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IS IT POSSIBLE TO USE ADDITIVE MANUFACTURING FOR ACCELERATOR UHV BEAM PIPES?

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MOTIVATION

- In particle accelerators under construction or planned, some systems are actually used to the limit of their possibilities

- The performance of components involved in accelerator technology is closely related to the characteristics and capabilities of the materials
  (morphology/finishing of surfaces, chemical purity, crystallographic quality, presence of defects)

- To face the challenges for the construction of the next-generation particle accelerators, technologies must evolve: new materials, new approaches of manufacturing must be considered

- Additive manufacturing (3D metallic printing)

<u>Main advantages</u>

- Rapid production of mechanical components with complex shapes
- Rapid prototyping
- Reduced Tooling Costs

http://www.sokaris-ingenierie.com/fabrication-additive/#

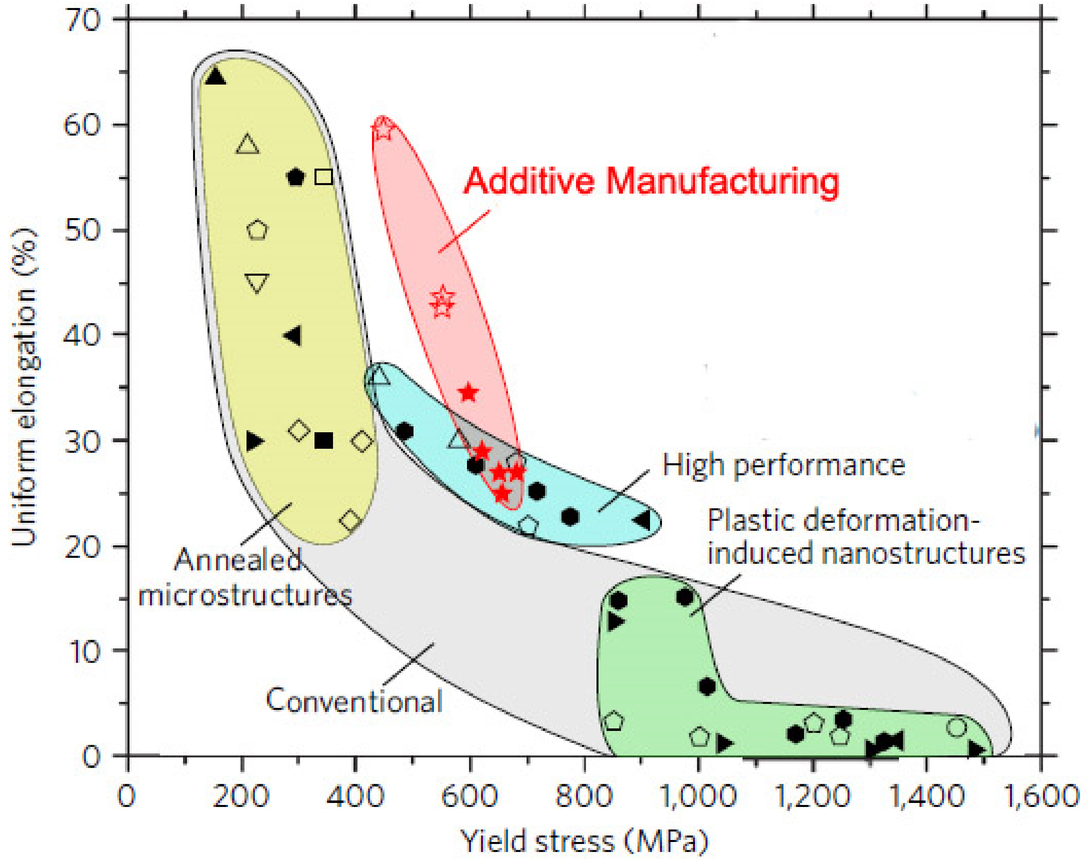
Component in the aerospace industry

gooseneck bracket, a part of an airplane wing

MOTIVATION

Changing the manufacturing process means changing the material properties!

Ex.: Mechanical properties of 316L stainless steel



Figures from Y.M. Wang et al Nature Materials (2017)

Large domain of mechanical properties

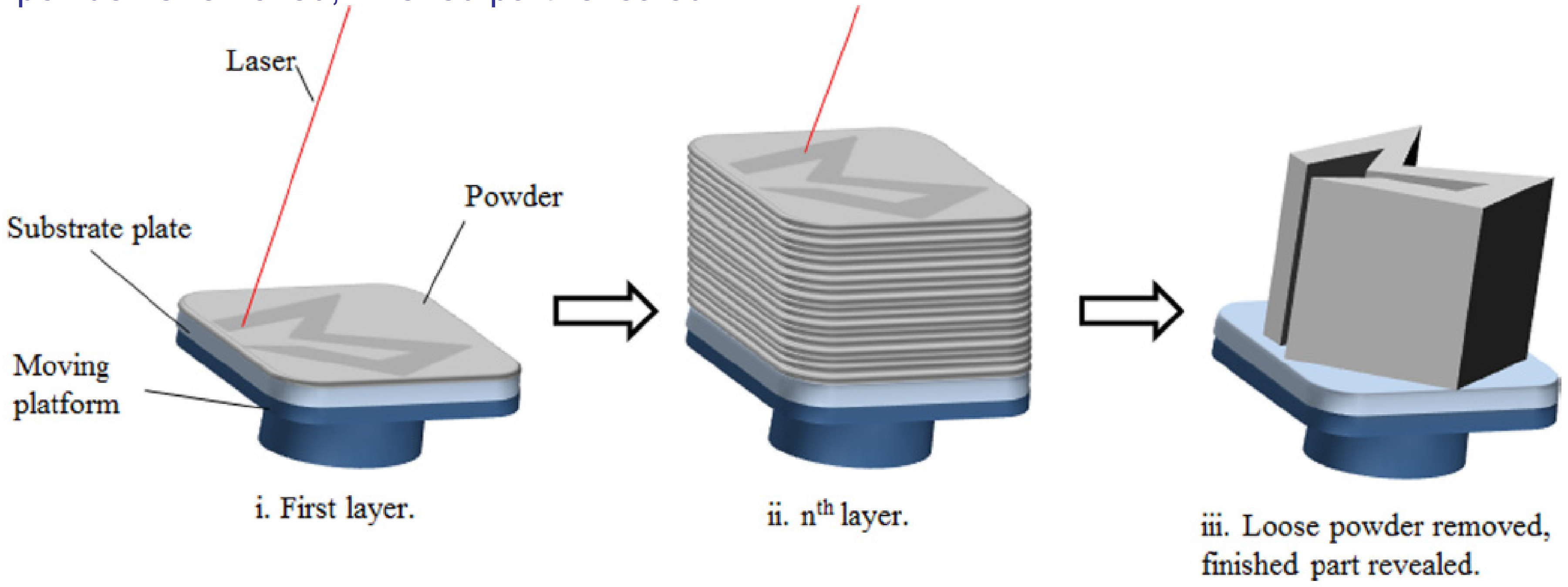
→ depend on microstructure

Additive manufacturing (3D printing)
Selective Laser Melting (SLM) process

Selective Laser Melting (SLM) is the most advanced AM technology

Principle:

- 3D printing based on a CAD model
- High-power laser melts selective areas of the powder bed (fine metal powder onto a substrate plate)
- Process repeats for successive layers (20-40µm) → layer by layer building
- Loose powder is removed, finished part revealed



Figures from Yap et al Applied physics Review (2015)

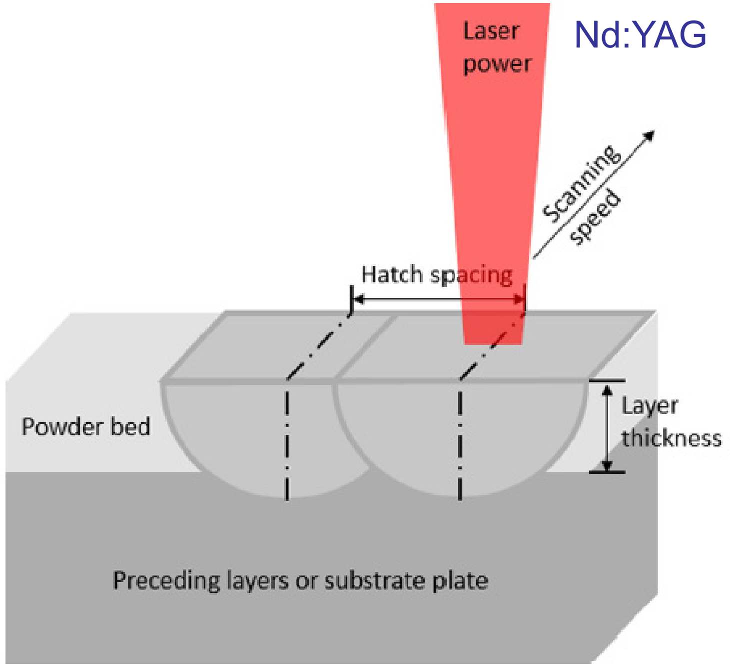
Material: copper, aluminum, stainless steel, cobalt-chromium, titanium and tungsten (+recently niobium)

Additive manufacturing (3D printing) WARNING

- Influence of many processing parameters (laser power, scanning speed, powder granulometry) ?
- Complex thermal history during the manufacturing (rapid solidification then heating and cooling with each additional layers)
- Even if you used the same AM process (e.g. SLM) : is the reproducibility of properties guaranteed?
- Production of heterogeneous and anisotropic microstructures that differ from traditional alloy counterparts

