Powder Bed Fusion
Additive Manufacturing

Prof. Dr. Ir. Jean-Pierre Kruth
KU Leuven university, Belgium
Introducing KU Leuven university

- Located 20 km East of Brussels, Belgium
- Founded anno 1425 as oldest catholic university
- 1970: split between KU Leuven and UCLouvain
- KU Leuven = largest university in Belgium (>30.000 student)
- Long tradition in manufacturing
  - CIRP Intern. Academy for Production Eng.
  - SME Univ. LEAD award (1998)
Introducing AM activities of KU Leuven university

• **Company:** Materialise N.V., Leuven
• Initial activity: producing prototypes in plastics by layerwise Rapid Prototyping techniques
• Spin-off of KU Leuven (Division PMA)
• Start: 1990 (Founder: W. Vancraen)
• Today:
  – Largest RP or AM service bureau
    (>85 RP/AM machines in one location; >300,000 parts/year in 2011)
  – Largest RP/AM software developer a world
• From 2 to 1000 persons
  (2011: Materialise Dental splits off)

1995: *Mammoth Stereolithography machine (build capacity 2200 x 840 x 800mm)*

Laser powder-bed fusion AM
Introducing AM activities of KU Leuven university

**Softwares**

- **Magics**
  (RP, RM, supports, ERP, e-software,...)

- **3-matic**
  (facetted CAD)

- **Mimics**
  (medical)

- **SurgiCase**
  (surgery planning)

- **RSM**
  (hearing aids)

- **Etc.**

Laser powder-bed fusion AM
Introducing AM activities of KU Leuven university

- **Company:** LayerWise N.V., Leuven
- **Field:** RP & AM of metallic products
- **Spin-off of KU Leuven (Division PMA)**
- **Start:** 2008 (Founders: P. Mercelis, J. Van Vaerenbergh)
- **Today:** 45 persons
- **Production:** > 20,000 metallic parts/year (2011)
- **Activities:**
  - Industrial, medical & dental applications (also artwork)
  - Several patents (dental and others)

Laser powder-bed fusion AM
Introducing AM activities of KU Leuven university

- **Company**: Metris N.V., Leuven (since 2009 Nikon Metrology Europe N.V.)
- Spin-off of KU Leuven (Division PMA)
- Start: 1995  (Founders: B. Van Coppenolle, L. De Jonge)
- Today: 1000 persons
- **Activities**: (Reverse engineering), 3D coordinate metrology & quality control
  - 3D CMM, laser scanning probes
  - X-ray CT for measuring [internal & external geometry](#) (tolerances) and [material quality](#) (e.g. porosity)
Materials and Processing Issues in Powder Bed Fusion Additive Manufacturing

Prof. Dr. Ir. Jean-Pierre Kruth
KU Leuven university, Belgium
Laser powder-bed fusion AM: SLS, SLM, ...

- Laser powder-bed fusion system
- Beam deflection system
- Focused and deflected beam
- Powder deposition system
- Energy beam
- Sintered pattern
- Loose powder
- Container

Materials:
- Polymer
- Ferro Metal (Steel)
- Ceramic (Al$_2$O$_3$)
- Composite (Cermet-HM)
- Non-ferro Metal (Ti) (WC-Co infiltrated with Cu)
Classification of binding mechanisms

1. Solid State Sintering
   - 2.1 different binder and structural materials
     - 2.1.1 separate structural and binder particles
     - 2.1.2 composite particles
     - 2.1.3 coated grains particles
   - 2.2 no distinct binder and structural materials

2. Liquid Phase Sintering
   - 2.1 separate structural and binder particles
   - 2.2 single phase material partially molten
   - 2.3 fusing powder mixture

3. Full Melting
   - 3.1 single component single material
   - 3.2 single component alloyed material
   - 3.3 fusing powder mixture

4. Chemically Induced Binding

Laser powder-bed fusion AM
Main binding mechanisms for polymers

Polymers

Binding mechanism classification

1. Solid State Sintering
   - 2.1 different binder and structural materials
     - 2.1.1 separate structural and binder particles
     - 2.1.2 composite particles
     - 2.1.3 coated grains particles
   - 2.2 no distinct binder and structural materials

2. Liquid Phase Sintering
   - 2.2.1 single phase material partially molten
   - 2.2.2 fusing powder mixture

3. Full Melting
   - 3.1 single component single material
   - 3.2 single component alloyed material
   - 3.3 fusing powder mixture

