METAL ADDITIVE MANUFACTURING – TECHNOLOGIES & MATERIALS

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DRESDEN concept

Fraunhofer IFAM

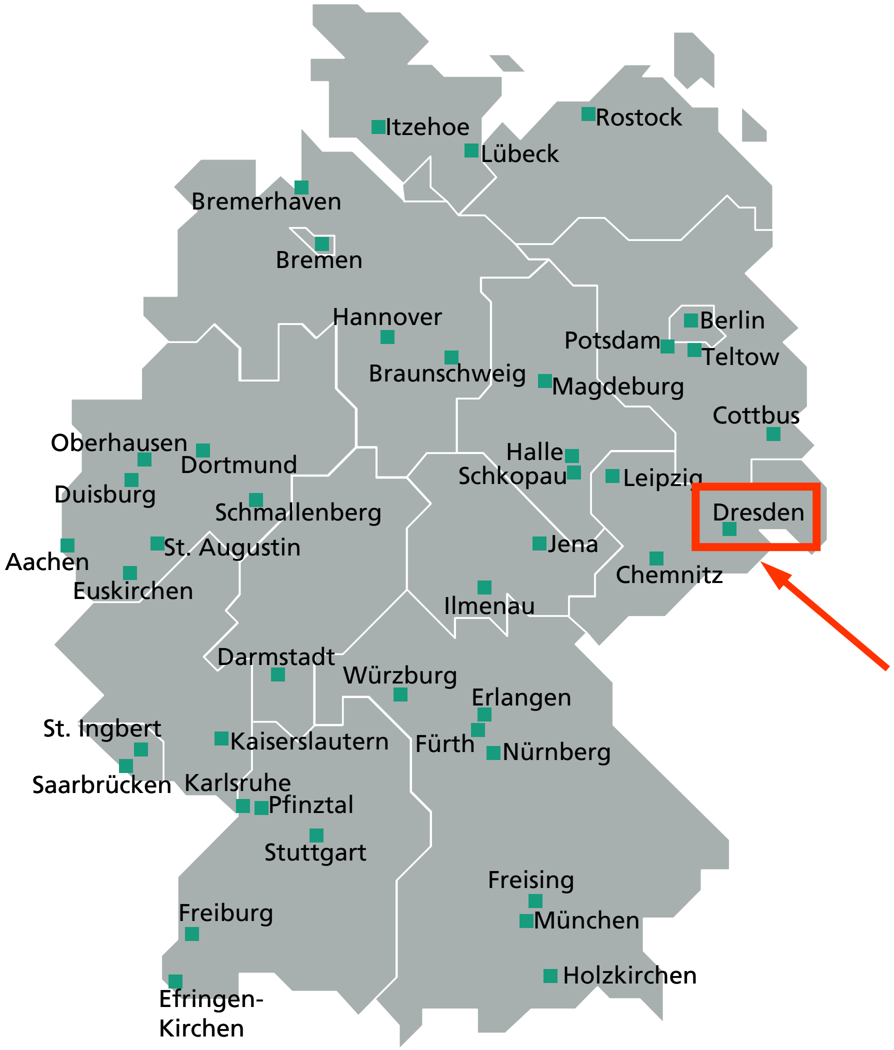
Branch Lab Dresden

Outline

Outline

2. Metal AM – Technologies

Fraunhofer-Gesellschaft



- 67 Fraunhofer institutes and independent research units in Germany
- 24.000 employees
- 10 institutes or branches in Dresden

→ 4 of these at the Fraunhofer Institute Center Dresden

DRESDEN concept

Fraunhofer IFAM

Branch Lab Dresden

Fraunhofer IFAM: Branch Lab Dresden

Permanent staff	74
Student employees	35
Budget	7,8 Mio. €
Industry	32 %
Projects	60 %
Public funding	8 %
Investments	0,7 Mio. €
Area	2850 m^2

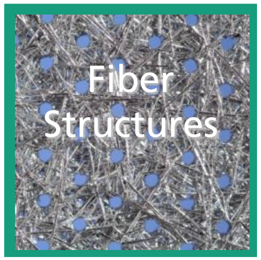
(Budget 2017)

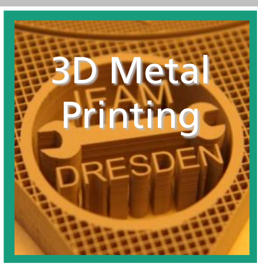
Head of IFAM Dresden
(prov. from 01/04/19):
Dr.-Ing. Thomas Weißgärber

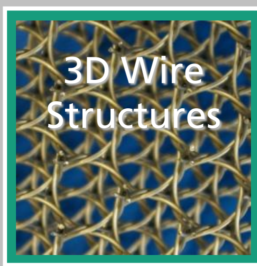
Profile of Fraunhofer IFAM Dresden

Fields of competence

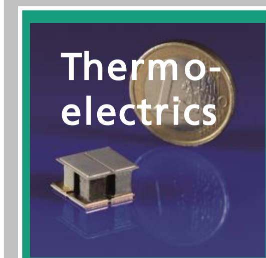
Cellular Metallic Materials

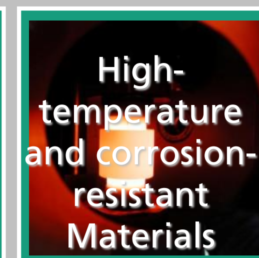




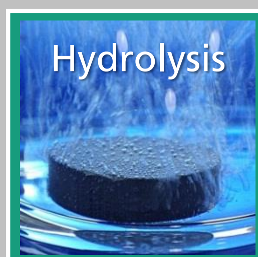


Sintered and Composite Materials

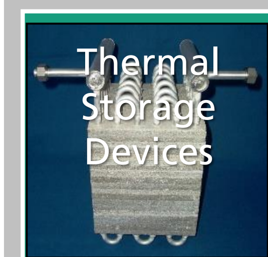


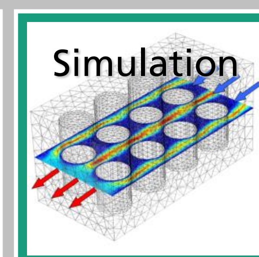


Hydrogen Technology



Energy und Thermal Management





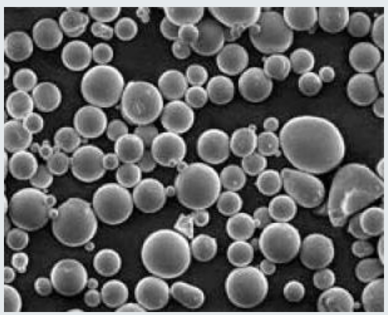
DRESDEN concept

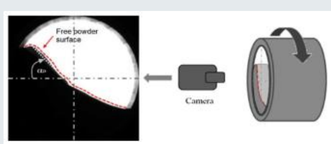
Fraunhofer IFAM Branch Lab Dresden

SEBM competence @ IFAM Dresden

Powder

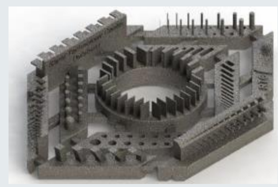
- Accredited lab for characterization
- Assessment of new powder analytics

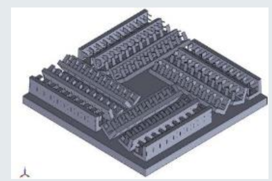


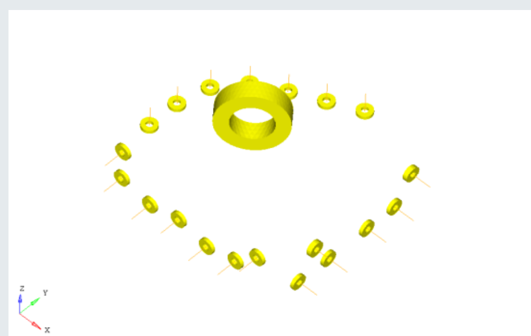


Design

- Design rules
- „Design for AM“, e.g. topology optimization

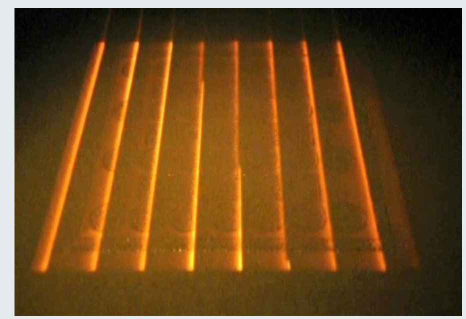






Process

- Process development
- New materials
- Prototypes and Components



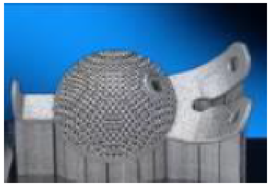
Fraunhofer Additive Manufacturing Alliance
Research areas

- **Engineering**
  to invent and design new products and develop suitable process chains

- **Materials**
  to adapt new materials

- **Technologies**
  to achieve (cost-)efficient processes

- **Quality**
  to control and ensure manufacturing reproducibility and product quality

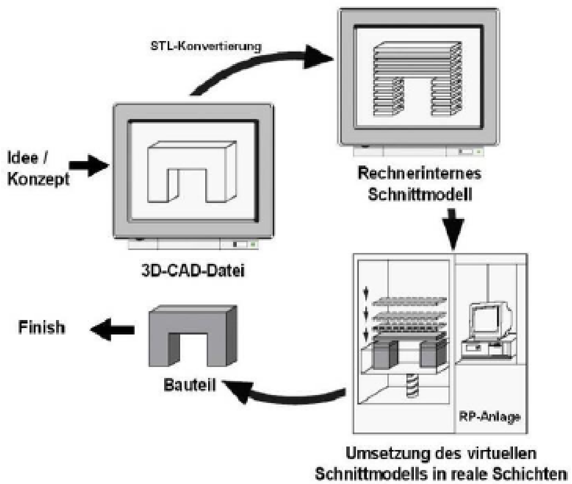


Additive Manufacturing: Definition

It is defined as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms are additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication.

1. Introduction AM Technologies

Introduction additive manufacturing
Overview



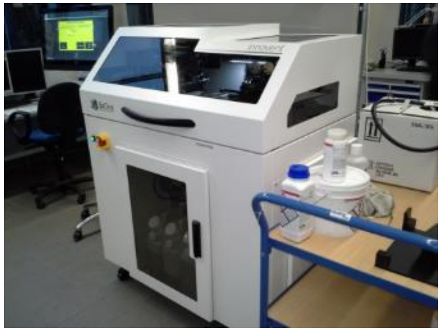
Principle sketch additive fabrication processes
(source: Gebhardt, A.: Generative Fertigungsverfahren)

- **Additive** [from Latin] – to add, to join; here: building procedure; for example: layer by layer, generative
- **Rapid Prototyping (RP):** additive fabrication of parts with limited functionality (prototypes, test parts)
- **Additive Manufacturing (AM):** additive fabrication of end products/ series production parts
- **3D Printing:** common term for low budget equipment (private usage)

Metal Additive Manufacturing at Fraunhofer IFAM

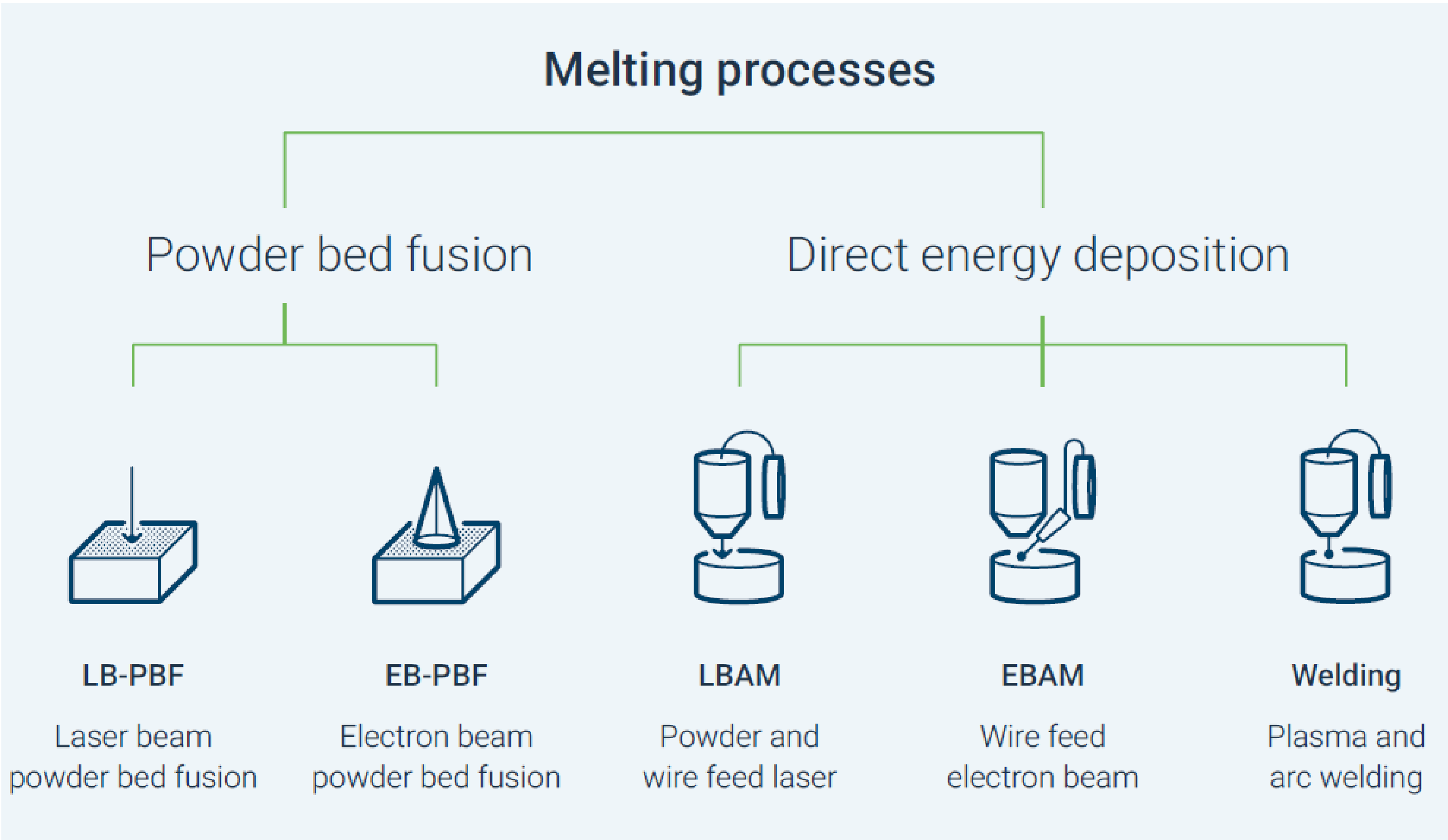
- Laser Beam Melting (LBM) [HB]
- Electron Beam Melting (EBM) [DD]
- 3D Metal Printing - Screen Printing approach (3DMP) [DD]

- 3D Metal Printing - Binder Jetting approach (3DP) [HB]
- 3D Metal Printing - Binder Jetting approach (3DP) [HB]