→ Materials produced by AM must be carefully characterized

Nd:YAG



CONTENT

1- Reproducibility of properties

Characterization of microstructure ↔ mechanical properties

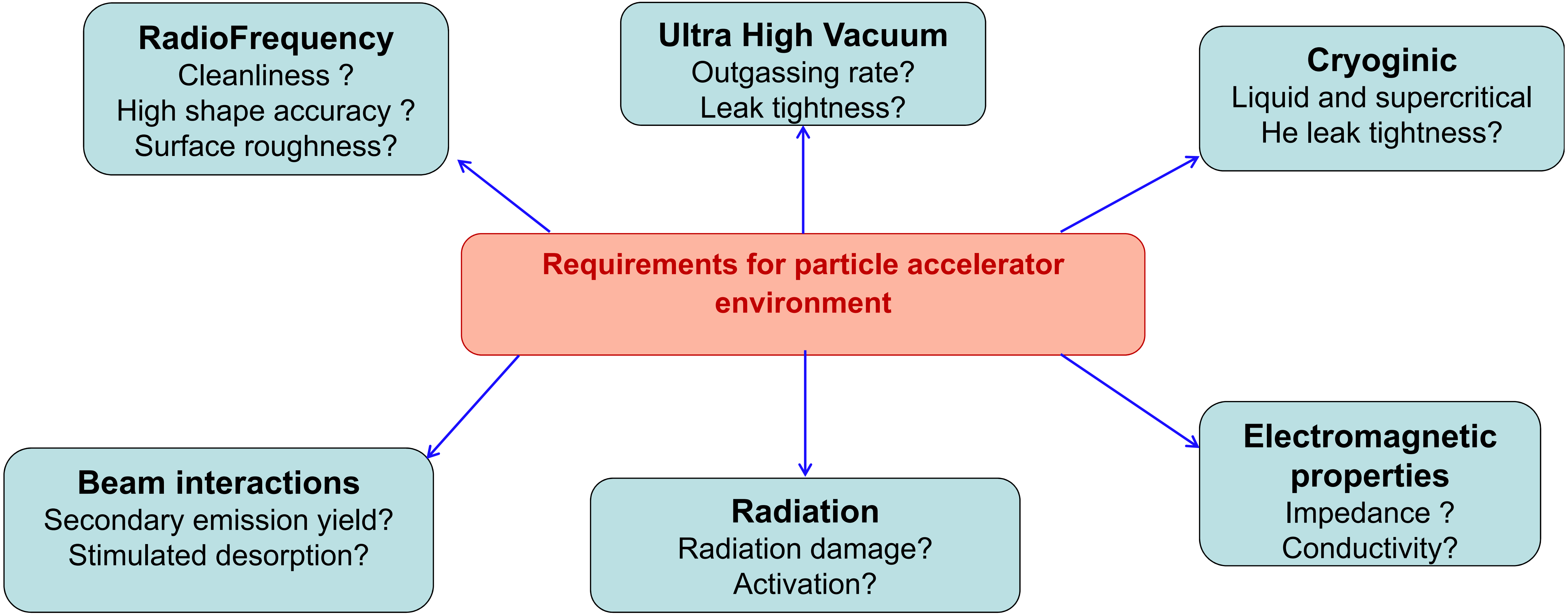
2- UHV compatibility : outgassing measurements

3- Beam interaction : Secondary Emission Yield

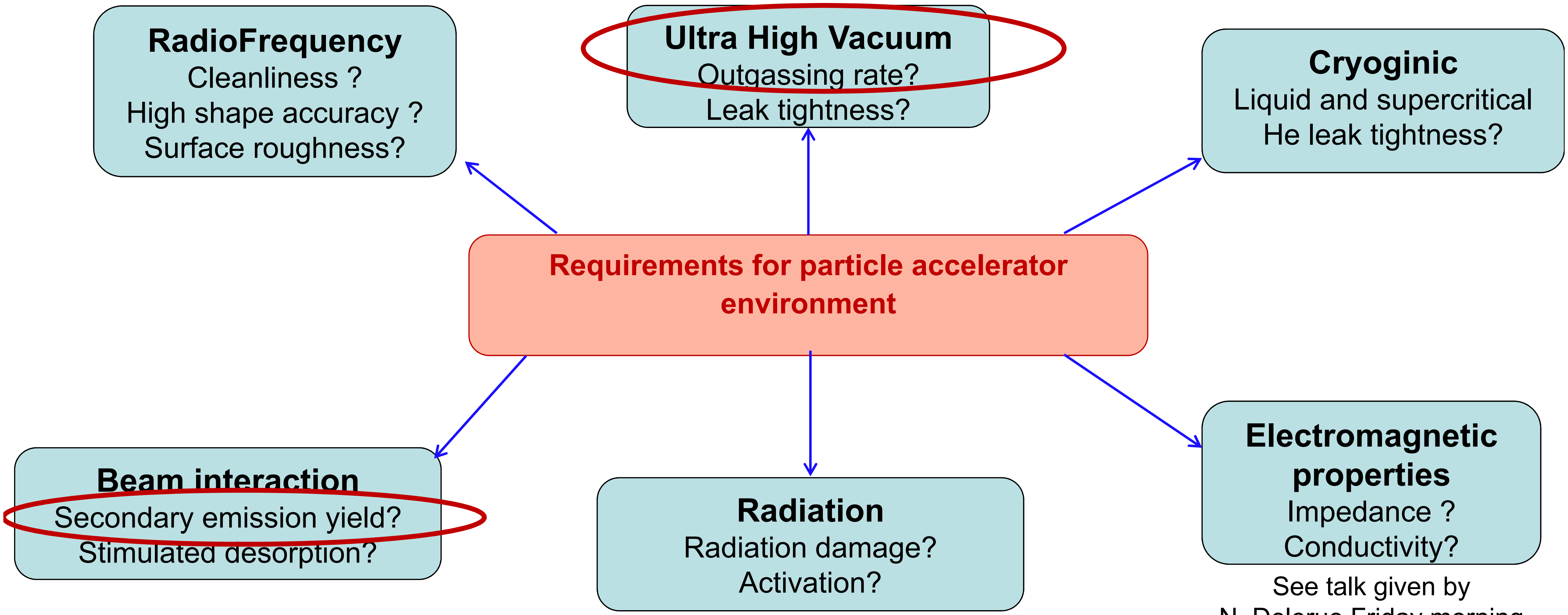
→ Material = 316 L Stainless steel

→ Tests performed on pieces of simple form

Specific constraints for applications in a particle accelerator



Specific constraints for particle accelerators



See talk given by
N. Delerue Friday morning
Tests of a 3d Printed BPM With
a Stretched Wire and With a Particle Beam

CONTENT

1- Reproducibility of properties

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Samples for the microstructural study

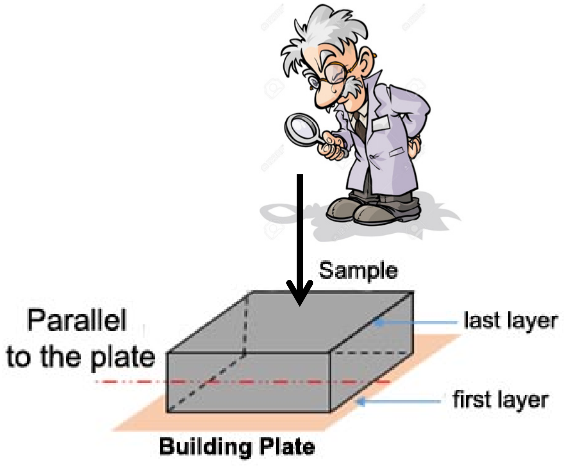
Material : 316L stainless steel

No SLM machine in the lab : manufacturing was sub-contracted to different companies

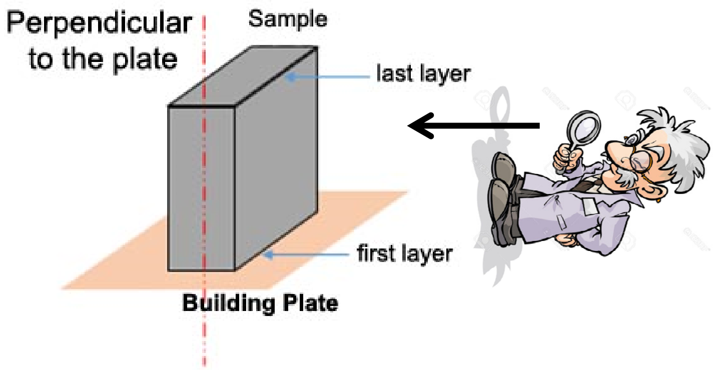
Manufacturers	Method	Powder granulometry (µm)	Layer thickness (µm)
A	SLM	20 - 125	40
B	SLM	20 - 50	40
C	SLM	?	40

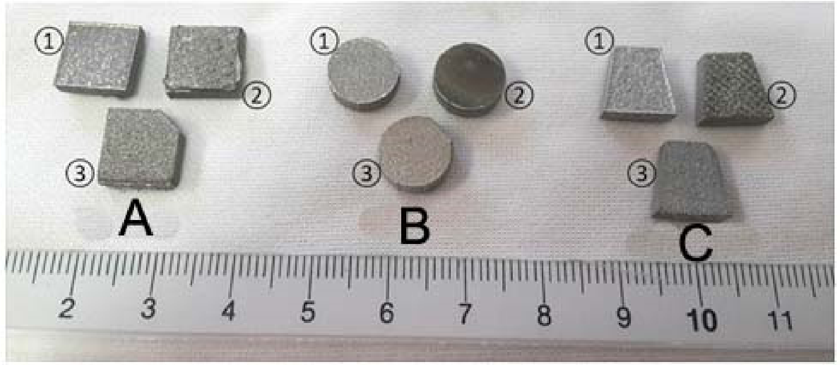
Two orientations:

