MINI – CAS ON MECHANICAL ENGINEERING

CHALLENGES IN ADDITIVE MANUFACTURING (of metals)

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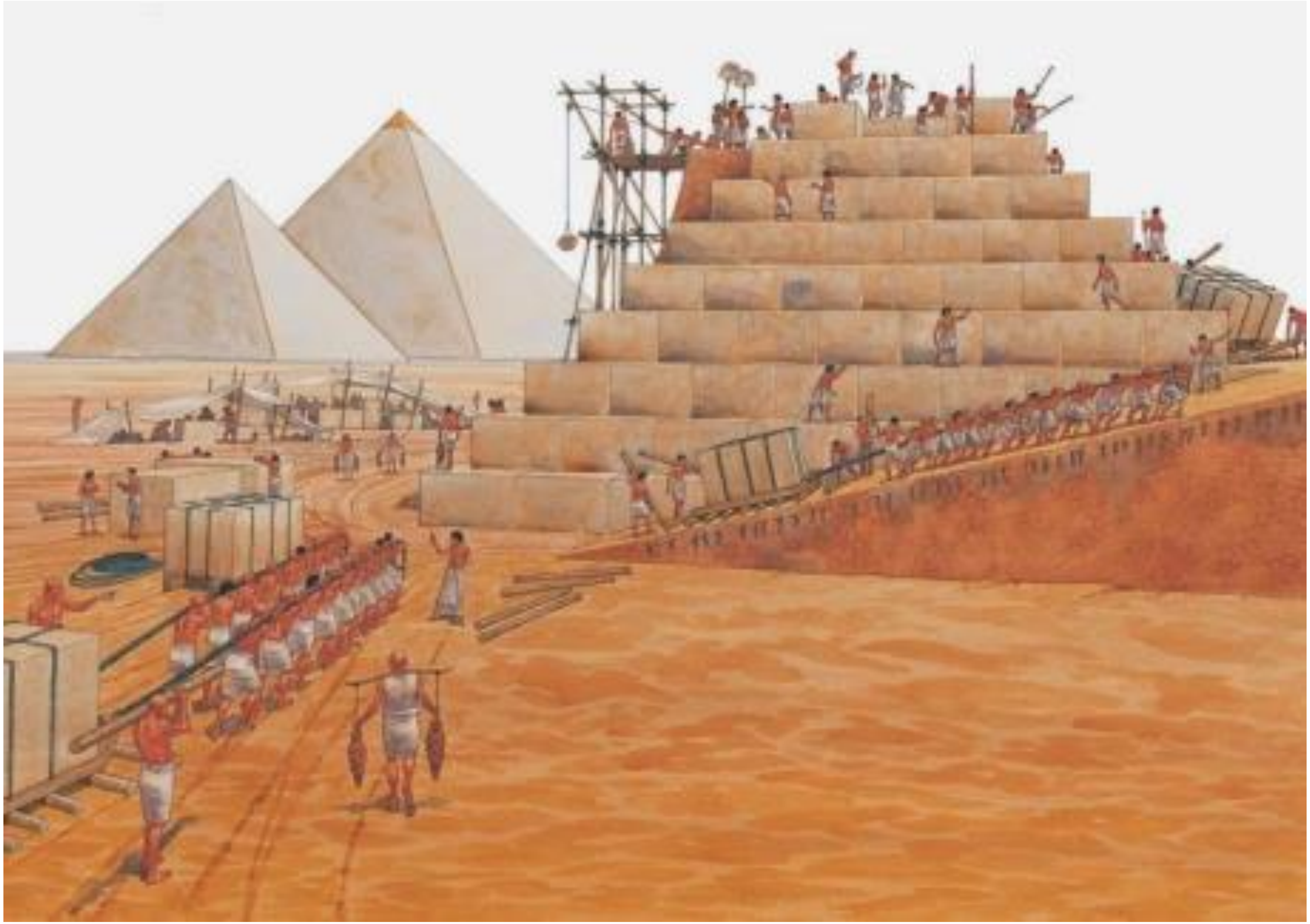
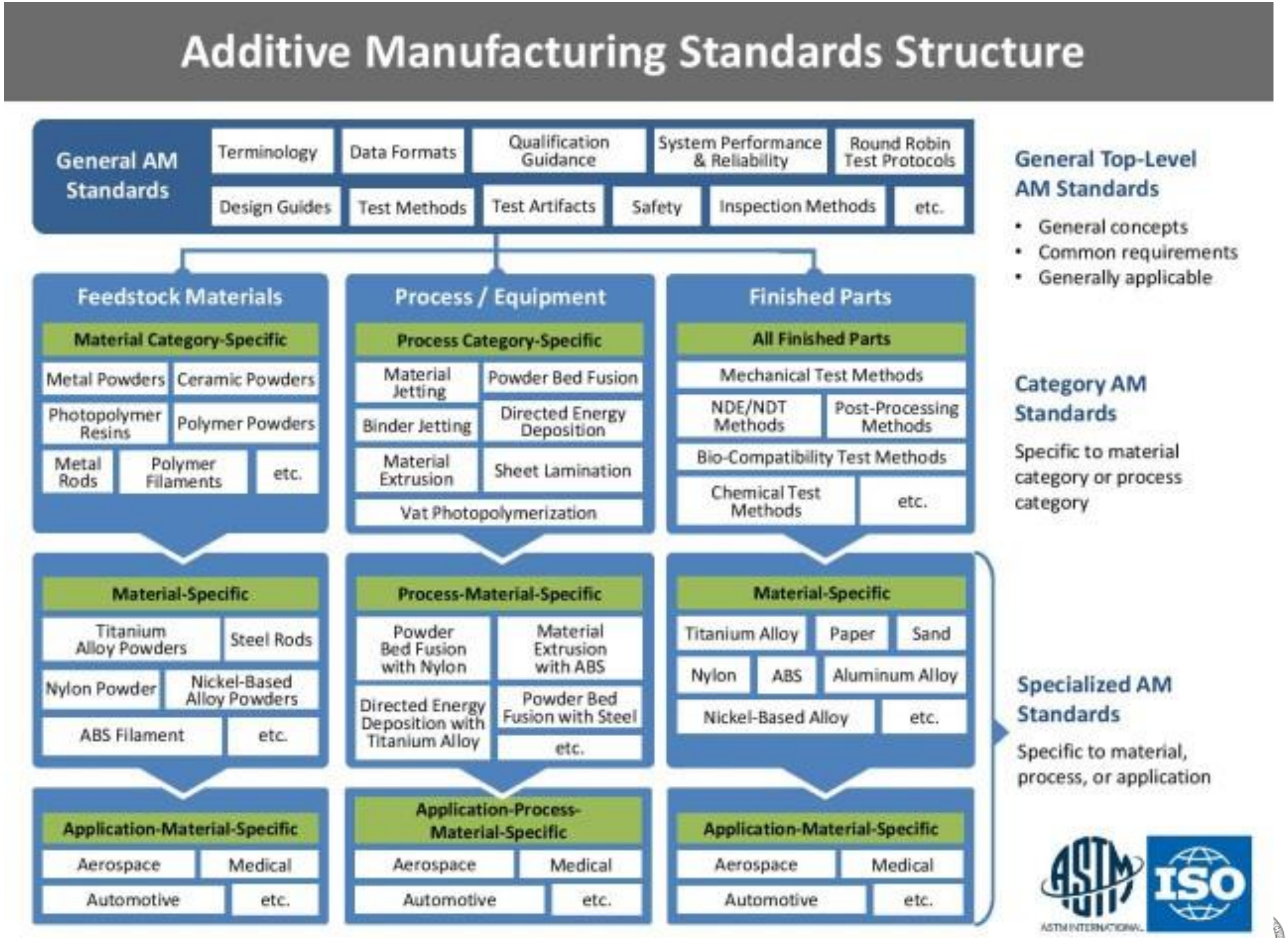
Introduction

Additive Layer Manufacturing (ALM) is a production process based on a processing idea called "Material Incremental Manufacturing" (MIM) in which a component is created, starting from a 3D model, by deposition material layer by layer





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Classification

CATEGORIES	TECHNOLOGIES	PRINTED "INK"	POWER SOURCE	STRENGTHS / DOWNSIDES
Material Extrusion	Fused Deposition Modeling (FDM)	Thermoplastics, Ceramic slurries, Metal pastes	Thermal Energy	• Inexpensive extrusion machine • Multi-material printing • Limited part resolution • Poor surface finish
	Contour Crafting			
Powder Bed Fusion	Selective Laser Sintering (SLS)	Polyamides /Polymer	High-powered Laser Beam	• High Accuracy and Details • Fully dense parts • High specific strength & stiffness • Powder handling & recycling • Support and anchor structure • Fully dense parts • High specific strength and stiffness
	Direct Metal Laser Sintering (DMLS)	Atomized metal powder (17-4 PH stainless steel, cobalt chromium, titanium Ti6Al-4V), ceramic powder		
	Selective Laser Melting (SLM)			
	Electron Beam Melting (EBM)		Electron Beam	
Vat Photopolymerization	Stereolithography (SLA)	Photopolymer, Ceramics (alumina, zirconia, PZT)	Ultraviolet Laser	• High building speed • Good part resolution • Overcuring, scanned line shape • High cost for supplies and materials
Material Jetting	Polyjet / Inkjet Printing	Photopolymer, Wax	Thermal Energy / Photocuring	• Multi-material printing • High surface finish • Low-strength material
Binder Jetting	Indirect Inkjet Printing (Binder 3DP)	Polymer Powder (Plaster, Resin), Ceramic powder, Metal powder	Thermal Energy	• Full-color objects printing • Require infiltration during post-processing • Wide material selection • High porosites on finished parts
Sheet Lamination	Laminated Object Manufacturing (LOM)	Plastic Film, Metallic Sheet, Ceramic Tape	Laser Beam	• High surface finish • Low material, machine, process cost • Decubing issues
Directed Energy Deposition	Laser Engineered Net Shaping (LENS) Electronic Beam Welding (EBW)	Molten metal powder	Laser Beam	• Repair of damaged / worn parts • Functionally graded material printing • Require post-processing machine

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Cosine Additive
nScrypt
microTEC
3DCERAM
LUXeXCEL
CMET CMET Inc.
formlabs
voxeljet
D-MEC
NASA
envisionTEC
ExOne Digital Part Materialization
3D Systems
RepRap
Advanced Solutions Life Sciences
Solidscape High Precision 3D Printers
3Geometry
AFS
vito
MicroFab Technologies • Inc.
Ultimaker
富奇凡科技 FoChif Tech
TRUMPF
blueprinter® empowering people to create
xlaFORM
RENISHAW apply innovation™
sisma Group
ASIGA
Z Corporation
Cyfuse
DWS
CAD to METAL arcam Arcam AB
SLM Solutions
Sciaky Inc.
Fabrisonic
carima
LITHOZ
FUJIFILM Value from Innovation
DM3D
eos e-Manufacturing Solutions
Tiertime
Kevvox
TNO innovation for life
mcor 10 Celebrating ten innovative years
TeVido BioDevices
XJRP
Aspect biosystems
Xery
organovo™
SINTEF
Roland® Roland DGA Store
amtech Advanced Manufacturing Technology
Unirapid
MakerBot Industries
BioBots
HUST Bin Hu
HUAKE 3D
CELLINK
Optomec Production Grade 3D Printers... with a Material Difference
MC Machinery Systems, Inc. a subsidiary of Mitsubishi Corporation
Prodways
Stratasys For a 3D World™
Realizer The Pioneer of 3-D Printers
ConceptLaser
Microfabrica
KEYENCE

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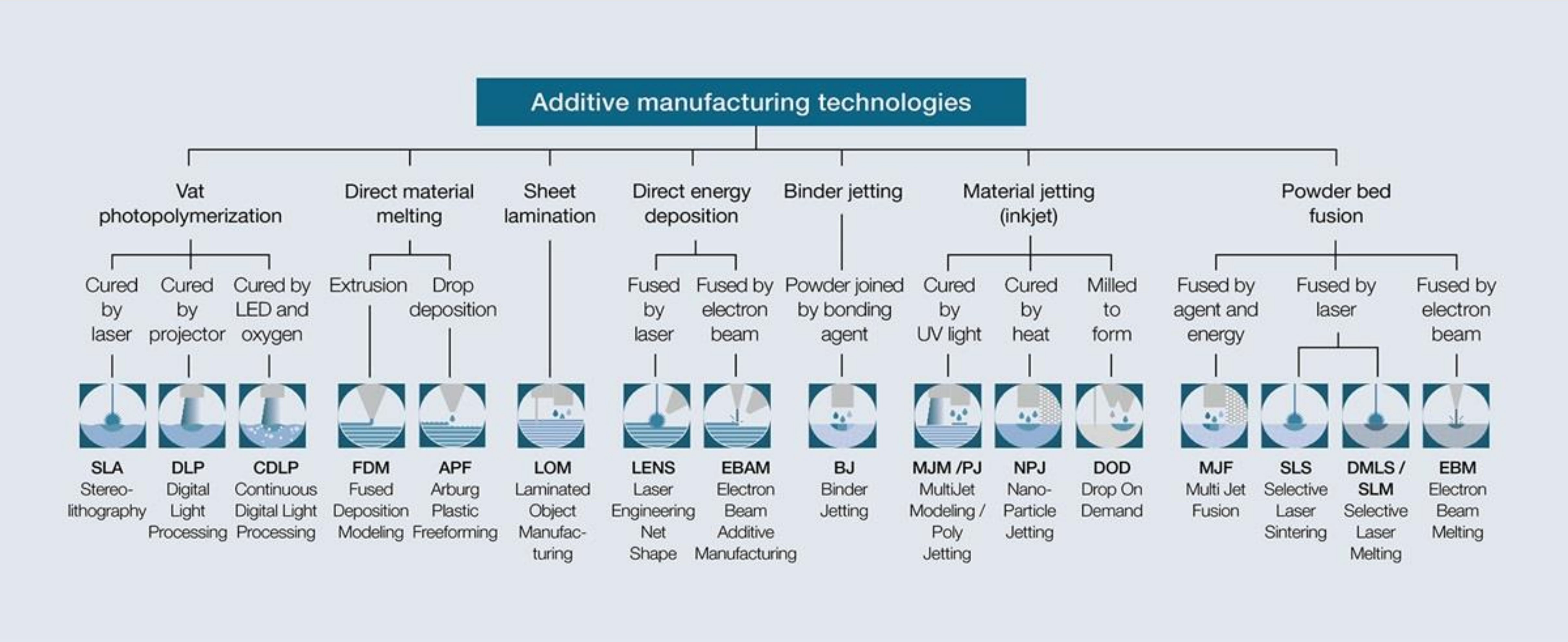

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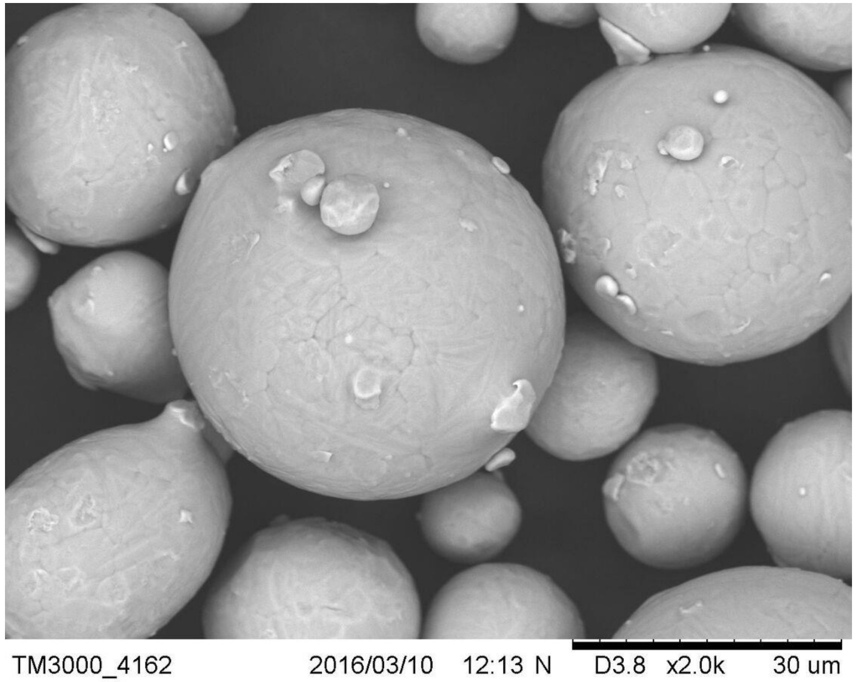
ADDITIVE MANUFACTURING OF METALS

CLASSIFICATION BASED ON FEEDSTOCK MATERIAL

- **WIRE**
- **POWDER**



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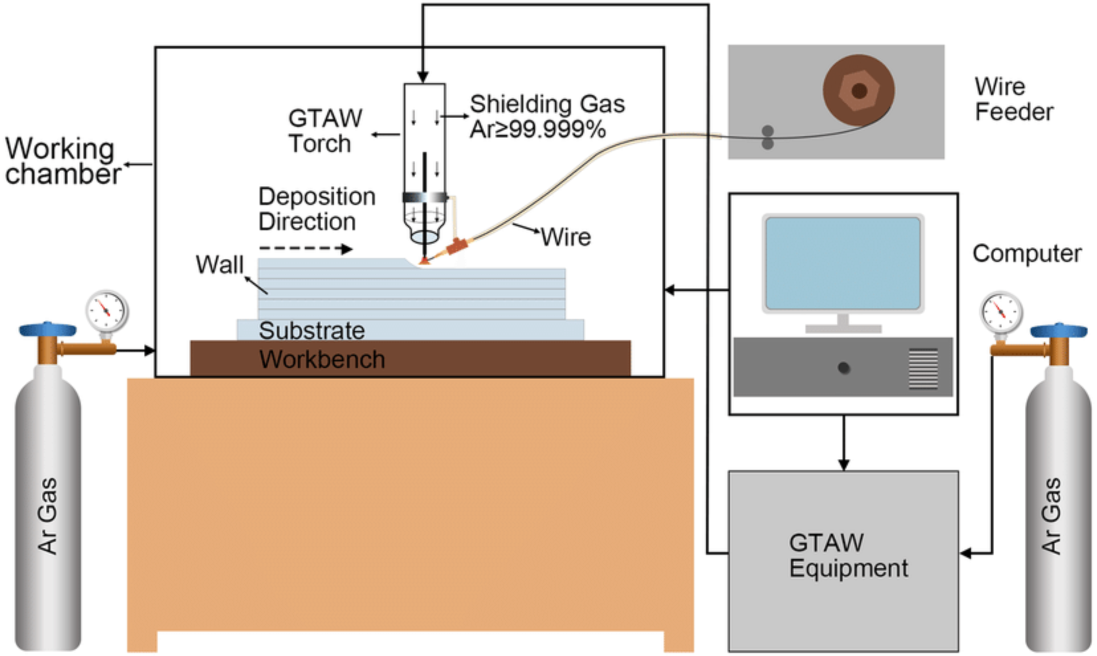
WIRE ARC ADDITIVE MANUFACTURING



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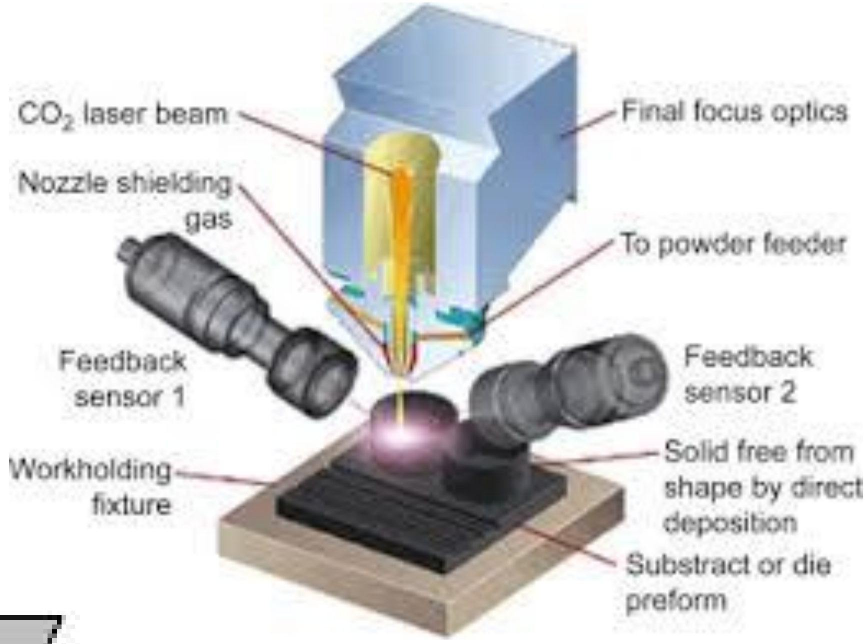
DIRECT METAL DEPOSITION



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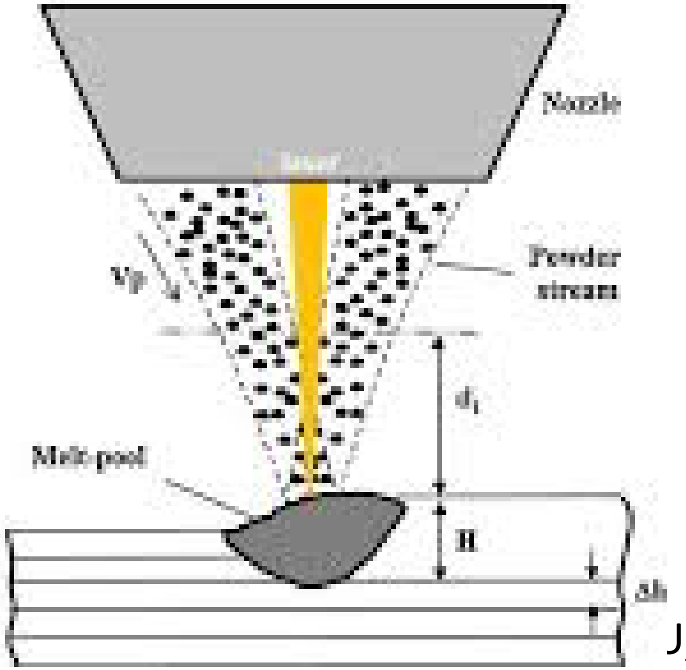

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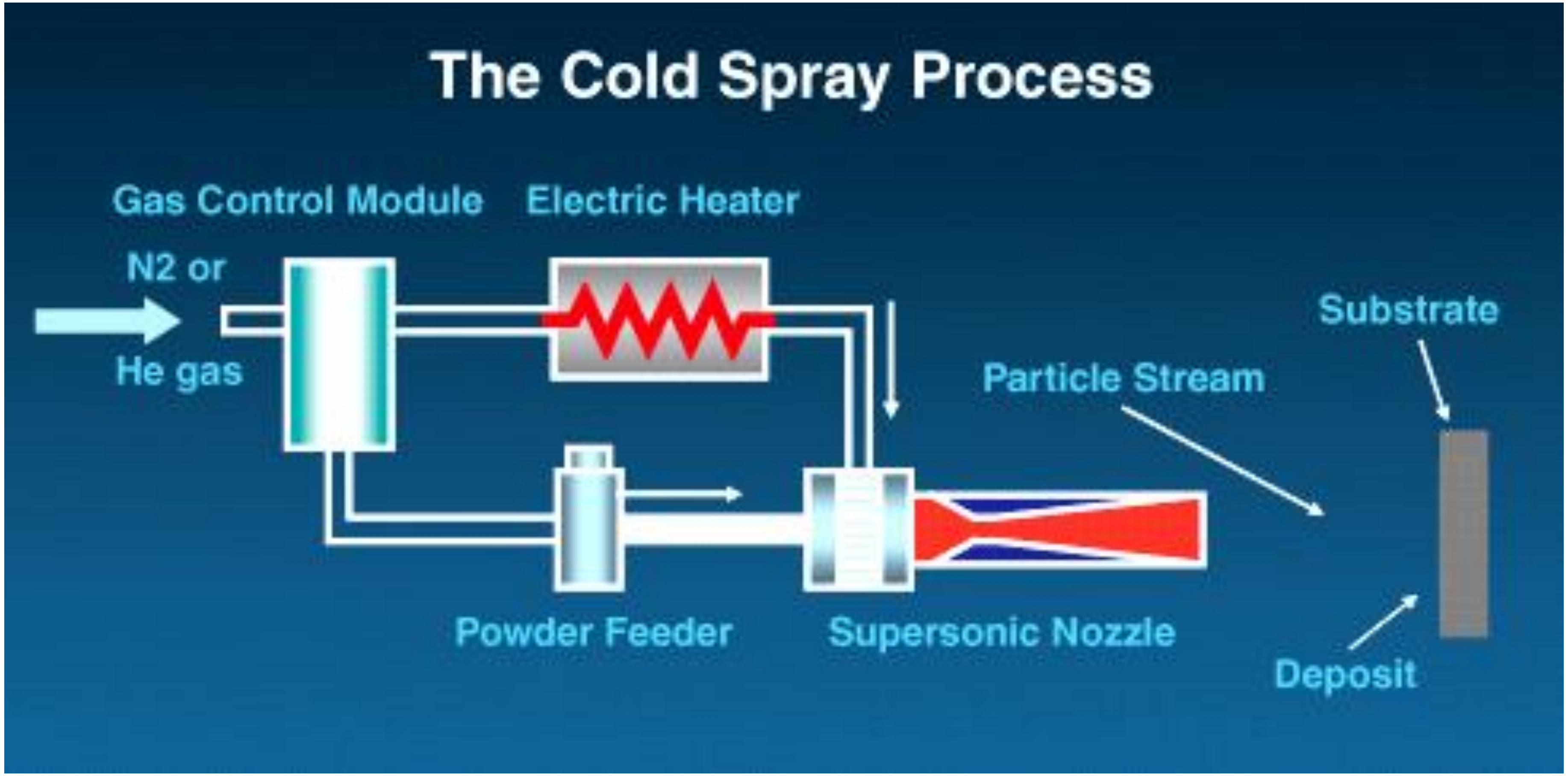
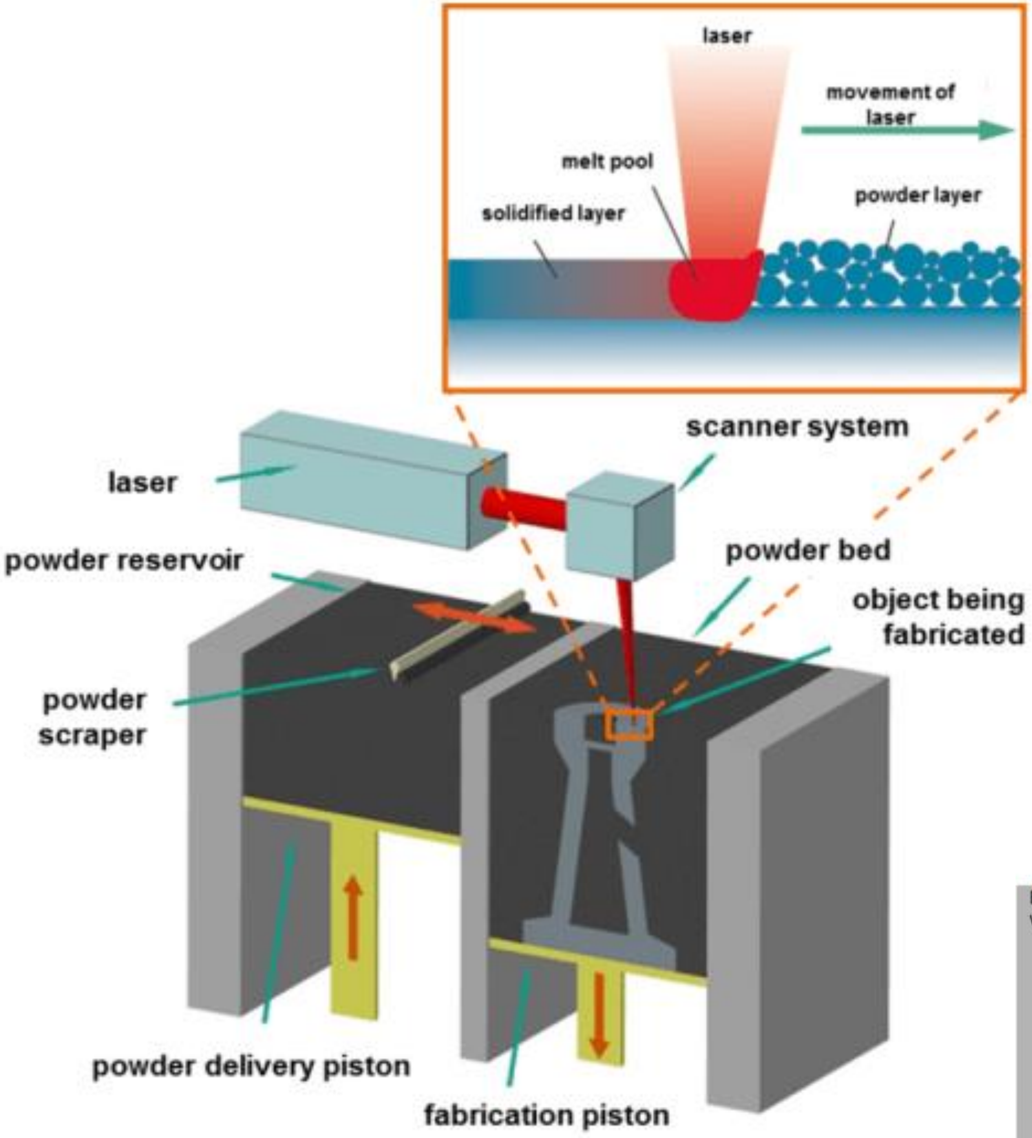
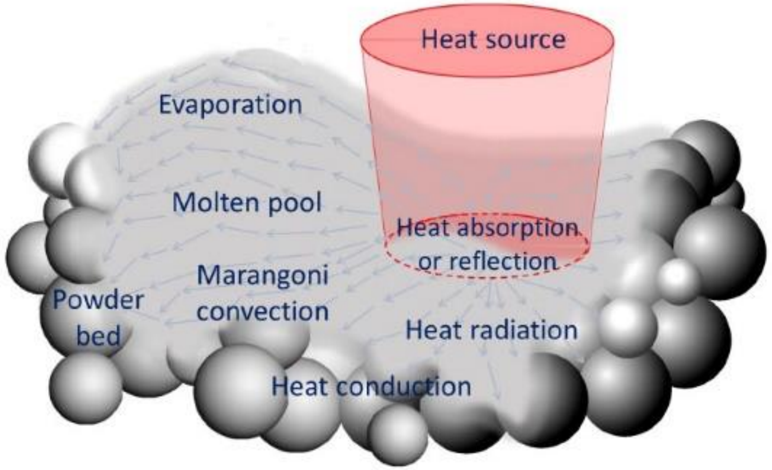
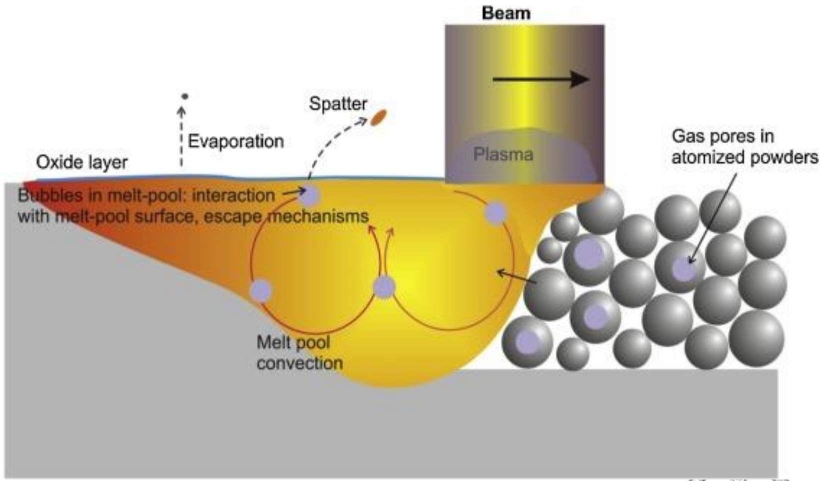
COLD SPRAY DEPOSITION ADDITIVE MANUFACTURING



POWDER BED FUSION ADDITIVE MANUFATURING







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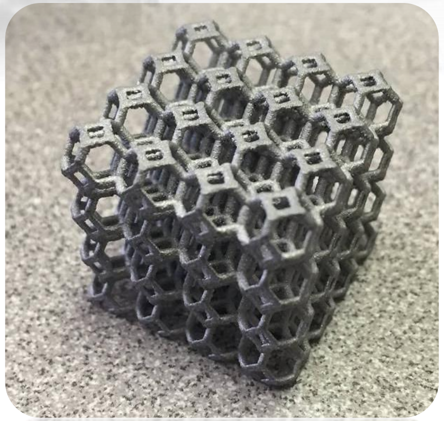
1

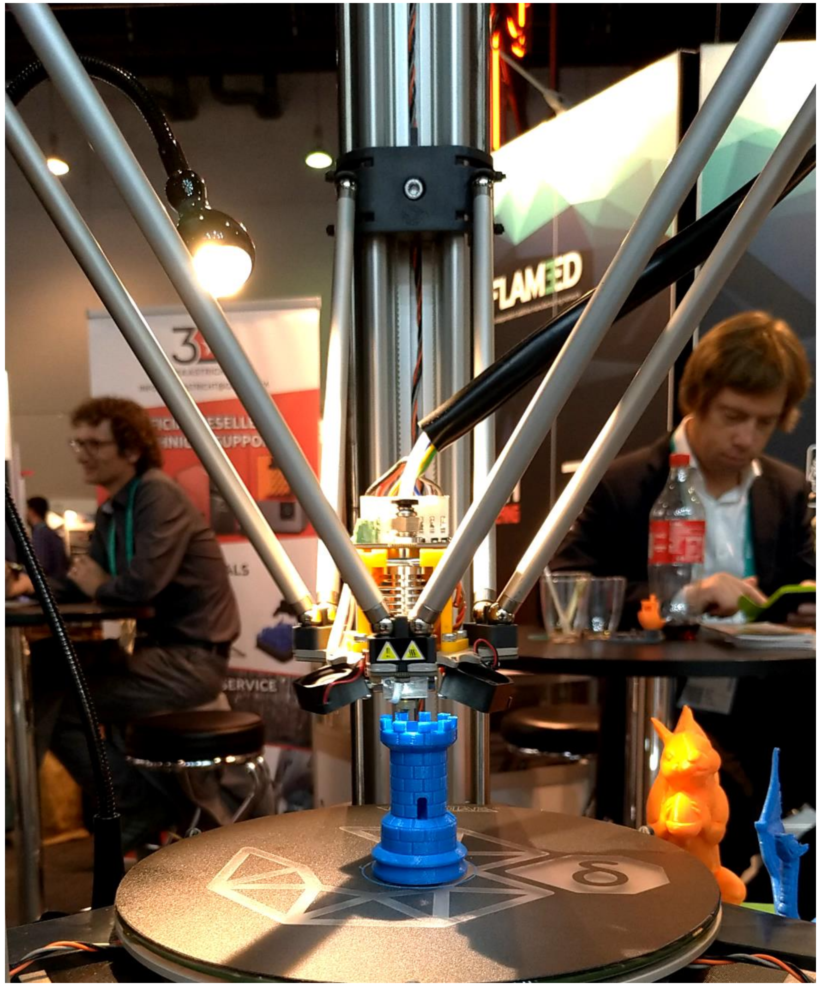
2. SDC

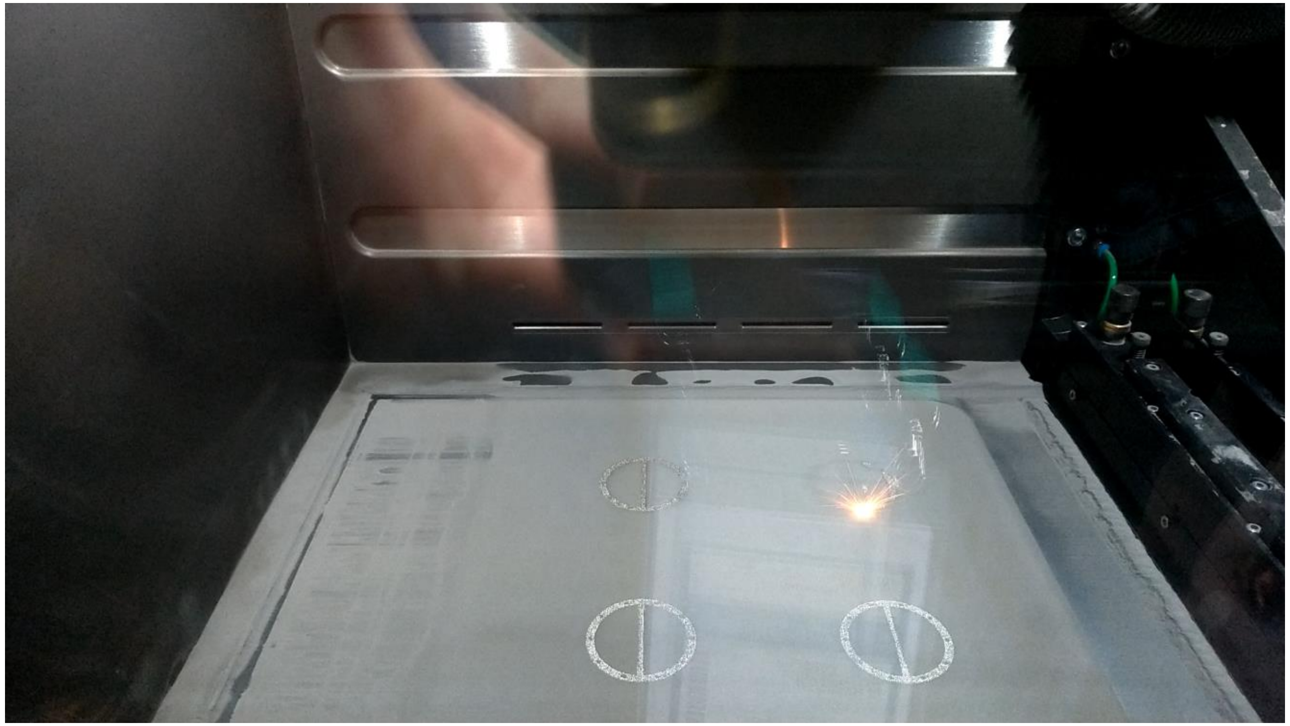


3.
Lattice structure

4. Small Isogrid

2. What You See Is What You Build





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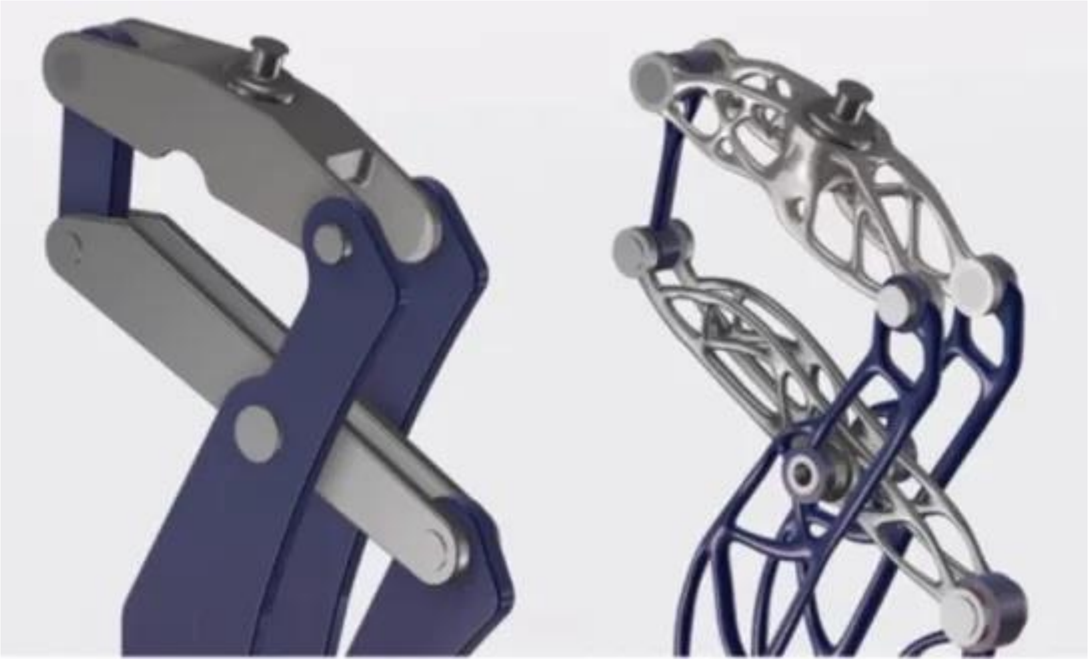
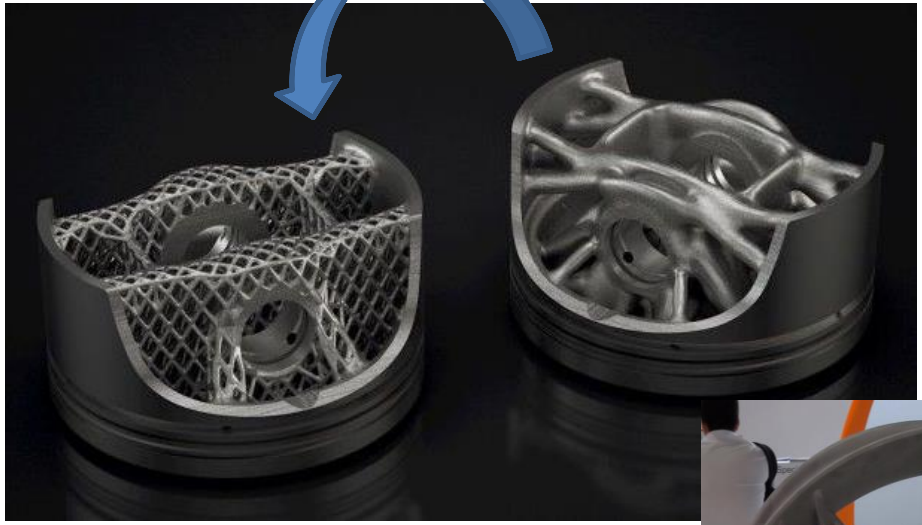


3. Weight Reduction



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TRADITIONAL DESIGN

Source: SAVING project

- A conventional steel buckle weights 155 g[1)]
- Weight should be reduced on a like-for-like basis within the SAVING project
- Project partners are Plunkett Associates, Crucible Industrial Design, EOS, 3T PRD, Simpleware, Delcam, University of Exeter

AM OPTIMIZED DESIGN

Source: SAVING project

- Titanium buckle designed with AM weighs 70 g – reduction of 55%
- For an Airbus 380 with all economy seating (853 seats), this would mean a reduction of 72.5 kg
- Over the airplane's lifetime, 3.3 million liters of fuel or approx. EUR 2 m could be saved, assuming a saving of 45,000 liters per kg and airplane lifetime

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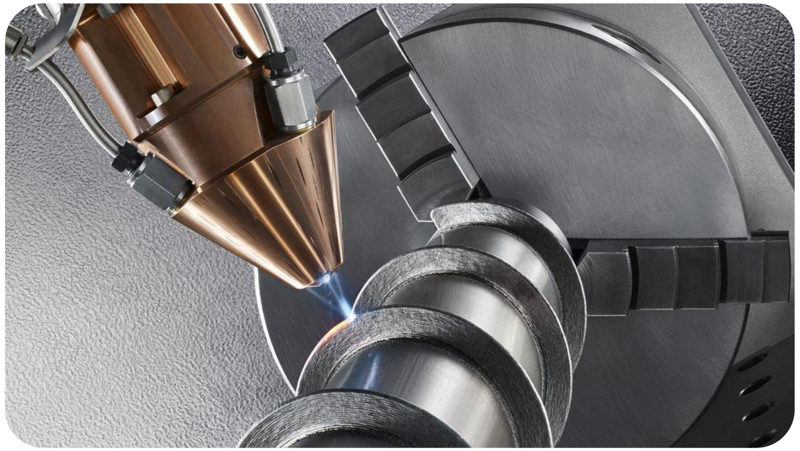
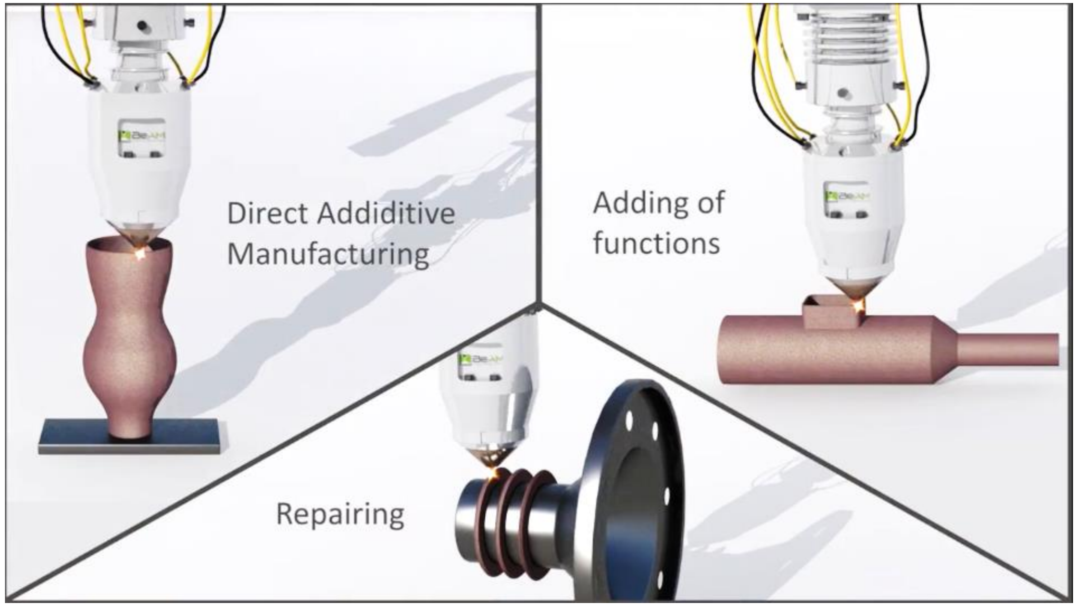
5. Customization