4. Chemically Induced Binding

Polymers

- Polyamide (nylon)
- SLS elastomer

Laser powder-bed fusion AM
Main binding mechanisms for metals

Metals

Binding mechanism classification

1. Solid State Sintering
   2. Liquid Phase Sintering
     Partial Melting
     2.1 different binder and structural materials
     2.1.1 separate structural and binder particles
     2.1.2 composite particles
     2.1.3 coated grains particles
     2.2 no distinct binder and structural materials
     2.2.1 single phase material partially molten
     2.2.2 fusing powder mixture
   3. Full Melting
     3.1 single component single material
     3.2 single component alloyed material
     3.3 fusing powder mixture
   4. Chemically Induced Binding

Steel

Titanium

Laser powder-bed fusion AM
Main binding mechanisms for ceramics

Ceramics

Binding mechanism classification

1. Solid State Sintering
   - 2.1 different binder and structural materials
     - 2.1.1 separate structural and binder particles
     - 2.1.2 composite particles
     - 2.1.3 coated grains particles
   - 2.2 no distinct binder and structural materials
     - 2.2.1 single phase material partially molten
     - 2.2.2 fusing powder mixture

2. Liquid Phase Sintering
   - Partial Melting
     - 3.1 single component single material
     - 3.2 single component alloyed material
     - 3.3 fusing powder mixture
     - 3.4 fusing powder mixture

3. Full Melting
4. Chemically Induced Binding

Alumina
Main binding mechanisms for composites

**Composites (cermets and others)**

**Binding mechanism classification**

1. **Solid State Sintering**
   - 2.1 different binder and structural materials
     - 2.1.1 separate structural and binder particles
     - 2.1.2 composite particles
     - 2.1.3 coated grains particles
   - 2.2 no distinct binder and structural materials
     - 2.2.1 single phase material partially molten
     - 2.2.2 fusing powder mixture

2. **Liquid Phase Sintering**
   - Partial Melting
     - 3.1 single component single material
     - 3.2 single component alloyed material
     - 3.3 fusing powder mixture
   - 3.2 single component alloyed material

3. **Full Melting**

4. **Chemically Induced Binding**

**Examples:**
- WC-Co (+ Cu) Cermet/HM
- Cu-PA mold
- Laser powder-bed fusion AM
Main binding mechanisms for polymers

**Polymers**

**Binding mechanism classification**

1. Solid State Sintering
   - 2.1 different binder and structural materials
     - 2.1.1 separate structural and binder particles
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3. Full Melting
   - 3.1 single component single material
   - 3.2 single component alloyed material
   - 3.3 fusing powder mixture

4. Chemically Induced Binding

**Main binding mechanisms for polymers**

- Polymers: Polyamide (nylon), SLS elastomer

Laser powder-bed fusion AM
Main distinction in SLS of polymers

Mainly thermoplastics:
- (Semi-)crystalline
- Amorphous

Main SLS consolidation:
Partial or full melting
Main distinction in SLS of polymers

Mainly thermoplastics:
- (Semi-)crystalline
- Amorphous

Main SLS consolidation:
Partial or full melting

Volume change (shrinkage):

<table>
<thead>
<tr>
<th>PE</th>
<th>TP</th>
<th>Crystalline</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP</td>
<td>Tg</td>
<td>Hard elastic, tough</td>
</tr>
<tr>
<td>PA6</td>
<td>Tg</td>
<td>Hard elastic, brittle</td>
</tr>
<tr>
<td>PS</td>
<td>Tg</td>
<td>Weak elastic</td>
</tr>
<tr>
<td>PMMA</td>
<td>Tg</td>
<td>Viscous melt</td>
</tr>
<tr>
<td>PC</td>
<td>Tn</td>
<td>Amorphous</td>
</tr>
</tbody>
</table>

Temperature (°C)

Tn = Weakening temperature
Tg = Glass transition temperature
Tf = Flow temperature
Tm = Melt temperature

Laser powder-bed fusion AM
Polymers

Main consolidation: Partial or full melting

Major distinction:
• (Semi-)crystalline
• Amorphous

Laser powder-bed fusion AM
Differential Scanning Calorimetry (DSC)
**DSC curve: melting & recrystallisation peaks**

- DSC curve for PA12 (Differential Scanning Calorimetry)
Semi-crystalline polymers – DSC curves

Comparison of DSC curves:
- PA12 for SLS (PA 2200)
- PA12 milled
- POM milled

Source: University Erlangen
SLS of Semi-crystalline plastics (e.g. POM)

Transmission light microscopy images of microtome sections

PA (rough surface)  POM (smooth surface)