- Parallel



- Perpendicular

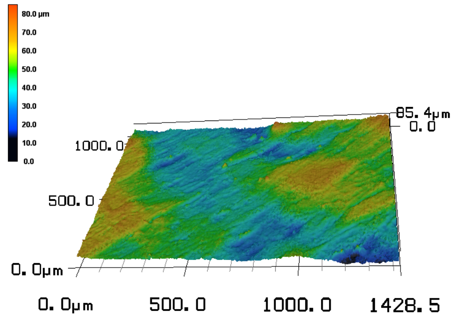




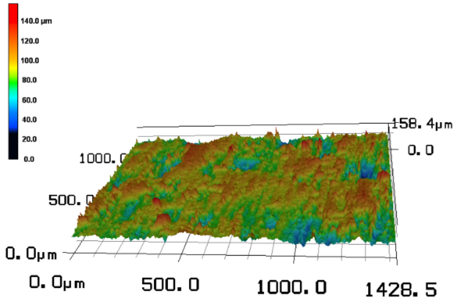
Surface quality
Confocal microscopy

Parallel

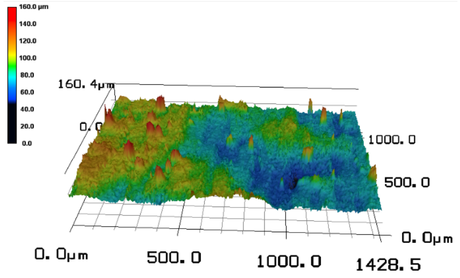
A

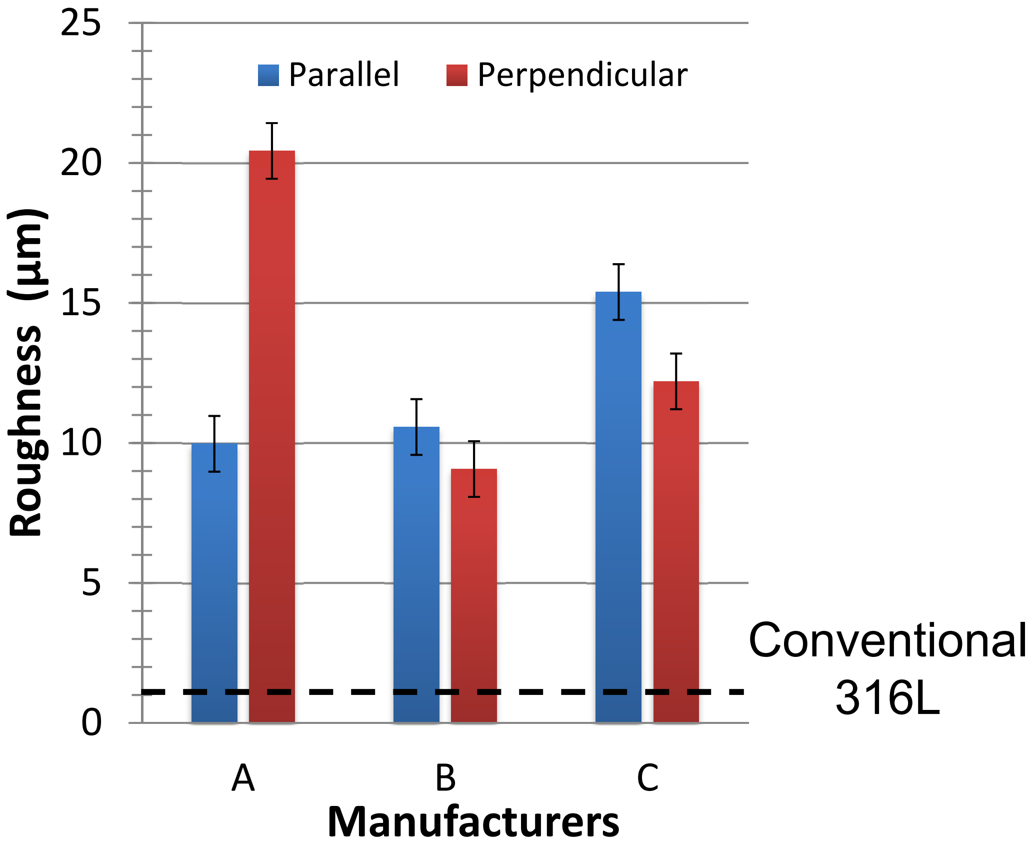


B



C



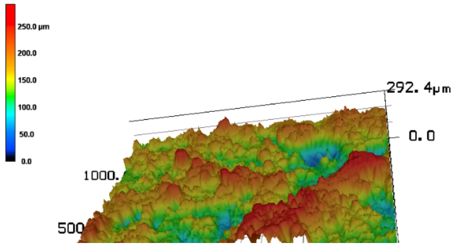


Surface roughness is much larger for AM samples than for conventional counterparts

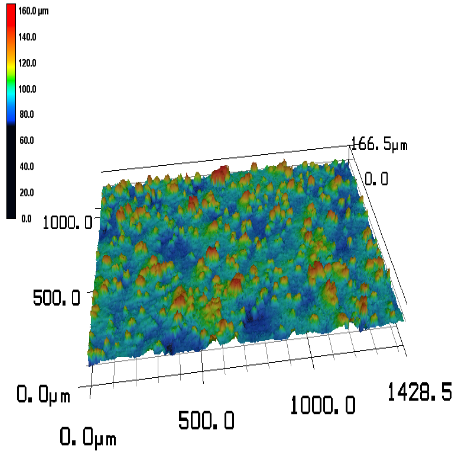
→ It could be a severe drawback for accelerator applications?

Perpendicular

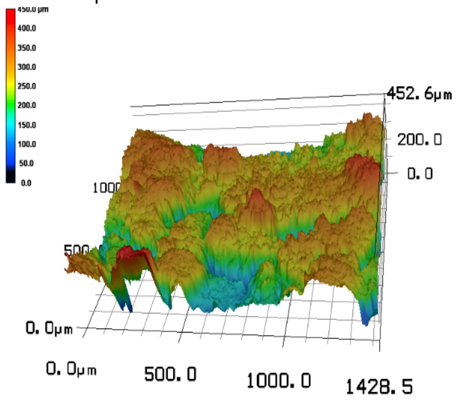
A



B

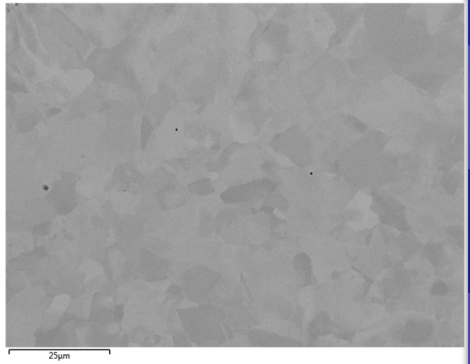


C

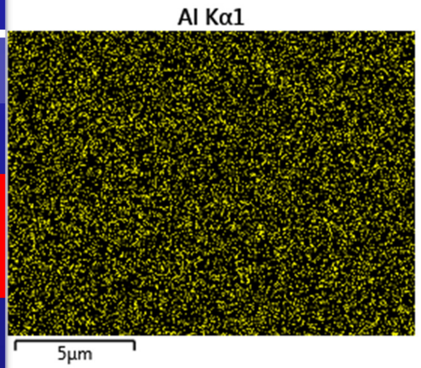


Composition

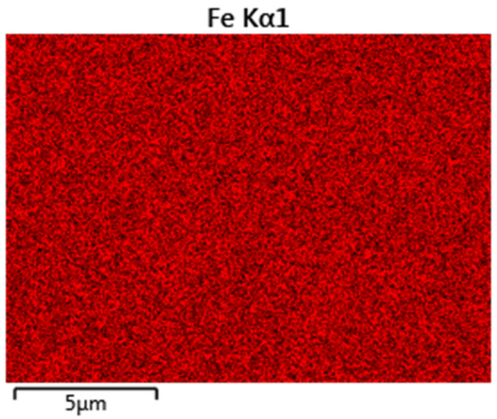
Elemental analysis : composition (SEM/EDX)

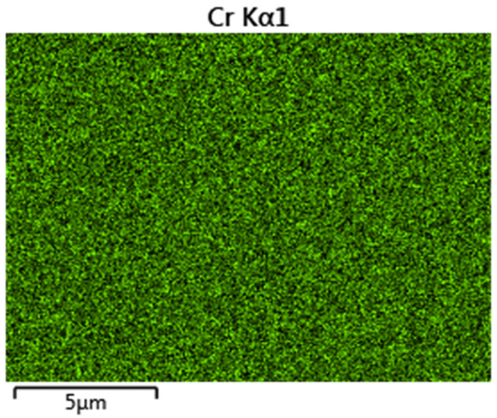


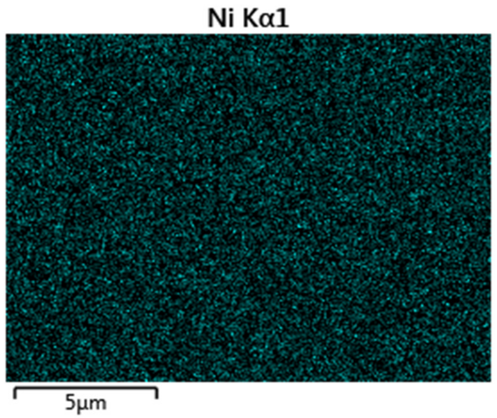
	Chemical composition (Weight %)						
	Fe	Cr	Ni	Mo	Mn	Si	Al
Std	Compl.	16 - 19	9 - 13	1,5 - 3	< 2	< 1	/
A	67.4 ± 0,4	17,3 ± 0.2	12.3 ± 0.3	2.2 ± 0.2	0.3 ± 0.2	0.4 ± 0.1	0.2 ± 0.1
B	63.1 ± 0.4	18.0 ± 0.2	14.7 ± 0.3	2.3 ± 0.2	1.6 ± 0.2	0.4 ± 0.1	/
C	67.2 ± 0.6	16.2 ± 0.3	11.7 ± 0.5	2.5 ± 0.3	1.9 ± 0.3	0.6 ± 0.1	/

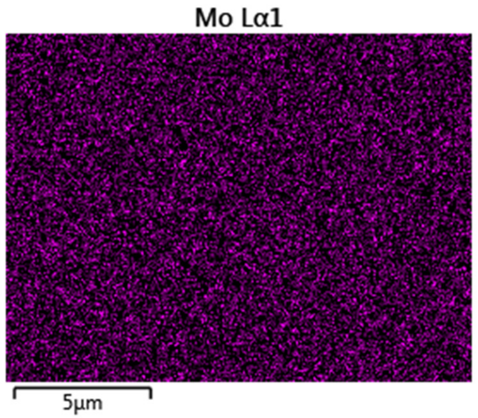


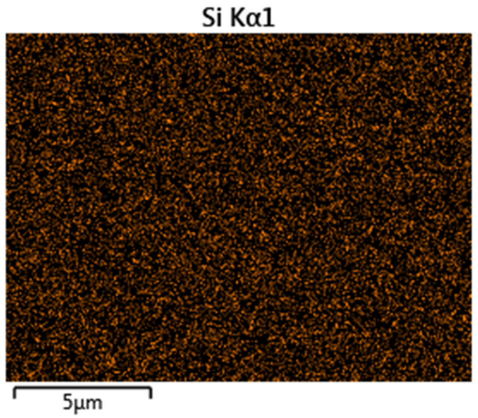
Al contamination
α-stabilizer!







