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Motivation

Additive Manufacturing (AM)

- Near-net-shape fabrication of complex parts
- Compared to casting fine-grained structures due to layer by layer build up
  - in a powder bed (SLM)
  - with a powder feed nozzle (LMD)
- High cooling rate \((10^4 \text{ – } 10^6 \text{ K/s})\) of laser processes (casting \(1 \text{ – } 10 \text{ K/s}\))
Motivation

Why iron aluminide?

- Substitution of Ni-based alloys and high alloyed steels
- Advantages
  - Relatively low density
  - Good corrosion and oxidation resistance
  - Good strength at high temperature
- Use in turbine parts
  - Heat shield
  - Turbine blade
- Lightweight production for aerospace industry
Fe-Al alloys

Alloys investigated

- Fe-28Al
- Fe-30Al-10Ti
- Fe-22Al-5Ti
  - Solid solution hardening
  - Stabilization of D0₃ structure at higher temperatures → L₂₁ (Heusler phase)
- Fe-30Al-5Ti-0.7B
  - Fixing of grain boundaries by titanium borides
Experimental Setups

Laser Metal Deposition (LMD) - principle

- Laser beam melts additive material (powder) and thin layer of substrate
- After solidification a layer is created with fine microstructure and metallurgical bonding to substrate
- Volumes can be built by multi layer deposition

- Particle size of powder: 45 - 90 µm
- Substrate material: stainless steel (1.4301)
Experimental Setups

Selective Laser Melting (SLM) - principle

- particle size of powder: 20 - 45 μm
- substrate material:
  → stainless steel (1.4301)
Additive Manufacturing / SLM & LMD

SLM and LMD are complementary

**Selective Laser Melting**

**Laser Metal Deposition**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>SLM</th>
<th>LMD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>• Monolithic</td>
<td>• Monolithic</td>
</tr>
<tr>
<td></td>
<td>• Gradient, hybrid</td>
<td></td>
</tr>
<tr>
<td>Part dimensions</td>
<td>limited by the process chamber (ø: 400 mm, height: 500 mm)</td>
<td>limited by the handling system</td>
</tr>
<tr>
<td>Part complexity</td>
<td>nearly unlimited</td>
<td>limited</td>
</tr>
<tr>
<td>Build-up rate</td>
<td>1 - 20 mm³/s</td>
<td>3 - 140 mm³/s</td>
</tr>
<tr>
<td>Build-up on</td>
<td>• flat surface</td>
<td>• 3D-surface</td>
</tr>
<tr>
<td></td>
<td>• flat preforms</td>
<td>• on existing parts</td>
</tr>
</tbody>
</table>

Unique process characteristics for both:

- Rapid heating and cooling ($10^3 - 10^6$ K/s)
- Unique (cyclic) thermal history
- Local metallurgy (melt pool size of a few mm³)
LMD – Fe-30Al-10Ti

Variation of pre-heating temperature

Volumes built with pre-heating temperatures of 600 – 800 °C

- **T = 600°C**
  - Porosity: 0.81%
  - Cracks

- **T = 700°C**
  - Porosity: 0.34%
  - No cracks

- **T = 800°C**
  - Porosity: 0.43%
  - Small cracks in the edge area (first 4 layers)

→ No cracks within the volumes built at > 700 °C
→ Small cracks in the edge area (first 4 layers)
SLM – Fe-28Al

Parameter study to achieve dense volumes

Density decreases with increasing scan rate
Density decreases with increasing laser power
Density > 99.5% achievable
Results – Fe-Al-Ti and Fe-Al-Ti-B

Influence of Ti and TiB on pre-heating temperature (SLM)

- Reduction of Ti decreases brittle-to-ductile transition temperature (BDTT)
- TiB leads to further decrease of pre-heating temperature for crack-free samples
- Density of > 99.5% is achieved
Results – Fe-Al-Ti and Fe-Al-Ti-B

Influence of Ti and TiB on pre-heating temperature

<table>
<thead>
<tr>
<th>Alloy</th>
<th>LMD</th>
<th>SLM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe-28Al</td>
<td>200 °C</td>
<td>600 °C</td>
</tr>
<tr>
<td>Fe-30Al-10Ti</td>
<td>700 °C</td>
<td>800 °C</td>
</tr>
<tr>
<td>Fe-22Al-5Ti</td>
<td>(&gt; 400 °C)</td>
<td>800 °C</td>
</tr>
<tr>
<td>Fe-30Al-5Ti-0,7B</td>
<td>400 °C</td>
<td>600 °C</td>
</tr>
</tbody>
</table>

- Misorientations / internal stresses lead to bigger difference between pre-heating temperature for LMD and SLM
- Addition of Ti increases BDTT
  → Increase of pre-heating temperature for crack-free samples
- Titanium borides decrease BDTT
Material – Fe-28Al

Typical parameters of LMD and SLM[1]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LMD</th>
<th>SLM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam diameter</td>
<td>600 µm</td>
<td>100 µm</td>
</tr>
<tr>
<td>Scan speed</td>
<td>13.3 mm/s</td>
<td>200 mm/s</td>
</tr>
<tr>
<td>Laser power</td>
<td>180 W</td>
<td>200 W</td>
</tr>
<tr>
<td>Layer thickness</td>
<td>300 µm</td>
<td>30 µm</td>
</tr>
<tr>
<td>Pre-heating</td>
<td>200 °C</td>
<td>600 °C</td>
</tr>
<tr>
<td>Density</td>
<td>&gt; 99.5 %</td>
<td>&gt; 99.95%</td>
</tr>
</tbody>
</table>

- Samples are crack-free

Local Solidification Conditions

LMD samples are crack-free at much lower preheating temperatures than SLM samples
-> Significant differences in process conditions
A fundamental understanding of how process parameters relate to solidification conditions is essential for Laser Additive Manufacturing, because these conditions strongly determine the microstructure and thus the functional properties.

