Influence of Process Conditions in Laser Additive Manufacturing on the Microstructure Evolution of Fe-Al Alloys: A Comparison of Laser Metal Deposition and Selective Laser Melting

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Max-Planck-Institut für Eisenforschung GmbH

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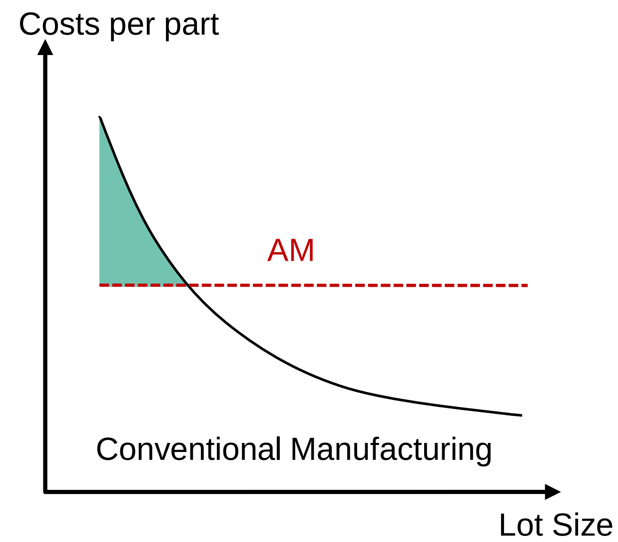
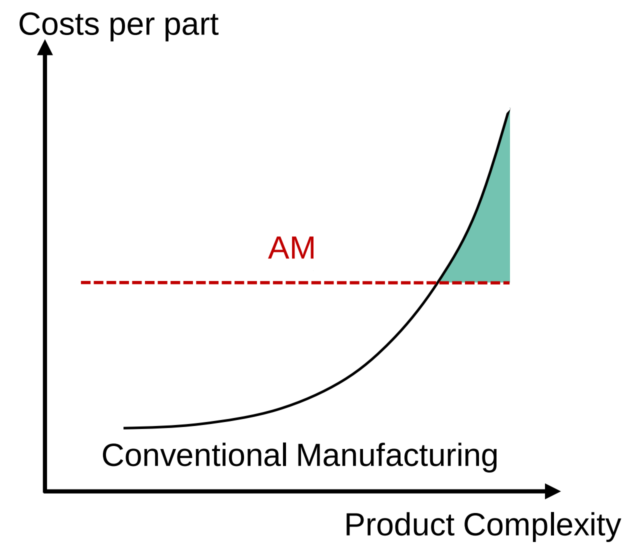
Motivation

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 – 10^6 K/s) of laser processes (casting 1 – 10 K/s)





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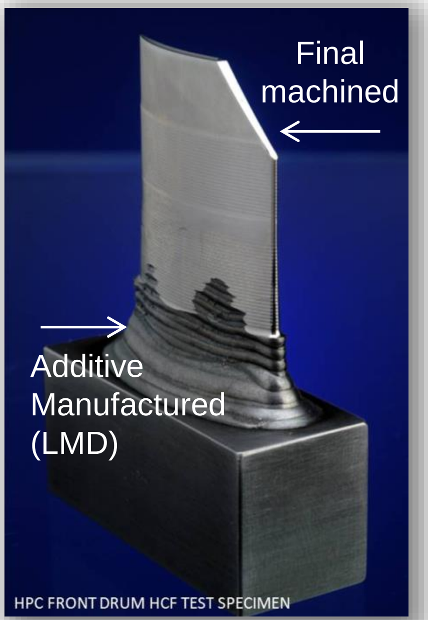
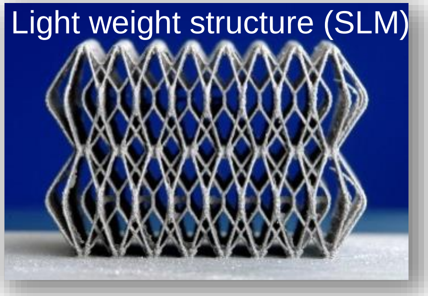
Motivation

Why iron aluminide?

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

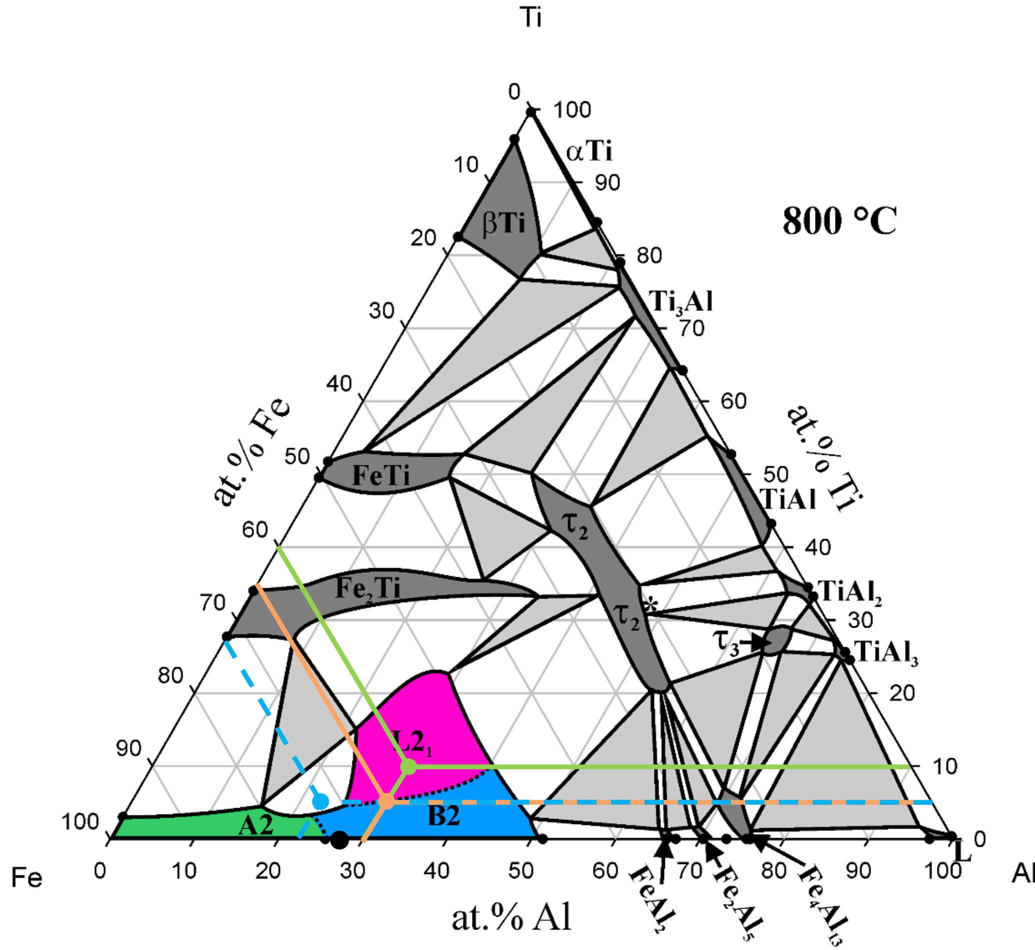




Fe-Al alloys

Alloys investigated

- Fe-28Al
- Fe-30Al-10Ti
- Fe-22Al-5Ti
  - Solid solution hardening
  - Stabilization of $D0_3$ structure at higher temperatures → $L2_1$ (Heusler phase)
- Fe-30Al-5Ti-0.7B
  - Fixing of grain boundaries by titanium borides



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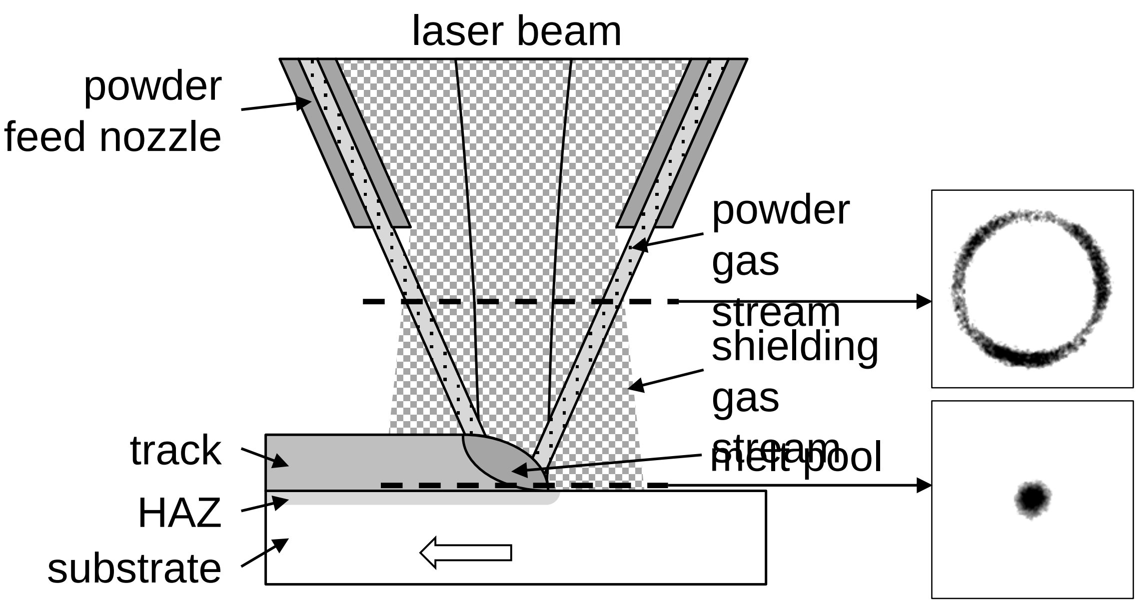
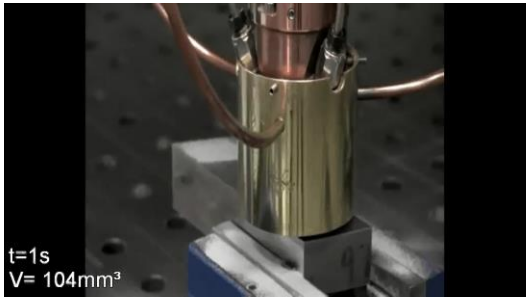
Experimental Setups