6. DLD: repairing





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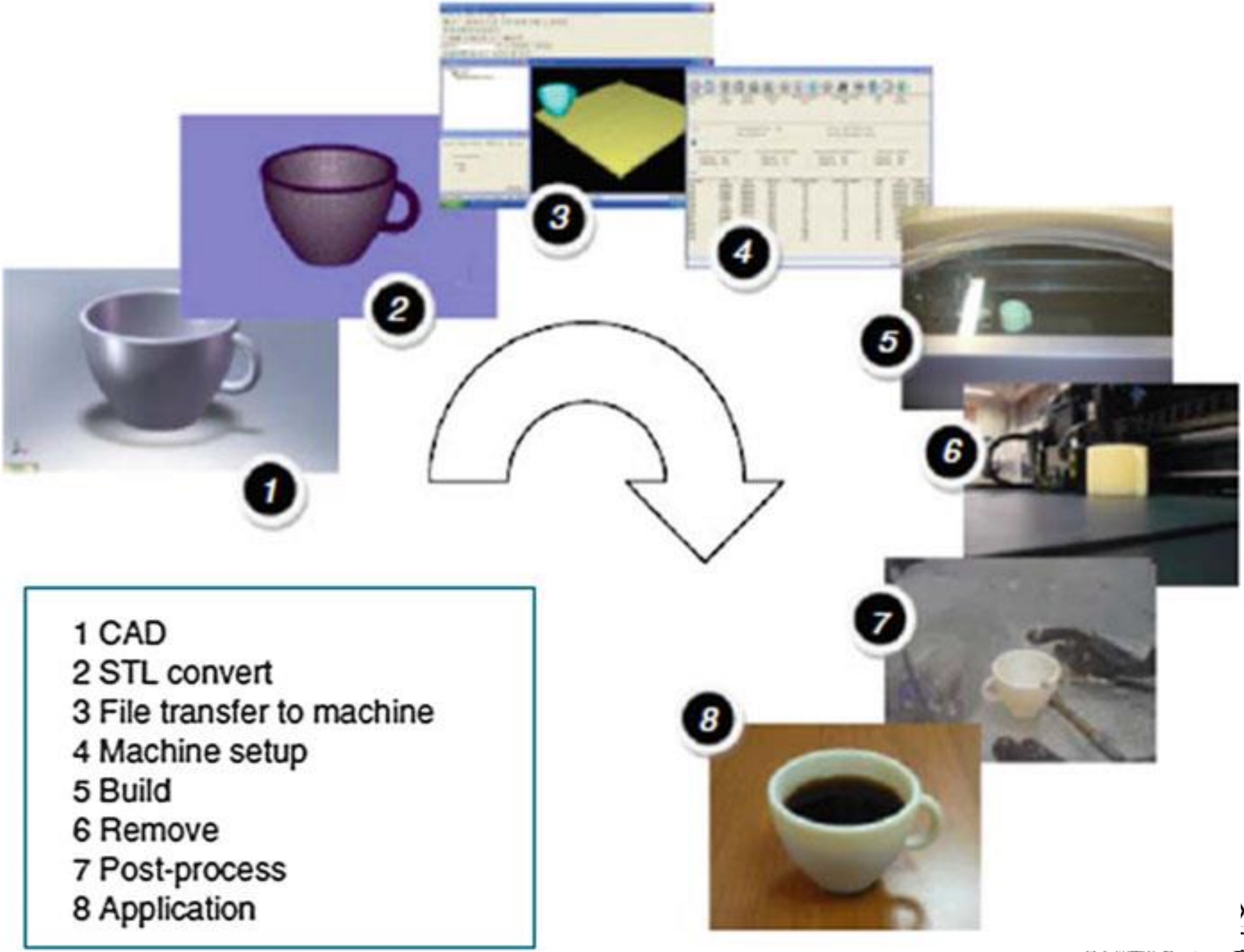
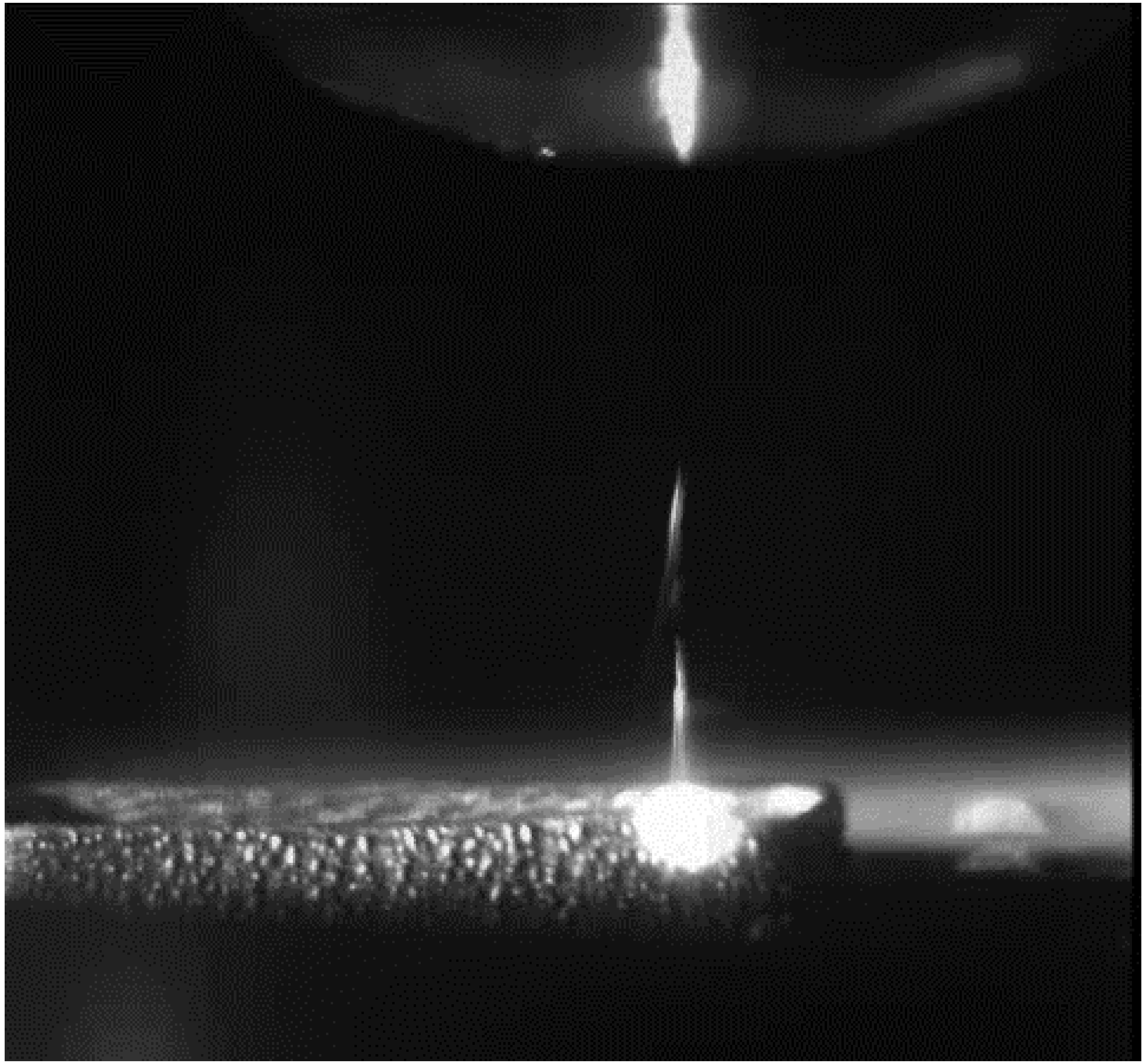
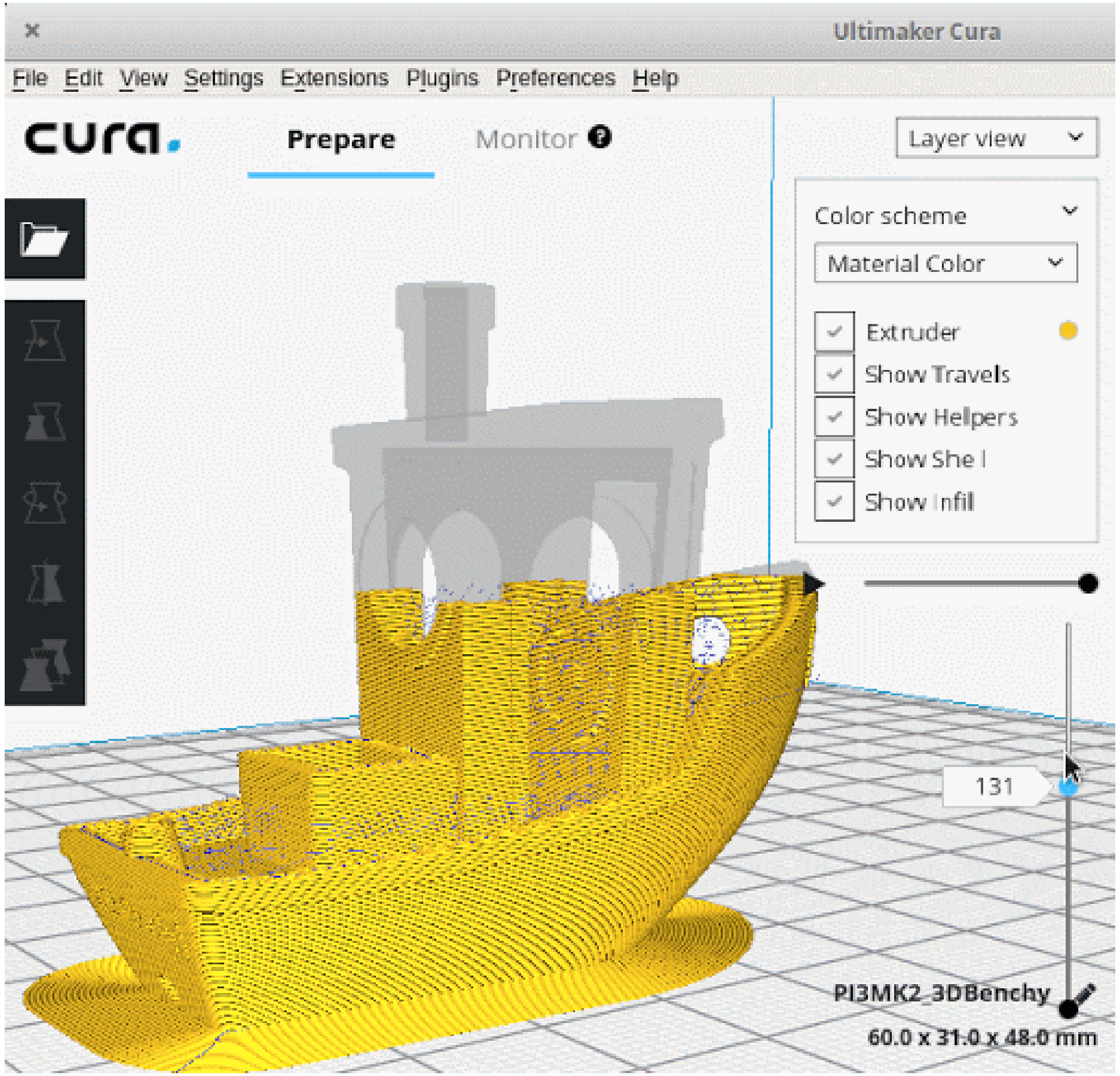
Additive Manufacturing (AM), Digital Fabrication


1 CAD
2 STL convert
3 File transfer to machine
4 Machine setup
5 Build
6 Remove
7 Post-process
8 Application





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DCU, 06/09/2018

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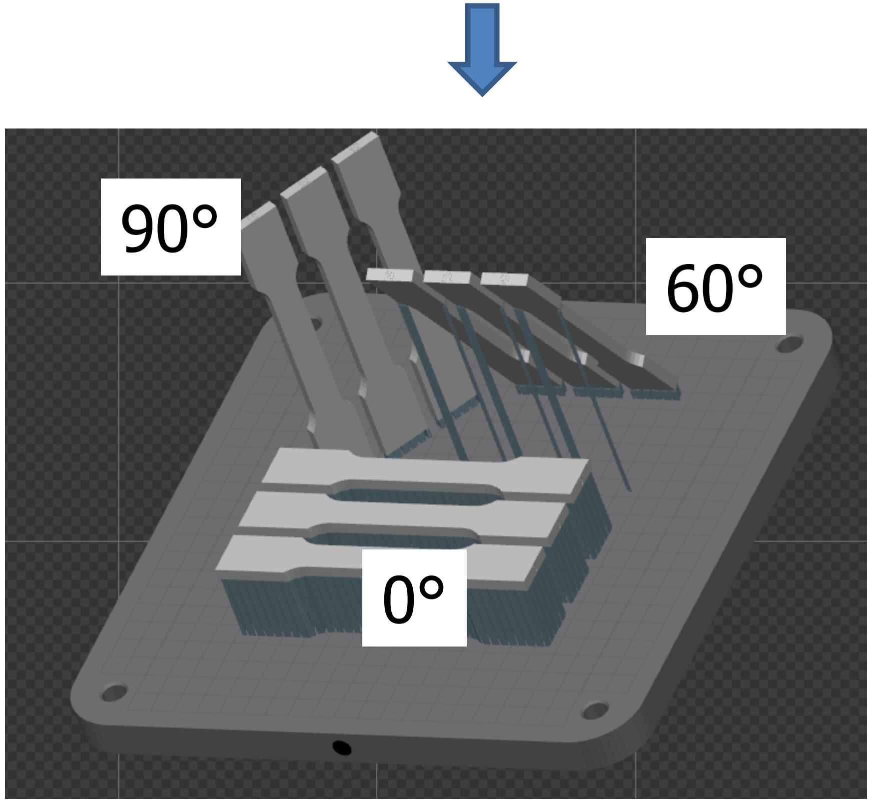
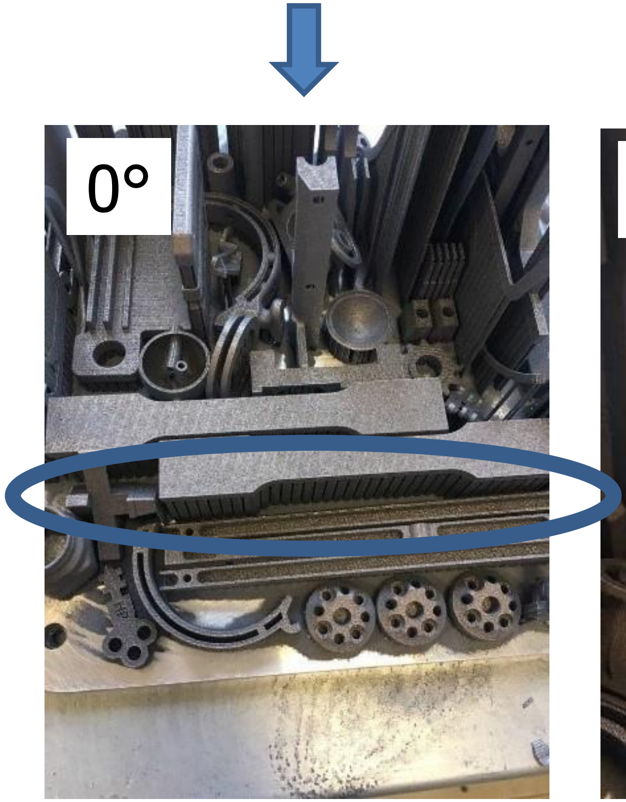
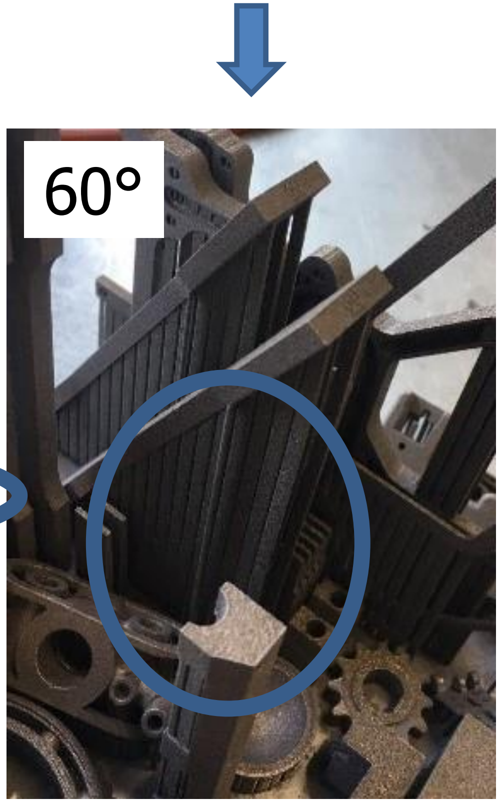


90°
60°
0°

90°



0°



60°

Polishing

Sandblasting

Sandpapering

Vapor smooth

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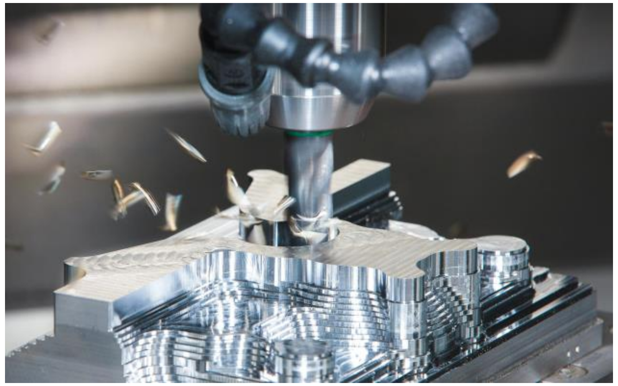
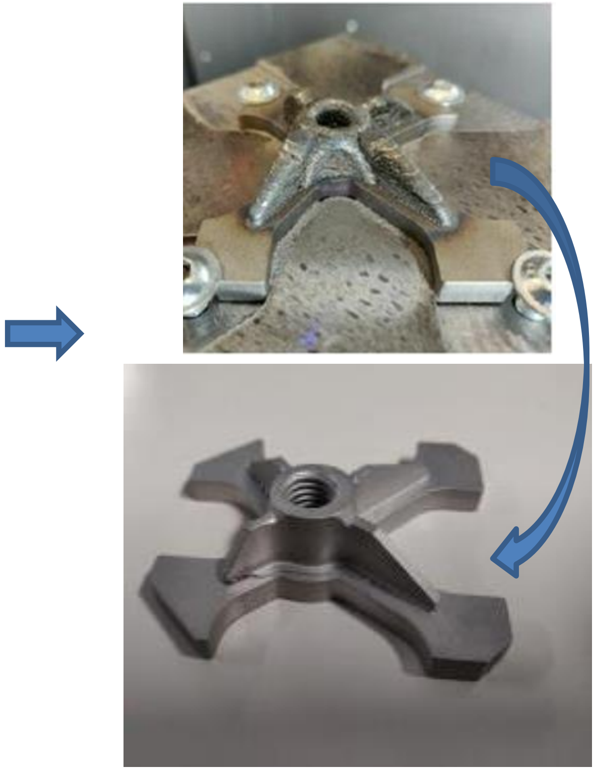
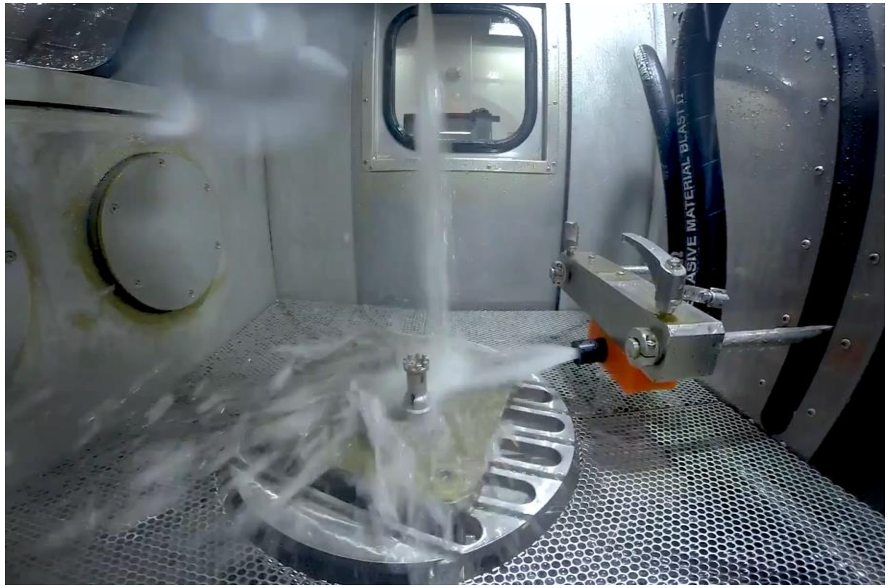
CNC MACHINING





Chemical Polishing



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8. Application

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POWDER BED FUSION ADDITIVE MANUFATURING

SOME FUNDAMENTAL ASPECTS

MATERIALS
- DEVELOP THE PROCESS FOR MORE MATERIALS

POWDERS
- HANDLING
- RE-USE
- CHOICE (SIZE, SHAPE, DISTRIBUTION, FABRICATION)
- MIX (TO TAILOR THE PROPERTIES OF THE COMPONENT

PROCESS
- PARAMETERS (POWER, SCAN SPEED, LAYER THICKNESS, GAS)
- REPETEABILITY (DIRECTION OF GROWTH, POSITION WITHIN THE BUILDING CHAMBER, ANISOTROPY)
- MAXIMUM DIMENSIONS
- DEFECTS (POROSITIES, RESIDUAL STRESSES, SURFACE ROUGHNESS)

POST TREATMENTS
- HOT ISOSTATIC PRESSING (REDUCE POROSITIES)
- HEAT TREATMENT (TAILOR MICROSTRUCTURE AND STRESS RELIEF)
- SURFACE TREATMENTS (IMPROVE SURFACE FINISHING)

TOPICS COVERED IN THIS PRESENTATION

POWDERS

- CHOICE
- MIX
- HANDLING
- RE-USE

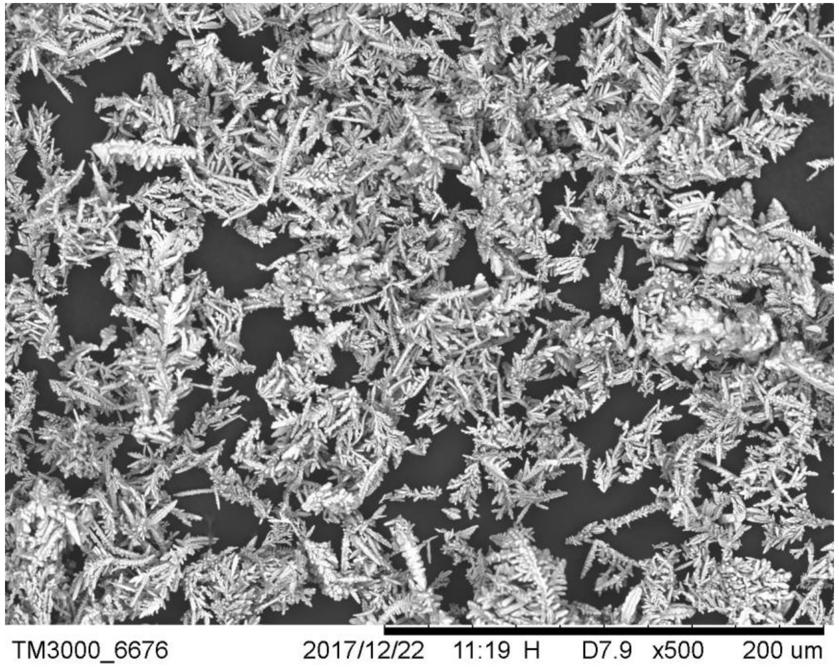
PROCESS

- PARAMETERS CHOICE FOR NEW MATERIALS
- SOLID JOINING OF ADDITIVELY MANUFACTURED PARTS

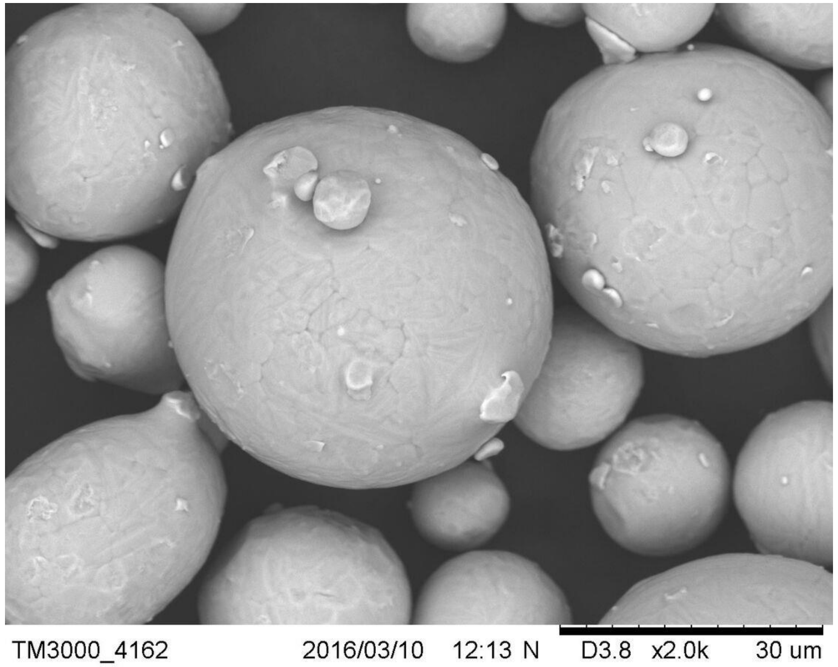
TREATMENTS

- CHEMICAL TREATMENTS
- HEAT TREATMENTS
- FLUIDIZED BED TREATMENTS

POWDERS
CHOICE: FABRICATION METHOD AND SHAPE



MECHANICAL PRODUCED POWDERS



GAS ATOMIZED POWDERS

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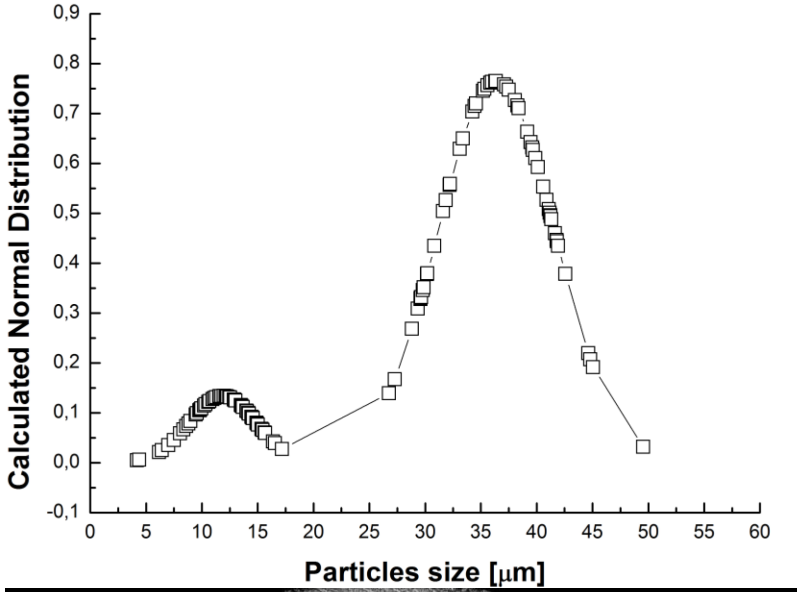
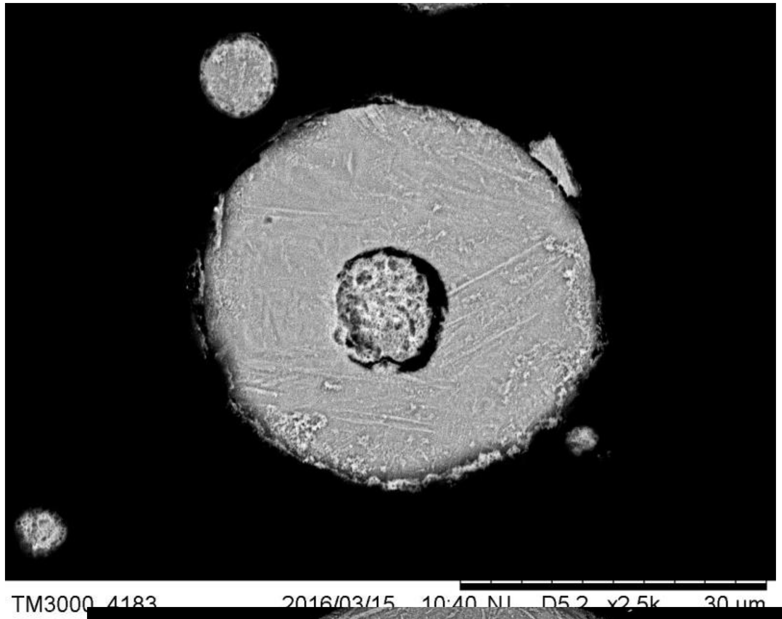
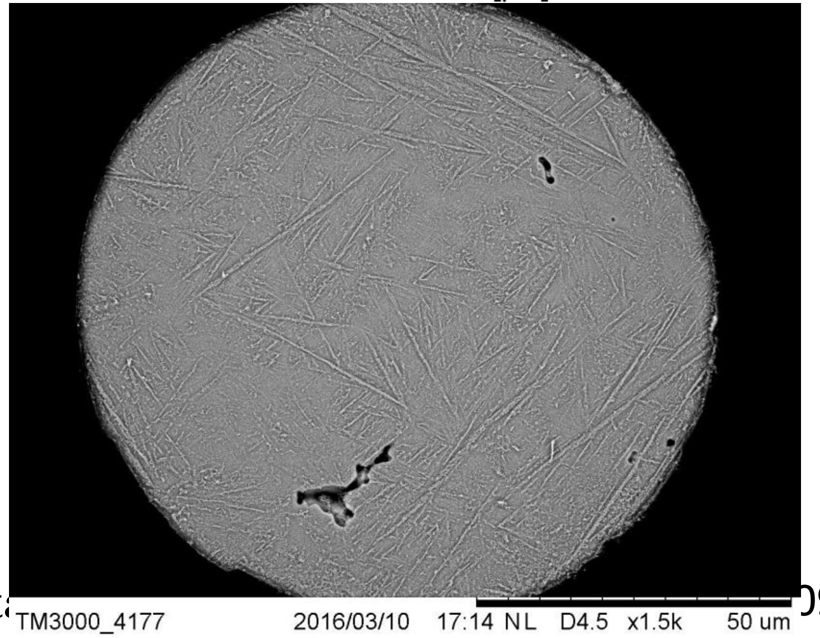
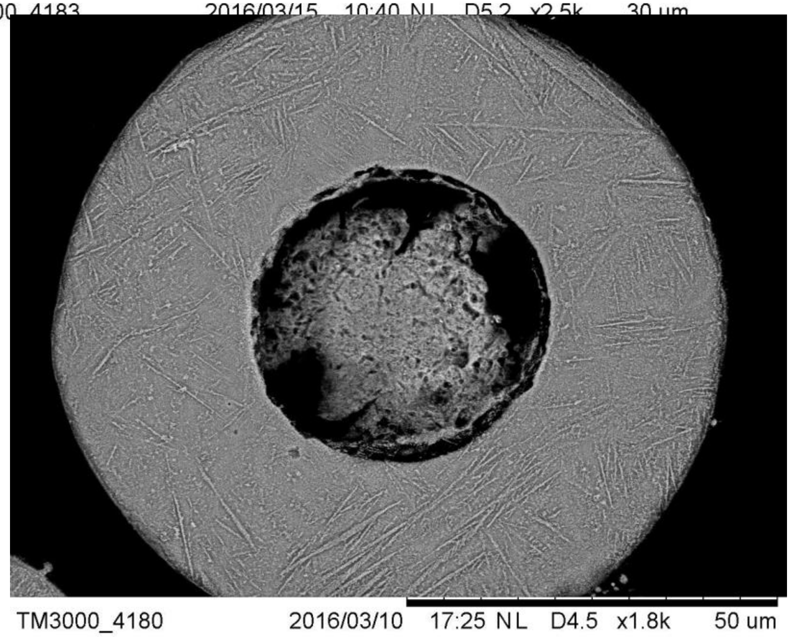
POWDERS

CHOICE: FABRICATION METHOD AND SHAPE









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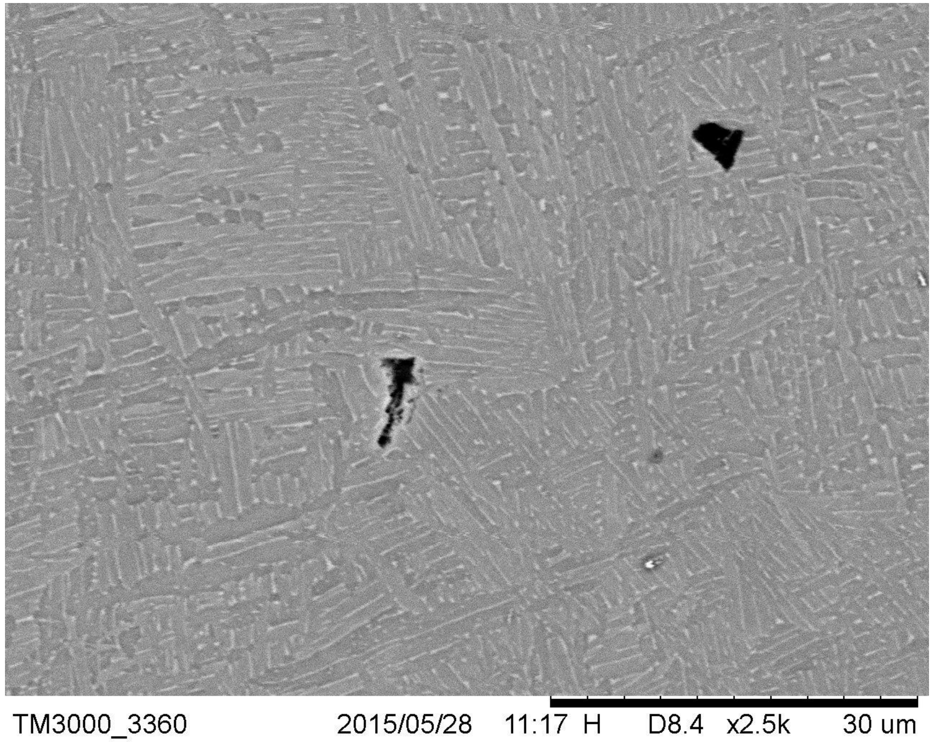
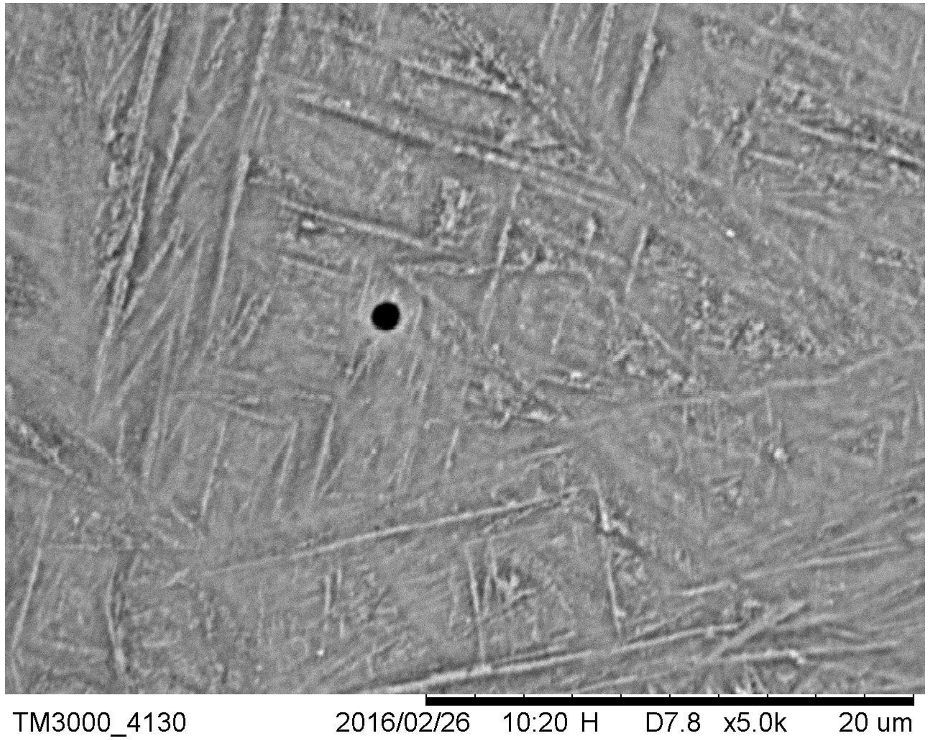
POWDERS

CHOICE: FABRICATION METHOD AND SHAPE





- **CONTROL THE GAS ATOMIZATION PROCESS**
- **CHECK THE POWDERS THAT YOU USE**

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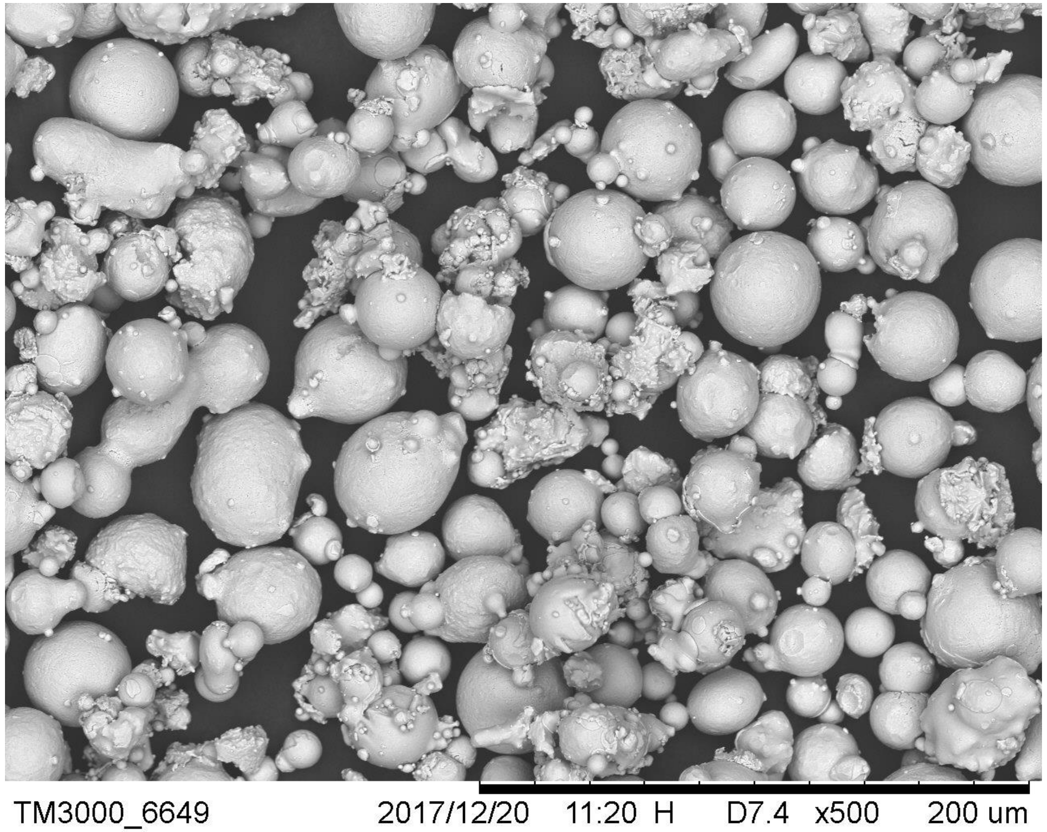
POWDERS

CHOICE: HANDLING AND RE-USE



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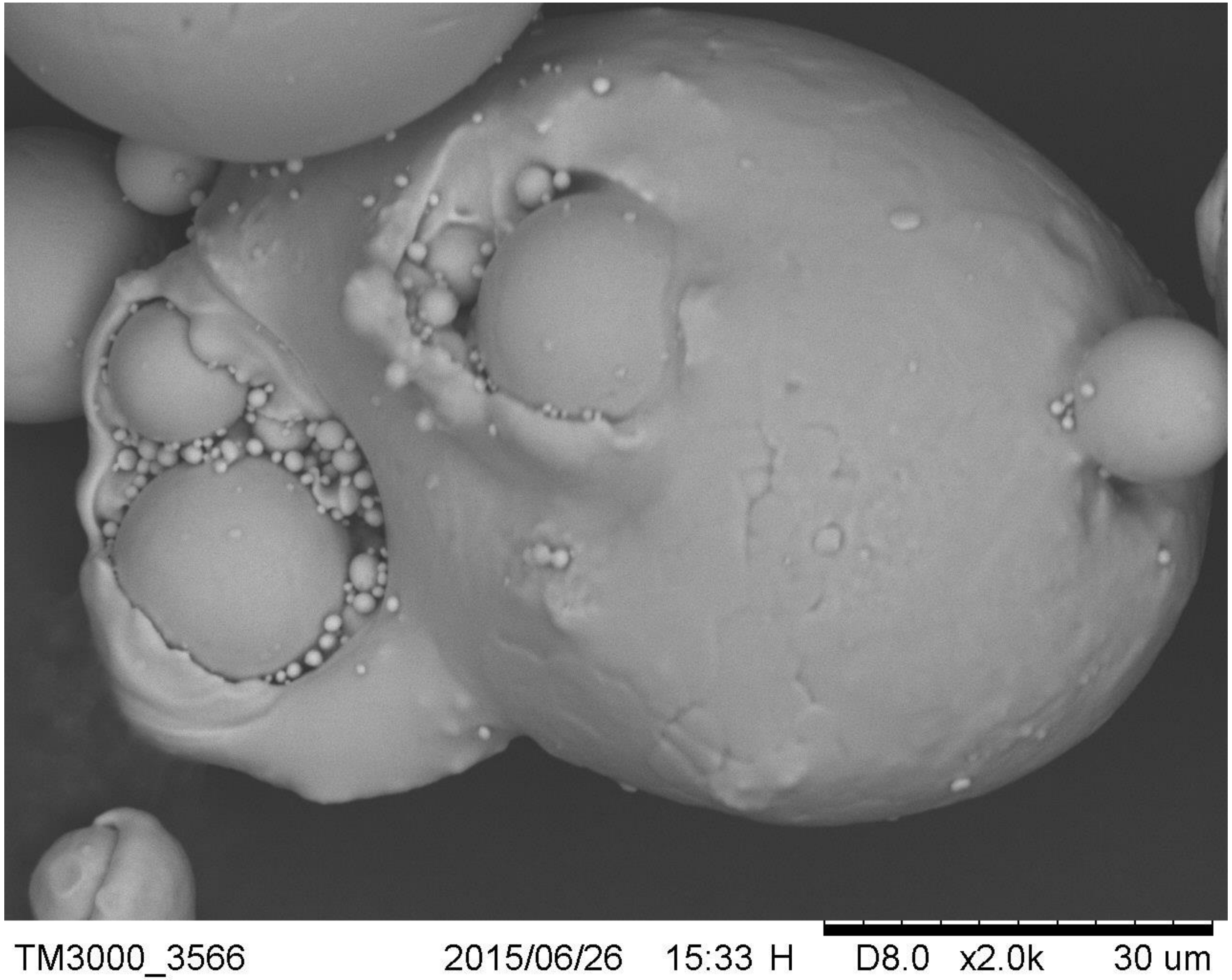

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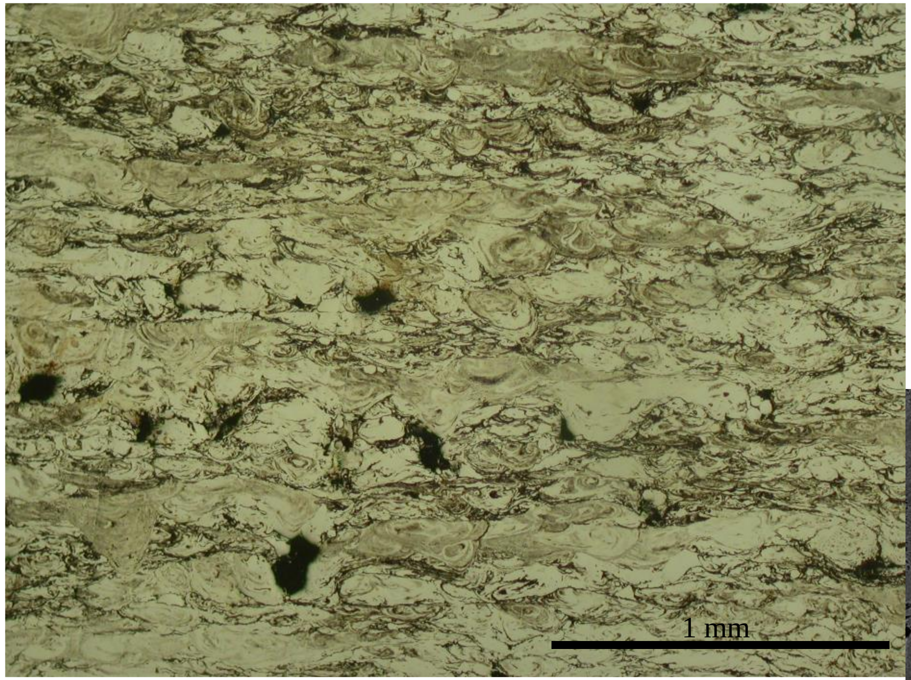
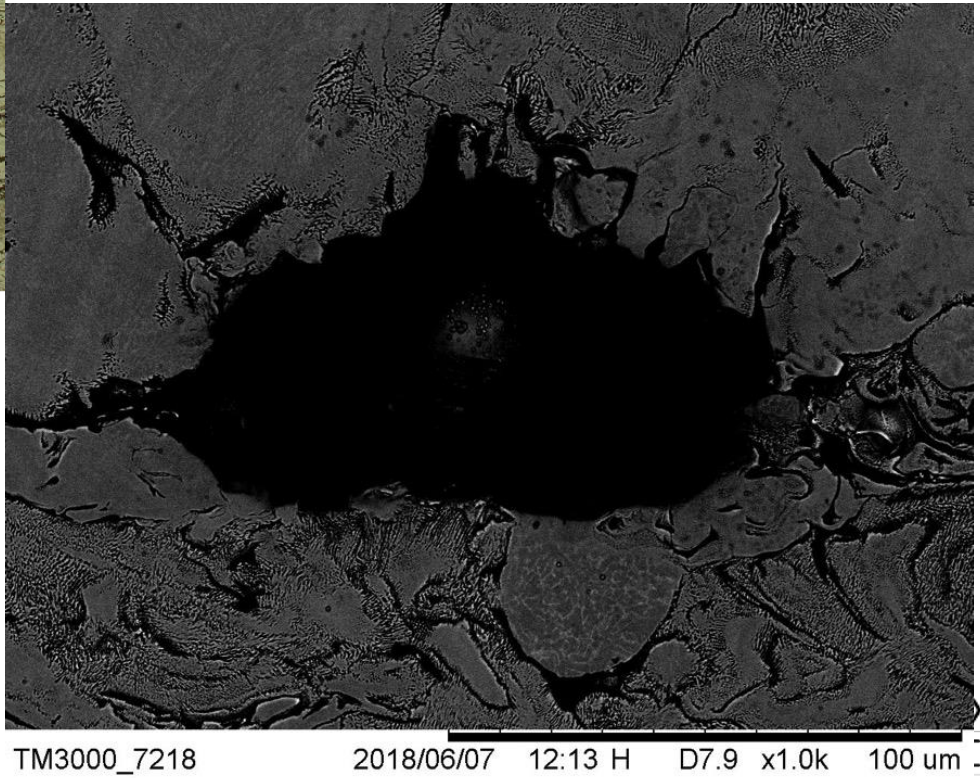
POWDERS

CHOICE: HANDLING AND RE-USE





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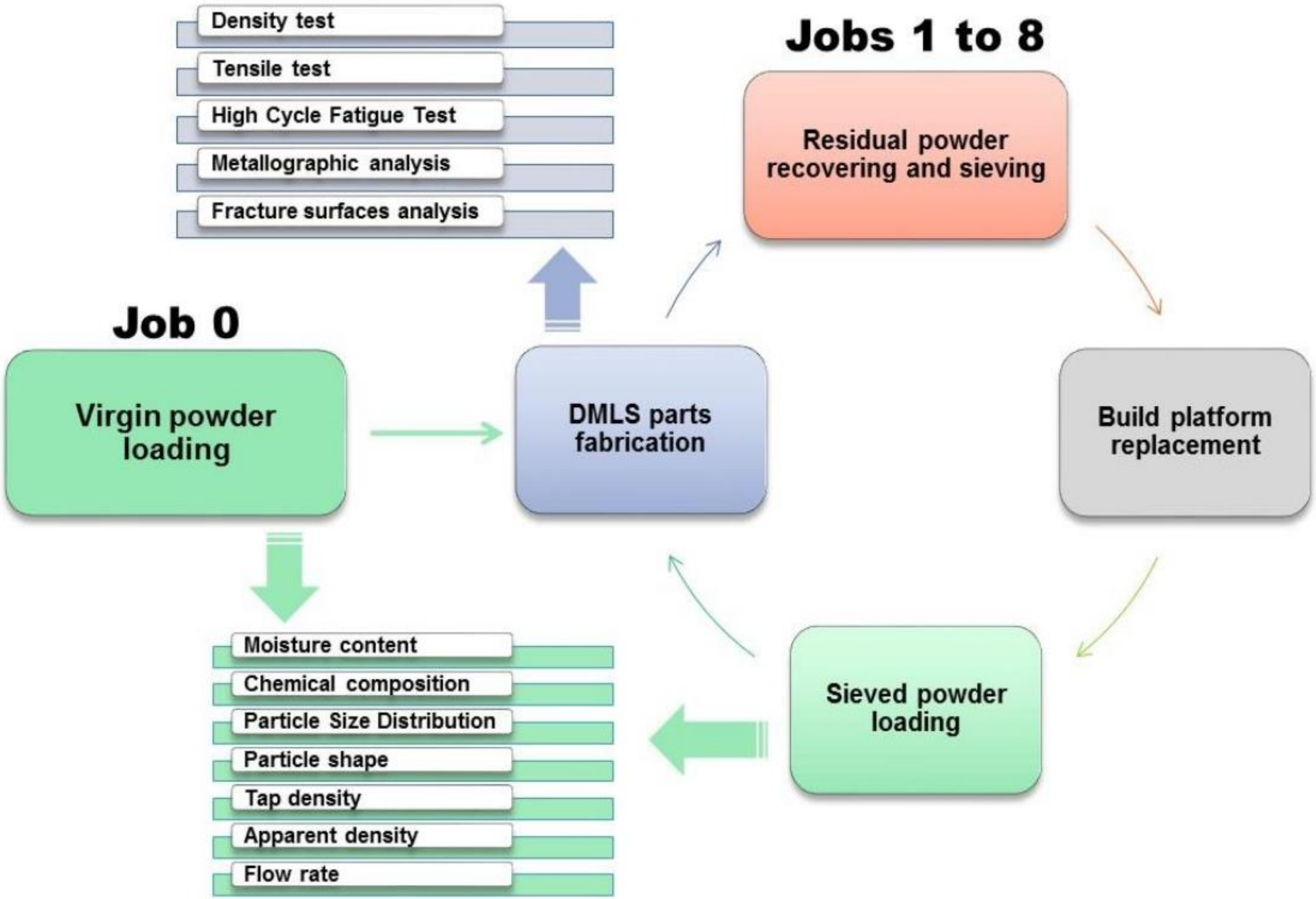

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POWDERS
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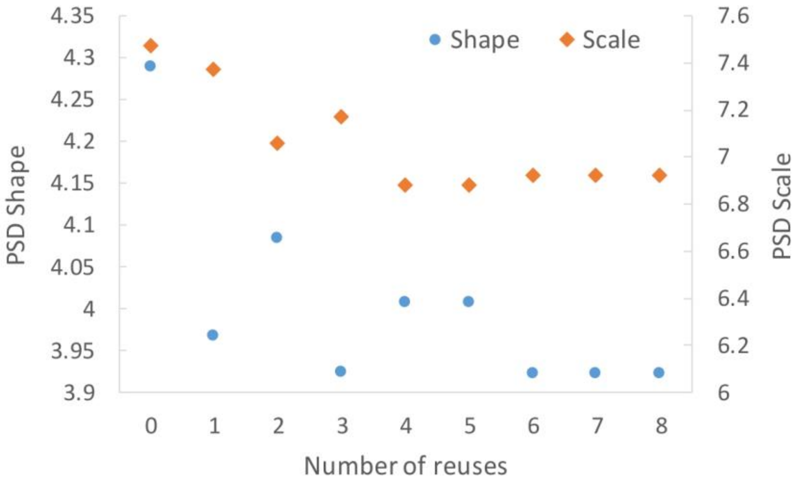

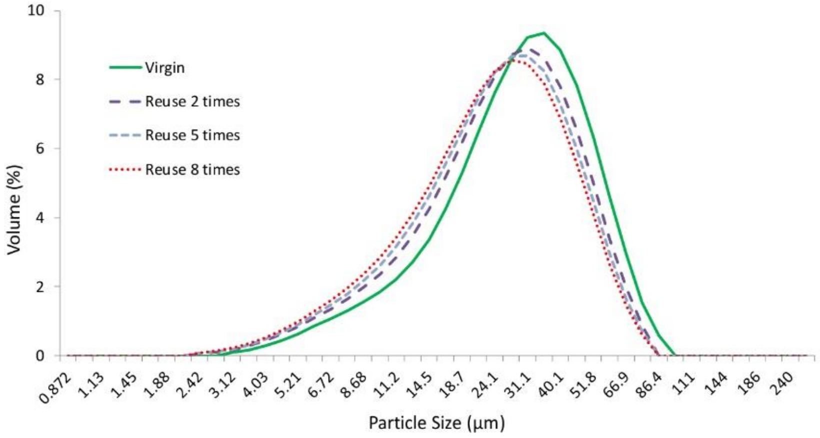

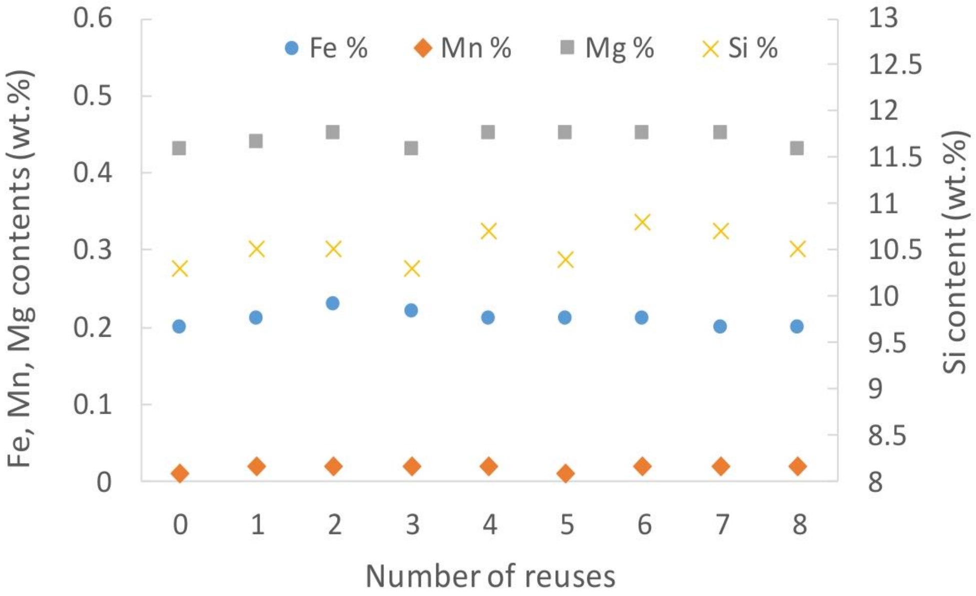

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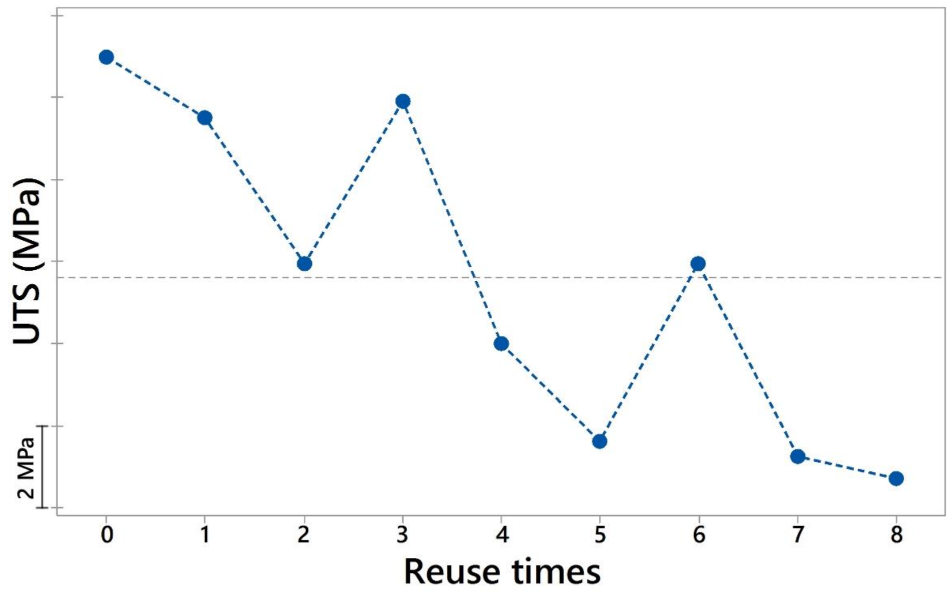