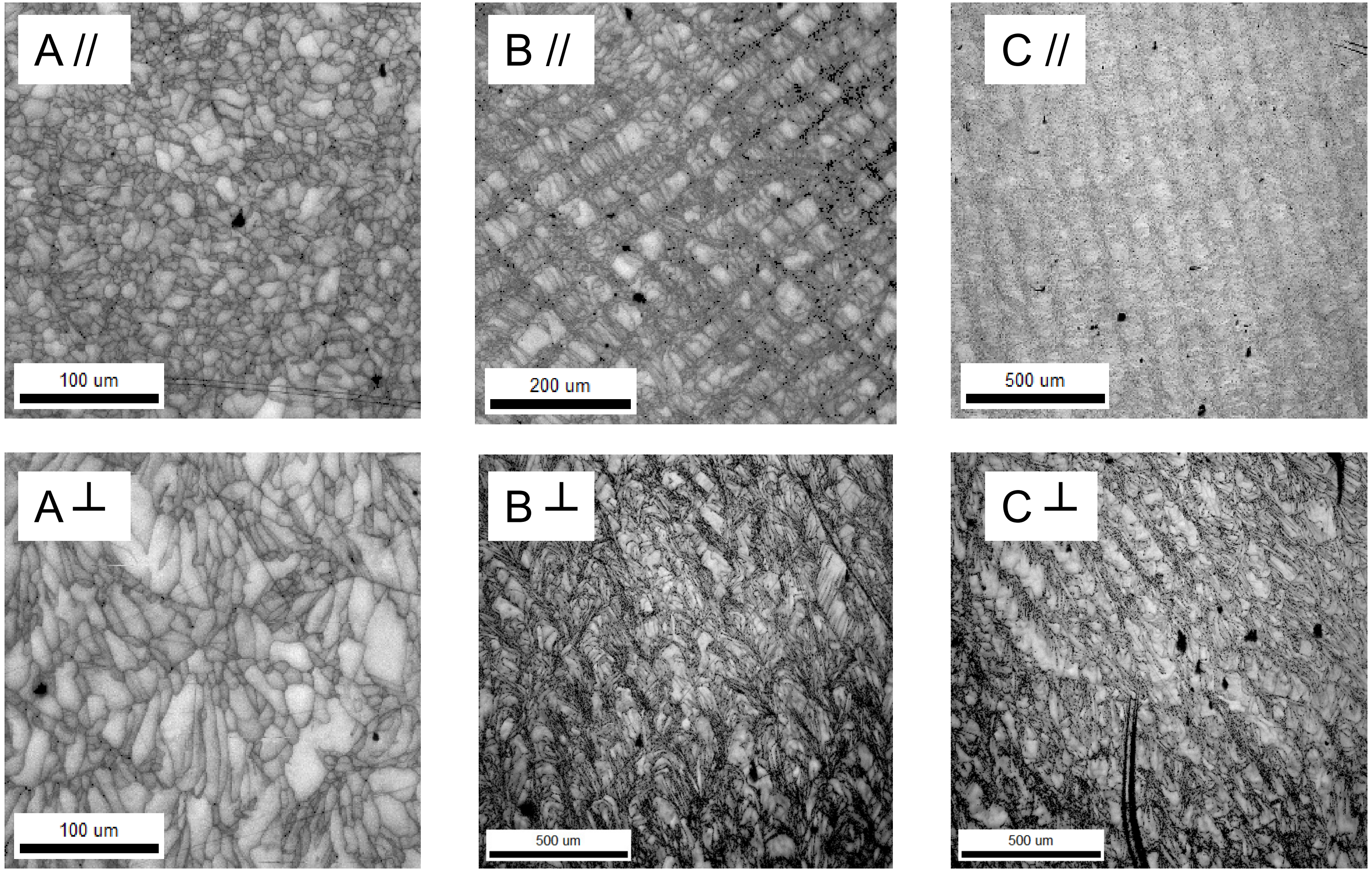




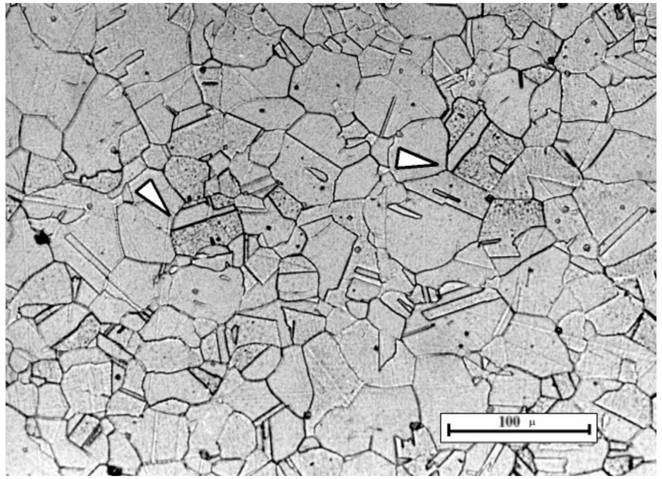
Homogeneous composition

Microstructure

Grain morphology and grain size (SEM)

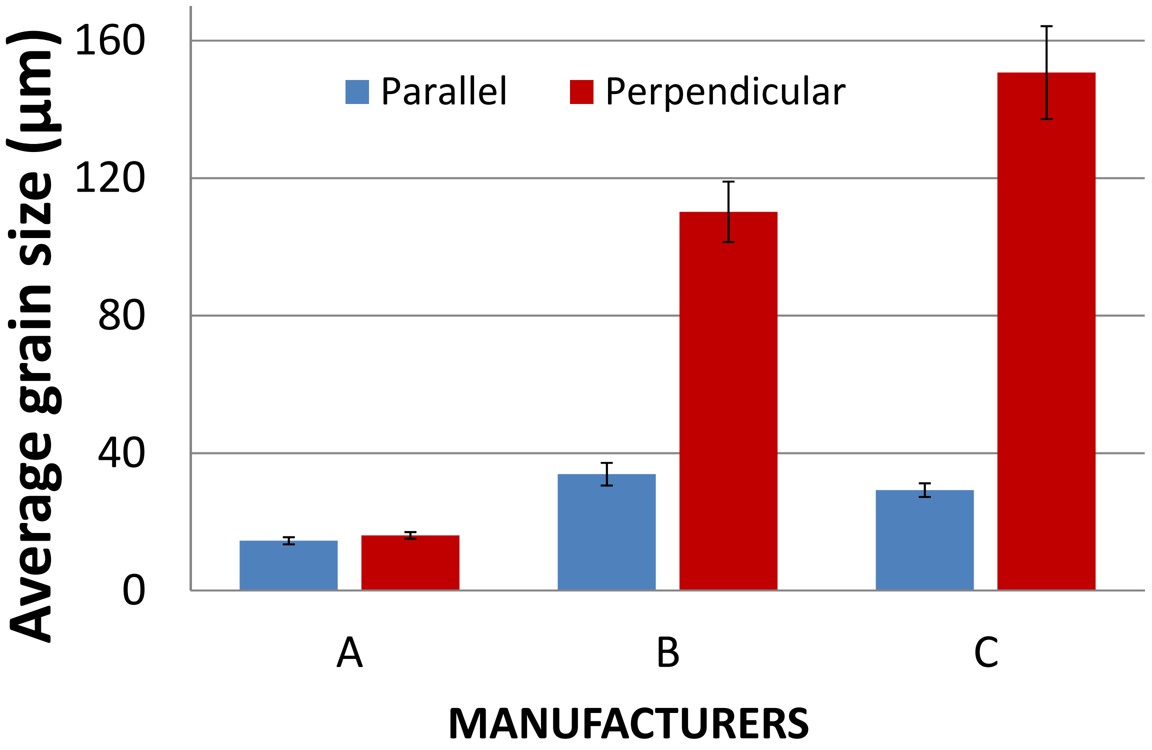


Conventional 316L



Grains exhibit a ripple pattern instead of a traditional faceted morphology
→ a highly nonconventional grain shape

Microstructure : grain size (SEM)



Grain size depends on manufacturers

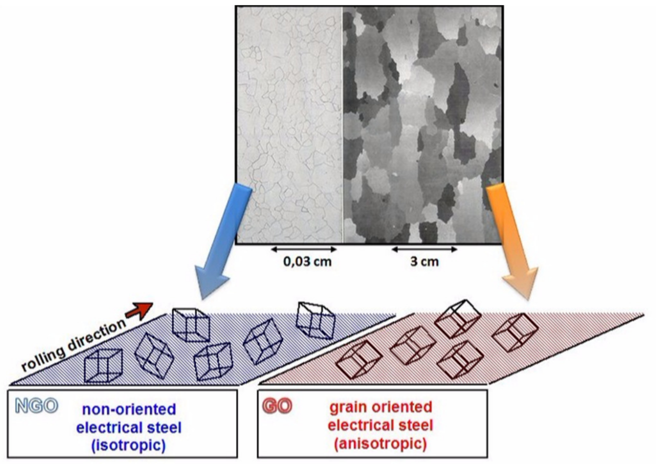
size in the perpendicular direction > size in the parallel direction

→ elongated columnar grains oriented along the build direction (perpendicular to the building plate)

→ large directional thermal gradients during the layer by layer deposition process

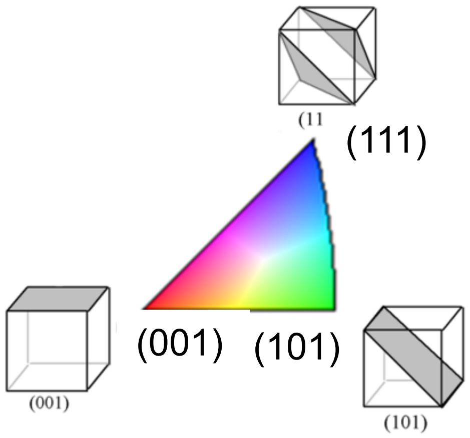
Crystalline texture : SEM-EBSD analysis

Crystalline texture
=
Preferred orientation



- If grain orientations are fully random = no distinct texture (no color is predominant)

- If a preferred orientation exists = texture (a color dominates)



Crystalline texture : SEM-EBSD analysis

Crystalline texture
=
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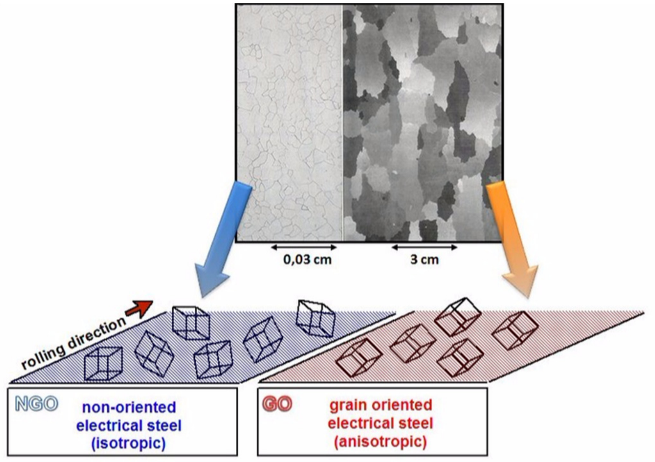