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

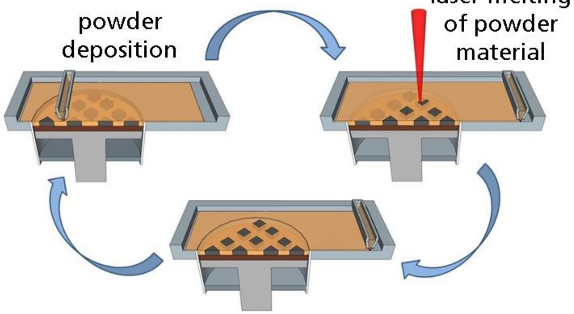


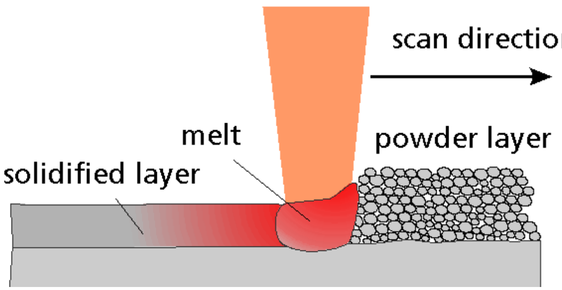


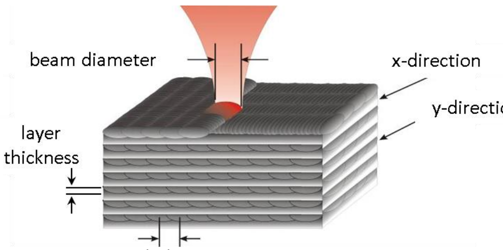
- particle size of powder: 45 - 90 µm
- substrate material:
  → stainless steel (1.4301)

Experimental Setups

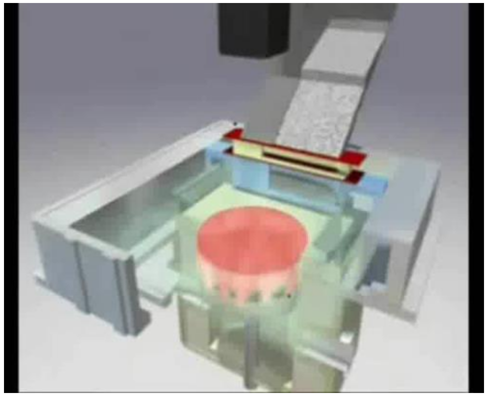
Selective Laser Melting (SLM) - principle







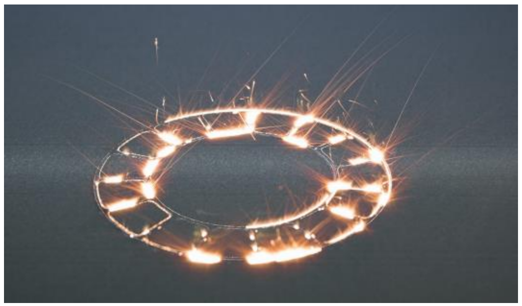
- particle size of powder: 20 - 45 µm
- substrate material:
  → stainless steel (1.4301)



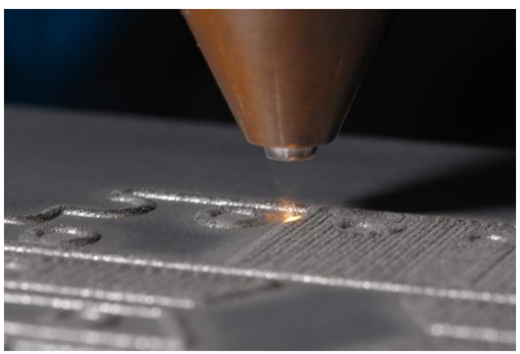
Additive Manufacturing / SLM & LMD

SLM and LMD are complementary

Selective Laser Melting



Laser Metal Deposition



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

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)

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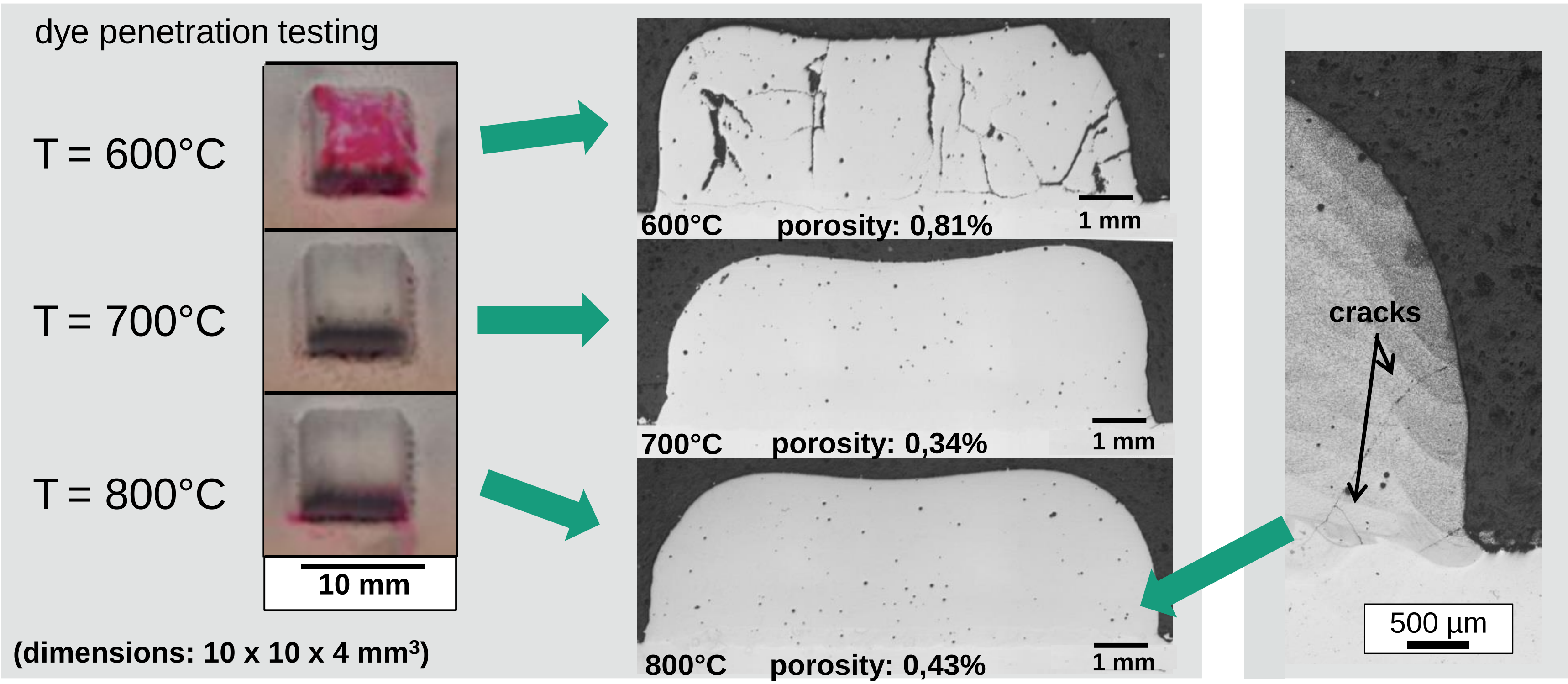
LMD – Fe-30Al-10Ti

Variation of pre-heating temperature

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



→ No cracks within the volumes built at > 700 °C

→ Small cracks in the edge area (first 4 layers)

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SLM – Fe-28Al

Parameter study to achieve dense volumes

Density decreases with increasing scan rate

Density decreases with increasing laer power

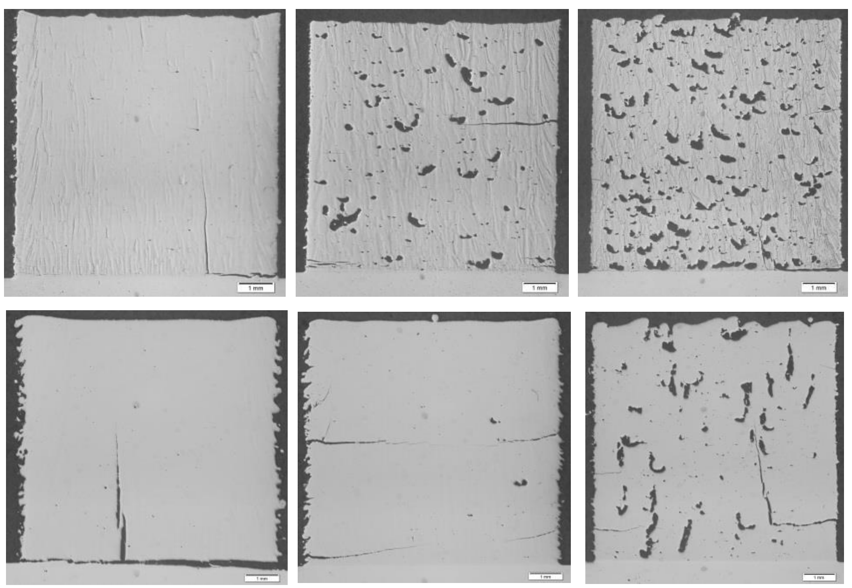
Density > 99,5 % achievable

100 mm/s | 300 mm/s | 500 mm/s

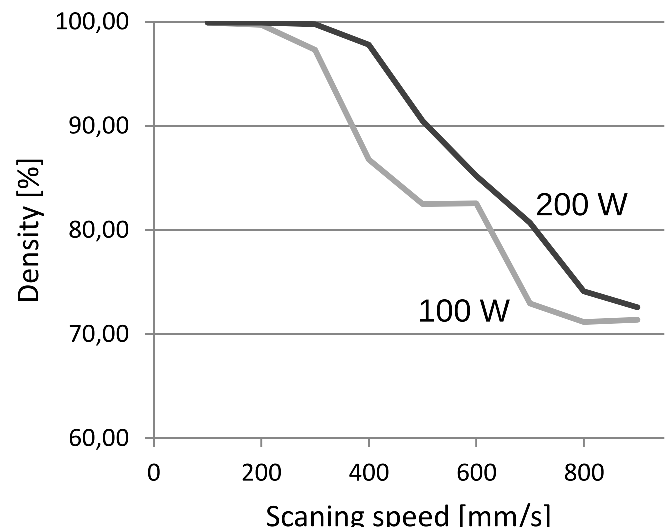
100 W

200 W

Δy = 30 µm



2 mm



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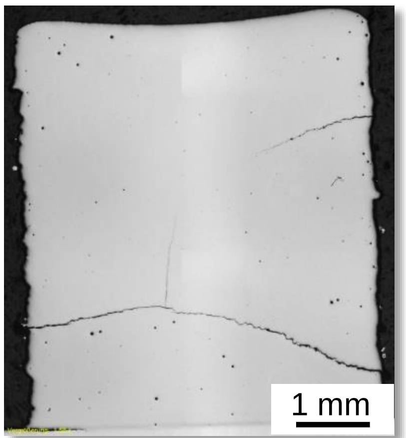
Results – Fe-Al-Ti and Fe-Al-Ti-B

