Processability of Cu and Cu-alloys with laser beam melting: Influence of powder coating and alloying elements

Dario Tiberto, Ulrich E. Klotz, Franz Held

fem | Research Institute for Precious Metals + Metals Chemistry
Katharinenstrasse 17
73525 Schwaebisch Gmuend, Germany

www.fem-online.de
Overview

- The additive manufacturing process
- The role of alloy properties in the AM process
- Effects of alloy composition and process parameters on porosity
- Effects of metallic and non-metallic coating on Cu powders
- Summary
- Outlook
Laser beam melting machine

Concept Laser Mlab cusing R

› Suitable for gold, CoCr, steel, bronze, titanium, nickel alloys
› Chamber size: 90x90x80 mm
› Atmosphere: Argon
› Laser power: 100 W (1064nm, cw)
› Spot size: 30 µm

⇒ Low energy density for copper alloys
Working principle of selective laser beam melting

- Layer based manufacturing process
- Every powder layer is selectively melted and joined to the previous one
- Powder size 10-45µm
- Layer thickness 10-25µm
Recent studies on additive manufacturing of copper alloys

- **EBM**: good welding, but high surface roughness
- **SLM**: requires high laser power for pure Cu (800-1000W)
- Current studies focus on 99.9% Cu and bronze
- Alloying significantly reduces porosity, but also conductivity
- Optimisation of strength and conductivity => CuNiSi alloys

- **CuSn11 by selective laser melting (SLM)**
  Peschke et al., Metall 70 (2016) 438

- **Pure Cu by SLM**
  Ikeshoji et al. JOM 70 (2018) 396

- **Pure Cu tool inserts by SLM**
  Fraunhofer ILT, Aachen, Germany
Typical parameters that influence porosity

Laser process parameters
› Laser energy
› Laser speed
› Scan overlap (hatch distance)

Powder parameters
› Power size distribution
› Layer thickness
› Fluidity

Alloy properties
› Temperature of melting interval
› Melting range ($\Delta T = T_{\text{liq}} - T_{\text{sol}}$)
› Reflectivity at laser wavelength
› Surface tension
› Viscosity
› Segregation behaviour
› Crystallisation formation
› …
# Thermophysical properties of Cu alloys

<table>
<thead>
<tr>
<th></th>
<th>Melting Range [°C]</th>
<th>Conductivity (%IACS)</th>
<th>Reflectivity (at 740nm) [%]</th>
<th>Surface tension [mN/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>1085</td>
<td>100</td>
<td>86,4</td>
<td>1340</td>
</tr>
<tr>
<td>CuSn4</td>
<td>960 – 1060</td>
<td>20,7</td>
<td>83,9</td>
<td>1210</td>
</tr>
<tr>
<td>CuSn5</td>
<td>910 – 1040</td>
<td>19,0</td>
<td>83,5</td>
<td>1182</td>
</tr>
<tr>
<td>CuSn6</td>
<td>900 – 1030</td>
<td>17,2</td>
<td>83,1</td>
<td>1155</td>
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<tr>
<td>CuSn8</td>
<td>875 – 1025</td>
<td>13,8</td>
<td>82,1</td>
<td>1105</td>
</tr>
<tr>
<td>CuSn10</td>
<td>845 – 1010</td>
<td>12,1</td>
<td>80,8</td>
<td>1061</td>
</tr>
<tr>
<td>CuNi1,5Si</td>
<td>1050 – 1070</td>
<td>48,8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CuNi3Si</td>
<td>1060 – 1085</td>
<td>29,0</td>
<td>81,0</td>
<td>1399</td>
</tr>
<tr>
<td>Steel 1.4404</td>
<td>1375 – 1400</td>
<td>2,3</td>
<td>56,0</td>
<td>1800</td>
</tr>
<tr>
<td>TiAl6V4</td>
<td>1630 – 1650</td>
<td>1,0</td>
<td>49,1</td>
<td>1520</td>
</tr>
</tbody>
</table>
Results with copper alloys

- **99.9% copper** shows the expected level of **very high porosity** (26%)
- The porosity decreases with increasing Sn content of the alloy
- Alloys with ≥ 10% Sn show residual porosity below 0.5%

![Porosity images](image_url)