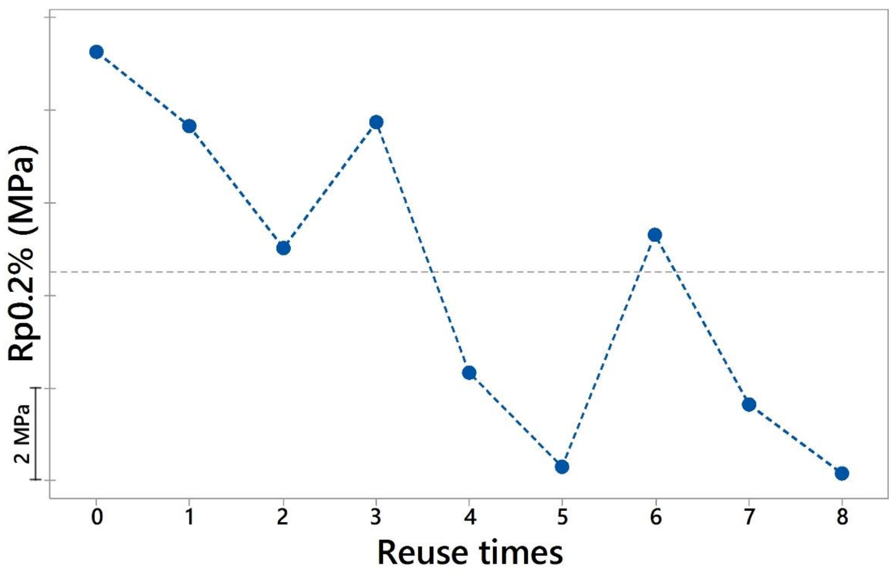

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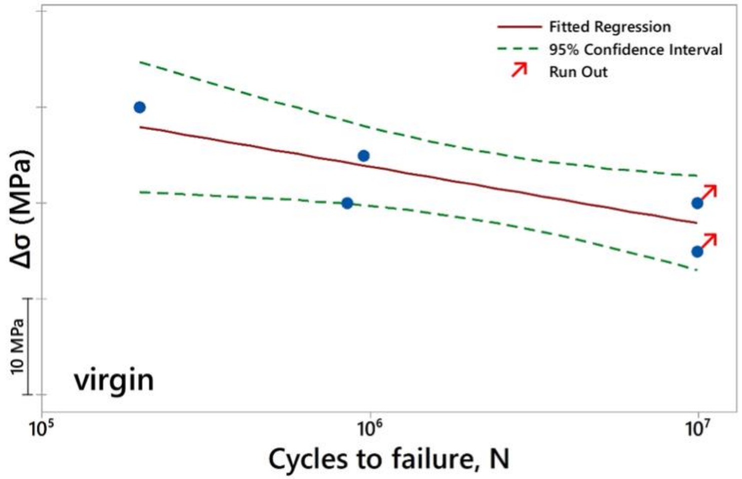
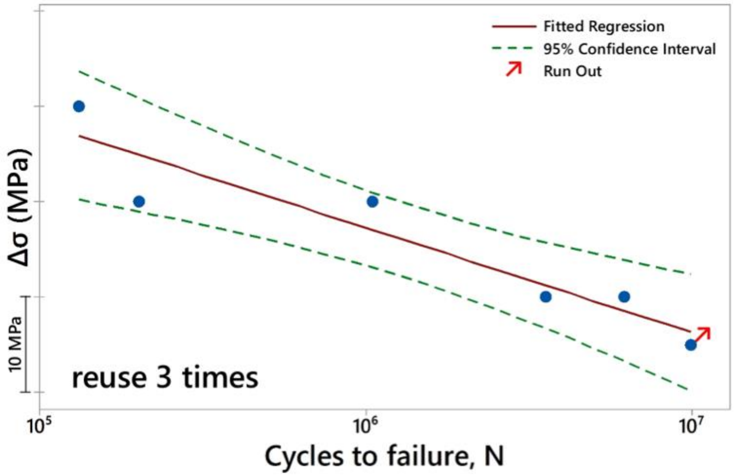
POWDERS

CHOICE: HANDLING AND RE-USE



a)



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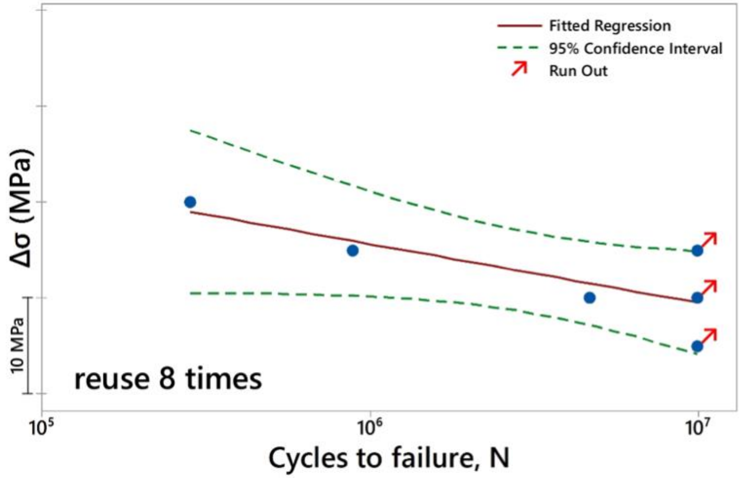

c)

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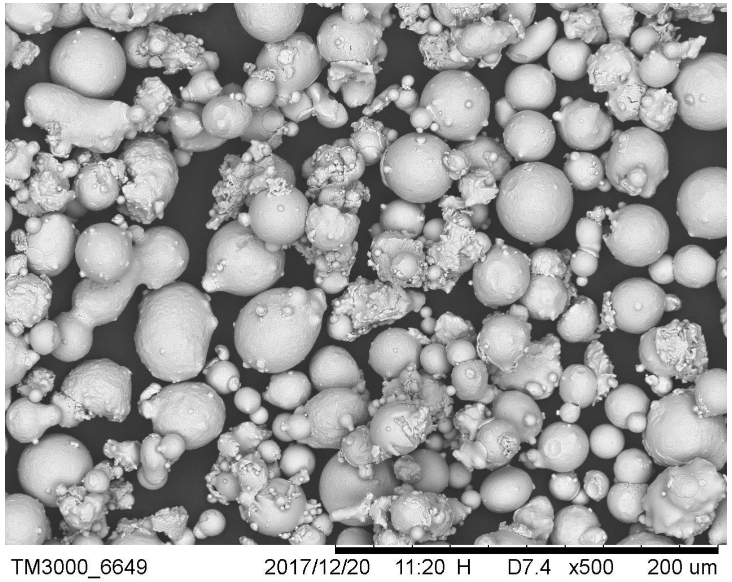
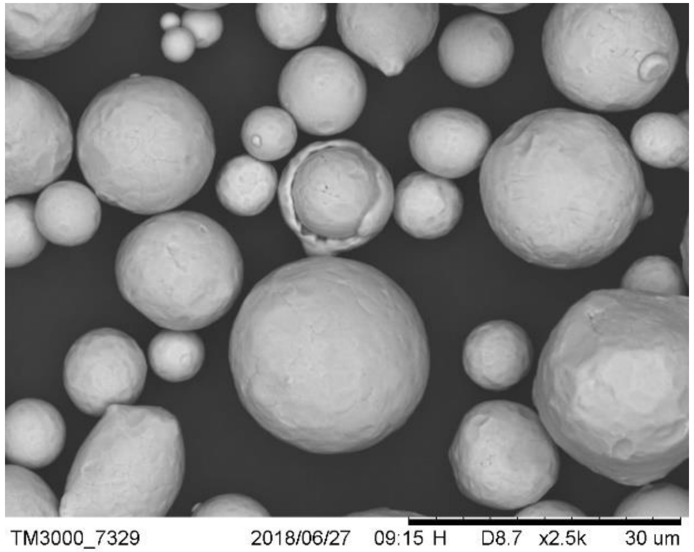
POWDERS

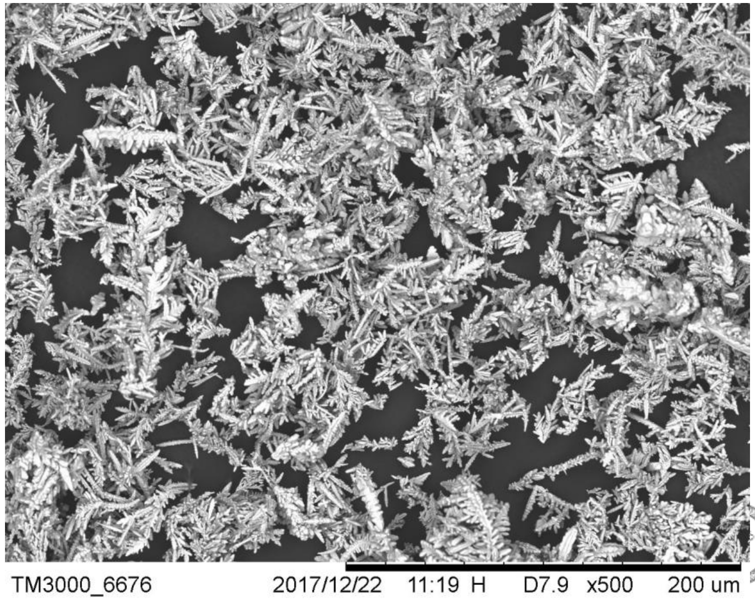
MIX: TAILOR THE PROPERTIES OF THE MATERIAL

INCONEL 718



PURE COPPER





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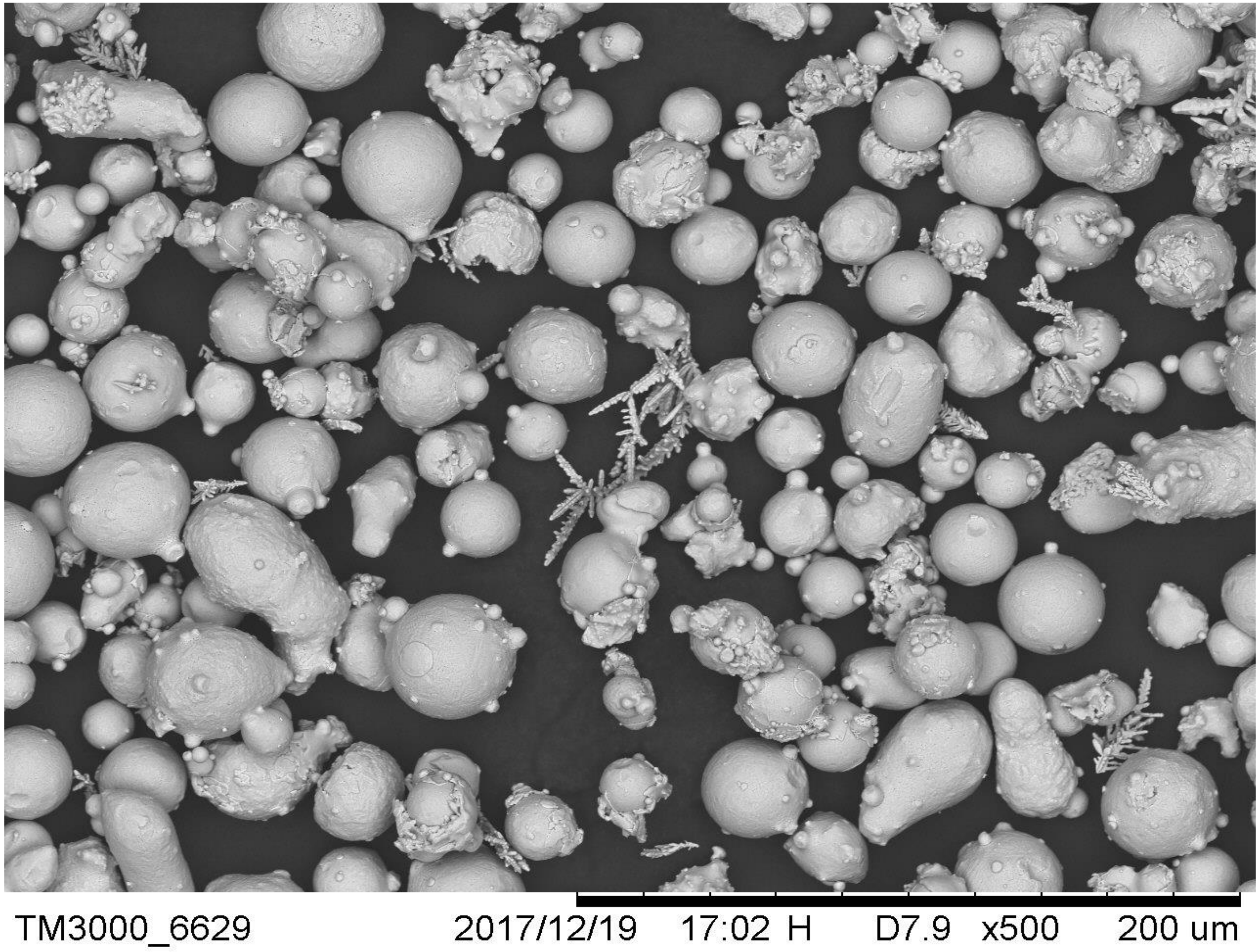
POWDERS
MIX: TAILOR THE PROPERTIES OF THE MATERIAL

1% CU
LEAF SHAPE



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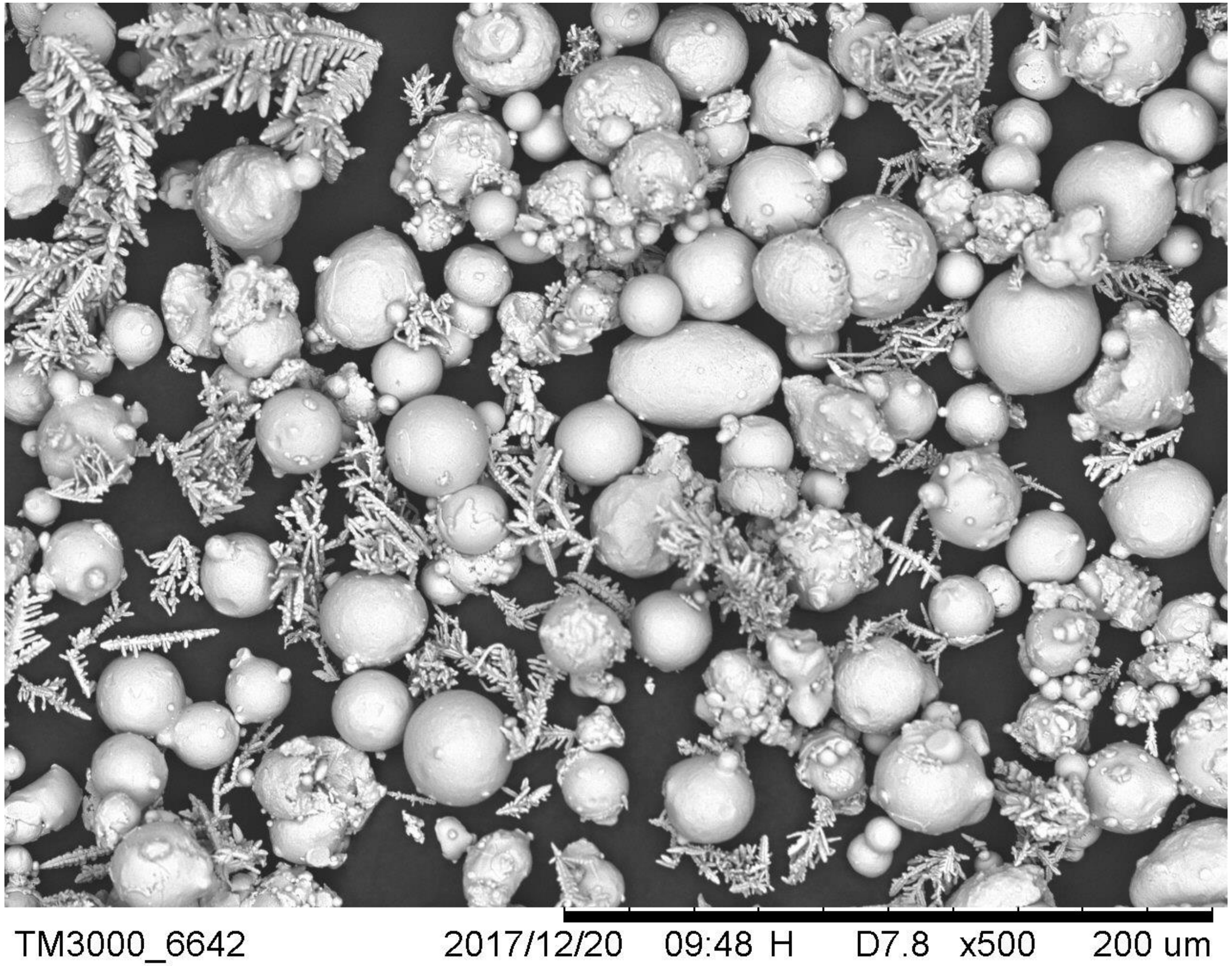
POWDERS

MIX: TAILOR THE PROPERTIES OF THE MATERIAL

5% CU
LEAF SHAPE



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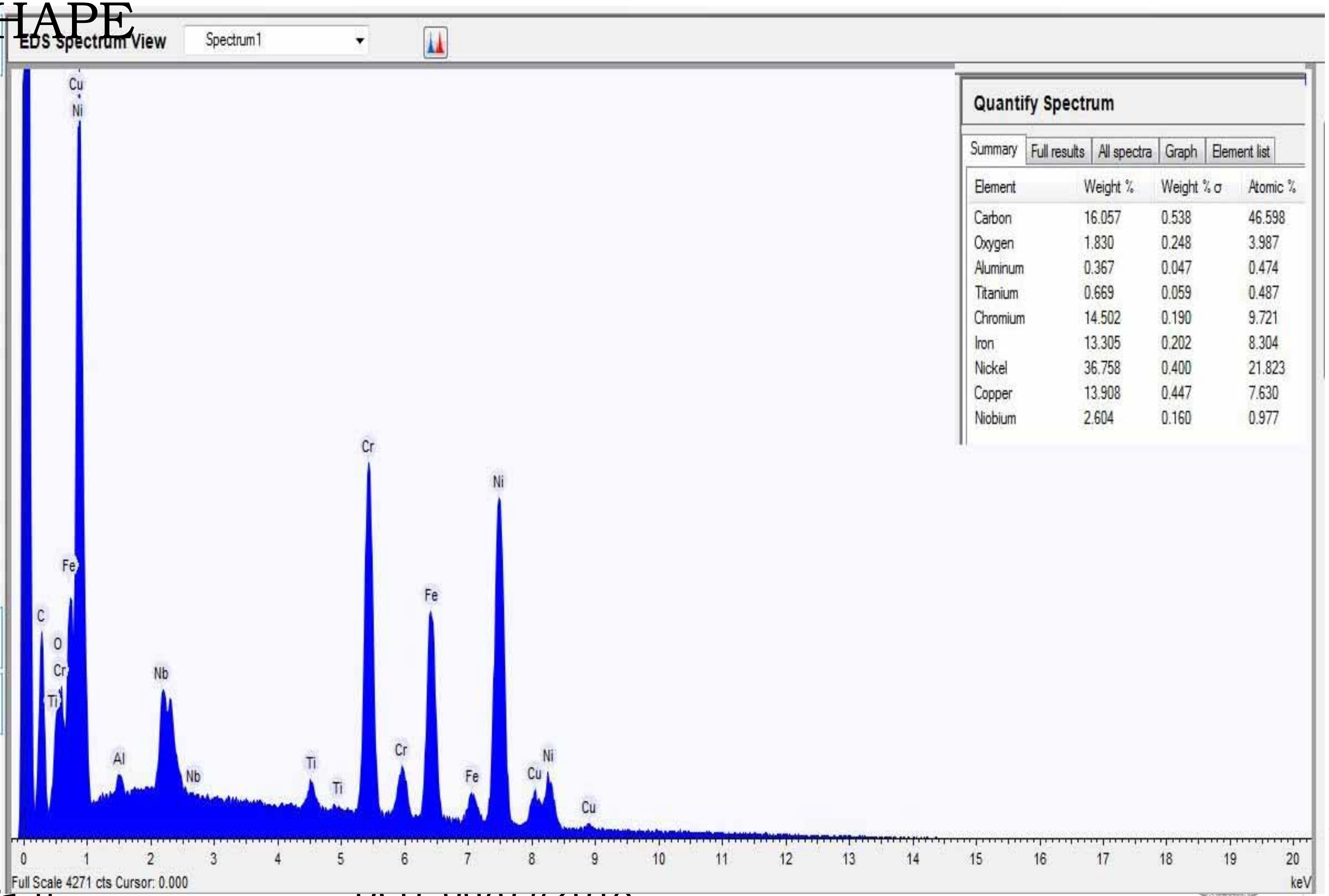
POWDERS

MIX: TAILOR THE PROPERTIES OF THE MATERIAL

1% CU
LEAF SHAPE



Element	Weight %	Weight % σ	Atomic %
Carbon	16.057	0.538	46.598
Oxygen	1.830	0.248	3.987
Aluminum	0.367	0.047	0.474
Titanium	0.669	0.059	0.487
Chromium	14.502	0.190	9.721
Iron	13.305	0.202	8.304
Nickel	36.758	0.400	21.823
Copper	13.908	0.447	7.630
Niobium	2.604	0.160	0.977

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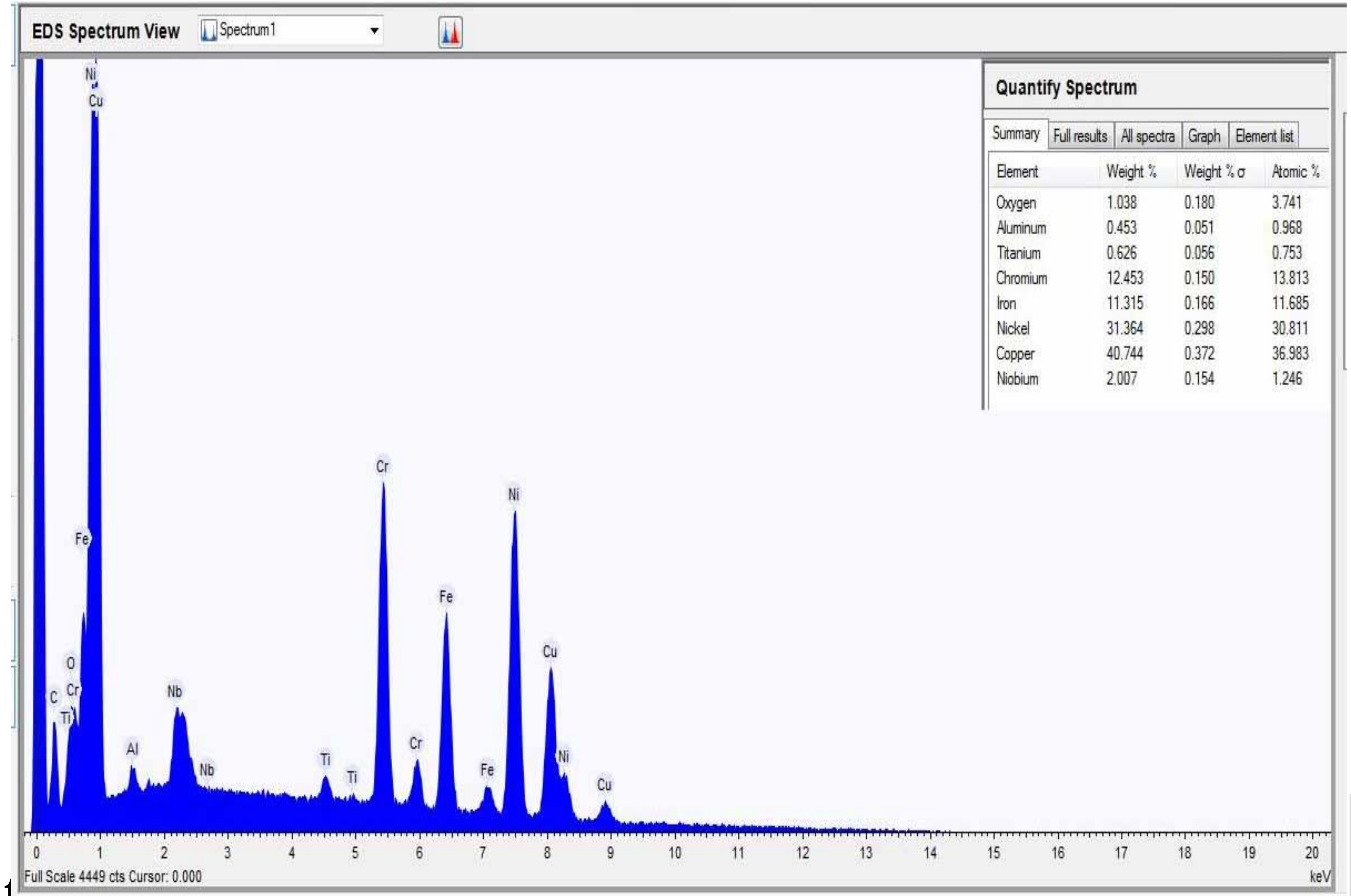
5% CU

LEAF SHAPE



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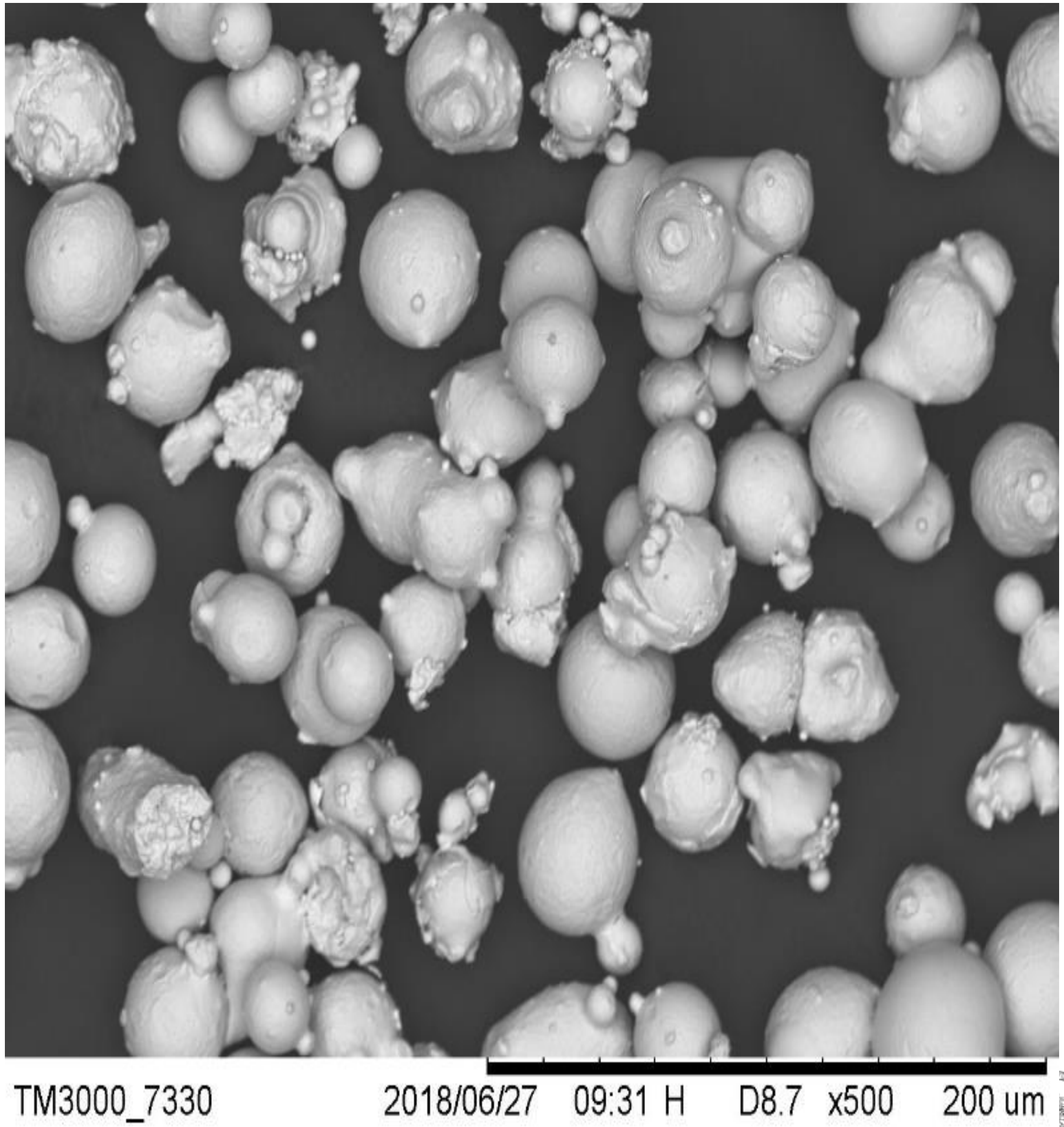
MIX: TAILOR THE PROPERTIES OF THE MATERIAL

5% CU

SPHERE SHAPE



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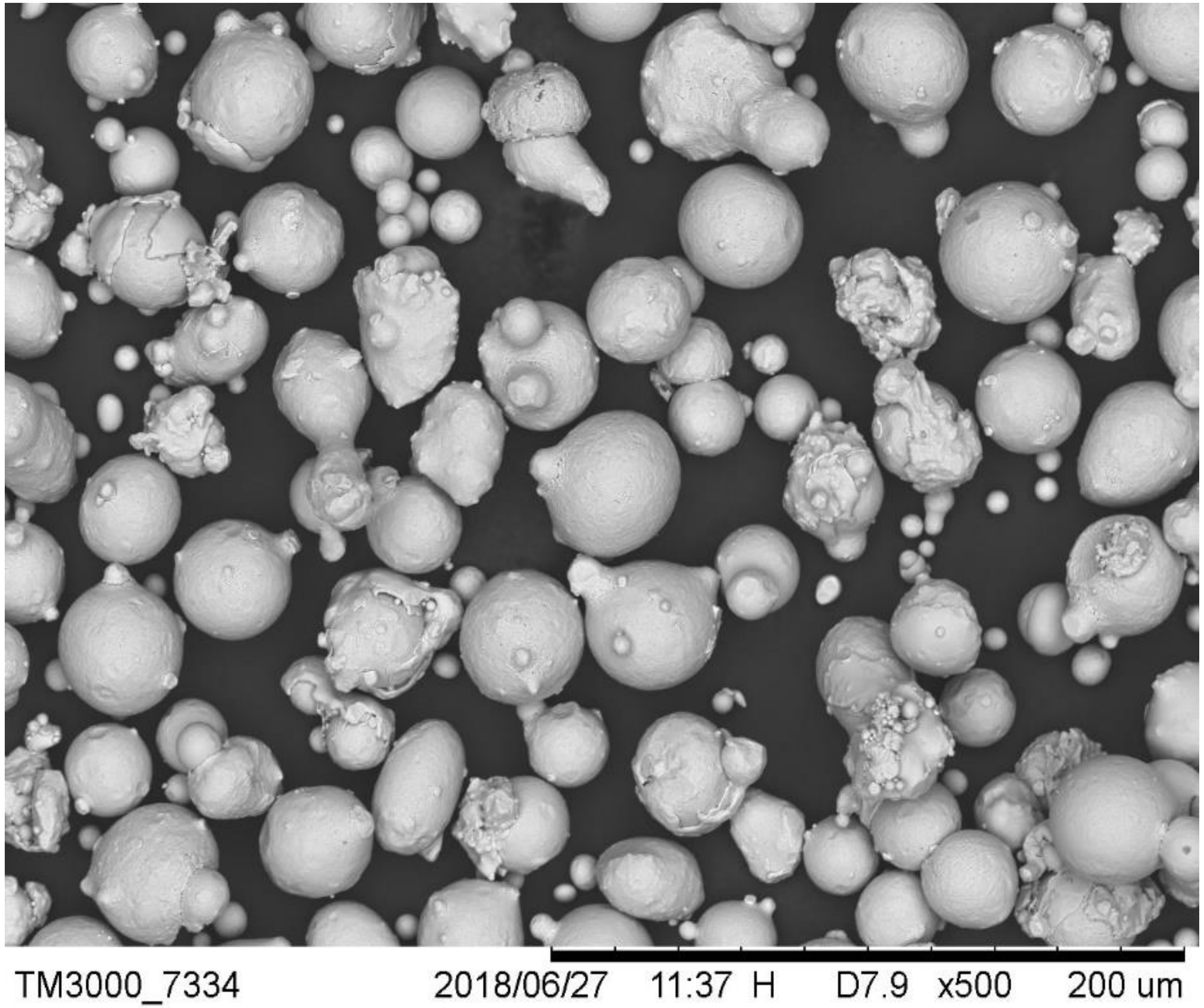
POWDERS

MIX: TAILOR THE PROPERTIES OF THE MATERIAL

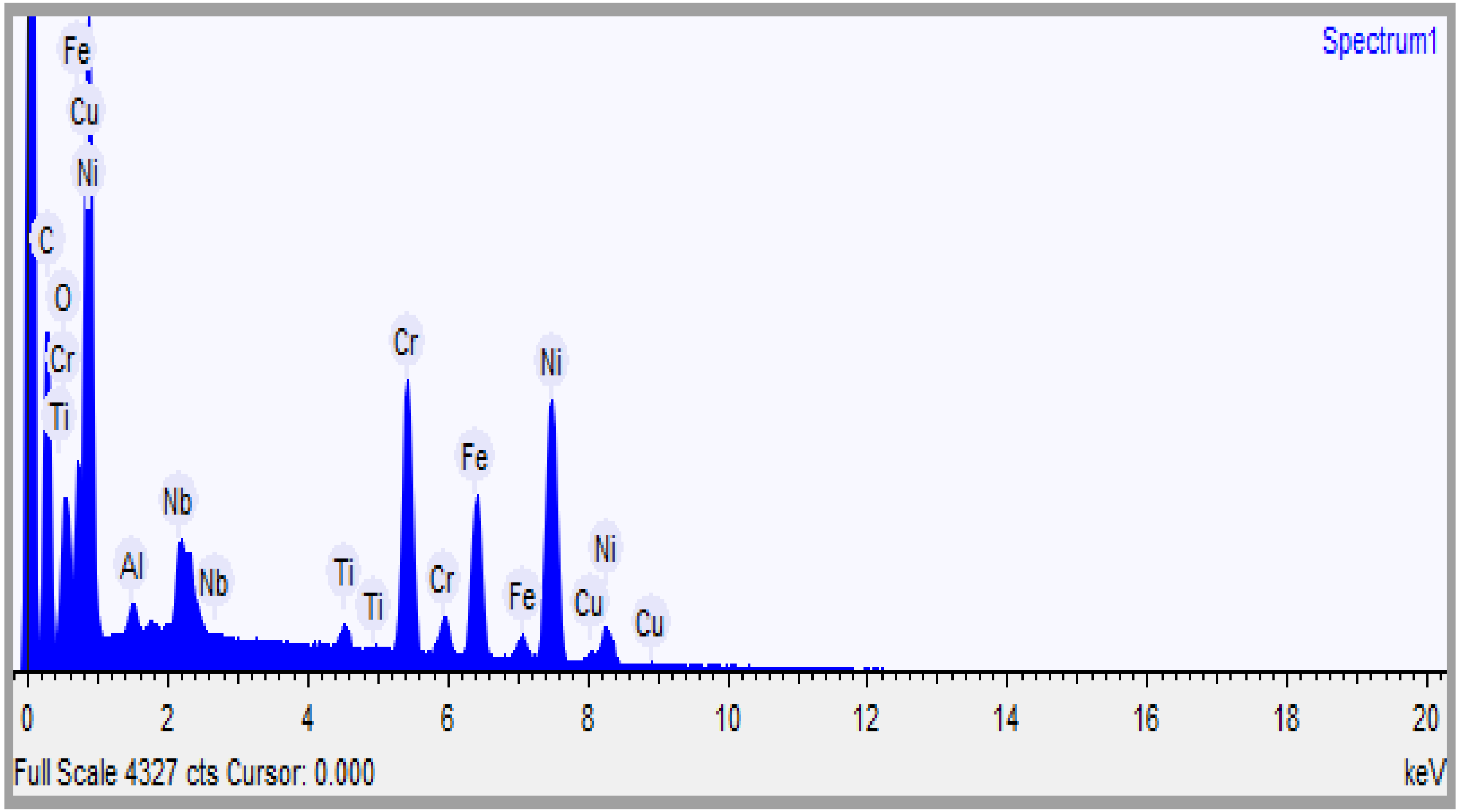
20% CU
SPHERE SHAPE



POWDERS

MIX: TAILOR THE PROPERTIES OF THE MATERIAL

5% CU
SPHERE SHAPE

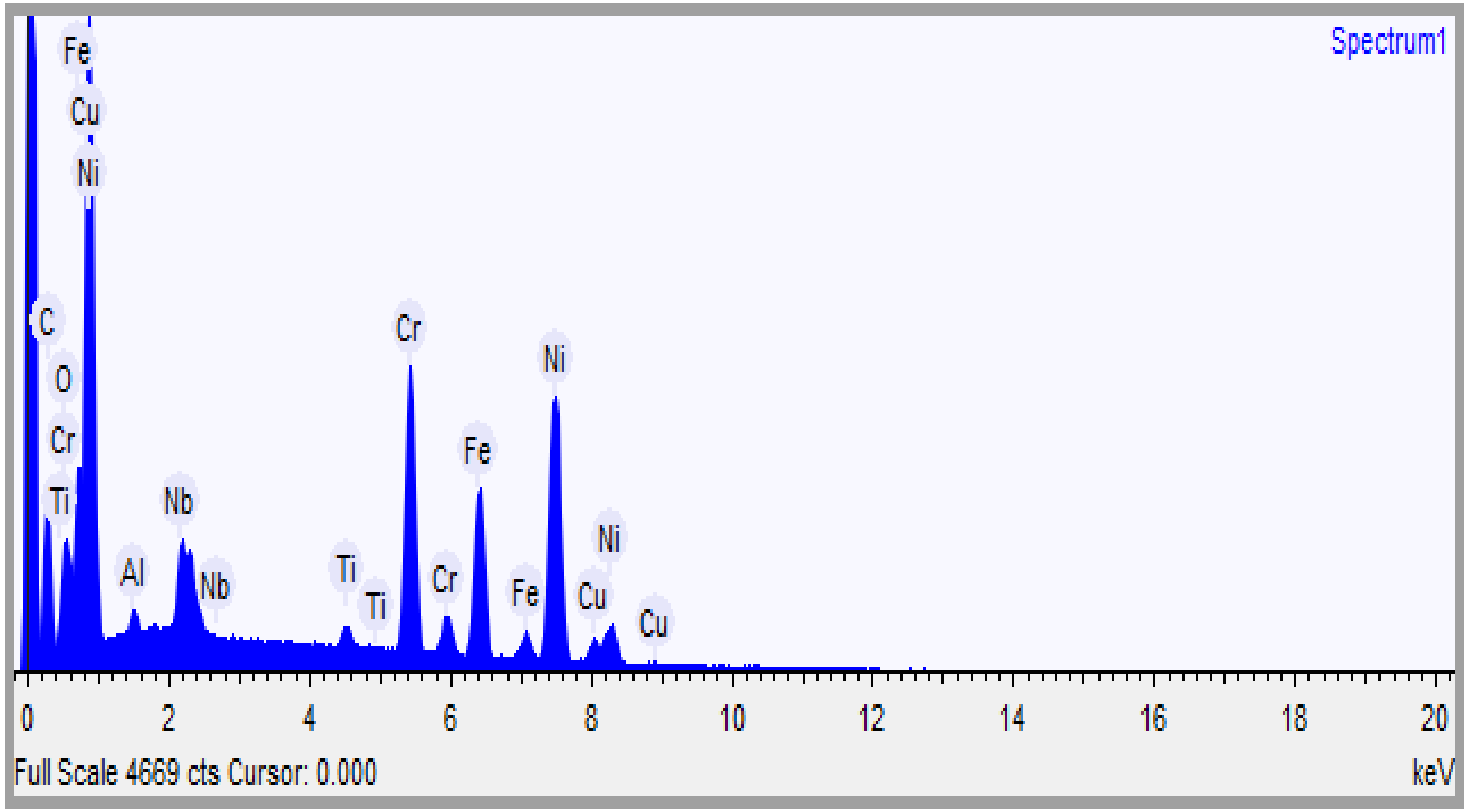


POWDERS

MIX: TAILOR THE PROPERTIES OF THE MATERIAL

20% CU

SPHERE SHAPE



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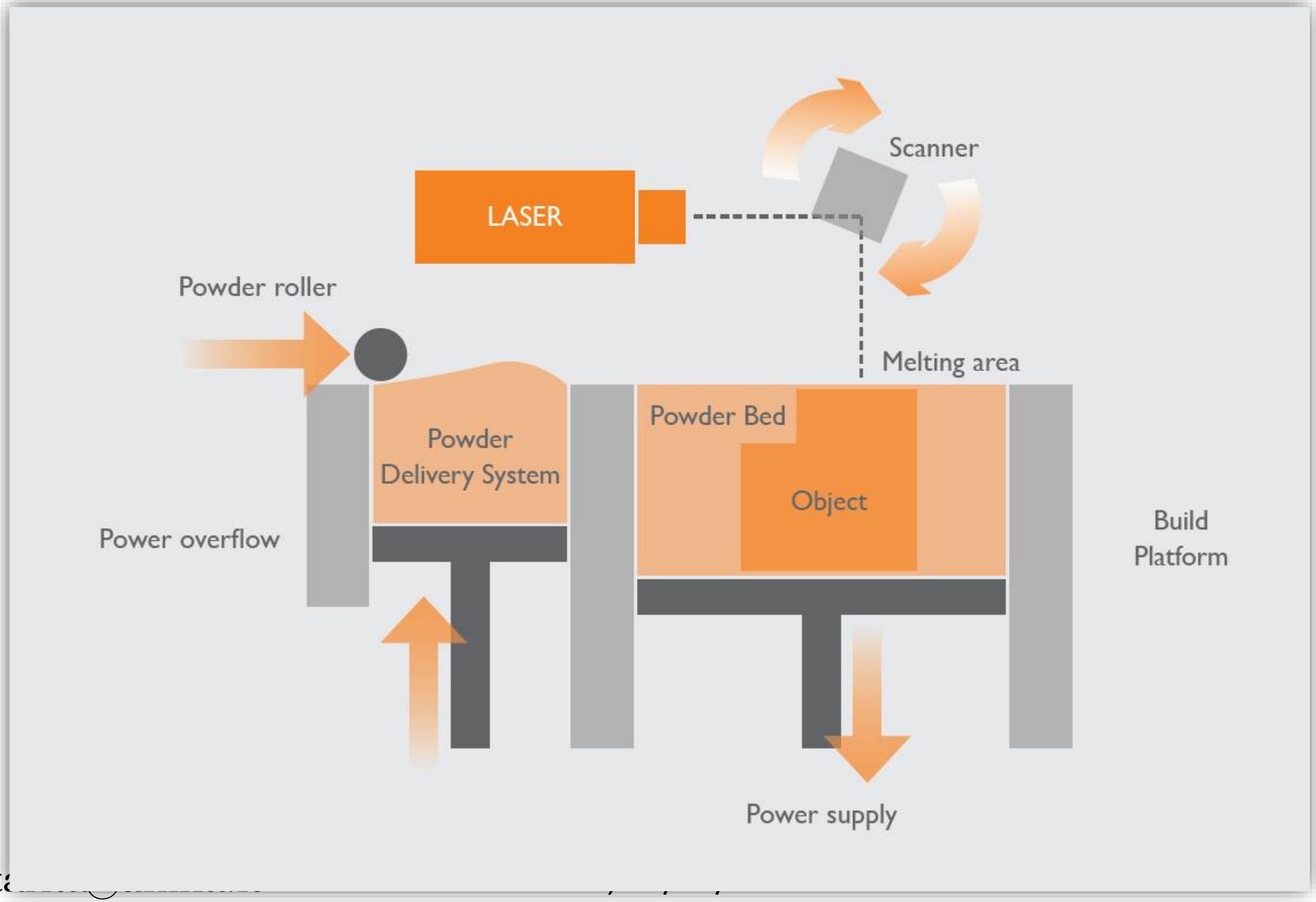
POWDERS

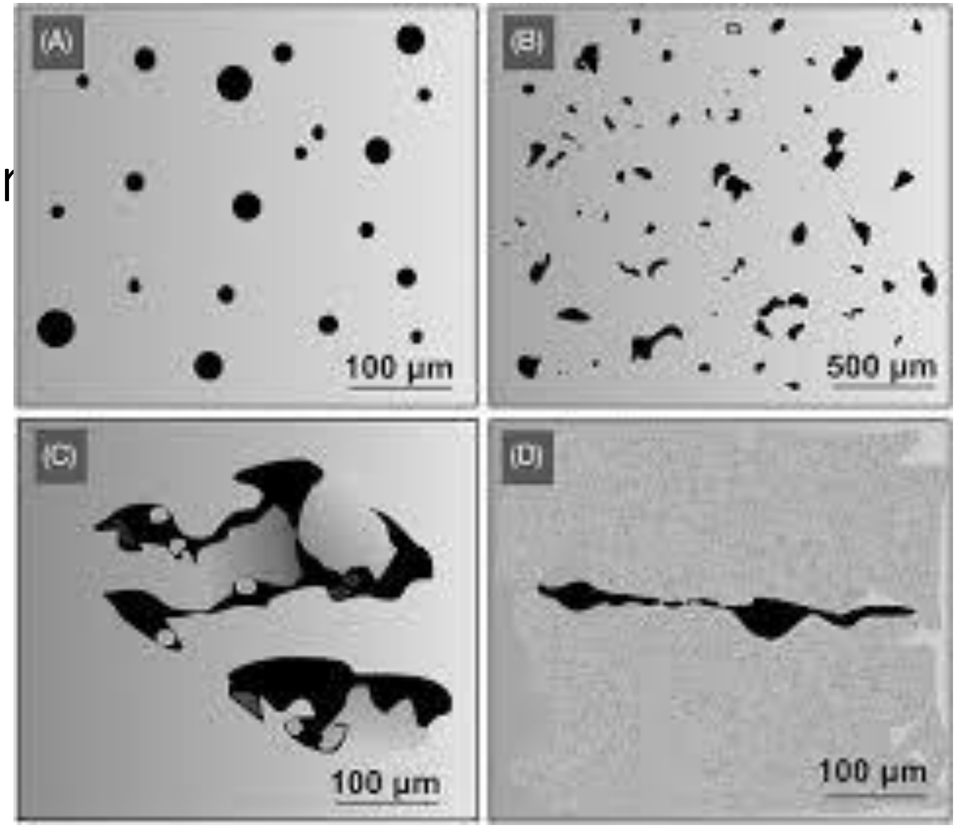
POWDER HANDLING: POWDER BED DEPOSITION

| *Additive manufacturing: how does it work ?*



| *Additive manufacturing: Issues*

- Repeatablity
- Variation of mechanical properties in the chamber
- Defects (keyhole, lack of fusion, porosity etc.)



