Metal powder and Design
Key elements for SLM process
Ph.D. Pedro Alvarez

Ordizia, 11th December 2014
Role of IK4-LORTEK in MERLIN Project

MERLIN
(8 FP7-AAT-2010-RTD-1)
Development of Additive manufacturing processes by Selective Laser Melting for the aeronautic sector.
Development of Additive manufacturing processes by Selective Laser Melting to produce components for aeronautical engines designed and optimized with less environmental impact.
Validation of methodology of demonstrators for recycling and manufacturing.

Technologies:
Laser metal deposition, LMD.
Selective Laser Melting, SLM.

Material:
Nickel superalloys.

Transport SECTOR

http://www.merlin-project.eu/home/index.jsp
Role of IK4-LORTEK in MERLIN Project

Validation of methodology of demonstrators for recycling (SLM) and manufacturing (SLM & LMD).

<table>
<thead>
<tr>
<th>Directed energy deposition</th>
<th>Powder bed fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire Laser Metal Deposition (LMD wire)</td>
<td>Laser Metal Deposition (LMD)</td>
</tr>
<tr>
<td><img src="image1" alt="Wire Laser Metal Deposition" /></td>
<td><img src="image2" alt="Laser Metal Deposition" /></td>
</tr>
<tr>
<td>Description</td>
<td>Deposition of wire fused using a laser beam in a chamber to produce part. Medium to high build rates.</td>
</tr>
<tr>
<td>Applications</td>
<td>Large scale parts manufacturing and repairing</td>
</tr>
</tbody>
</table>
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  - Key parameter of SLM process
  - Powder quality assessment process
  - Recycling and handling

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  - Topology Optimization VS Fitness for SLM
  - Case study (Inco 718 brackets)
Metal Powder
Key parameters of SLM process

Powder, machine and human factor (1/3 rule)

Powder

Machine

Human factor (Design and part preparation)
Key parameters of SLM process
Why powder quality influences the process?

- Powder must be:
  - fed in a constant and stable way
  - spread in thin and uniform layers
  - melt and solidify
What are main problems related to powder?

**Powder induced process instabilities**
- Defective feeding
- Defective filling of layers
- Porosity in final parts
- Lack of fusion defects
- Convex shapes

**Powder properties**
- Particle size distribution
- Morphology (circularity, satellites)
- Internal porosity
- Chemical composition
- Roughness

**Powder testing**
- Flowability
- Density (tap density)
- Particle cohesiveness
What are main problems related to powder?

- Defective feeding and filling of layers are more critical in new generation of SLM machines:
  - One shot concept: bidirectional powder spreading system (just one movement of wiper)
  - Very short powder deposition times (less than 7 s)

Conventional equipment: “round trip” wiper movement
VS
New generation equipment: “single trip” wiper movement
INCO 718 powder quality assessment process

- Flowability test
- Particle size distribution
- Morphology (particle aspect ratio, satellites)
- Internal porosity
- Humidity
- Chemical composition
- Surface condition: oxides, roughness
INCO 718 powder quality assessment process

Flowability test:

ASTM B213: 50 g of metallic powder through funnel

<table>
<thead>
<tr>
<th>Size range</th>
<th>0-25 µm</th>
<th>0-45 µm</th>
<th>15-45 µm</th>
<th>45-106 µm</th>
<th>45-250 µm</th>
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</thead>
<tbody>
<tr>
<td>Morphology</td>
<td>spherical</td>
<td>spherical</td>
<td>spherical</td>
<td>spherical</td>
<td>spherical</td>
</tr>
<tr>
<td>Size distribution</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d10</td>
<td>7 µm</td>
<td>15 µm</td>
<td>20 µm</td>
<td>50 µm</td>
<td>60 µm</td>
</tr>
<tr>
<td>d50</td>
<td>15 µm</td>
<td>34 µm</td>
<td>70 µm</td>
<td>144 µm</td>
<td></td>
</tr>
<tr>
<td>d90</td>
<td>22 µm</td>
<td>48 µm</td>
<td>105 µm</td>
<td>225 µm</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Flowability</th>
<th>ASTM B213</th>
<th>&lt; 120 s</th>
<th>&lt; 45 s</th>
<th>&lt; 25 s</th>
<th>&lt; 25 s</th>
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</thead>
<tbody>
<tr>
<td>ASTM B964</td>
<td>x</td>
<td>&lt; 25 s</td>
<td>&lt; 20 s</td>
<td>&lt; 5 s</td>
<td>&lt; 5 s</td>
</tr>
</tbody>
</table>

Typical Physical Properties

Apparent density

<table>
<thead>
<tr>
<th>Apparent density</th>
<th>2.52 g/cm³</th>
<th>2.50 g/cm³</th>
<th>2.55 g/cm³</th>
<th>2.70 g/cm³</th>
</tr>
</thead>
</table>

Flowmeter funnel
INCO 718 powder quality assessment process

Particle size distribution: image analysis of SEM pictures

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>D10</td>
<td>23.36</td>
</tr>
<tr>
<td>D50</td>
<td>37.79</td>
</tr>
<tr>
<td>D90</td>
<td>52.31</td>
</tr>
</tbody>
</table>

25-30 μm

45-50 μm
INCO 718 powder quality assessment process

Morphology: image analysis of SEM pictures

Particle aspect ratio (circularity), satellite, craters
INCO 718 powder quality assessment process

Internal porosity: image analysis of LOM pictures

1.2% internal porosity

0.5% internal porosity
INCO 718 powder quality assessment process

- Humidity
- Chemical composition
- Surface condition: oxides, roughness
INCO 718 powder quality assessment process
INCO 718 powder quality assessment process

SLM in-process performance

Manufacturing of control cubes or cylinders

Powder fulfilling acceptance criteria

Powder out of acceptance criteria
• Recycling and handling

Motivation: Consequences of powder reuse on SLM

Virgin Powder Stock ➔ SLM Fabrication ➔ Powder Storage

Porosity

1 cycle
porosity: 0.11 %

12 cycles
porosity: 0.05 %

Overall it decreases but lacks of fusion increases!

