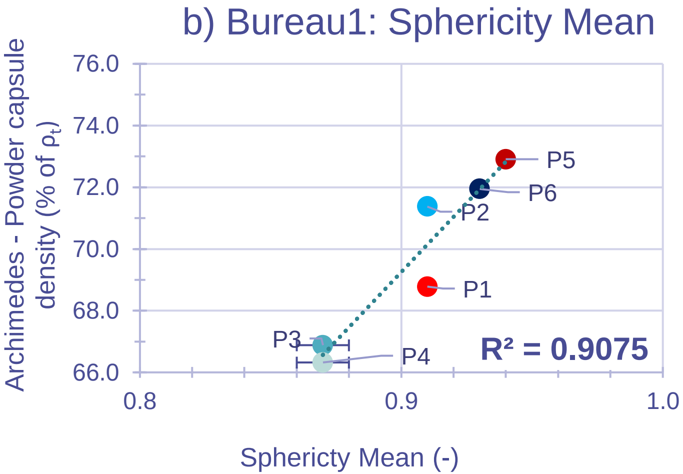
GranuPack

Autotap density analysed

Effect of particle shape and size on the formation of a spread layer

	Laser Diffraction:					DIA (x_area)				Archimedes: Powder capsule (% of ρ_t)	
	> 63 µm (%)	d10 (µm)	d50 (µm)	d90 (µm)	Span (-)	Sphericity Mean (-)	Sphericity d10 (-)	Aspect ratio Mean (-)	Aspect ratio d10 (-)		
	MTC	MTC	MTC	MTC	MTC	MTC	MTC	MTC	MTC	B1	B2
P1	5.60	24.7	38.3	57.8	0.86	0.91	0.91	0.82	0.71	68.78	71.53
P2	15.6	29.7	45.6	67.6	0.83	0.91	0.93	0.85	0.73	71.38	72.73
P3	12.4	25.8	41.2	65.5	0.96	0.87	0.84	0.74	0.59	66.88	69.24
P4	14.3	24.7	40.9	68.1	1.06	0.87	0.85	0.74	0.56	66.32	69.14
P5	14.5	29.6	45.0	66.9	0.83	0.94	0.94	0.86	0.75	72.91	75.28
P6	8.78	26.1	40.4	61.6	0.88	0.93	0.94	0.85	0.73	71.95	74.61





- There is great correlation between particle shape and powder capsule density

Density correlations from powder to part

	Pycnometry: Average particle density (g/cm³)	Archimedes: % of porosity in tensiles (%)		Archimedes: Powder capsule (% of ρ_t)	
	EXT	B1	B2	B1	B2
P1	2.659	0.46	0.49	68.78	71.53
P2	2.648	0.39	0.41	71.38	72.73
P3	2.658	0.50	0.44	66.88	69.24
P4	2.635	1.82	0.68	66.32	69.14

	Pycnometry: Average particle density (g/cm³)	Image analysis: Percentage of total area covered by pores (%)		Archimedes: Powder capsule (% of ρ_t)	
	EXT	B1	B2	B1	B2
P5	2.671	0.18	0.13	72.91	75.28
P6	2.676	0.14	0.04	71.95	74.61

- Solid parts appear (as evaluated via image analysis) to exhibit greater correlation with individual particle porosity than with the bulk material density (powder capsule density)

The summary of the observed correlations

- The spreading testbed at Inspire was found to best replicate in-process powder spreading behaviour as evaluated using Archimedes powder capsule.
- Apparent and tapped densities found to correlate well within the in-process powder capsule density.
- The particle shape appears to correlate more to powder capsule density than the particle size for PBF-LB AlSi10Mg feedstock with the nominal particle size within 20-63 µm.
- The results suggest there is a correlation between the individual particle porosity and density of fully densified AM parts.
- Control of moisture content via Karl Fischer might serve to improve the in-process powder bed density.

Powder procurement specification PS3

	Chemical composition (Inductively Coupled Plasma Emission Spectroscopy; O,N, H determined via Inert Gas Fusion)															
Element	Al	Si	Mg	Fe	Cu	Mn	Ni	Zn	Pb	Sn	Ti	N	O	H	Other (each)	Other (total)
PS3	Balance	9-11	0.25-0.45	< 0.25	< 0.05	< 0.10	< 0.05	< 0.10	< 0.02	< 0.02	< 0.15	< 0.20	< 0.03	< 0.003	< 0.05	< 0.15
Variation of PS2 and PS3 to ASTM F3318				(< 0.55) ✓		(< 0.45) ✓			(<0.05) ✓	(0.05) ✓				None ✓		

	Particle size (Laser diffraction)					Morphology (Dynamic Image Analysis)	
Parameter	D10 (µm)	D50 (µm)	D90 (µm)	Volume % < 20 µm (%)	Volume % > 63 µm (%)	Aspect ratio: d50 (xc_min or x_area)	Sphericity: d50 (xc_min or x_area)
PS3	None	None	None	< 5%	< 10%	≥ 0.85	≥ 0.95

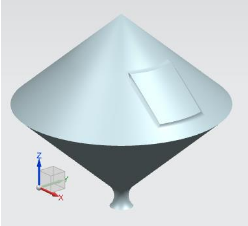
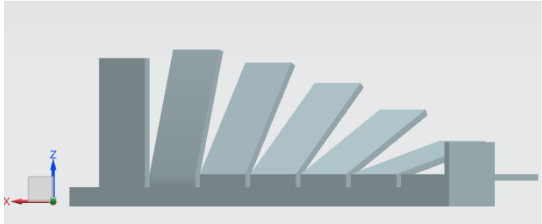
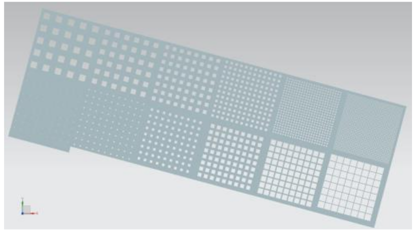
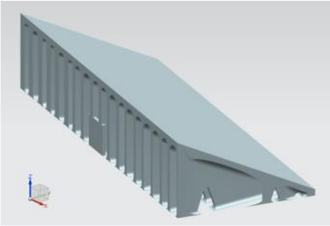
	Density		Particle density (Helium Pycnometry)
Parameter	Apparent density (g/cm³)	Tapped density (g/cm³)	Average particle density (g/cm³)
PS3	> 1.30	> 1.65	> 2.660

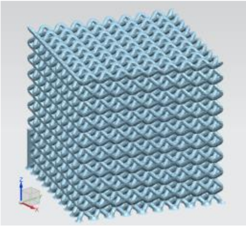
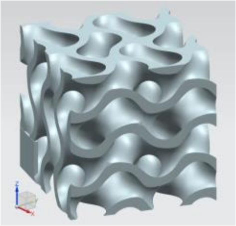
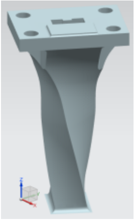
Analysis campaign of AM artefacts

AM artefacts and characterisation

Artifacts

- Design activity led by Swedish Space Corporation
- Tensile bars, benchmarking designs, generic space parts
- Campaign 1: 469 parts
- Campaign 2: 140 parts