Powder bed deposition

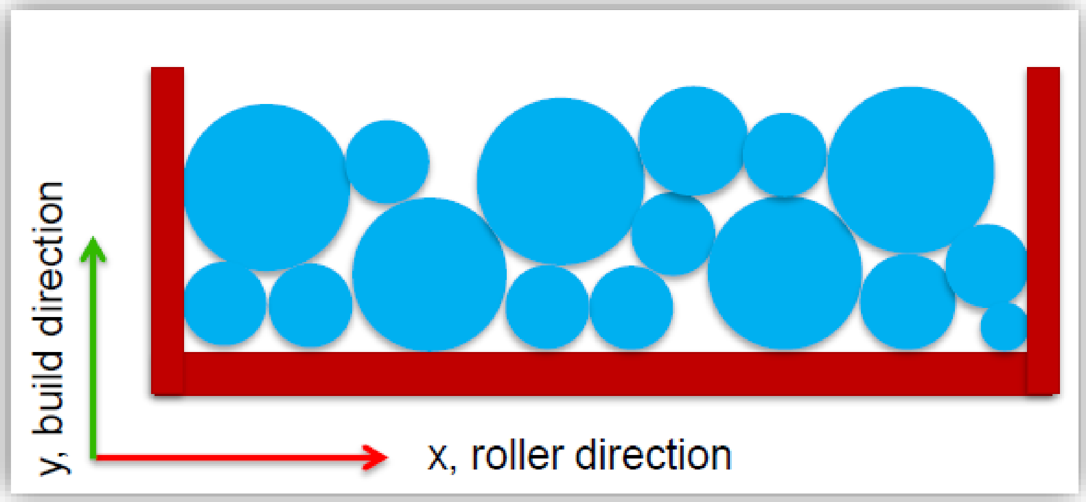
↓

Laser melting

↓

Cooling and solidification

| *Focus: the powder bed*

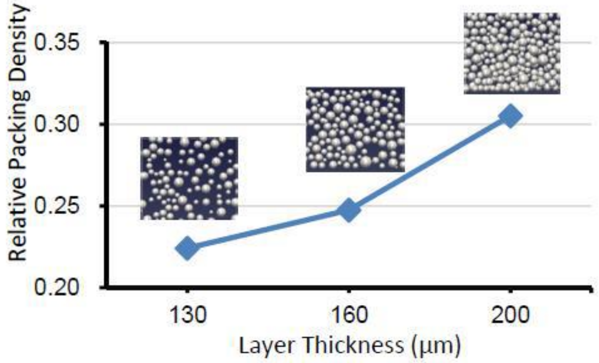


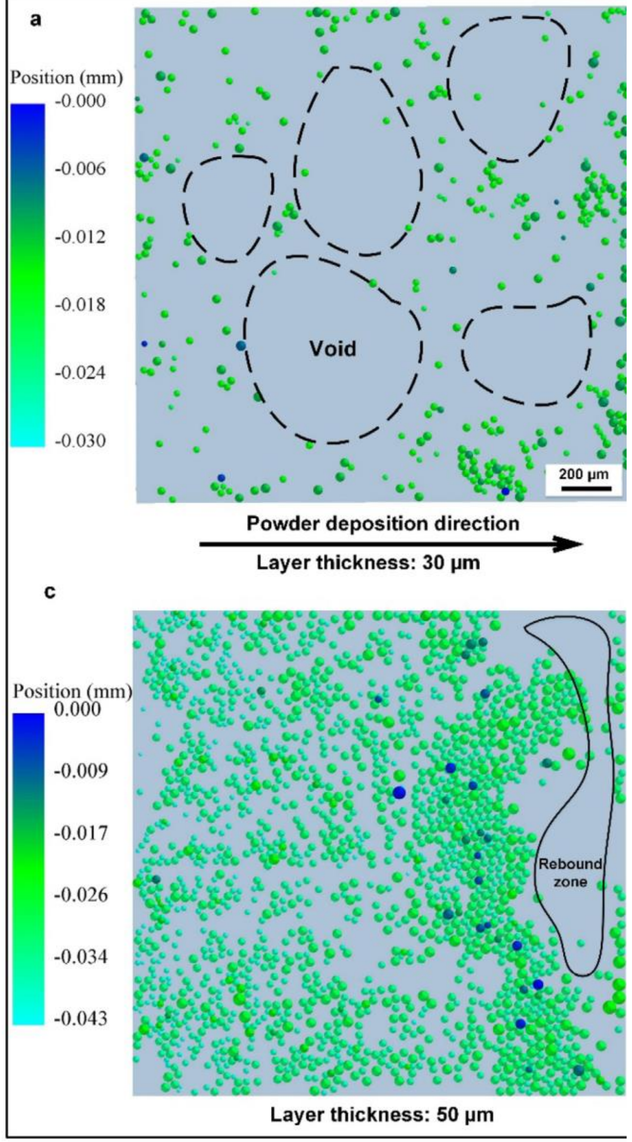
- Speed of the recoating device.
- Layer thickness.
- Shape of the recoating device.

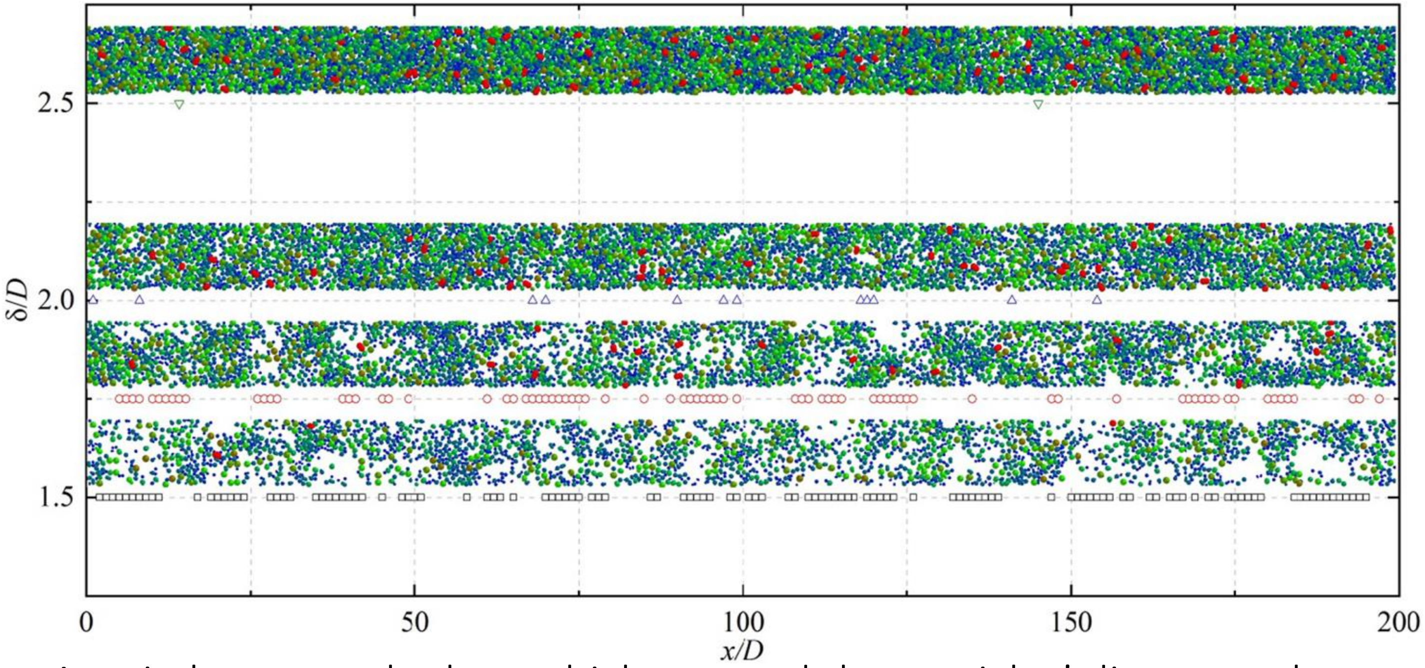
- Powder bed solid volume fraction.
- Effective layer thickness.
- Material/shape segregation.

| *Literature*

Layer thickness
[1,2,3]







A ratio between the layer thickness and the particles' diameter close to 1 can hinder the spreading process leading to the formation of voids and jamming phenomena

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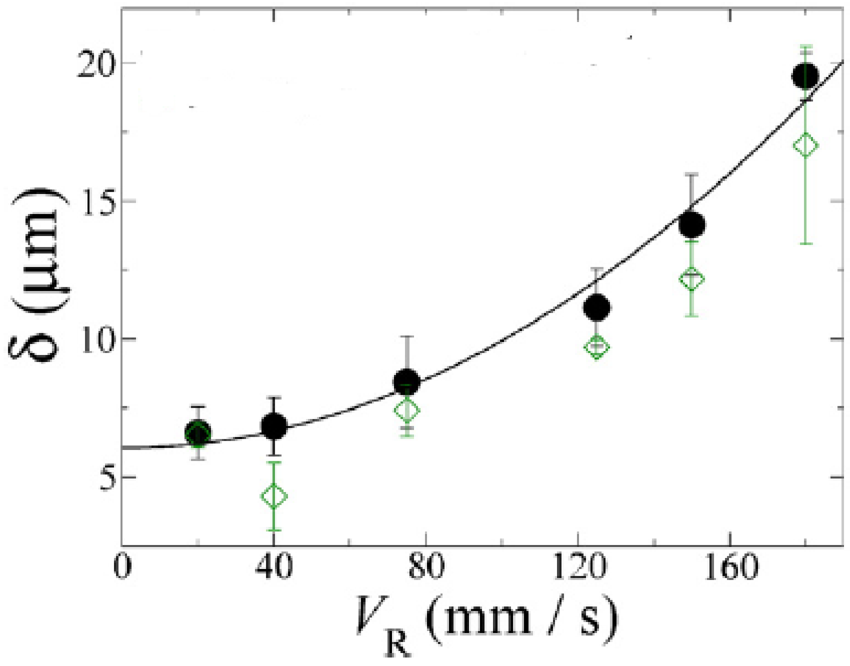
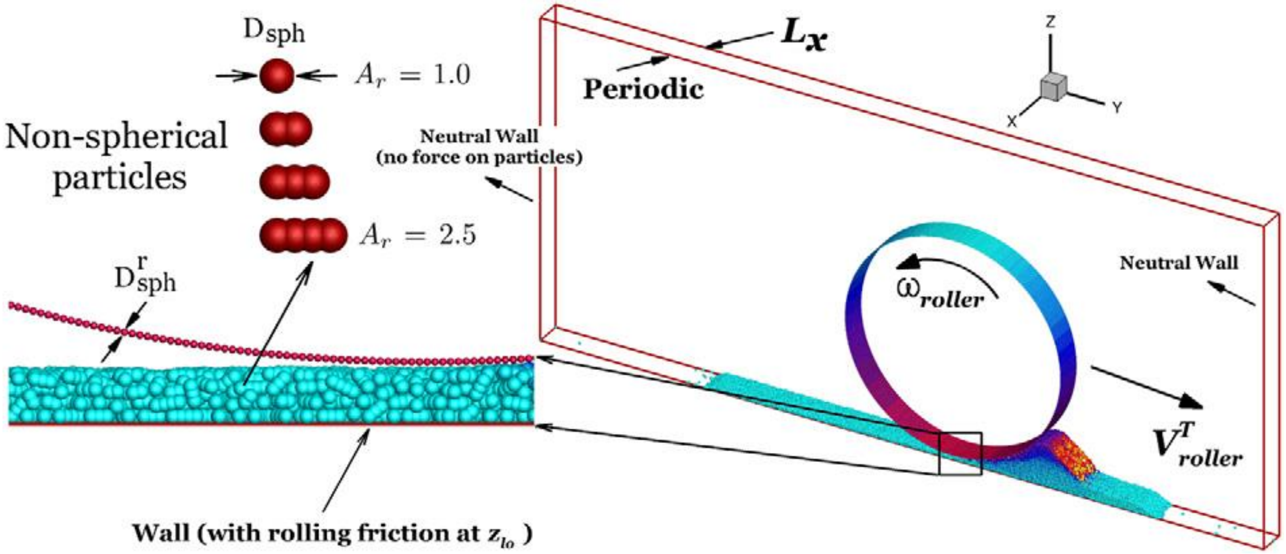
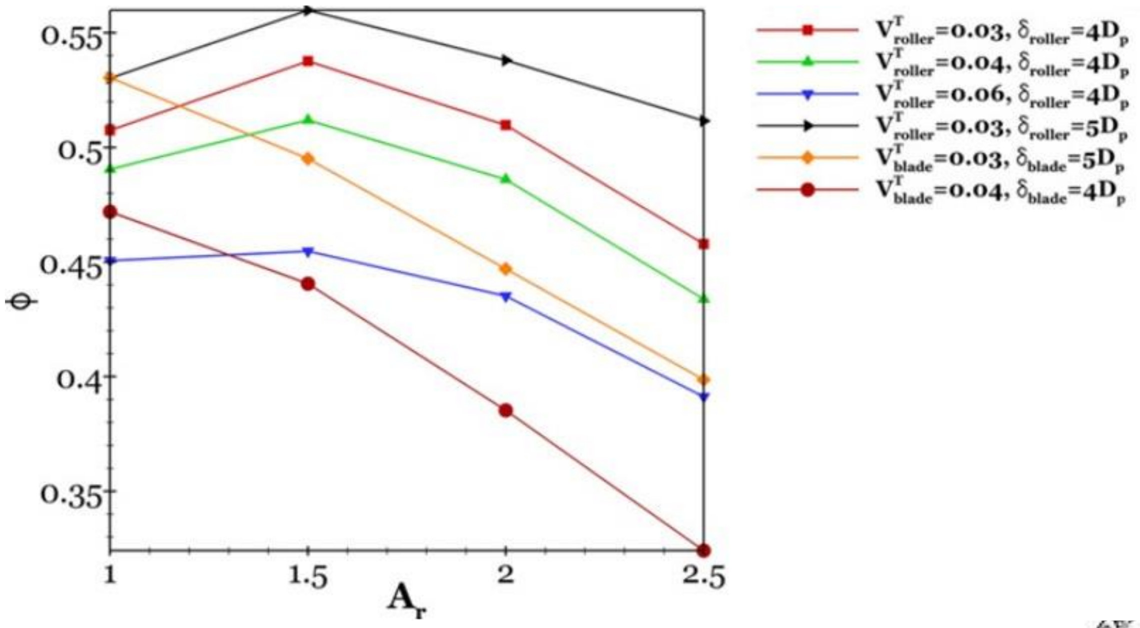
| *Literature*

Speed of the recoating device [4,2]



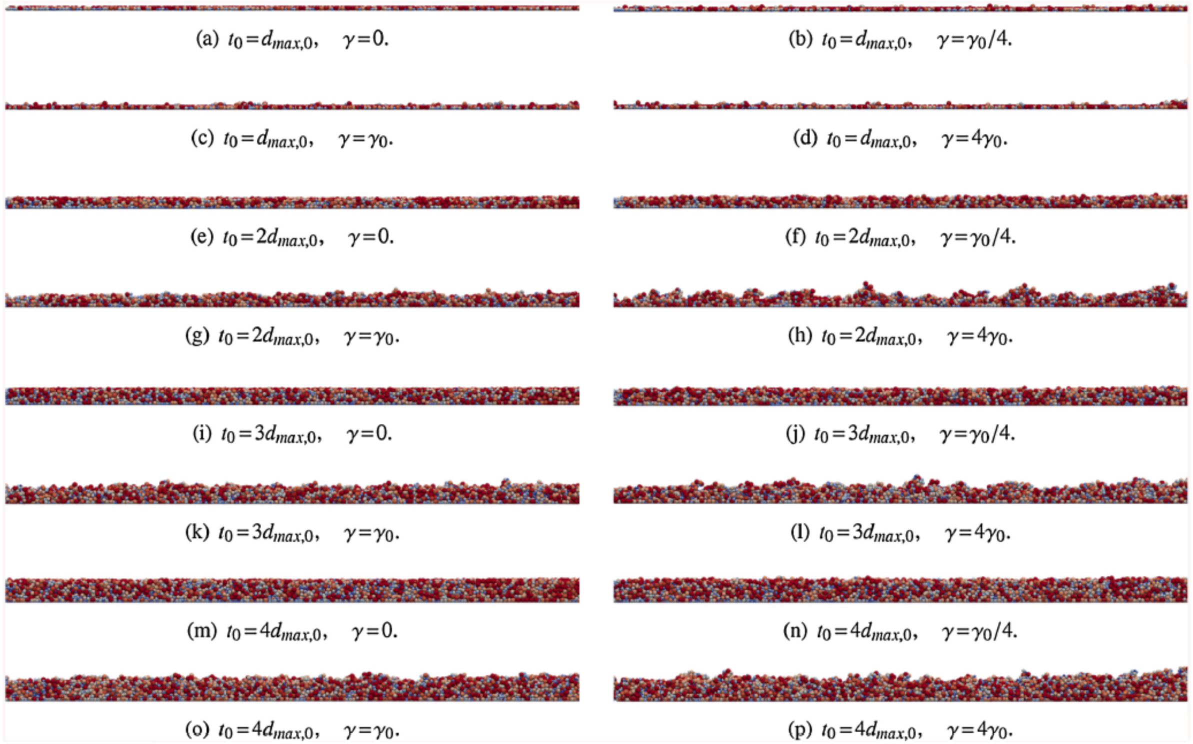


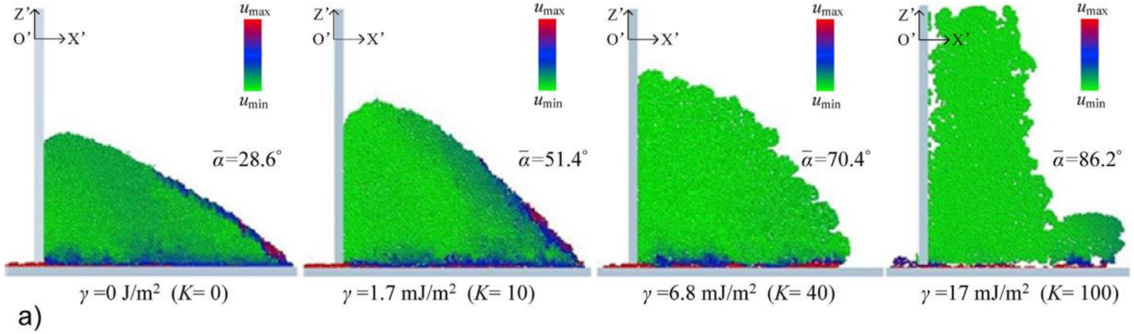


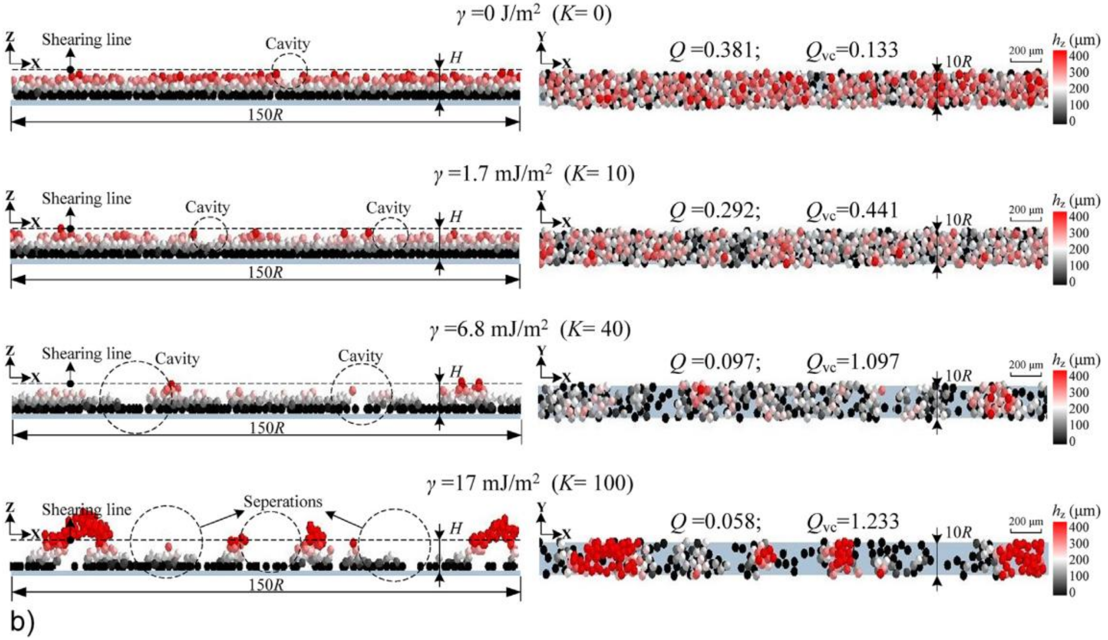
A lower spreading speed gives better results in term of void fraction and roughness of powder bed. However this impact is strongly related to the shape of the recoating device and to the characterisics of the powder.

| *Literature*

Cohesive effects [5,6]



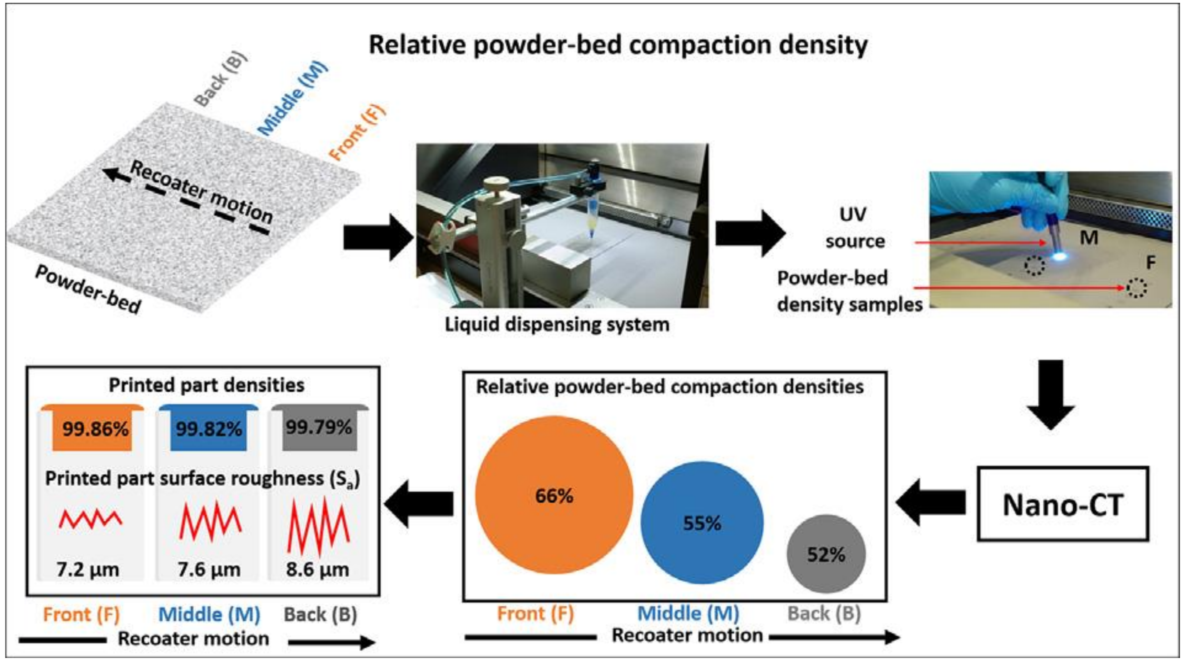


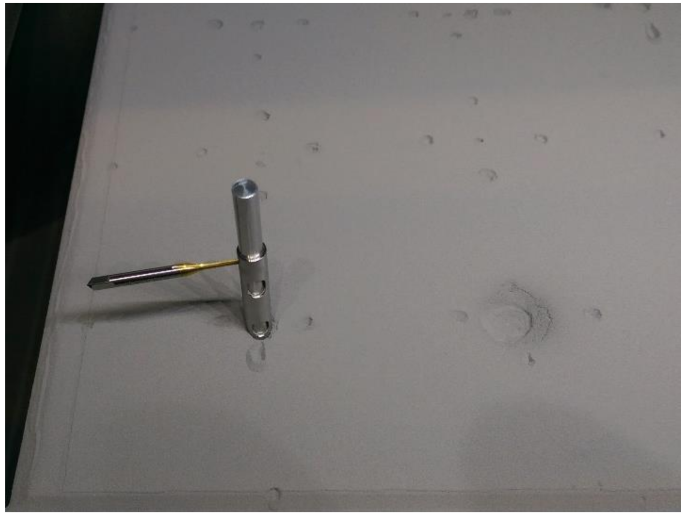


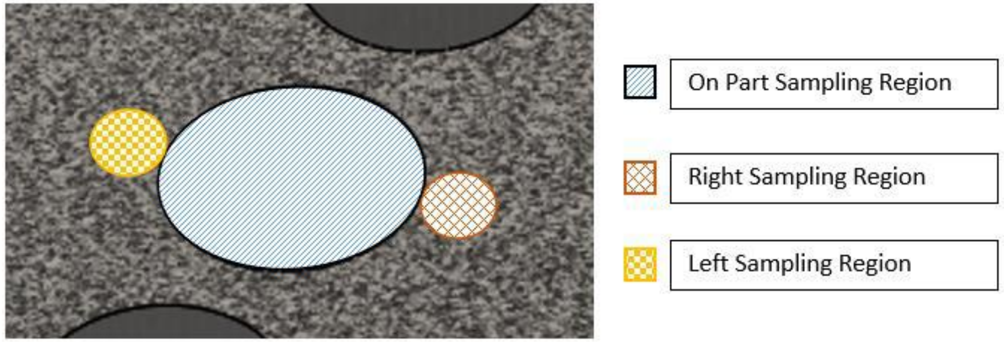
An incorrect modeling of the cohesion effects can compromise the results and lead to anti physical bheaviour

| *Literature*

Experimental analysis
[7,8]







Most of the works are still focues on developing a reliable strategy to obtain the powder bed characteristics at the loose state. Usually focused on one characteristic.

| *Literature*

Numerical

- Not calibrated
- Does not faithfully reproduce the process (i.e. gemoetry, only considers one part of the process etc.)
- Mostly not validated

Experimental

- General scarcity of data
- No reliable strategy to acquire the characteristics of the powder bed

Open questions

- Interaction with geometrical features
- Experimental analysis of the loose powder bed
- Mix of heterogeneous powders
- Parameter optimization
- Interaction with the previous layer

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| *Discrete element method*

Contact detection and particle overlap

Overlap δ

Force-displacement law applied to each contact

Force

Apply Newton’s second law to calculate the resultant motion of the particle

Update position and velocity

Δt

Force-displacement law:

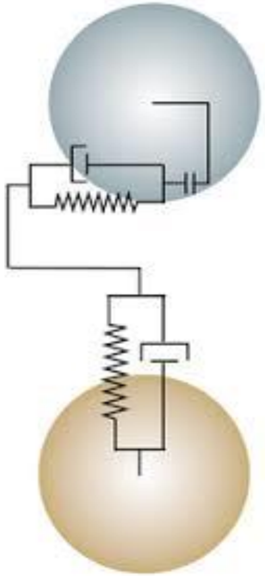
$$F = \left(k_n \delta n_{ij} - y_n v n_{ij}\right) + \left(k_t \delta t_{ij} - y_t v t_{ij}\right)$$

Nonlinear Hertz-Mindlin

$$k_n = \frac{4}{3} E' \sqrt{R' \delta_n}$$

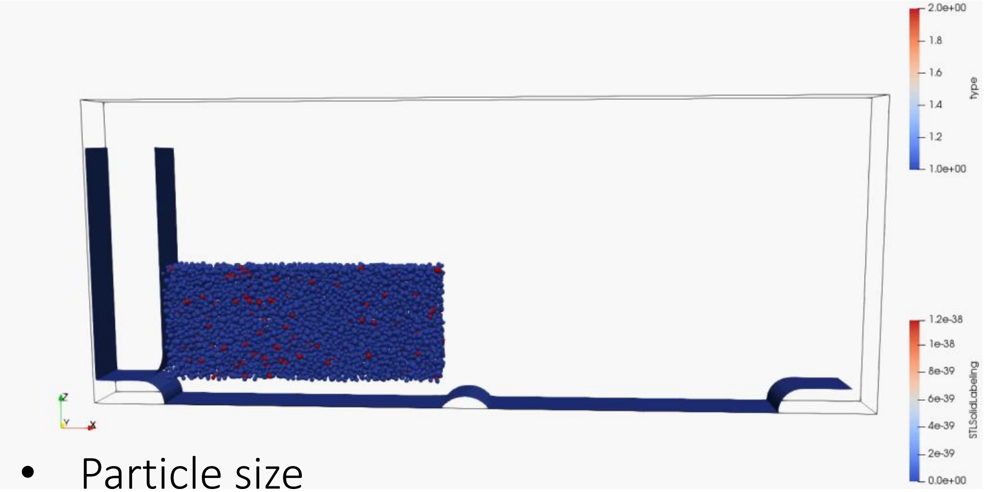
Additional cohesive force simplified Johnson-Kendall-Roberts

$$F = kA$$

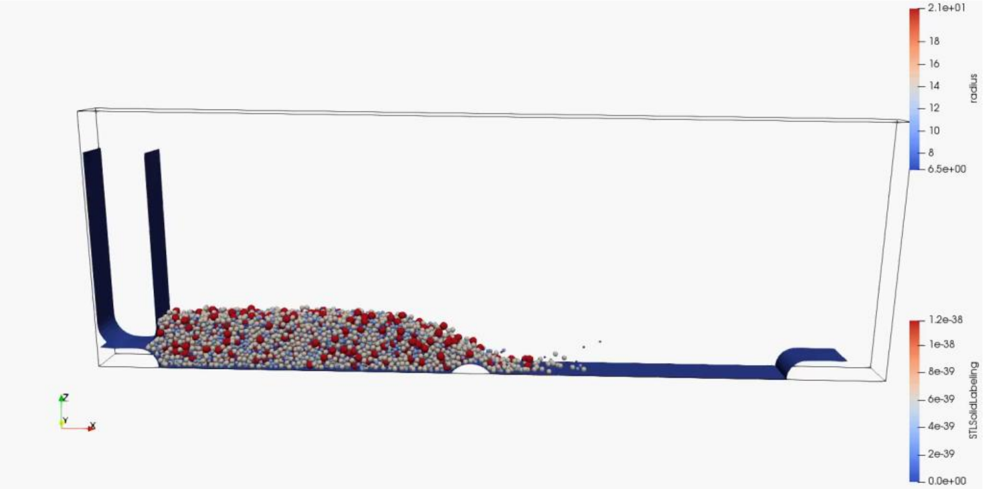


| *Powder Spreading simulation*

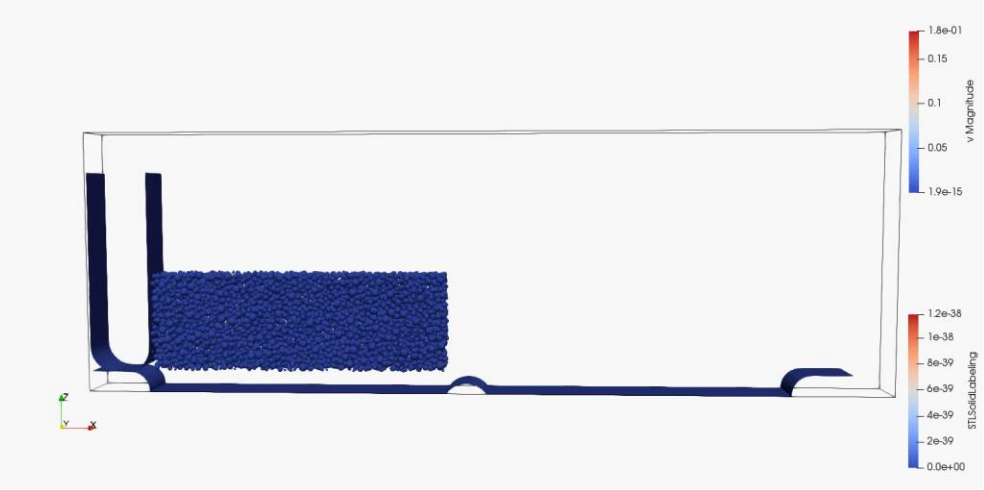
- Material segregation



- Particle size

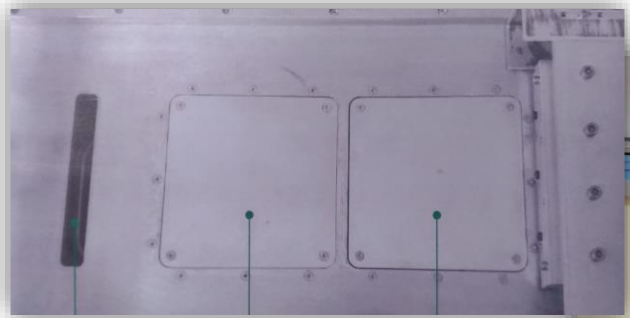


- Velocity profile

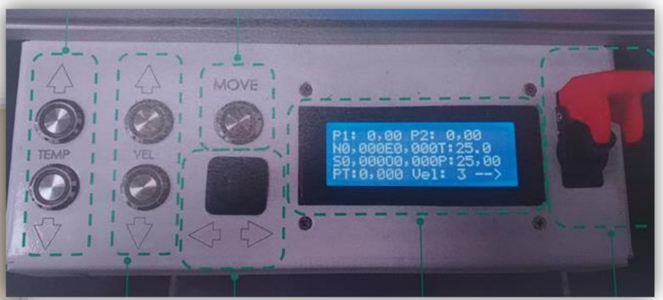


- Local packing factor and density
- Local variation of the PSD
- Effective layer thickness

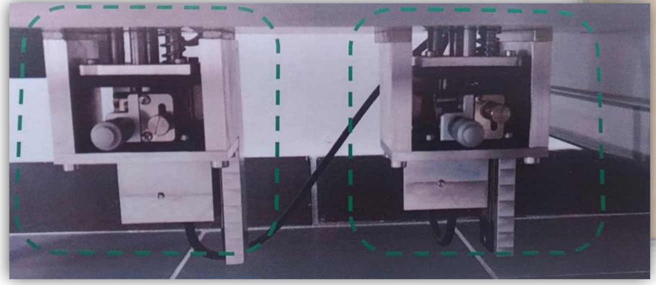
| *Experimental device*



Removable blade



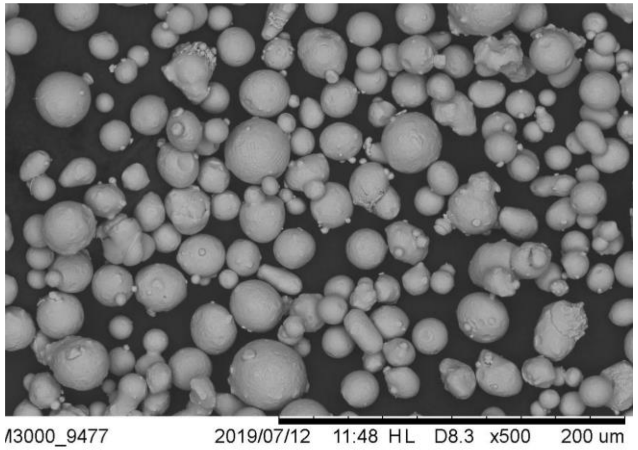
Control panel with 6 different blade's speeds and selectable temperature for the plate



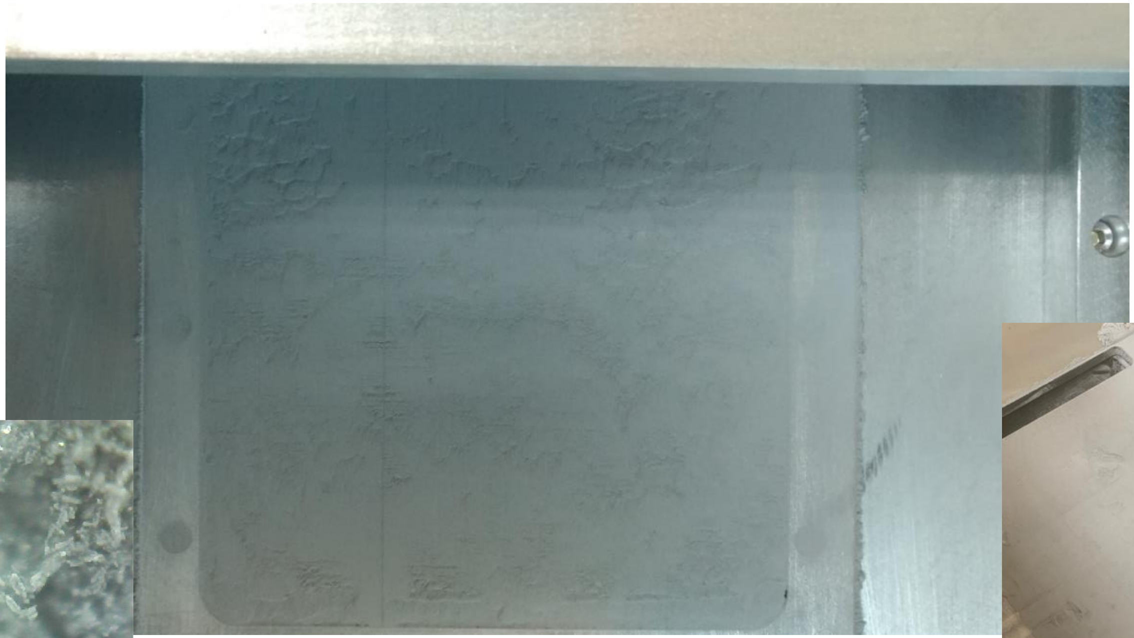
Micrometric screws to adjust the layer thickness and powder feedstock

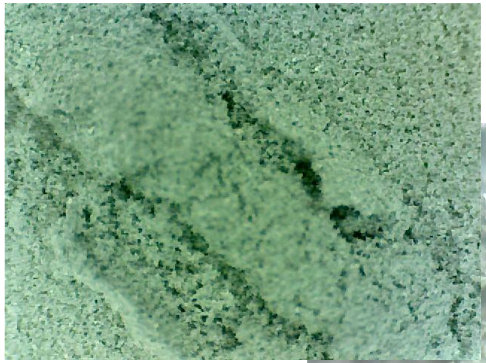
Set of portable microscopes with different leves of magnification

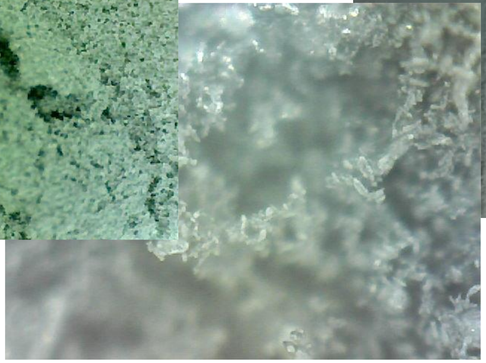
| *Experimental device*

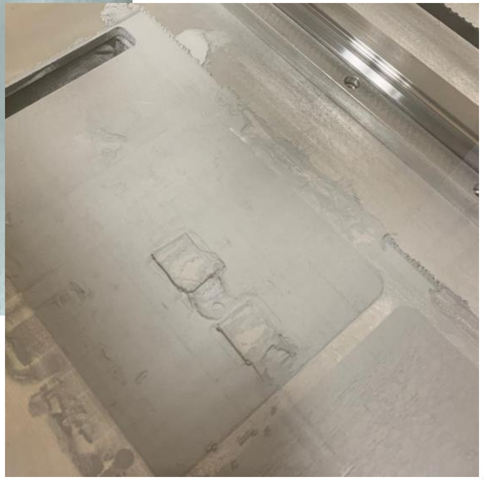


Analysis of Sem images to study variations in the PSD and characteristcs of the powders







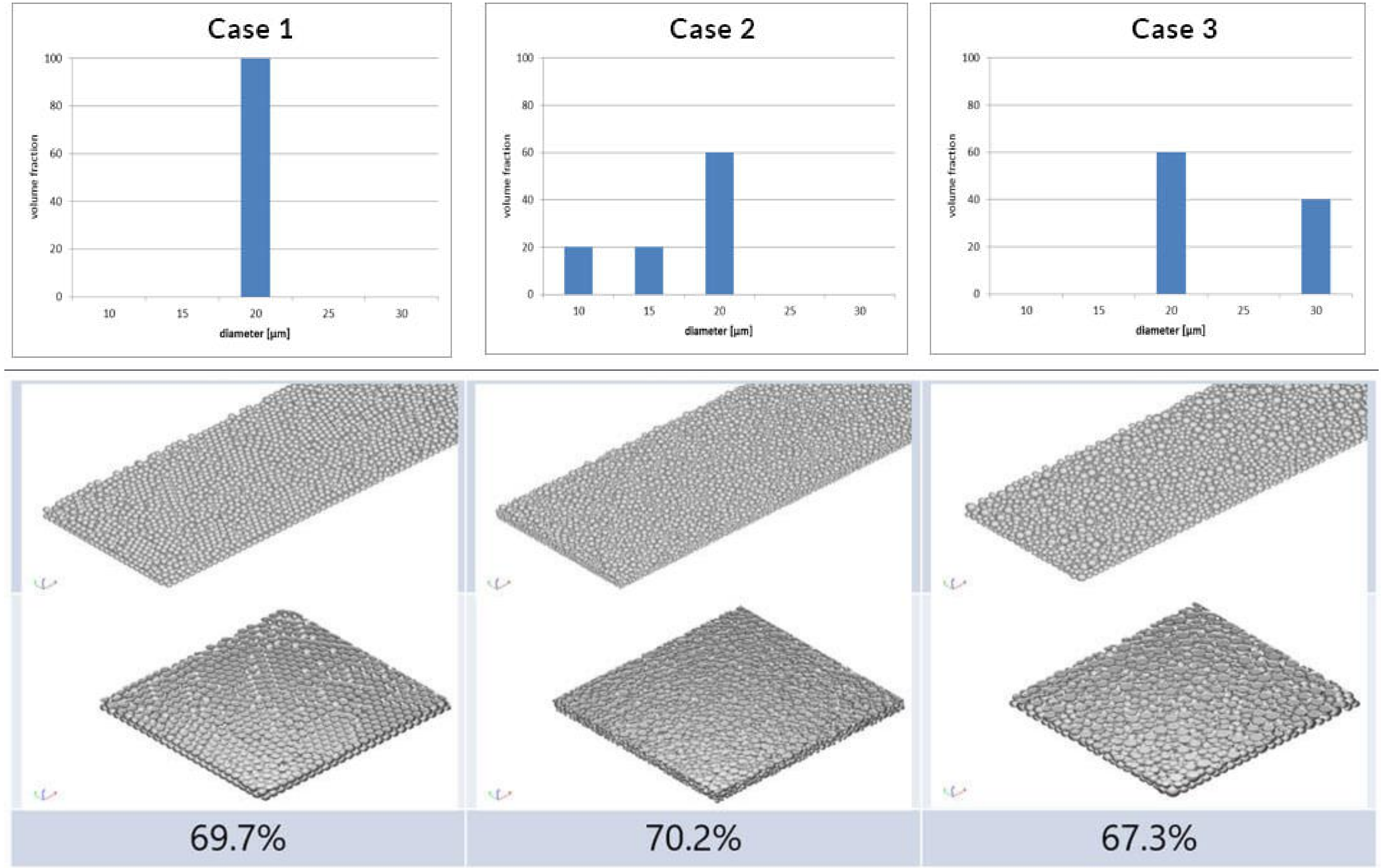


Acquire images on situ at different levels of zoom with a portable microscope to perform analysis of the powder bed

Extract samples of the powder bed to measure the local density

POWDERS

POWDER HANDLING: POWDER BED DEPOSITION



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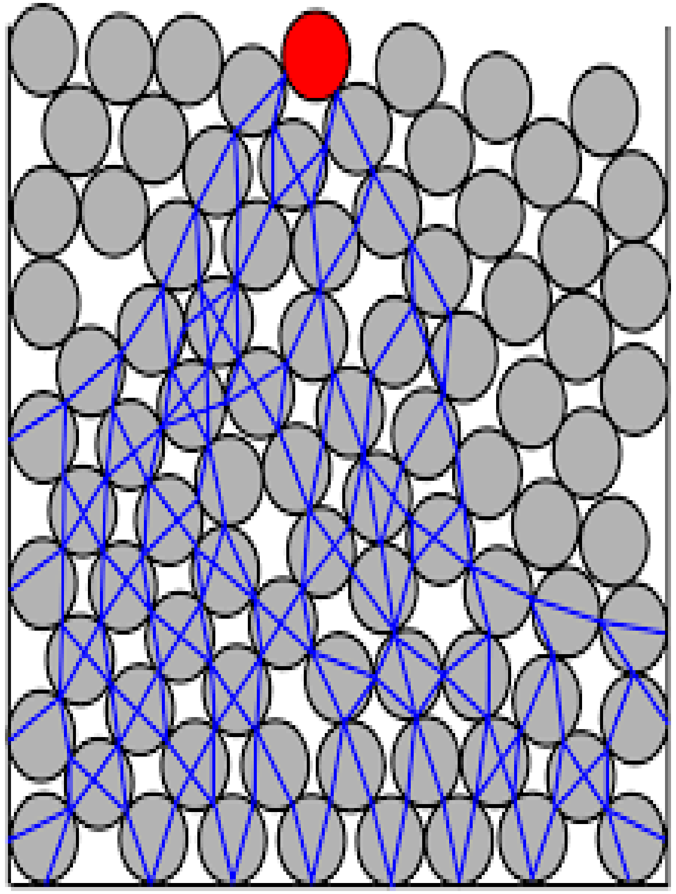
POWDERS

POWDER HANDLING: POWDER BED DEPOSITION



A force chain can occur during the fabrication process.
The resultant forces can damage the fabricated part

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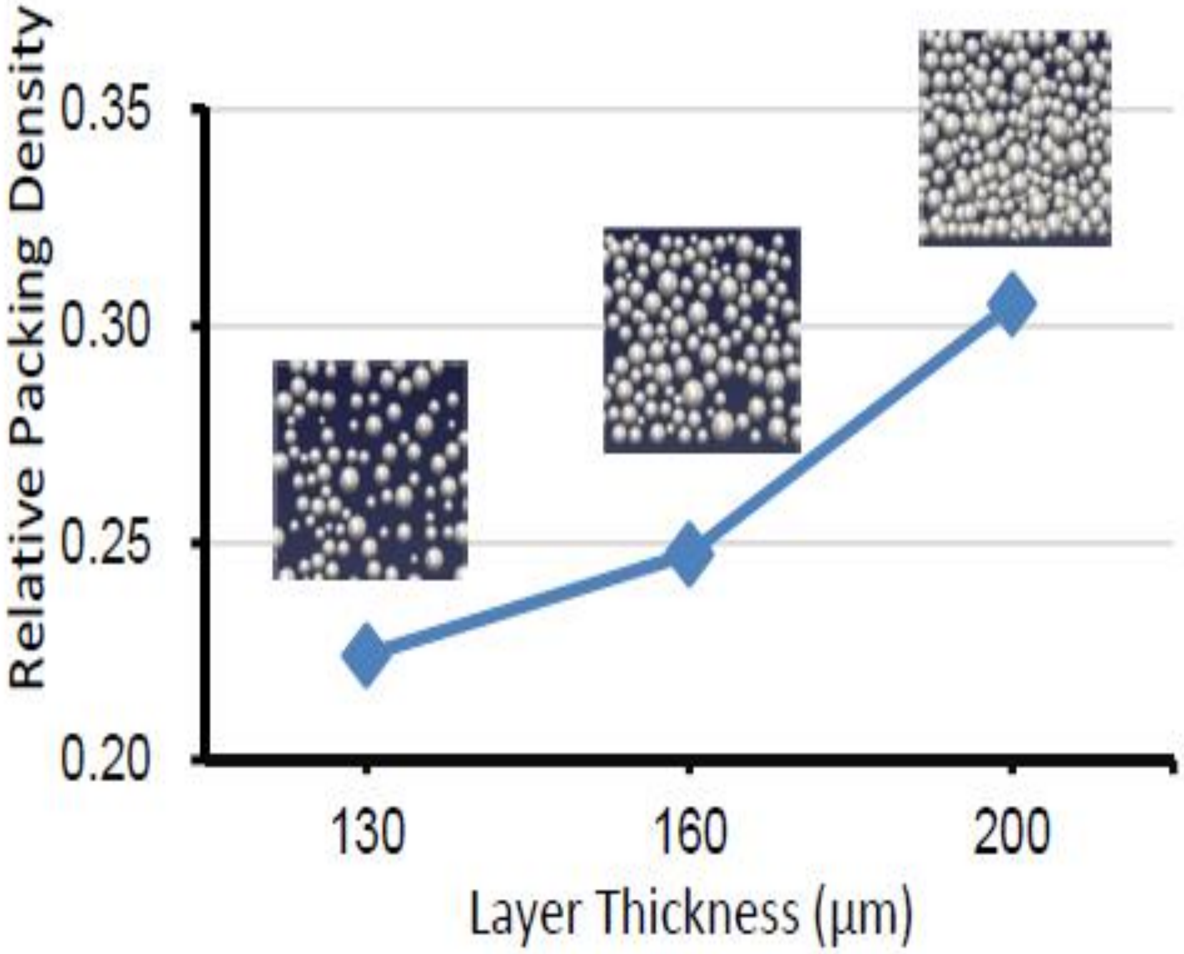
POWDERS