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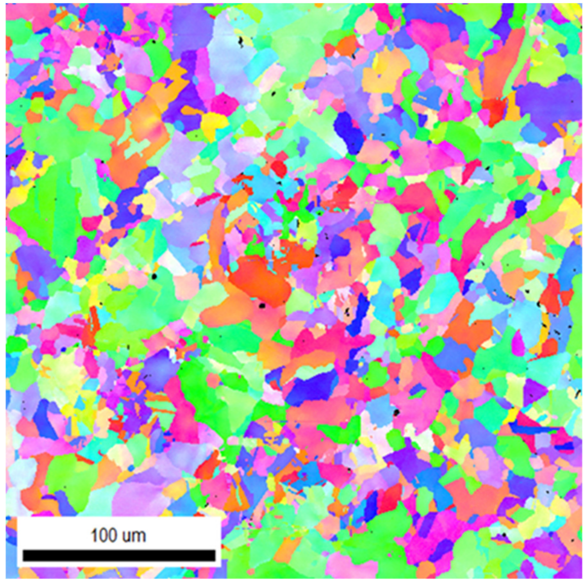
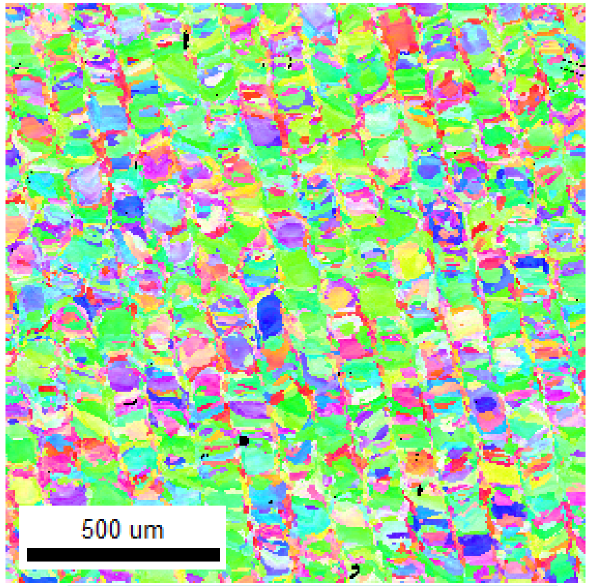
A //



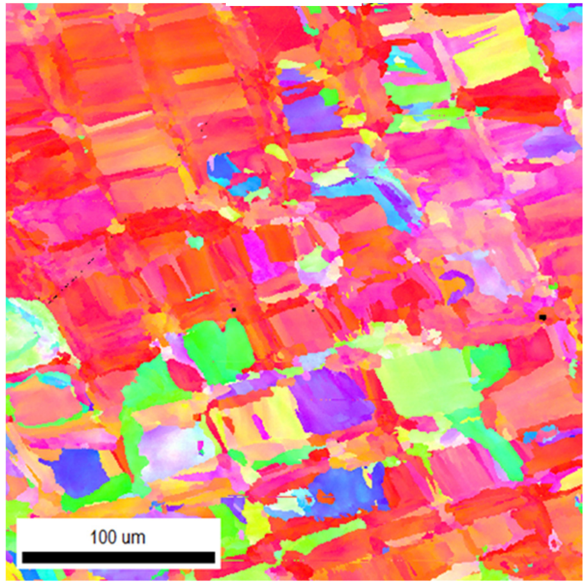
No texture

B //

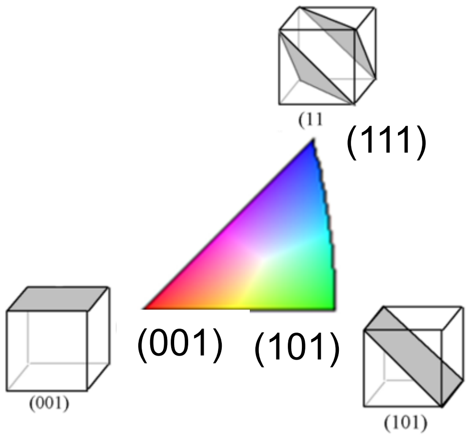


(101) and (111) texture

C //



(001) texture



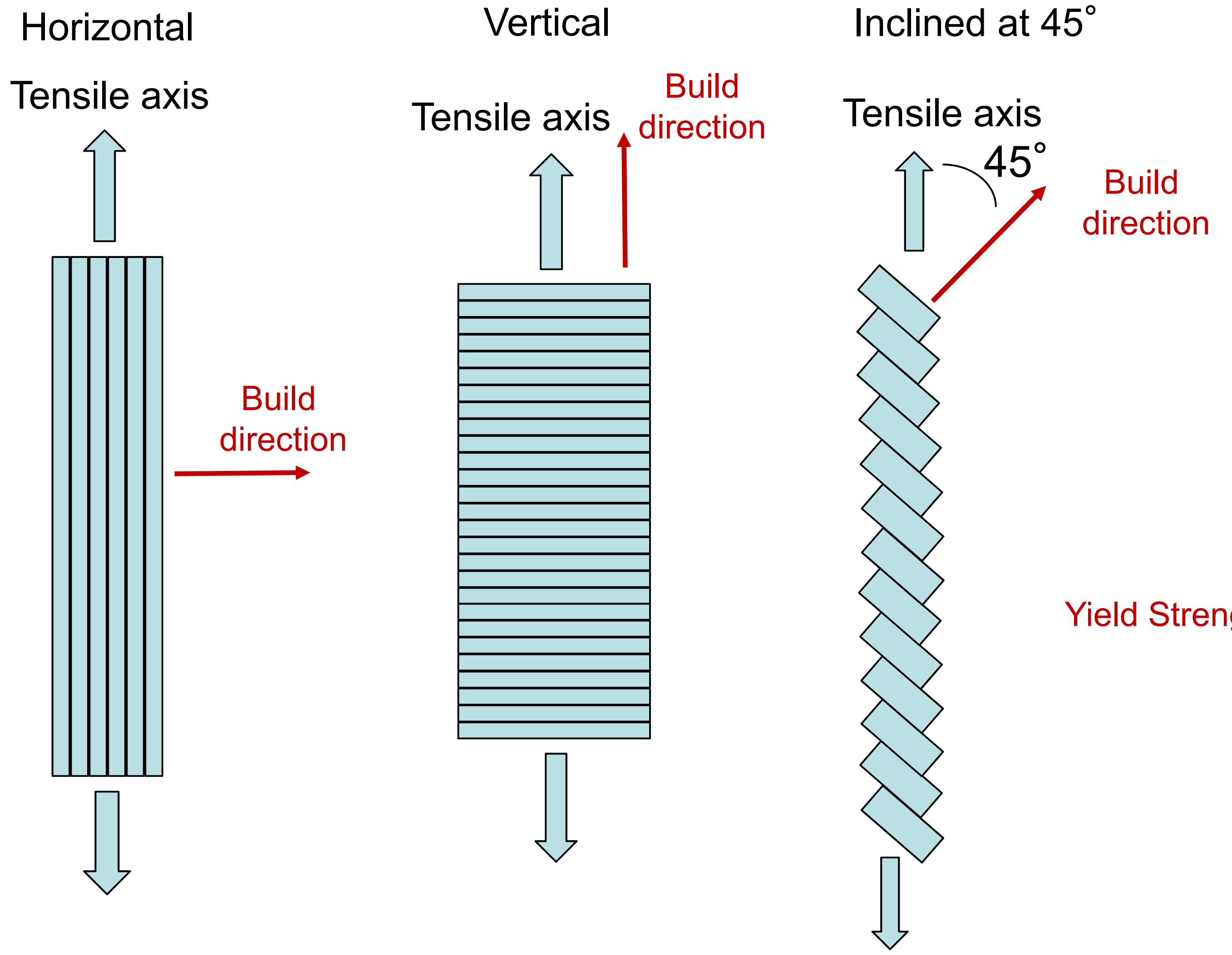
Microstructure of AM samples depends on manufacturers

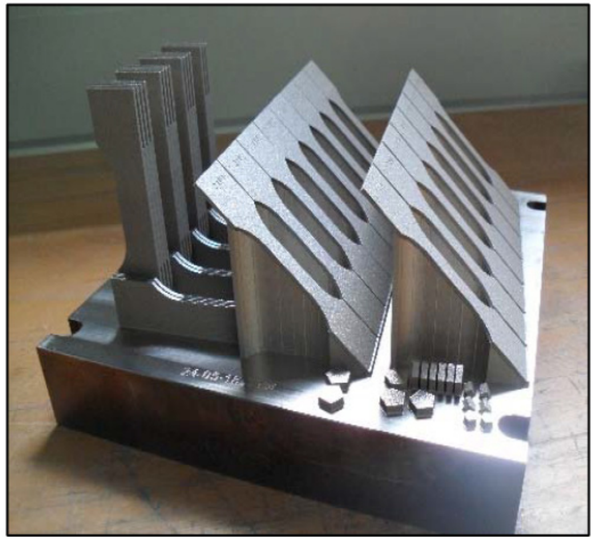
microstructural anisotropy → anisotropic properties

Mechanical properties

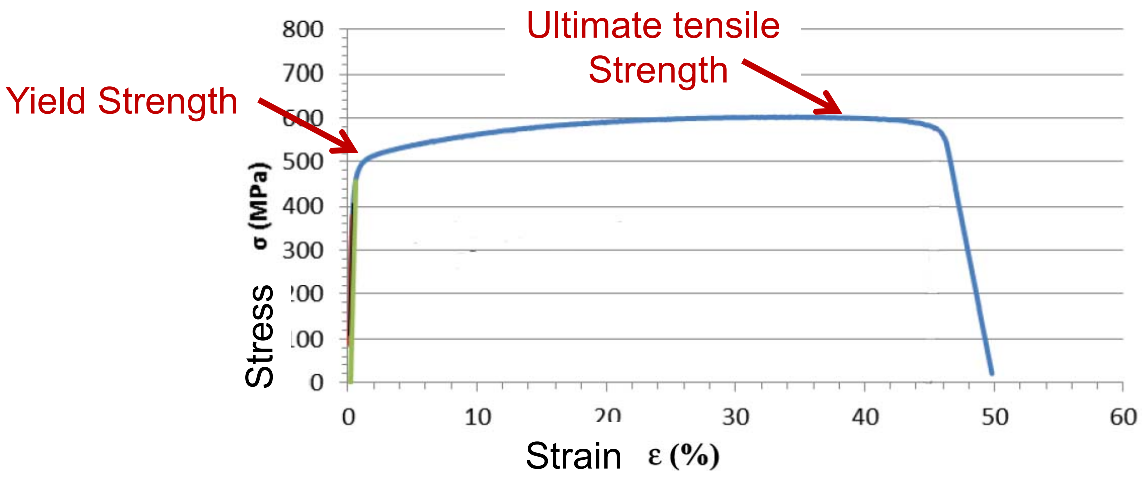
Tensile test

Tensile specimens printed in 3 directions: horizontally, vertically and inclined at 45°