Source: University Erlangen
**DSC curve: melting & recrystallisation peaks**

- DSC curve for PA12 (Differential Scanning Calorimetry)
### Polymers: types and applications

<table>
<thead>
<tr>
<th>Polymer powder material</th>
<th>Application field</th>
<th>Example</th>
<th>Main properties</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Semi Crystalline Polymers</strong></td>
<td>(Semi-)Rigid polymer parts</td>
<td></td>
<td>Long term useable</td>
</tr>
<tr>
<td>e.g. PA-12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Amorphous Polymer</strong></td>
<td>Investment Casting</td>
<td></td>
<td>Long term useable</td>
</tr>
<tr>
<td>e.g. PS</td>
<td>Lost patterns</td>
<td></td>
<td>Accurate</td>
</tr>
<tr>
<td><strong>Sacrificial Polymers used as binder</strong></td>
<td>Metal or Ceramic Parts</td>
<td></td>
<td>Thermally degradable amorphous polymers</td>
</tr>
<tr>
<td>e.g. PMMA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Filled Semi Crystalline Polymers</strong></td>
<td>Parts with special properties</td>
<td></td>
<td>Long term useable</td>
</tr>
<tr>
<td>e.g. PA-GF, PA-Al, PA-Cu</td>
<td></td>
<td></td>
<td>Can withstand high loads</td>
</tr>
<tr>
<td><strong>Elastomeric Polymers</strong></td>
<td>Elastic parts</td>
<td></td>
<td>Long term useable</td>
</tr>
<tr>
<td>e.g. Polyester</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Polymer-Polymer Blends</strong></td>
<td>Emerging Extreme Applications</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Thermo-setting Polymers</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e.g. epoxy resin</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Polymers 1: Semi-crystalline (e.g. PA12)

Partial or full melting

Loose un-sintered PA-12 powder

Tensile break surface showing some air voids
Polymers 2: Amorphous (e.g. PS)

Partial melting

**Low strength:** only partial consolidation

**Better accuracy:** no sudden shrink (jump) when solidifying (crystalline shrink at $T_m$)

![Loose un-sintered PS powder](image1)

![Tensile break surface showing some air voids](image2)

![Graph showing relative volume vs temperature](graph)
Polymers 3: Debindable polymers (e.g. amorph. PMMA)

Partial melting / LPS

- Thermal debinding (depolymerisation) should occur in furnace at 350°-450°C, while not occurring during SLS
- Suited polymers: PMMA or MMA-BMA co-polymers, PA, PP
- May involve some cross-linkers (thermosetters)

Examples:

- Steel (RapidSteel, Laserform)
- AW glass ceramics (Dalgaro)

Examples:

- Green RapidSteel part
- AW glass ceramic + MMA-BMA

- Powder mixture
- Green part (i.e. after SLS)
- Brown part (i.e. after debinding & firing)
Polymers 4: Reinforced polymers (e.g. PA-GF)

Partial melting / LPS

Loose un-sintered PA-Glass powder

Polyamide + Glass beads

Tensile break surface showing some air voids

Polyamide + Alu beads

Loose un-sintered PA-Al powder (30% Al)

Tensile break surface showing some air voids

Laser powder-bed fusion AM
Polymers 4: Reinforced polymers (e.g. PA-Cu)

Partial melting / LPS

Injection mold made from Cu-filled Polyamide and Polypropylene molded parts (injected at 2.76 MPa and 230°C)
Polymers 4: Reinforced polymers (long fillers)

Polyamide (nylon) with elongated filler

<table>
<thead>
<tr>
<th>Property</th>
<th>DF-M*</th>
<th>3D PA</th>
<th>3D GF</th>
<th>3D AF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength (MPa)</td>
<td>49.00</td>
<td>43.00</td>
<td>27.00</td>
<td>35.00</td>
</tr>
<tr>
<td>Tensile elongation %</td>
<td>5.00%</td>
<td>14.00%</td>
<td>1.50%</td>
<td>1.50%</td>
</tr>
<tr>
<td>Tensile Modulus (MPa)</td>
<td>5376</td>
<td>1586</td>
<td>4068</td>
<td>3960</td>
</tr>
<tr>
<td>HDT [1.82 Mpa]</td>
<td>165</td>
<td>95</td>
<td>134</td>
<td>137</td>
</tr>
</tbody>
</table>

Source: FHSG - Valspar

Source: EMPA SG 1.0kV 4.5mm x200 SE(M)

Elongated fibers (new)

Spherical glass particles (old)

Laser powder-bed fusion AM
Polymers 5: Elastomeric polymer (e.g. polyester)

Partial melting

Polyester-based elastomer

Green part
(i.e. after SLS and without infiltration)

Part after infiltration with polyurethane

Laser powder-bed fusion AM
Polymers 6: Others (polymer blends, thermosets)

• **Polymeric blends**: Partial melting
  – Multiphase materials $\rightarrow$ tuned microstructure!
  – Example 1: mixed PA – HDPE (80/20, 50/50, 20/80 wt%)
  – Example 2: polymer 1 coated with low melting (thermoplastic) polymer 2
    ($T_m < 70^\circ\text{C}$, e.g. polyvinyl acetal, heptadecanoic acid,...)