POWDER HANDLING: POWDER BED DEPOSITION

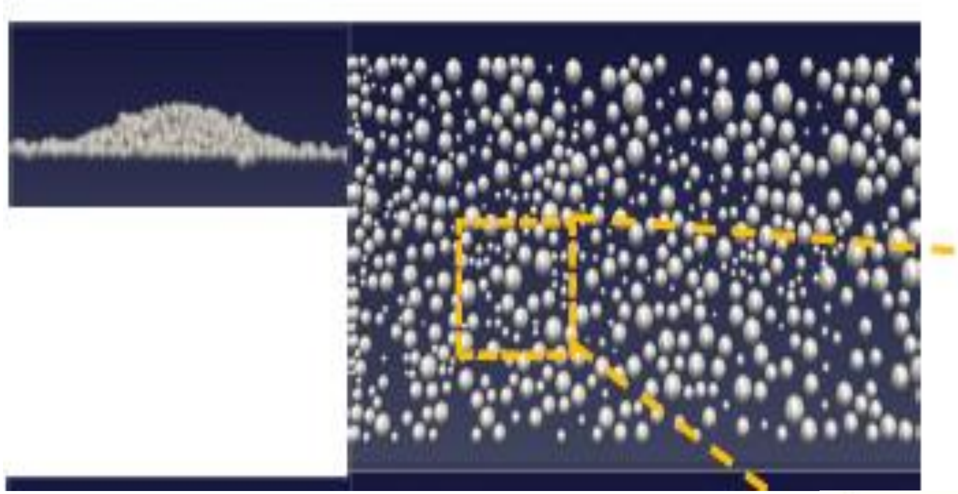
INFLUENCE OF LAYER THICKNESS ON PACKING DENSITY

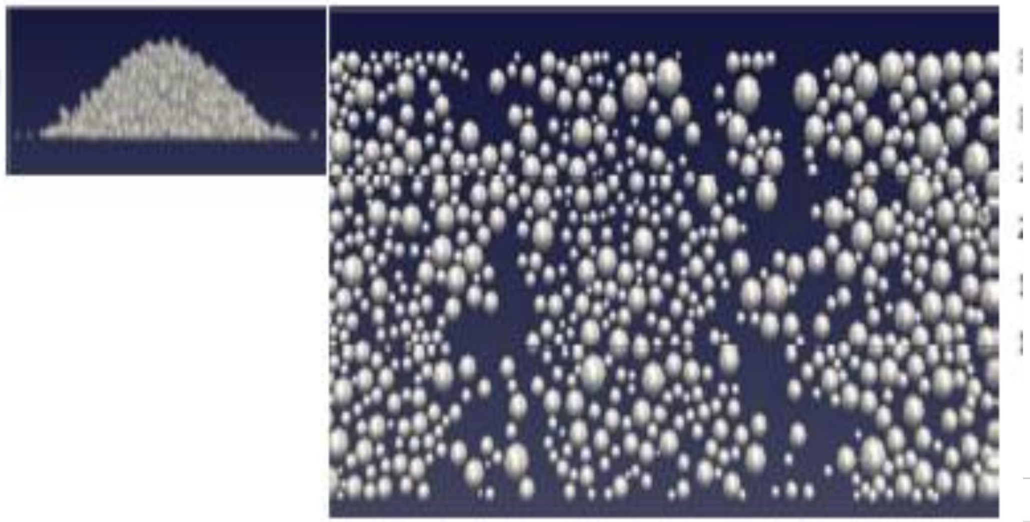


POWDERS

POWDER HANDLING: POWDER BED DEPOSITION

INFLUENCE OF POWDERS FLOWABILITY





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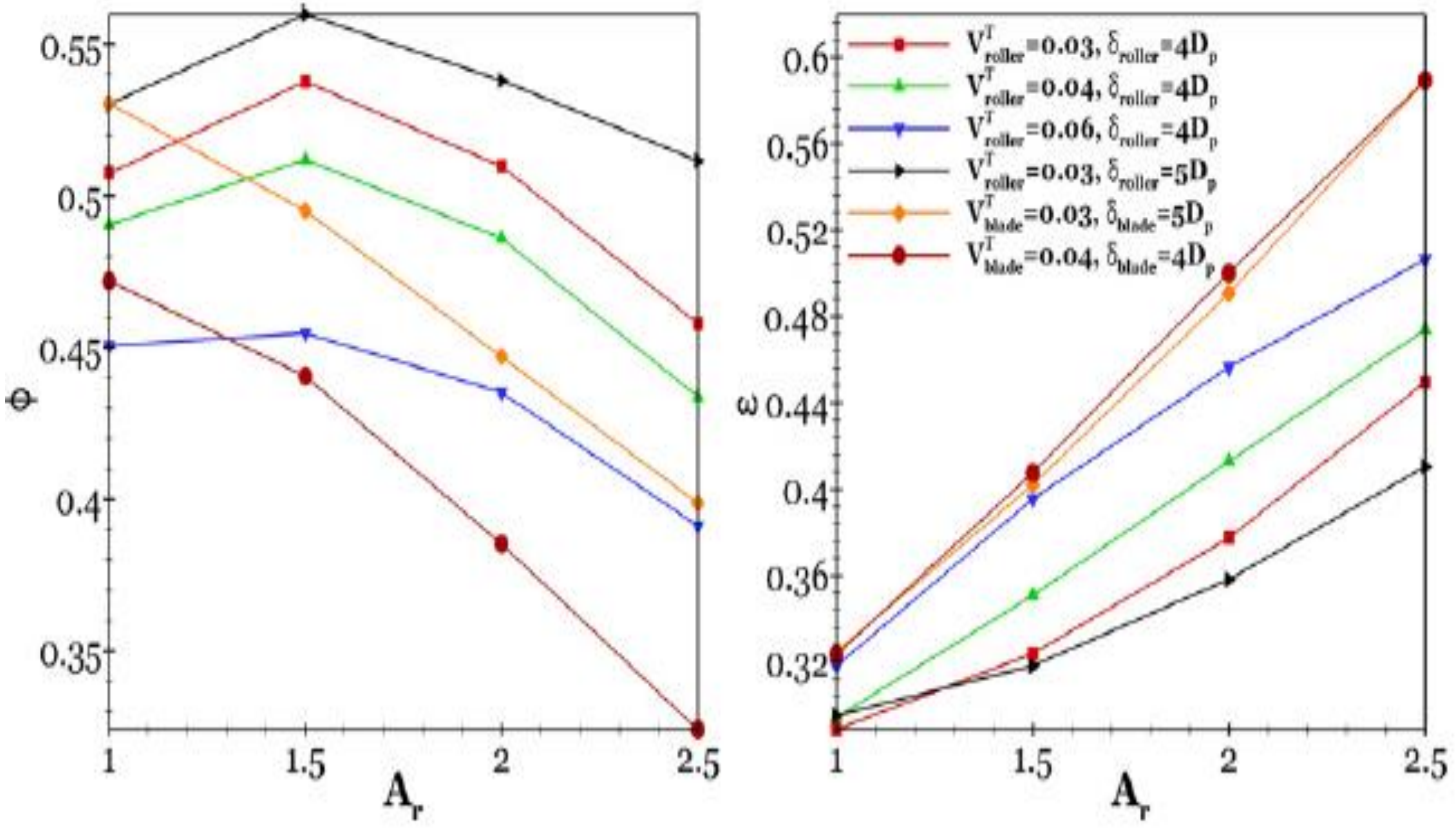
POWDERS

POWDER HANDLING: POWDER BED DEPOSITION



(a) Volume Fraction (b) Bed Roughness

Ar= ASPECT RATIO OF THE PARTICLES

V = SPREADING VELOCITY OF THE POWDERS

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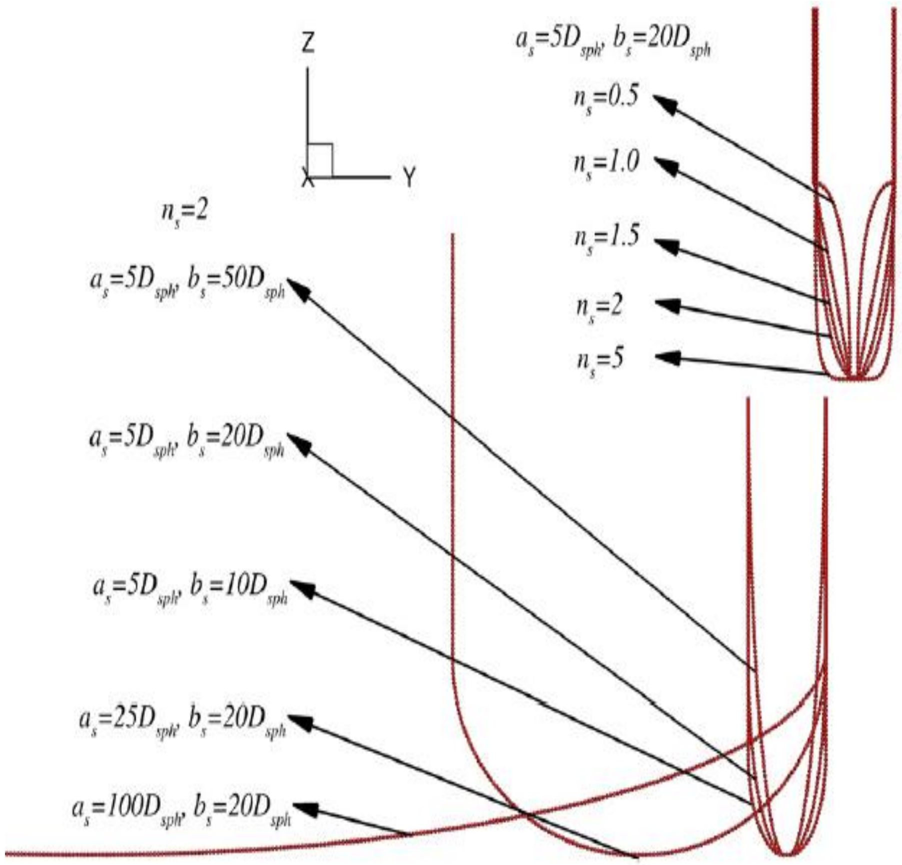
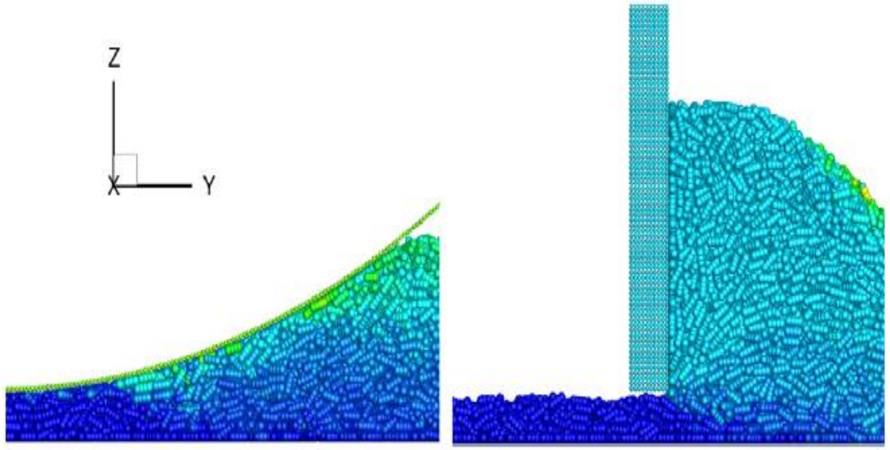
POWDERS

POWDER HANDLING: POWDER BED DEPOSITION

SPREADER GEOMETRY





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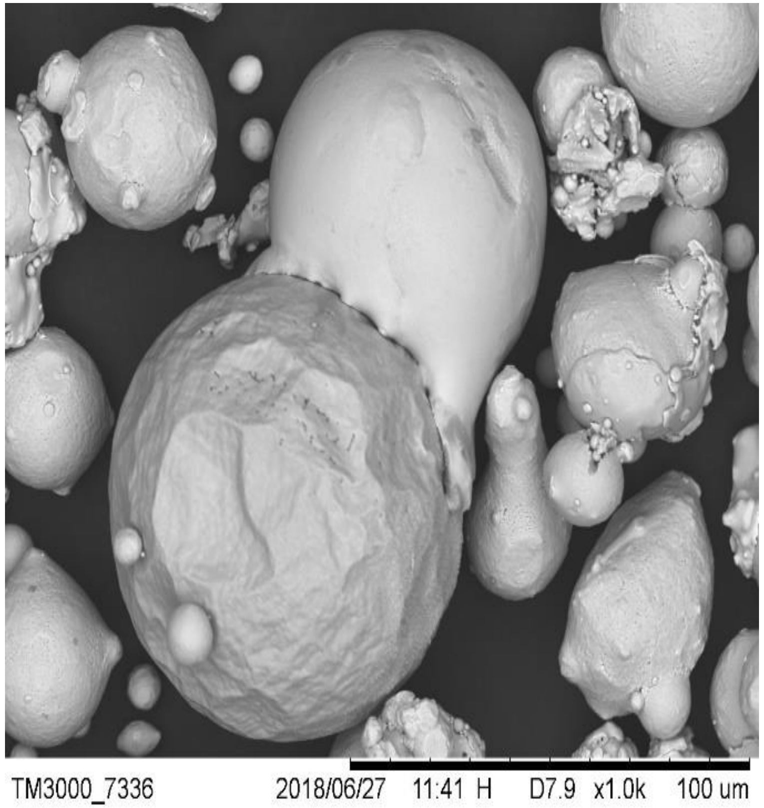
TAKE CARE OF THE POWDERS!!!
THEY RULE THE PROCESS!!!



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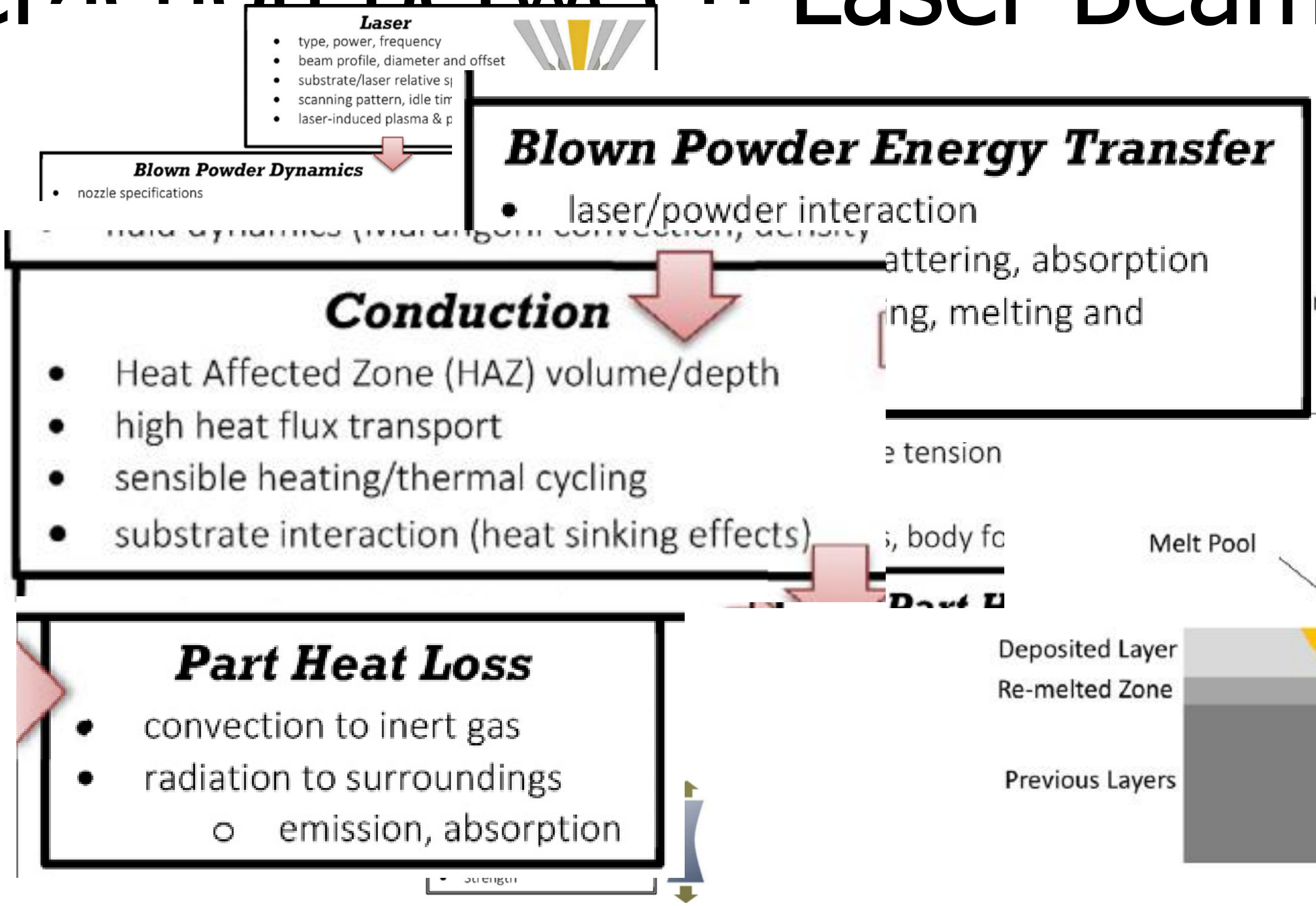
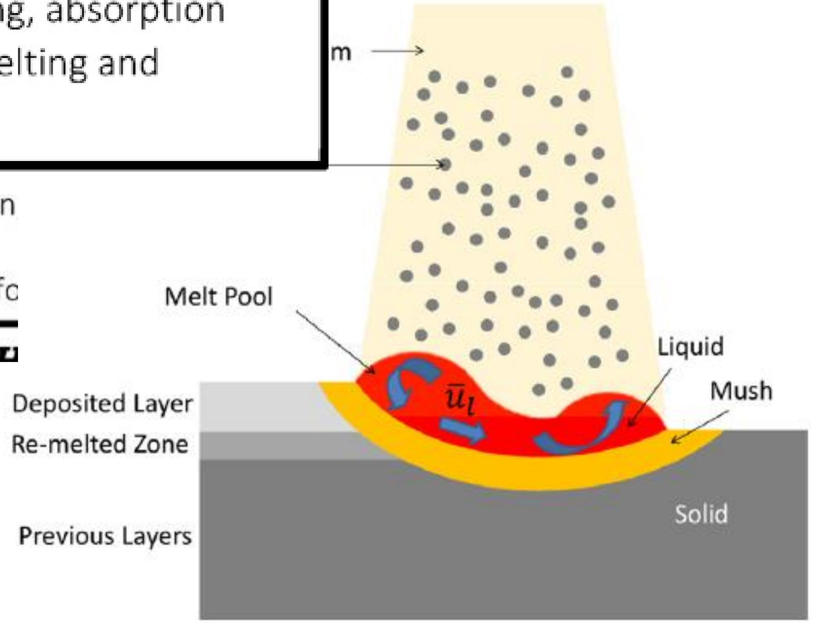
Interaction between Laser Beam and Powders





S.M. Thompson et al. An overview of Direct Laser Deposition for additive manufacturing; Part I: Transport phenomena, modeling and diagnostics, Addit. Manuf. 8 (2015) 36-62.

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Interacti… …n …ders

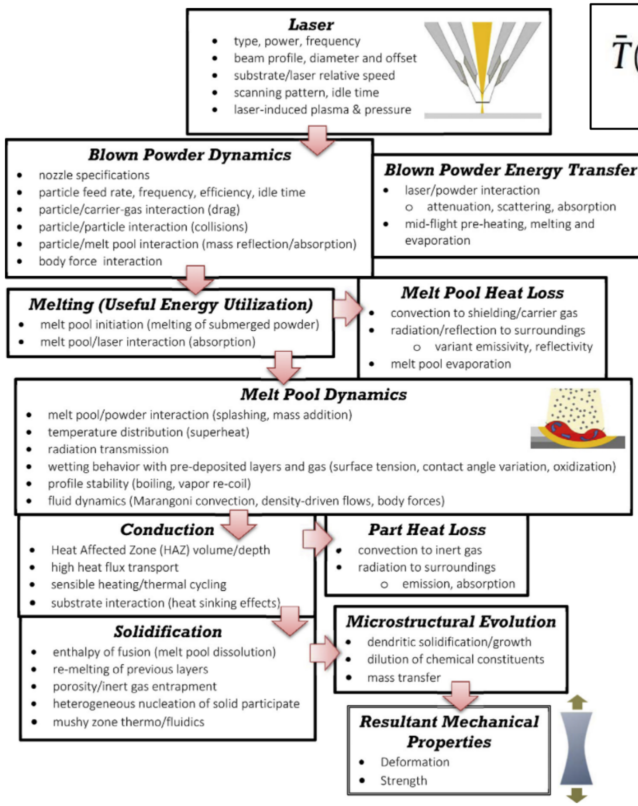
$$q''_{\mathrm{laser}} = \frac{2\alpha_{\mathrm{m}}P}{\pi R^2} \exp\left(-\frac{2r^2}{r_{\mathrm{b,i}}^2}\right)$$

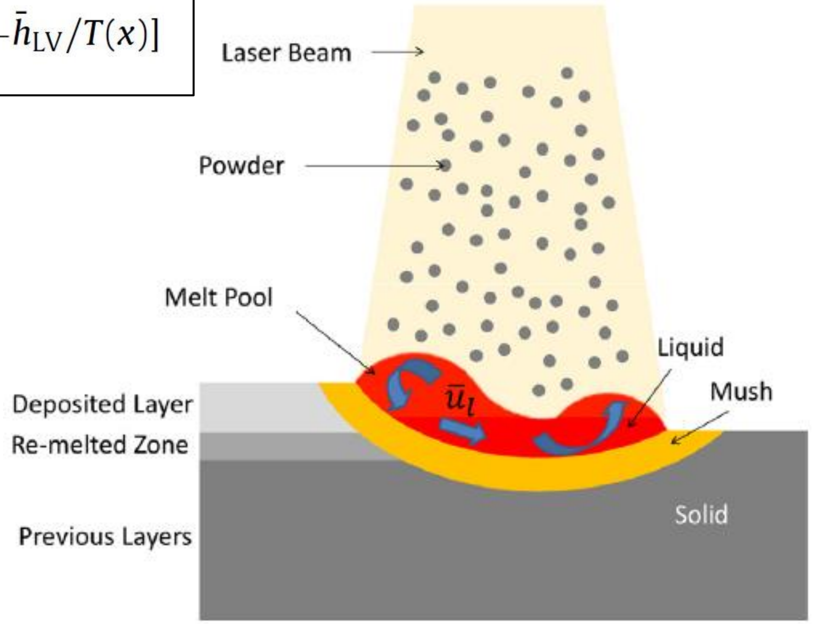
$$q''_{\mathrm{loss}} \cong h_x(T(x) - T_\infty) + \varepsilon\sigma(T^4(x) - T_\infty^4) + \rho_{\mathrm{L}} \left|\frac{\Delta x}{\Delta t}\right|_{\mathrm{e}} h_{\mathrm{LV}}$$

$$\bar{T}(x^*, z^*) = \mathrm{e}^{-x^*} K_{\mathrm{o}}\left(\sqrt{x^{*2} + z^{*2}}\right)$$

$$\left|V_{\mathrm{iso}}\right| = \left|V_{\mathrm{beam}}\right| \cdot \cos\theta$$

$$\left|\frac{\Delta x}{\Delta t}\right|_{\mathrm{e}} = c_{\mathrm{s}} \exp[-\bar{h}_{\mathrm{LV}}/T(x)]$$





S.M. Thompson et al. An overview of Direct Laser Deposition for additive manufacturing; Part I: Transport phenomena, modeling and diagnostics, Addit. Manuf. 8 (2015) 36-62.

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PROCESS

PROCESS STUDY FOR INCONEL 718/COPPER MIX

EXPERIMENTAL PLAN

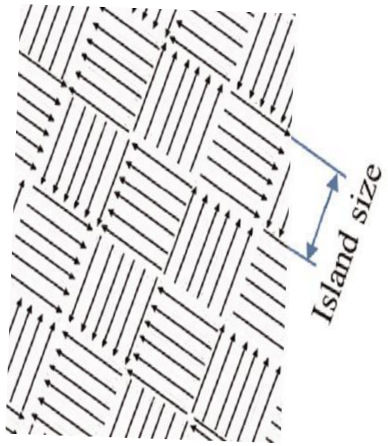
PROCESS PARAMETERS

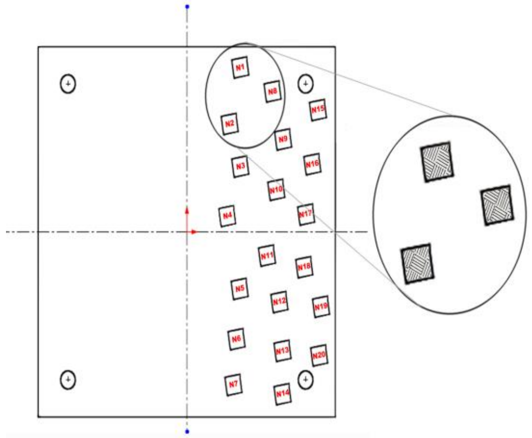
COPPER CONTENT (0%; 1%; 5%; 20%)
COPPER PARTICLES SHAPE (SPERICAL, COMPLEX SHAPE)
LAYER THICKNESS (30 MICRONS; 45 MICRONS)
SCAN SPEED (20 DIFFERENT VALUES)
LASER POWER (20 DIFFERENT VALUES)
SCAN STRATEGY KEPT CONSTANT

MEASURED OUTPUT

MICROSTRUCTURE
MICROHARDNESS
DENSITY
THERMAL CONDUCTIVITY
POROSITY ANALYSIS

Island size = 5 mm

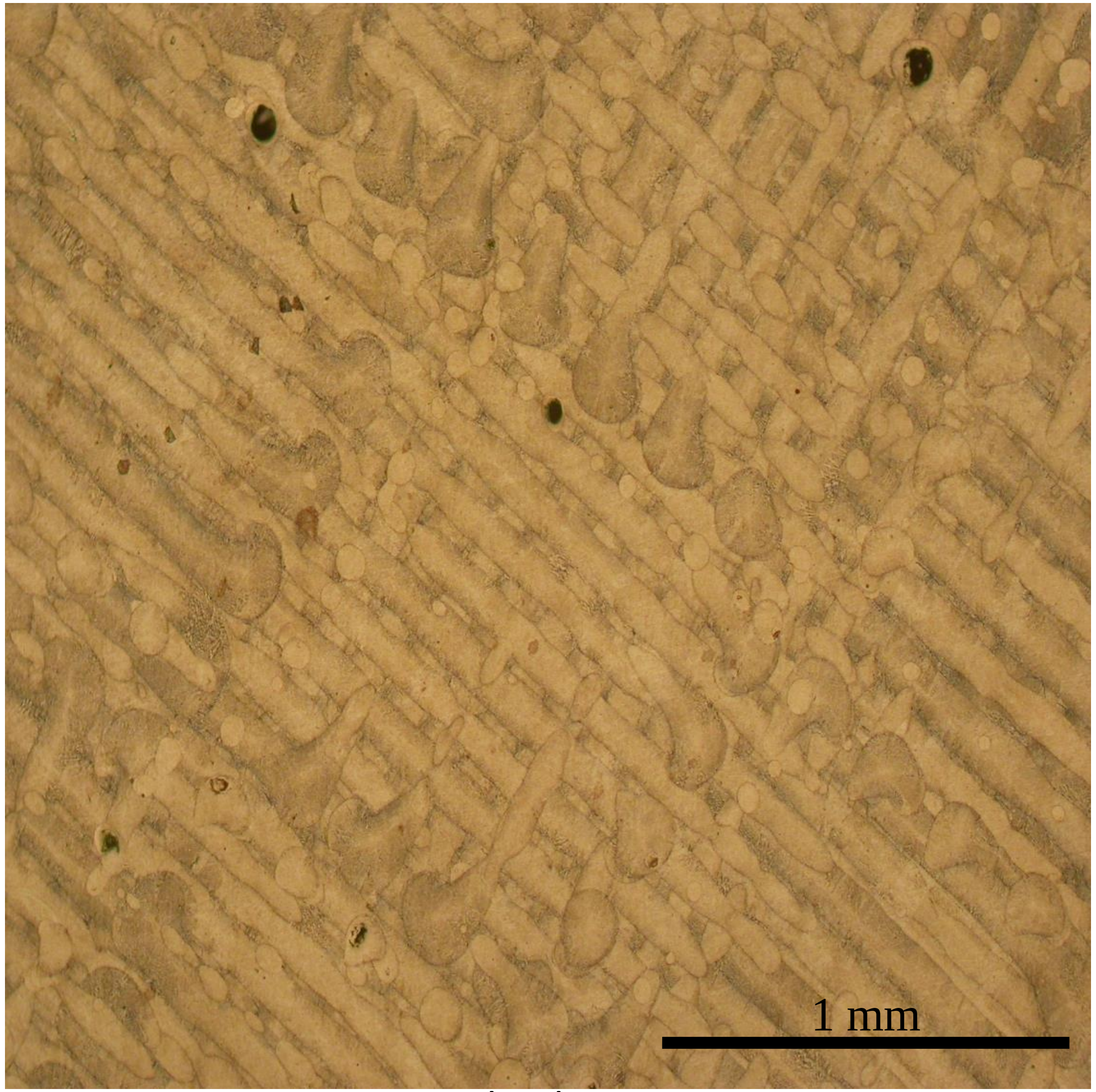




PROCESS

PROCESS STUDY FOR INCONEL 718/COPPER MIX

MICROSTRUCTURE



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PROCESS

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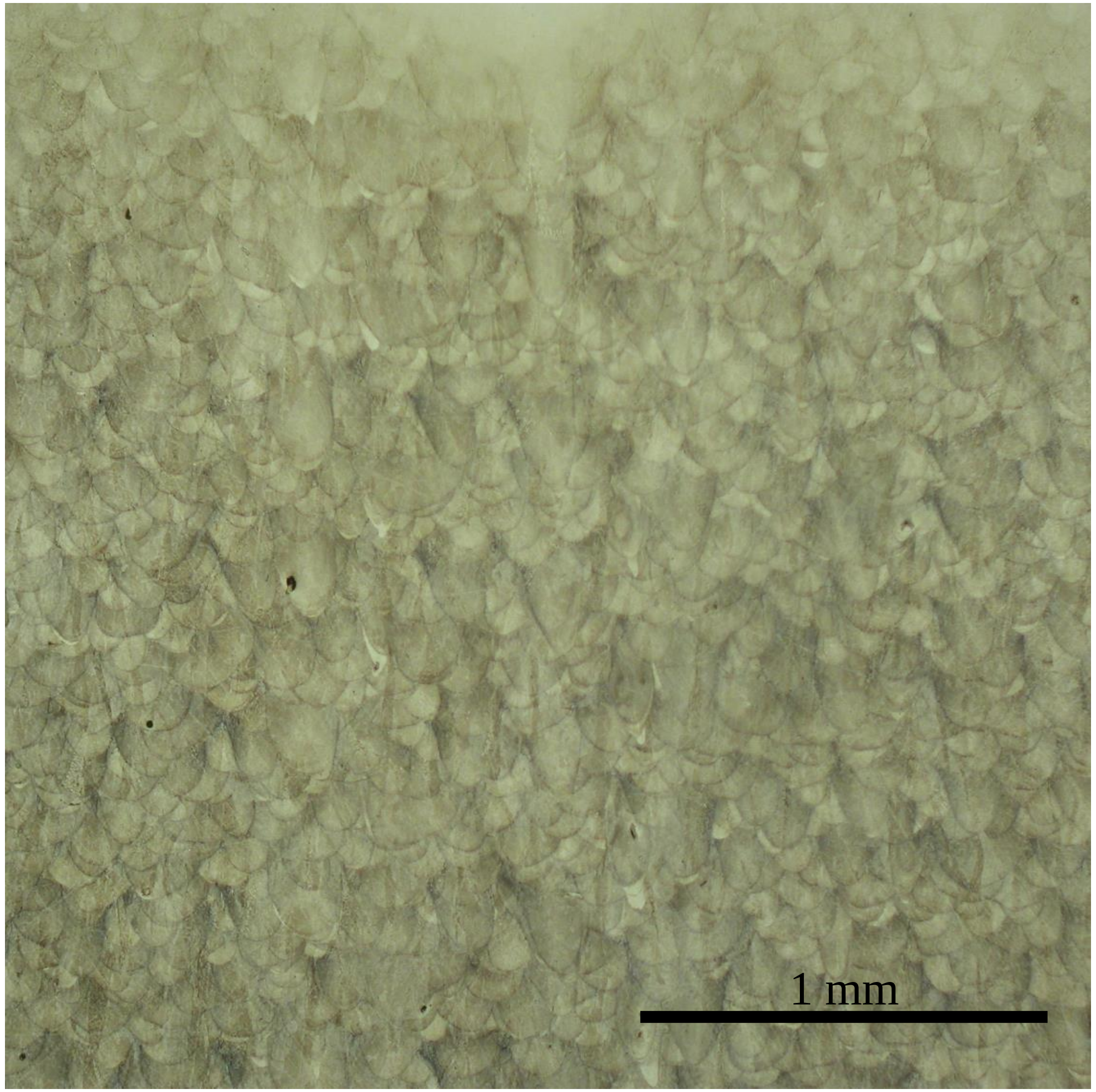
MICROSTRUCTURE

Upskin – IN1; P=170 W; Vs = 530 mm/s;



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PROCESS

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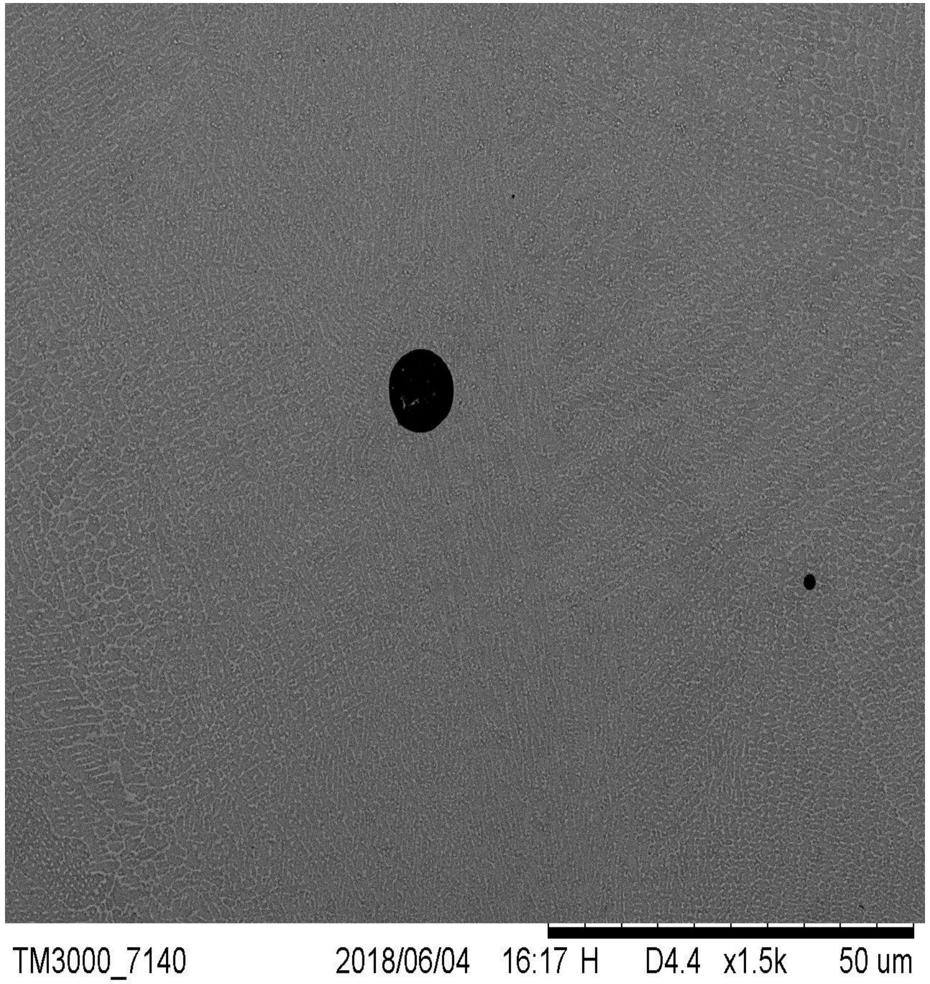
MICROSTRUCTURE

Upskin – IN10; P= 210 W; Vs = 655 mm/s;



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PROCESS

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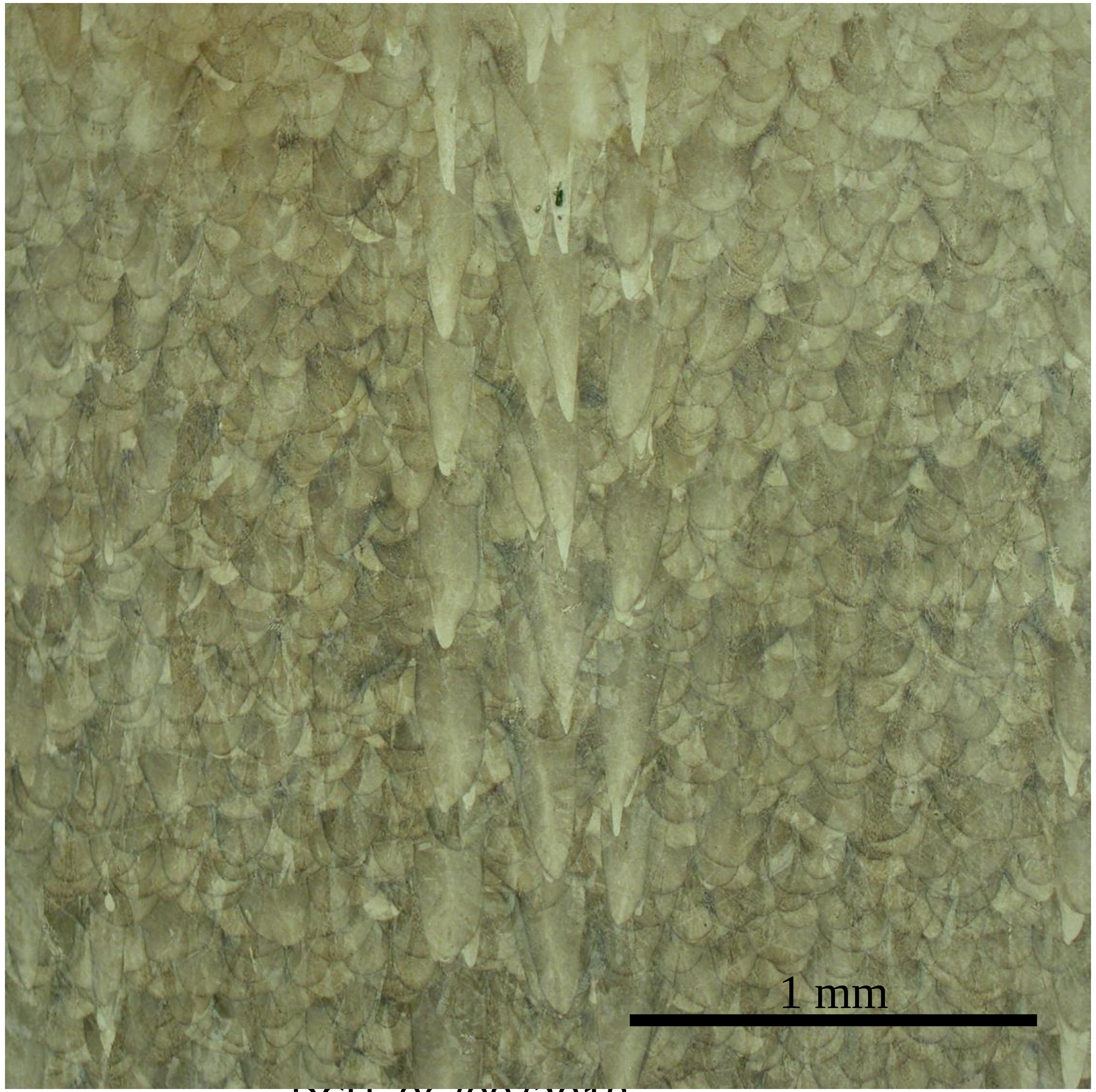
MICROSTRUCTURE

Upskin – IN20; P= 220 W; Vs = 820 mm/s;



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PROCESS

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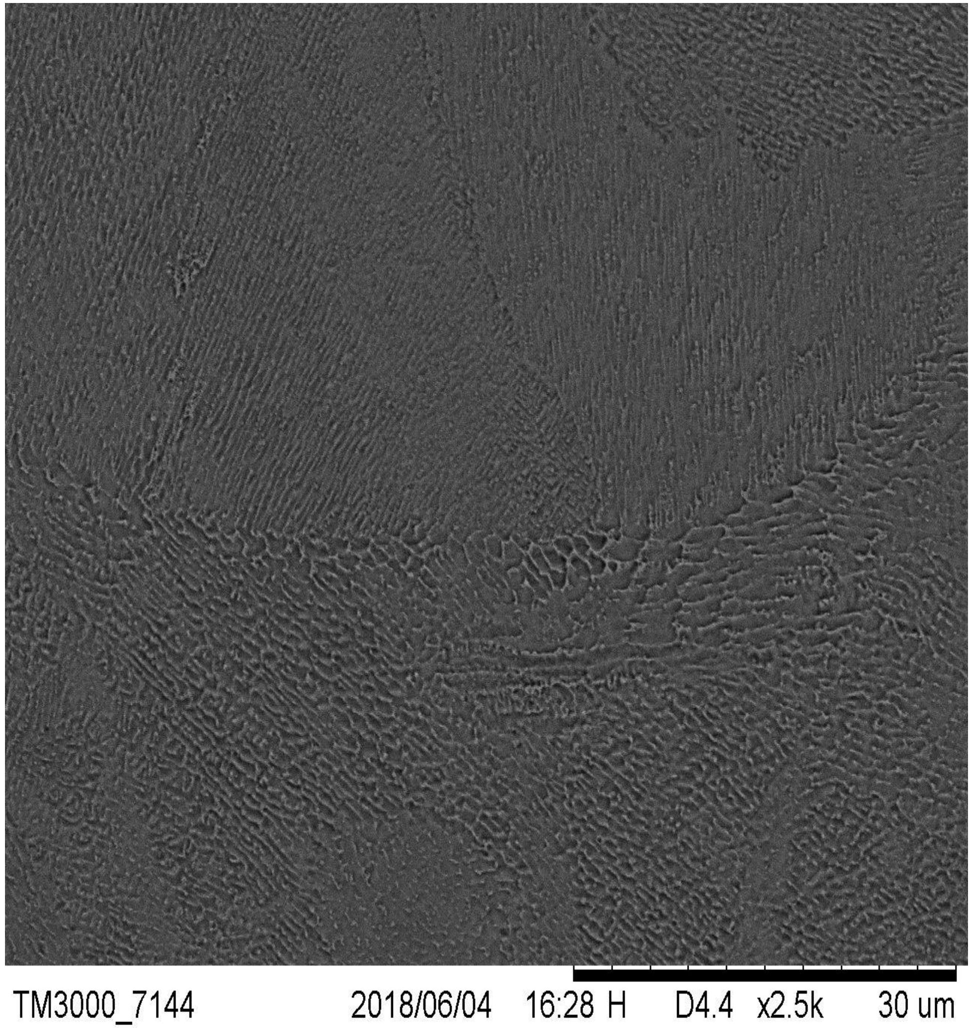
MICROSTRUCTURE

Upskin – IN20; P= 220 W; Vs = 820 mm/s;



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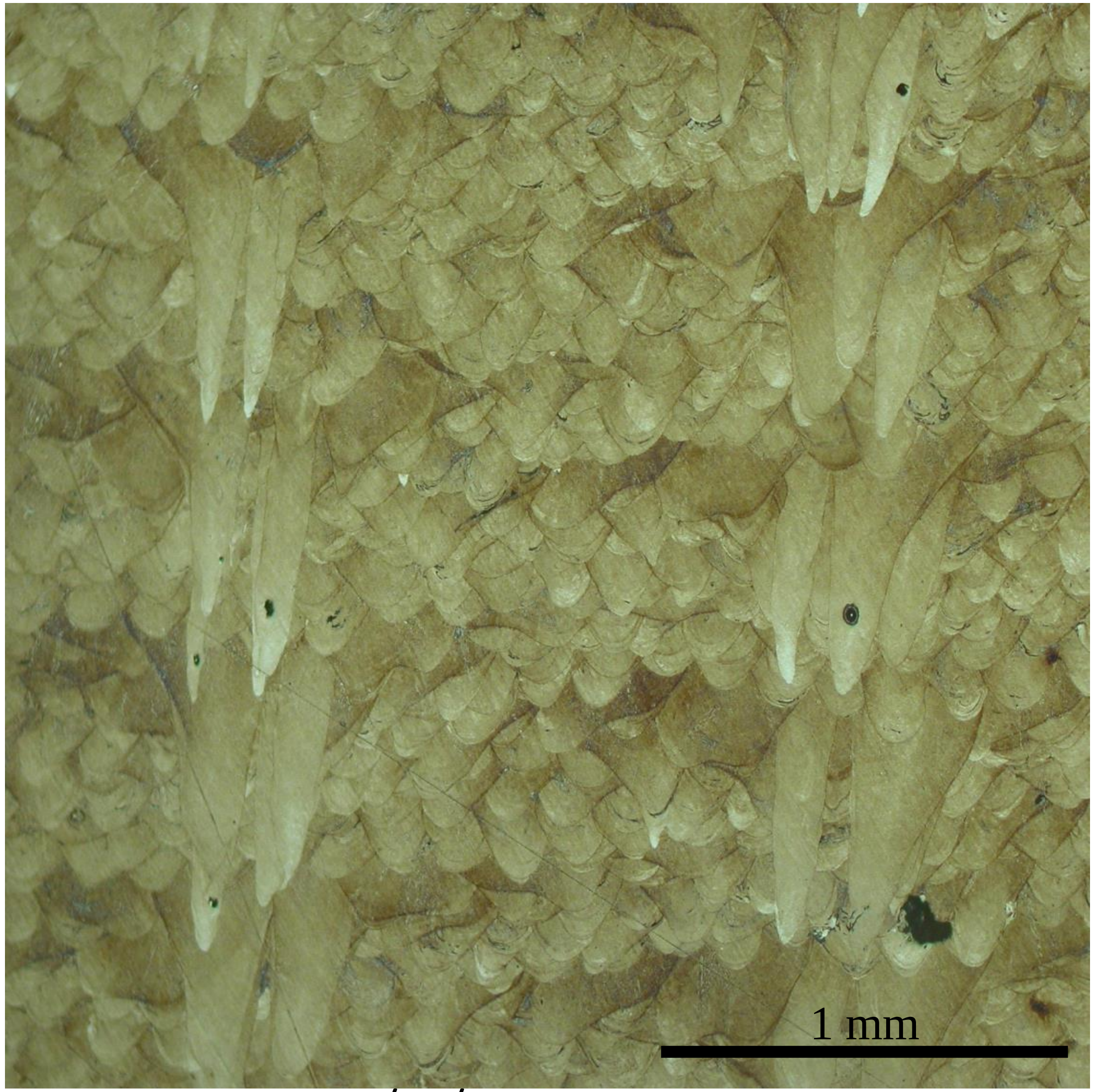
MICROSTRUCTURE

Core – N1;
P=350 W;
Vs=1700 mm/s;



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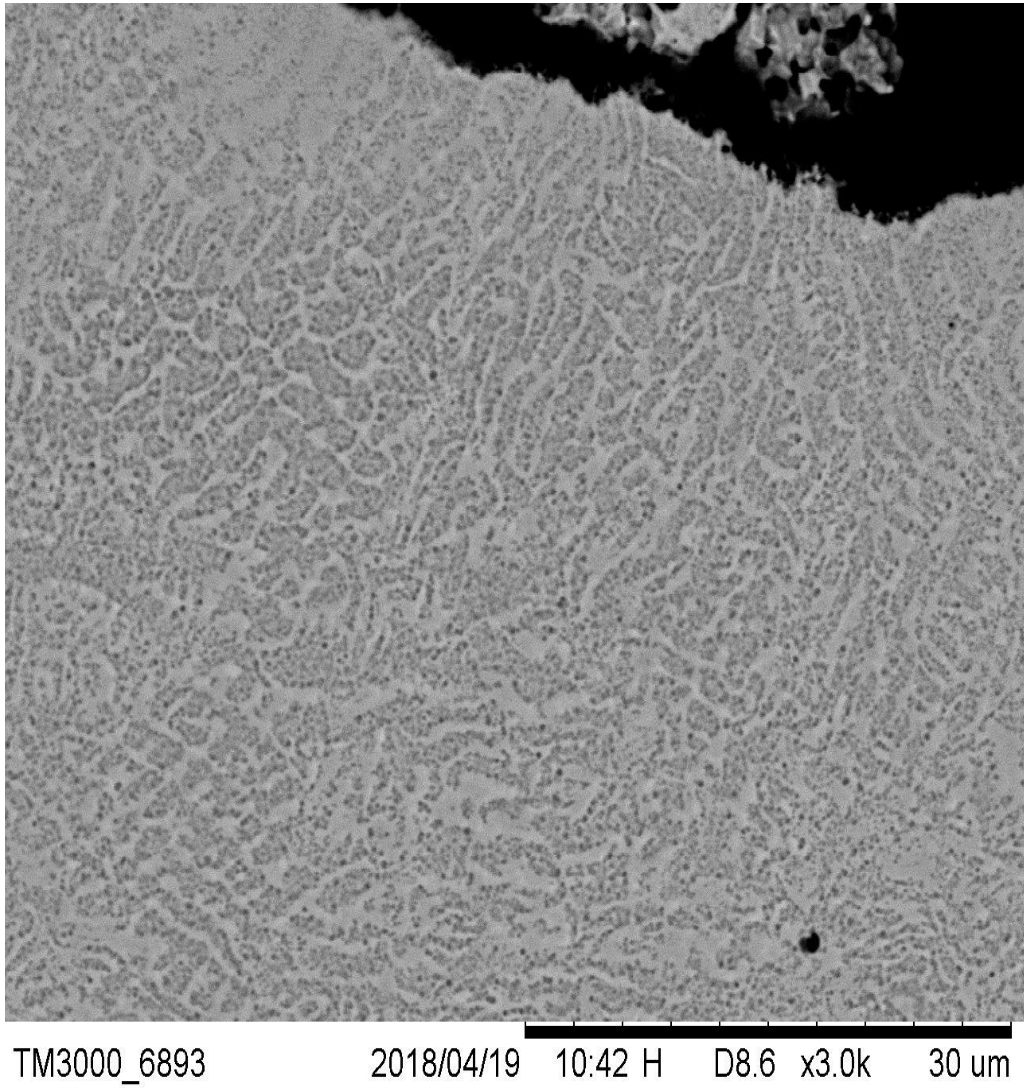
PROCESS

PROCESS STUDY FOR INCONEL 718/COPPER MIX

MICROSTRUCTURE

Upskin– N1; P=350 W; Vs=1700 mm/s;



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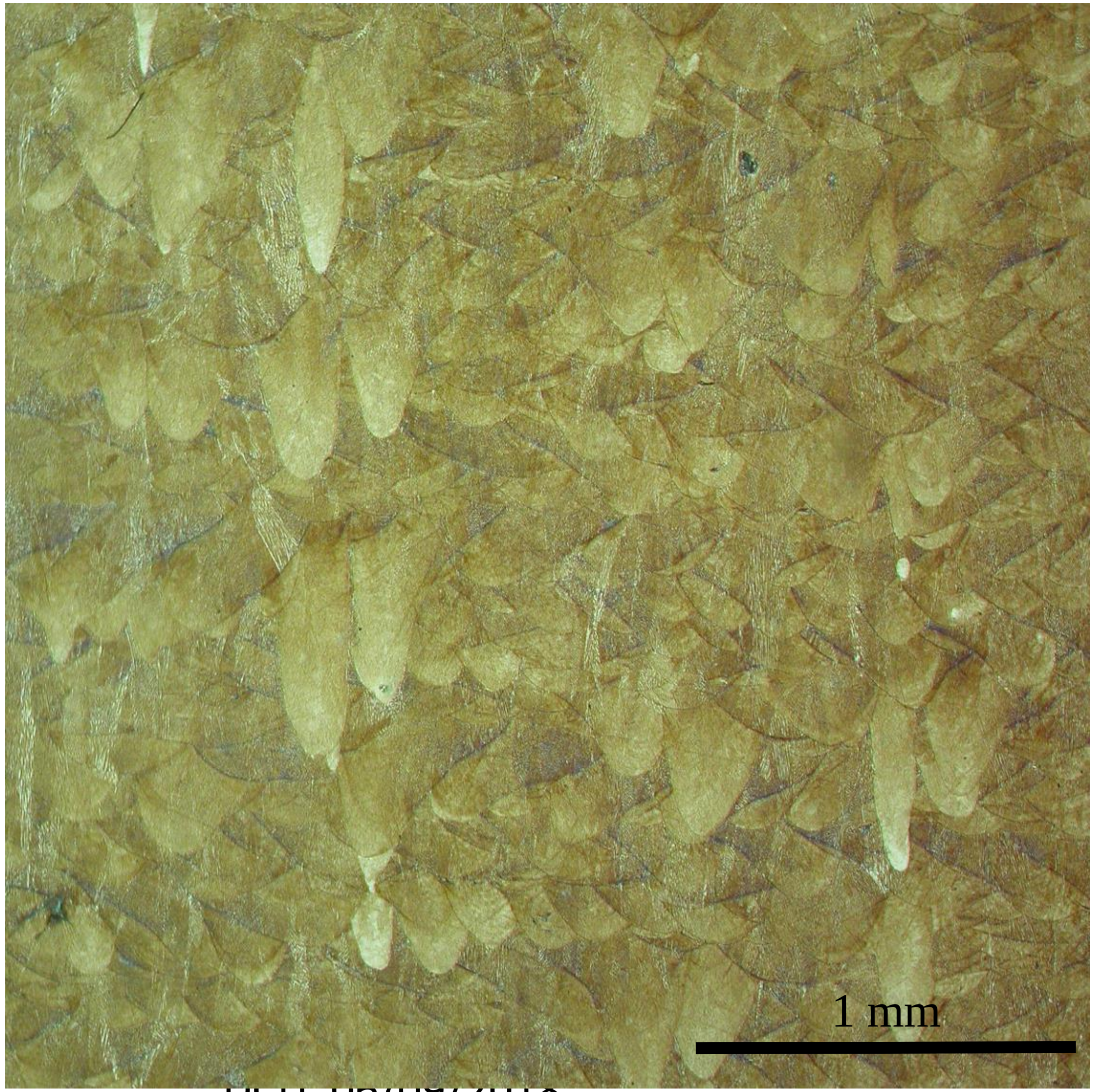
PROCESS