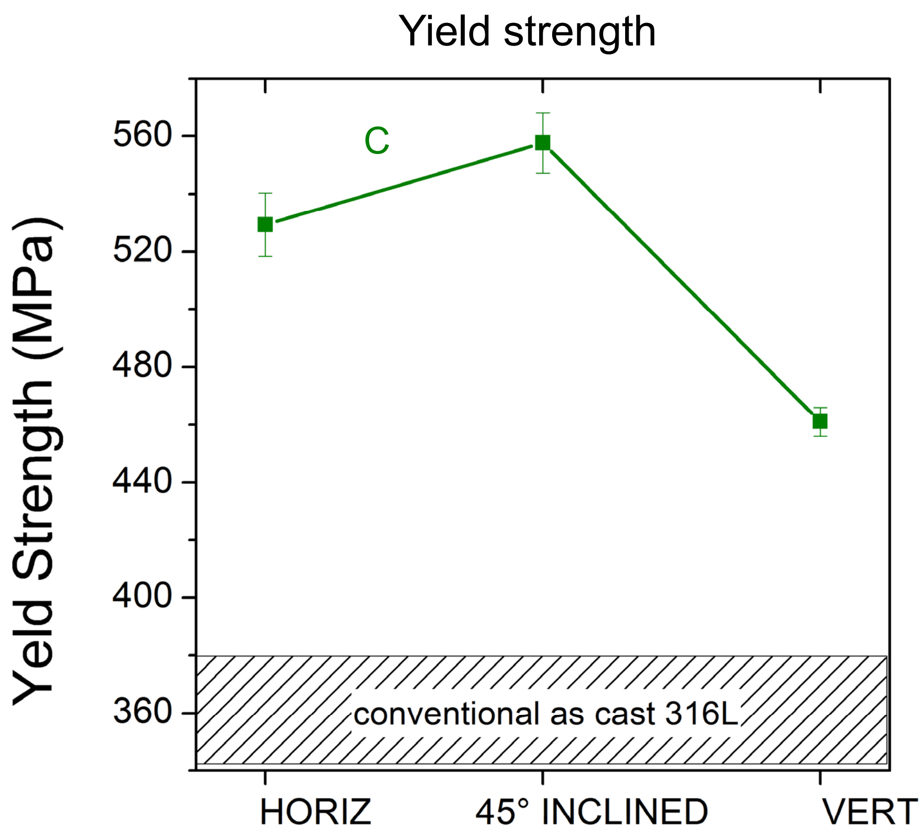


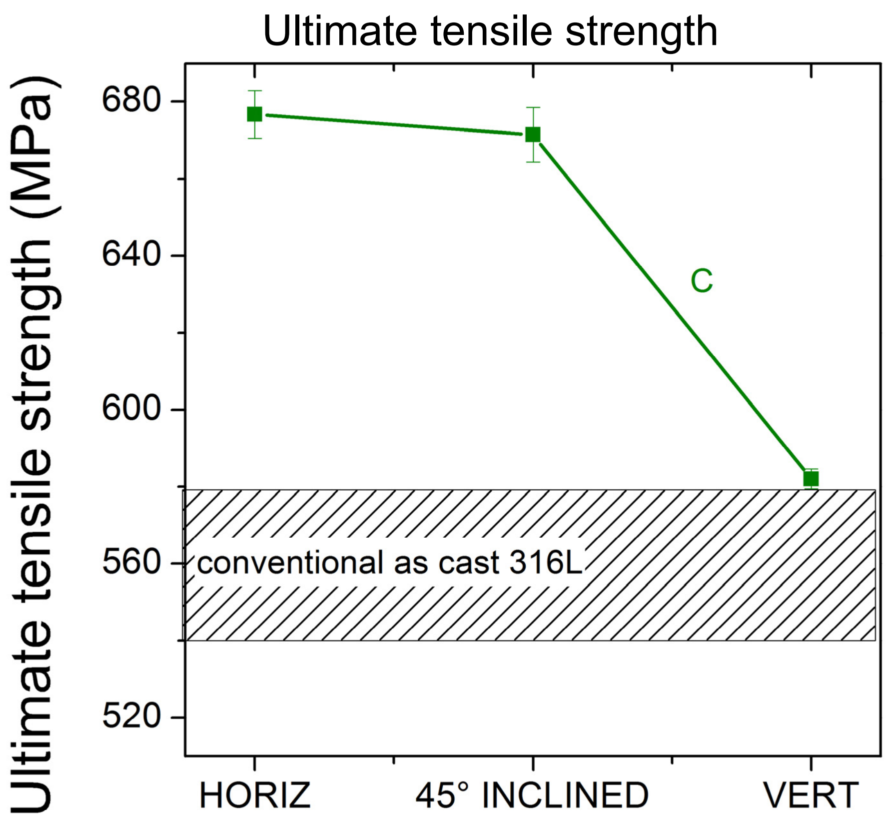


Typical tensile curve



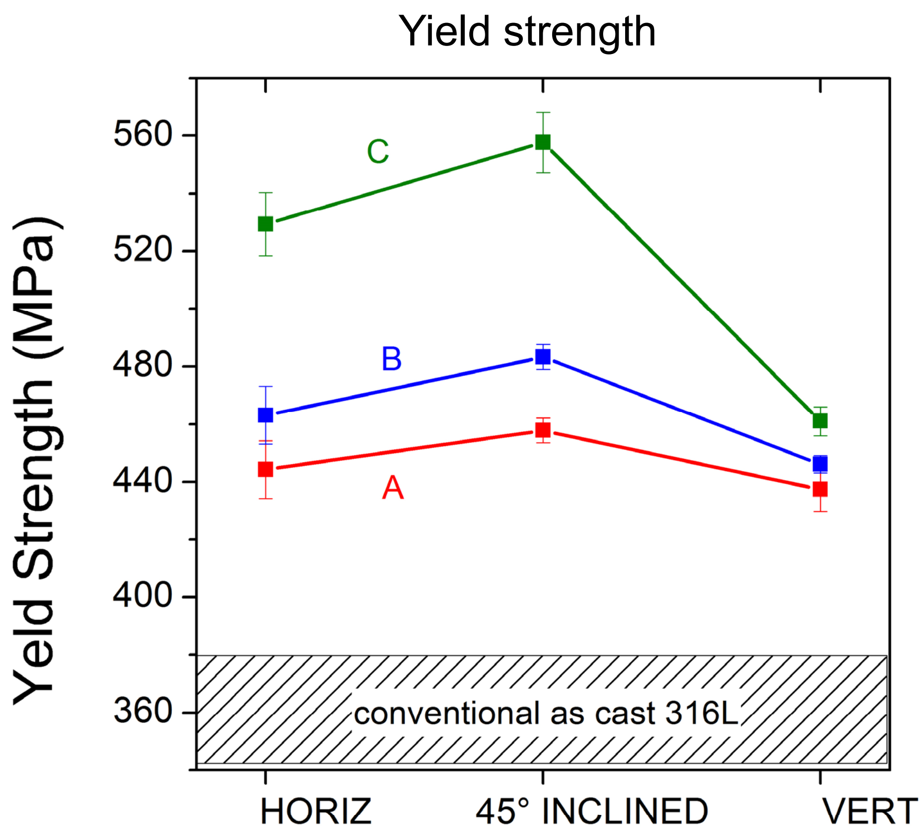
Tensile test

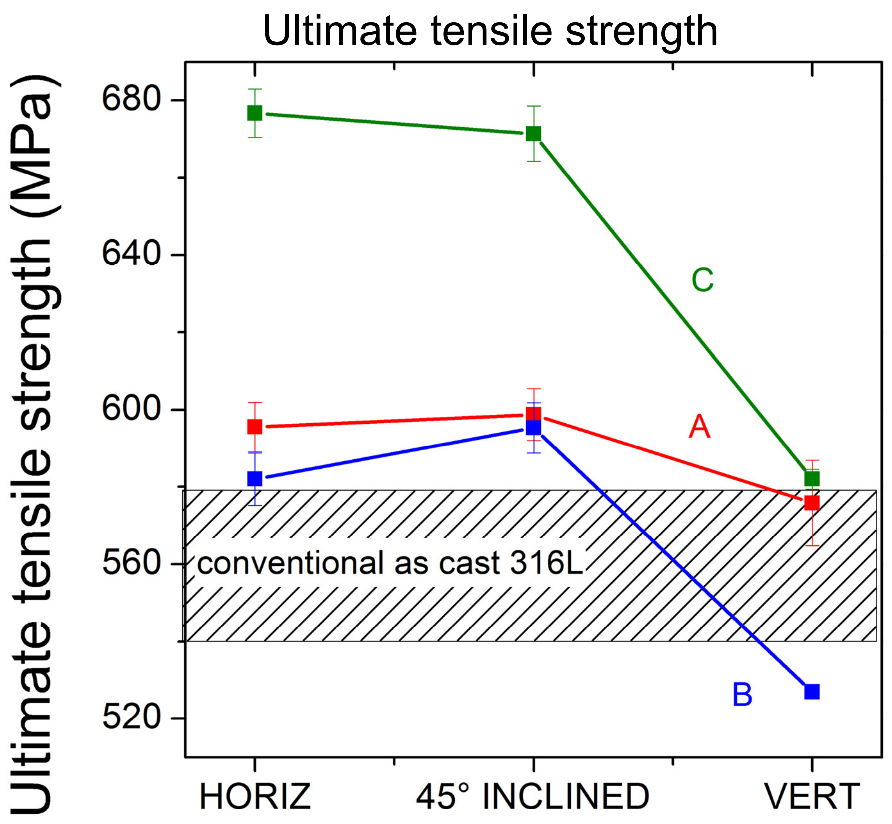




- Mechanical properties depends on the orientation : they are anisotropic (related to the microstructure anisotropy)
  →Inclined specimens exhibit the highest yield strength

Tensile tests





- ➢ Mechanical properties depends on the orientation : they are anisotropic (related to the microstructure anisotropy)
  - →The inclined specimens exhibit the highest yield strength
- ➢ Samples C exhibit the highest mechanical properties
- ➢ AM samples have better mechanical properties than conventional counterparts

CONTENT

1- Reproducibility of properties

Compare the microstructure of samples delivered by three different manufacturers (SLM)

Characterization of microstructure ↔ mechanical properties

2- UHV compatibility : outgassing measurements

3- Beam interaction : Secondary Emission Yield

→ Material = 316 L Stainless steel

→ Tests performed on pieces of simple form

UHV compatibility : Outgassing

DN40CF tubes
in 316L stainless steel by AM

The surface quality of 3D printed tubes is very different of that obtained from conventional techniques.