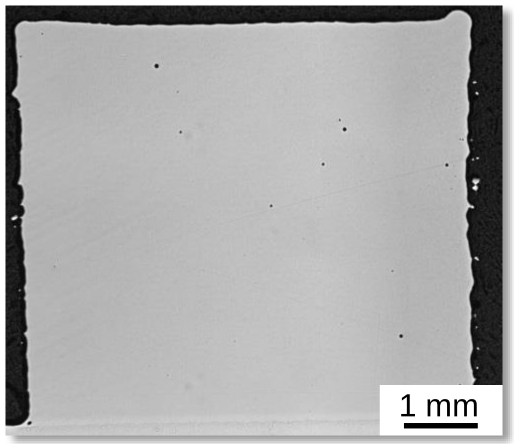
Influence of Ti and TiB on pre-heating temperature (SLM)

Fe-22Al-5Ti

600 °C

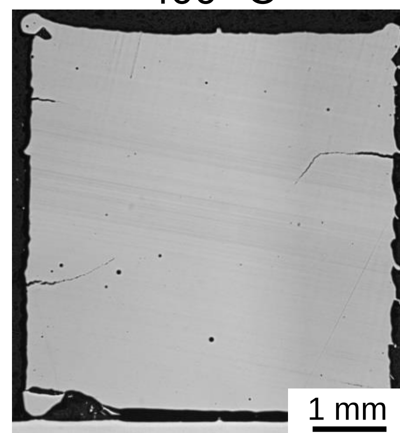


800 °C

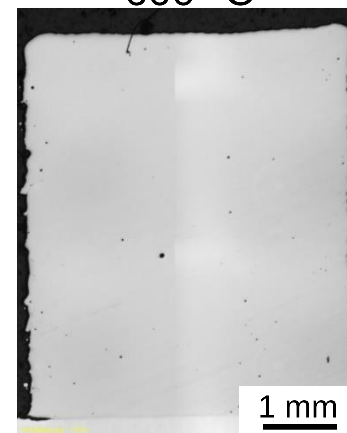


Fe-30Al-5Ti-0.7B

400 °C



600 °C



- 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

Alloy	LMD	SLM
Fe-28Al	200 °C	600 °C
Fe-30Al-10Ti	700 °C	800 °C
Fe-22Al-5Ti	(> 400 °C)	800 °C
Fe-30Al-5Ti-0,7B	400 °C	600 °C

- Misorientations / internal stresses lead to bigger difference between pre-heating temperature for LMD and SLM
- Addition of Ti increases BDTT

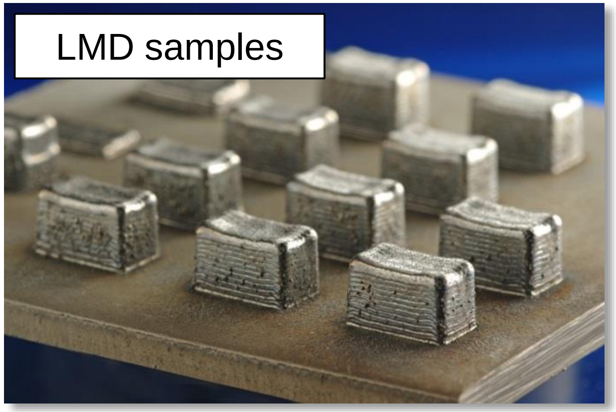
  → Increase of pre-heating temperature for crack-free samples
- Titanium borides decrease BDTT

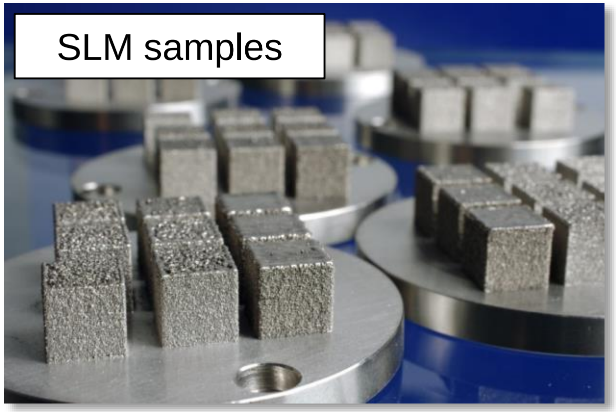
Material – Fe-28Al

Typical parameters of LMD and SLM[1]

Parameter	LMD	SLM
Beam diameter	600 µm	100 µm
Scan speed	13.3 mm/s	200 mm/s
Laser power	180 W	200 W
Layer thickness	300 µm	30 µm
Pre-heating	200 °C	600 °C
Density	> 99.5 %	> 99.95%

- Samples are crack-free





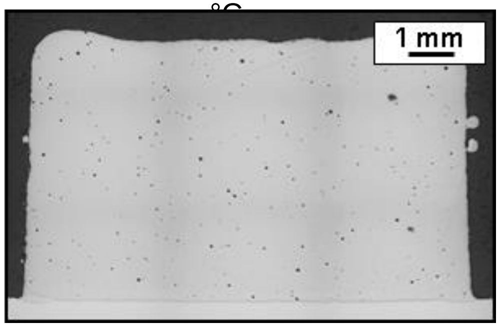
10 mm

[1] Rolink et al.: J. Mater. Res. (2014)

Local Solidification Conditions

LMD

300 °C

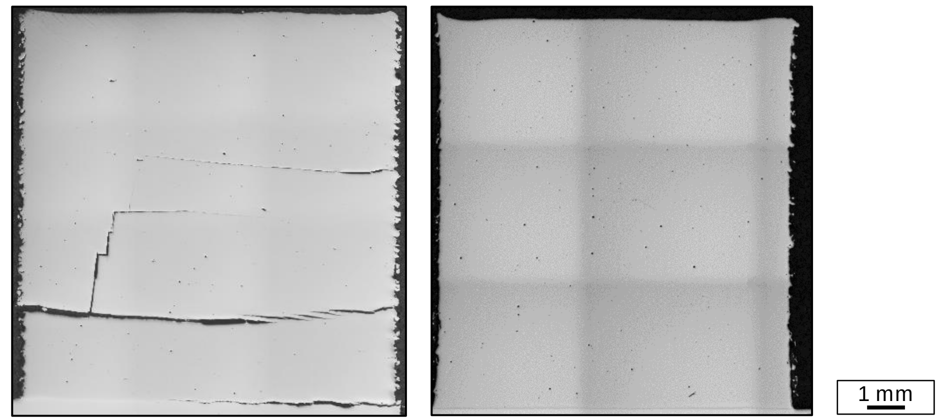


Fe-28Al

SLM

300 °C

600 °C

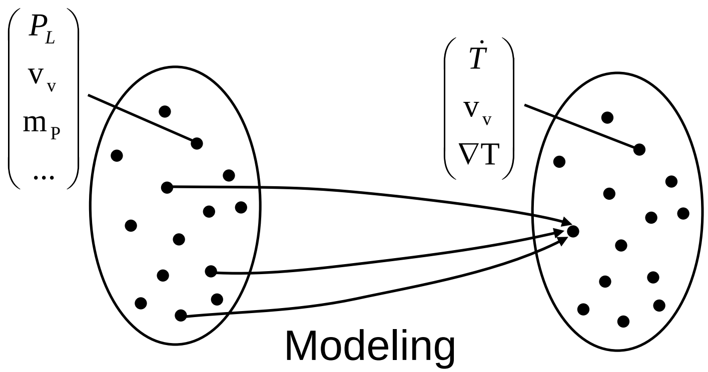


- LMD samples are crack-free at much lower preheating temperatures than SLM samples
  -> Significant differences in process conditions