Non-destructive analysis
- Shape accuracy
- Density
- Surface roughness

Destructive analysis
- Tensile testing
- Fractography
- Microstructure

AM activity

- Three bureaus with aerospace/space experience
- Deliverables of the bureaus:
  - AM services
  - Information on powder handling procedures & AM processing
    - Pre-treatment for dehumidification
  - Process observations
  - Communication

Bureau	Machine	Strategy	Baseplate Start T (°C)	Re-coater	Max O% ppm	Argon Gas Pressure	Flow rate
Bureau 1	EOS M290	In-house expertise on AlSi10Mg 30 µm	35	carbon brush	170	6000 mbar	1 l/min
Bureau 2	3DSystems DMP 320		20	silicon blade	150	250 mbar	2,5 m/s
Bureau 3	EOS M290		60	silicon blade	100		

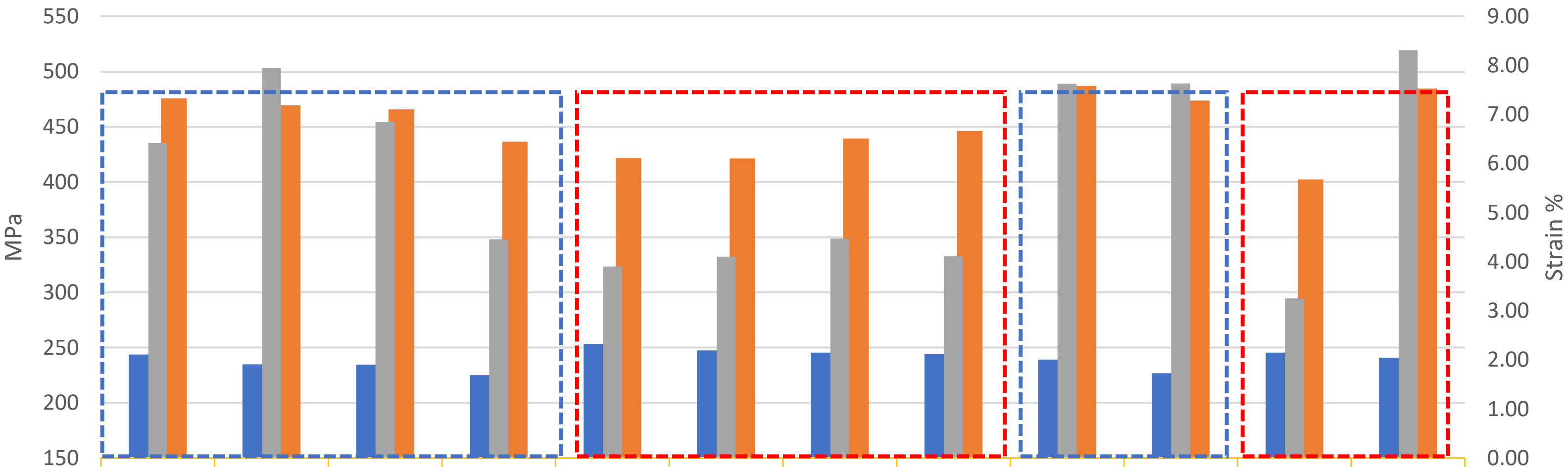
Outline

- The aim of the activity was to evaluate the trends of properties across all characterisations, in order to identify possible correlations between the powder, the used AM process and the properties of the parts

- Examples of found correlations
  - Mechanical properties — tensiles
  - Microstructure — heat pipes
  - Shape accuracy — thin lattice squares, space designs
  - Surface roughness — angled walls

Mechanical properties

Tensile testing: EN ISO 6892-1 Method A1



	B1 P2	B1 P1	B1 P3	B1 P4	B2 P2	B2 P1	B2 P3	B2 P4	B1 P5	B1 P6	B2 P5	B2 P6
Rp0.2	244	235	235	225	253	247	246	244	239	227	246	241
Rm	476	470	466	436	422	421	439	446	487	474	402	485
At [%]	6.42	7.95	6.85	4.46	3.90	4.11	4.47	4.11	7.63	7.63	3.25	8.31

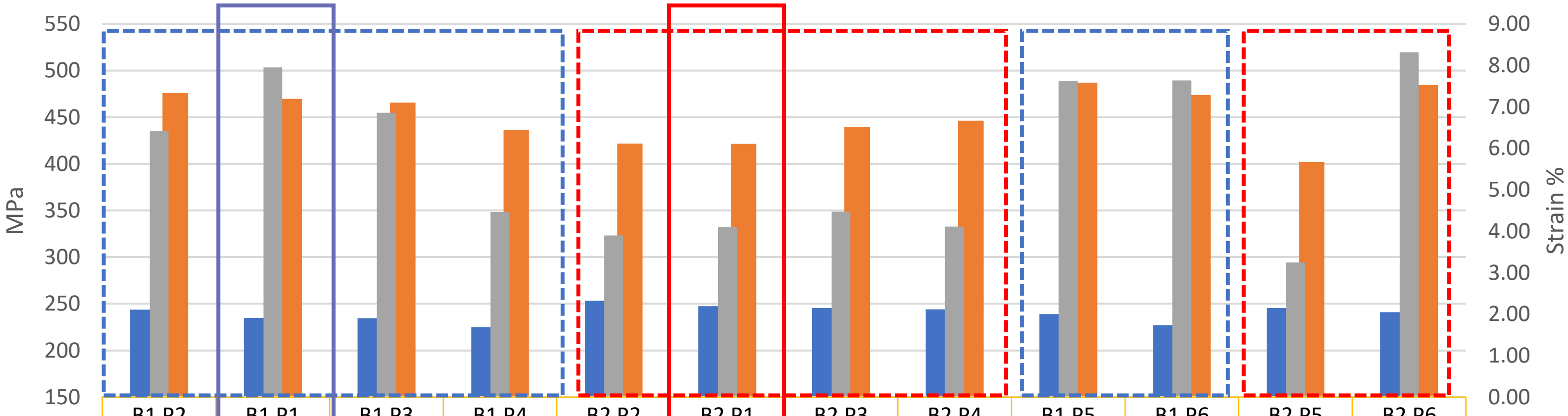
Rp0.2 Rm At [%]