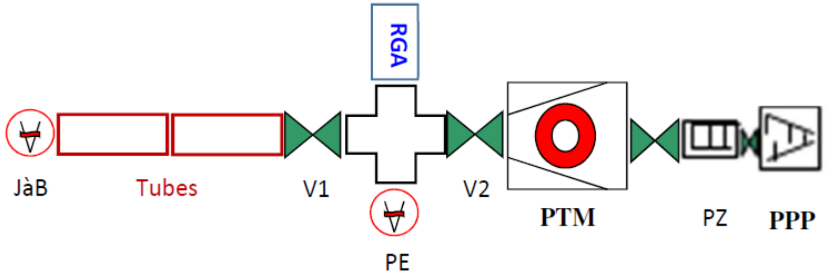
The surface roughness of the raw tubes : Ra = 8.5 µm to 10 µm.

A previous work showed that the flanges must be lathed to avoid leaks!

2 cases were studied :
- only the flanges are lathed (to avoid leaks)
- both the flanges and the tube inside are lathed

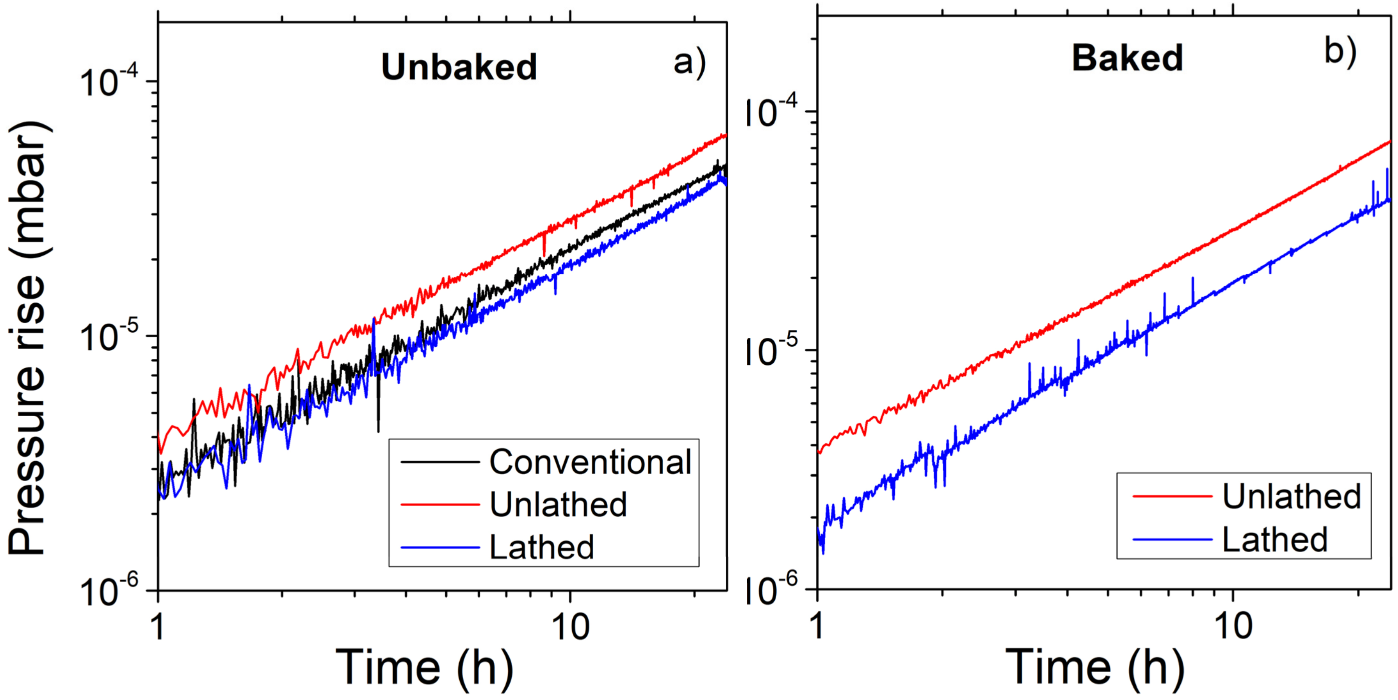
Outgassing measured by the gas accumulation method

copper joints
all-metal UHV valves



-Tubes are pumped down
-Valve 1 is closed
-Pressure rise is measured by a spinning rotor gauge

UHV compatibility : Outgassing



Outgassing rates for 100h of pumping after baking under vacuum at 200° C during 72h.

Treatment	Tube	Outgassing rate (mbar.l/s.cm^2)
Unbaked	Conventional	6.0×10^{-12}
	Unlathed AM	5.6×10^{-12}
	Lathed AM	7×10^{-12}
Baked at 200 °C	Unlathed AM	3.6×10^{-13}
	Lathed AM	3.4×10^{-13}

- Values for AM tubes and the conventional one are equivalent, in agreement with literature data
- Surface roughness has no impact on these results (unlathed vs lathed)
- Outgassing rate is one order of magnitude lower for baked tubes than for unbaked ones.

UHV compatibility : OK!