Modeling of LAM

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**



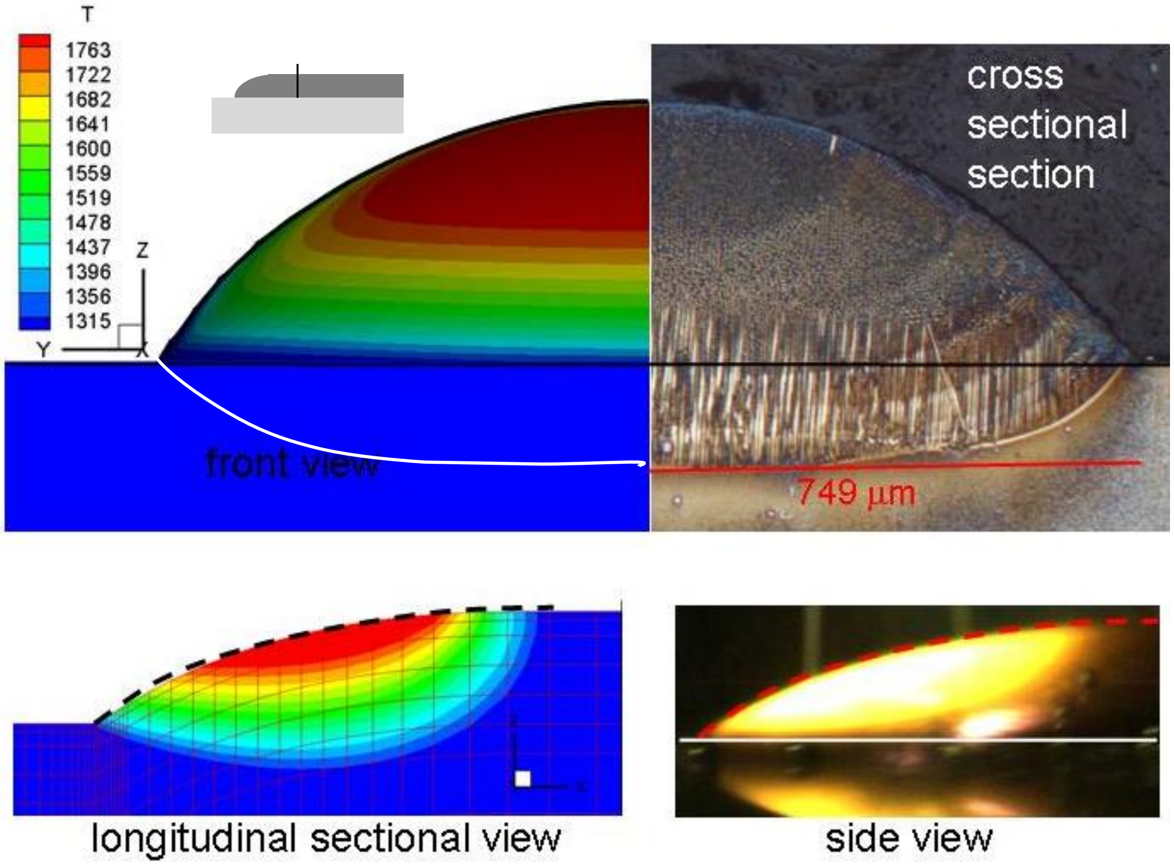
Solidification conditions:
- **solification rate**
- **cooling rate**
- **crystal orientation**

Design of experiment	
Conventional approach	New approach
Parametric design for processing parameters	Parametric design for solidification conditions

Modelling LMD

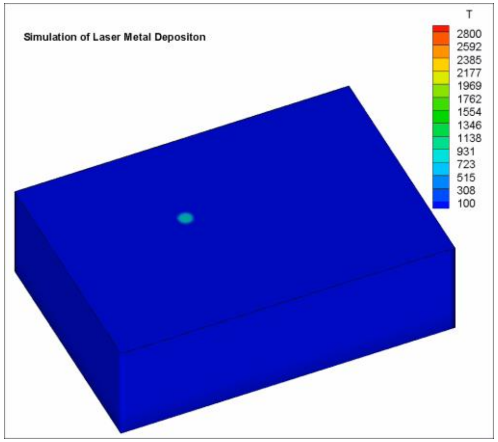
Comparison experimental and computed results

Melt pool surface in longitudinal and cross section of single track



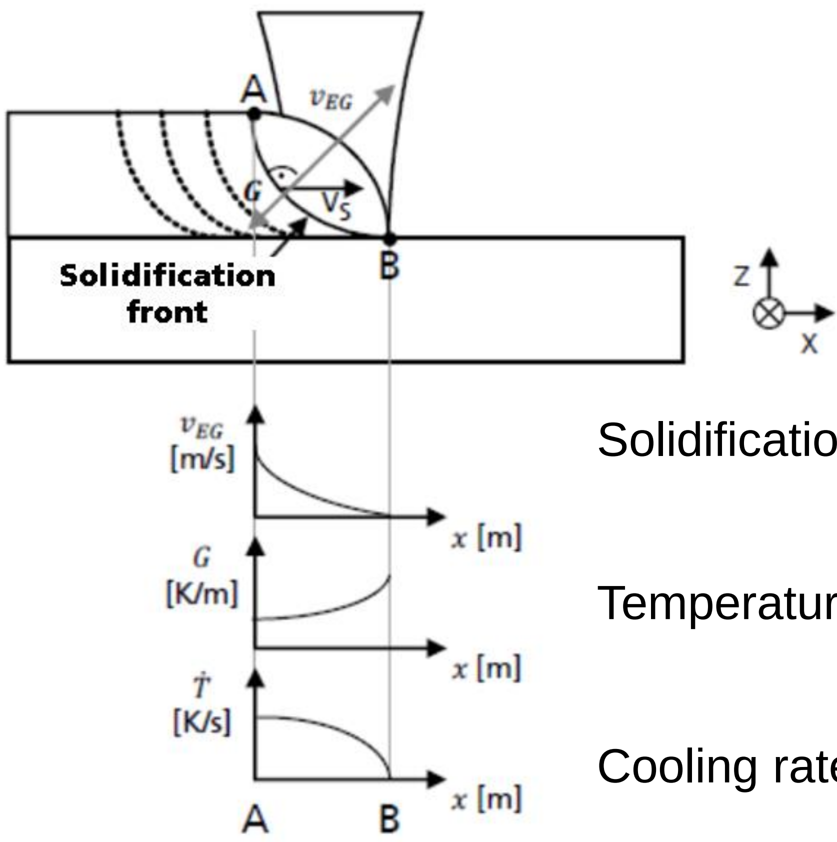
Ni-based alloy

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



Local Solidification Conditions

Solidification conditions change along the front



Solidification rate

Temperature gradient

Cooling rate

$\dot{T} = v_{EG} \times G$

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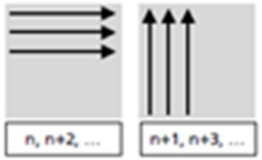
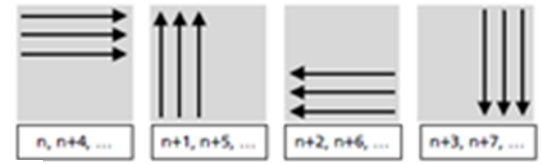
Local Solidification Conditions

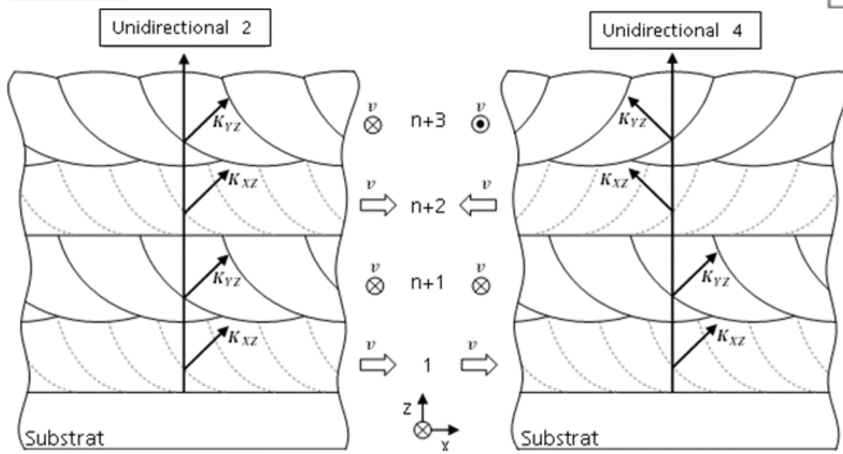
LMD: Build-up strategy influences crystal growth direction…