• **Thermosetting materials**: Chemical binding
  – E.g. mixture epoxy-iron
  – Hydrogen bounds between polar $\text{O}^-$ from resin and $\text{H}^+$ on iron surface

![Diagram of hydrogen bonding](image)
Polymers: Conclusion

• Different classes of polymers covered
  – Semi-crystalline
  – Amorphous
  – Debindable
  – Filled polymers
  – Elastomeric
  – Polymer-polymer blends
  – Thermosetting

• Scope of applicable polymers still limited
  – Still mainly PA (plain or filled)

• Good, but no extreme properties

<table>
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<th>INJECTION</th>
<th>SLS</th>
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<tr>
<td>1</td>
<td>a</td>
</tr>
<tr>
<td>Grivory HTV</td>
<td>Windform PROB</td>
</tr>
<tr>
<td>2</td>
<td>b</td>
</tr>
<tr>
<td>Peek c</td>
<td>DuraForm GF</td>
</tr>
<tr>
<td>3</td>
<td>c</td>
</tr>
<tr>
<td>Peek b</td>
<td>DuraForm Ex</td>
</tr>
<tr>
<td>4</td>
<td>d</td>
</tr>
<tr>
<td>PA 6</td>
<td>DuraForm Flex</td>
</tr>
<tr>
<td>5</td>
<td>e</td>
</tr>
<tr>
<td>PP a</td>
<td>SOMOS 201</td>
</tr>
<tr>
<td>6</td>
<td>f</td>
</tr>
<tr>
<td>PC</td>
<td>DuraForm Flex infiltrated</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Injection</th>
<th>SLS</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Grivory HTV</td>
<td>a</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Peek c</td>
<td>b</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Peek b</td>
<td>c</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>PA 6</td>
<td>d</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>PP a</td>
<td>e</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>PC</td>
<td>f</td>
</tr>
</tbody>
</table>

Laser powder-bed fusion AM
Laser powder-bed fusion AM
Metals 1: Liquid Phase Sintering (different materials)

Binding mechanism classification

1. Solid State Sintering
2. Liquid Phase Sintering
   - Partial Melting
     - 2.1 different binder and structural materials
       - 2.1.1 separate structural and binder particles
       - 2.1.2 composite particles
       - 2.1.3 coated grains particles
     - 2.2 no distinct binder and structural materials
       - 2.2.1 single phase material partially molten
       - 2.2.2 fusing powder mixture
   - Full Melting
3. Chemically Induced Binding

Steel + Cu

WC + Co

WC + Co powder mixture
mech. alloyed WC-Co powder
sintered powder mixture
sintered mech. alloyed WC-Co powder

Laser powder-bed fusion AM
Laser powder-bed fusion AM
Metals 3: Full Melting (e.g. Titanium)

Binding mechanism classification

1. Solid State Sintering
2. Liquid Phase Sintering
   - Partial Melting
     - 2.1 single component single material
     - 2.2 single component alloyed material
     - 3.3 fusing powder mixture
3. Full Melting
   - 3.1 single component single material
   - 3.2 single component alloyed material
   - 3.3 fusing powder mixture
4. Chemically Induced Binding

Laser powder-bed fusion AM

Scan speed (mm/sec)

- 190
- 140
- 90

Density

- 96.92 %
- 95.11 %
- 99.71 %
- 99.54 %
- 99.83 %
- 99.98 %

Laser power = 95 W
Layer thickness = 30 µm

Ti6Al4V

Pure Ti (CP Ti)

KATOLIEKE UNIVERSITEIT LEUVEN

Density

Scan space (mm)

- 0.120
- 0.140

Overlap (%)

- 40
- 30

500 µm
Metals 3: Full Melting (e.g. Titanium)

Binding mechanism classification

1. Solid State Sintering
2. Liquid Phase Sintering Partial Melting
3. Full Melting
4. Chemically Induced Binding

3.1 single component
- single material
3.2 single component
- alloyed material
3.3 fusing powder mixture