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Secondary Emission Yield

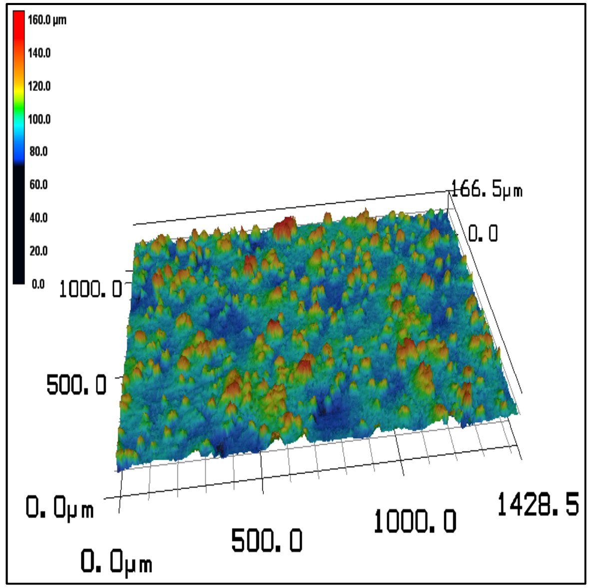
Surface roughness of samples

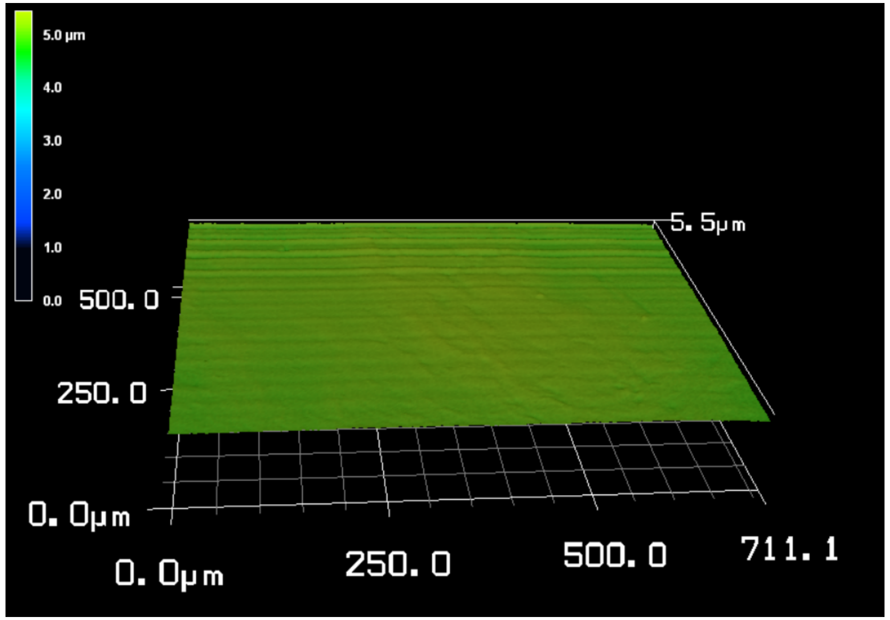
AM 316L

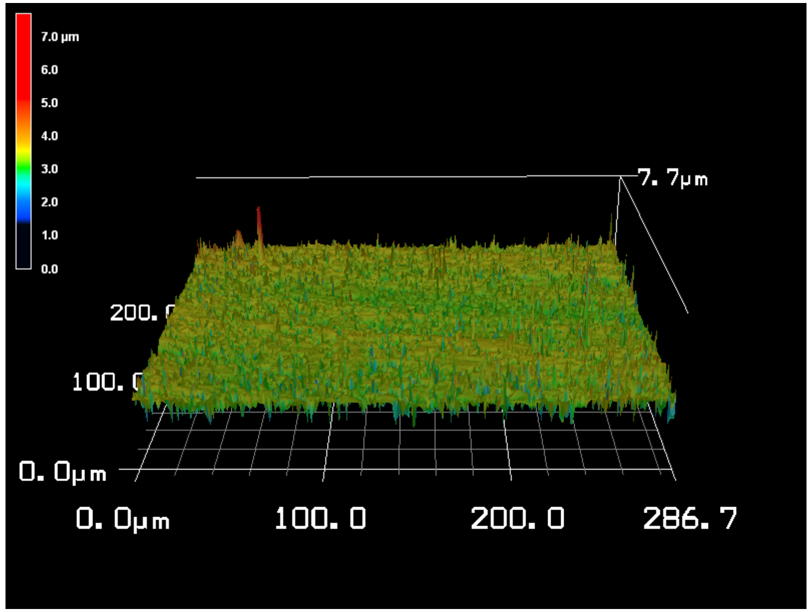
as-received

polished

Conventional 316L







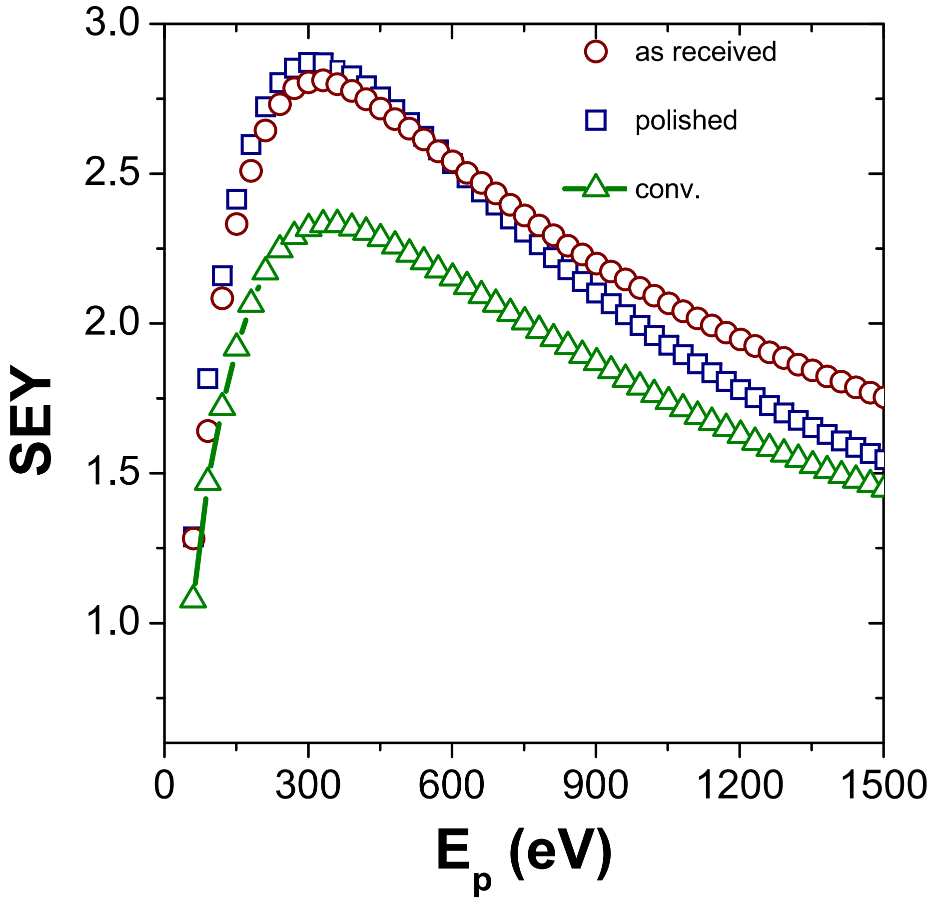
Ra = 9±1µm

Ra = 0.35±0.05µm

Ra = 2.9 ±0.5 µm

Secondary Emission Yield

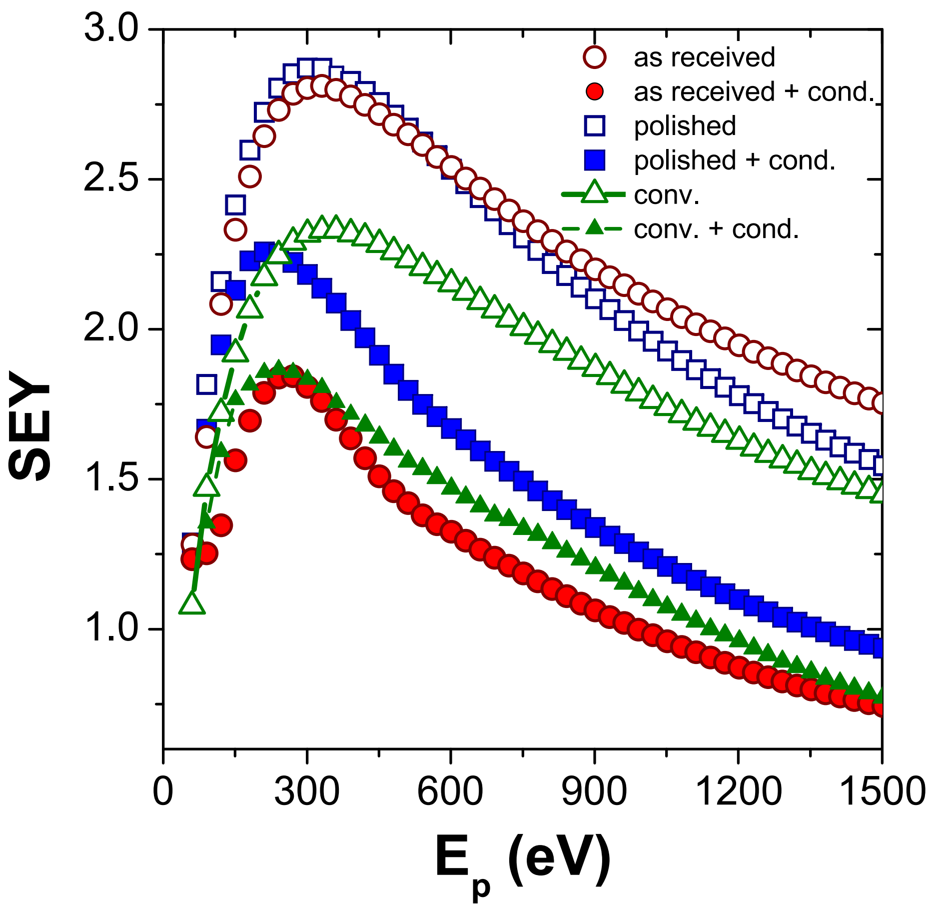
Before conditioning



SEY max of the conventional 316L is lower than the one of AM samples (2.3 vs 2.8)

Secondary Emission Yield

Before conditioning
+ after e- conditioning (E_p=500 eV - Q=$1.5x10^{-2}$ Cb/mm^2)



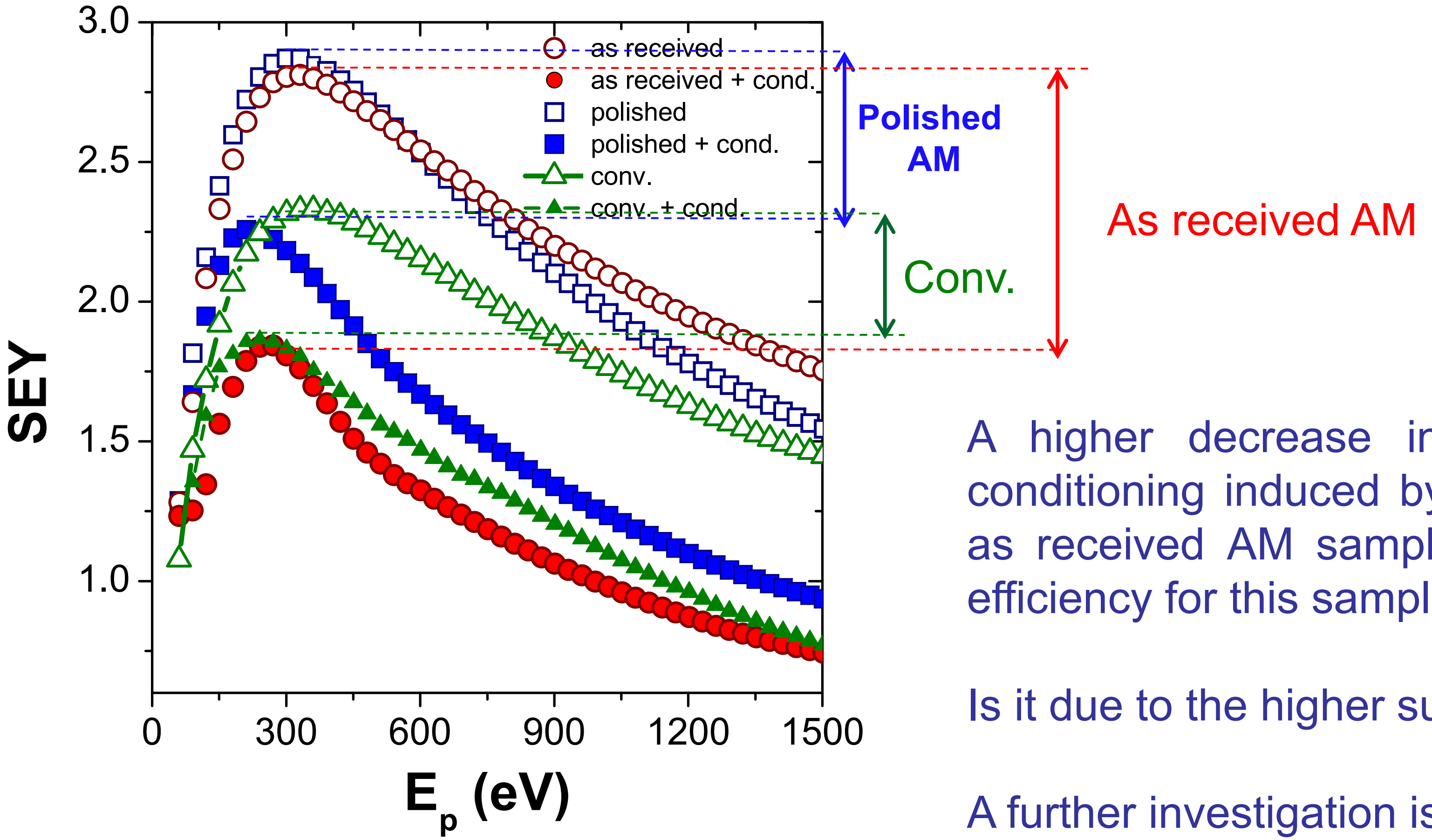
A higher decrease in the SEY due to the surface conditioning induced by the e- beam is observed for the as received AM sample (the surface scrubbing is more efficiency for this sample!)

Is it due to the higher surface roughness for this sample?

A further investigation is needed!

Secondary Emission Yield

Before conditioning
+ after e- conditioning (E_p=500 eV - Q=1.5x10^{-2} Cb/mm^2)



A higher decrease in the SEY due to the surface conditioning induced by the e- beam is observed for the as received AM sample (the surface scrubbing is more efficiency for this sample!)

Is it due to the higher surface roughness for this sample?

A further investigation is needed!

Summarize

- 316 L stainless steel samples were fabricated using AM *via* SLM in order to investigate:
- Anisotropy induced by the manufacturing processing for both microstructure and mechanical properties
- Outgassing (UHV compatible?)
- Secondary Emission Yield

- Using the same method of additive manufacturing (SLM) does not guarantee to get the same properties
  → Problem of reproducibility !
  → Heterogeneity / anisotropy of properties
  → Higher mechanical properties can be reached
  → **It is important to control the conditions of manufacturing !!!**

- Outgassing rates : same values are obtained for AM tubes than for conventional counterparts → **UHV compatible** !

- SEY of AM samples is similar to the one of conventional 316L after electron conditioning of both types of samples

- The high surface roughness of AM components seems not to be a limiting parameter: further investigations are needed!

Is it possible to use additive manufacturing for accelerator UHV beam pipes ?

Yes! But for specific components : e.g. Beam Position Monitors (talk given by N. Delerue Friday morning)

Thank you for your attention !