Machined tensile bars – no heat treatment in WP3 &WP4

Mechanical properties

The effect of powder: premium powder

Un-treated machined bars - WP3 & WP4

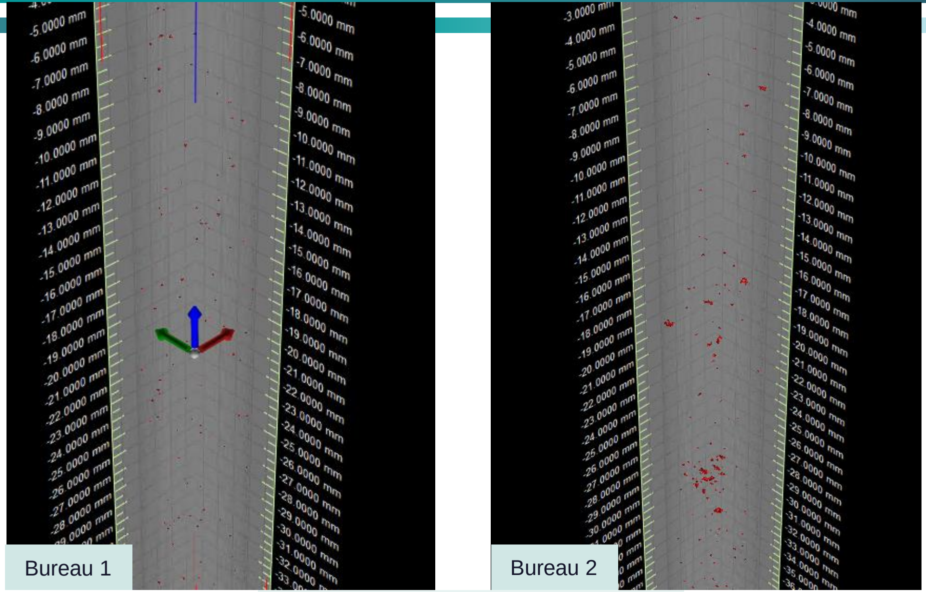


	B1 P2	B1 P1	B1 P3	B1 P4	B2 P2	B2 P1	B2 P3	B2 P4	B1 P5	B1 P6	B2 P5	B2 P6
Rp0.2	244	235	235	225	253	247	246	244	239	227	246	241
Rm	476	470	466	436	422	421	439	446	487	474	402	485
At [%]	6.42	7.95	6.85	4.46	3.90	4.11	4.47	4.11	7.63	7.63	3.25	8.31

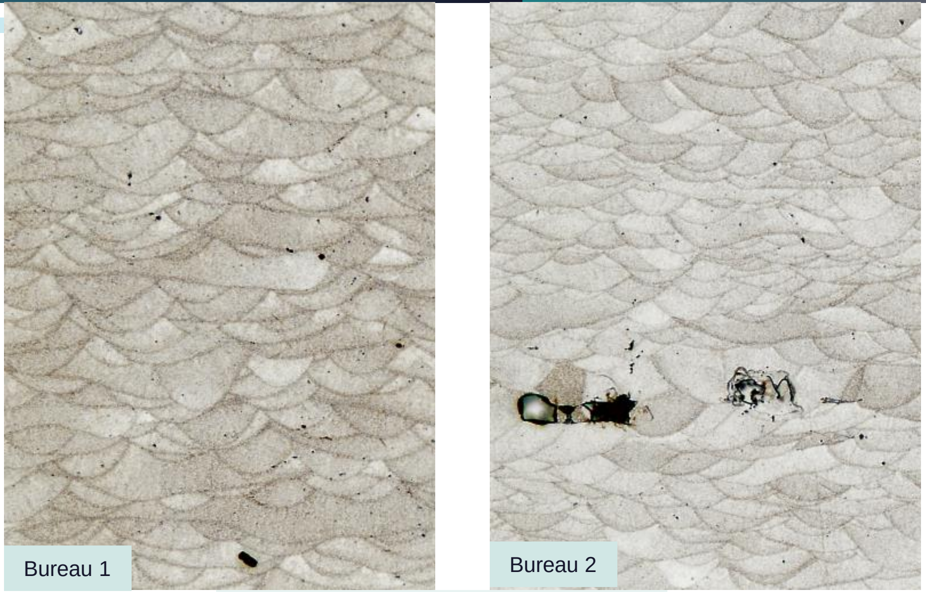
Rp0.2 Rm At [%]

Characterisation of defects

The effect of powder: premium powder



Defect distribution in tensile bar by XCT



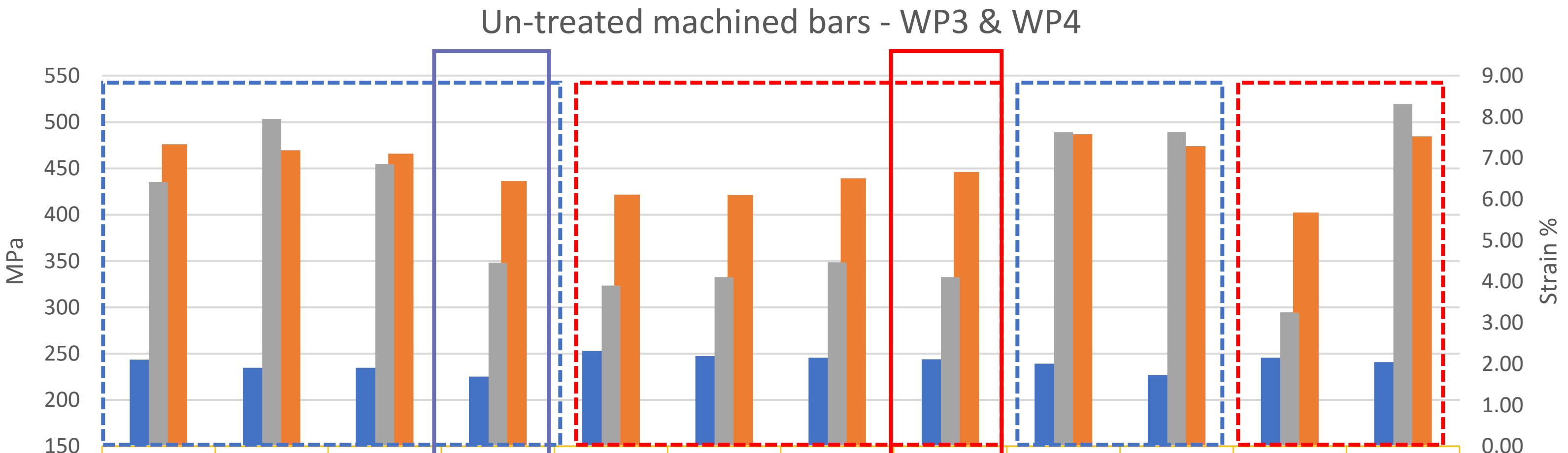
Defects in XZ direction of the build by LOM

Premium powder P1

- Bureau 1: A low number of defects – high A_t (7,95 %)
  - Powder pre-treatment for dehumidification
  - Route card: good spreading behavior in process
- Bureau 2: Some very large random defects - low A_t (4,11%)
  - No powder pre-treatment
  - Route card: powder sticking to blade, drag lines, sensitivity for humidity

Mechanical properties

The effect of powder: standard powder

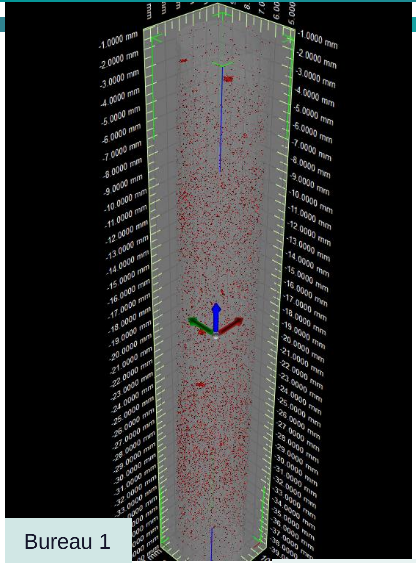


	B1 P2	B1 P1	B1 P3	B1 P4	B2 P2	B2 P1	B2 P3	B2 P4	B1 P5	B1 P6	B2 P5	B2 P6
Rp0.2	244	235	235	225	253	247	246	244	239	227	246	241
Rm	476	470	466	436	422	421	439	446	487	474	402	485
At [%]	6.42	7.95	6.85	4.46	3.90	4.11	4.47	4.11	7.63	7.63	3.25	8.31