Ti6Al4V

<table>
<thead>
<tr>
<th>Ti6Al4V</th>
<th>SLM</th>
<th>Bulk annealed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [kg/m³]</td>
<td>4415 ≈</td>
<td>4430</td>
</tr>
<tr>
<td>Hardness [Vickers]</td>
<td>405 &gt;</td>
<td>350</td>
</tr>
<tr>
<td>Yields strength [MPA]</td>
<td>1125 &gt;</td>
<td>1035</td>
</tr>
<tr>
<td>UTS [MPa]</td>
<td>1250 &gt;</td>
<td>1035</td>
</tr>
<tr>
<td>Elongation [%]</td>
<td>6 &lt;</td>
<td>11</td>
</tr>
<tr>
<td>E modulus [GPa]</td>
<td>94 &lt;</td>
<td>114</td>
</tr>
</tbody>
</table>

Ti dental frame

Laser powder-bed fusion AM
Metals 3: Full Melting (e.g. Fe alloys)

Binding mechanism classification

1. Solid State Sintering
2. Liquid Phase Sintering
   - Partial Melting
3. Full Melting
   - 3.1 single component single material
   - 3.2 single component alloyed material
   - 3.3 fusing powder mixture
4. Chemically Induced Binding

Stainless steel 316

Fe-Fe3P-Ni-Cu powder mixture

Track direction y

Track direction x

50 μm
Metals 4: Chemical binding (e.g. Al, reinforced Cu)

Binding mechanism classification

1. Solid State Sintering
2. Liquid Phase Sintering
   2.1.1 separate structural and binder particles
   2.1.2 composite particles
   2.1.3 coated grains particles
   2.2.1 single phase material partially molten
   2.2.2 fusing powder mixture
2.2. no distinct binder and structural materials
3. Full Melting
4. Chemically Induced Binding

Cu-based composite:

Cu + Ti + C → TiC + heat for fusing Cu

SLS of Aluminium:

Chemically bounded skeleton in N₂ atmosphere:

After infiltration with eutectic Al-13.8Si-4.7Mg infiltrant:
# Mechanical properties of metals

(${}^*\text{ Conventional material (not heat treated)}$)

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Hardness</th>
<th>Charpy Impact</th>
<th>E-modulus</th>
<th>Tensile Strength</th>
<th>Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium alloy Ti6Al4V</td>
<td>410HV (396HV)*</td>
<td>11,5±0,5J (21J)*</td>
<td>96GPa (114GPa)*</td>
<td>1250MPa (1170MPa)*</td>
<td>6% (14%)</td>
</tr>
<tr>
<td>Stainless Steel 316L</td>
<td>59,2±3,9J (160J)*</td>
<td></td>
<td></td>
<td>719MPa (515MPa)*</td>
<td>51% (60%)</td>
</tr>
<tr>
<td>Maraging Steel 18Ni300</td>
<td>390HV (324HV)*</td>
<td>10,1±1,4J (18J)*</td>
<td>163GPa (180GPa)*</td>
<td>1290MPa (1000MPa)*</td>
<td>1,6% (12%)*</td>
</tr>
<tr>
<td>Aluminium alloy AlSi10Mg</td>
<td>127HV (86HV)*</td>
<td></td>
<td>56GPa (71GPa)*</td>
<td>396MPa (317MPa)*</td>
<td>2,75% (3,5%)*</td>
</tr>
<tr>
<td>Tool steel M2</td>
<td>760HV (250HV)*</td>
<td></td>
<td>110GPa (150GPa)*</td>
<td>300MPa (750MPa)*</td>
<td>0,35% (15%)*</td>
</tr>
<tr>
<td>Tantalum (Cold Worked)*</td>
<td>207HV (200HV)*</td>
<td></td>
<td>168GPa (186Gpa)*</td>
<td>513MPa (900MPa)*</td>
<td>29%</td>
</tr>
<tr>
<td>Cobalt Chroom</td>
<td>392HV (477HV)*</td>
<td></td>
<td>169GPa (207GPa)*</td>
<td>963MPa (925MPa)*</td>
<td>20% (5%)*</td>
</tr>
</tbody>
</table>

*Other materials: Ni alloys (Inconel, Hastelloy), Pure CP-Ti, β-Ti, Nitinol, W, …*
### Mechanical properties: microstructure