2. METAL AM TECHNOLOGIES

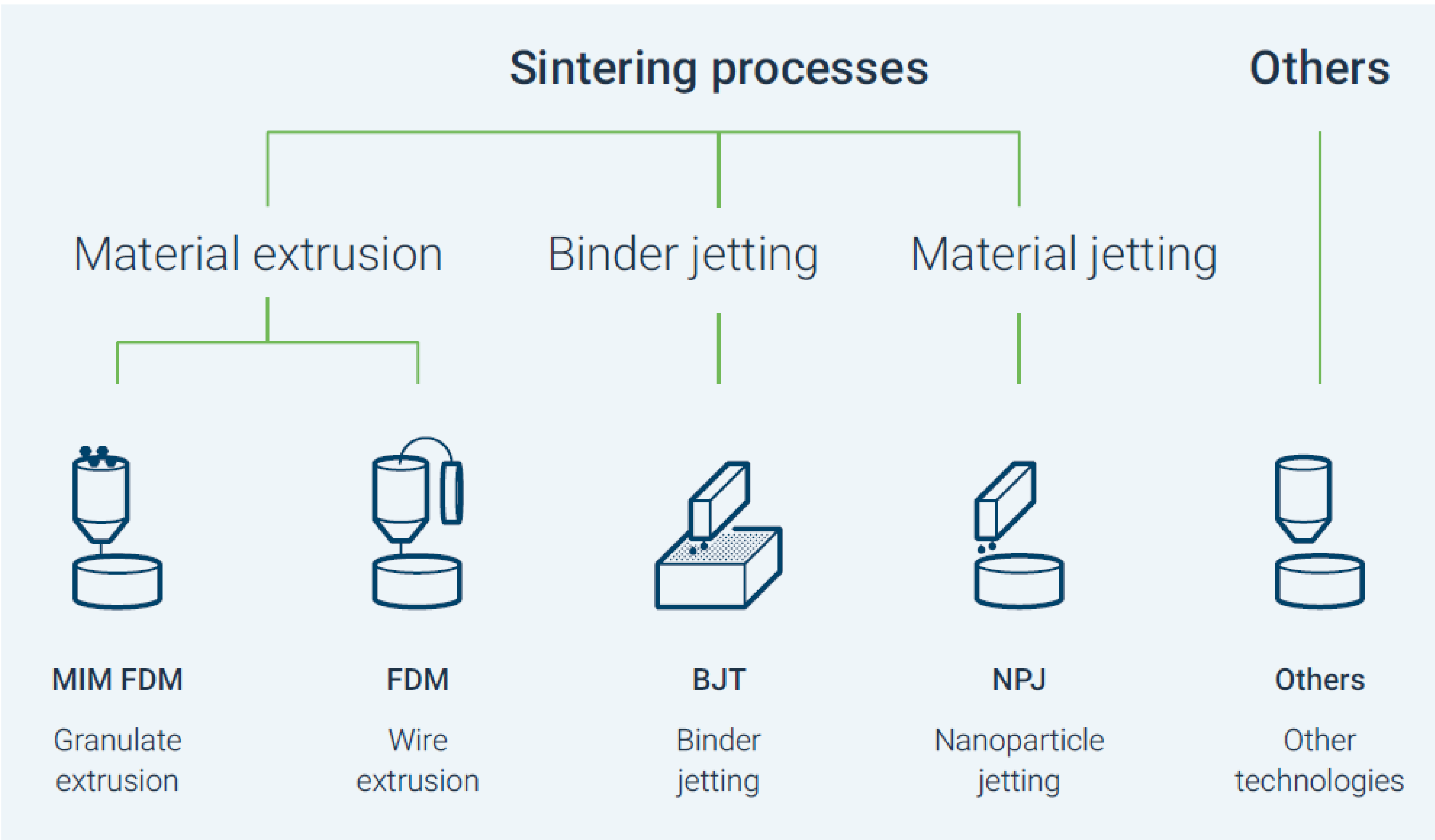
2.1 OVERVIEW



http://am-power.de/insights/

2. METAL AM TECHNOLOGIES

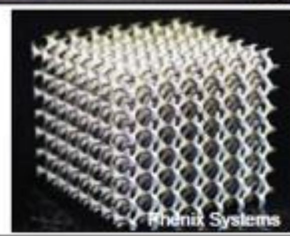
2.1 OVERVIEW



http://am-power.de/insights/

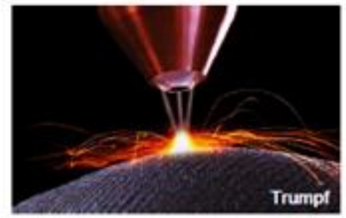
Comparison between different AM Technologies

Powder Bed



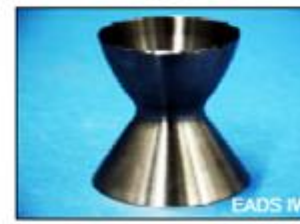
laser beam
e^- beam

Powder Feed



laser beam

Wire Feed

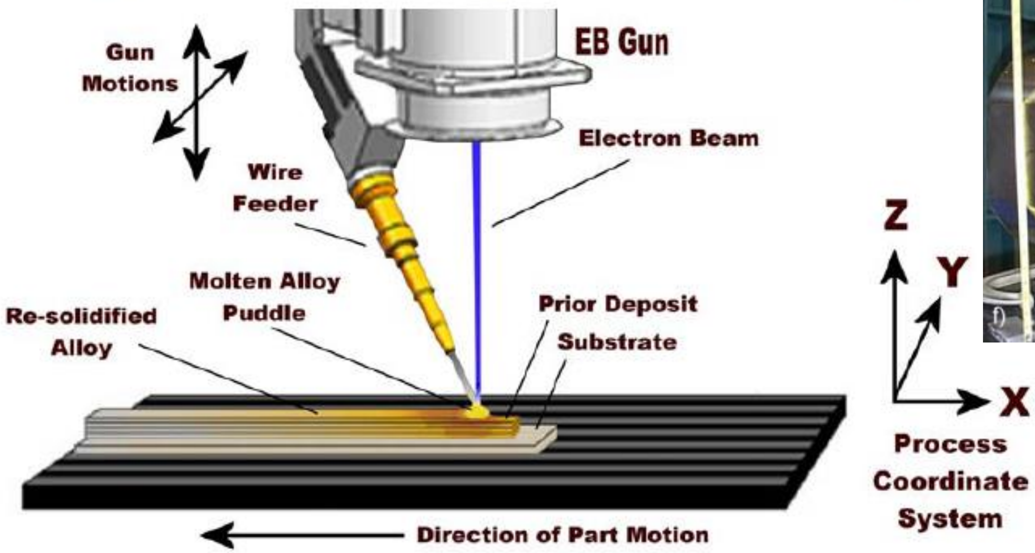


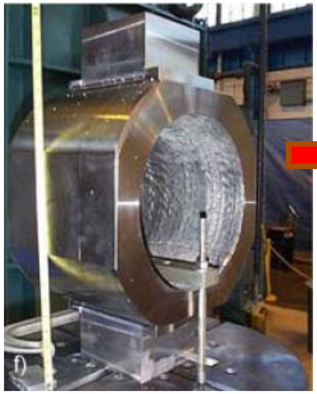
laser beam
e^- beam
plasma

	Powder Bed		Powder Feed	Wire Feed	
	laser	e^- beam	laser	laser	e^- beam
Part complexity	+++	+++	+(+)	+	+
Accuracy	+++	++	++	+	+
Part size	+	+	+(+)	+++	+++
Build rate	+	+	+(+)	+++	+++
Material variety	+	+	+++	++	++
Material quality	+	++	+	+++	+++

2.2.1 Electron Beam Free Form Fabrication (EBFF)

Figure 1: Schematic Diagram of the EBFFF Process





Selected Parameters:

Wire diameter: 2,36mm (TiAl6V4)

Wire feeding: 1780mm/min

Wall Thicknesses: bis zu 0,76mm möglich

Part Dimensions:

Diameter up to 40cm

Length / Width app.. 60cm

Built Rate: 2,3kg/h

50% Material Saving compared with machining

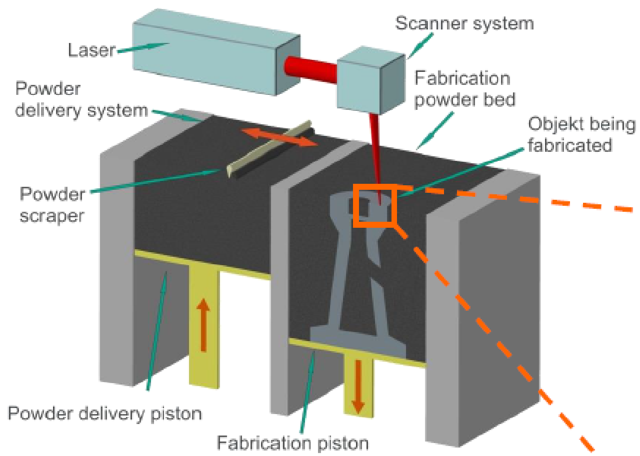
Sciaky, Inc.

2.2.3 Laser Beam Melting (LBM)

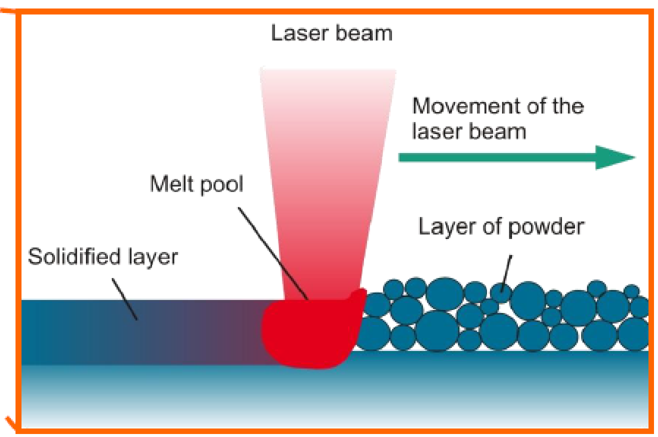
Manufacturing methods

Laser beam melting (LBM)

- **direct, single step process,** creating parts out of **series-like metallic material**
- **complete local melting** of the metal powder to a **99.5 - 100 % dense microstructure**



Principle sketch of a laser melting machine



Schematic diagram of laser beam melting

Source: Fraunhofer-IWU

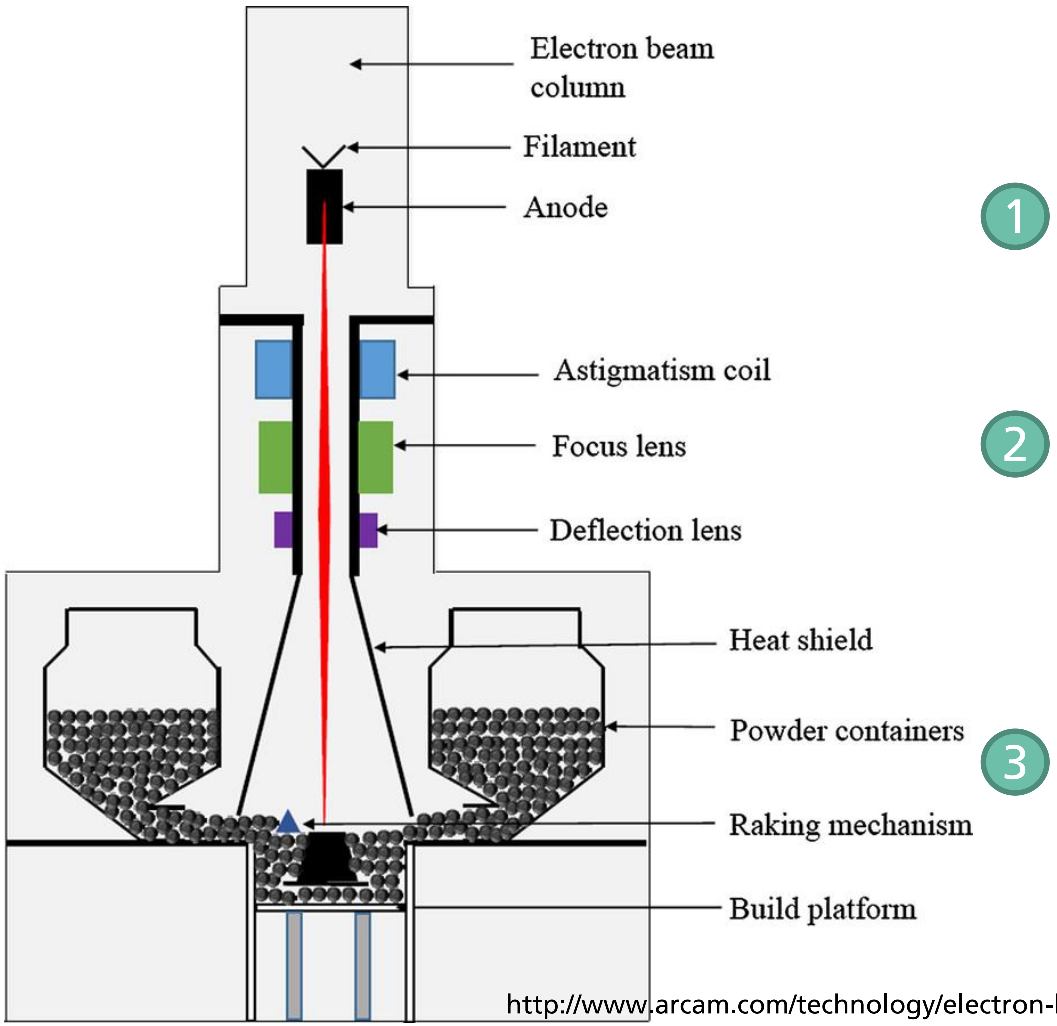
$$E_V = \frac{P_L}{h_P \cdot v_L \cdot h_L}$$

2.2.4 Electron Beam Melting (EBM)

- **EBM is a hot process**
  - each layer of powder is pre-heated, temperature is material-dependent (e.g. Ti-6Al-4V: ca. 700°C, TiAl: > 1000°C)
  - powder "smoke" due to local buildup of charge is prevented by slight sintering of powder particles
  - thermal stresses can be minimized

- **EBM uses high vacuum as process atmosphere**
  - this is required in order for the electron beam to work
  - highly reactive materials can be processed
  - outgassing of impurities
  - thermal insulation

Construction of an EBM-machine



http://www.arcam.com/technology/electron-beam-melting/hardware/

Methods of the powder evaluation

property	norm	relevance
Particle size distribution	DIN 13320	Flowability (powder feed and raking)
Hall Flow/Gustavsson (time)	DIN ISO 4490/DIN EN ISO 13517	Flowability Layer homogeneity
Morphology (SEM)		Flowability (powder feed and raking)
Apparent density	DIN ISO 3923/DIN ISO 3953	Layer homogeneity
Impurities	DIN EN ISO 9556 (C, S) DIN ISO 4491 (O, N)	Contamination before & after process, Component quality and properties
Moisture measurement (TGA)		Flowability (powder feed and raking) Component quality (internal faults)
Composition (ICP-OES, carrier gas hot extraction)		Component quality and properties
Powder density	DIN 51 913	Component quality (internal faults)

Powder properties: comparison LBM - EBM

Powder		EOS	Concept Laser	SLM Solutions	Arcam
D_{10}	µm	21.9	20.2	28.2	51.4
D_{50}	**µm**	**31.9**	**29.8**	**36.6**	**73.2**
D_{90}	µm	46.3	43.7	49.2	107.8
Flowability	s	39.3	53.2	31.7	21.8
Bulk density	g/cm³	2.46	2.54	2.45	2.59
Apparent density	g/cm³	2.83	2.83	2.73	2.81
Al- proportion	%	6.49	6.38	6.37	5.75
V- proportion	%	4.09	3.91	3.90	3.97
Fe- proportion	%	0.24	0.22	0.22	0.21
O- proportion	%	0.188	0.147	0.143	0.116
N- proportion	%	0.010	0.009	0.016	0.017

LBM:

differences in particle size (~8 µm)

differences in flowability (32 – 53s)

EBM:

low Al content (at lower limit but within specifiaction)

low Oxygen content

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Powder properties, surplus powder EBM