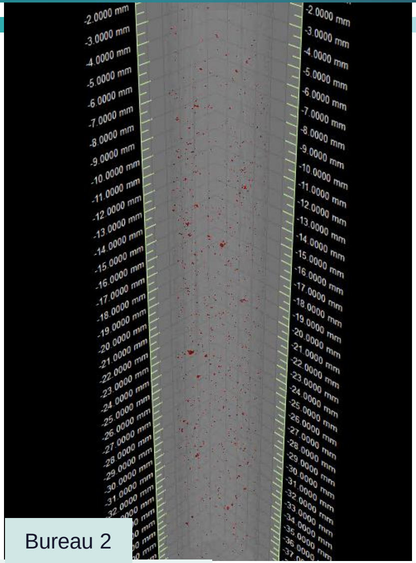
Rp0.2 Rm At [%]

Characterisation of defects

The effect of powder: standard powder

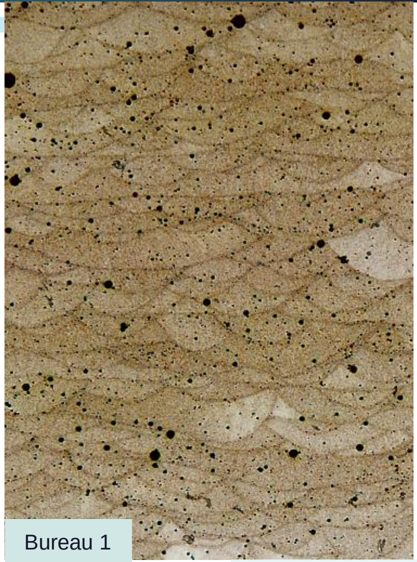


Bureau 1

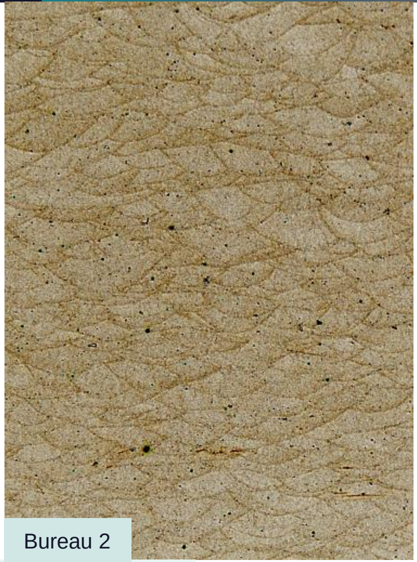


Bureau 2

Defect distribution in tensile bar by XCT



Bureau 1



Bureau 2

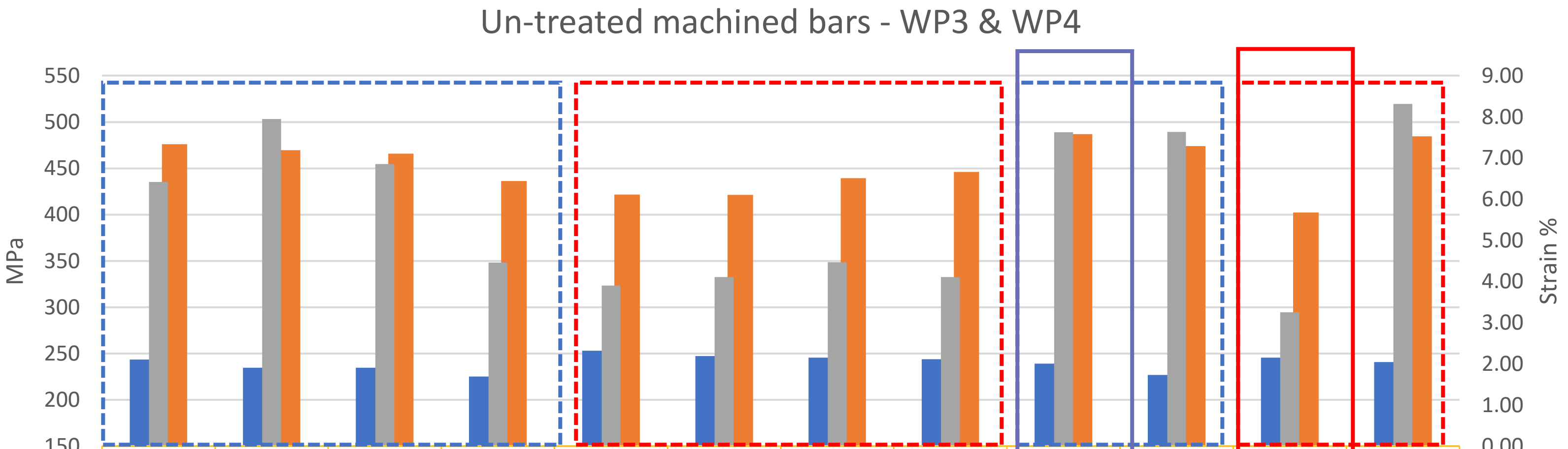
Defects in XZ direction of the build by LOM

Standard powder P4

- Bureau 1: Spherical pores & some large defects – low A_t (4,46%)
    - Powder pre-treatment for dehumidification
    - Route card: bad spreading behavior in process
- Bureau 2: Some large defects - low A_t (4,11%)
    - No powder pre-treatment
    - Route card: good spreading behavior, oversized particles cause empty spots

Mechanical properties

The effect of powder pre-treatment: Premium powder

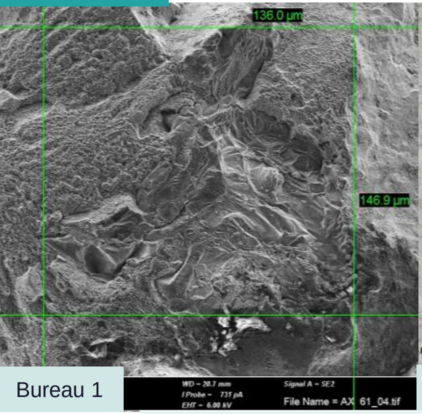


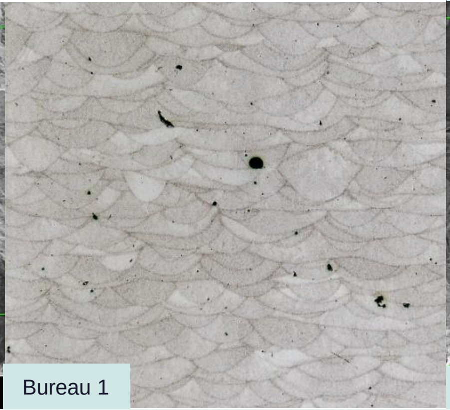
	B1 P2	B1 P1	B1 P3	B1 P4	B2 P2	B2 P1	B2 P3	B2 P4	B1 P5	B1 P6	B2 P5	B2 P6
Rp0.2	244	235	235	225	253	247	246	244	239	227	246	241
Rm	476	470	466	436	422	421	439	446	487	474	402	485
At [%]	6.42	7.95	6.85	4.46	3.90	4.11	4.47	4.11	7.63	7.63	3.25	8.31