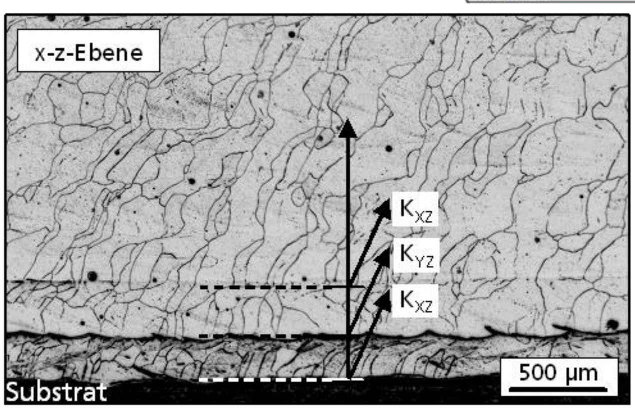
Unidirectional 2



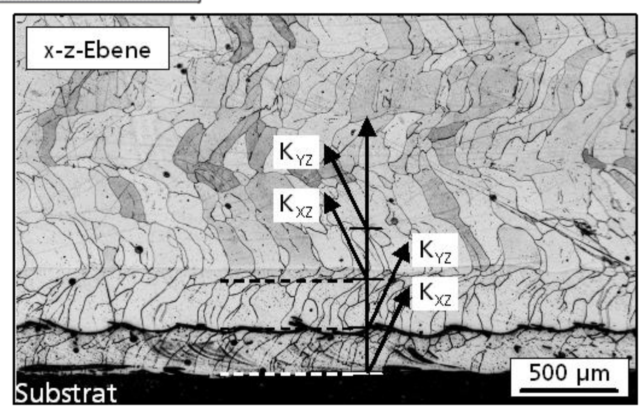
Unidirectional 4





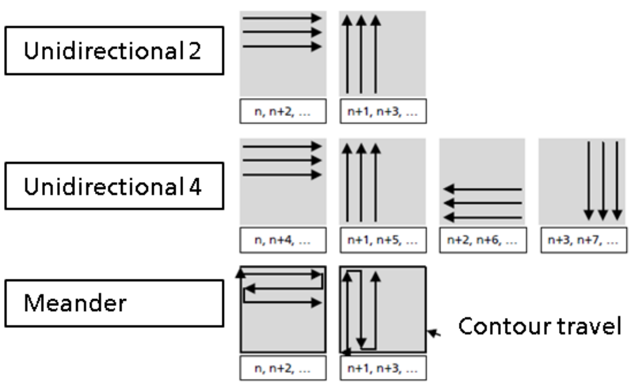


Fe-28Al

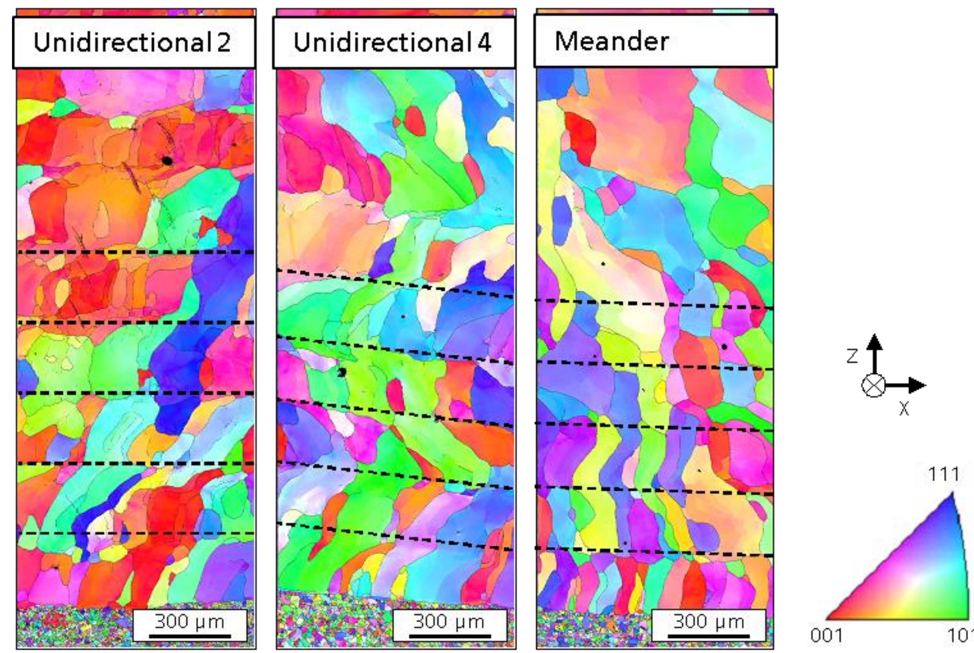


Local Solidification Conditions

…but not necessarily crystal orientation



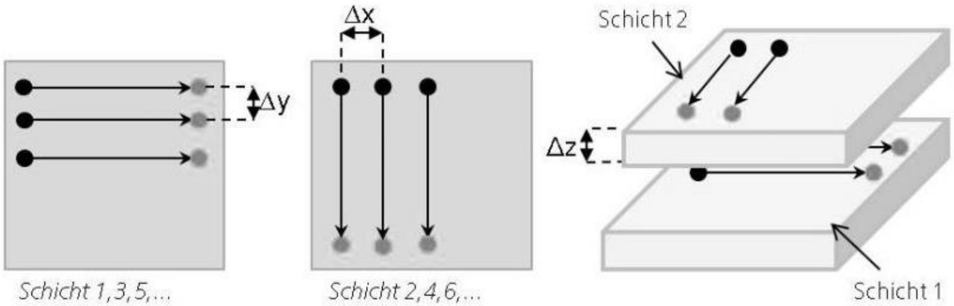
Fe-28Al



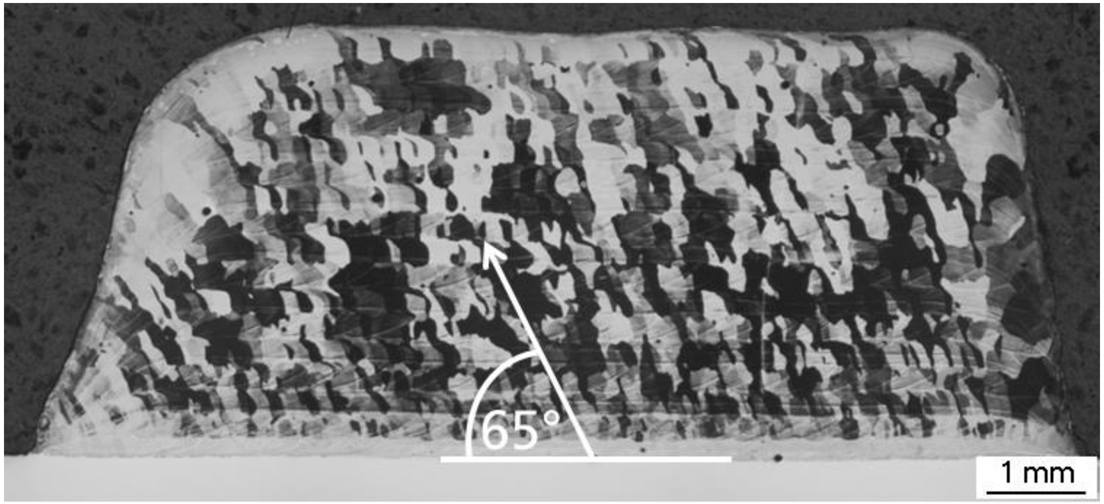
Local Solidification Conditions

Crystal growth as a factor of build-up strategy

Strategy:
Unidirectional 2



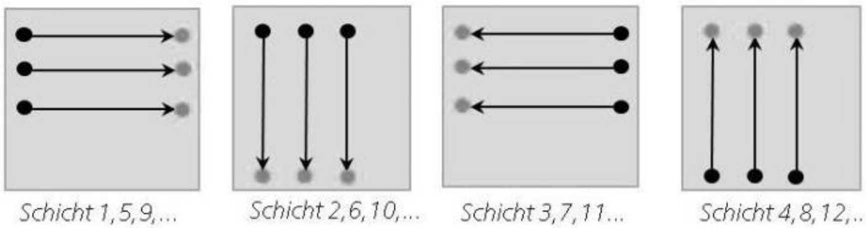
Fe-28Al

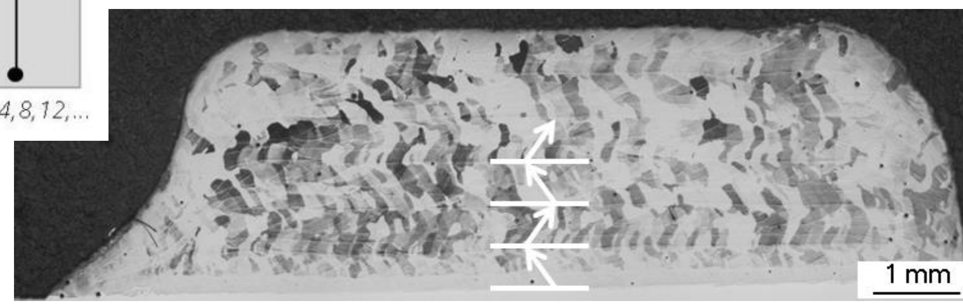


Local Solidification Conditions

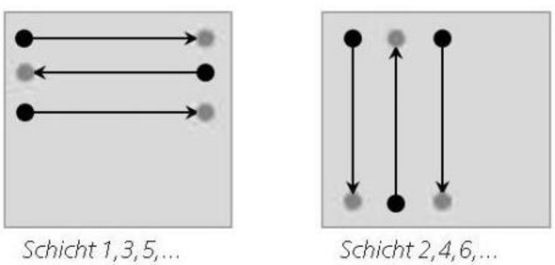
Crystal growth as a factor of build-up strategy