PROCESS STUDY FOR INCONEL 718/COPPER MIX

MICROSTRUCTURE

Core – N10;
P=372 W;
Vs=930 mm/s;



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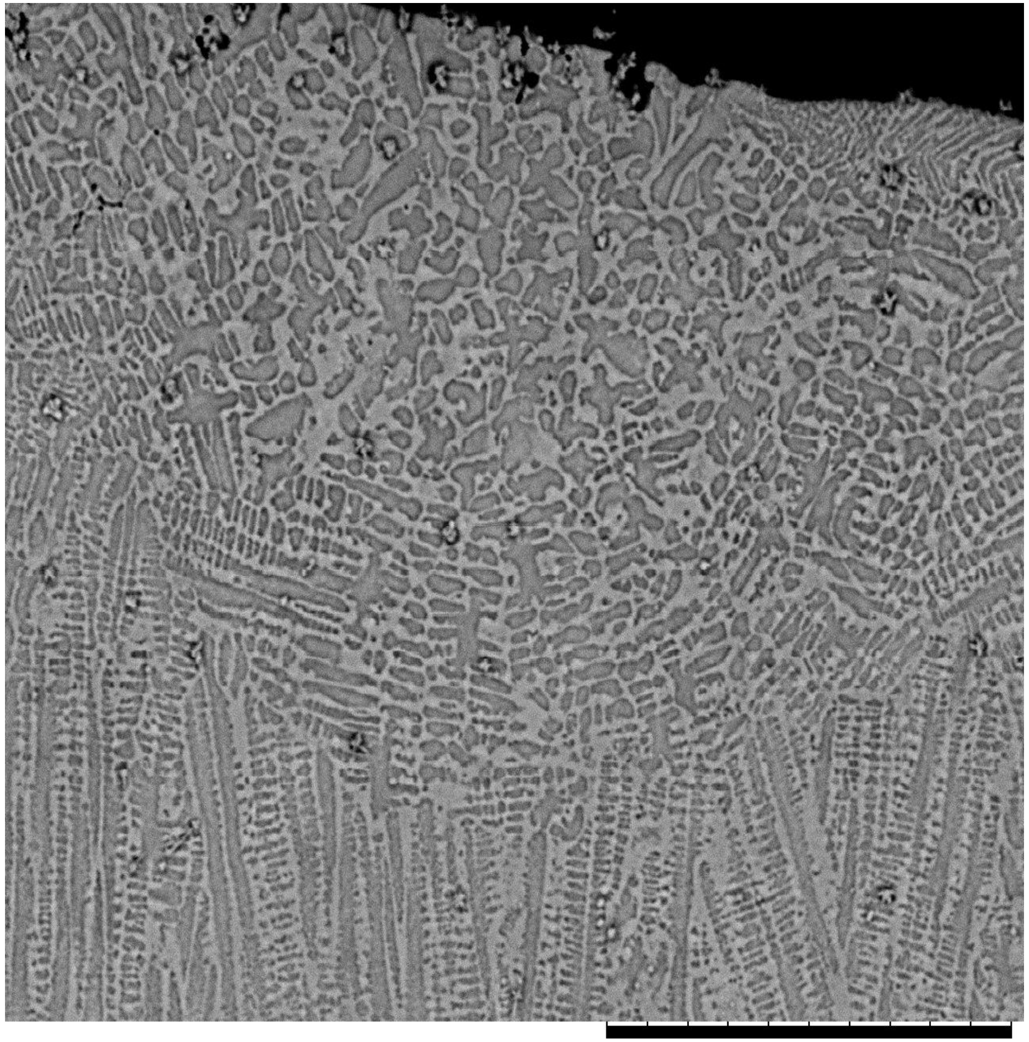
MICROSTRUCTURE

Upskin – N10; P=372 W; Vs=930 mm/s;



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PROCESS

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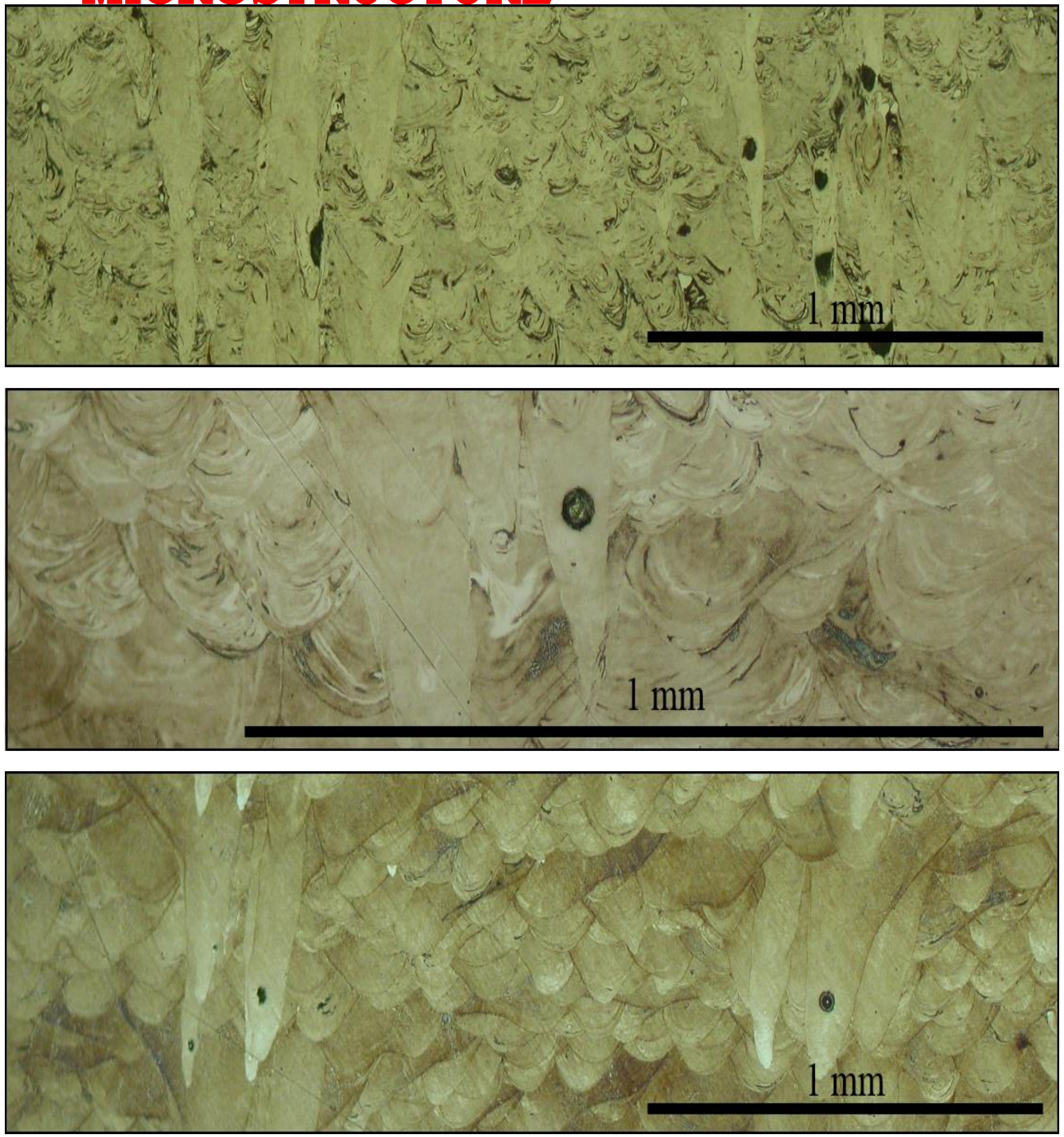
MICROSTRUCTURE

% CU



N1;
P=350 W;
Vs=1700 mm/s;

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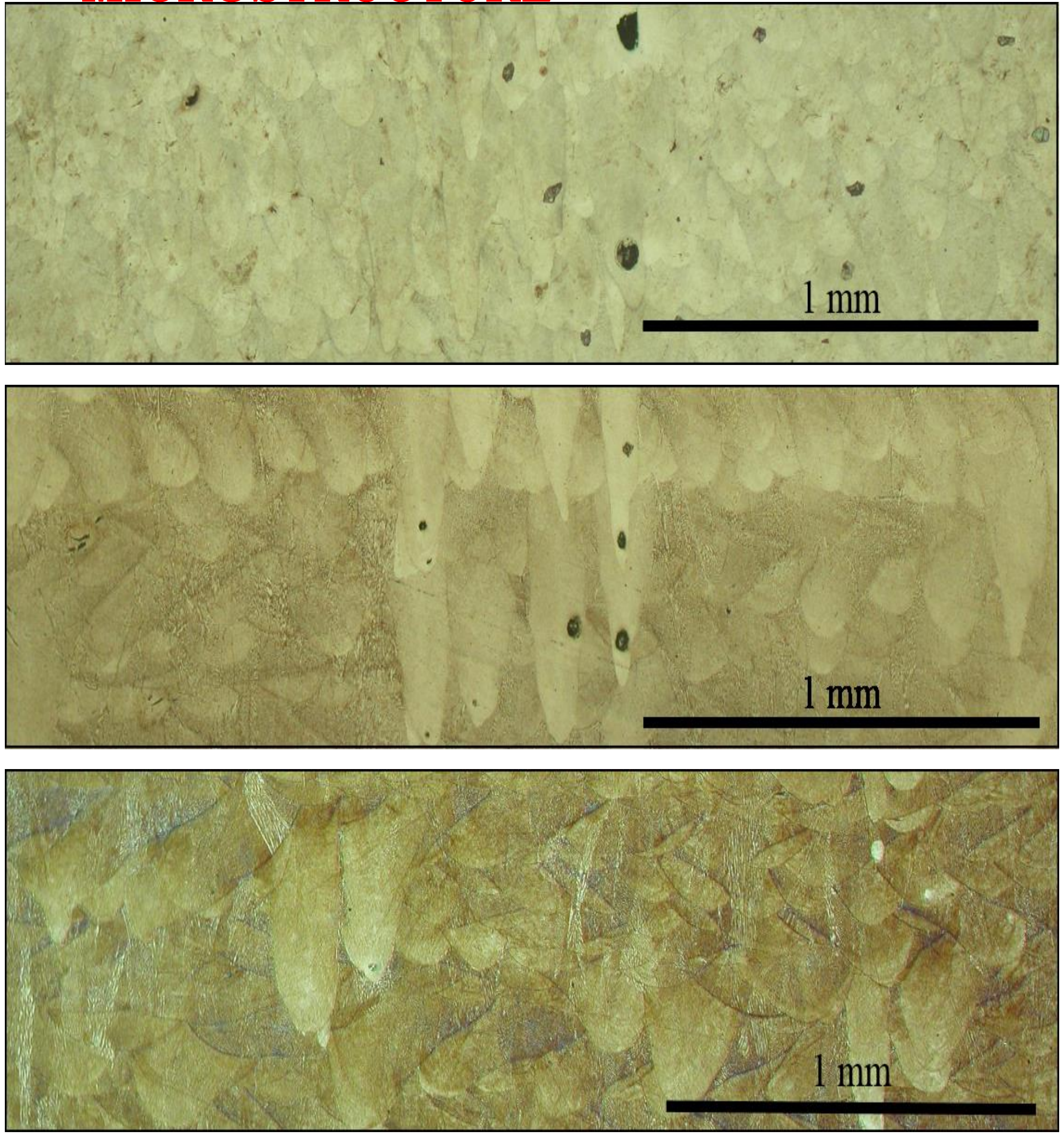
MICROSTRUCTURE

% CU



N10;
P=372 W;
Vs=930 mm/s

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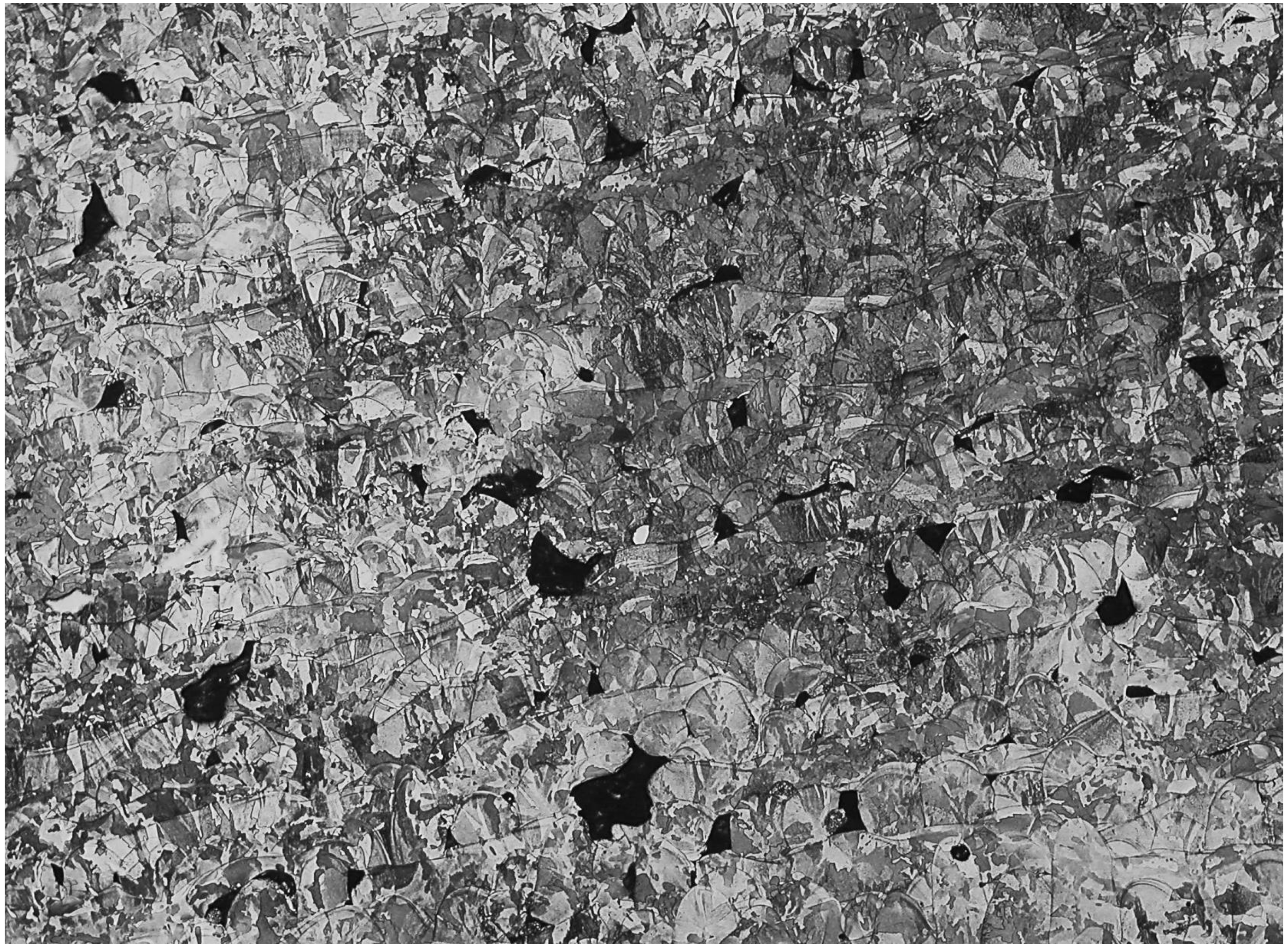
PROCESS
SOLID STATE JOINING OF AM PARTS

ADDITIVE MANUFACTURING: MULTILEVEL MICROSTRUCTURE



0,5 mm

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PROCESS

SOLID STATE JOINING OF AM PARTS

ADDITIVE MANUFACTURING: MULTILEVEL MICROSTRUCTURE

100 µm

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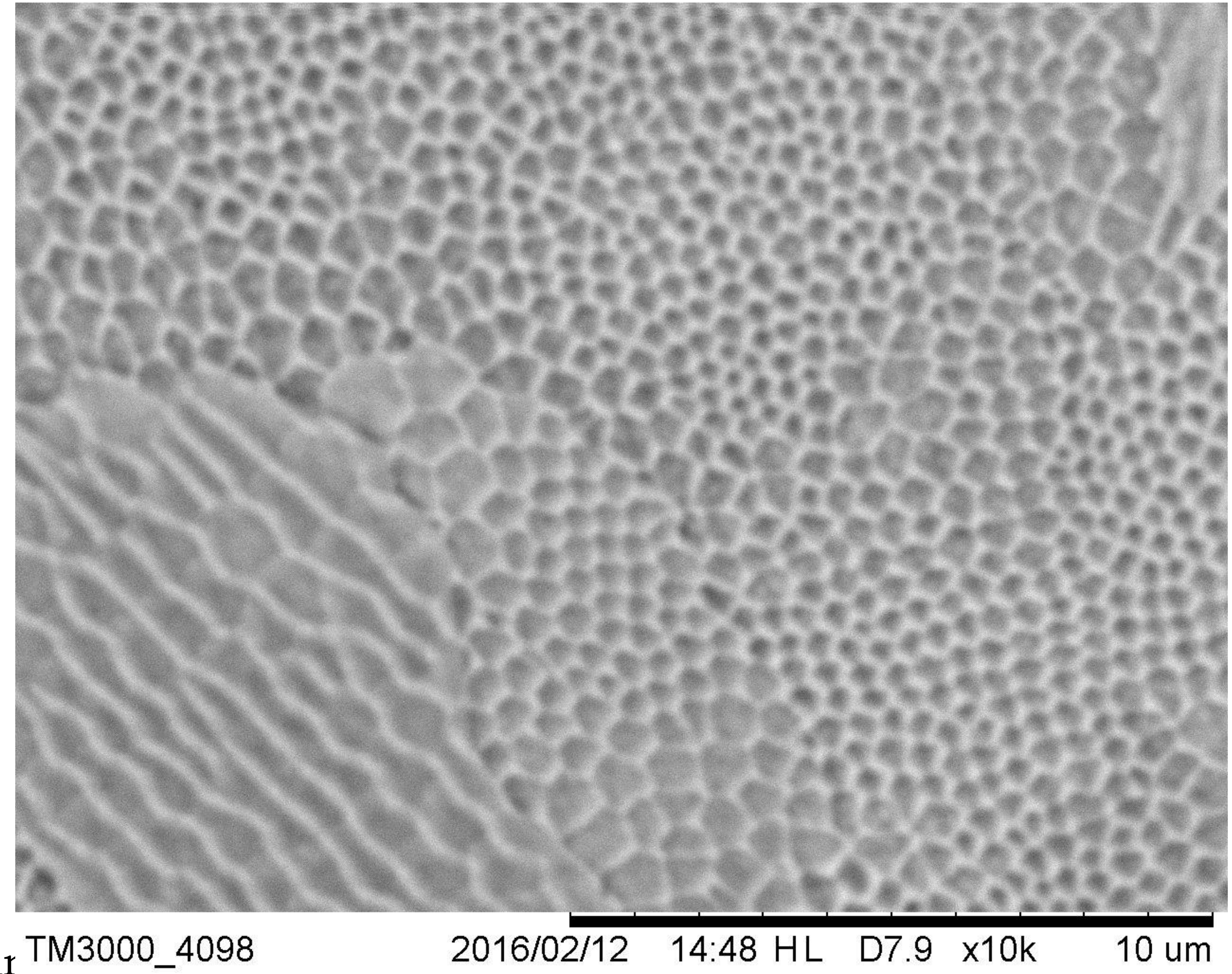
PROCESS
SOLID STATE JOINING OF AM PARTS



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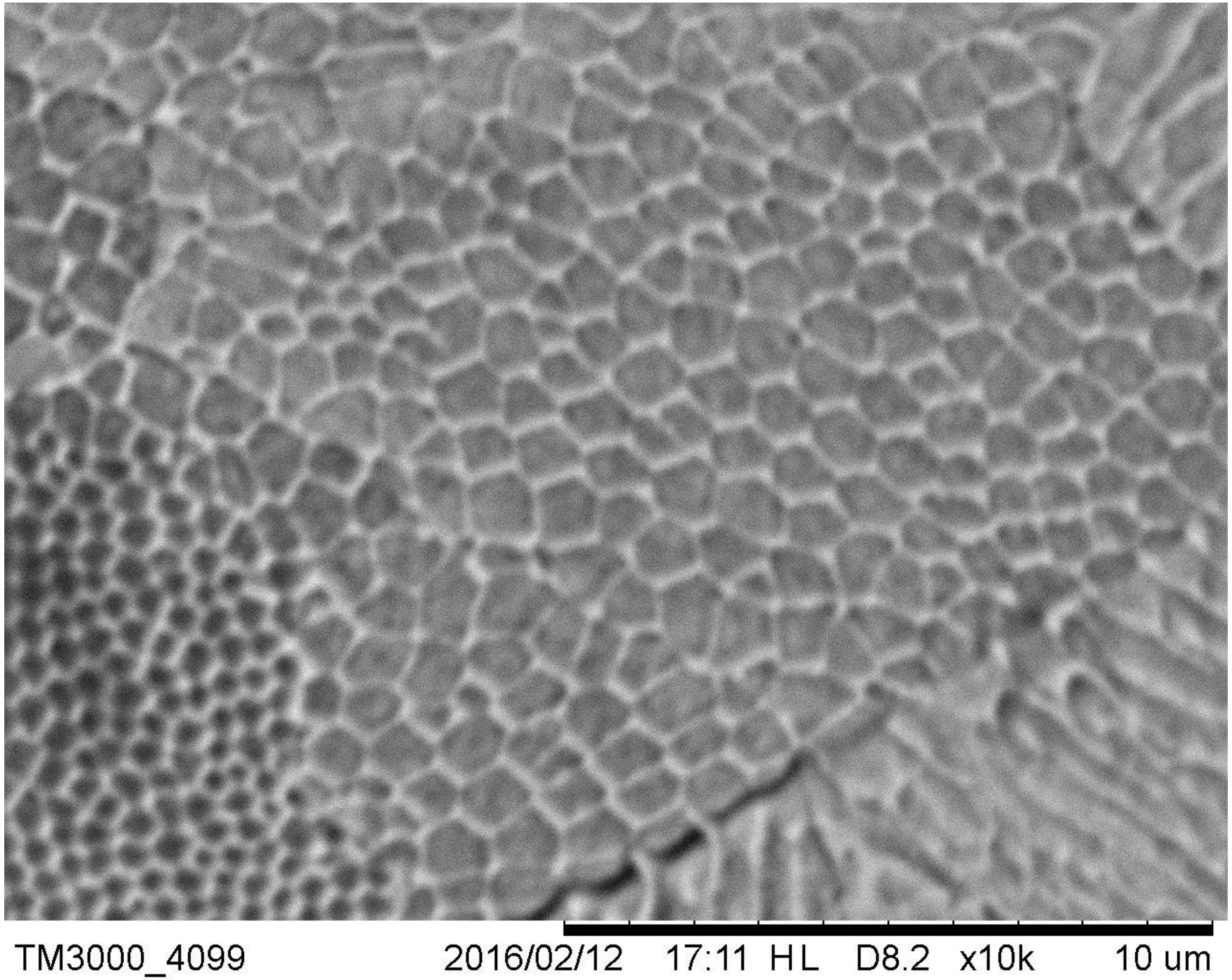
PROCESS

SOLID STATE JOINING OF AM PARTS



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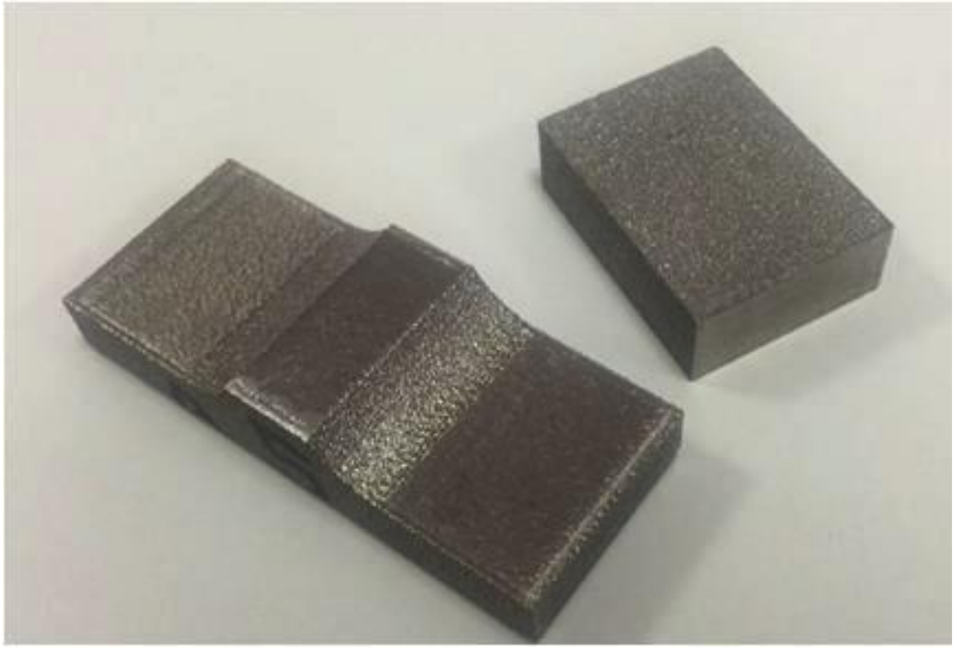
PROCESS

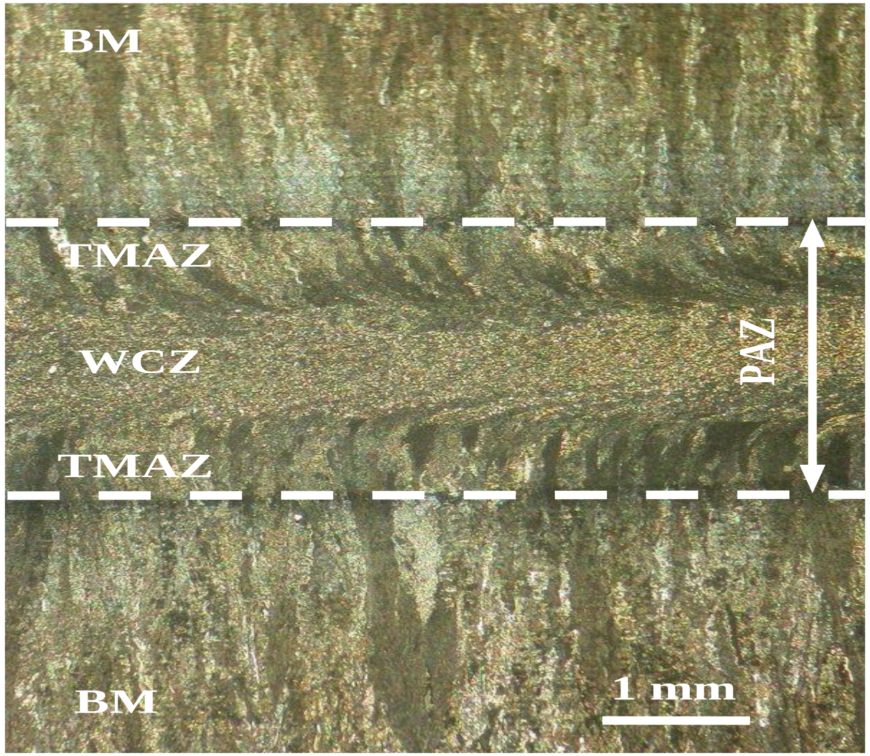
SOLID STATE JOINING: LINEAR FRICTION WELDING

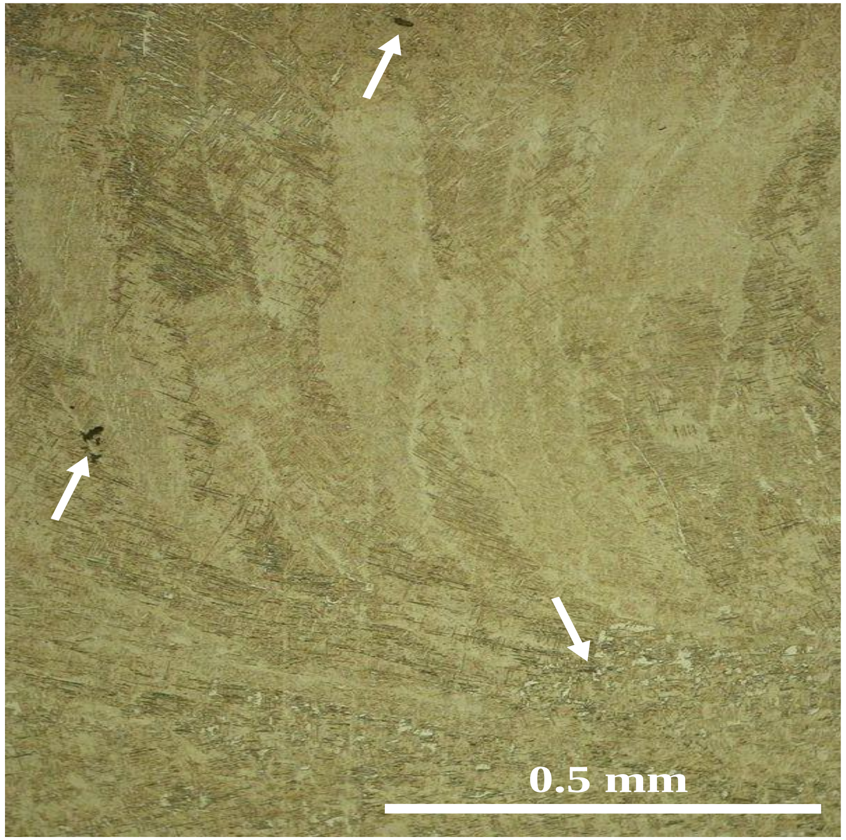
LINEAR FRICTION WELDING OF TI6AL4V PARTS MADE THROUGH ELECTRON BEAM MELTING



PROCESS

SOLID STATE JOINING: LINEAR FRICTION WELDING





		Oscillation frequency [Hz]		
		40	**45**	**50**
Pressure [MPa]	**55**	0.70 W/mm^2	0.79 W/mm^2	0.87 W/mm^2
	75	0.95 W/mm^2	1.10 W/mm^2	1.19 W/mm^2

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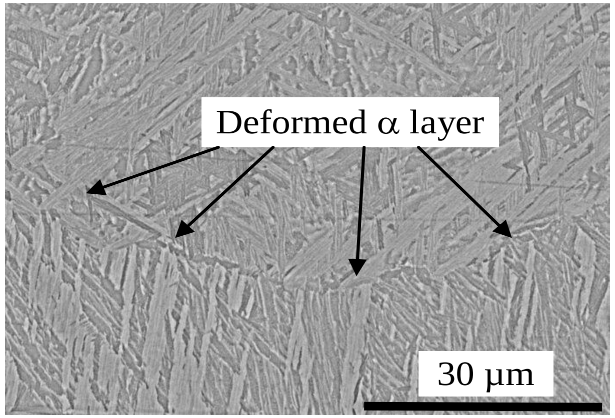
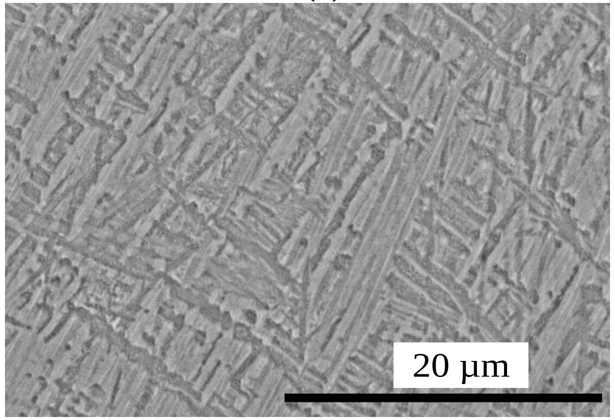
PROCESS

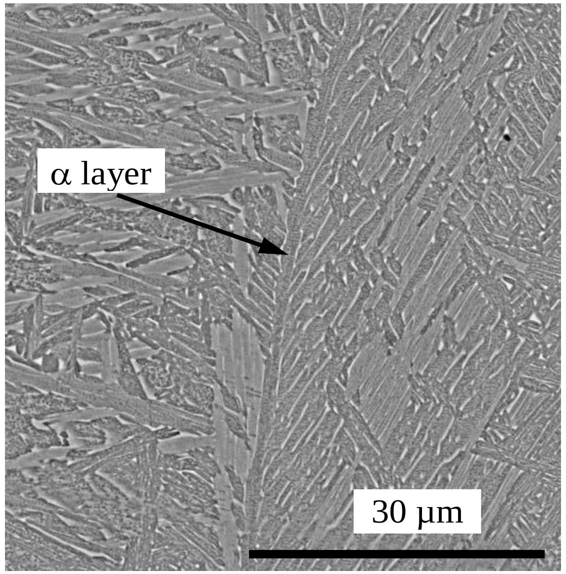
SOLID STATE JOINING: LINEAR FRICTION WELDING



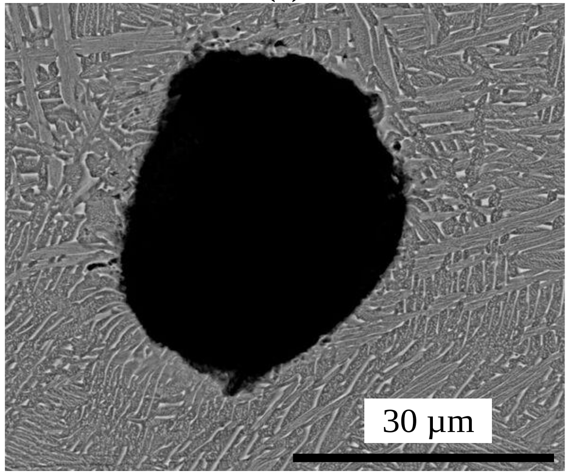
(a)



(b)



(a)



(b)

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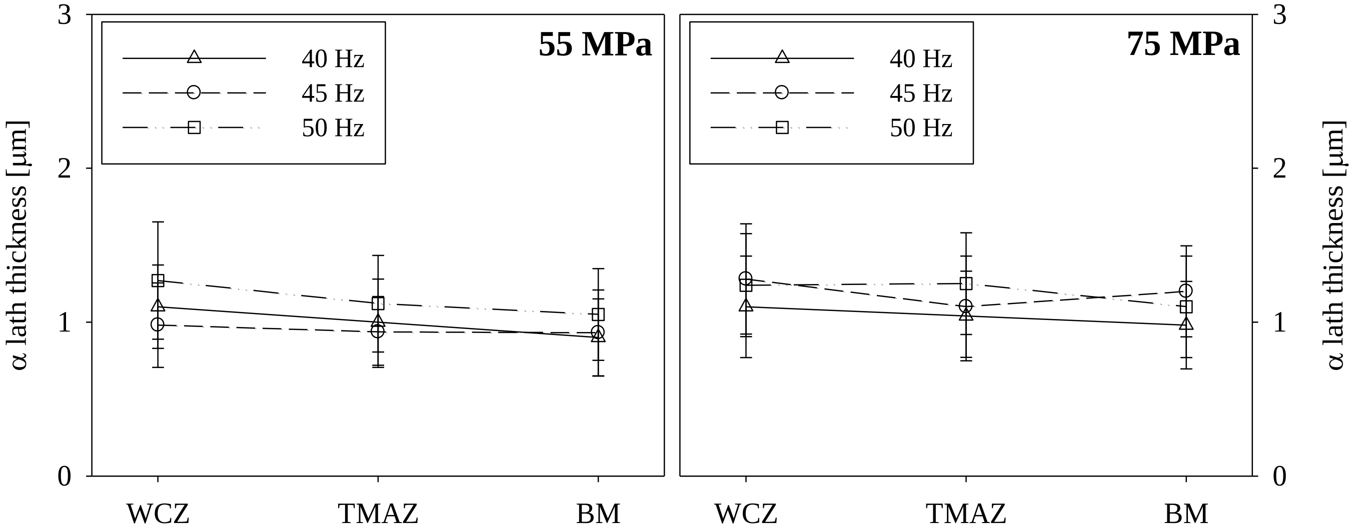
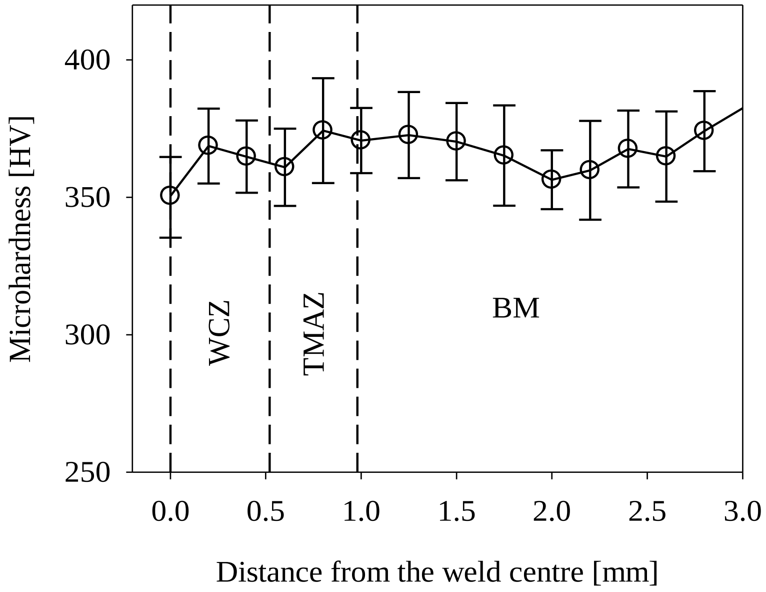
PROCESS
SOLID STATE JOINING: LINEAR FRICTION WELDING





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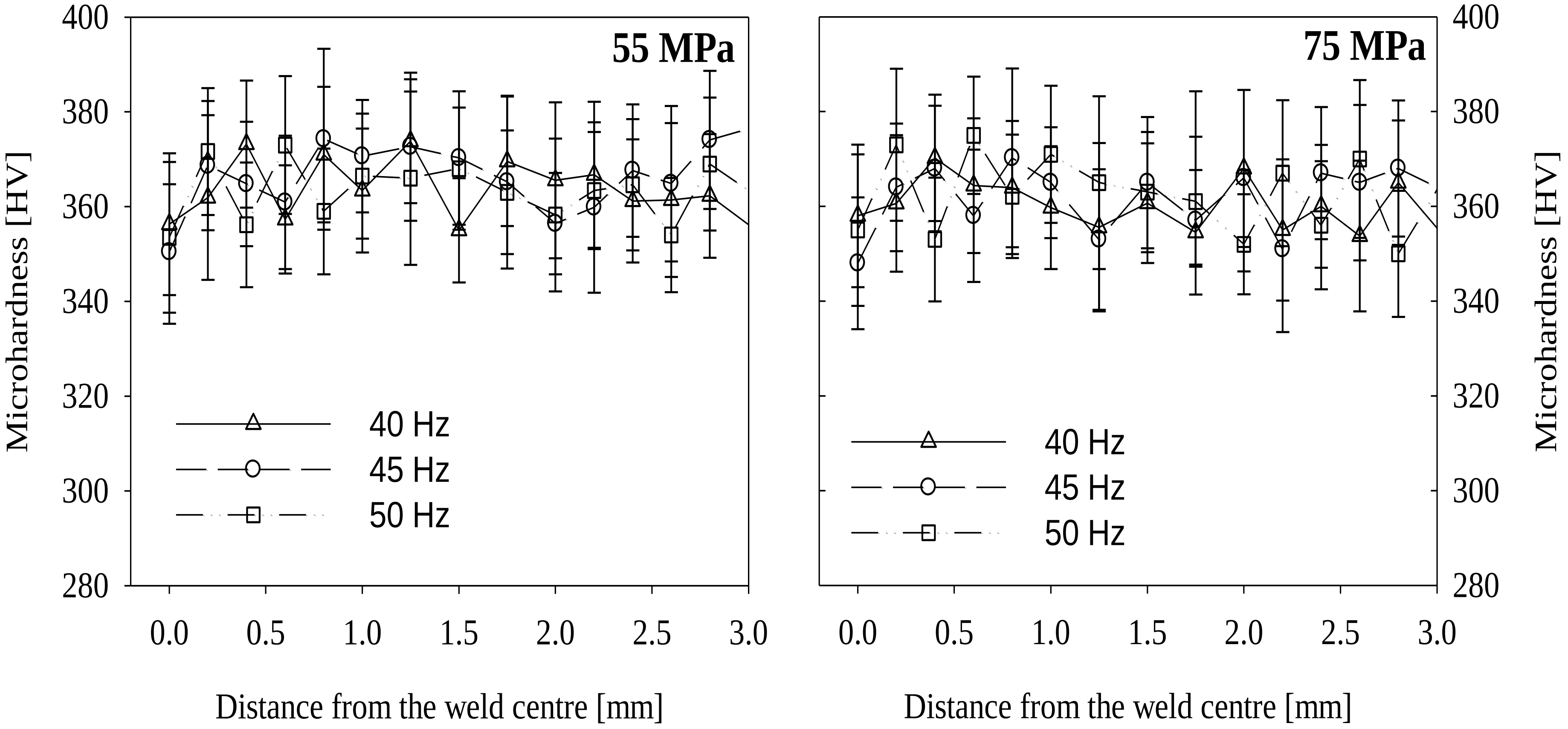
PROCESS

SOLID STATE JOINING: LINEAR FRICTION WELDING



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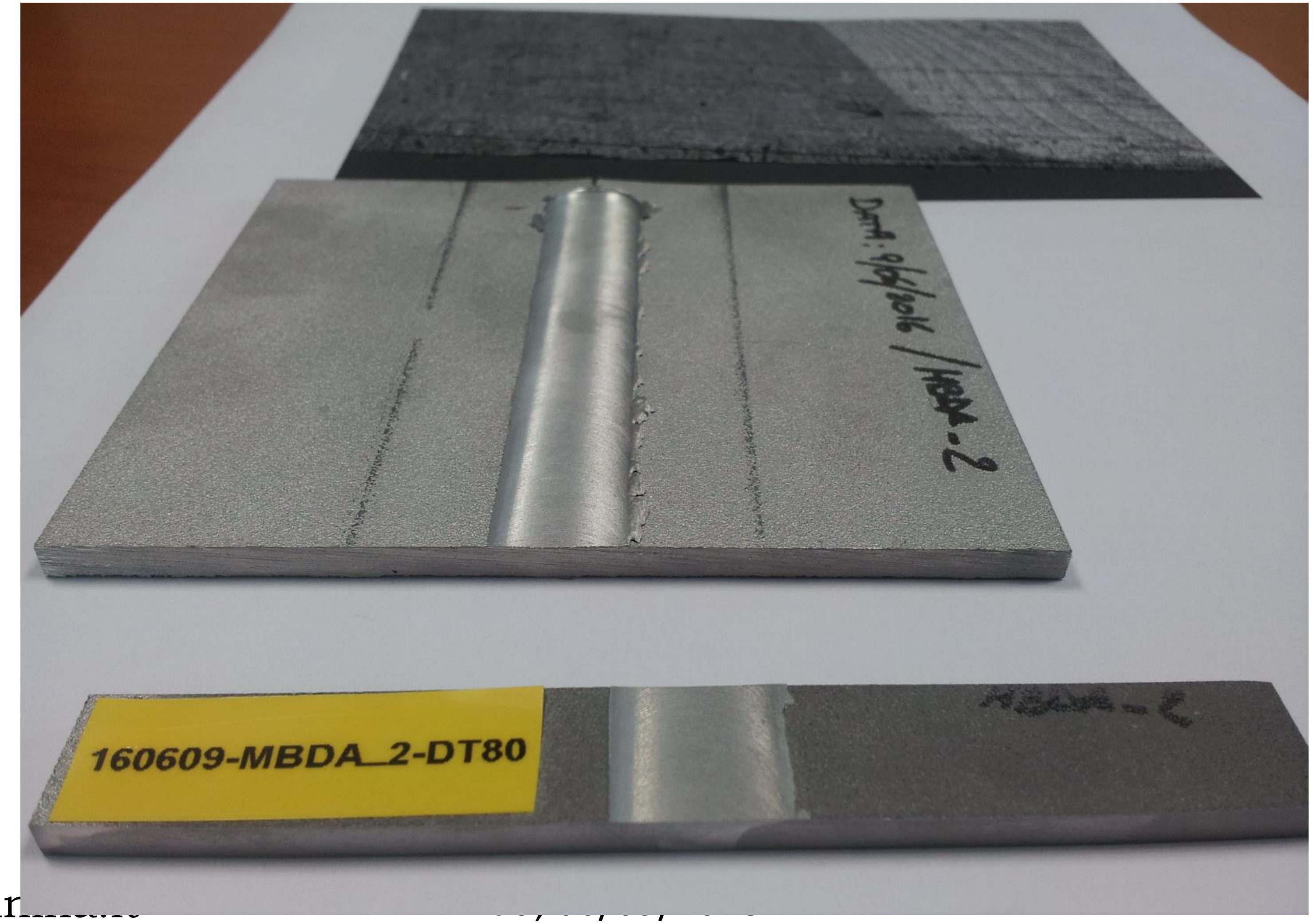
PROCESS

SOLID STATE JOINING: FRICTION STIR WELDING

FRICTION STIR WELDING OF ALSI10 PLATES MADE THROUGH SELECTIVE LASER MELTING



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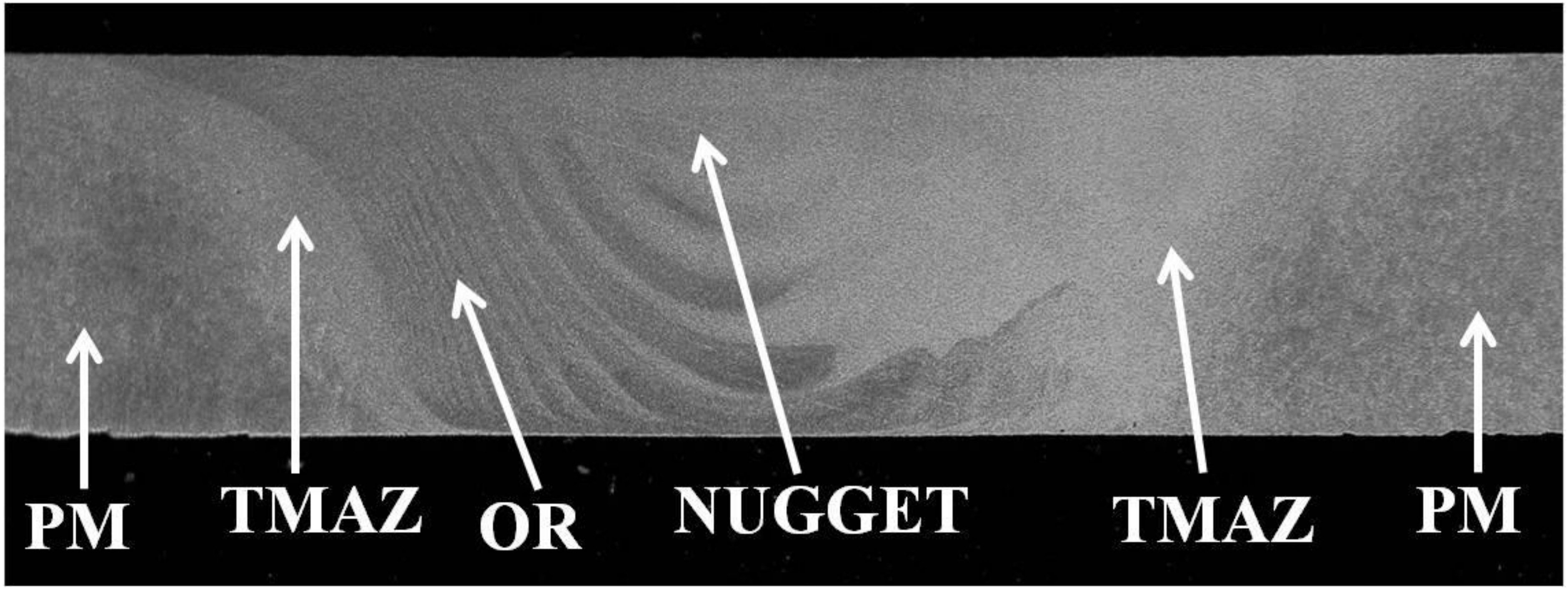
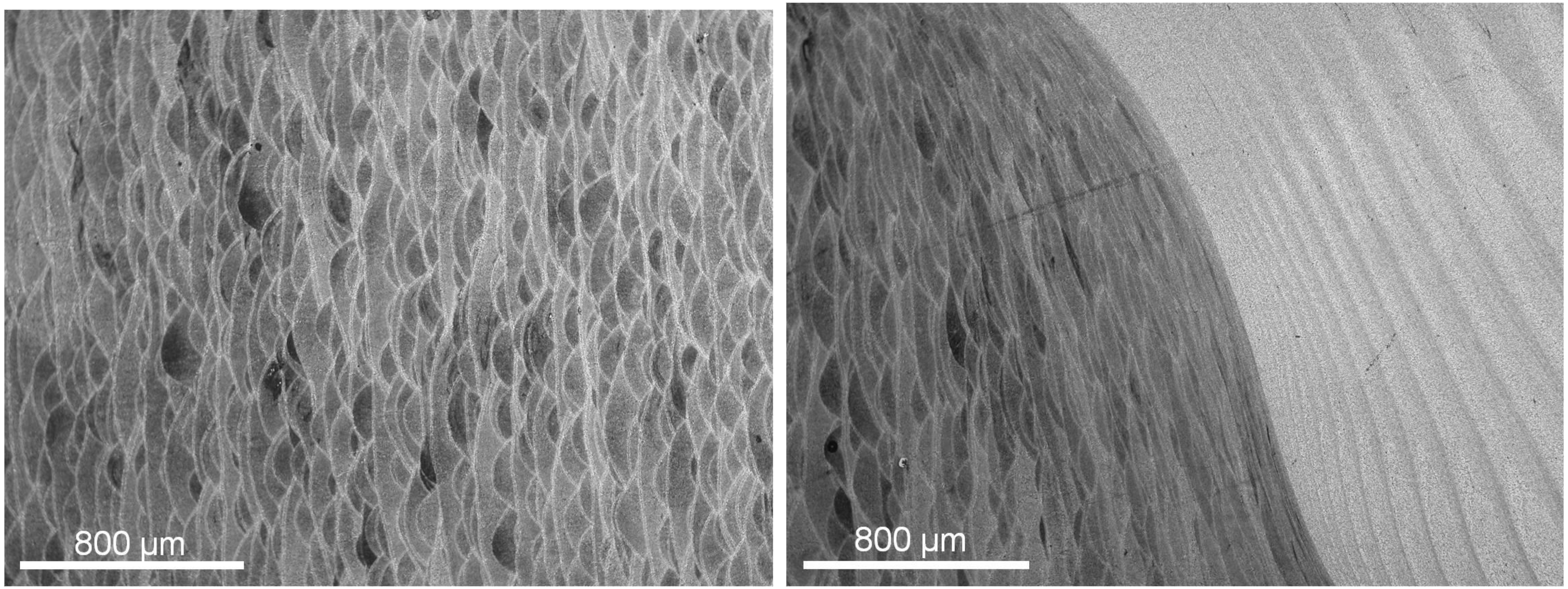
PROCESS