Fractography and microstructure

The effect of powder pre-treatment: Premium powder

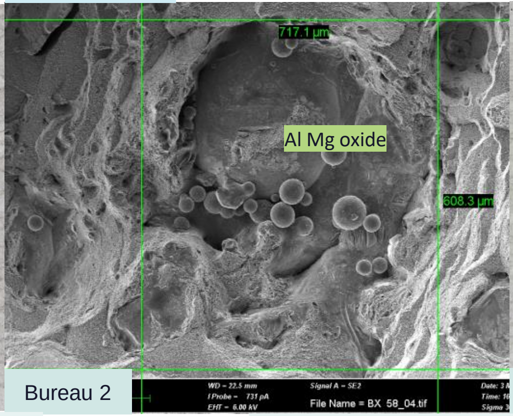
B1 P5

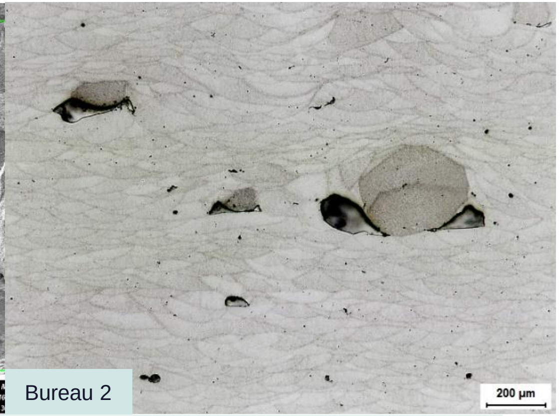




Defects by fractography in SEM & by cross-section in XZ direction by LOM

B2 P5





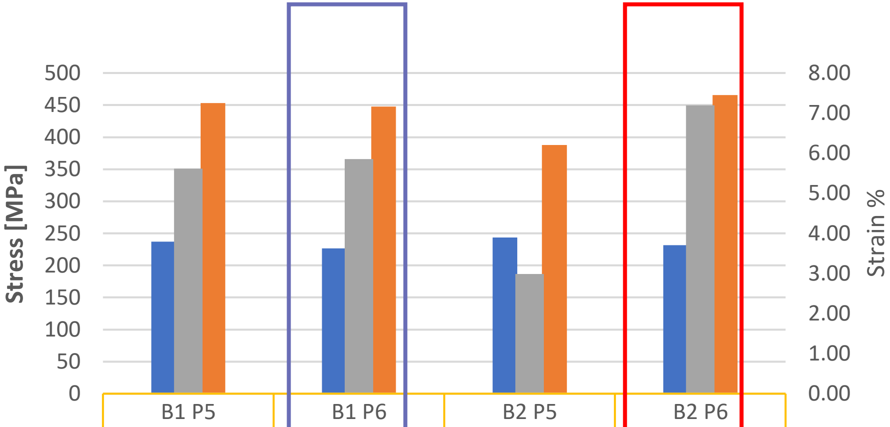
Defects by fractography in SEM & by cross-section in XZ direction by LOM

Premium powder P5

- Bureau 1: A low number of defects – high A_t (7,63 %)
  - Powder pre-treatment for dehumidification
  - Route card: good spreading behavior in process
- Bureau 2: Large defects with Al Mg -oxide films - low A_t (3,25%)
  - Powder pre-treatment for dehumidification
  - Route card: high surface roughness, bad spreading behavior, formation of black smoke (typical for Mg)

Mechanical properties

The effect of contours: Premium powder



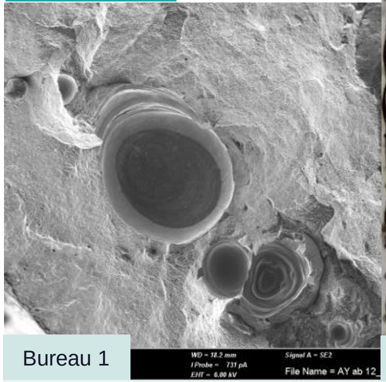
	B1 P5	B1 P6	B2 P5	B2 P6
Rp0.2	237	227	243	231
Rm	453	447	388	466
At [%]	5.61	5.85	2.99	7.19