**Processing parameters**
- laser power
- scanning velocity
- powder feed rate

**Solidification conditions**
- solidification rate
- cooling rate
- crystal orientation

**Design of experiment**

<table>
<thead>
<tr>
<th>Conventional approach</th>
<th>New approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parametric design for processing parameters</td>
<td>Parametric design for solidification conditions</td>
</tr>
</tbody>
</table>
Modelling LMD
Comparison experimental and computed results

Melt pool surface in longitudinal and cross section of single track

Good agreement of experimental and computed details of the geometry of the melt pool surface

Ni-based alloy
Local Solidification Conditions

Solidification conditions change along the front

\[ \dot{T} = v_{EG} \times G \]

Solidification rate
Temperature gradient
Cooling rate
Local Solidification Conditions

LMD: Build-up strategy influences crystal growth direction...

Fe-28Al
Local Solidification Conditions

...but not necessarily crystal orientation
Local Solidification Conditions

Crystal growth as a factor of build-up strategy

Strategy: Unidirectional 2

Fe-28Al
Local Solidification Conditions

Crystal growth as a factor of build-up strategy

Strategy: Unidirectional 4

![Diagram of unidirectional strategy](image)

Strategy: Meander

![Diagram of meander strategy](image)
Local Solidification Conditions

Effect of parameters for SLM

Decreasing cooling rate
coarse (and elongated) grains

- $P = 300 \, \text{W}$
  $v = 1000 \, \text{mm/s}$

- $P = 275 \, \text{W}$
  $v = 750 \, \text{mm/s}$

- $P = 200 \, \text{W}$
  $v = 500 \, \text{mm/s}$

Fe-28Al

300 µm

300 µm

300 µm
Comparison LMD – SLM

Geometry of the melt pool

Fe-28Al

- Smaller and longer melt pool for SLM
- Stronger curveture of the liquid-solid interface in LMD
Comparison LMD – SLM

Simulation of solidification rate $v_{EG}$ and temperature gradient $\dot{T}$

LMD: $v_{EG}$ at $v = 13 \, \text{mm/s}$

Fe-28Al

SLM: $v_{EG}$ at $v_S = 400 \, \text{mm/s}$

$LMD: \dot{T}$ at $v = 13 \, \text{mm/s}$

$SLM: \dot{T}$ at $v_S = 400 \, \text{mm/s}$

$v_{EG \, \text{max}} \sim x 30$

$\dot{T}_{\text{max}} \sim x 40$
Comparison LMD – SLM

Grain structure of LMD and SLM samples \(\rightarrow\) EBSD\(^{[1]}\)

- Finer-grained first layers \(\rightarrow\) selection of grains \(\rightarrow\) large elongated grains
- SLM: higher temperature gradients and faster cooling \(\rightarrow\) smaller grains concerning width of grains
- Misorientations within the grains, more pronounced in SLM samples

Comparison LMD – SLM

SLM: Reduction of scan rate reduces $v_{EG}$ and $T$

Fe-28Al

$v_{EG}$ for $v_s = 20 \text{ mm/s}$

$v_{EG}$ for $v_s = 60 \text{ mm/s}$

$\dot{T}$ for $v_s = 20 \text{ mm/s}$

$\dot{T}$ for $v_s = 60 \text{ mm/s}$

$v_{EG}$ for $v_s = 20 \text{ mm/s}$ $v_{EG}$ for $v_s = 60 \text{ mm/s}$

$\dot{T}$ for $v_s = 20 \text{ mm/s}$ $\dot{T}$ for $v_s = 60 \text{ mm/s}$
Comparison LMD – SLM

SLM: Reduction of scan rate reduces $v_{EG}$ and $T$

- Similar microstructure when solidification parameters are similar

Green: LMD
Red: SLM

![Diagram showing effective solidification rate vs. scan rate](image-url)
Demonstrator Parts
Demonstrator Parts

Planetary Gear and Impeller by SLM

- Generated in “one piece”
- Not demountable

- Small specific weight
- Resistance against heat and oxidation
Demonstrator Parts

Turbine Blade by LMD and SLM

→ Comparison of same geometry made by LMD and SLM
→ Hollow structure with wall thickness of 2 mm
Conclusions

- Fe-28Al, Fe-30Al-10Ti, Fe-22Al-5Ti and Fe-30Al-5Ti-0.7B can be processed by LMD and SLM
- Crack-free bulk volumes can be built up
  → pre-heating necessary
- Density of more than 99.5% is attainable
- Understanding the evolution of the microstructure requires knowledge about the local solidification conditions
- Differences in local solidification conditions of SLM and LMD lead to significant difference in microstructure and properties (see next presentation of Martin Palm)
Acknowledgement

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Thank you for your attention!

Any questions

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