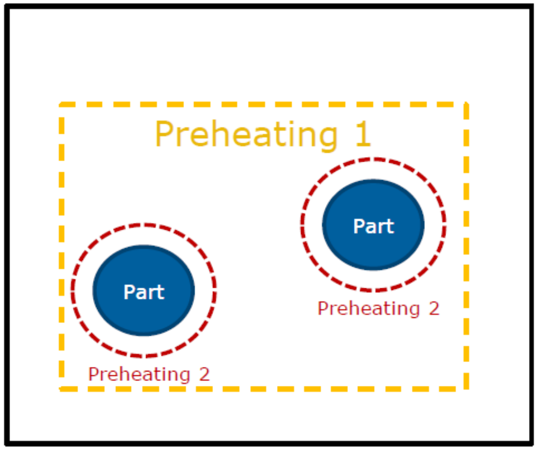
		new	13 build jobs
d10	µm	51,4	53,7
d50	**µm**	**73,2**	**75,7**
d90	µm	107,8	110,2
Hall-Flow (2.5 mm)	**s**	**21,8**	**20,8**
Rohdichte	g/cm³	2,59	2,56
O	**m%**	**0,12**	**0,14**
N	m%	0,017	0,018

- slight increase of oxygen content
- better flowability
- all other properties remain constant

Pre-heating

General principles

- Strongly de-focussed beam is led above the area
- Due to the thermal energy introduced: formation of sinter necks between the powder particles (diffusion)
- The process step is necessary because of the process stability
  - Electron beam is interacting with the powder
  - Charge concentration in particles leads to rejection → „smoke“
- 2 steps
  - Preheating 1
  - Preheating 2

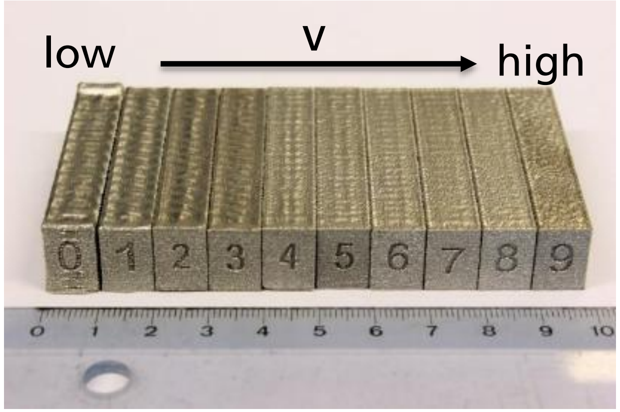


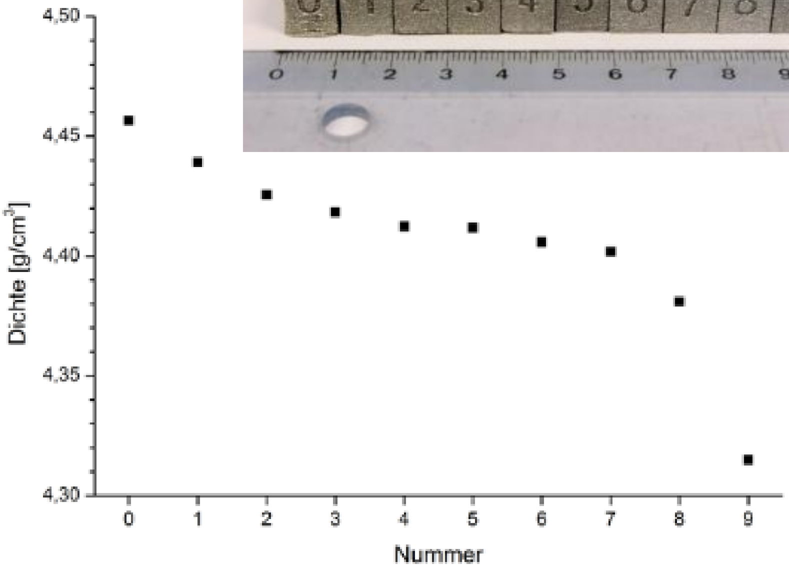
Source: Arcam

Melting

Processing and properties of Ti-6Al-4V
Process development - influence of scan-speed (I = constant)

- v = low
  - Very uneven surface, dents
    → too much powder has molten
  - Density > 100%
    → possible evaporating of Al
- v = high
  - Uneven surface
  - Density < 100%
    → inner Porosity





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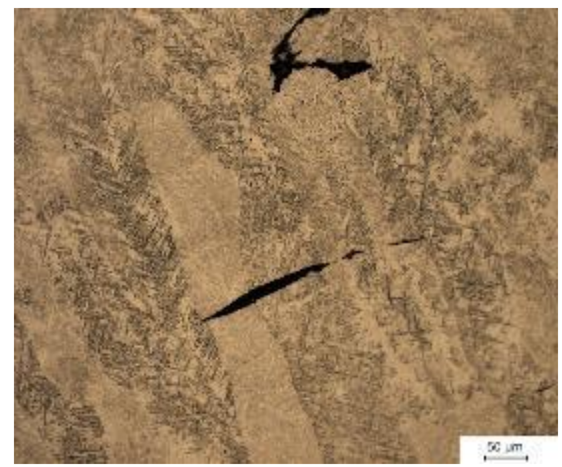
Melting

Processing and properties of Ti-6Al-4V
Process development - influence of scan-speed (I = constant)

- v = low → medium: grain refining
- v = low/medium → high: porosity (= construction errors), martensite formation

low

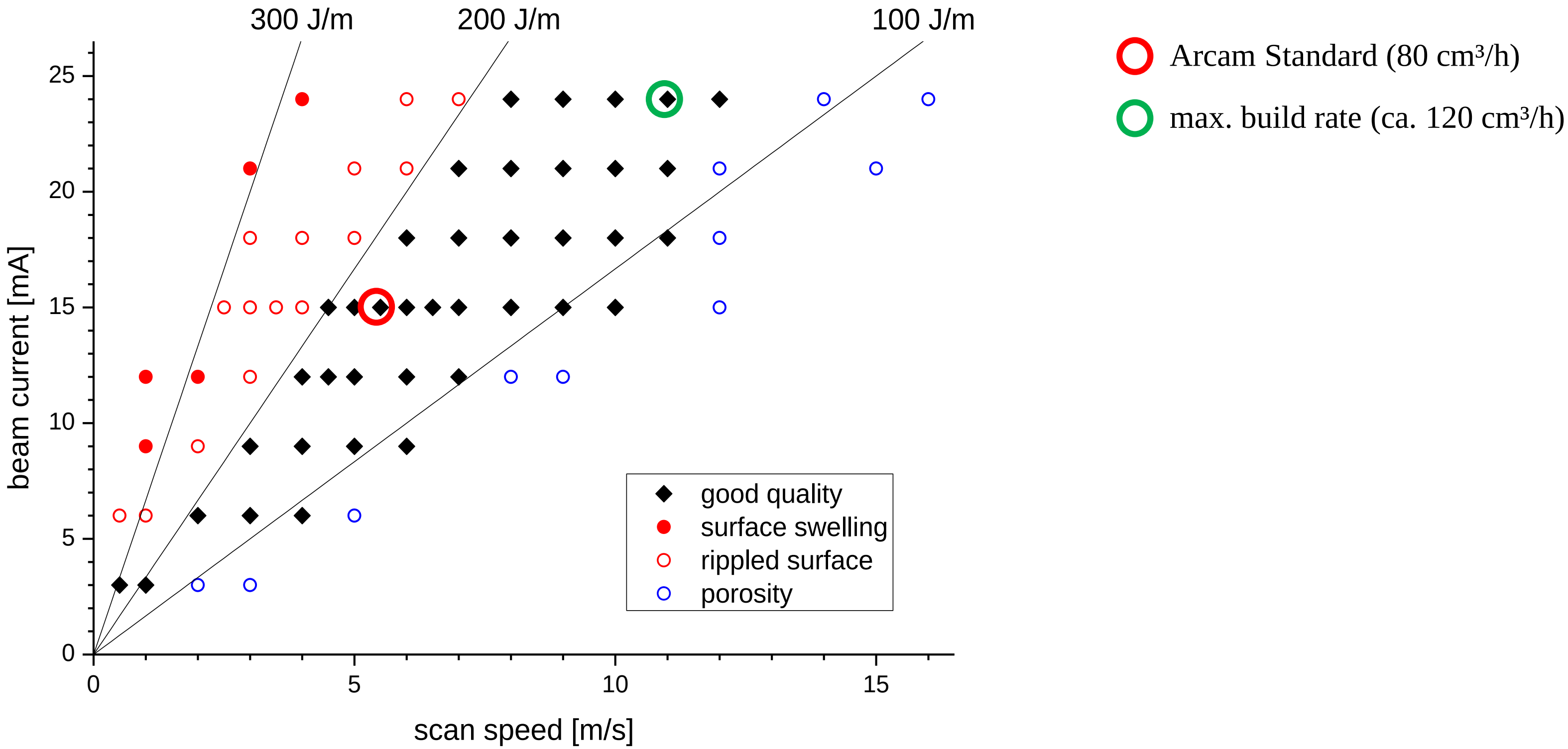
medium



high

scan-speed

Melting – increasing productivity

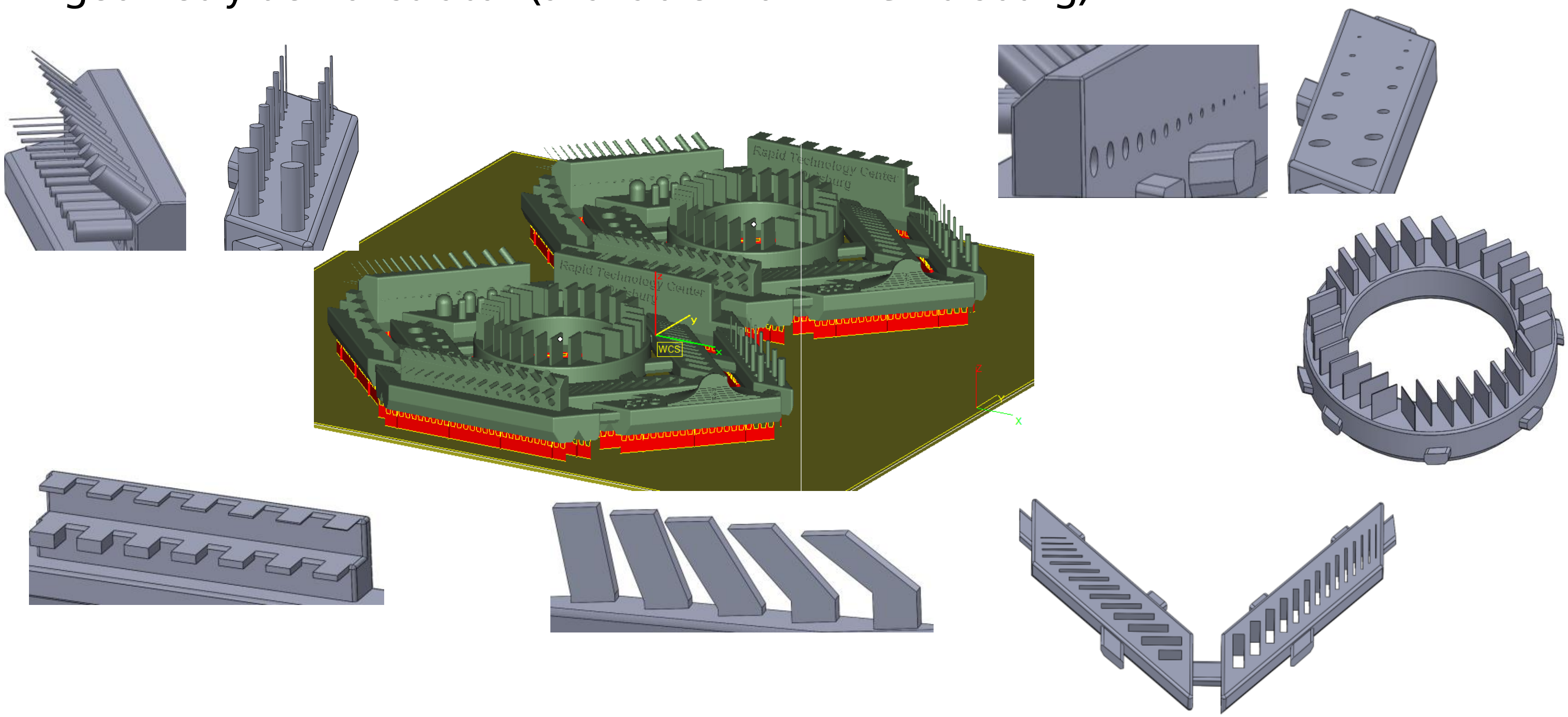


- without the need to change machine and powder, respectively: factor of 1,5 in build rate is possible

Design rules for EBM

Design limits for small structures

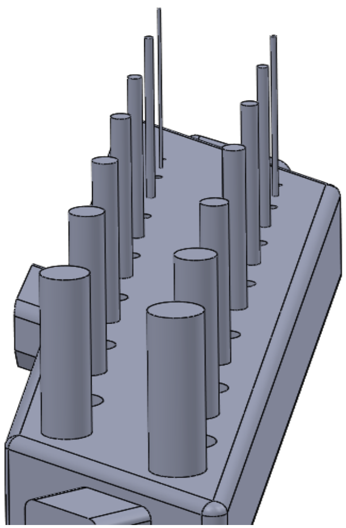
- geometry demonstrator (available from RTC Duisburg)

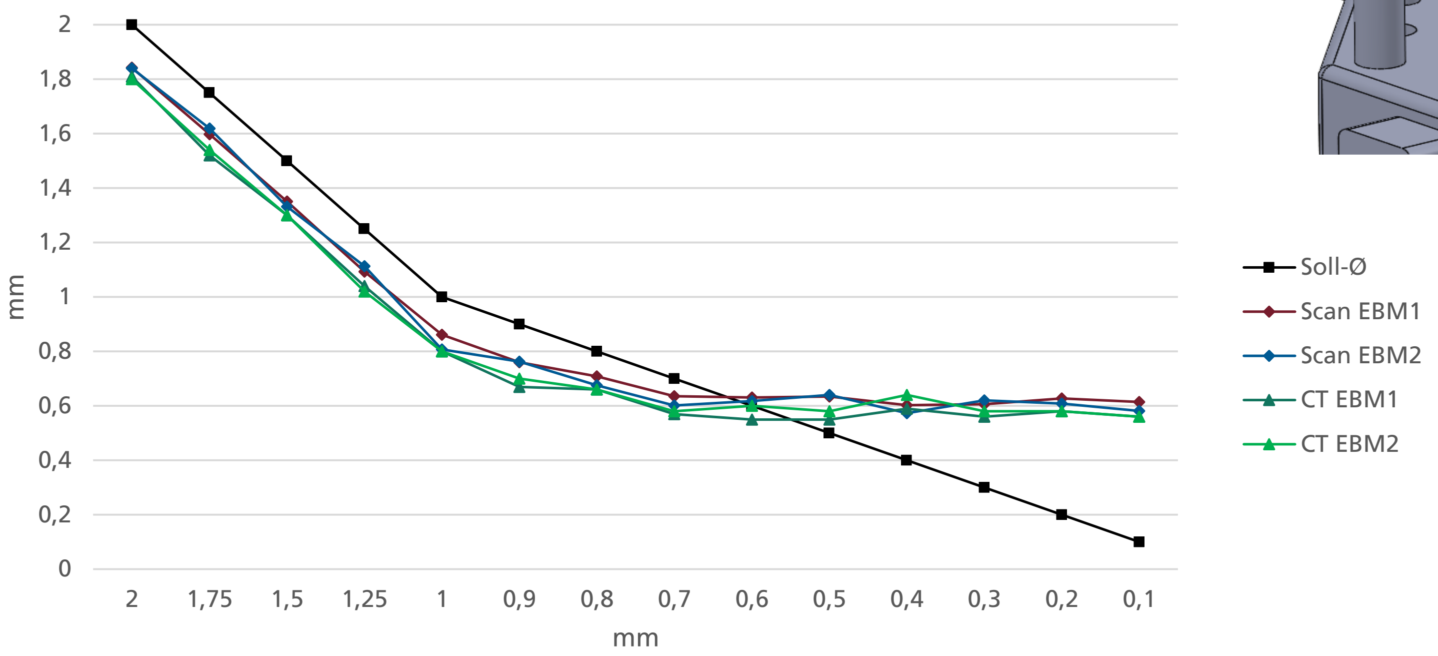


Design rules for EBM

Design limits for small structures example (I) – cylinders (Ti6Al4V; A2X)

- Minimum diameter: 0.6 mm
- systematic offset for d > 0.6 mm: 0.15 – 0.2 mm





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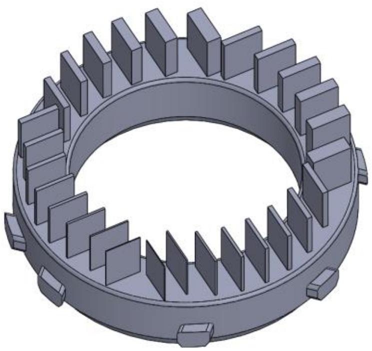
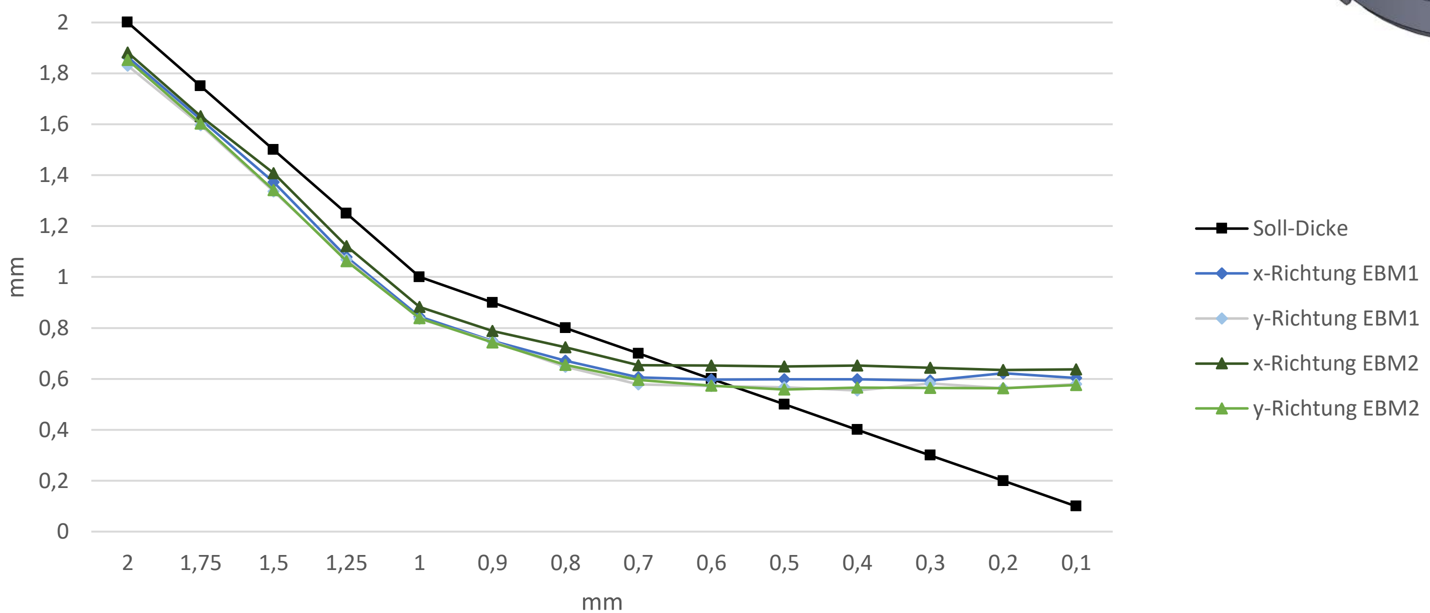
Design rules for EBM

Design limits for small structures example (I) – walls (straight) (Ti6Al4V; A2X)

- minimum wall thickness ≥ 0.6 mm
- systematic offset for d > 0.6 mm: up to 0.2 mm





Materials

„comparison“ LBM – EBM

material	LBM	EBM
Ti-6Al-4V	☑	☑
Ni-Basis (e.g. IN 718, IN 625)	☑	☑
TiAl (RNT650, TNM)	☒	☑
Al-bases (e.g. AlSi-X, AlMgSc)	☑	☒
CoCr	☑	☑
Stainless steel (e.g. 1.4404, 17-4PH)	☑	☑
tool steel (e.g. 1.2709)	☑	---
Copper alloys (e.g. CuNi2SiCr)	☑	---
pure copper	☒	☑

Materials

Ti-6Al-4V

MECHANICAL PROPERTIES

Quelle: http://www.arcam.com/wp-content/uploads/Arcam-Ti6Al4V-Titanium-Alloy.pdf

	Arcam Ti6Al4V, Typical	Ti6Al4V, Required**	Ti6Al4V, Required***
Yield Strength (Rp 0,2)	950 MPa	758 MPa	860 MPa
Ultimate Tensile Strength (Rm)	1020 MPa	860 MPa	930 MPa
Elongation	14%	>8%	>10%
Reduction of Area	40%	>14%	>25%
Fatigue strength* @ 600 MPa	>10,000,000 cycles		
Rockwell Hardness	33 HRC		
Modulus of Elasticity	120 GPa		

*After Hot Isostatic Pressing **ASTM F1108 (cast material) ***ASTM F1472 (wrought material)

The mechanical properties of materials produced in the EBM process are comparable to wrought annealed materials and are better than cast materials.

- Mechanical properties comparable to wrought and cast alloys

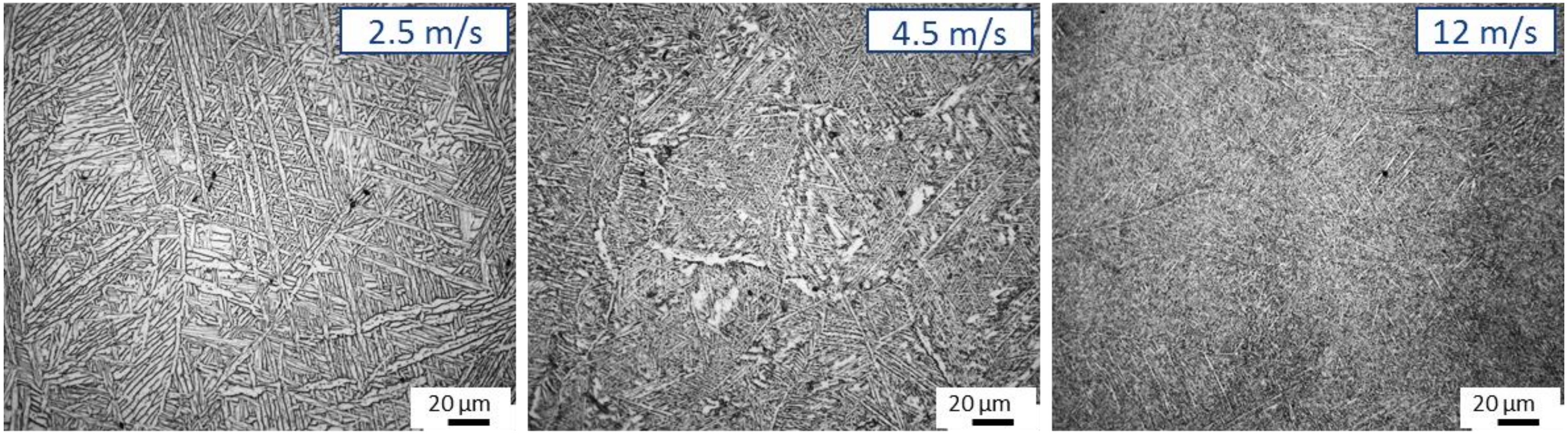
METAL AM TECHNOLOGIES (Electron Beam Melting (EBM))

Materials

- Ti-6Al-4V

- **EBM (Arcam A2X, 3 kW)**
- Ti6Al4V Powder
  45-105 µm, 1200-1400 ppm O
- Beam current: 15mA
- 700 °C (for Ti-6Al-4V)

- fully lamellar (basket weave) at low scan speeds (α-lamellae thickness app. ca. 20 µm)
- Refining up to 2…3 µm at higher scan speeds
- Formation of needle like α'-martensite at very high scan speeds



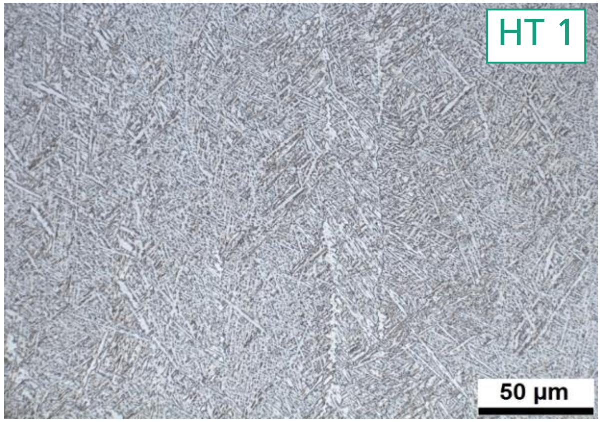
Kirchner et al., Process window for electron beam melting of Ti-6Al-4V, Powder Metallurgy 58 (2015), 246-249

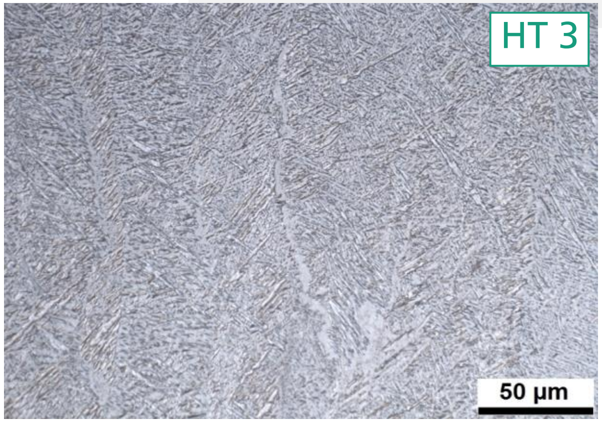
Materials

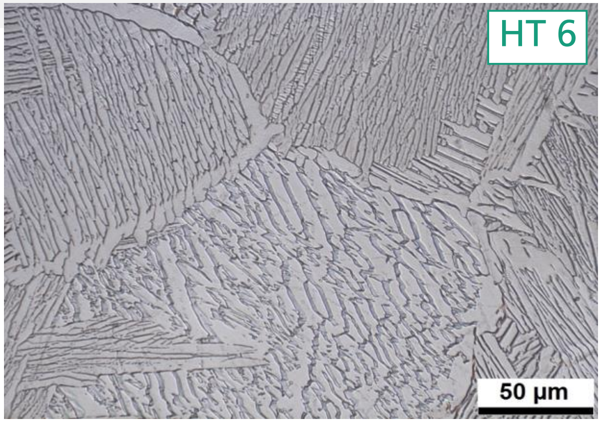
- Ti-6Al-4V

- **EBM (Arcam A2X, 3 kW)**
- Ti6Al4V Powder
  45-105 µm, 1200-1400 ppm O
- Heat Treatment of „as-built“ parts

- Low temperature: no significant microstructural changes compared to "as-built", **α-lamellas up to** 3µm thcik
- With increasing temperature coarsening of the α-Phase, in particular along former β-grain boundaries
- above β-Transus temperature coarsening of the α-phase







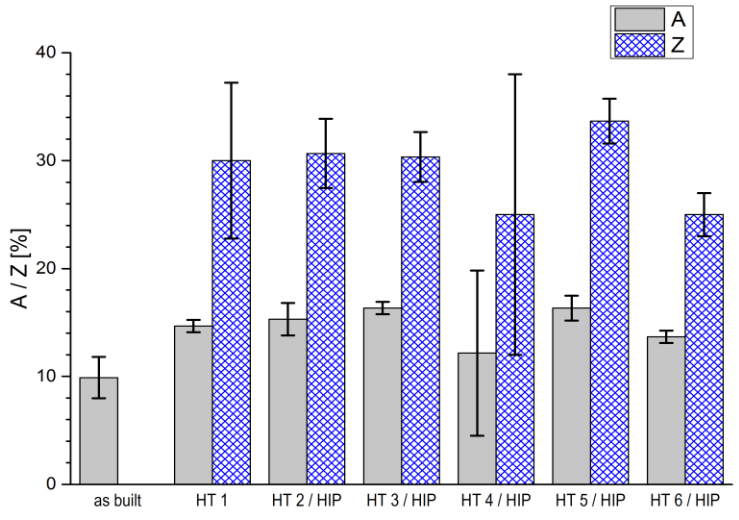
Kirchner et al., Mechanical Properties of Ti-6Al-4V fabricated by Electron Beam Melting, Key. Eng. Mat. 704 (2016), 235-240

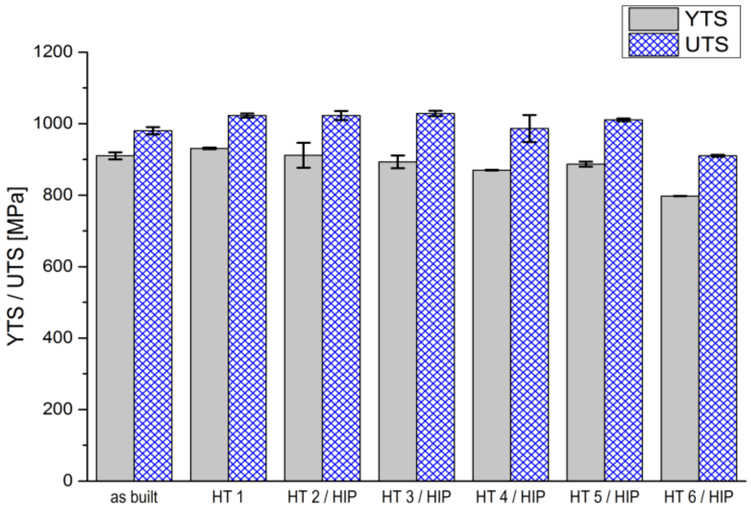
Materials

- Ti-6Al-4V

- **BM (Arcam A2X, 3 kW)**
- Ti6Al4V Powder
  45-105 µm, 1200-1400 ppm O
- Heat Treatment of „as-built“ Bauteile

- Youngs Modulus 114…123GPa, comparable with dense material without texture
- HT1 tensile strength of1023MPa nearly identical with "as-built", elongation 15%
- Higher heat treatment temperature leads to small reduction of strength
- AMS 4928 Specification is fullfilled



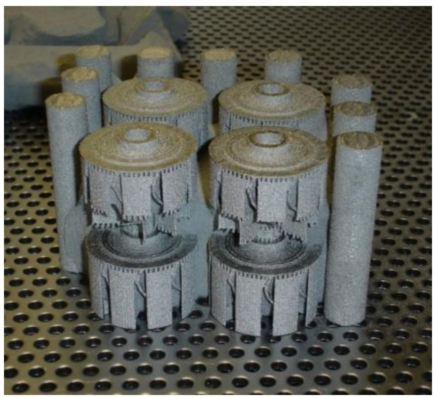


Kirchner et al., Mechanical Properties of Ti-6Al-4V fabricated by Electron Beam Melting, Key. Eng. Mat. 704 (2016), 235-240

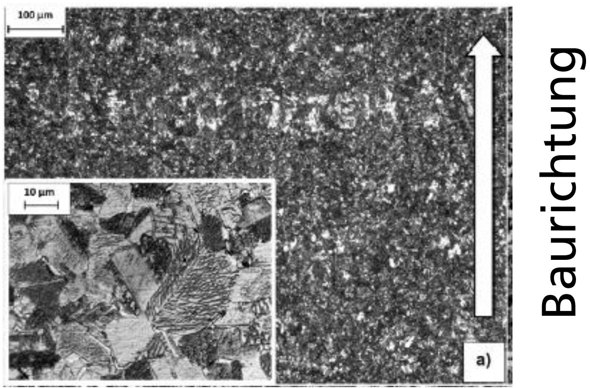
Materials

TiAl

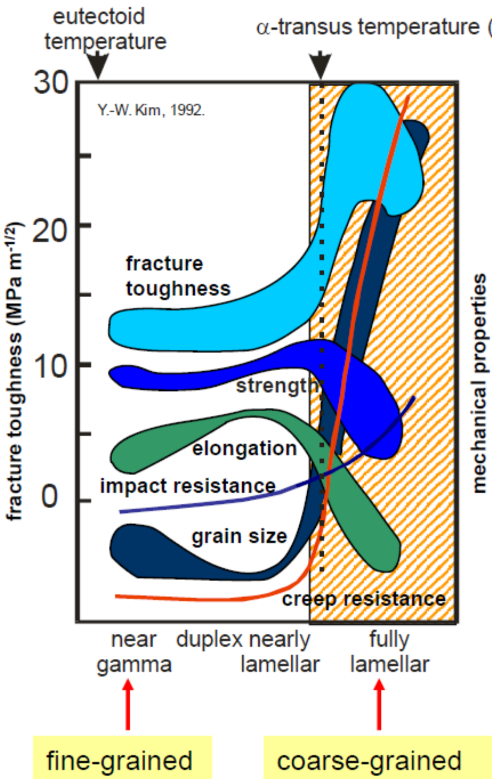
- EBM (Arcam A2X, 3 kW)



IFAM Dresden



Baudana et al



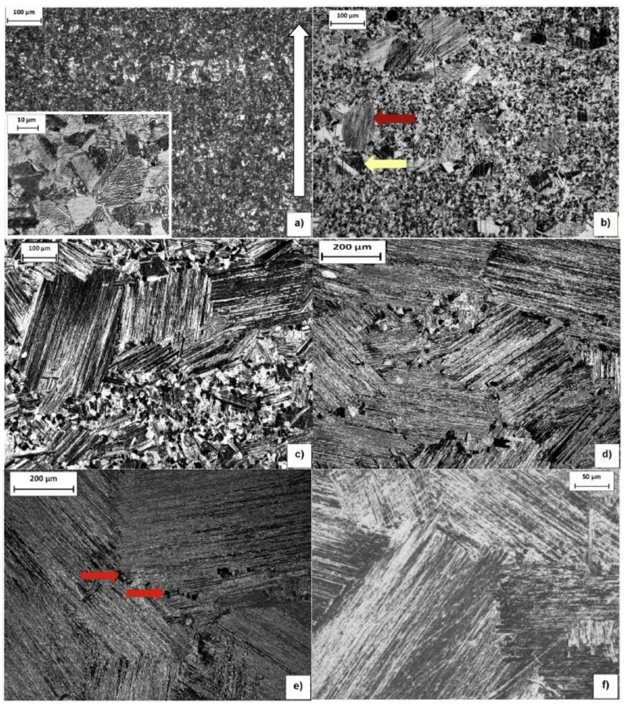
H. Clemens:, Montanuniversität Leoben

METAL AM TECHNOLOGIES (Electron Beam Melting (EBM))

Materials

TiAl

- **EBM (Arcam A2X, 3 kW)**



Heat Treatment of TiAl EBM-Parts

- Material: RNT650 (Ti48Al2Nb0.7Cr0.3Si)
- A: "as-built" - "fine-grained, equiaxed" (Porosität <1%)
- B: 1300 °C / 2h - "fine-grained equiaxed" with small amount of lamella grains
- C: 1350 °C / 2h - "duplex"
- D: 1360 °C / 2h - "near lamellar"
- E: 1365 °C / 2h - "fully lamellar" with small amount of globular grains
- F: 1370 °C / 2h - "fully lamellar"

➡ Microstructure can be tailored but "temperature window" is relatively small

G. Baudana, et al.Electron Beam Melting of Ti-48Al-2Nb-0.7Cr-0.3Si: Feasibility investigation, Intermetallics, Volume 73, 2016, 43-49

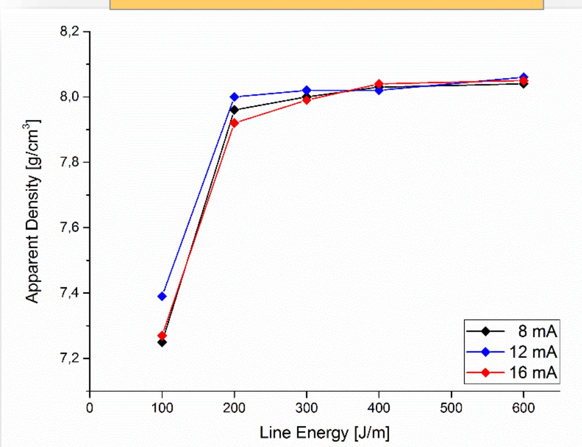
METAL AM TECHNOLOGIES (Electron Beam Melting (EBM))

Materials

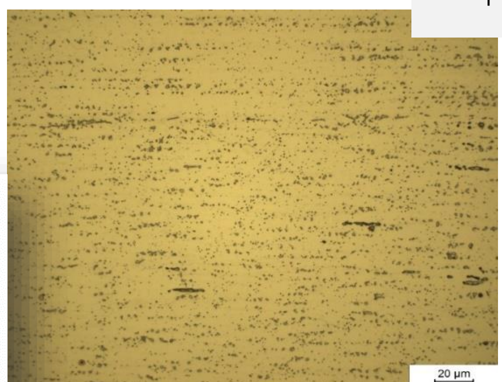
IN 718

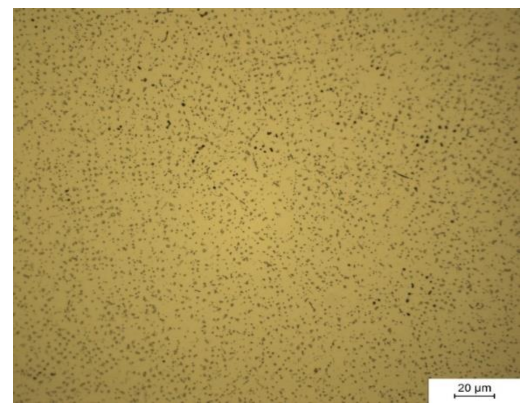
- **EBM (Arcam A2X, 3 kW)**
- Inconel 718 / NiCr19Fe19Nb5Mo3 / 2.4668

$$E_L = \frac{U_B \times I_{beam}}{v_{scan}}$$



- Strong (100)-Texture parrallel to building direction
- Microstructure design possible by choosing proper scan parameters





Kirchner et al, Electron Beam Melting of Inconel 718, Proceedings DDMC 2018, Berlin, March 14 – 15 2018, 154, ISBN 978-3-8396-1320-7

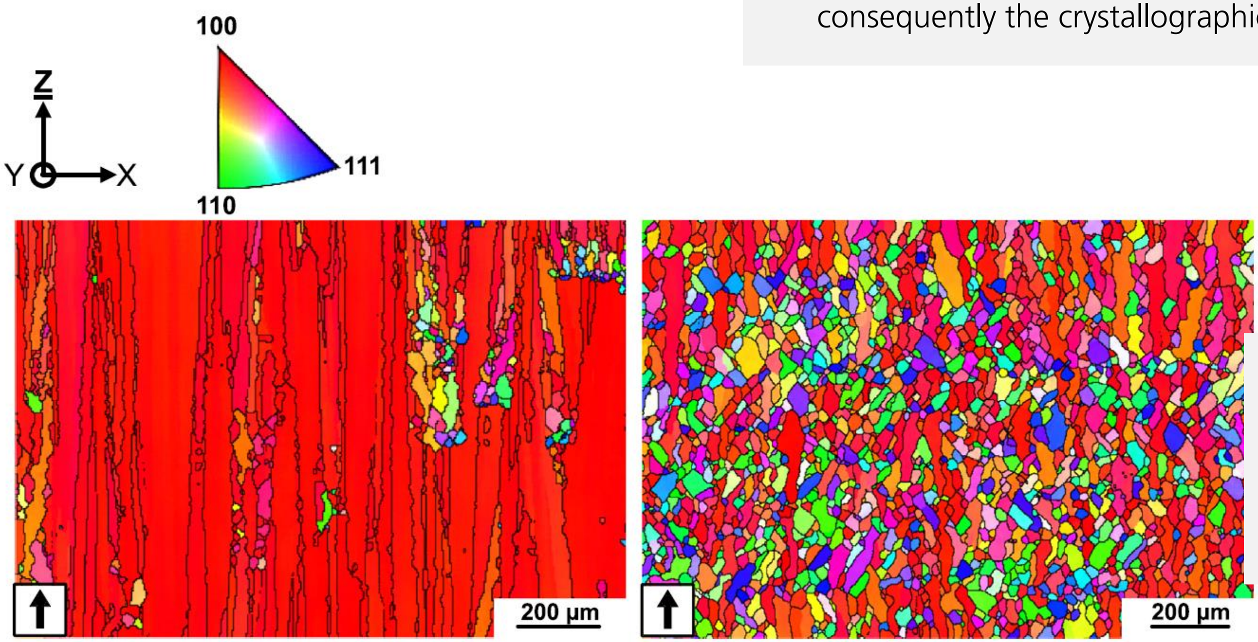
Materials

IN 718

- EBM
- Inconel 718 / NiCr19Fe19Nb5Mo3 / 2.4668

→ Scan speed and hatch distance influencing the melt pool geometry

→ Melt pool geometry defines temperature gradient and consequently the crystallographic growing direction



(a) (b)

a) E_A=1,8 Jmm^{-2}, v=2,2 ms^{-1}, L_{off}=150 µm

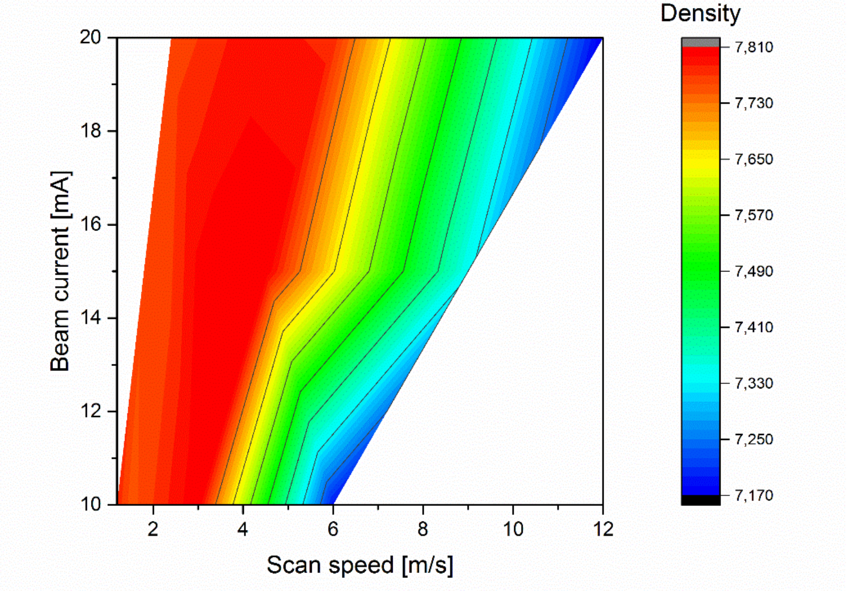
b) E_A=1,9 Jmm^{-2}, v=8,8 ms^{-1}, L_{off}=37,5 µm

H. Helmer et al. / Materials Science & Engineering A 668 (2016) 180–187

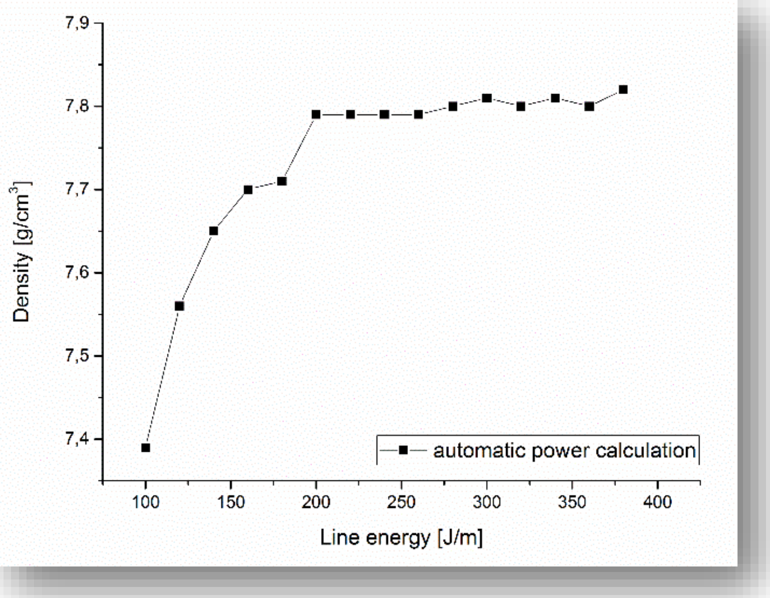
Materials

304L

- **EBM**
- 304L / X2CrNi19-11 / 1.4306
- Pre-Heating: 880 °C, layer thickness: 70 µm, hatch distance: 100 µm
- 200 J/m line energy for complete densification necessary



Kirchner et al., Selective Electron Beam Melting Of Austenitic Stainless Steel, EBAM 2018



Applications

Topology optimization of aerospace part

optimization result (II)

- step 1: scale 1:2, material: Ti-6Al-4V (1st design)
- step 2: full scale part (recalculated design after changes in loads, rivet holes, …)
  - dimensions in build chamber (x/y/z): 171 / 179 / 158 mm
  - build time: 29h
- for testing, part has been completely surface-treated (CNC + electro-polish)


1st design


2nd design, as-built


2nd design, finished

Applications

serial and prototype parts – Avio GE TiAl

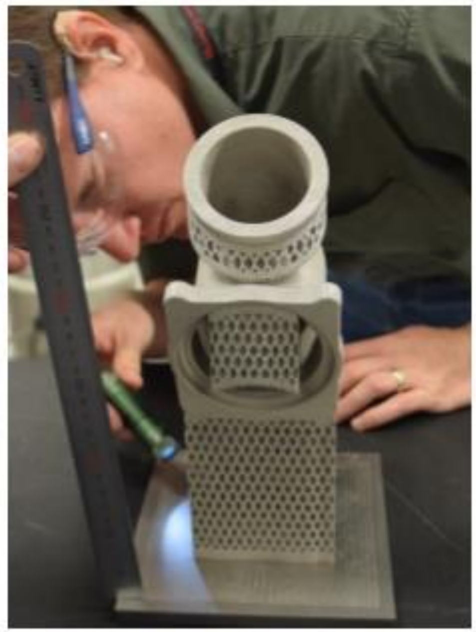
- EBM-manufactured turbine blades for different aero engines (from left to right):

Source: http://www.gereports.com/post/94658699280/this-electron-gun-builds-jet-engines/ (last access: 02 Dec 2016)

Applications

IN718

Medina, Optimizing EBM Inconel 718 Mechanical Properties with "Post Treating", S. 28


Built time: 37:00 Stunden
Cooling time: 08:00 Stunden

Built time: 76:00 Stunden
Cooling time: 12:00 Stunden

- Examples from aerospace

Applications

CoCr

Arcam AB, Arcam ASTM F75 CoCr, p. 2

- application:
  - Medicine (Knee, tooth)
  - Turbines (nozzles and blades)

„comparison“ SLM - EBM

property	EBM	LBM
source	electron beam	laser beam
Beam power	high (up to 3kW)	medium (up to 1 kW)
Atmosphere	Vacuum	e.g. Ar
Powder	coarse (45 – 150 µm)	fine (10 – 45 µm)
Beam deflection	EM coils	galvanometer
Scan speed	very fast	fast
Build Rate (Ti-6Al-4V)	high (≥ 80 cm³/h)	medium (20-30 cm³/h)
Pre-heating	yes (electron beam)	in development
Cooling rate	medium	high
Residual stresses	low	high
Surface quality	low (Ra = 40µm)	medium (Ra = 20 µm)

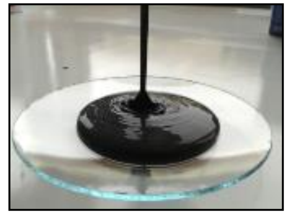
2. METAL AM TECHNOLOGIES

2.3 Solid State TECHNOLOGIES

2.3.1 Introduction

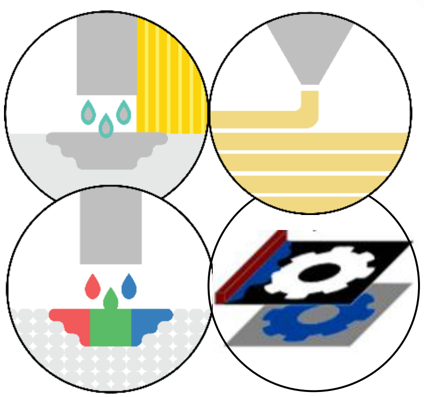
CAD design

(format e.g. .stl)



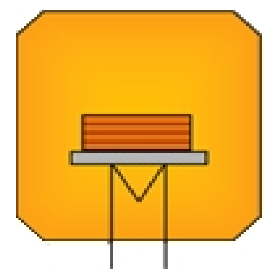
printing material

(e.g suspension, filament)



process technologies

„green part“



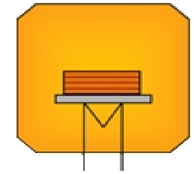
sintering

Solid state processes:

- No melting of particles
- Multi step production process
- 1. Preparation of green parts
- 2. Sintering process
- 3. Post Processing (optional)

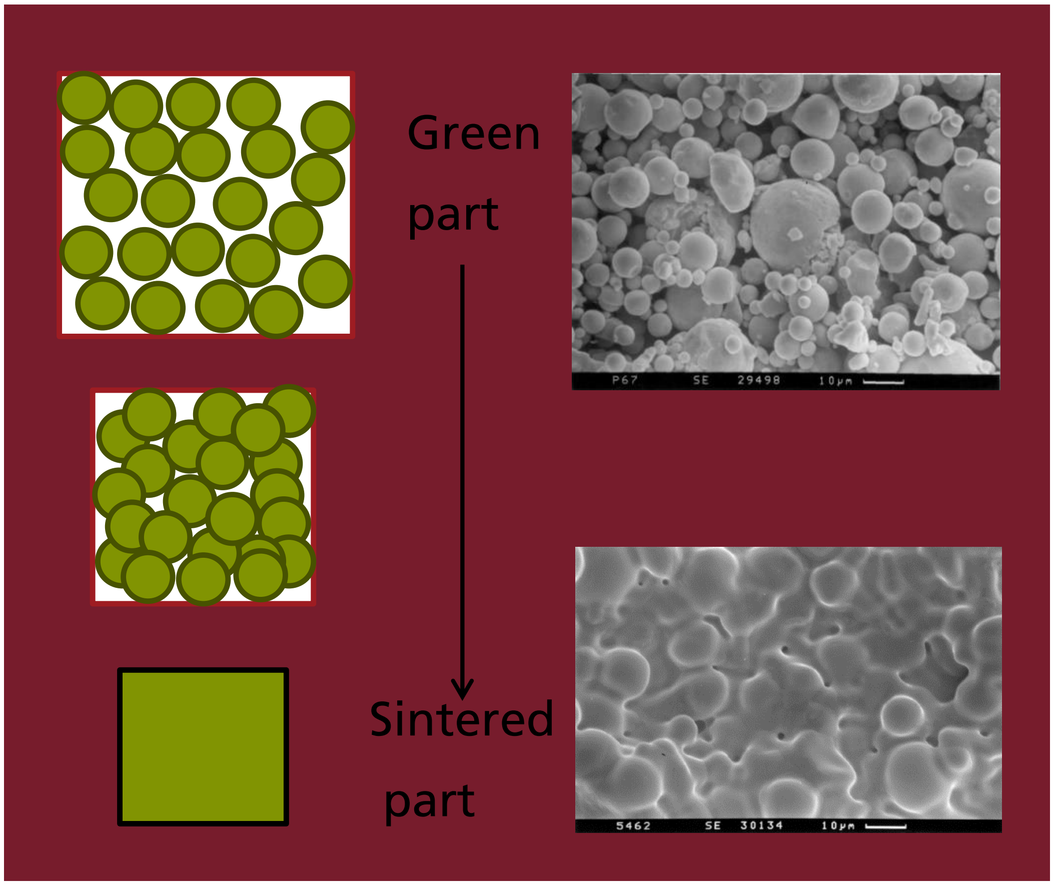
Exception: LOM/UAM

2.3.1 Introduction



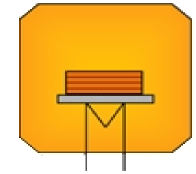
sintering

Fundamentals of sintering



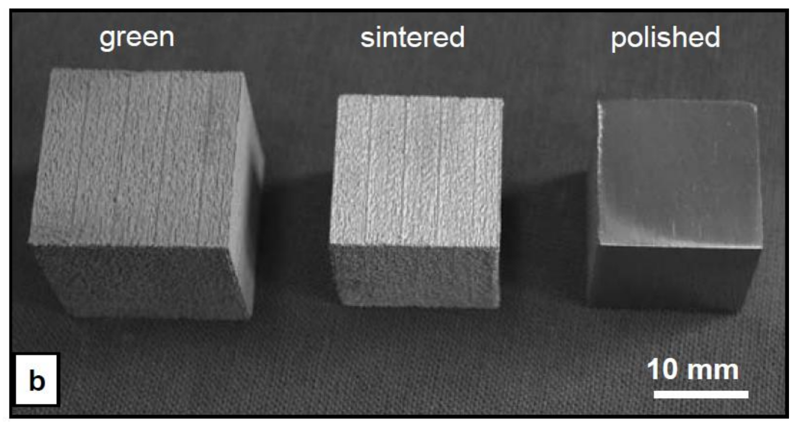
- First step: **Debindering**
  - Removal of binders by
  - Heat
  - Solvent

2. METAL AM TECHNOLOGIES
2.3 Solid State TECHNOLOGIES
2.3.1 Introduction



Fundamentals of sintering

- Second step: **Sintering**
  - thermal treatment at a temperature below the melting point of the main constituent
  - Driving force: reduction of the surface area, surface energy
  - determines most of the material properties via density or residual porosity
  - Shrinkage of printed parts
  - Linear shrinkage 10 – 20 %



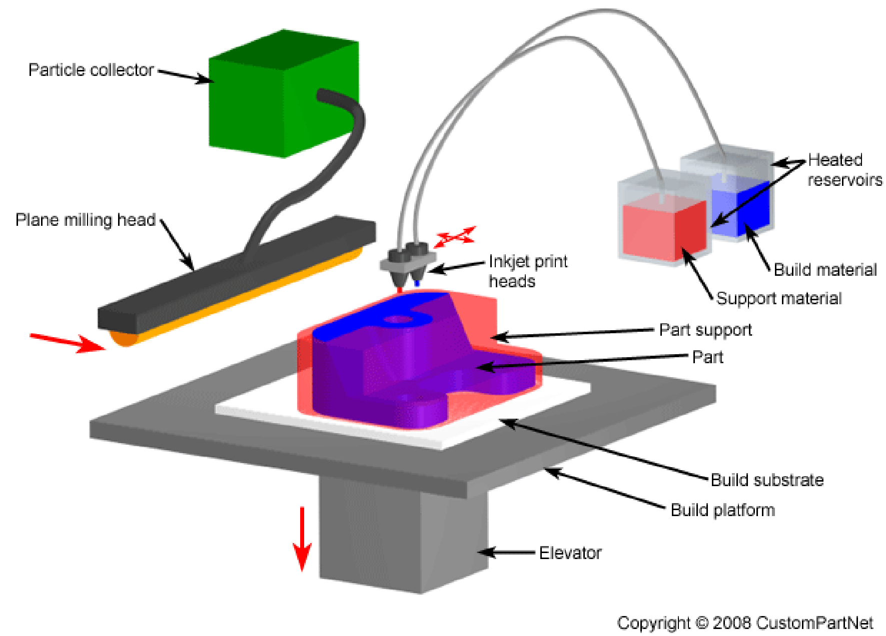
Material Jetting – process outline

- Process available for materials like:
  - Waxes, photopolymers → Drop on Demand (DOD)
  - Metallic nano particles → Nano particle Jetting (NPJ)

Process - Step by Step

1. Generation of droplets
2. Droplets wet the substrate
3. UV curing (DOD)

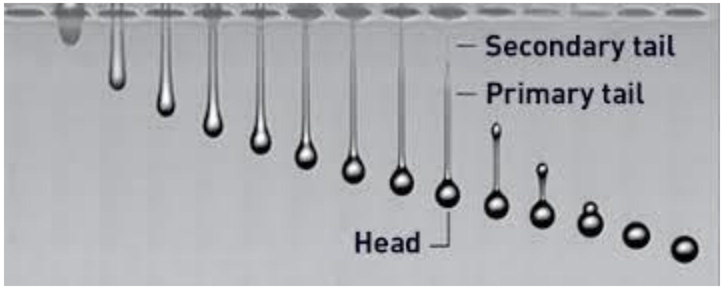
   Removal of solvent by heat (NPJ)
4. Lowering position of build platform
5. Next layer is added



Material Jetting – process characteristics

- Process properties:
  - Resolution: 30 – 100 µm
  - Build rate: 6 – 24 cm^3/h
  - Layer thickness: up to 2 µm
  - Support structures: yes, printed parallel
  - Materials: metals, ceramics
  - Powder requirements: < 2 µm

Source: XJET



Droplets created by Inkjet Printing

Material Jetting– examples and properties

- AM part properties:
  - Surface quality: high
  - Density: full density possible
  - Post treatment: not necessary
- Applications
  - Medical Technology
- Industrial Suppliers:
  - XJET (Israel)
  - Stratasys (USA) → Polymers


Source: XJET

Source: XJET

Material Jetting– examples and properties

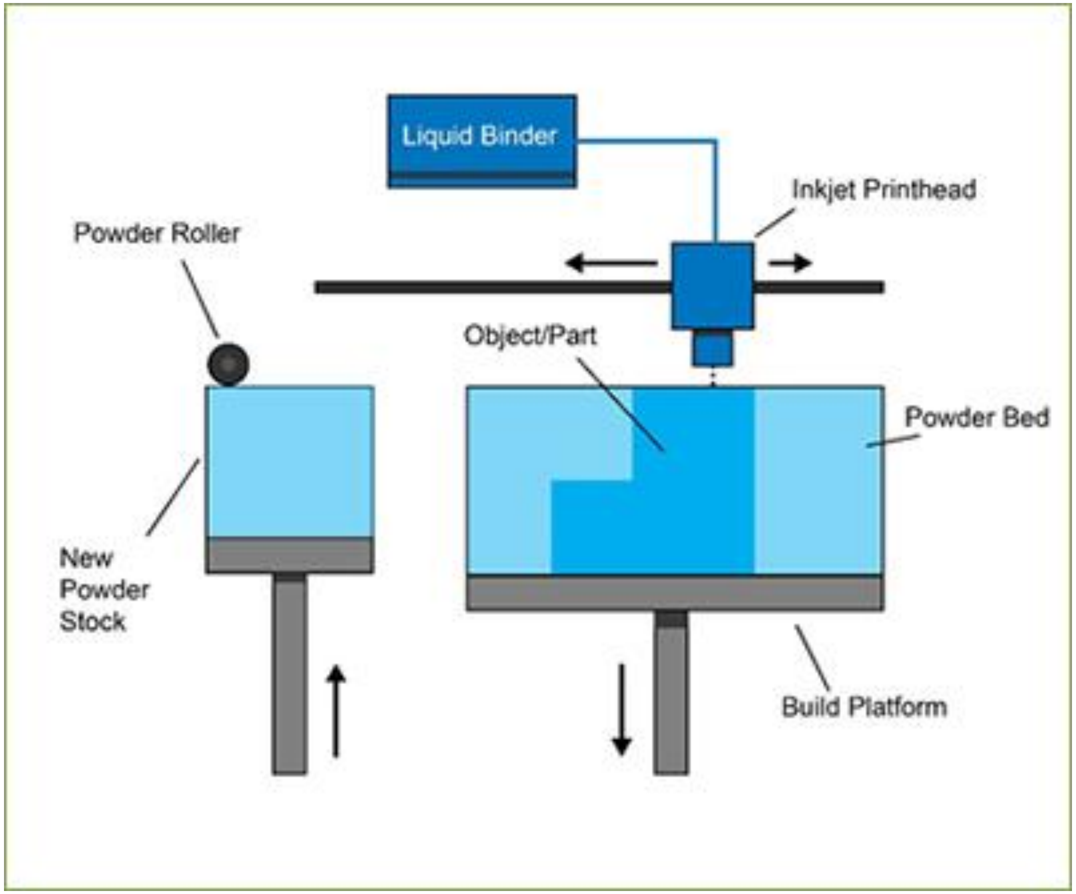
- Advantages
  - High accuracy
  - Smooth surfaces
  - Low sintering temperatures
- Disadvantages
  - Expensive powders
  - Slow process

Source: XJET

Source: XJET

2.3. Solid State TECHNOLOGIES

2.3.3 Binder Jetting



Source: Loughborough University, Additive Manufacturing Group

Process - Step by Step

1. Spread fresh powder layer
2. Printing of binder
3. Drying of binder
4. Lowering position of build platform
5. Next layer is added

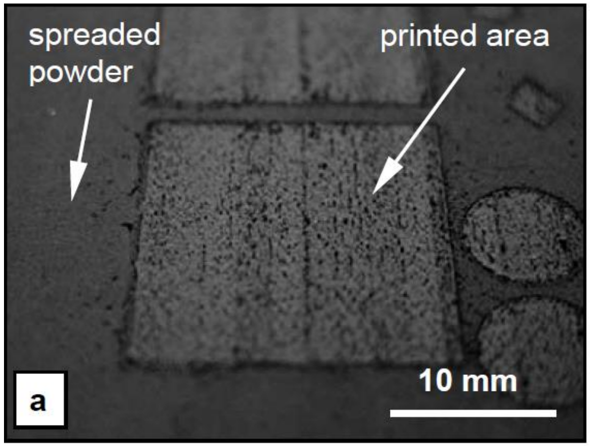
Binder Jetting – process characteristics

- Process properties:
  - Resolution: > 125 µm
  - Large parts possible
  - Build rate: up to 1000 cm^3/h
  - Layer thickness: > 90 µm
  - Support structures: not needed
  - Materials:

    Full range of MIM materials

    Ceramics, Steels
  - Powder requirements: > 20 µm

Source: Ex One



Binder Jetting – examples and properties

- AM part properties:
  - Surface quality: $R_Z \approx 50$ µm
  - Density: 95 -98%
  - Post treatment: e.g.Infiltration, Annealing or Polishing

- Applications
  - Metal parts for artistic purposes
  - Sand casting molds

- Industrial Suppliers:
  - Ex One (USA)
  - Hogänäs (Sweden)

Design: Airbus Deutschland GmbH

Binder Jetting – examples and properties

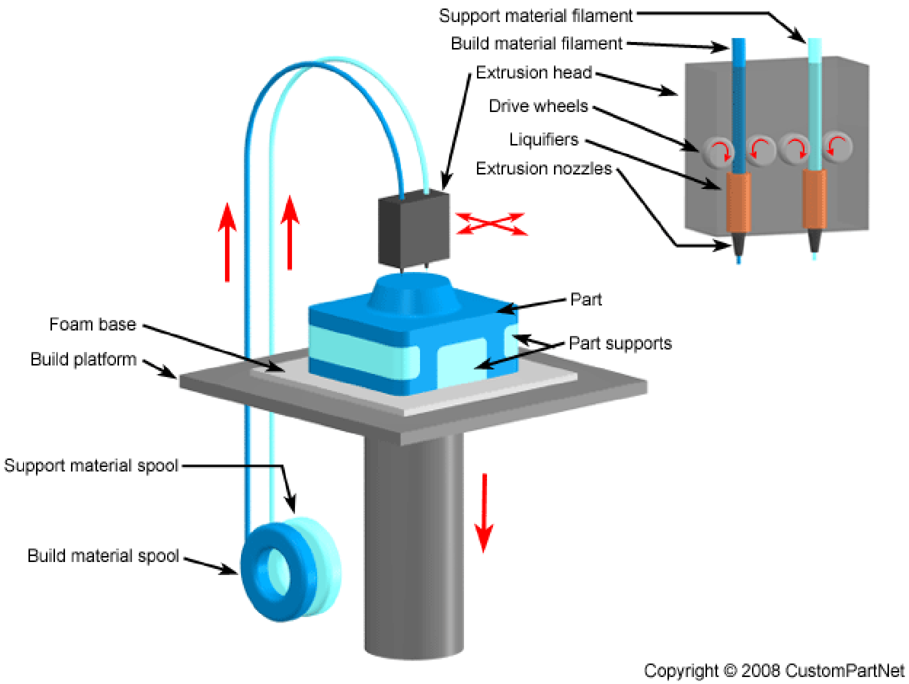
- Advantages
  - High resolution
  - Material variety
  - No supports structures
  - Fast process

- Disadvantages
  - Post-processing steps necessary
  - Shrinkage during sintering

Design: Airbus Deutschland GmbH

2.3. Solid State TECHNOLOGIES

2.3.4 Fused Filament Fabrication (FFF)



www.additive3D.com

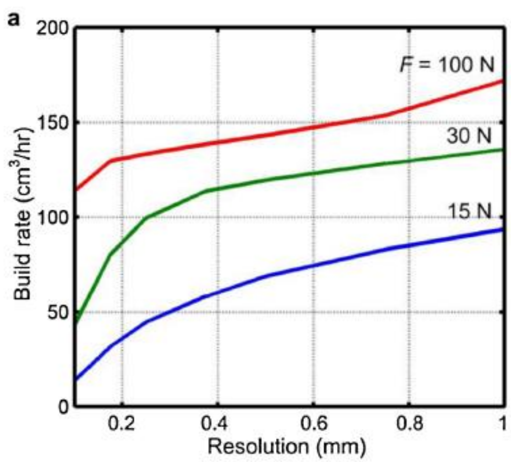
Source: www. Ultimaker.com

Process - Step by Step

1. Feed of filament to the print head
2. Extrusion of filament by heat
3. Deposition of filament on the build platform
4. Lowering position of build platform

Fused Filament Fabrication – process characteristics

- Process properties:
  - Resolution: 0.2 -1 mm (nozzle size) xy-direction, 0,05 mm z-direction
  - Build rate: 10 – 150 cm³/h



J. Go. et. al.,

Additive Manufacturing 16, 2017

  - Support structures: yes
  - Materials: polymers (ABS, PLA, PET, …), metals in R&D: 316L, tool steel, copper, titanium
  - Combinations of up to 5 different materials possible (number of nozzles on hot end)

Fused Filament Fabrication – examples and properties

- AM part properties:
  - Surface quality: waviness depending on layer height
  - Density: full density parts possible
  - Layering effects possible
- Applications
  - Prototyping (e.g.Medical, Aviation)
- Industrial Suppliers:
  - German Rep Rap (Germany)
  - Stratasys (USA)

http://www.javelin-tech.com

Fraunhofer IFAM

Fused Filament Fabrication – examples and properties

- Advantages
  - Low machinery invest
  - Low machinery complexity
  - Multimaterial systems possible

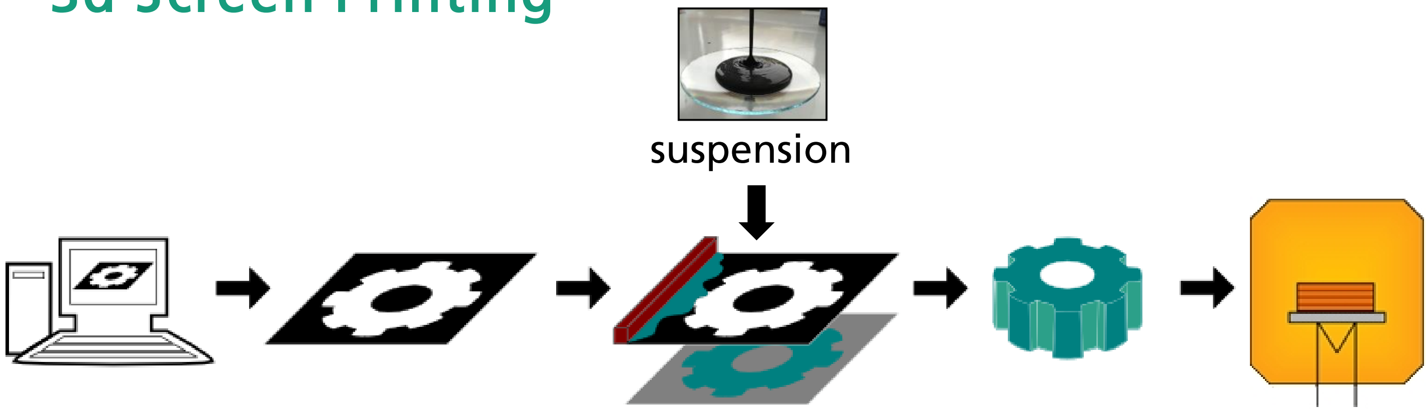
- Disadvantages
  - Poor surface quality
  - Post processing necessary
  - Metallic systems not commercially available

http://www.javelin-tech.com

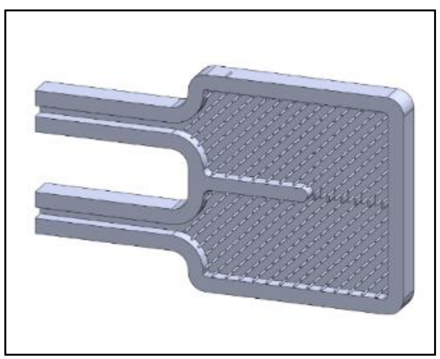
Fraunhofer IFAM

2.3. Solid State TECHNOLOGIES

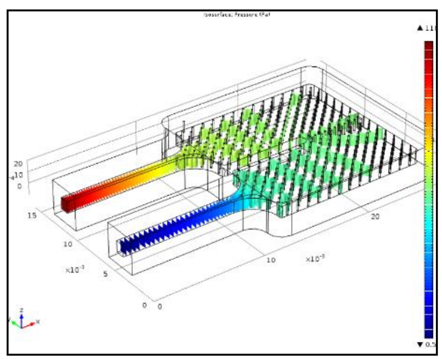
2.3.5 3d Screen Printing



design | screen/stencil | printing | „green part“ | sintering

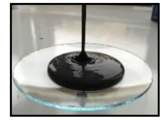


heat exchanger

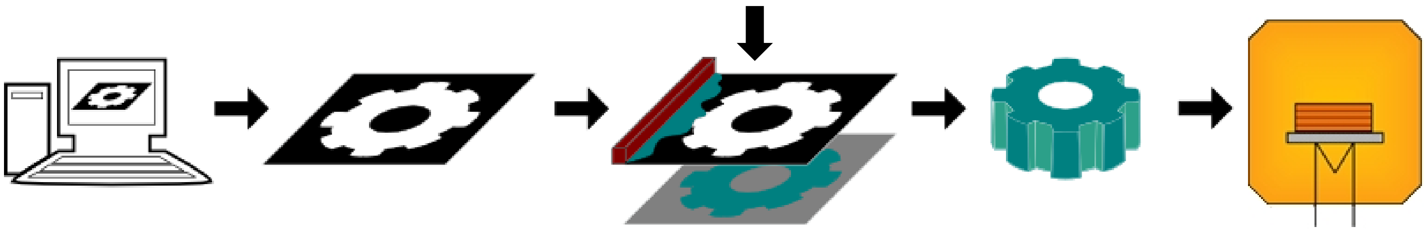


- #-planes -> #-screens
- Small #-planes preferred
- Screen can be seen as tool

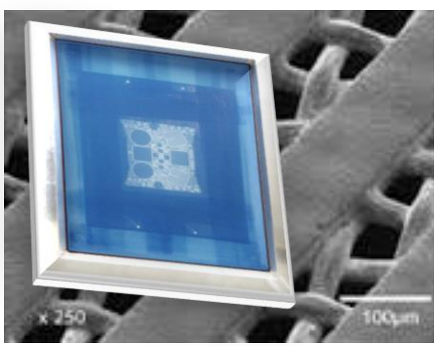
3D screen printing – process outline

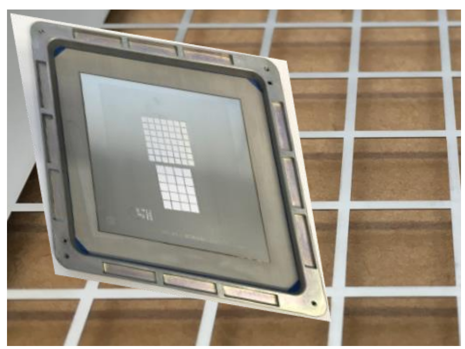


suspension



design | screen/stencil | printing | „green part“ | sintering

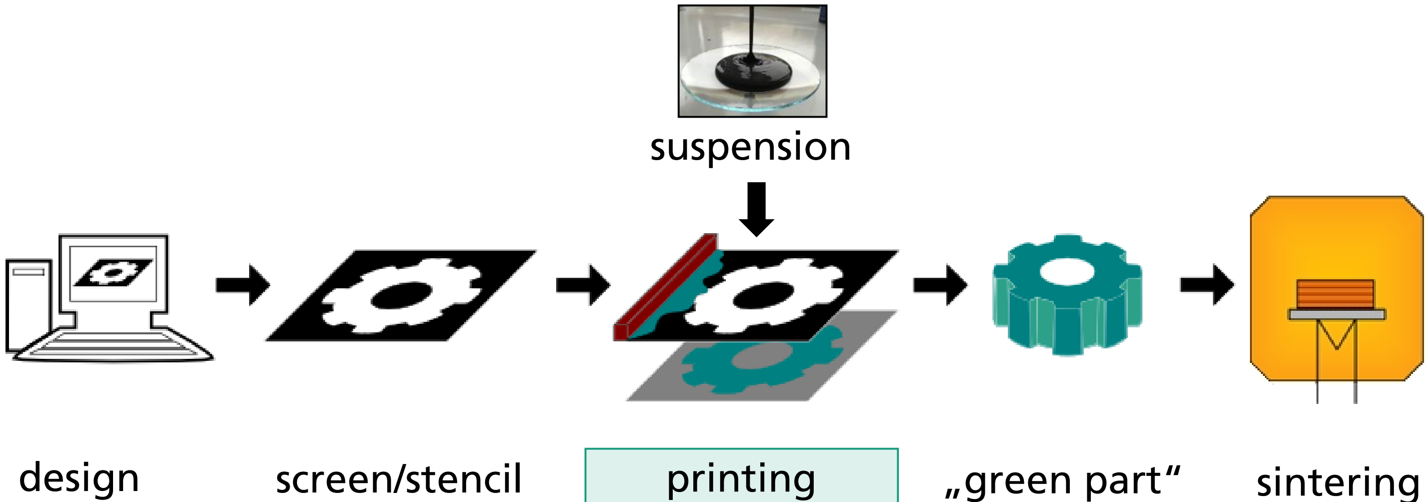


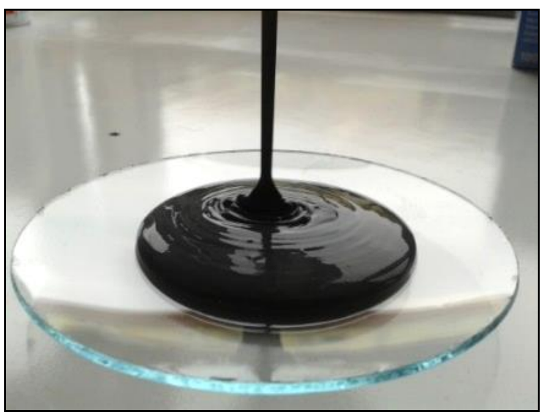


Sample screen (left) and close-up showing coating (right)

- Screen printing:
  Polymer coating defines layout
- Stencil printing:
  Cut openings define layout
- Fineline-printing: ~80 µm
- std. screen ~70 µm mesh opening

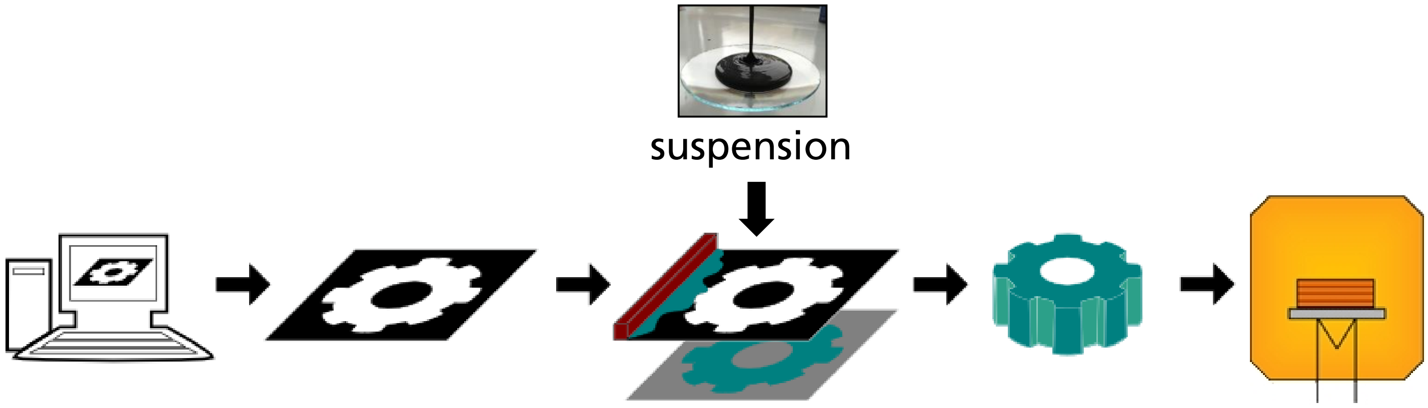
3D screen printing – process outline

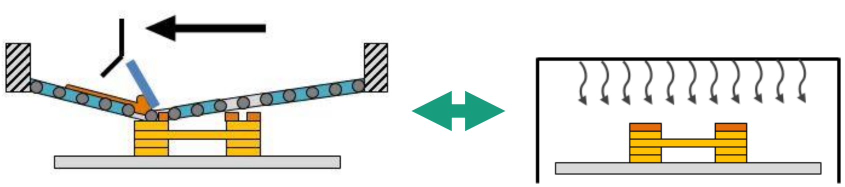




- Paste: powder, additives, binder, carrier
- Solid loading 20-45 vol%
- Adjusting viscosity right is crucial
- Layer height 5-50 µm (screen)
- Layer height 300 µm (stencil)

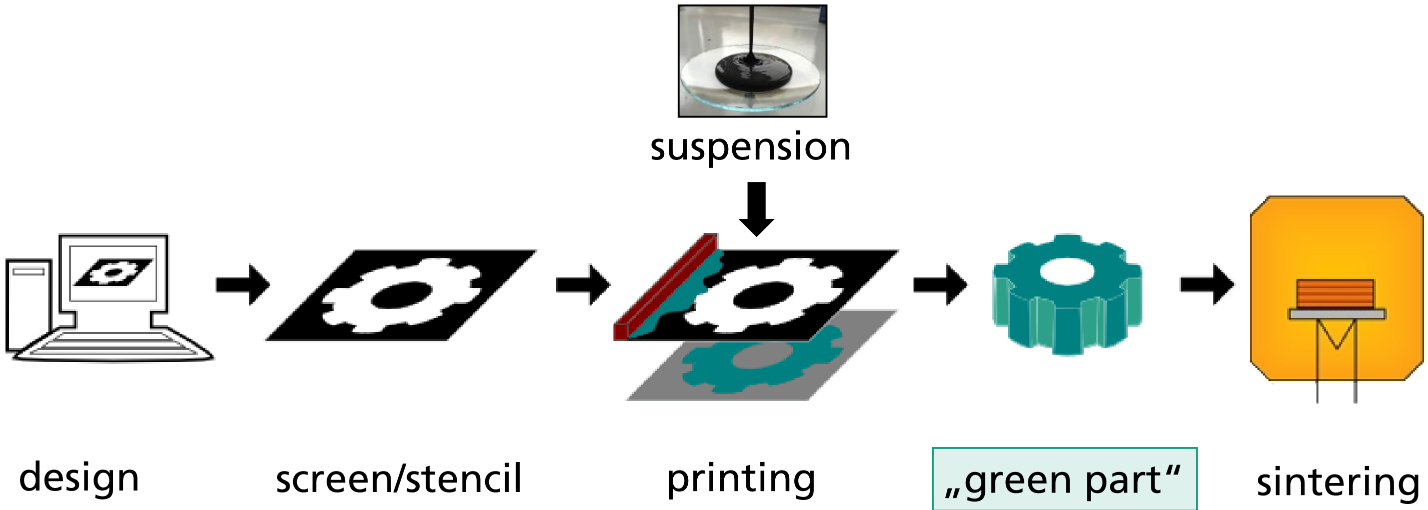
3D screen printing – process outline

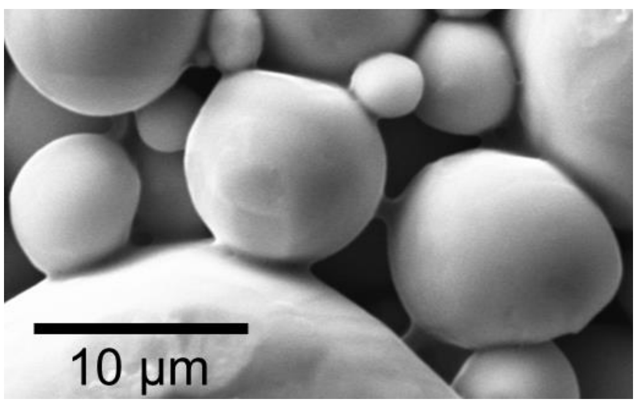




- Repeated printing and curing
- Layer thickness 10-300 µm
- Printing time per layer ~3 s
- Drying time per layer 15-30 s
- Print-sealing of cavities possible

3D screen printing – process outline

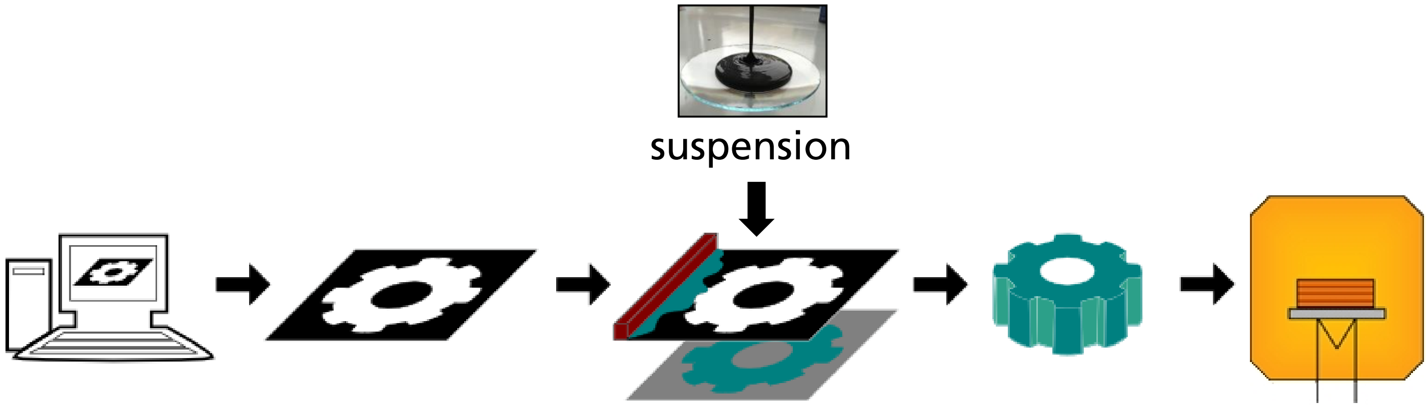




TiAl6V4 green part, green density 69.9%

- green part: powder particles glued together with binder
- Green density 50-70%
- Organics content ~1-5 wt%
- Printing on sinter substrate
- Green machining possible

3D screen printing – process outline



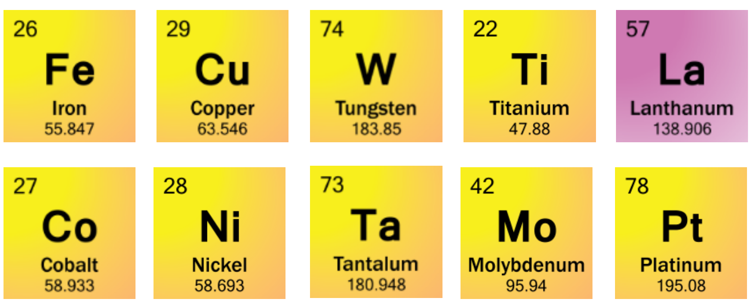
design → screen/stencil → printing → „green part“ → sintering

heat treatment at Fraunhofer IFAM, branch lab Dresden

- Removal of binder/additives
- Select atmospheres/pressures
- FTIR assisted optimization
- Sintering to nearly full density
- Shrinkage ~15-20 % (lin.)

3D screen printing– process characteristics

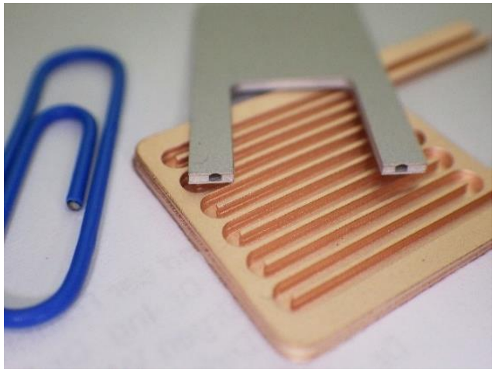
- Process properties:
  - Resolution: 60 - 80 µm
  - Typical dimensions / highest height: small parts preferred
  - Build rate: 60 – 120 cm^3/h
  - Support structures: not necessary
  - Materials: Metals + Ceramics with d_{90}< 1/3 of mesh opening



3D Screen Printing Unit at Fraunhofer IFAM

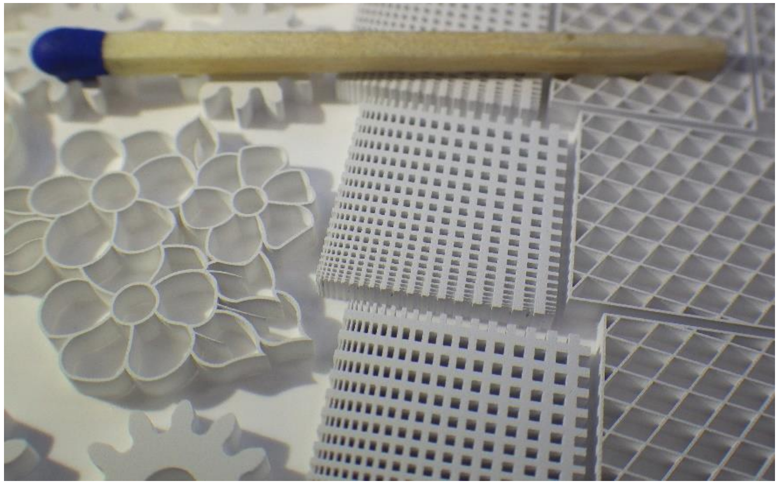
3D screen printing – examples and properties

- AM part properties:
  - Surface quality: R_a= 1-2 µm (powder d_{90}<10 µm)
  - Density: full density
  - Post treatment: possible but not necessary



IFAM:Screen printed heat exchanger

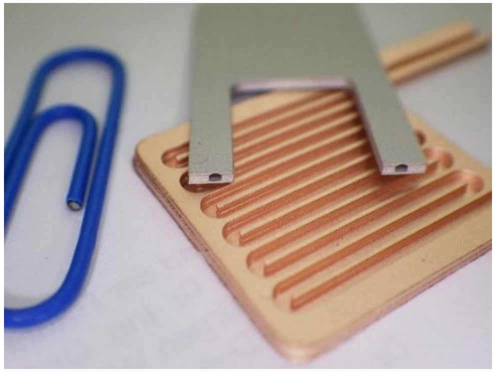
- Applications
  - Medical technology
  - Electronics
  - Aviation
  - Heat Exchanger



IFAM: Screen printed test parts made from Al_2O_3

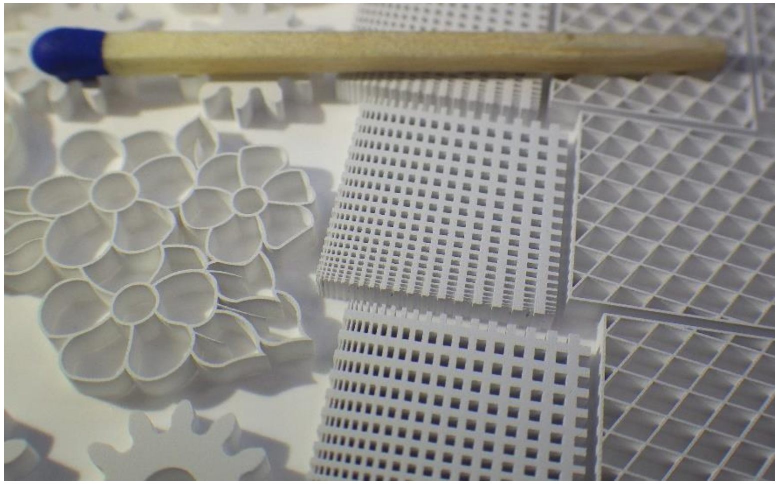
3D screen printing – examples and properties

- Advantages:
  - Material variety
  - Mass production process
  - Good surface quality
  - High resolution
  - Intricate internal structures, cavities printable



IFAM: Screen printed heat exchanger

- Disadvantages
  - Limited Design Freedom
  - No large parts (z-direction)
  - Shrinkage



IFAM: Screen printed test parts made from Al_2O_3

2.3. Solid State TECHNOLOGIES

2.3.6 Sheet Lamination

- Process available for materials like:
  - Paper, plastic sheets → Layer objective Modelling (LOM)
  - Metallic sheets → Ultrasonic additive manufacturing (UAM)

Process - Step by Step

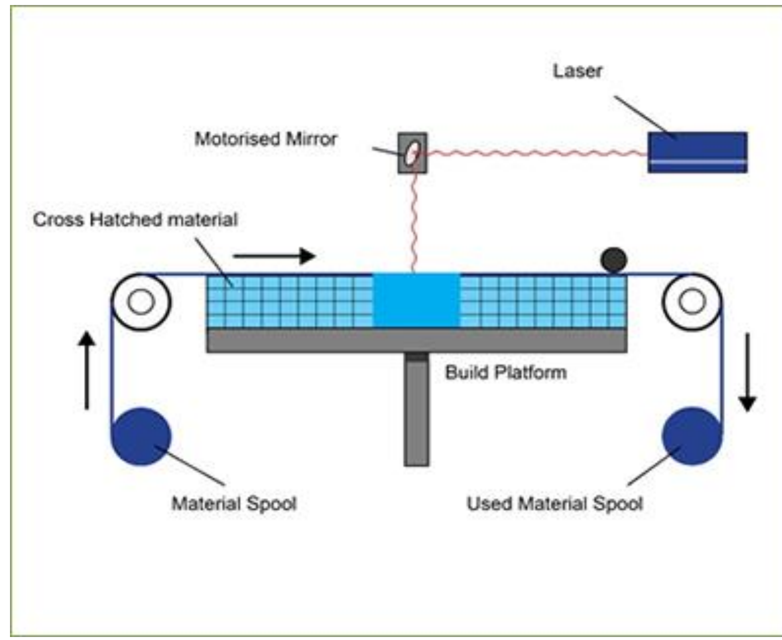
1. A sheet of material is placed on a cutting bed

2. The sheet is cutted / milled in the desired shape (laser / milling cutter)

3. Sheets are bonded to the previous layers using an adhesive (LOM) or welding (UAM)

4. The next layer is added.

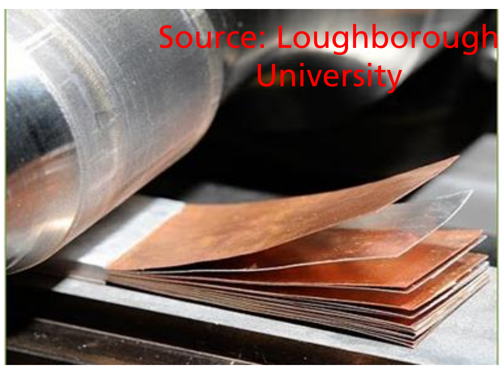
(Steps two and three can be reversed and alternatively, the material can be cut before being positioned and bonded)



Source: Loughborough University, Additive Manufacturing Group

Sheet lamination – process characteristics

- Process properties:
  - Resolution: > 1 mm
  - Typical dimensions : large parts up to 500 x 500 x 400 mm possible
  - Sheet thickness: 0.05 to 0.2 mm
  - Build rate: 50 – 150 cm^3/h
  - Support structures: are cutted and removed after processing
  - Materials: Sheets of paper, plastics or metals

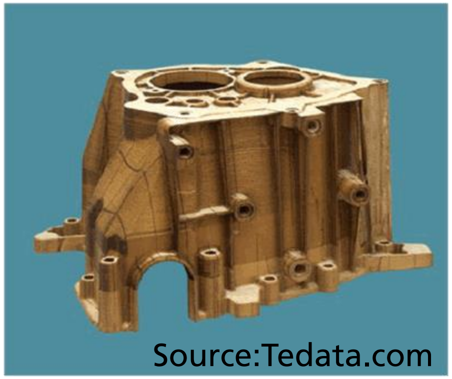


laminated copper sheets (left) and UAM machine by Fabrisonic (right)

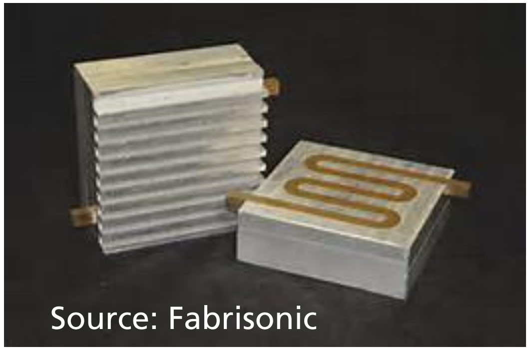
Source: Mcor Technologies

Sheet Lamination– examples and properties

- AM part properties:
  - Surface quality: good
  - Density: full density
  - Post treatment: not necessary
- Applications
  - Decorative Objects (LOM)
  - Models for Casting Molds (LOM)
  - Injection molding dies (UAM)
  - Parts with internal channels
- Industrial Suppliers:
  - Fabrisonic (USA)
  - Mcor (Ireland)


Source:