As-build tensile bars – no heat treatment in WP4

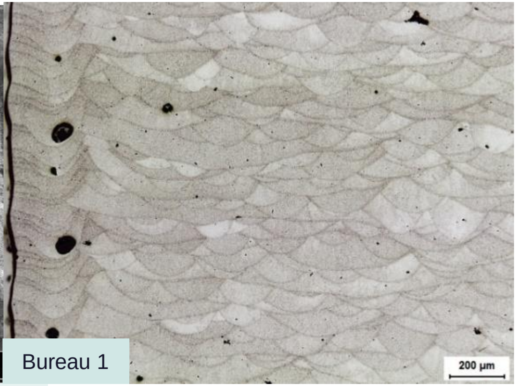
Fractography and microstructure

The effect of contours: Premium powder

B1 P6



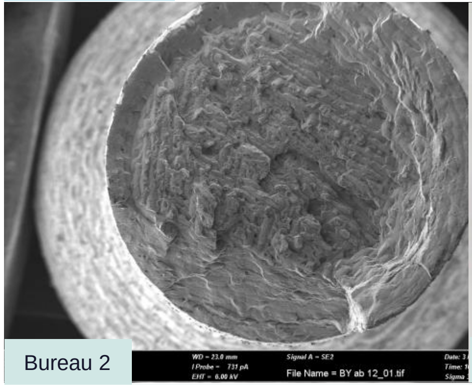
Bureau 1



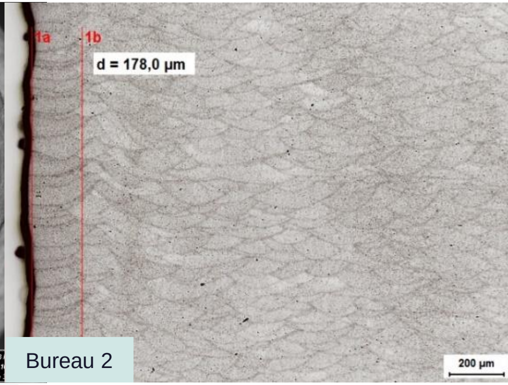
Bureau 1

Defects on fracture surface

B2 P6



Bureau 2



Bureau 2

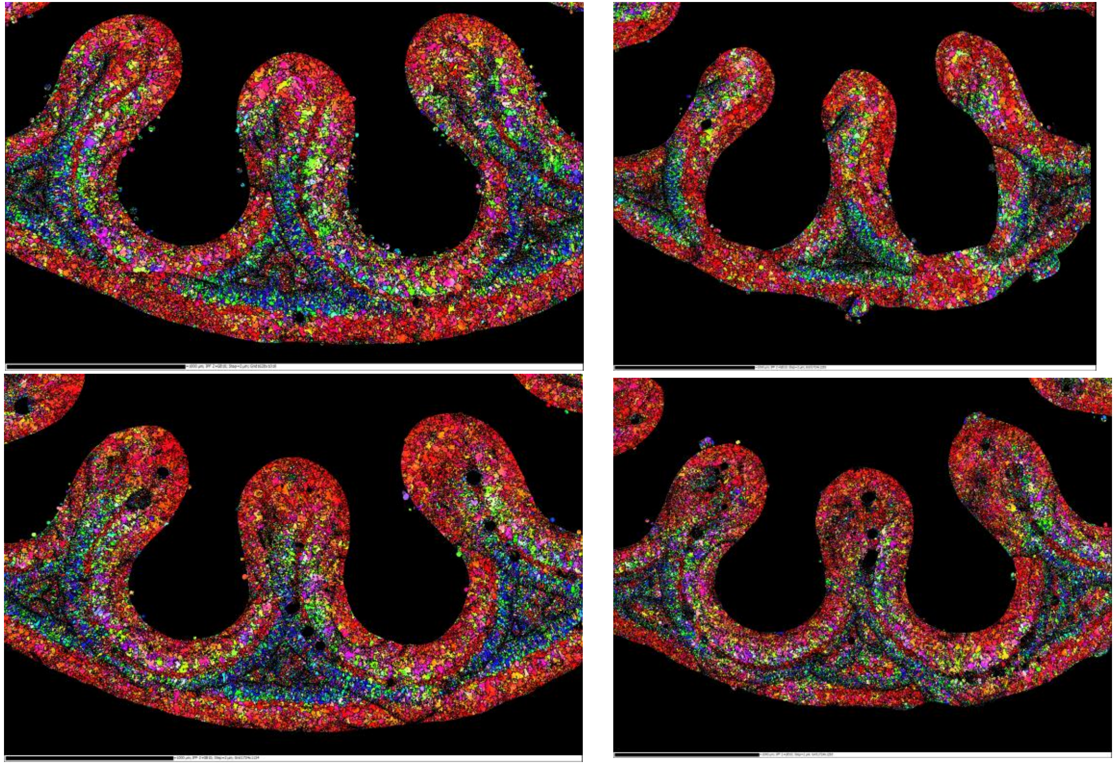
No defects on fracture surface

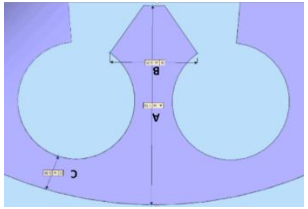
Contours
Premium powder P6

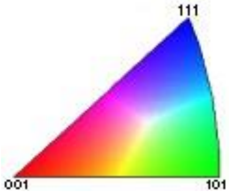
- Bureau 1: Spherical defects at contours – low A_t (5,85 %)
  - Powder pre-treatment for dehumidification – method not known
  - Rupture initiated at contours
- Bureau 2: No porosity at contours - high A_t (7,18 %)
  - Powder pre-treatment for dehumidification – vacuuming cycles

Microstructure of heat pipes

XY cross-section on wick structure





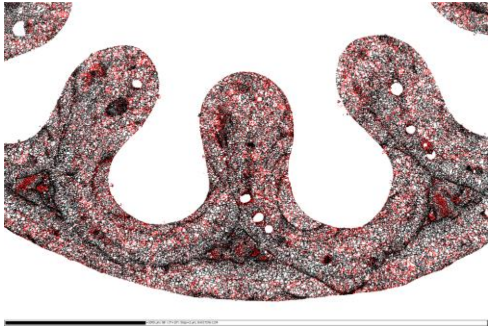


Crystal orientation map (IPF Z) of the heat pipe by EBSD (step size 2 µm). Scale bar 1000 µm.

Microstructure of heat pipes

XY cross-section on wick structure

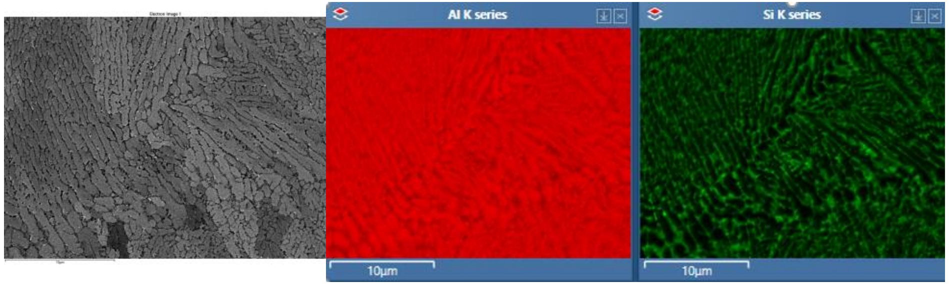
B1 P6



Spherical porosity at contours

B2 P6

Spherical porosity at contours



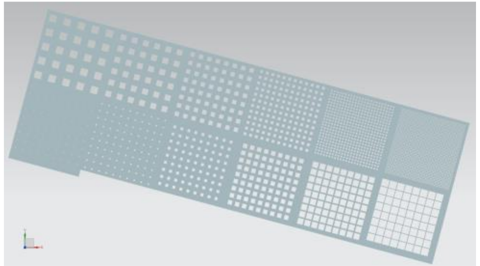
Fine Al-Si eutectic structure (BS) EDS map for Al and Si K series

Contours
Heat pipes

- Wicks build mostly by using contours that contain spherical porosity
  - Negative for thermal conductivity and mechanical strength
- The overlapping scan beams created a very fine grain size
- Silicon rich areas typical for overlapping scan beams induce inhomogeneous thermal conductivity for the material as silicon displays low thermal conductivity
- The applied contouring and scanning strategy is of importance for providing a homogenous and defect free microstructure

Shape accuracy of thin lattice squares

Contours in fine features



Powder	Area % out of tolerance					
	B1		B2		B3	
	ROI 1	RO1 2	ROI 1	ROI 2	ROI 1	ROI 2
P1	8	30,2	51	39	4,9	3,2
P2	10,5	31,6	35,2	30	3,4	4,8
P3	14,3	20,5	45,1	52,9	3,4	3,4
P4	12,4	22,1	40,2	23,3	3,3	3,5

Square feature	ROI 1	ROI 2
Wall thickness (mm)	0.4	0.4
Hole size (mm)	0.6	0.4
Height (mm)	10	10