SOLID STATE JOINING: FRICTION STIR WELDING



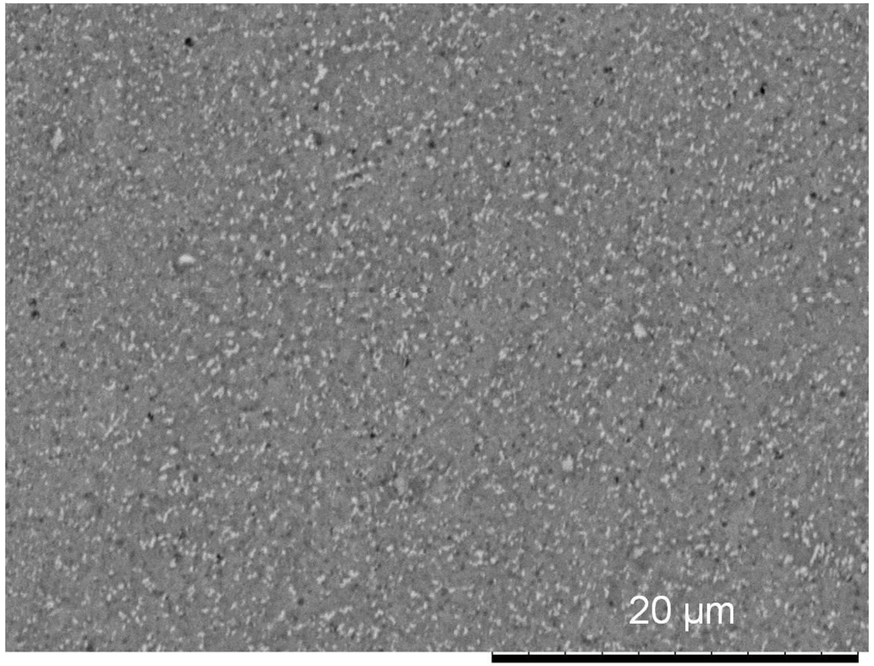
PROCESS

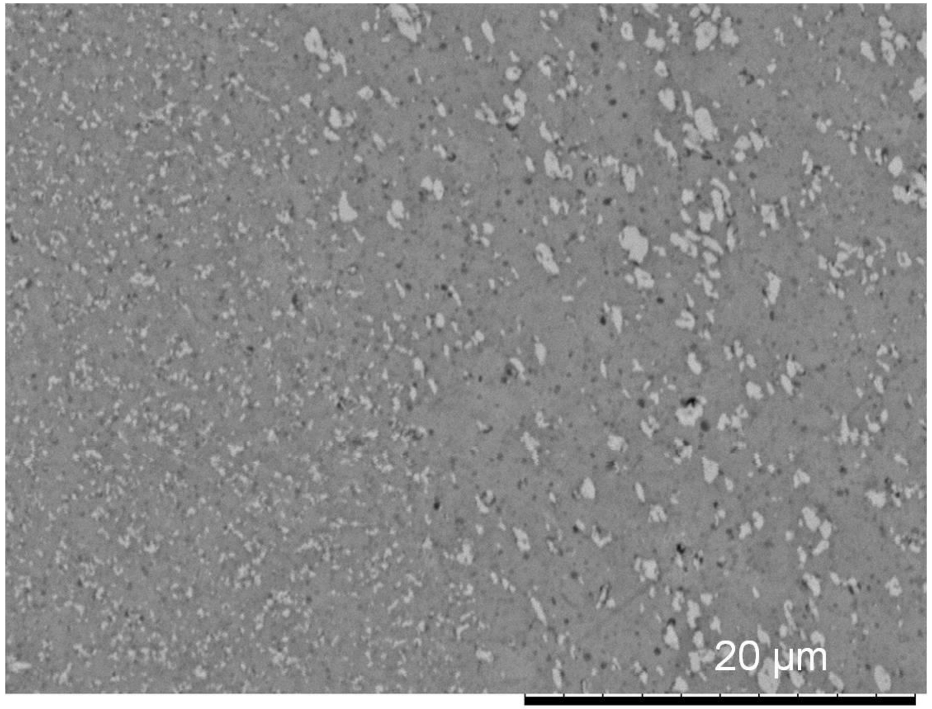
SOLID STATE JOINING: FRICTION STIR WELDING



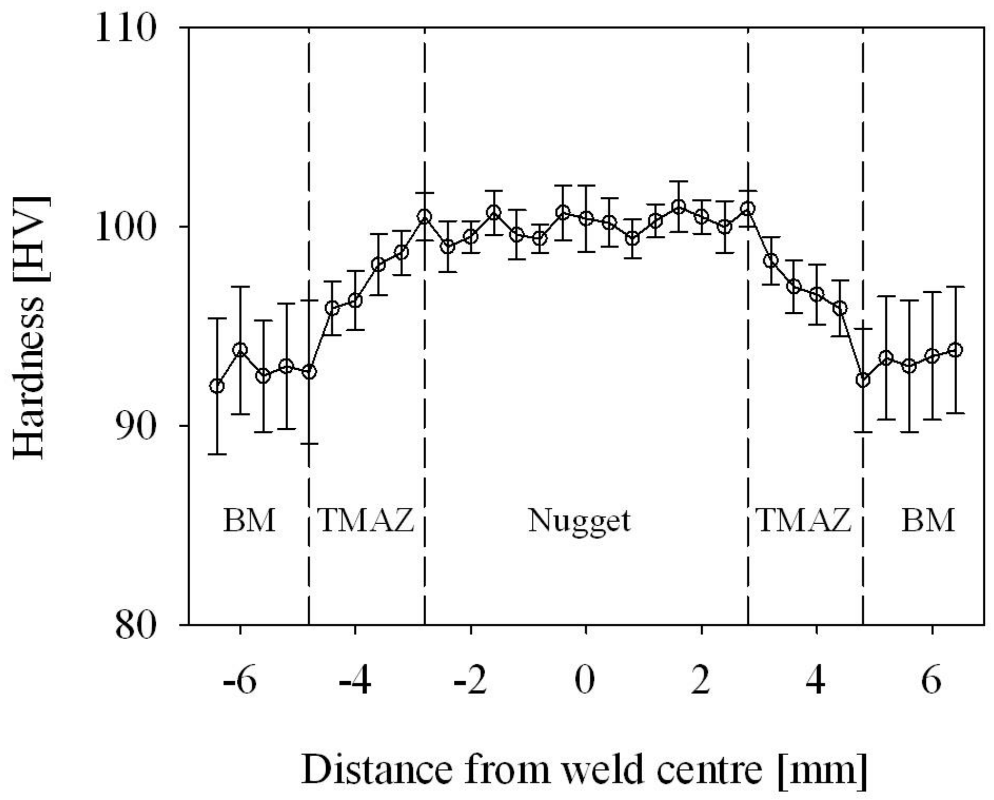
PROCESS

SOLID STATE JOINING: FRICTION STIR WELDING

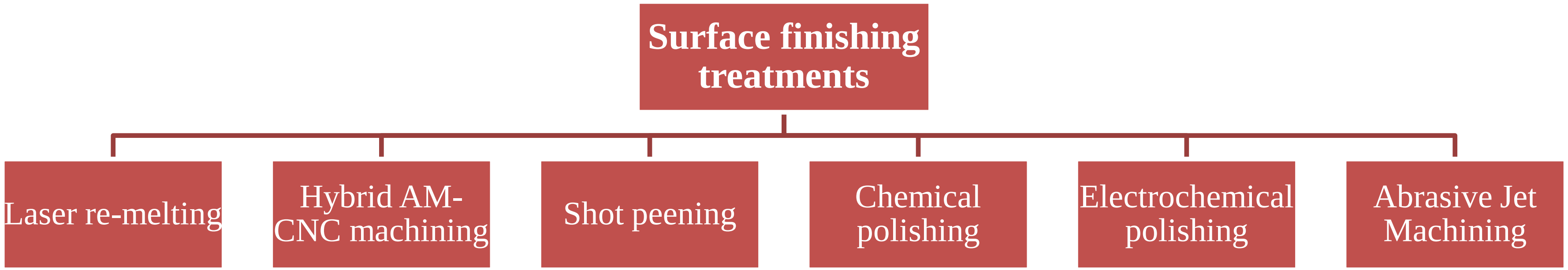




PROCESS
SOLID STATE JOINING: FRICTION STIR WELDING



TREATMENTS
RECAP



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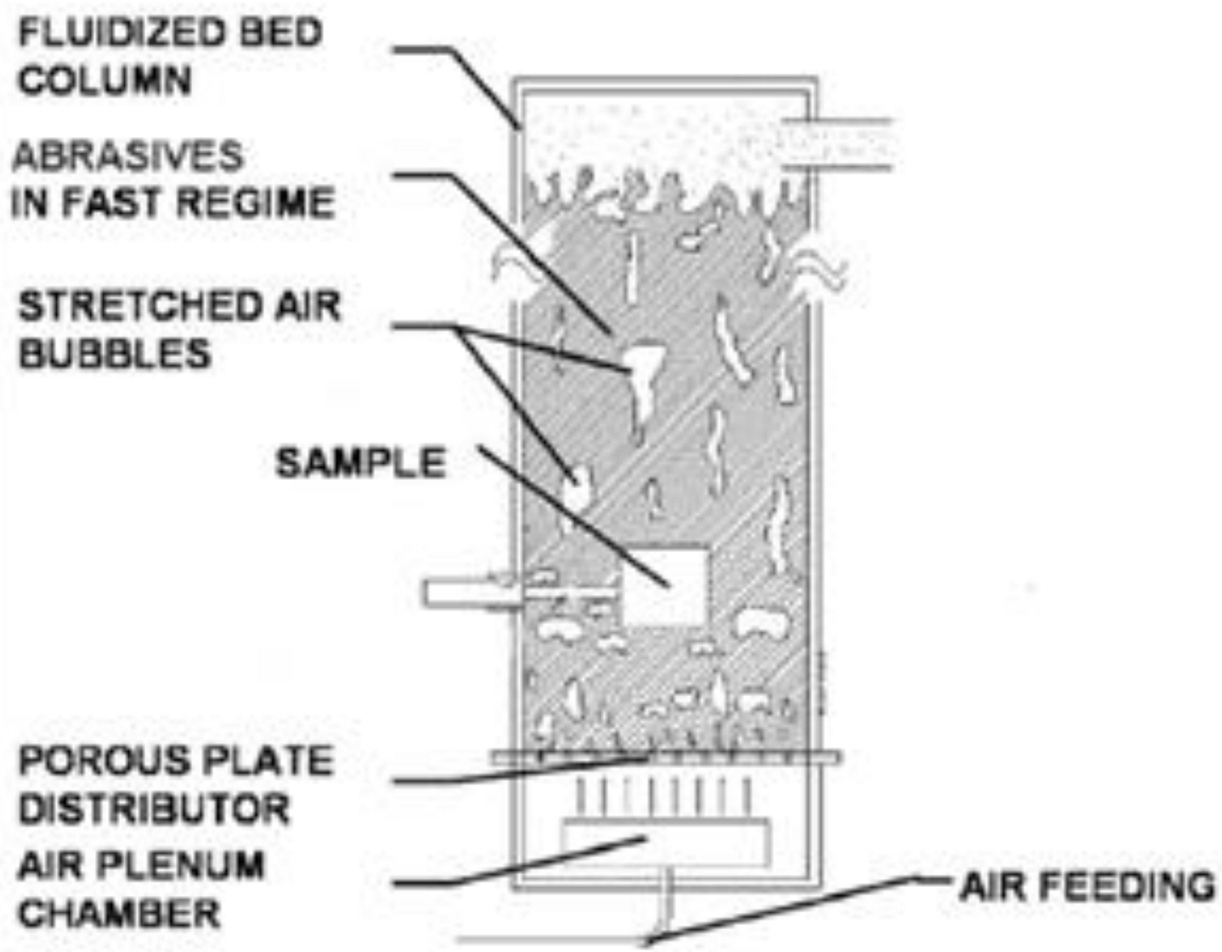
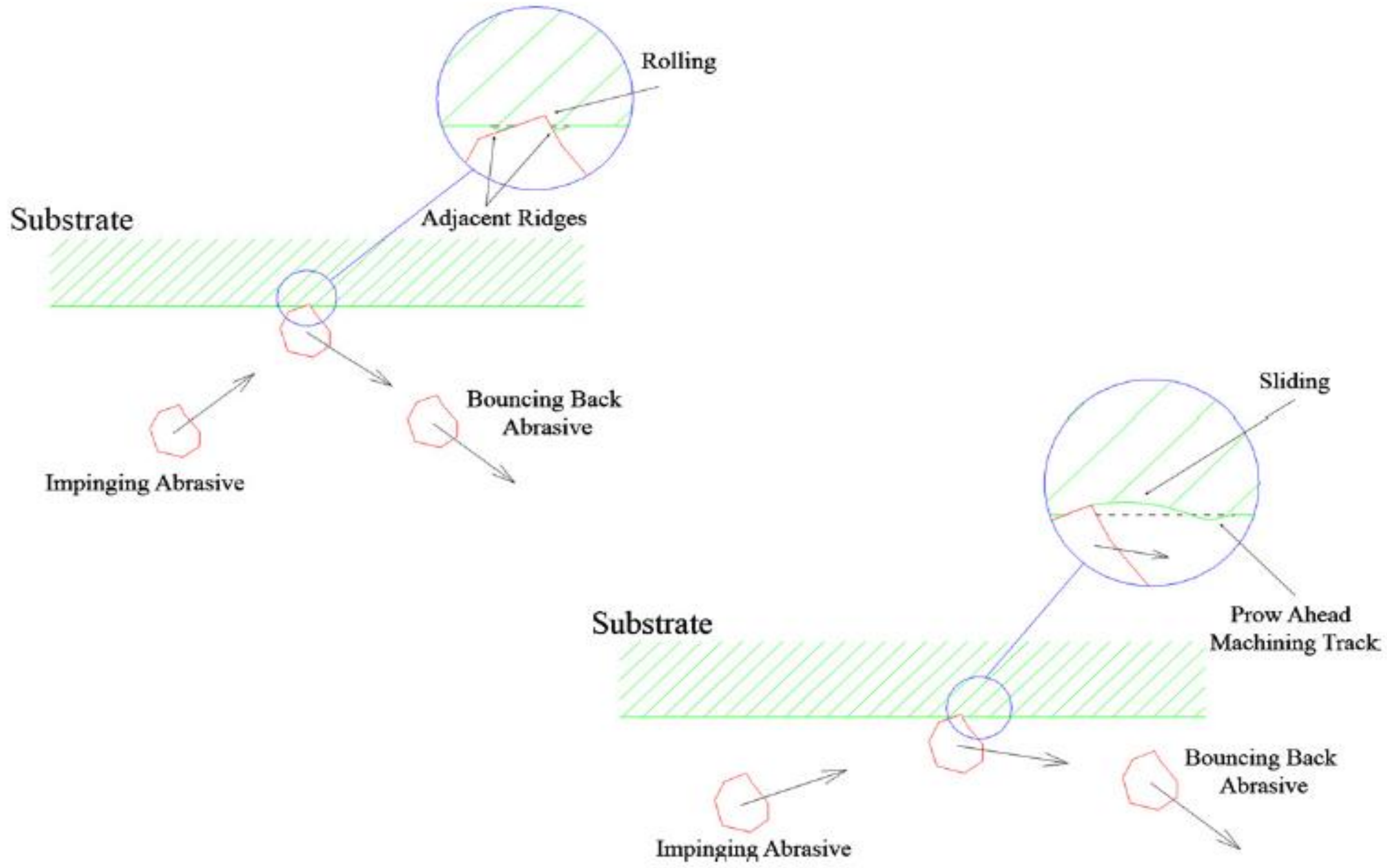
TREATMENTS

FLUIDIZED BED SURFACE FINISHING



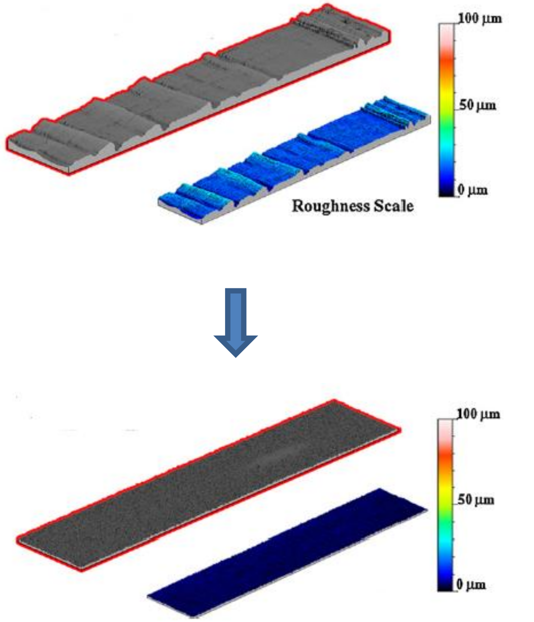
TREATMENTS
FLUIDIZED BED SURFACE FINISHING



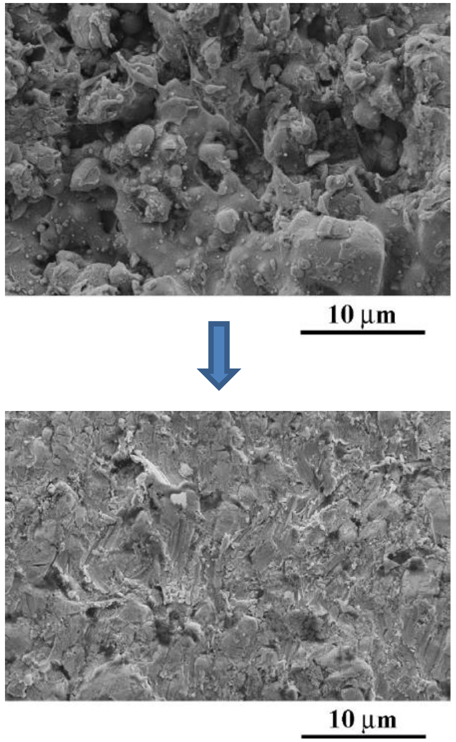
TREATMENTS

FLUIDIZED BED SURFACE FINISHING

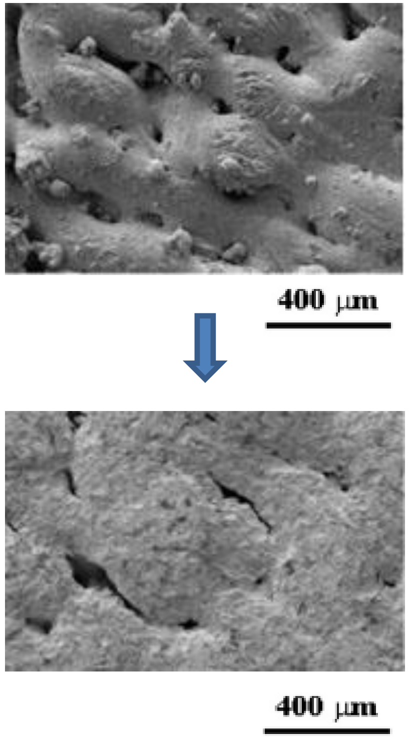
Internal pipe finishing
(Tagliaferri et Al., 2006)



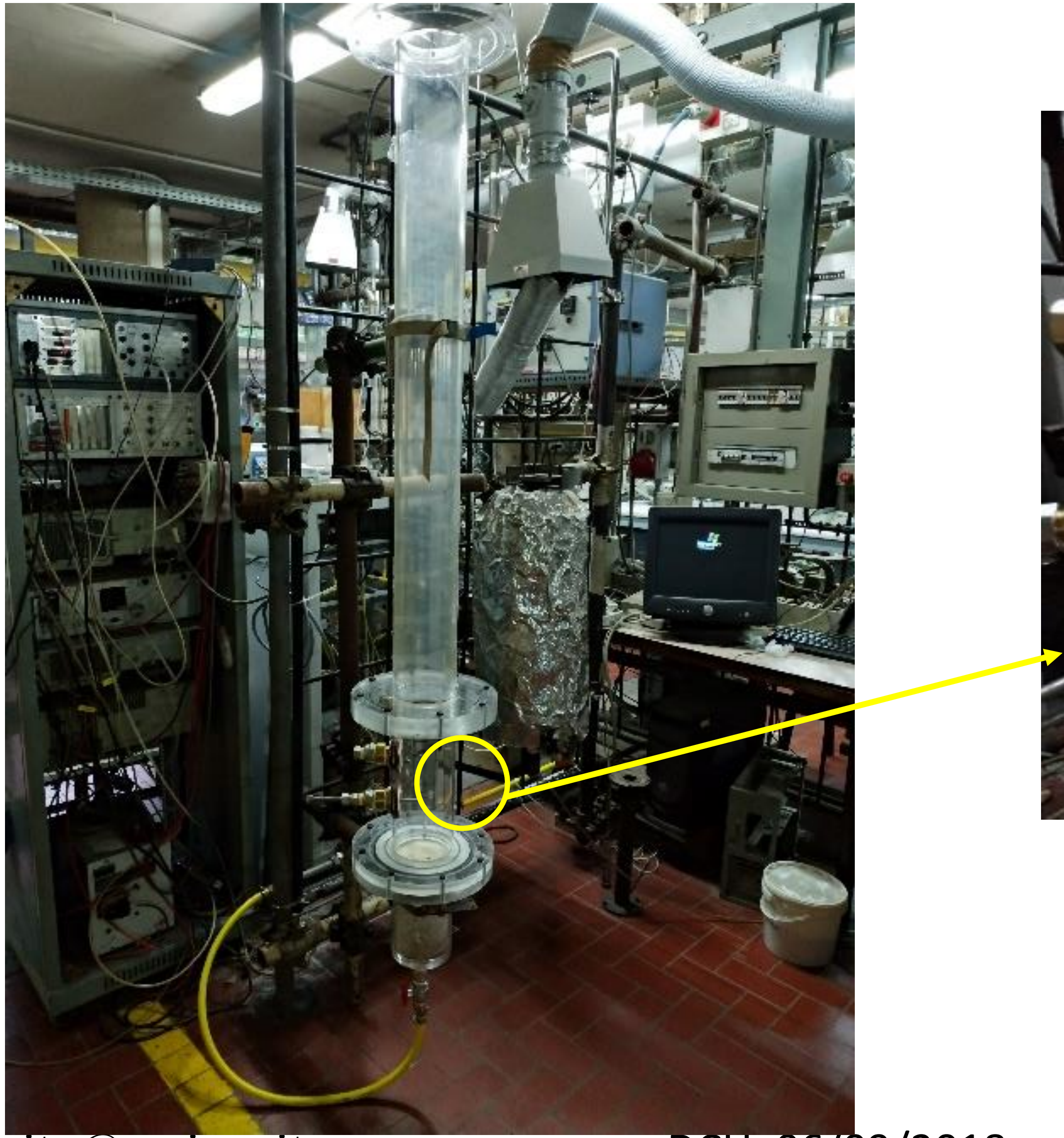
Finishing di Thermally-Sprayed Coatings
(Barletta et Al., 2008)

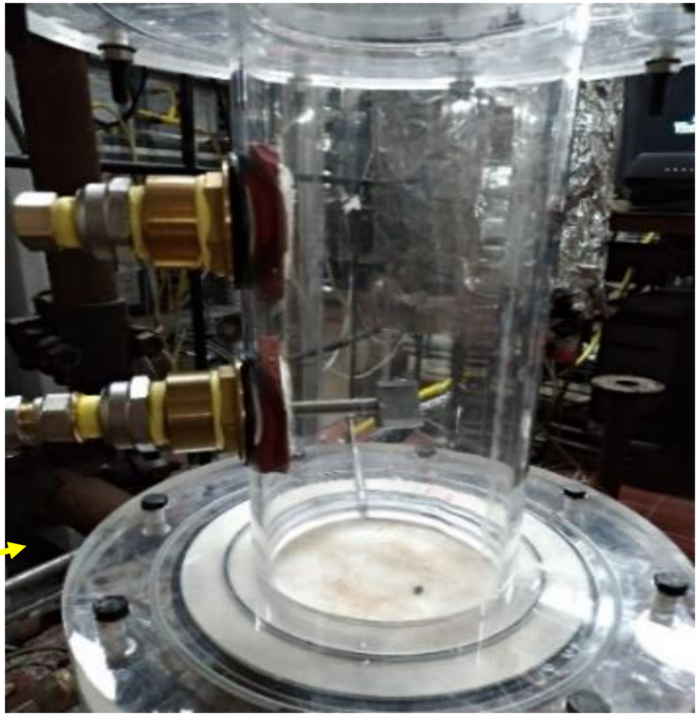


Finishing additively manufactured plates
(Barletta et Al., 2016)



TREATMENTS
FLUIDIZED BED SURFACE FINISHING





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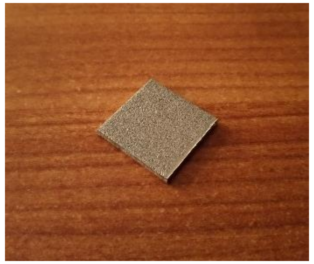
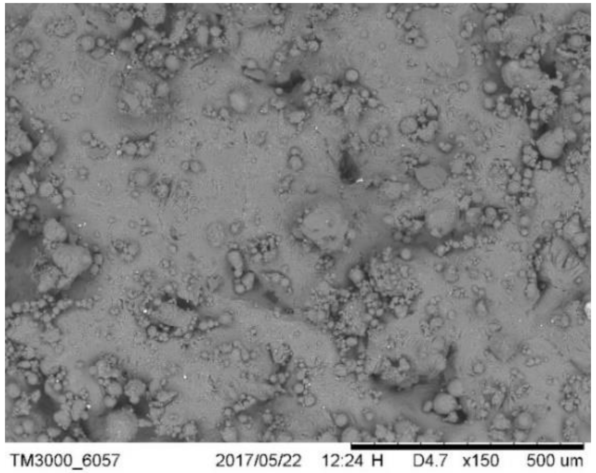
TREATMENTS

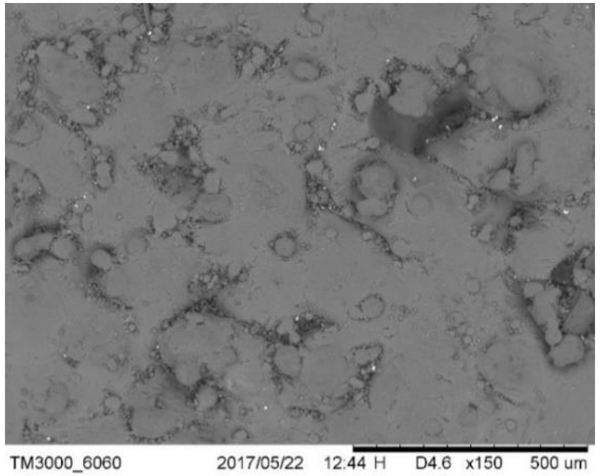
FLUIDIZED BED SURFACE FINISHING: AL-SI10 AM PART



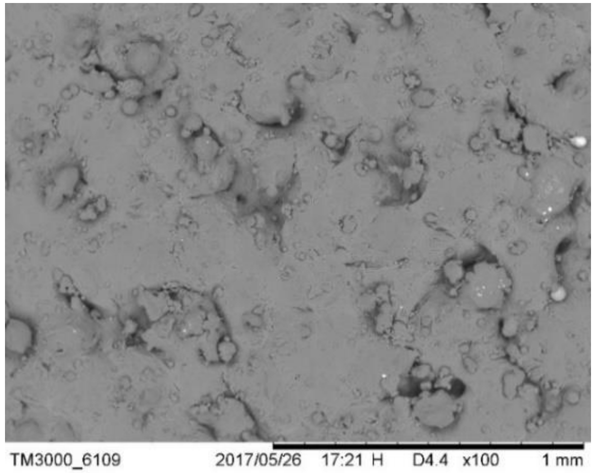
UNTREATED



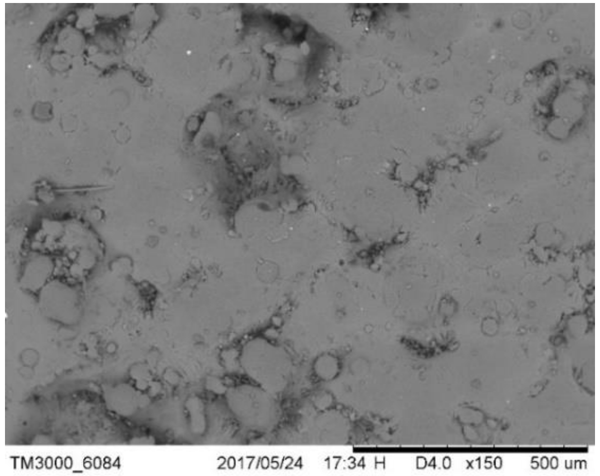
ANGLE 0°



ANGLE 90°



ANGLE 150°



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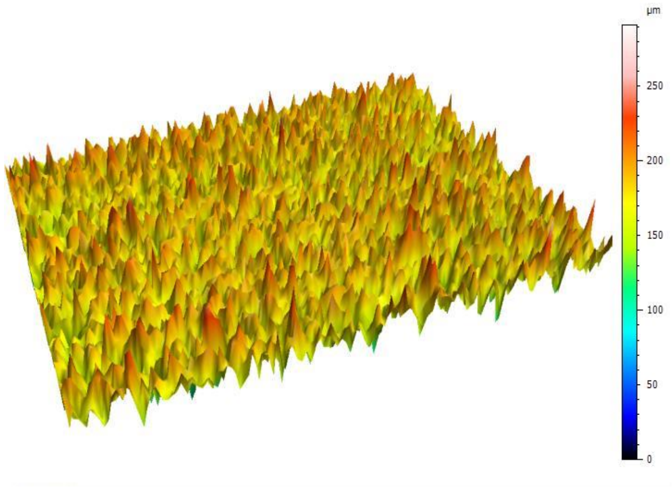
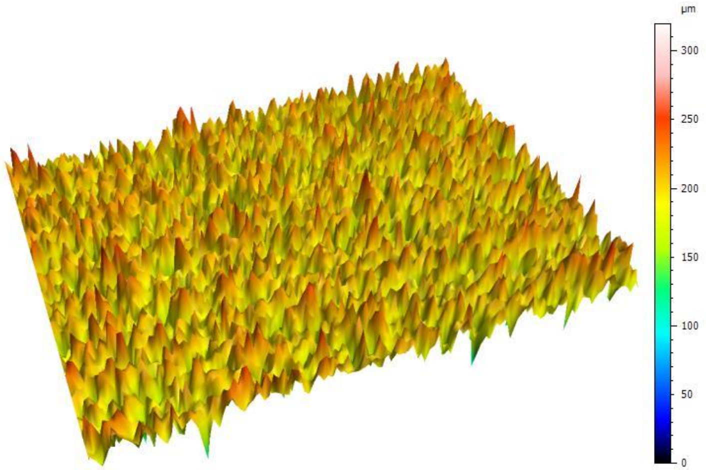
TREATMENTS

FLUIDIZED BED SURFACE FINISHING: AL-SI10 AM PART

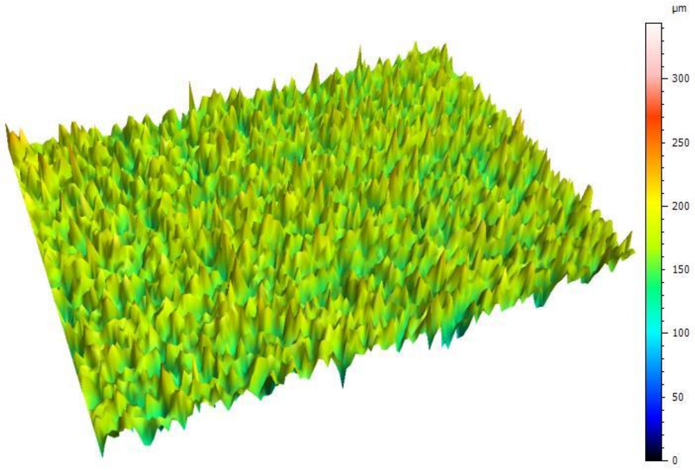
UNTREATED



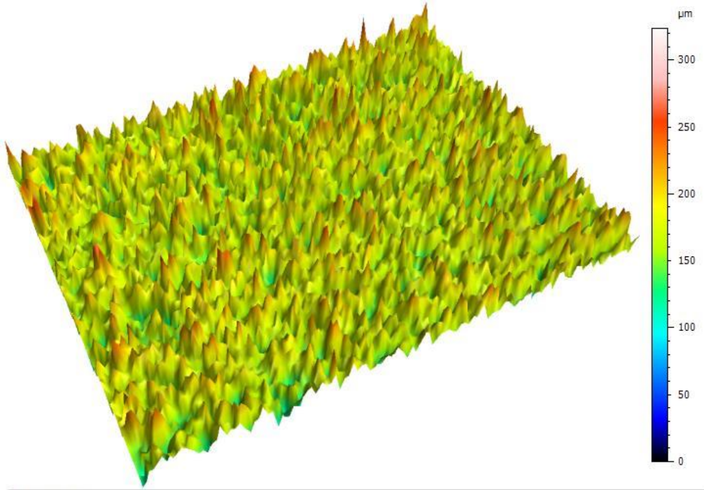
ANGLE 0°



ANGLE 90°



ANGLE 15°



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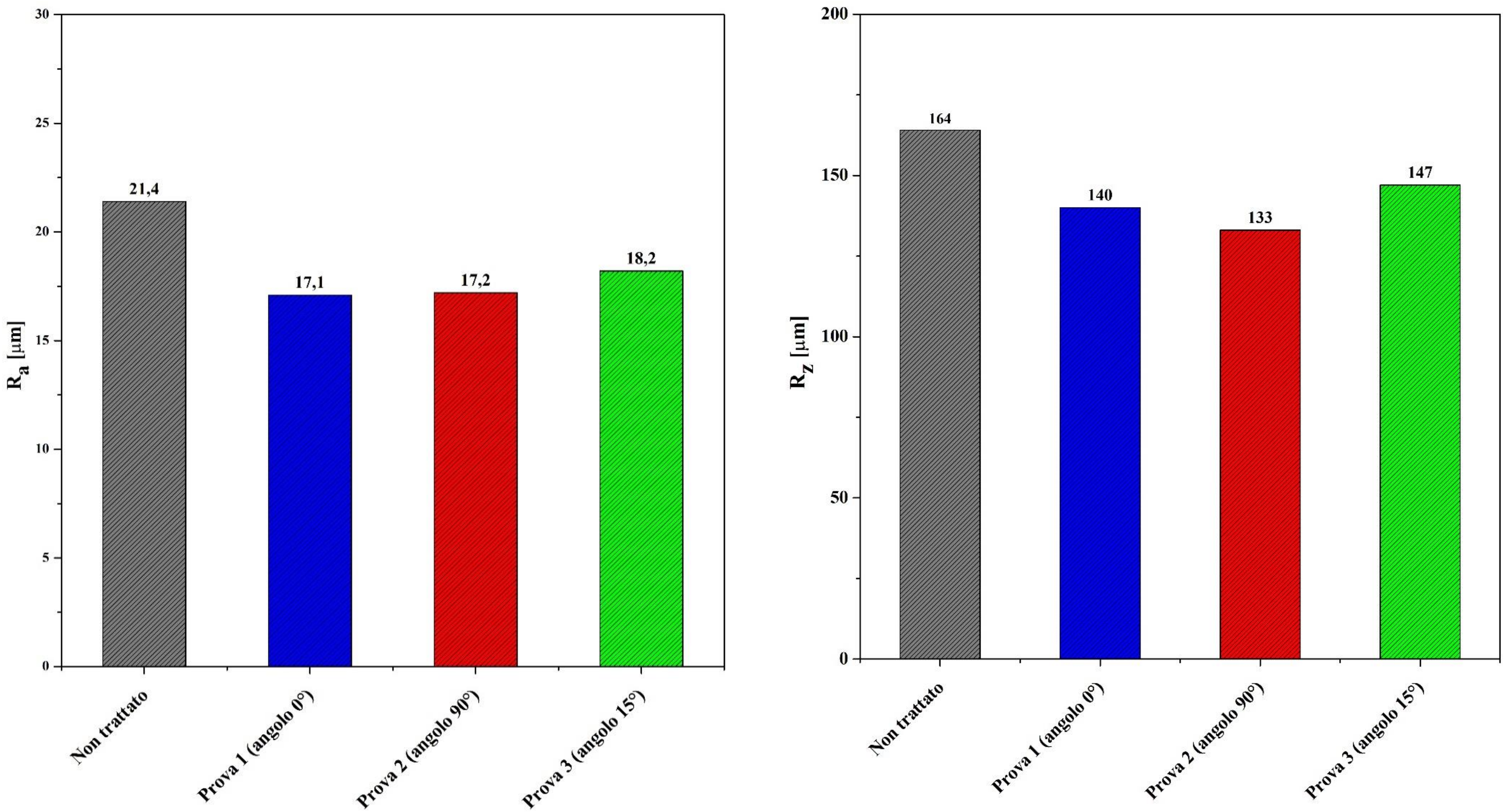
TREATMENTS
FLUIDIZED BED SURFACE FINISHING: AL-SI10 AM PART



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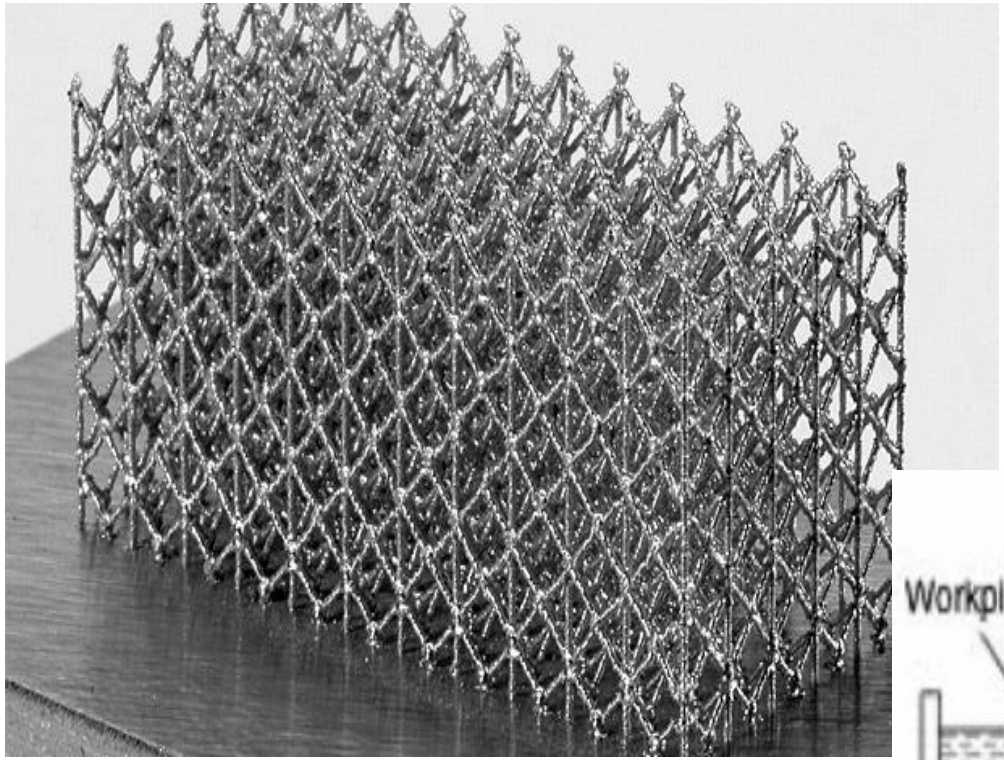
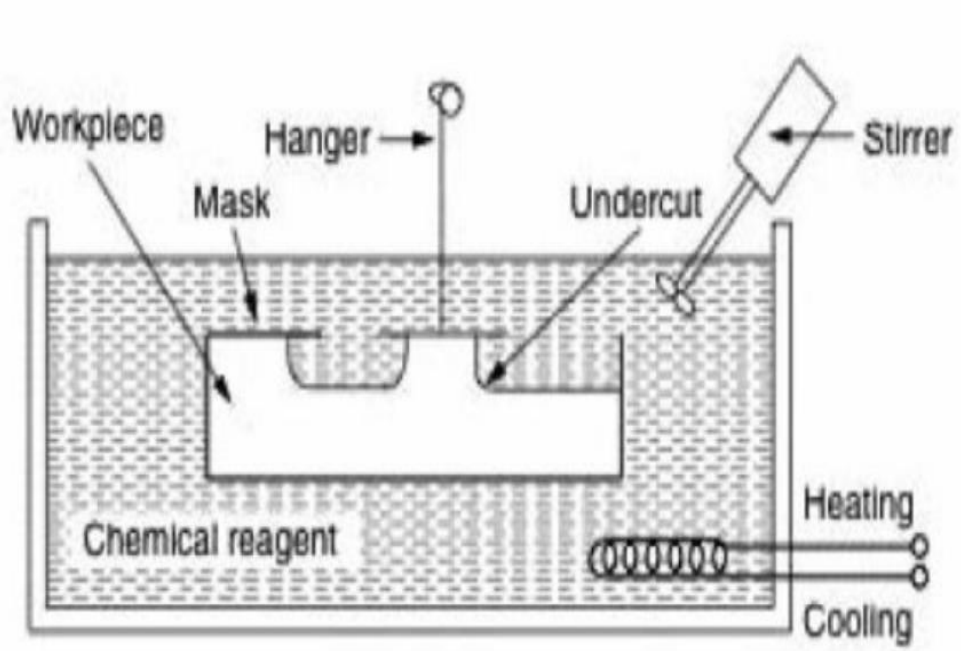
TREATMENTS

CHEMICAL FINISHING OF ALSI10 PARTS





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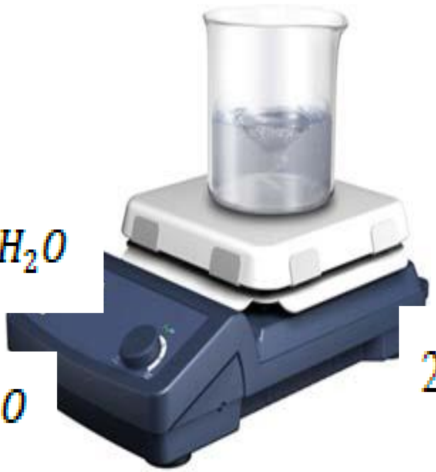
CHEMICAL FINISHING OF ALSI10 PARTS

CHEMICAL MACHINING:	CHEMICAL BRIGHTENING:
20 ml HF,	150 ml H_2PO_4,
50 ml HNO_3,	34 ml H_2SO_4,
930 ml H_2O.	12 ml HF,
	12 ml H_2NO_3.
	0,106 g $CuSO_4$.