<table>
<thead>
<tr>
<th>Ti6Al4V</th>
<th>CoCrMo</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Micro</strong></td>
<td></td>
</tr>
<tr>
<td>• Fine, needle-like martensitic $\alpha'$</td>
<td>• Fine, cellular $\alpha$-Co</td>
</tr>
<tr>
<td>• HCP</td>
<td>• FCC</td>
</tr>
<tr>
<td><img src="image1" alt="Ti6Al4V microstructure" /></td>
<td><img src="image2" alt="CoCrMo microstructure" /></td>
</tr>
<tr>
<td><strong>Macro (side view)</strong></td>
<td></td>
</tr>
<tr>
<td>• Elongated prior $\beta$ grains in the build direction</td>
<td>• Melt tracks clearly visible in both side and top view</td>
</tr>
<tr>
<td><img src="image3" alt="Ti6Al4V macro structure" /></td>
<td><img src="image4" alt="CoCrMo macro structure" /></td>
</tr>
</tbody>
</table>
### Mechanical properties – Heat treatments

#### Heat treatments after SLM of Ti6Al4V

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>540</td>
<td>5</td>
<td>WQ</td>
<td>112.6 ± 30.2</td>
<td>1118 ± 39</td>
<td>1223 ± 52</td>
<td>5.36 ± 2.02</td>
</tr>
<tr>
<td>2</td>
<td>850</td>
<td>2</td>
<td>FC</td>
<td>114.7 ± 3.6</td>
<td>955 ± 6</td>
<td>1004 ± 6</td>
<td>12.84 ± 1.36</td>
</tr>
<tr>
<td>3</td>
<td>850</td>
<td>5</td>
<td>FC</td>
<td>112.0 ± 3.4</td>
<td>909 ± 24</td>
<td>965 ± 20</td>
<td>- (premature failure)</td>
</tr>
<tr>
<td>4</td>
<td>1015</td>
<td>0.5</td>
<td>AC</td>
<td>114.9 ± 1.5</td>
<td>801 ± 20</td>
<td>874 ± 23</td>
<td>13.45 ± 1.18</td>
</tr>
<tr>
<td></td>
<td>843</td>
<td>2</td>
<td>FC</td>
<td>114.9 ± 1.5</td>
<td>801 ± 20</td>
<td>874 ± 23</td>
<td>13.45 ± 1.18</td>
</tr>
<tr>
<td>5</td>
<td>1020</td>
<td>2</td>
<td>FC</td>
<td>114.7 ± 0.9</td>
<td>760 ± 19</td>
<td>840 ± 27</td>
<td>14.06 ± 2.53</td>
</tr>
<tr>
<td>6</td>
<td>705</td>
<td>3</td>
<td>AC</td>
<td>114.6 ± 2.2</td>
<td>1026 ± 35</td>
<td>1082 ± 34</td>
<td>9.04 ± 2.03</td>
</tr>
<tr>
<td>7</td>
<td>940</td>
<td>1</td>
<td>AC</td>
<td>115.5 ± 2.4</td>
<td>899 ± 27</td>
<td>948 ± 27</td>
<td>13.59 ± 0.32</td>
</tr>
<tr>
<td></td>
<td>650</td>
<td>2</td>
<td>AC</td>
<td>115.5 ± 2.4</td>
<td>899 ± 27</td>
<td>948 ± 27</td>
<td>13.59 ± 0.32</td>
</tr>
<tr>
<td>8</td>
<td>1015</td>
<td>0.5</td>
<td>AC</td>
<td>112.8 ± 2.9</td>
<td>822 ± 25</td>
<td>902 ± 19</td>
<td>12.74 ± 0.56</td>
</tr>
<tr>
<td></td>
<td>730</td>
<td>2</td>
<td>AC</td>
<td>112.8 ± 2.9</td>
<td>822 ± 25</td>
<td>902 ± 19</td>
<td>12.74 ± 0.56</td>
</tr>
</tbody>
</table>

WQ = water quenching. AC = air cooling. FC = furnace cooling.

Treatment 6 to 8 are well known Ti6AL4V heat treatments [26].

Samples for treatment 3 were built in a different batch: building errors led to premature failure of components.
**Mechanical properties – Toughness and fatigue**

Ti6Al4V: ductility, toughness & fatigue (without thermal treatment)

- **Charpy V-notch:** the roughness of SLM parts does NOT act as a stress concentrator.
  - SLM: $11.5 \pm 0.5$
  - Investment cast: 15-19
  - Wrought: 15-20

- **Fracture toughness:** (ongoing research)
  - $K_{IC}$ [MPa√(m)]
    - SLM: 52
    - Cast: 70-100
    - Wrought: 65-70

- **Fatigue:** (ongoing research)
  - HCF limit [MPa]
    - SLM: >250
    - Cast: >200
    - Wrought: >400