Shape accuracy by XCT

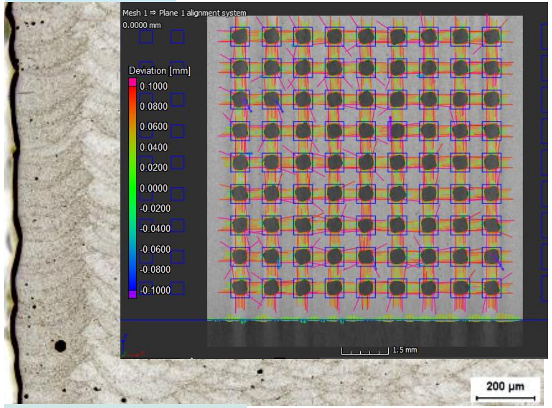
Shape accuracy of thin lattice squares

Contours in fine features

B1 P3

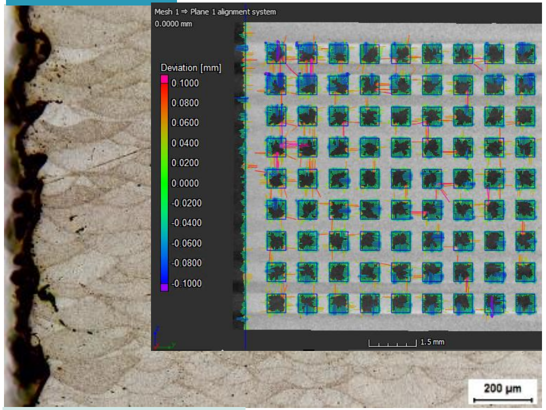
Bureau 1 – Powder 3

B2 P3



Bureau 2 – Powder 3

B3 P3

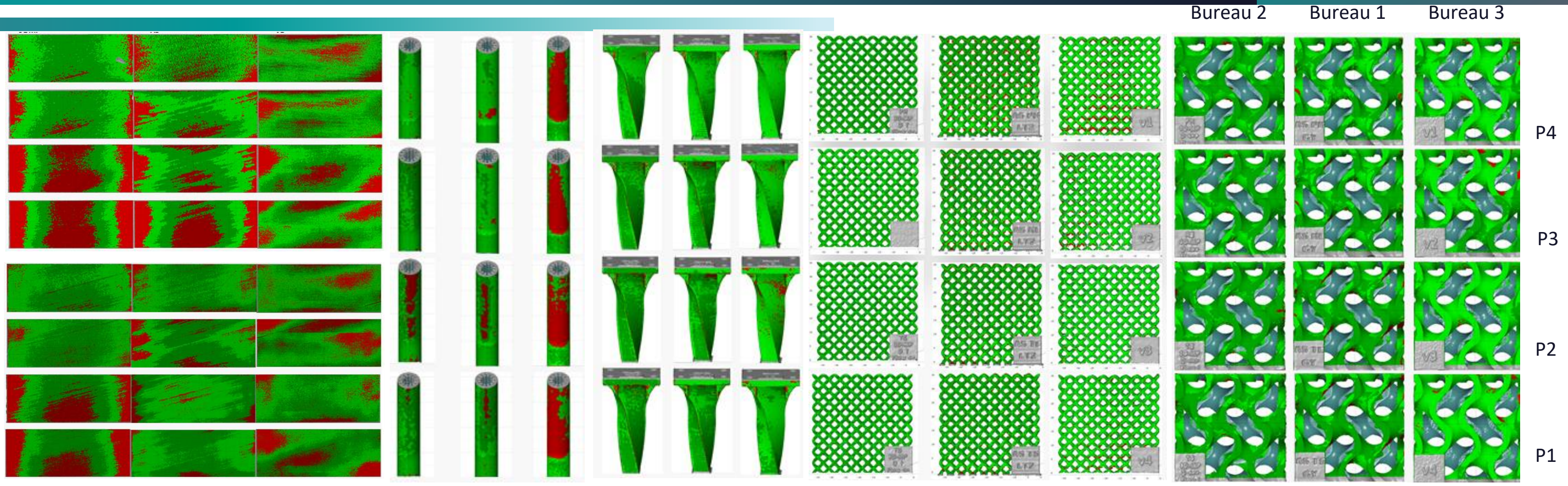


Bureau 3 – Powder 3

Shape accuracy of fine features

- Shape accuracy clearly influenced by the AM process
- Route card: In bureau 3 a very low energy was applied for the contouring. The contours were hidden behind the bulk parameters.
- It is assumed that the very thin contours increased the shape accuracy of the thin features in the lattice

