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

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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)

Main advantages:
- 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
Changing the manufacturing process means changing the material properties!

Ex.: Mechanical properties of 316L stainless steel

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

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

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
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

- **RadioFrequency**
  - Cleanliness?
  - High shape accuracy?
  - Surface roughness?

- **Ultra High Vacuum**
  - Outgassing rate?
  - Leak tightness?

- **Cryogenic**
  - Liquid and supercritical He leak tightness?

- **Beam interactions**
  - Secondary emission yield?
  - Stimulated desorption?

- **Radiation**
  - Radiation damage?
  - Activation?

- **Electromagnetic properties**
  - Impedance?
  - Conductivity?
Specific constraints for particle accelerators

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- Radiation
  - Radiation damage?
  - Activation?

- Electromagnetic properties
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  - Conductivity?

See talk given by N. Delerue Friday morning
Tests of a 3d Printed BPM With a Stretched Wire and With a Particle Beam
1- Reproducibility of properties
   Characterization of microstructure ↔ mechanical properties

2- UHV compatibility: outgassing measurements

3- Secondary Emission Yield measurement
   → Material = 316 L Stainless steel
   → Tests performed on pieces with simple forms
1- Reproducibility of properties
   Characterization of microstructure ↔ mechanical properties

2- UHV compatibility : outgassing measurements

3- Beam interaction : Secondary Emission Yield measurement

   → Material = 316 L Stainless steel

   → Tests performed on pieces with simple forms
Samples for the microstructural study

Material : 316L stainless steel

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

<table>
<thead>
<tr>
<th>Manufacturers</th>
<th>Method</th>
<th>Powder granulometry (μm)</th>
<th>Layer thickness (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>SLM</td>
<td>20 - 125</td>
<td>40</td>
</tr>
<tr>
<td>B</td>
<td>SLM</td>
<td>20 - 50</td>
<td>40</td>
</tr>
<tr>
<td>C</td>
<td>SLM</td>
<td>?</td>
<td>40</td>
</tr>
</tbody>
</table>

Two orientations:
- Parallel
- Perpendicular
Surface quality
Confocal microscopy

Surface roughness is much larger for AM samples than for conventional counterparts → It could be a severe drawback for accelerator applications?
Composition
### Elemental analysis: composition (SEM/EDX)

#### Chemical composition (Weight %)

<table>
<thead>
<tr>
<th></th>
<th>Fe</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Mn</th>
<th>Si</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Std</td>
<td>Compl.</td>
<td>16 - 19</td>
<td>9 - 13</td>
<td>1.5 - 3</td>
<td>&lt; 2</td>
<td>&lt; 1</td>
<td>/</td>
</tr>
<tr>
<td>A</td>
<td>67.4±0.4</td>
<td>17.3±0.2</td>
<td>12.3±0.3</td>
<td>2.2±0.2</td>
<td>0.3±0.2</td>
<td>0.4±0.1</td>
<td>0.2±0.1</td>
</tr>
<tr>
<td>B</td>
<td>63.1±0.4</td>
<td>18.0±0.2</td>
<td>14.7±0.3</td>
<td>2.3±0.2</td>
<td>1.6±0.2</td>
<td>0.4±0.1</td>
<td>/</td>
</tr>
<tr>
<td>C</td>
<td>67.2±0.6</td>
<td>16.2±0.3</td>
<td>11.7±0.5</td>
<td>2.5±0.3</td>
<td>1.9±0.3</td>
<td>0.6±0.1</td>
<td>/</td>
</tr>
</tbody>
</table>

**Al contamination**

**α-stabilizer**

**Homogeneous composition**
Microstructure
Grain morphology and grain size (SEM)

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 = 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 = Preferred orientation

- If grain orientations are fully random = no distinct texture (no color is predominant)
- If a preferred orientation exists = texture (a color dominates)

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°

Horizontal

Tensile axis

Vertical

Tensile axis

Inclined at 45°

Build direction

Build direction

Build direction

45°

Tensile axis

Typical tensile curve

Stress (MPa)

Strain (ε (%))

Yield Strength

Ultimate tensile Strength
Mechanical properties depend on the orientation: they are anisotropic (related to the microstructure anisotropy).

- Inclined specimens exhibit the highest yield strength.
Tensile tests

Mechanical properties depend 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.
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
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: $Ra = 8.5 \, \mu m$ to $10 \, \mu m$.

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

- Tubes are pumped down
- Valve 1 is closed
- Pressure rise is measured by a spinning rotor gauge
Outgassing rates for 100h of pumping after baking under vacuum at 200°C during 72h.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Tube</th>
<th>Outgassing rate (mbar.l/s.cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unbaked</td>
<td>Conventional</td>
<td>6.0x10⁻¹²</td>
</tr>
<tr>
<td></td>
<td>Unlathed AM</td>
<td>5.6x10⁻¹²</td>
</tr>
<tr>
<td></td>
<td>Lathed AM</td>
<td>7x10⁻¹²</td>
</tr>
<tr>
<td>Baked at 200°C</td>
<td>Unlathed AM</td>
<td>3.6x10⁻¹³</td>
</tr>
<tr>
<td></td>
<td>Lathed AM</td>
<td>3.4x10⁻¹³</td>
</tr>
</tbody>
</table>

- 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!
1- Reproducibility of properties
Compare the microstructure of samples delivered by three different manufacturers (SLM)
Characterization of microstructure ↔ mechanical properties

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Secondary Emission Yield

Surface roughness of samples

AM 316L

- as-received: Ra = 9 ± 1 µm
- polished: Ra = 0.35 ± 0.05 µm

Conventional 316L

- 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 ($E_p=500 \text{ eV} - Q=1.5 \times 10^{-2} \text{ Cb/mm}^2$)

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

A further investigation is needed!
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 !