Strategy: Unidirectional 4

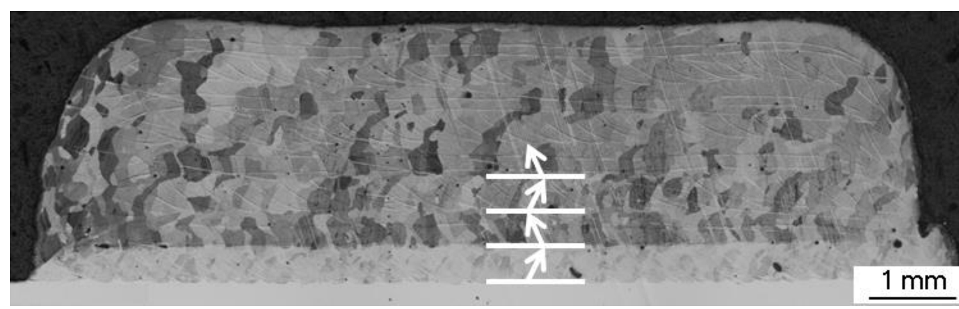




Strategy: Meander



Fe-28Al



Local Solidification Conditions

Effect of parameters for SLM

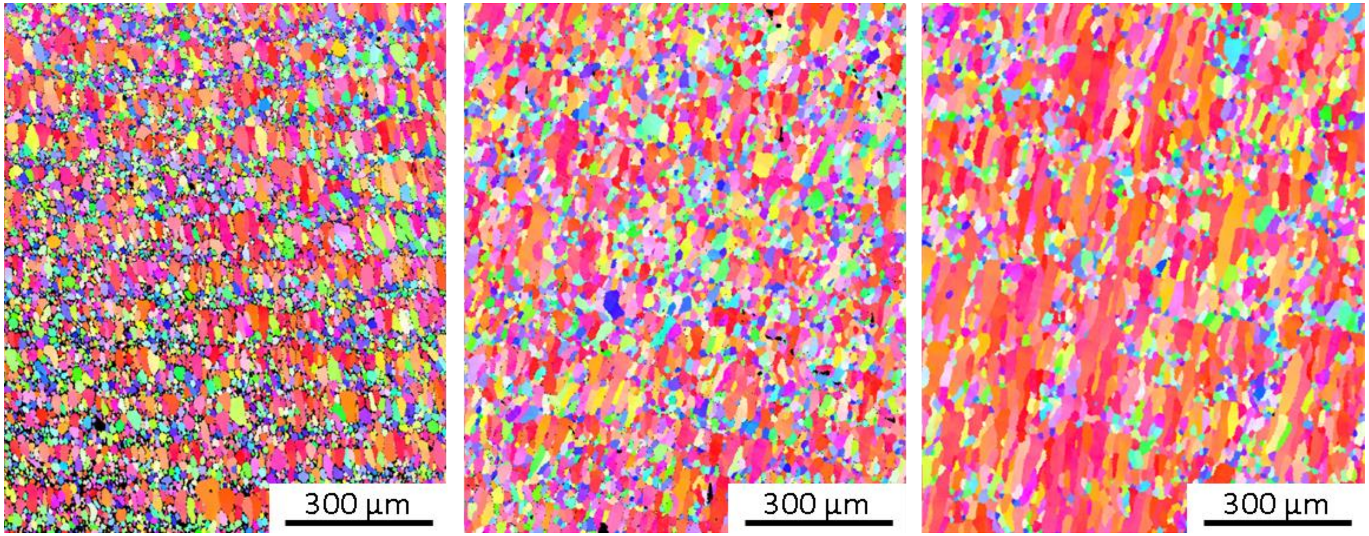
Decreasing cooling rate

coarse (and elongated) grains

P = 300 W
v = 1000 mm/s

P = 275 W
v = 750 mm/s

P = 200 W
v = 500 mm/s



Fe-28Al

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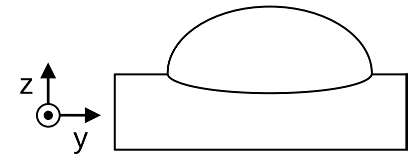
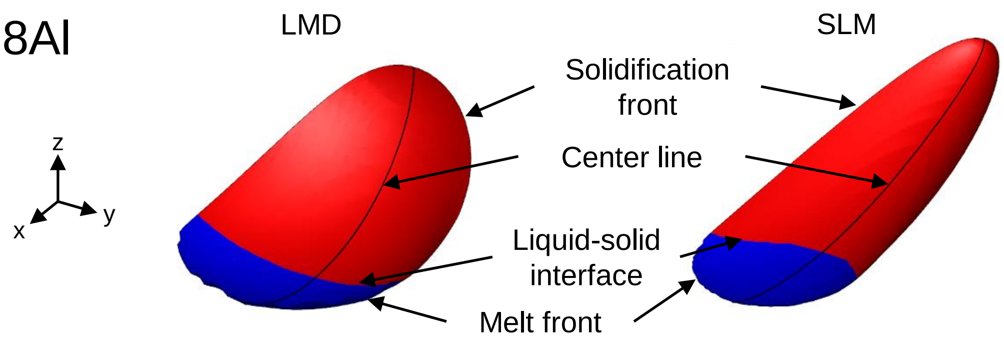
Comparison LMD – SLM

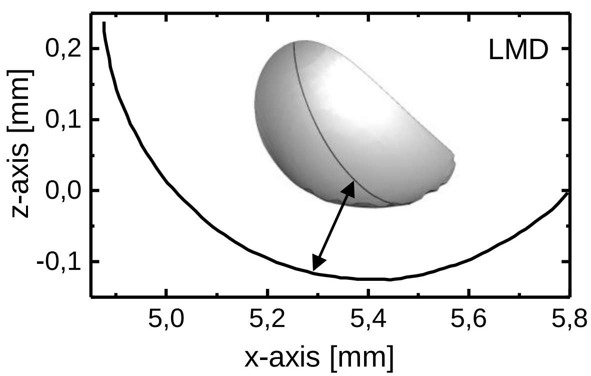


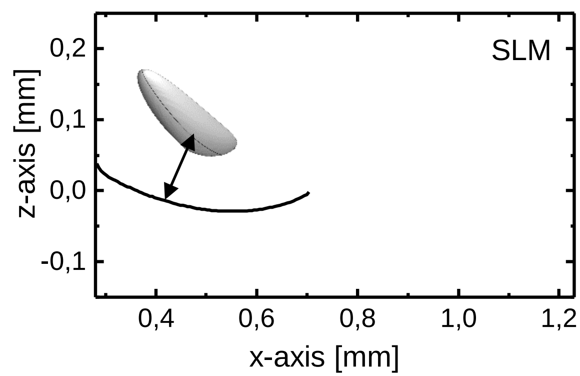
Geometry of the melt pool

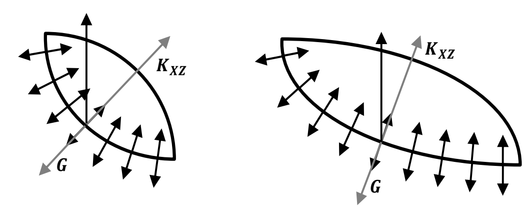
Fe-28Al



Parameter	LMD	SLM
Beam diameter	600 µm	100 µm
Scan speed	13 mm/s	400 mm/s
Laser power	240 W	200 W
Layer thickness	300 µm	30 µm
Pre-heating	300 °C	600 °C

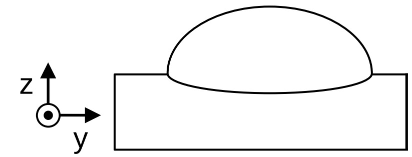






- Smaller and longer melt pool for SLM
- Stronger curverture of the liquid-solid interface in LMD