- **Crack growth rate**
Ceramics

Binding mechanism classification

1. Solid State Sintering
   - 2.1 different binder and structural materials
     - 2.1.1 separate structural and binder particles
     - 2.1.2 composite particles
     - 2.1.3 coated grains particles
   - 2.2 no distinct binder and structural materials

2. Liquid Phase Sintering
   - Partial Melting
     - 2.2.1 single phase material partially molten
     - 2.2.2 fusing powder mixture

3. Full Melting
   - 3.1 single component single material
   - 3.2 single component alloyed material
   - 3.3 fusing powder mixture

4. Chemically Induced Binding

Examples:
- Al₂O₃, ZrO₂, or eutectic mixture
- Micro SLS of SiC
- Transparent Ta₂O₅ dielectric ceramic
- SiO₂ investment casting shells
- HA biocompatible medical implants
- TCP/Glass biocompatible implants
- Bismuth-titanate (Bi₄Ti₃O₁₂) radiation detectors
- Bismuth-germanate (Bi₄Ge₃O₁₂)
## Ceramics: Classification

### Major distinction:

<table>
<thead>
<tr>
<th>Ceramic type</th>
<th>Main Consolidation type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Silicate ceramics</strong></td>
<td>• Liquid Phase Sintering</td>
</tr>
<tr>
<td></td>
<td>• Partial Melting</td>
</tr>
<tr>
<td></td>
<td>• Full melting</td>
</tr>
<tr>
<td><em>Multi-phase material</em> made from clay, kaolin, silicate carriers (feldspar, soapstone) (+ Al(_2)O(_3), ZrSiO(_4))*</td>
<td></td>
</tr>
<tr>
<td><strong>Oxide ceramics</strong></td>
<td>• Solid State Sintering</td>
</tr>
<tr>
<td></td>
<td>• Partial Melting</td>
</tr>
<tr>
<td></td>
<td>• Full melting</td>
</tr>
<tr>
<td><em>90% single phase / single component metal oxides</em></td>
<td></td>
</tr>
<tr>
<td>(Al-oxide, Mg-oxide, Zr-oxide, Al-titanate, Piezo-ceramic)</td>
<td></td>
</tr>
<tr>
<td><strong>Non-oxide ceramics</strong></td>
<td>• Chemical Induced Binding</td>
</tr>
<tr>
<td></td>
<td>• Partial Melting</td>
</tr>
<tr>
<td></td>
<td>• Full melting</td>
</tr>
<tr>
<td><em>Si and Al, with N or C</em></td>
<td></td>
</tr>
<tr>
<td>• Carbide ceramics</td>
<td></td>
</tr>
<tr>
<td>• Nitride ceramics</td>
<td></td>
</tr>
</tbody>
</table>
Ceramics: Classification

Binding mechanism classification

1. Solid State Sintering
   2. Liquid Phase Sintering
      2.1 different binder and structural materials
         2.1.1 separate structural and binder particles
         2.1.2 composite particles
         2.1.3 coated grains particles
      2.2 no distinct binder and structural materials
         2.2.1 single phase material partially molten
         2.2.2 fusing powder mixture
   2. Liquid Phase Sintering / Partial melting
   3. Full Melting
      3.1 single component single material
      3.2 single component alloyed material
      3.3 fusing powder mixture
   4. Chemically Induced Binding

1. Solid State Sintering
   2a. SLS using sacrificial polymer binder
   2b. Liquid Phase Sintering / Partial melting
   2c. SLS of ceramic slurry
   3. Selective Laser Melting
   4. Chemical or self-induced binding
Selective laser processing of ceramics (e.g. Al$_2$O$_3$)

- **Indirect SLS** of e.g. Al$_2$O$_3$ (partial melting of polym. binder)

- Densification strategies
  - infiltration of green/brown/final parts with highly loaded Al$_2$O$_3$ suspensions
  - isostatic pressing of green parts

- Final Al$_2$O$_3$ densities after applying densification strategies
  - Carnauba wax: 75% => under investigation
  - PS: 66% => 85%
  - PA (ball milled): … => 94% (bad geometrical accuracy)
  - PA: 48% => 71%
  - PP: 48% => 82% (bending strength: 96 MPa)

It's only the beginning. Further improvements are expected!!