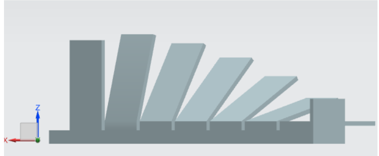
Shape accuracy of space design

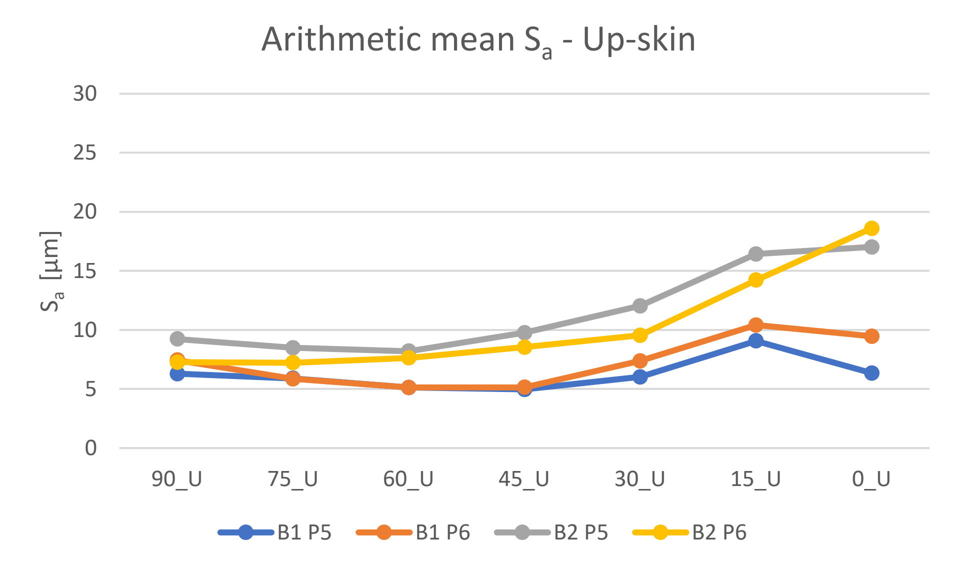


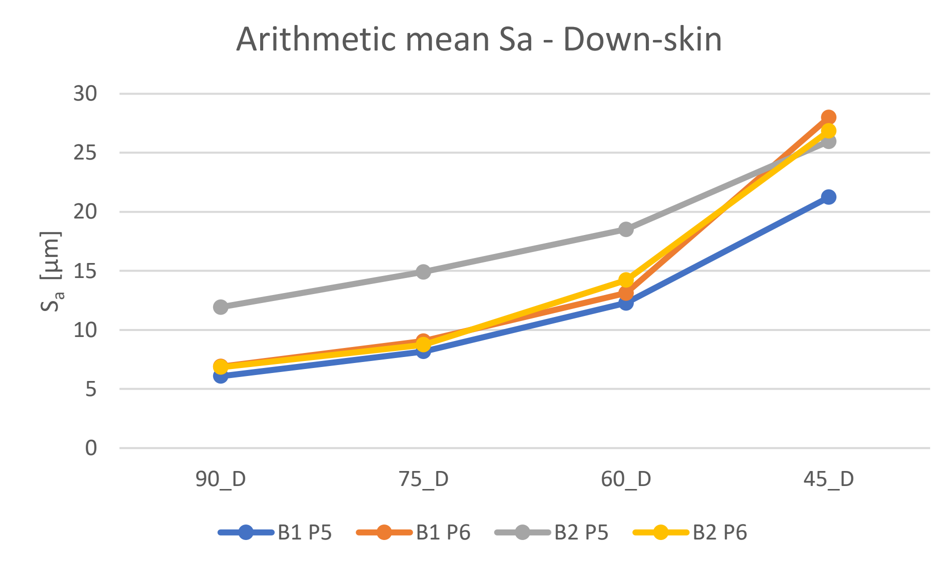
Shape accuracy of space designs

- Relatively small deviations from the CAD model
- A clear trend for the effect of the AM can be observed:
- 1- Bureau 2 2- Bureau 1 3-Bureau 3
- The influence of powder secondary
- Route cards: positive factors for good shape accuracy – high laser focus, high overlaps of the laser scans, long build times, high density of powder bed, high powder dosing ratio, low partial pressure in build chamber

Surface roughness

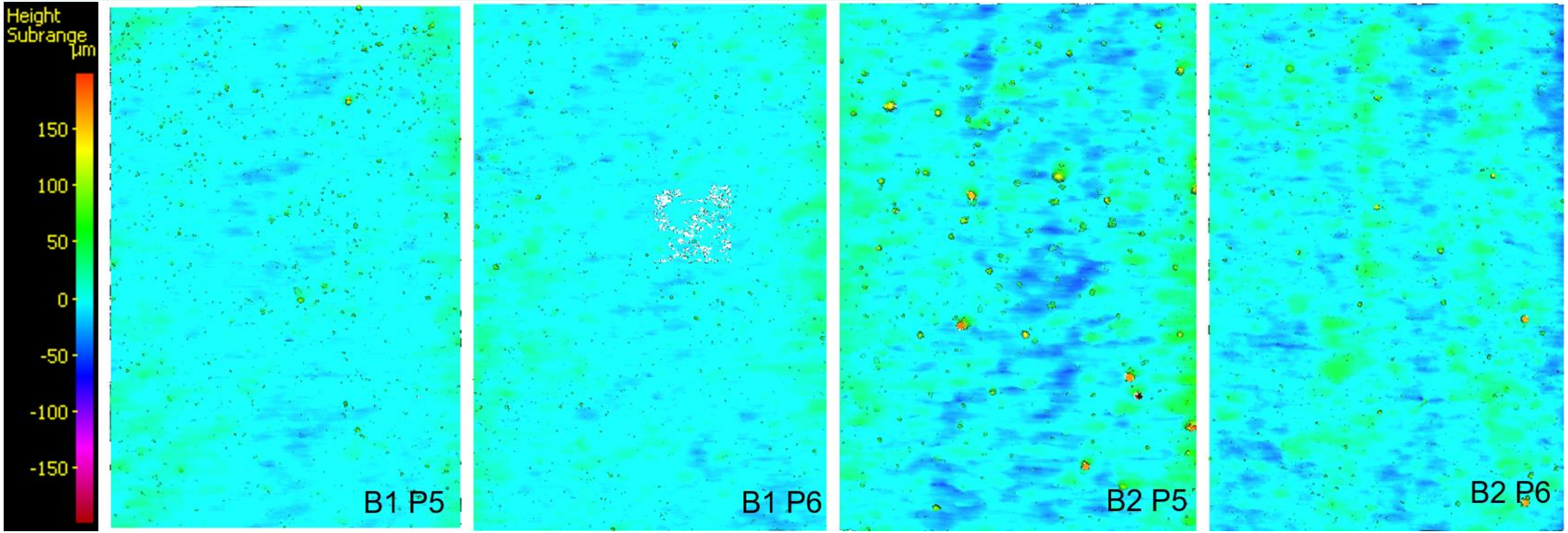






Surface roughness

Surface roughness by focus variation microscopy, wall 45° up-skin



Surface roughness
Premium powder

- Surface roughness of the artefacts was influenced by the used manufacturing method and the powder.
- Up-skins display lower roughness than down-skins
- Route cards: large effect on the post-processing, also effects from contouring, powder bed density
- P5 at bureau 2: high roughness

Key highlights

Analysis campaign of AM artefacts

- The mechanical properties of the studied 18 batches displayed significant variations
- Premium and standard powder specification can result in variable tensile properties
- The powder, its pre-treatment and the applied AM processing (hardware and parameters) are together of importance for the mechanical properties
- Mechanical properties can serve as an indicator of the quality of the build
- The contouring strategy and parameters are of importance for defect-free contours
- Contouring in delicate designs is of importance as it influences the parts shape accuracy, microstructure and physical properties
- Shape accuracy of complex, larger design is primary influenced by the AM process
- Surface roughness displays correlation to applied the AM process, powder and post-processing
- AM process displays a major effect for quality and properties of the parts when using a powder fulfilling the criteria in the powder specification. AM processing displays sensitivity for formation of defects and it is therefore motivated to increase understanding on topics related to powder pre-treatment, and the effect of the used hardware, AM processing parameters and strategy for achieving improved part quality.

Lessons learnt

- Better insight into powder properties required for improved part properties
- Effectiveness of a wide range of powder characterisation techniques
- Method development and recommendations for powder storage, handling and testing
- There are some final part properties more dominated by the AM process, some more dominated by the powder, but most are dominated by the combined effect of the AM process and the powder properties.
- It can be concluded that even a powder batch that meets strict requirements, might generate AM parts exhibiting different properties depending on the applied AM process.
- However, it was also observed that all the powders purchased from the AM powder supply chain in this study were processable via AM and produced parts.
- The powder procurement specification PS3 (valid only for AlSi10Mg 20-63 µm, investigated in the project), targeting powder properties that will manufacture of AM parts with optimal properties, was developed.

Next steps

1. Adoption of PS3 specification within AM community would require individual engagement with powder suppliers.
2. Further development and standardisation of powder test rigs would provide better insight into powder behaviour during spreading than currently available lab-based techniques.
3. The impact of powder conditioning practices on powder performance in AM process and AM part properties should be better understood.
4. The latest research suggests that moisture content present within the AlSi10Mg might change when the powder is stored in a sealed container (ASTM F3606). It possesses need of (1) understanding actual impact of moisture content present within feedstock on AM part properties; (2) revision current storage strategies for AlSi10Mg; and (3) control of moisture content within metal feedstock and determination of specification limit for moisture content.
5. It was observed that the formation of defects and microstructure at the contouring area is sensitive to the strategy for contouring. Additionally, the design of heat pipes manufactured in the project, was sensitive for formation of large defects exhibiting spherical morphology. It is proposed that grain and crystallography characteristics of the contours in both un-treated and heat-treated conditioned should be investigated in detail. It is suggested that the research would increase our understanding of the effect of contours on mechanical properties of AM test pieces. Additionally, the research would enable optimising of contours parameters and thus, the reduction of sensitivity for formation of stress concentrations at the surface areas.

THANK YOU