1) $2Al + 6HNO_3 \rightarrow Al_2O_3 + 6NO_2 + 3H_2O$

3) $Si + 4HNO_3 \rightarrow SiO_2 + 4NO_2 + 2H_2O$



2) $Al_2O_3 + 6HF \rightarrow 2AlF_3 + 3H_2O$

4) $SiO_2 + 4HF \rightarrow SiF_4 + 2H_2O$

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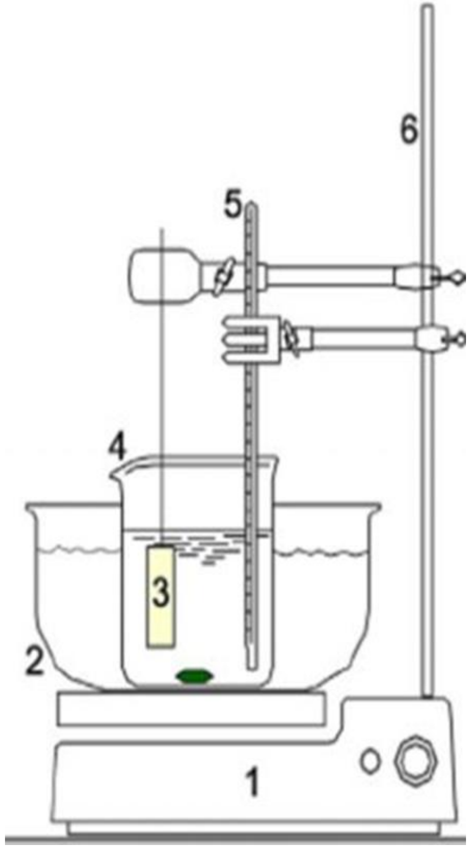
CHEMICAL FINISHING OF ALSI10 PARTS



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TREATMENTS

CHEMICAL FINISHING OF ALSI10 PARTS

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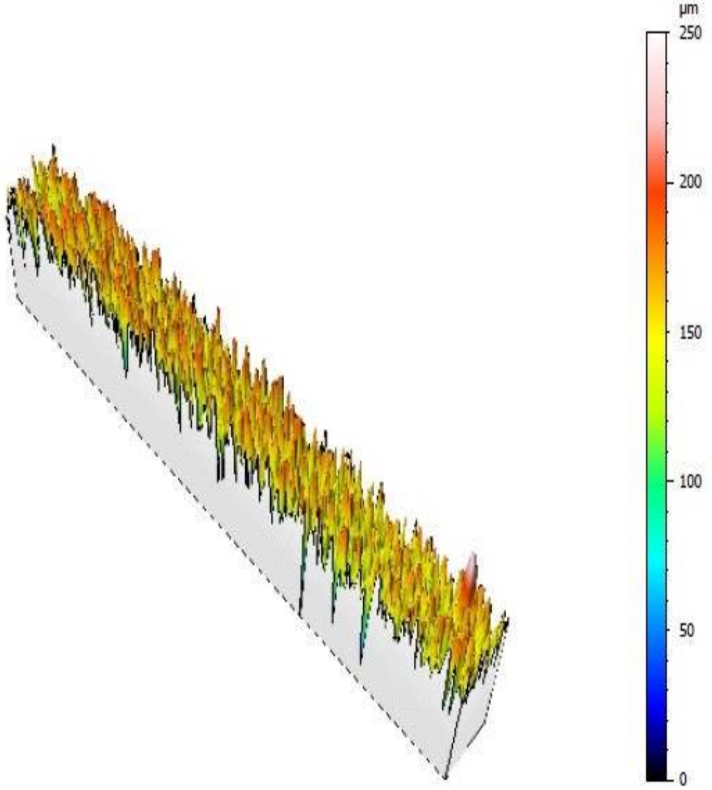

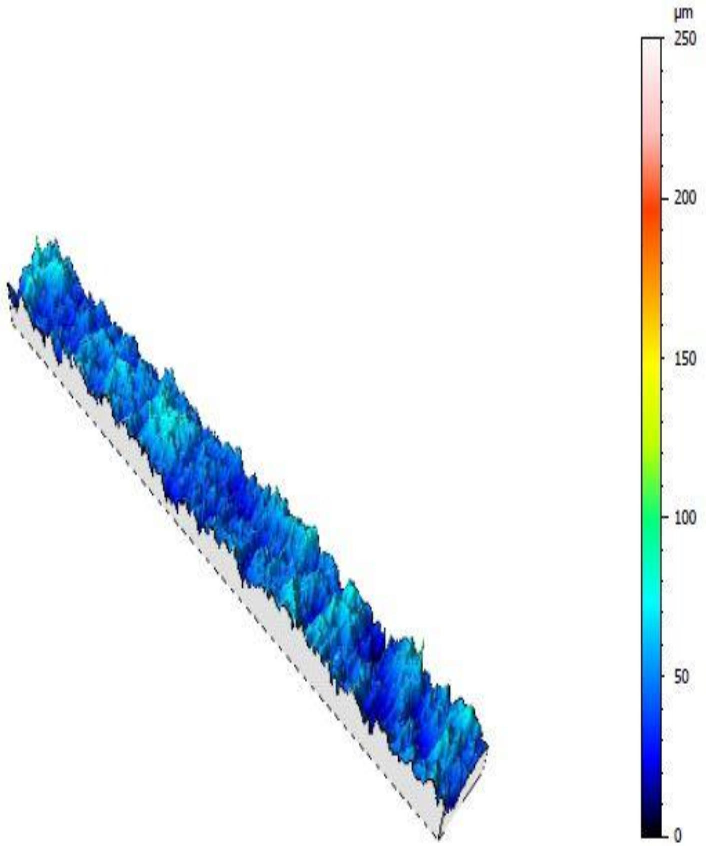

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CHEMICAL FINISHING OF ALSI10 PARTS

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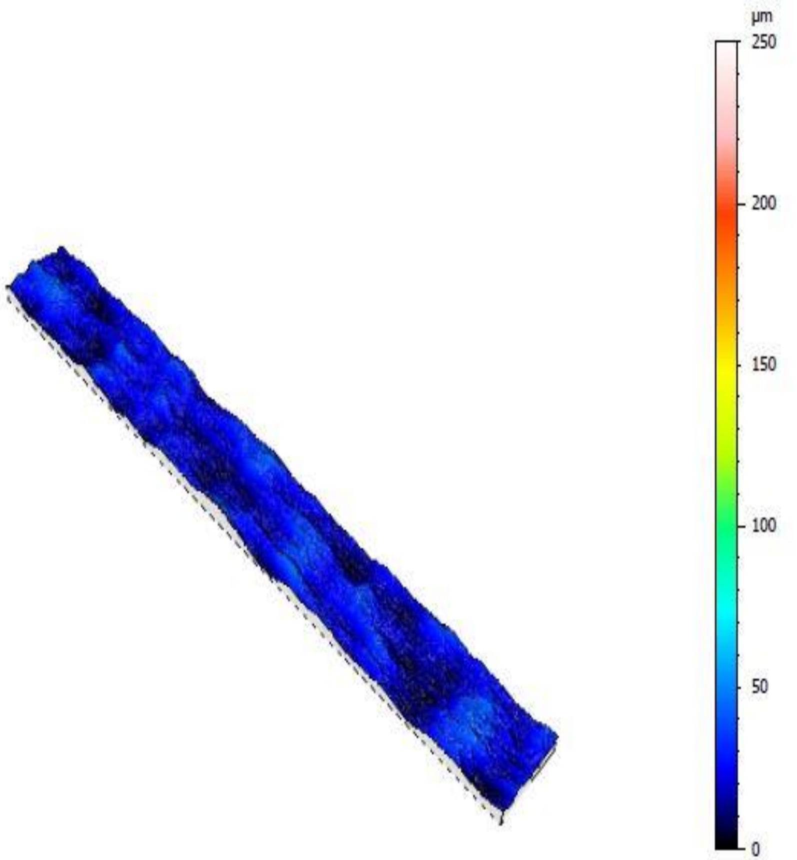

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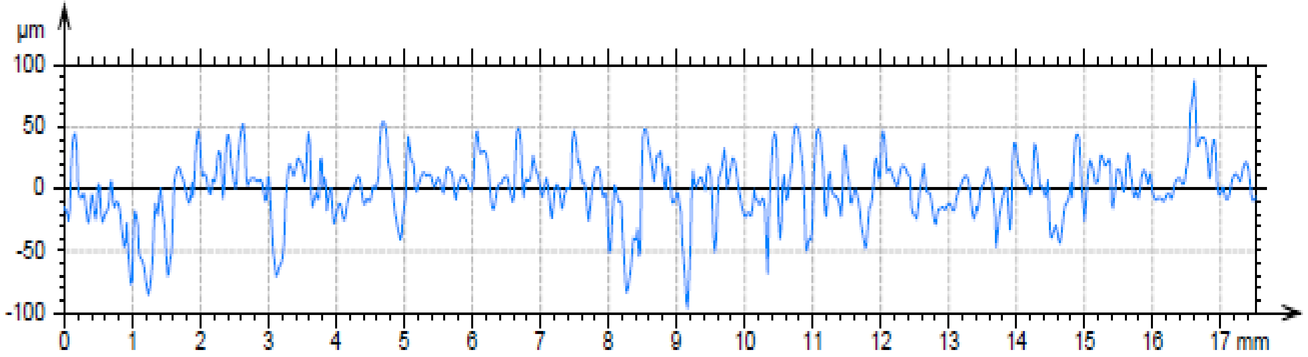

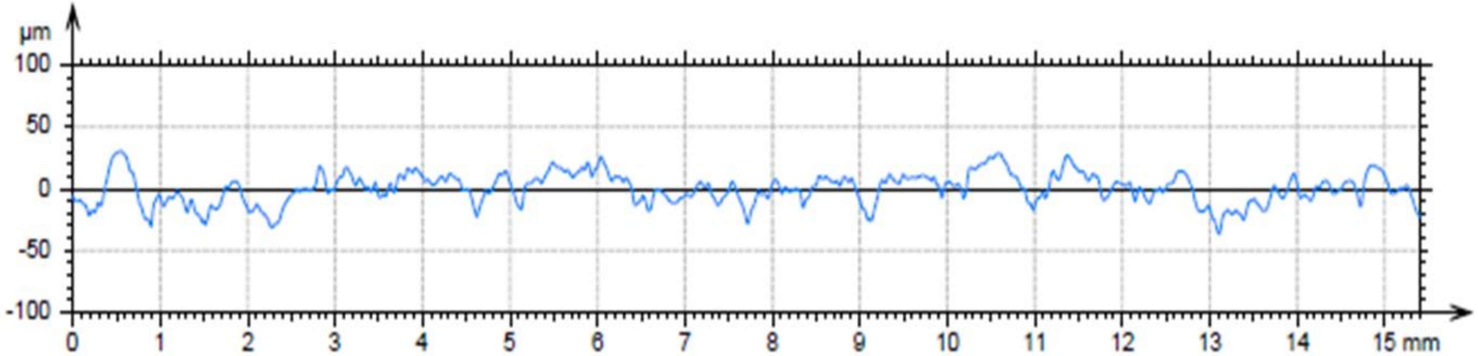

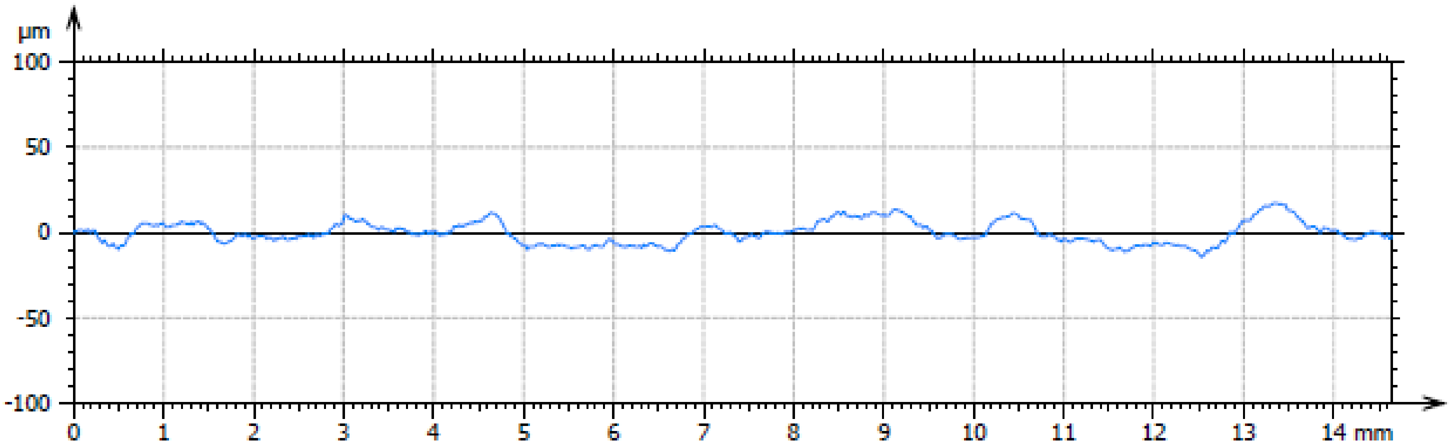

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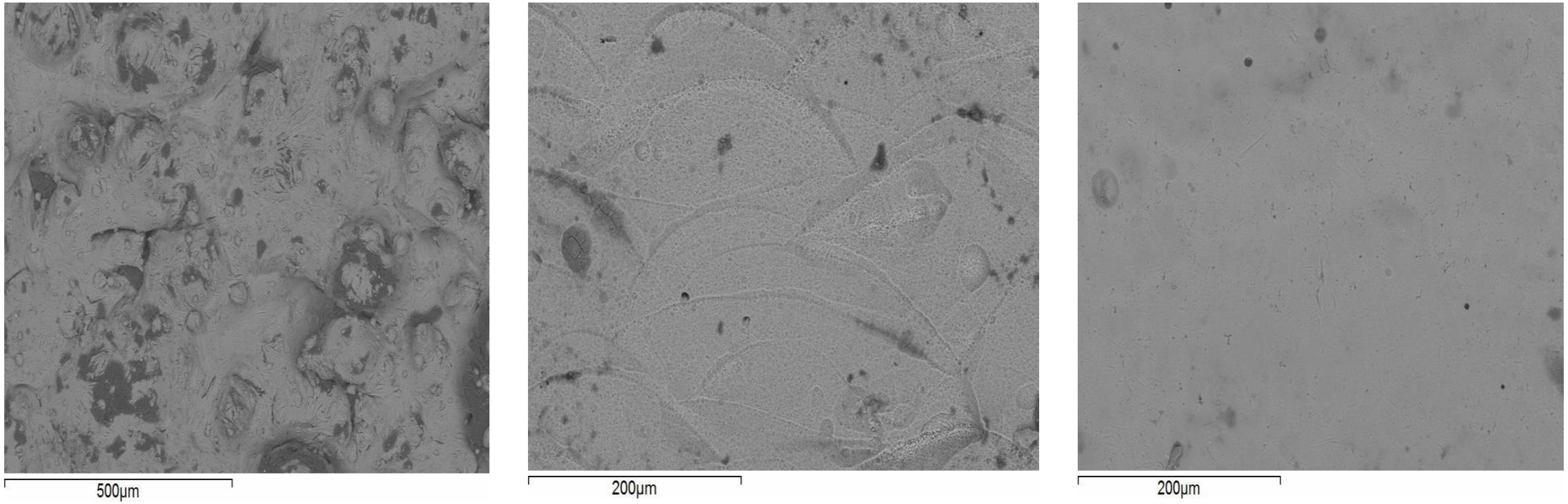

TREATMENTS
CHEMICAL FINISHING OF ALSI10 PARTS

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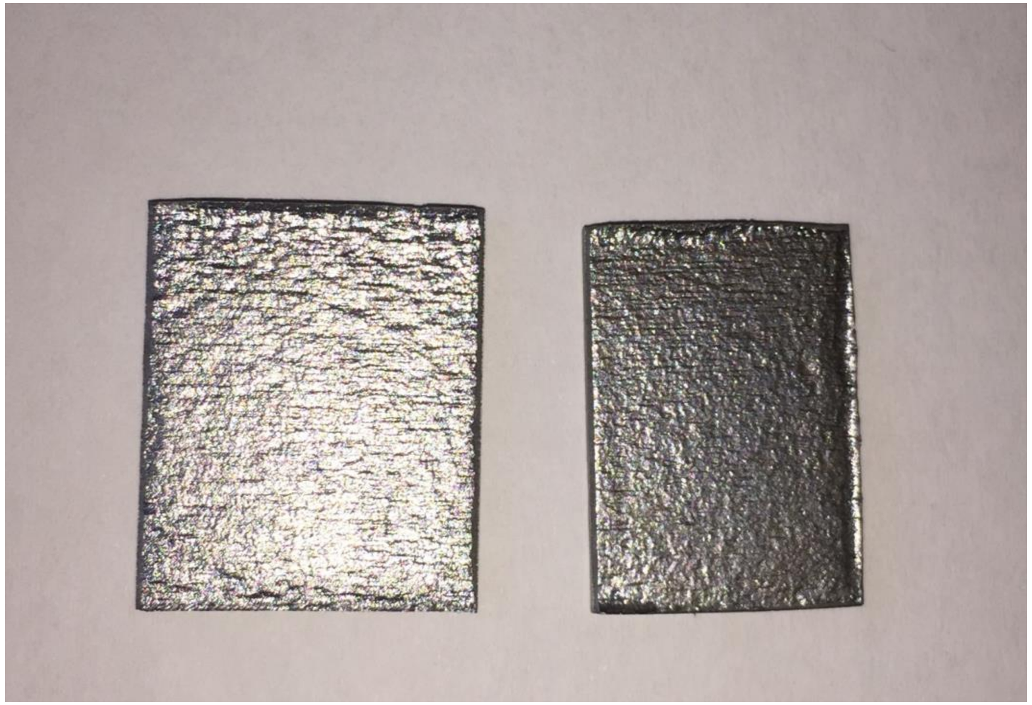

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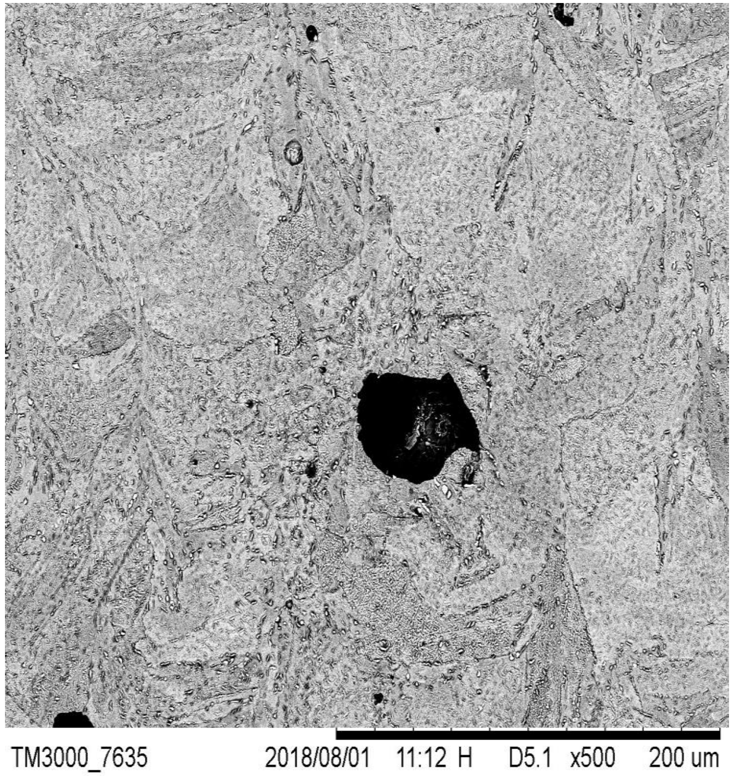
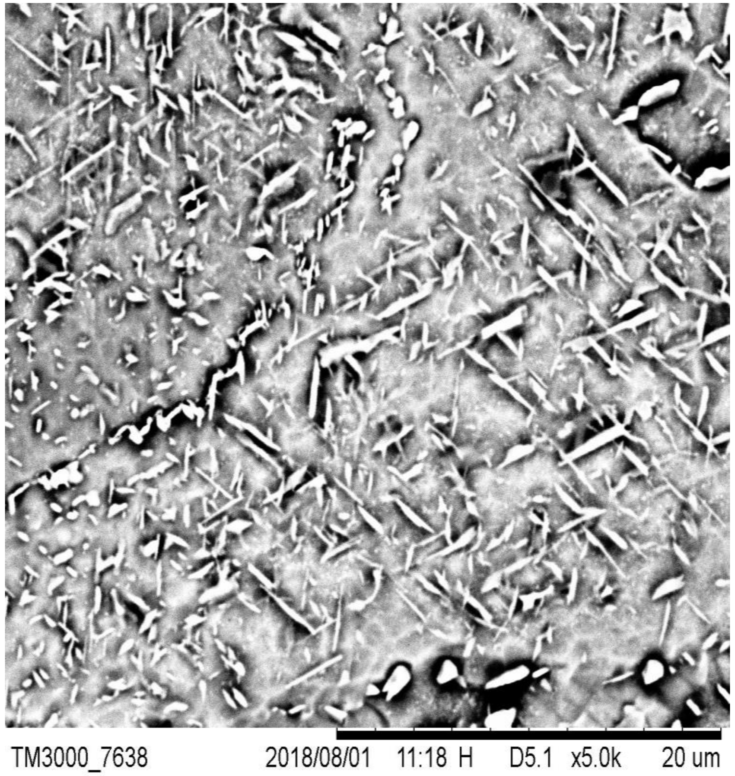
TREATMENTS
HEAT TREATMENT OF IN 718/CU SAMPLES



Core – 500x



Core – 5000x

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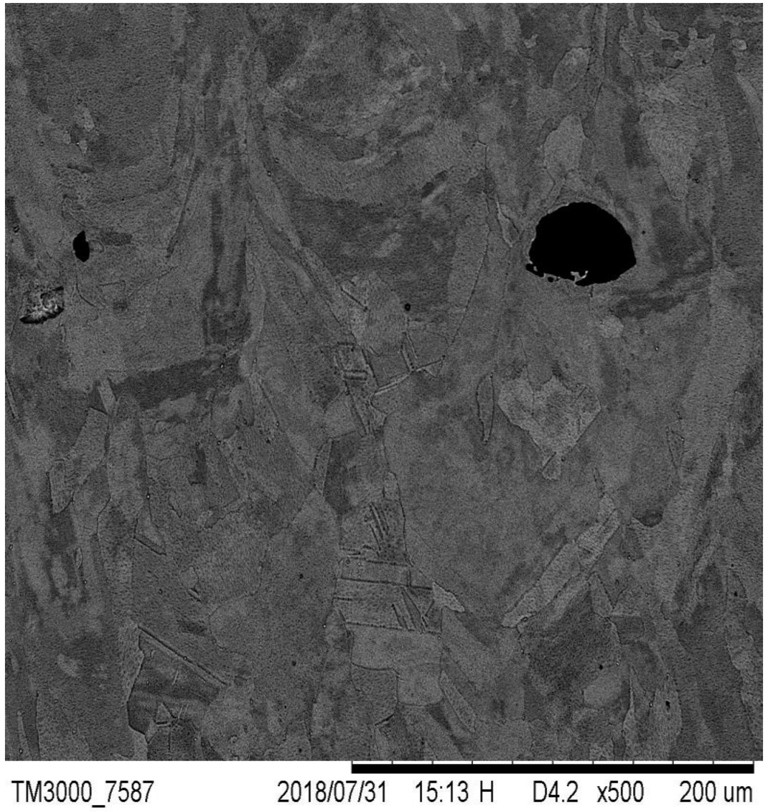

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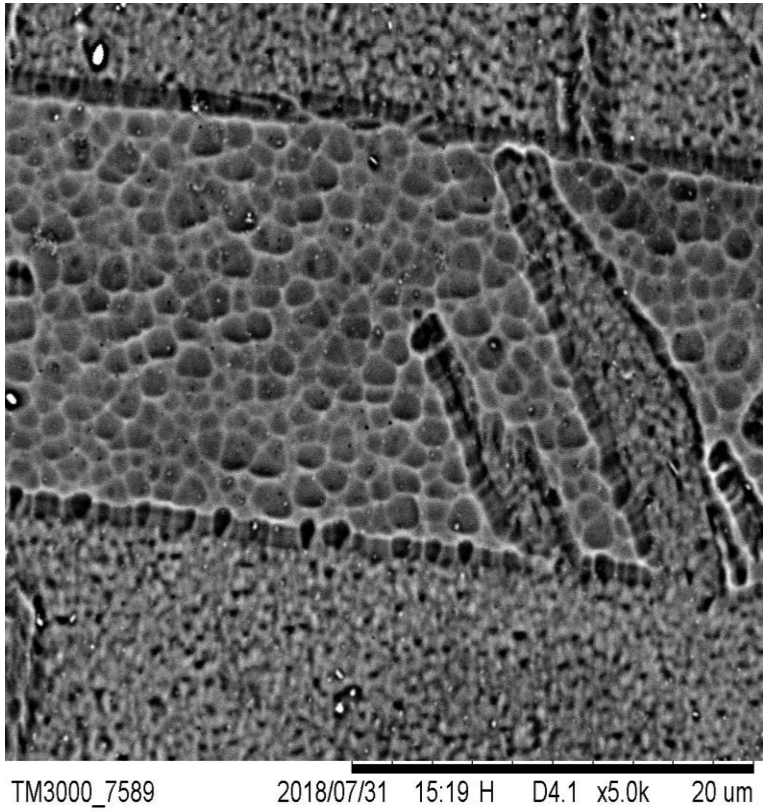

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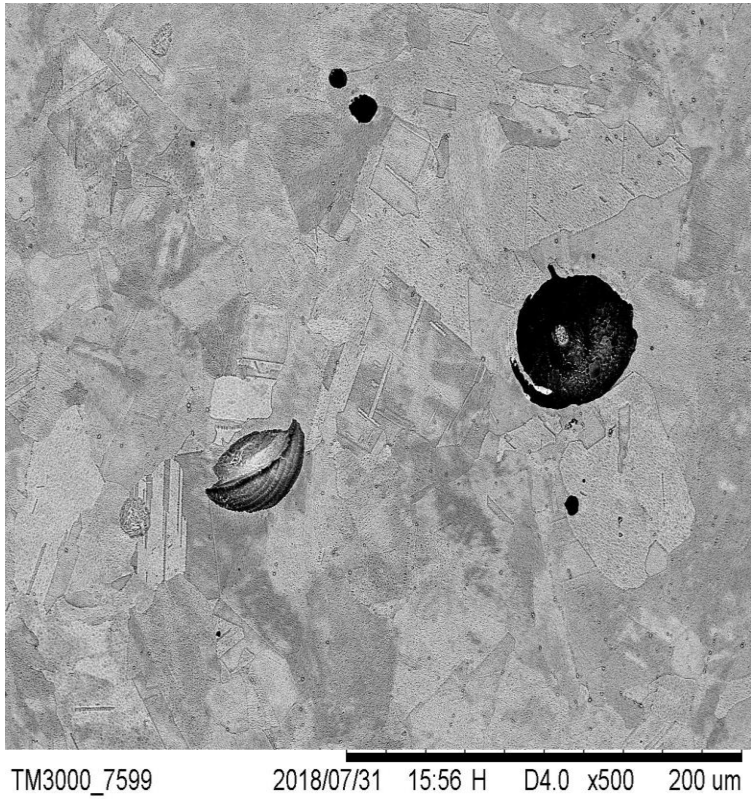

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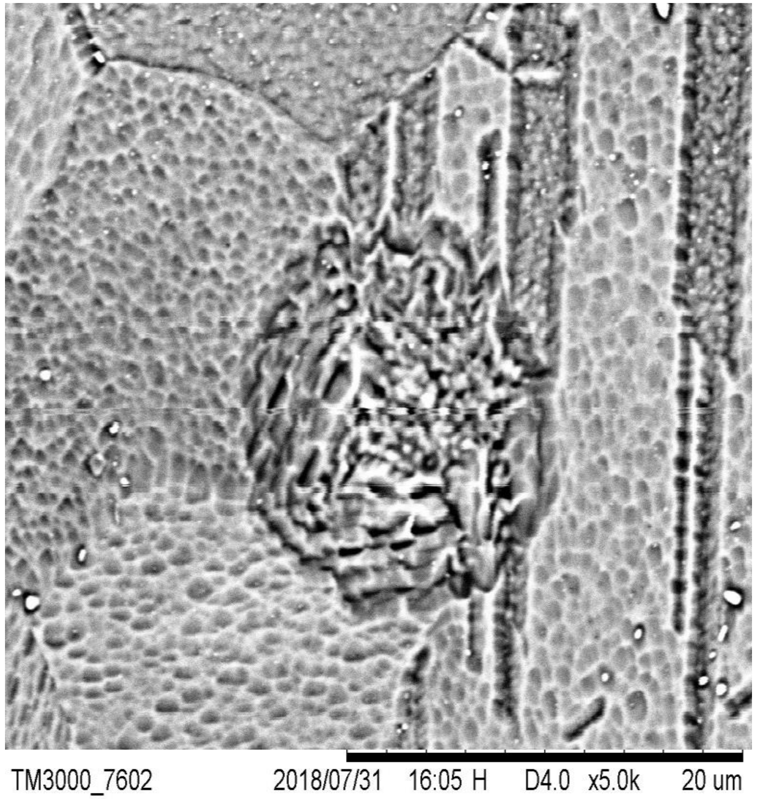

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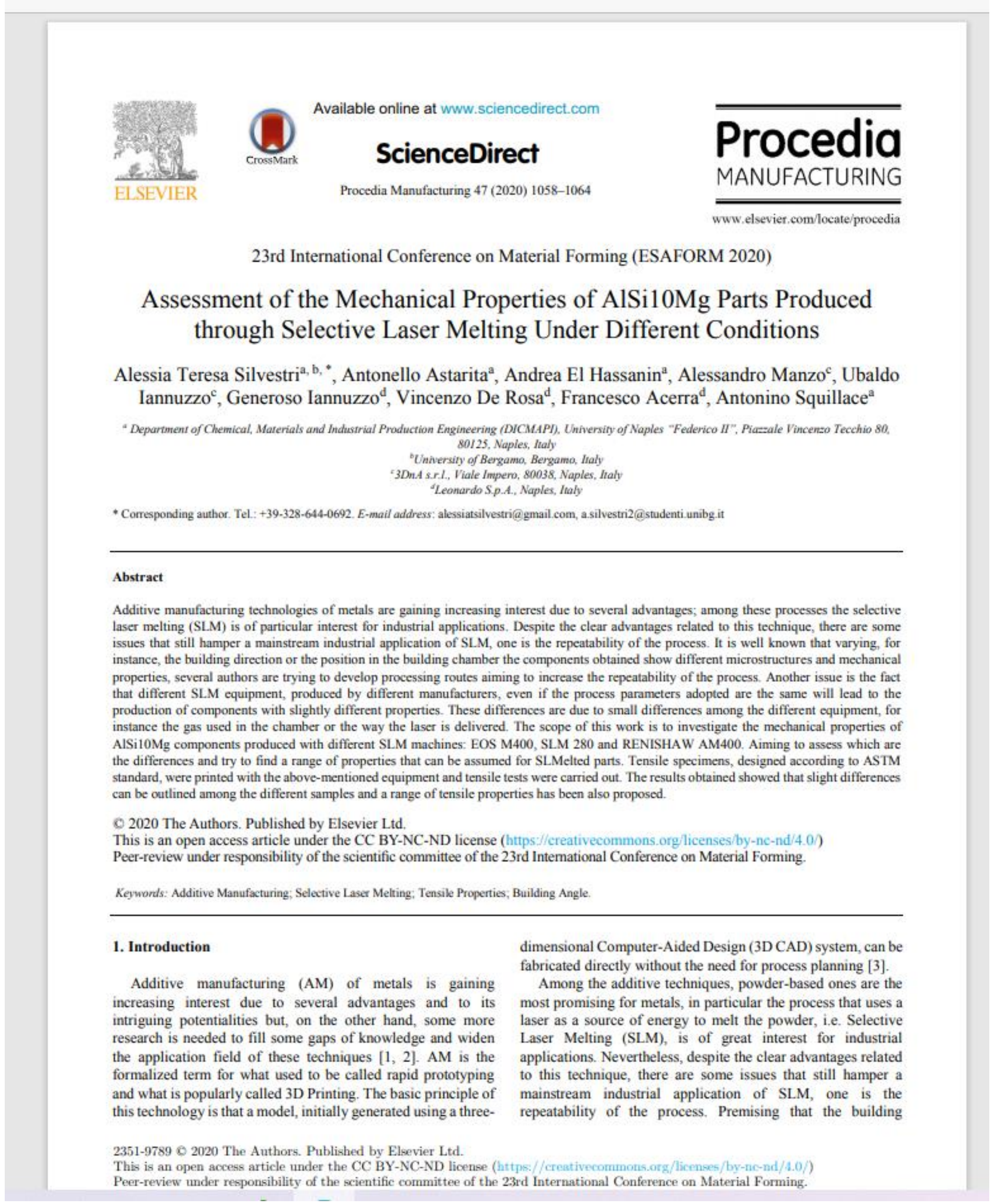

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23rd International Conference on Material Forming (ESAFORM 2020)

Assessment of the Mechanical Properties of AlSi10Mg Parts Produced through Selective Laser Melting Under Different Conditions

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Abstract

Additive manufacturing technologies of metals are gaining increasing interest due to several advantages; among these processes the selective laser melting (SLM) is of particular interest for industrial applications. Despite the clear advantages related to this technique, there are some issues that still hamper a mainstream industrial application of SLM, one is the repeatability of the process. It is well known that varying, for instance, the building direction or the position in the building chamber the components obtained show different microstructures and mechanical properties, several authors are trying to develop processing routes aiming to increase the repeatability of the process. Another issue is the fact that different SLM equipment, produced by different manufacturers, even if the process parameters adopted are the same will lead to the production of components with slightly different properties. These differences are due to small differences among the different equipment, for instance the gas used in the chamber or the way the laser is delivered. The scope of this work is to investigate the mechanical properties of AlSi10Mg components produced with different SLM machines: EOS M400, SLM 280 and RENISHAW AM400. Aiming to assess which are the differences and try to find a range of properties that can be assumed for SLMelted parts. Tensile specimens, designed according to ASTM standard, were printed with the above-mentioned equipment and tensile tests were carried out. The results obtained showed that slight differences can be outlined among the different samples and a range of tensile properties has been also proposed.

Keywords: Additive Manufacturing; Selective Laser Melting; Tensile Properties; Building Angle.

1. Introduction

Additive manufacturing (AM) of metals is gaining increasing interest due to several advantages and to its intriguing potentialities but, on the other hand, some more research is needed to fill some gaps of knowledge and widen the application field of these techniques [1, 2]. AM is the formalized term for what used to be called rapid prototyping and what is popularly called 3D Printing. The basic principle of this technology is that a model, initially generated using a three-dimensional Computer-Aided Design (3D CAD) system, can be fabricated directly without the need for process planning [3].

Among the additive techniques, powder-based ones are the most promising for metals, in particular the process that uses a laser as a source of energy to melt the powder, i.e. Selective Laser Melting (SLM), is of great interest for industrial applications. Nevertheless, despite the clear advantages related to this technique, there are some issues that still hamper a mainstream industrial application of SLM, one is the repeatability of the process. Premising that the building

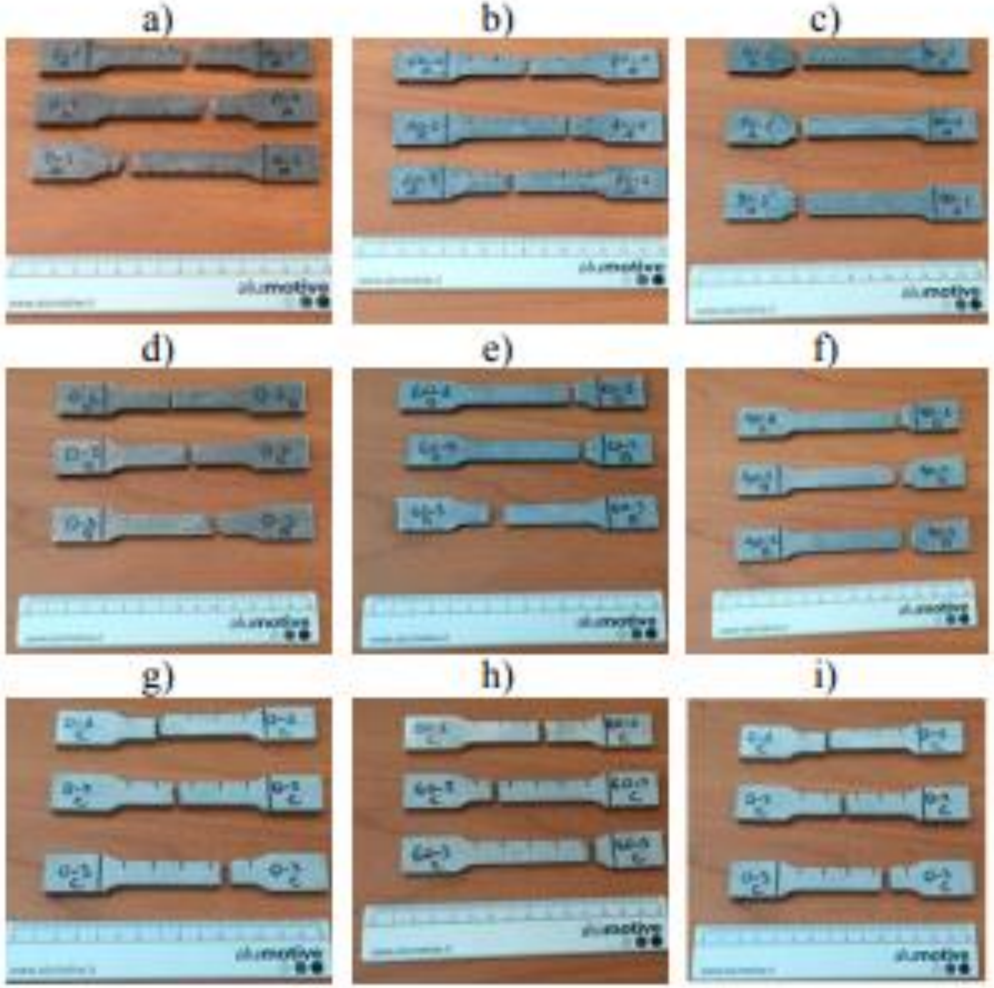
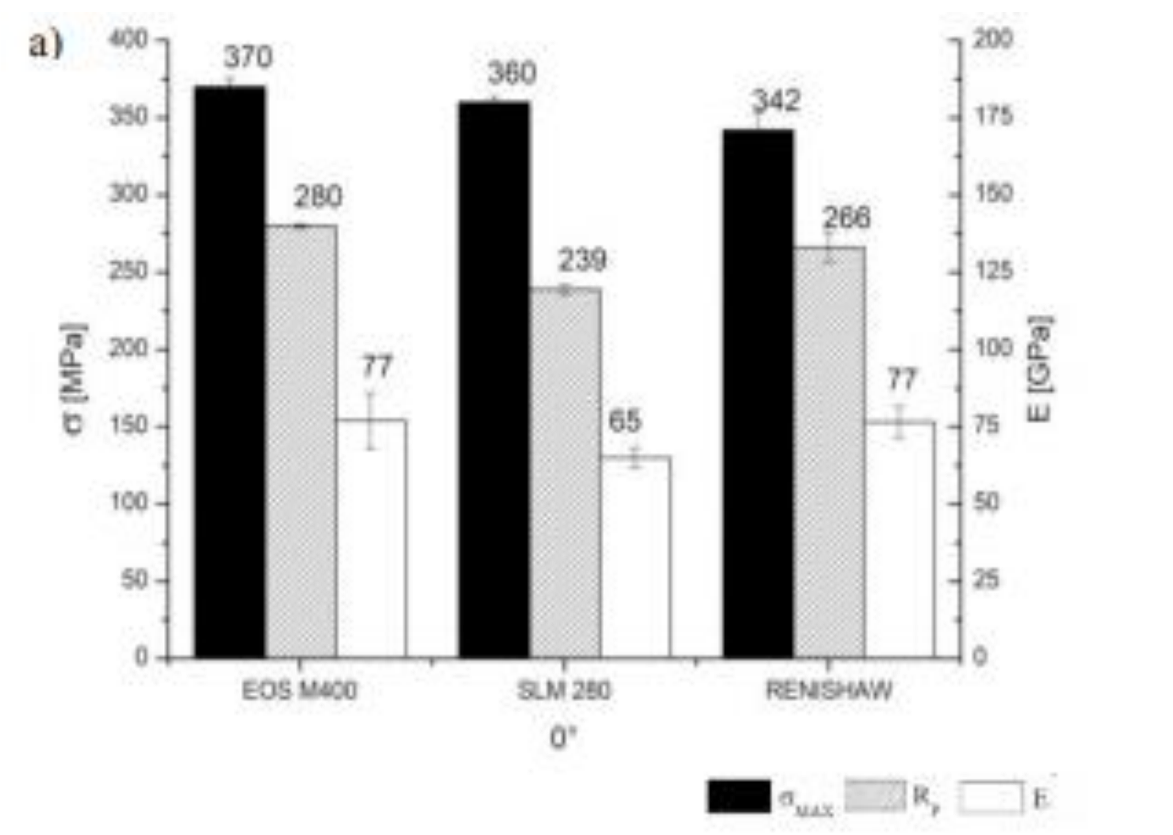
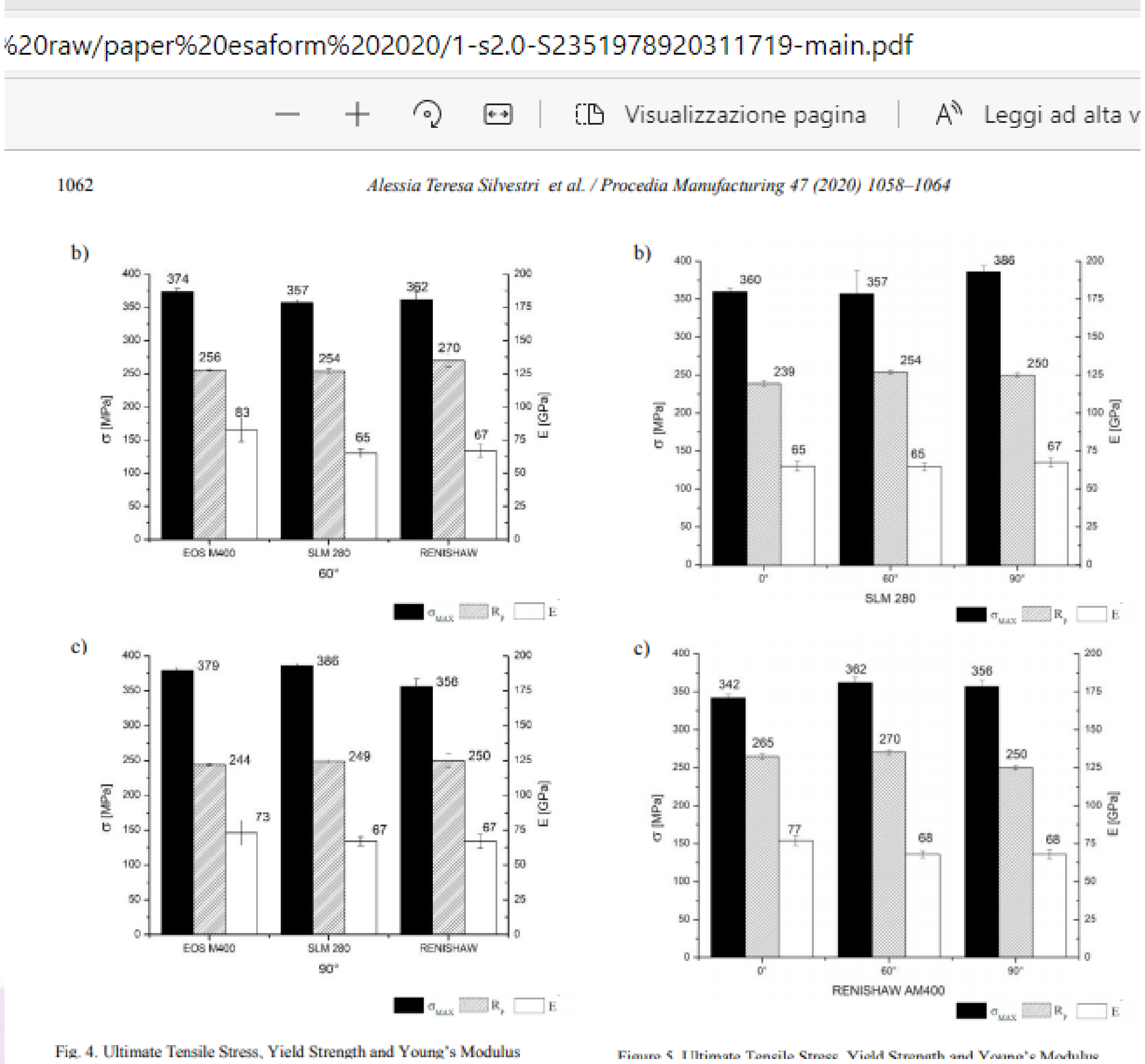


Fig. 3. Images of the two fractured parts after the tensile tests that compose





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ELSEVIER

Electron beam melting of Ti6Al4V: Role of the process parameters under the same energy density

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ARTICLE INFO

Keywords:
Electron beam melting
Ti6Al4V
Process parameters
Energy density
Roughness
Microstructure
Hardness

ABSTRACT

The role of the process parameters under a fixed energy density in Electron Beam Melting of Ti6Al4V was investigated. The beam current, scan speed and line offset were varied in a wide range keeping constant the energy density achieved, aiming to highlight the influence of each parameter on the properties of the printed parts. Microstructure, microhardness and top surface roughness were chosen as measured output. The results obtained showed that the amount of energy adsorbed by the metal is depending on beam current and scan speed, this due to the complex interaction between the electrons of the beam and the atoms of the material. As a consequence, the samples showed different properties, even if the adopted energy density was the same, the influence of the process parameters on the above-mentioned measured output was assessed.

Introduction

Additive manufacturing (AM) processes are finding an increasing, and apparently endless, interest in the last years. Referring to the fabrication of metallic parts, the most used processes are the direct energy deposition (DED) and the powder bed fusion (PBF), which includes the following commonly used printing techniques: selective laser melting (SLM) and electron beam melting (EBM) [1]. In these processes, a high-intensity heat source, a laser or an electron beam, interacts with the feedstock powders and produces a melt pool, where rapid melting and solidification take place [2]. Among these techniques, EBM is of high interest to the aerospace, biomedical and energy industries because it involves some intriguing advantages concerning the laser based techniques [3]. EBM builds parts in a high vacuum chamber providing an ideal contamination free atmosphere for the printing of reactive materials, such as titanium alloys, that have a high affinity to nitrogen and oxygen. Another advantage is that the deposition occurs at elevated temperatures, the build temperature is higher than 700 °C, reducing residual stresses in the final part [4]. Additionally, EBM generates a faster build rate, compared to SLM and DED, due to its superior energy input and faster scan rate [5]. As a drawback, the EBM produces parts with a high roughness [6].

During the EBM process, the material undergoes a complex process, made of a succession of preheating, melting, rapid cooling (with solidification and phase transformation) and partial remelting of each layer and powder [7], therefore a fundamental understanding of the mechanisms occurring during the process, as well as the link between processing conditions and properties of the component are required.

According to previous studies, the processing variables for EBM can be divided into two main categories: inter build and intra-build. The former are parameters that can vary across multiple builds (e.g. chemistry, build plate temperature, powder morphology) whereas the latter parameters can vary within the same build (e.g. energy input, location, orientation) [8]. In this paper the attention was put on the intra-build parameters to assess their influence on the properties of the final part. In particular, it has been proved that the microstructural evolution, as well as the formation of defects, depend on many factors, such as electron beam current, scanning rate, powder particle size, layer thickness, hatching strategy and others [9,10].

The alloy under investigation in this paper is the Ti6Al4V which is a typical alpha plus beta dual phase alloy, where alpha phase normally precipitates in beta matrix with the typical Burger relationship $(0001)_{\alpha}//(110)_{\beta}$, $[1120]_{\alpha}$, $[111]_{\beta}$ [[11]] . Concerning Aluminium, it is added to increase the strength of the alloy through solid solution

* Corresponding author.

high magnification SEM images revealing some details.

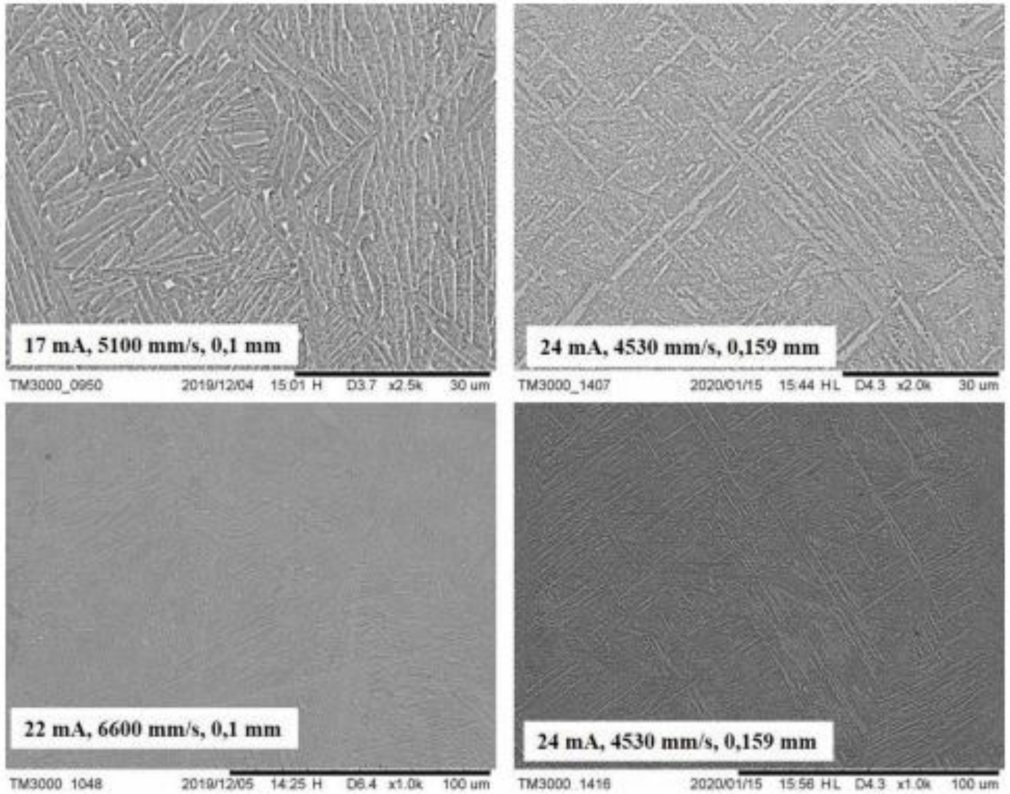

Fig. 19. Cross-section micrographs showing the observed different microstructures at different magnifications.

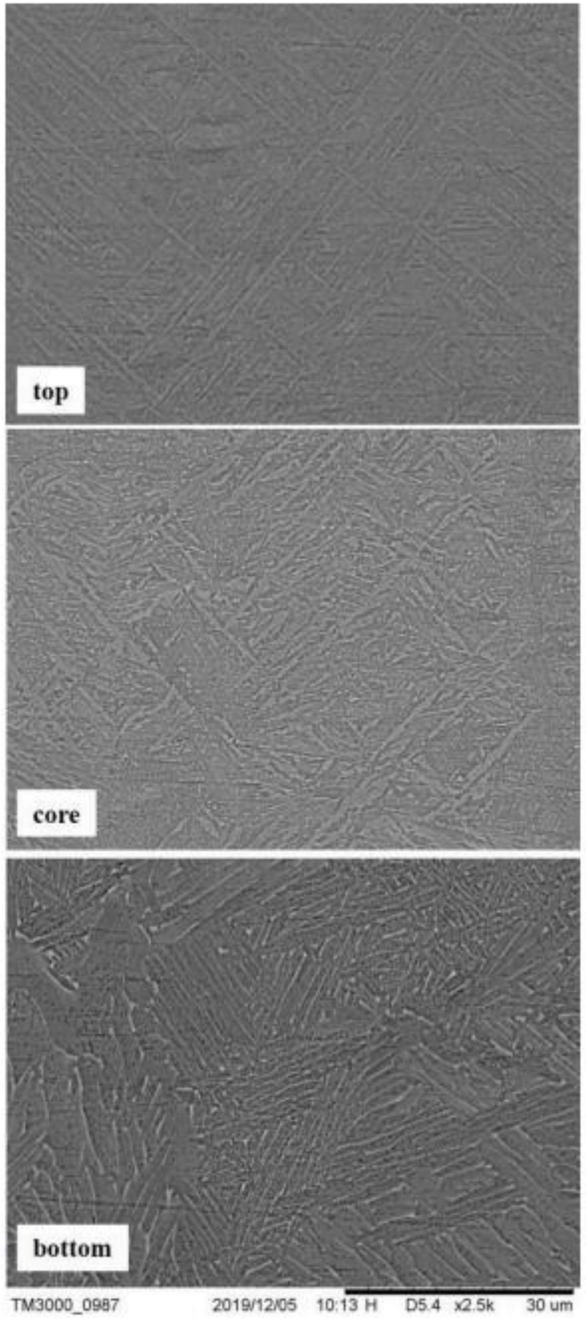

Fig. 20. Graded microstructure observed in the cross-section of the sample 20 mA, 1800 mm/s, 0,1 mm.

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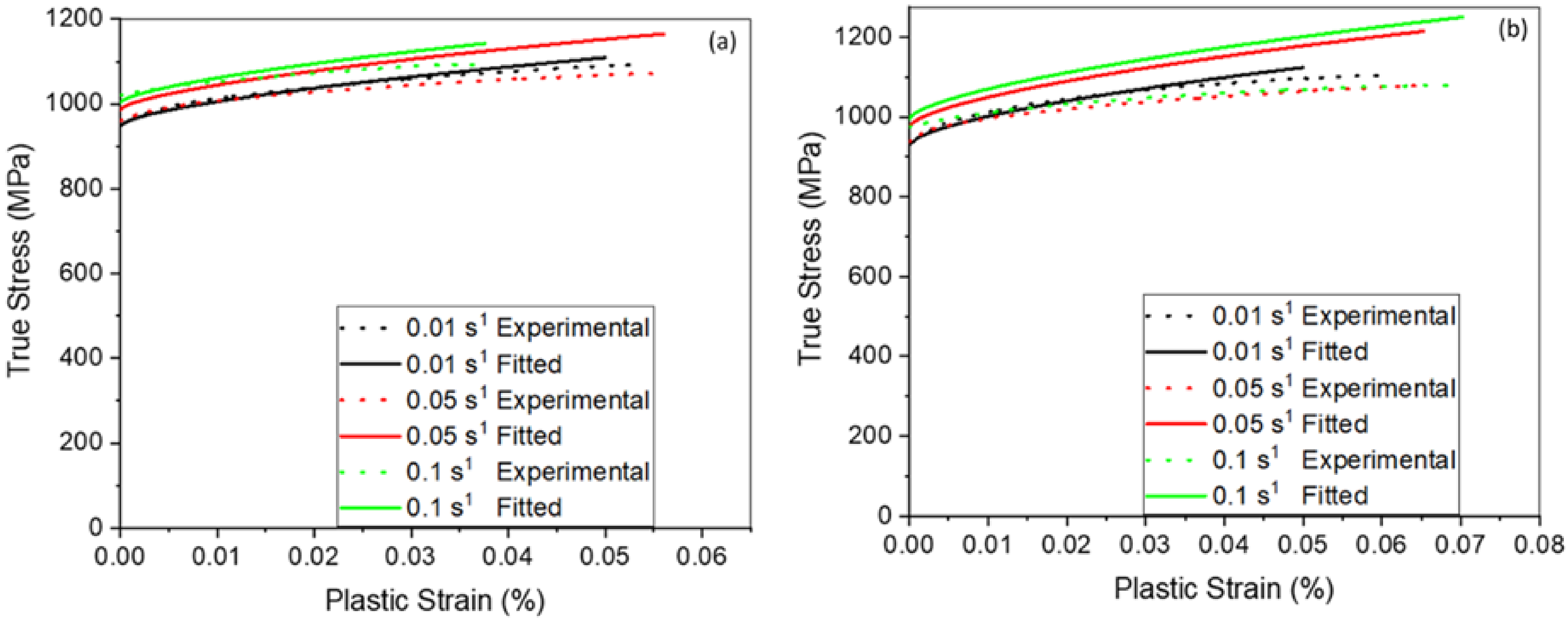
Experimental vs Johnson Cook model fitted curve for (a) EBM Ti-6Al-4V, (b) Conventional Ti-6Al-4V



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Processing condition	Material constants						
	A	B	n	C	m	T_{ref}	$\dot{\varepsilon}_o$
Massive Ti-6Al-4V	930	1106	0.6225	0.02977	1	303 K	0.01 /s
EBM Ti-6Al-4V	949	1093	0.6515	0.02419	0.85	303 K	0.01/s

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