Laser powder-bed fusion AM
Selective laser processing of ceramics (e.g. Al₂O₃)

- E.g.:
  - **Powder synthesis**
    - 40 vol% Al₂O₃
    - 60 vol% PP

  → SLS → debinding (deb.) & furnace SSS

  - **Green density:** 48%
  - **Density:** 38%

  *97% with carnauba wax

- **Powder synthesis**
  - 40 vol% Al₂O₃
  - 60 vol% PP

  → SLS → WIP 120°C → debinding & furnace SSS

  - **Green density:** 48%
  - **Green density:** 86%
  - **Density:** 63%

- **Powder synthesis**
  - 40 vol% Al₂O₃
  - 60 vol% PP

  → SLS → **Infiltration**
    - 40 vol% Al₂O₃
    - 60 vol% ethanol

  → deb. → **Infiltration**
    - 40 vol% Al₂O₃
    - 60 vol% ethanol

  → SSS

  - **Density:** 48%
  - **Density:** 82%
Selective laser processing of ceramics (e.g. Al₂O₃)

- **Direct SLM** of Al₂O₃ (full melting of ceramic itself, without polymer binder)

### Requirements:
- high packing density of sub micrometer particles (>50% Al₂O₃)
- preheating > 800°C
- no full melting

Experimental setup for direct SLS of Al₂O₃ under development…

Laser powder-bed fusion AM
**Ceramics: SLS of ceramic slurries**

**Principle:**
- Replacing dry powder by slurry with smaller ceramic particles (high green density)
- Additional “drying” step, before “laser sintering”: capillary forces increase packing

**Example (Univ. Clausthal):**
- **Hydroxyapatite + H₂O**
  (up to 66% solid loading)
- **Al₂O₃/SiO₂ + H₂O**
  - binder free, highly loaded slurry + drying + SLS
  - low melting SiO₂ + reaction sintering with Al₂O₃

---

**Diagram:**
- **Deposition**
  - Slurry deposition
  - Sintered and unsintered layers

- **Sintering**
  - Laser sintering

- **Re-coating**
  - 1 Spray nozzle
  - 2 Heat source
  - 3 Laser beam

- **Drying**
  - 4 Layer thickness

- **Lowering platform**

---

Laser powder-bed fusion AM
Ceramics: Chemically and Self-induced binding

Principle:
• Induce chemical reaction that binds powder particles

Examples:
- SiC $\rightarrow$ disintegration SiC $\rightarrow$ Si + C
  - Si + O$_2$ $\rightarrow$ SiO$_2$ binder for SiC
  - infiltration with Si + reaction bounded
- CuO + Al $\rightarrow$ Al$_2$O$_3$ + Cu
  • Heat comes from laser + exothermal reaction
  • Self propagation controlled by addition of Cu
- Ti + Al $\rightarrow$ TiAl
  • Heat comes from laser + exothermal reaction
  • Self propagation controlled by addition of TiAl
- Also tested: TiC-Al$_2$O$_3$ (mixture of TiO$_2$, Al and C; self-propagating), ZiSiO$_4$, MoSi$_2$
Composites

SLS/SLM well suited for all kind of composites:

- polymer-metal (e.g. PA-Cu, PA-Al)
- polymer-ceramic (e.g. PE-HA, PCL-HA, PS-Al$_2$O$_3$)
- polymer-glass (e.g. PA-GF)
- metal-metal (e.g. Fe-Cu)
- metal-ceramic (e.g. WC-Co, Cu-TiC-TiB$_2$, Al$_2$O$_3$-Cu)
- …

Liquid Phase Sintering

Chemical binding from mixture of CuO and Al

Chemical binding from mixture of Cu, Ti and B$_4$C

Mixed

Coated (no agglomeration; uniform distribution)

Composite powder (uniform; no agglomeration; possible problems with fibers)
Conclusion

- Laser powder-bed fusion is may be the most versatile AM technology
- It basically allows processing any material:
  - **Polymers** (semi-crystalline, amorphous, elastomeric, thermosetting)
    - Although 20 years old, **still very limited pallet of polymers** (few semi-crystalline polymers)
    - Even with PA11-12, **density needs improvement** (still 5…8% porosity)
  - **Metal** (ferro, non-ferro, reactive,…)
    - Pallet is increasing rapidly
    - Density mostly above 99 to 99.8% (even up to 99.95% for several materials)
  - **Ceramics**
    - Still under development
    - **OK for porous parts** (filters and scaffolds), but **too low for structural parts** (94..97%)
  - **Composites** (polymer-metal, polymer-ceramic, metal-ceramics, metal-metal, reinforced)
    - All kind of composites feasible (see above)
    - Technologically possible, but few industrial applications so far.

Further developments may take decades, but this was also the case for subtractive and forming processes that have been developed for centuries.
Laser powder-bed fusion AM: SLS, SLM, …

Thank you for your attention