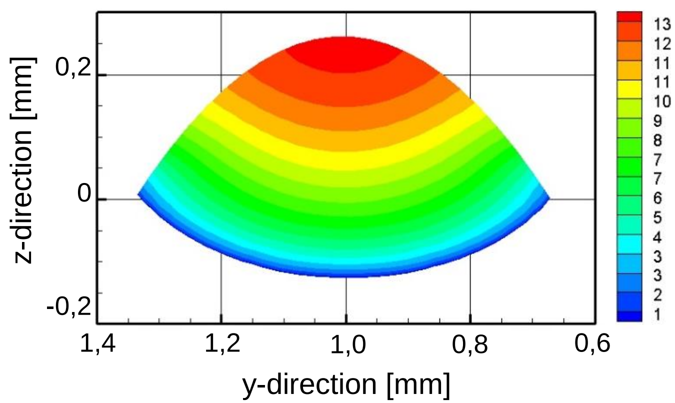
Comparison LMD – SLM



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

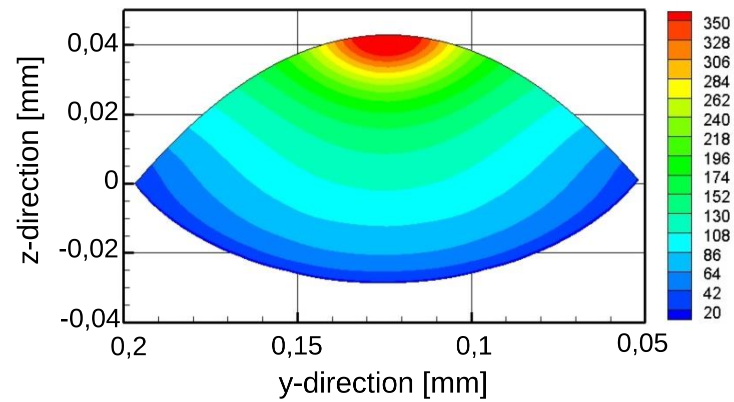
Fe-28Al

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

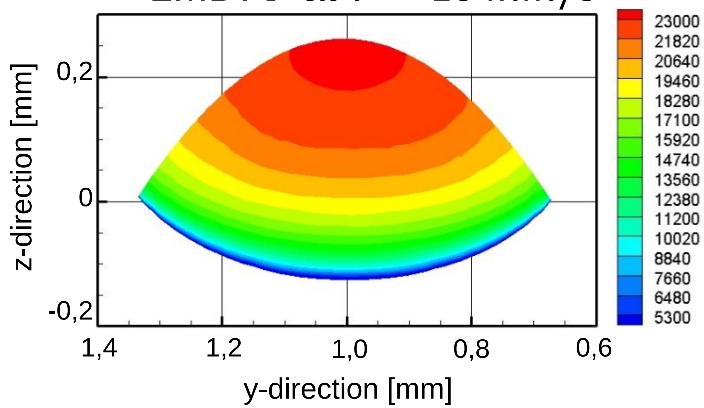


$\xrightarrow{v_{EG\_max}}$ $\sim x\,30$

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

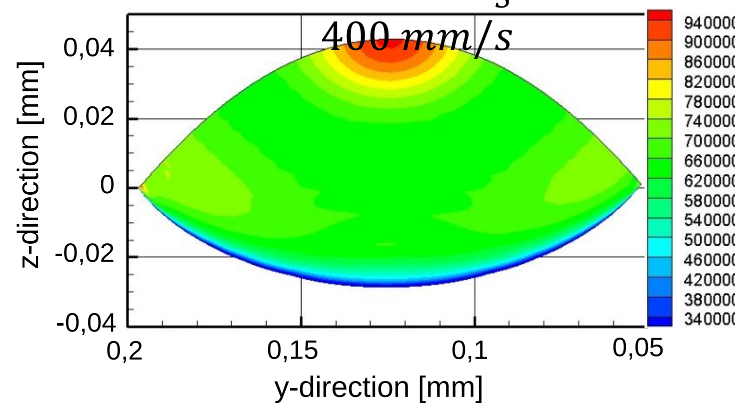


LMD: $\dot{T}$ at $v = 13\, mm/s$



$\xrightarrow{\dot{T}_{max}}$ $\sim x\,40$

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



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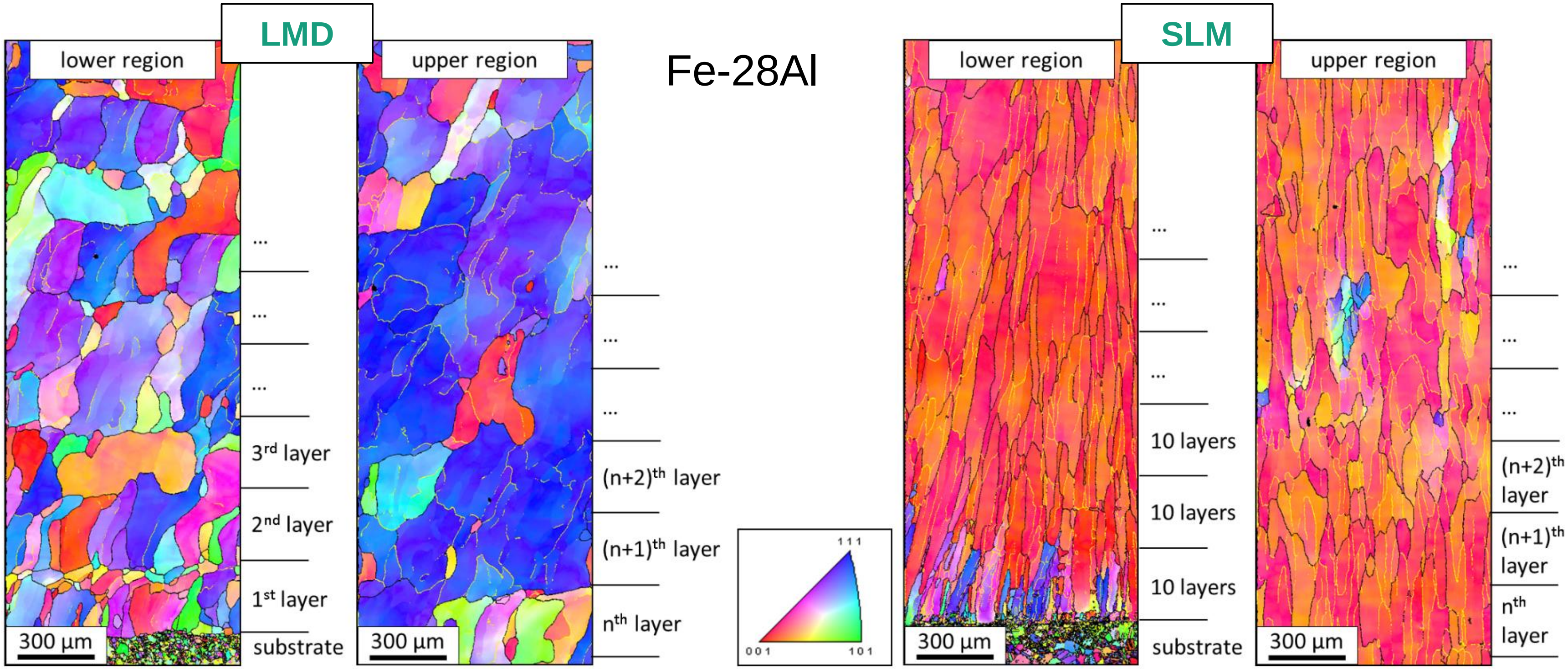
Comparison LMD – SLM

Grain structure of LMD and SLM samples → EBSD[1]



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

[1] Rolink et al.: J. Mater. Res. (2014)

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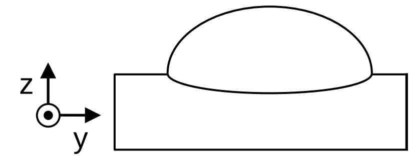
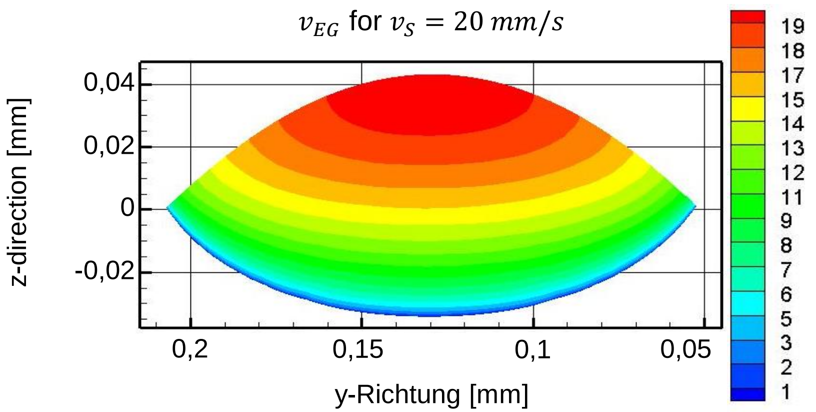
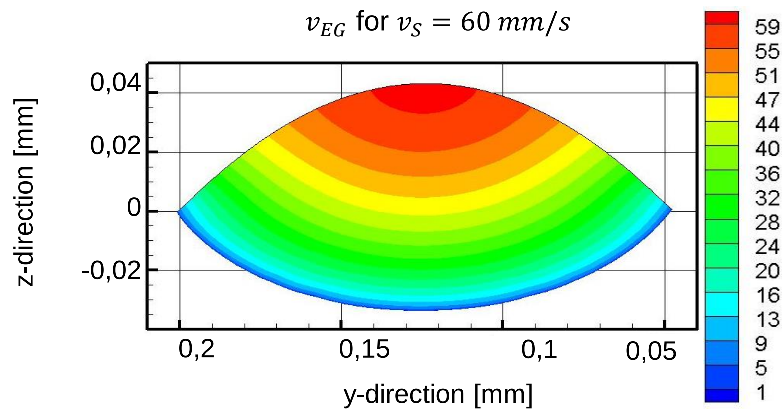
Comparison LMD – SLM

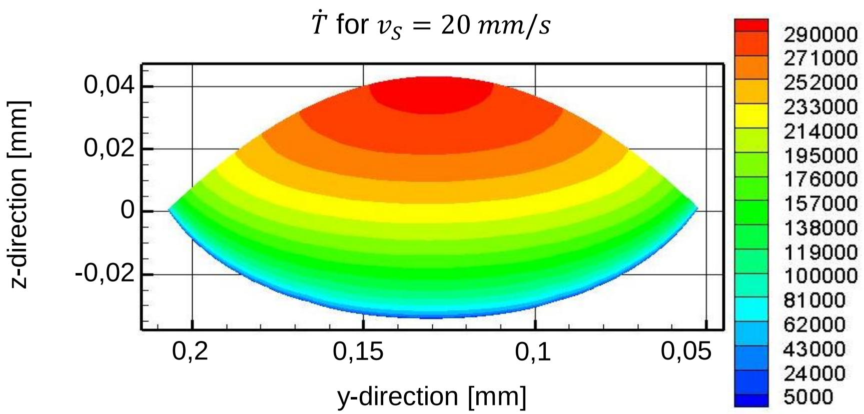


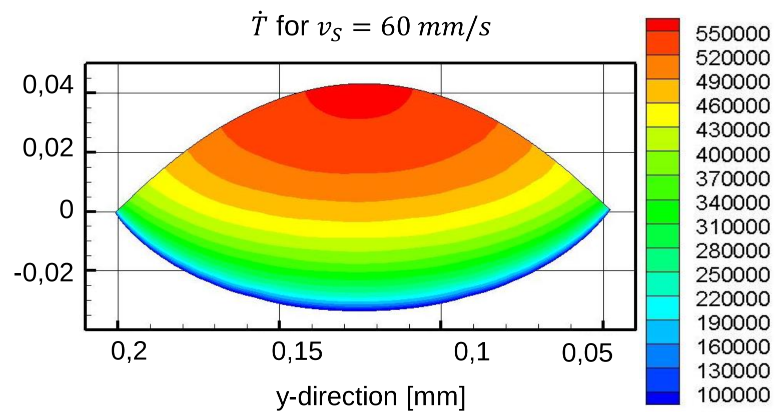
SLM: Reduction of scan rate reduces v_{EG} and $\dot{T}$

Fe-28Al









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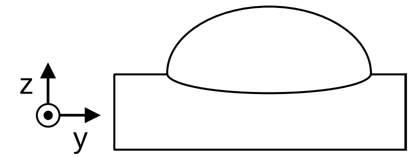
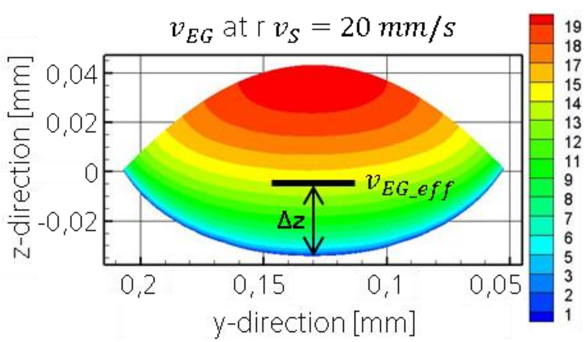
Comparison LMD – SLM