*Tiberto et al., Metall 71 (2017) 452*
Experimental procedure

- Process parameter study on sheet material
  - Determination of melting depth and heat affected zone
  - Material and parameter screening
- Gas atomisation of alloy powders
  - CuNi1.5Si and CuNi3Si
- Classification of powders
  - Sieving: Selection of suitable size range (10-45µm)
  - Air classification: removal of the fine fraction below 5µm
- Manufacturing of test parts
  - Variation of laser speed and hatch distance
  - Variation of layer thickness
  - Use of powder fractions with different size distributions
- Characterisation of test parts
  - Metallography: porosity, microstructure
  - Electric conductivity
  - Hardness
- Manufacturing of electric coils
Powder size distribution

- Three powder batches
  - 5 – 20 µm
  - 10 – 25 µm
  - 10 – 45 µm
- Fine powder tends to agglomerate
- Coarse powder is difficult to melt with low power
The test object
(5x5x3mm)
### Powder properties and layer thickness

<table>
<thead>
<tr>
<th>Powder size</th>
<th>10-45µm</th>
<th>10-25µm</th>
<th>5-20µm</th>
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<tbody>
<tr>
<td>Layer thickness</td>
<td>20µm</td>
<td>20µm</td>
<td>20µm</td>
</tr>
<tr>
<td></td>
<td>15µm</td>
<td>15µm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10µm</td>
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**Processability of Cu and Cu-alloys with LBM**

*Workshop OpP3D, Schwäbisch Gmünd, 05.08.2018*  |  *Dario Tiberto et al.*
Effect of powder size and layer thickness on porosity

- Decreasing porosity with decreasing layer thickness
  - 20µm layer
    - 4-8% porosity
    - High fluctuation of porosity
  - 15µm layer
    - ca. 3% porosity
  - 10µm layer
    - 1-2% porosity
    - Thin powder layers require suitable powder size
Effect of powder layer thickness on porosity

Surface appearance

- **Alloy:** CuNi1,5Si, UNS C19010
- **Gas atomised powder:** 10-25µm
- **Hatch distance:** 36µm
- **Laser speed:** 200mm/s

20µm – 5,8% porosity
15µm – 2,3% porosity
10µm – 1,6% porosity
Effect of powder layer thickness on porosity

Metallographic cross section

- **Alloy: CuNi1,5Si, UNS C19010**
- **Gas atomised powder:** 10-25µm
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Effect of powder layer thickness on porosity

Surface appearance

- **Alloy:** CuNi3Si, UNS C70250
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<th>Porosity</th>
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Effect of powder layer thickness on porosity

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Effect of laser scanning parameters on porosity

CuNi3Si / C70250

- Minimum porosity for hatch distance 25-45µm
- Hatch distance <25µm
  - Balling effect
  - Strong increase of porosity
- Hatch distance >45µm
  - Gap between laser tracks
- Scanning speed
  - Small effect on porosity
  - Optimum speed: 150 – 250 mm/s

Powder size: 10-25µm
Layer thickness: 15µm
Laser power: 95W
Laser speed:
- 75mm/s
- 100mm/s
- 150mm/s
- 200mm/s
- 250mm/s

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Effect of laser scanning parameters on porosity

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- **Gas atomised powder:** 10-25µm
- **Layer thickness:** 15µm
- **Laser speed:** 200mm/s

**Porosity at different Hatch distances:**
- 9µm Hatch distance: 9.6% porosity
- 20µm Hatch distance: 4.2% porosity
- 36µm Hatch distance: 3.0% porosity
Effect of laser scanning parameters on porosity

CuNi3Si / C70250

- **Alloy:** CuNi3Si, UNS C70250
- **Gas atomised powder:** 10-25µm
- **Layer thickness:** 15µm
- **Laser speed:** 200mm/s

Hatch distance 9µm
- 9.6% porosity

Hatch distance 20µm
- 4.2% porosity

Hatch distance 36µm
- 3.0% porosity
Effect of alloy composition on porosity

- Strong effect of Si content on the porosity
- Si lowers the surface tension of the alloy and increases its wettability
- The molten tracks are wider and smoother
- The porosity is reduced
- The use of finer powder size allows a further porosity reduction

![Graph showing the effect of Si content on porosity](image)

- Cu
- CuNiSiCr
- CuNi1.5Si
- CuNi3Si

Porosity [%] vs Si Content [mass%]
Effect of alloy composition on porosity

- Powder fraction: 10-45 µm
- Hatch distance: 36 µm
- Layer thickness: 20 µm
- Laser speed: 200 mm/s

<table>
<thead>
<tr>
<th>Alloy Composition</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Cu</td>
<td>25.4%</td>
</tr>
<tr>
<td>CuNiSiCr</td>
<td>14.0%</td>
</tr>
<tr>
<td>CuNi1.5Si</td>
<td>6.6%</td>
</tr>
<tr>
<td>CuNi3Si</td>
<td>5.5%</td>
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Comparison of CuNi1.5Si and CuNi3Si