Particle size distribution

Roughness

• Recycling Strategy Description

New powder recycling strategy studied INCO 718

Basic Procedure

Virgin Powder Stock

SLM Fabrication

Powder Storage

Proposed New Strategy

Virgin Powder Stock

Powder Analysis

SLM Fabrication

Mechanical & Metallurgical Analysis

Residual Powder Sieving & Drying

Powder Storage
• Powder analysis (Morphology)

Virgin Powder Feedstock → Powder Analysis

SLM Test Part Fabrication → Mechanical & Metallurgical Analysis

Residual Powder Sieving & Drying → Powder Storage

Iteration

n = 1

SEM images

Particle accretion / aggregates

n = 14

Particle fusion
• Powder analysis (Morphology)

Average particle size slightly increases with iteration despite the recycling procedure.

Particle size distribution **is stable up to 7th iteration.** From this, an increase is observed, yet smaller than a 10% with respect to nominal values.
• Powder analysis (Composition)

EDS measurements

Iteration

n = 1

No traces of oxygen

Virgin Powder Feedstock

Powder Analysis

SLM Test Part Fabrication

Mechanical & Metallurgical Analysis

Residual Powder Sieving & Drying

Powder Storage

EDS measurements

Iteration

n = 14

No traces of oxygen

Powder is not oxidized!
These results were not fully conclusive at this stage.

Small porosity values but... Is there a trend or not?
• Sample analysis (Microstructure)

- Virgin Powder Feedstock
- Powder Analysis
- SLM Test Part Fabrication
- Mechanical & Metallurgical Analysis
- Residual Powder Sieving & Drying
- Powder Storage

- XY section
- Transversal section

- Lave Phase (rich in Nb)
- γ Phase (poor in Nb)

Identical microstructure in each iteration
Sample analysis (Mechanical)

Charpy impact test

Virgin Powder Feedstock → Powder Analysis → SLM Test Part Fabrication → Mechanical & Metallurgical Analysis

Residual Powder Sieving & Drying → Powder Storage

Values are typical for IN718

Small and random variation

Notch
• Conclusions

• Initial Powder Stock: 25 Kg – Samples weight: 10 Kg – Leftovers: 0.6 Kg

• Material use efficiency larger than 95%

• Powder properties do not significantly change during its reutilization with this recycling methodology (in terms of particle size distribution, chemical composition, etc.)

• Samples present very similar mechanical and metallurgical properties, no trends are observed as a function of recycling iterations.

• Confirmation: a new powder recycling methodology for INCO 718 has been validated
Design for SLM
Additive manufacturing enables the production of geometries that were expensive to produce or simply not possible with traditional subtractive processes, i.e. traditional design restrictions do not apply anymore.

Design complexity does not come at additional cost during the production process with additive manufacturing techniques.

(The 85,000 nozzles are for engine orders that will enter full production in late 2015.)
• **Topology Optimization**

  - **Definition**: is a mathematical approach that optimizes material layout within a given design space, for a given set of loads and boundary conditions such that the resulting layout meets a prescribed set of performance targets.

  - **Goal**: Part lightening, production cost/time reduction (by means of additive manufacturing)
Despite SLM has a large freedom of design, there are some design limitations related with the collapse risk.

Support are required in critical details (overhangs,...) in order to avoid collapse.

Supports are hard to remove, costly and sometimes impossible (accessibility).

Topology Optimization VS Fitness for SLM manufacturing
One of the current issues is originated when surfaces below 45 degrees are found in the part because they need supports to avoid distortions.

Supports, while necessary, present several drawbacks: mainly post-processing, poor surface quality, increased production times, increased amount of leftovers, reduced efficiency

Solution: **New design rules for SLM parts!!**

- First Law: Avoid using flat ceilings: **use lancet arcs**
- Second Law: Overhangs must not be flat either: **use 45º planes (or lancet arcs again)**
- Third Law: In general, avoid any kind of surface below 45º inclination angle without supports.
This challenge consisted in using additive manufacturing as the basis for optimizing an existing aircraft engine bracket.

Winner!
This challenge consisted in using additive manufacturing as the basis for optimizing an existing aircraft engine bracket.  

\textbf{Is this really true??}

\begin{itemize}
  \item Case study (INCO 718 brackets)
\end{itemize}

\textbf{Fitness for SLM point of view}

\textbf{Winner!}
• Case study (INCO 718 brackets)

Less support volume required
Supports are accessible for removal

Not always the lightest design is the best one from a SLM manufacturing point of view.
CONCLUSIONS

Correlations between INCO 718 powder characteristics (according to new QA process) and SLM in-process performance have been established.

New powder acceptance criteria for optimum SLM process performance have been defined.

A new INCO718 powder recycling methodology has been validated.

Lightweight possibilities through topology optimization have been analysed but optimum designs must be linked to SLM design rules (fitness for SLM).
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