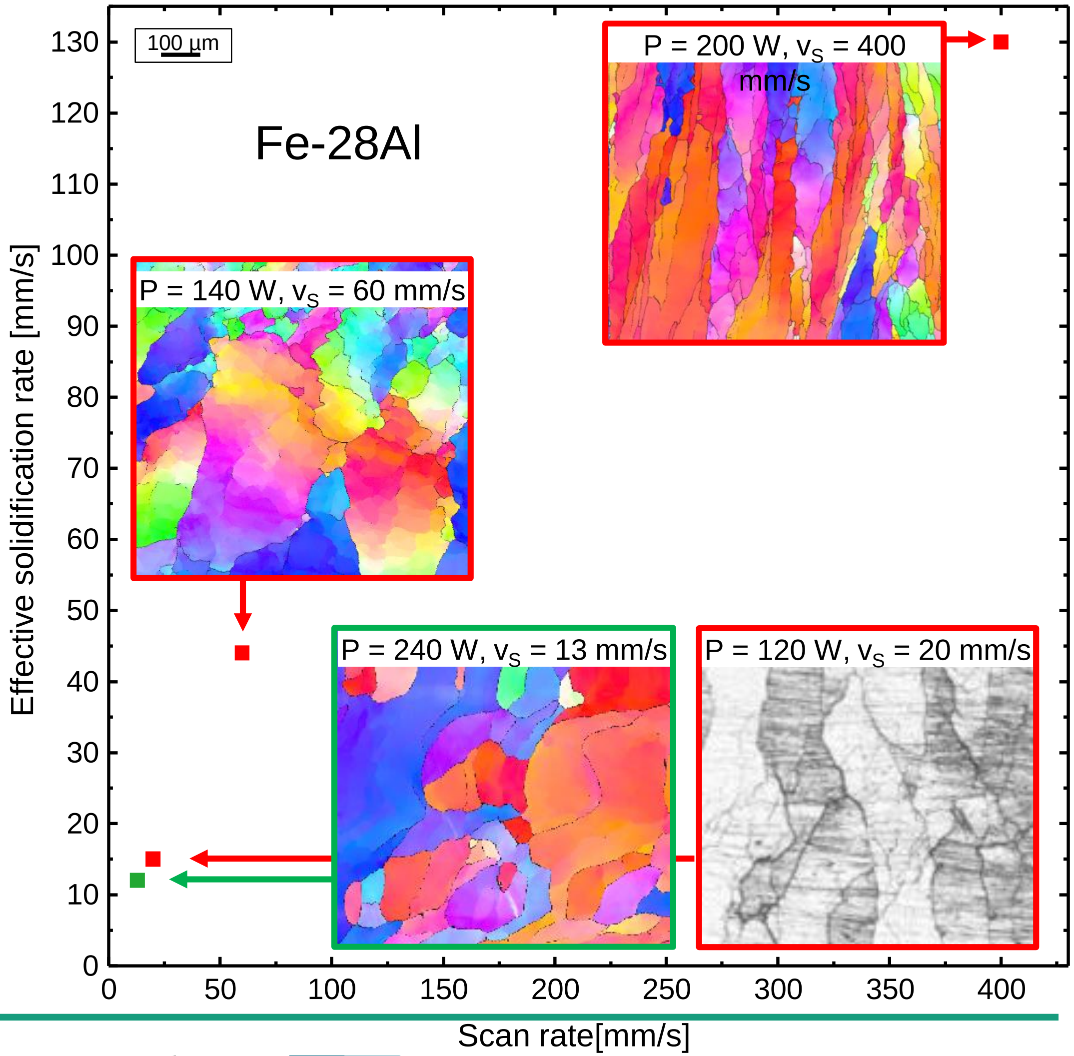


SLM: Reduction of scan rate reduces v_{EG} and $\dot{T}$

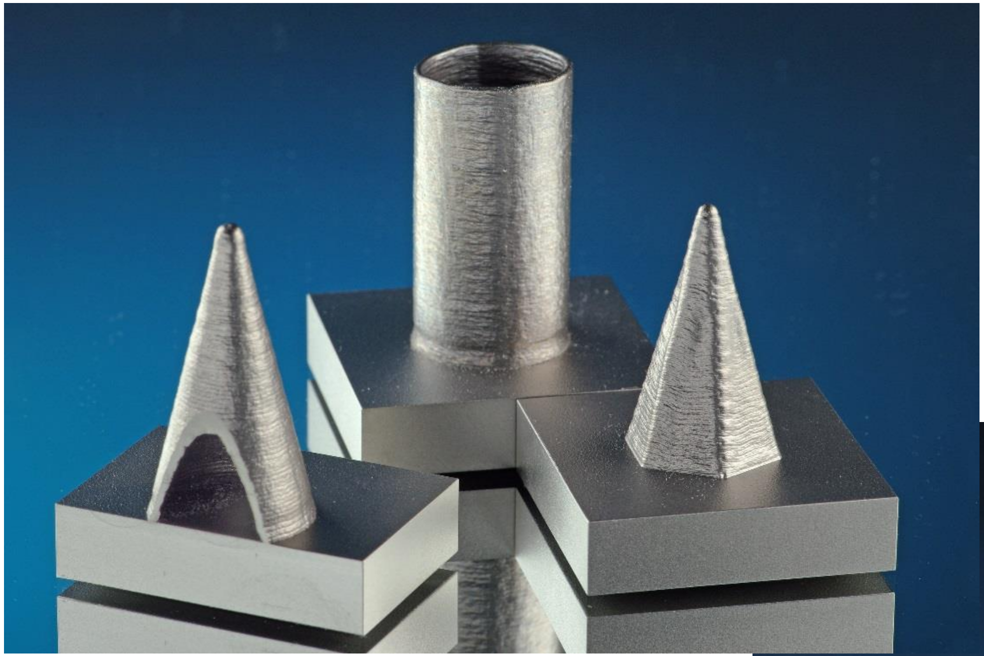
- Similar microstructure when solidification parameters are similar

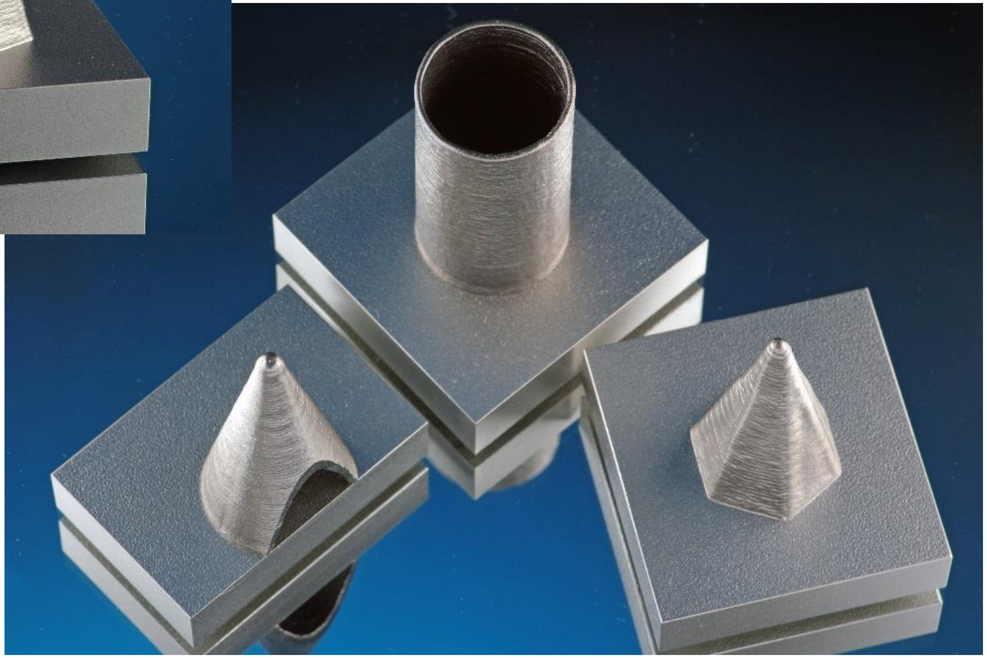


Green: LMD
Red: SLM



Demonstrator Parts

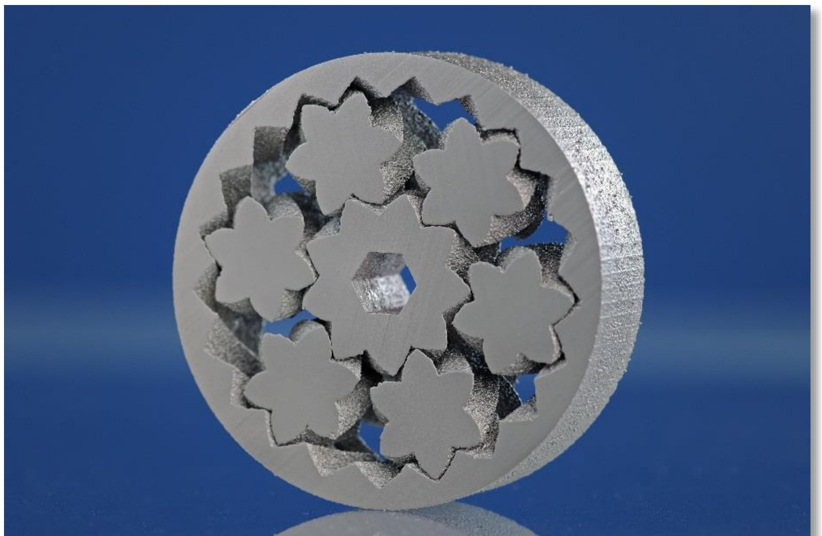




Demonstrator Parts

Planetary Gear and Impeller by SLM

Movable Planetary Gear	Impeller for Turbo Charger



- Generated in “one piece”
- Not demountable

→ Small specific weight

→ Resistance against heat and oxidation

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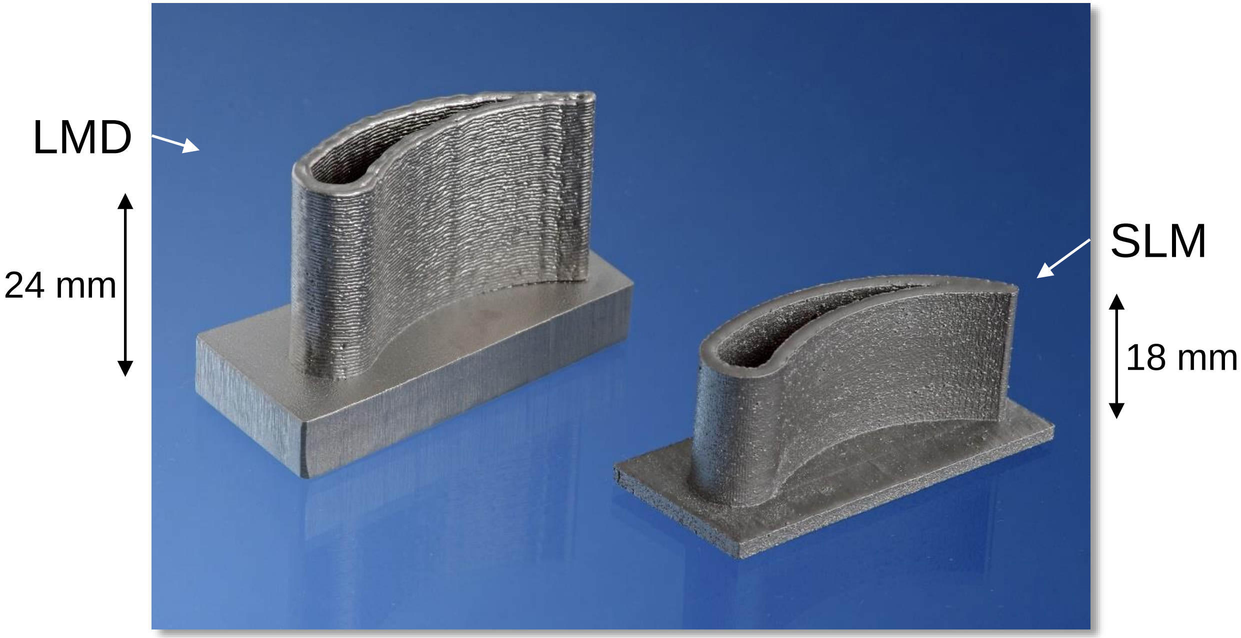
Demonstrator Parts

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

This work was funded in the frame of the project RADIKAL

„Ressourcenschonende Werkstoffsubstitution durch additive & intelligente FeAl-Werkstoff-Konzepte für angepassten Leicht- und Funktionsbau“

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MatRessource

With contributions of MPIE:

- Dr. Martin Palm
- Dr. Alena Michalcová
- Dr. Lucia Senčekova

Thank you for your attention!

Any questions 

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