Effect of process parameters

- Gas atomised powder: 10-45µm
- Layer thickness: 20µm
- Laser speed: 200mm/s

- Gas atomised powder: 10-25µm
- Layer thickness: 10µm
- Laser speed: 200mm/s

CuNi1,5Si 6,6% porosity
CuNi3Si 5,5% porosity
CuNi1,5Si 1,6% porosity
CuNi3Si 1,3% porosity
Microstructure and properties

Test plates for hardness and conductivity testing

> Process parameters
  - Layer thickness 15 µm
  - Laser speed 200 mm/s

Hatch distance 36 µm
Resulting porosity 6 %

As manufactured

<table>
<thead>
<tr>
<th>1000 µm</th>
</tr>
</thead>
</table>

Solution annealed

| 1000 µm |
Comparison of manufacturing processes

Effect of heat treatment

- Comparison of sheet, cast and AM material
  - Sheet material as benchmark
  - Porosity of AM part was about 6%

- Effect of heat treatment
  - AM condition similar to SA condition
  - Pronounced hardening from the as-manufactured or SA condition
  - Similar hardness but lower conductivity than sheet material

- Properties of AM part exceed cast part despite the high porosity
Application of AM copper parts

*Coils for highly efficient electric motors*

- Iron-free motor design with optimised coil geometry
- Light weight design and high efficiency for mobile applications
Application of AM copper parts

*Coils for highly efficient electric motors*

Metallographic cross section

- Thin sections (~0,2mm) show higher porosity than thicker ones
- The geometry reaches the limits of the process
- Optimisation of wall thickness can reduce the porosity
Application of AM copper parts

*Coils for highly efficient electric motors*

Metallographic cross section

- Thin sections (~0,2mm) show higher porosity than thicker ones
- The geometry reaches the limits of the process
- Optimisation of wall thickness can reduce the porosity

0,2mm thickness

0,5mm thickness
Summary – Effects of alloying and process parameters

- Copper alloys are challenging for laser based additive manufacturing
  - High reflectivity
  - High thermal conductivity
- Alloying significantly improves processability
  - Effect on melting range, conductivity and reflectivity
- High energy densities are required
  - Small laser spot size
  - Thin powder layers
  - Small powder particles

- Applications are complex heat exchangers, electric parts, etc.
- Geometry needs to be optimized for the process
- Properties of AM parts exceed those of cast parts
- Further reduction of porosity requires higher laser power
Effect of powder coating

*Optimised, coated powders with low reflectivity*

- Cu shows 99% reflectivity at 1064nm wavelength
- Objectives:
  - Reduction of reflectivity
  - Increase of absorbed laser power
  - Reduction of porosity
- Approach:
  - Coating of copper powder with metallic and non-metallic elements
  - With Ti → Magnetron sputtering (performed by Materia Nova)
  - With S → Isopiestic sulfidation (performed by Fraunhofer Umsicht)
Effect of powder coating with Ti

SEM Investigation on coated powder
Effect of powder coating with Ti

FIB Investigation on coated powder

1st Coating trial - irregular Ti thickness
2nd coating Continuous Ti thickness
Effect of powder coating with Ti

Reduction of laser reflectivity results in lower porosity

99.9% Cu  
(23% porosity)  

Irregular Ti coating  
(18% porosity)  

Continuous Ti coating  
(3.5% porosity)
Effect of powder coating with S
SEM / FIB Investigation on coated powder

Processability of Cu and Cu-alloys with LBM | Workshop OpP3D, Schwäbisch Gmünd, 05.08.2018 | Dario Tiberto et al. | 34
Effect of powder coating with S

Reduction of laser reflectivity results in lower porosity

Pure Cu-powder
23.4% Porosity

Cu-Powder coated with S
15.8% Porosity
Summary & Outlook – Effects of powder coating

- The powder coating approach was successful
- Treated powders show an increased processability
  - Reduction of reflectivity
  - Enhanced energy absorption
- The density of parts built with Ti-coated powder increased significantly
- Further optimisation of the coating regularity and thickness is needed to improve the results

Future development is towards surface modified powders
- Plasma coating with low reflectivity
- Great freedom in alloy design
- In-situ formation of an age-hardenable alloy
- Production of alloys that cannot be processed by conventional metallurgy (e.g. immiscible systems)
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Thank you very much!

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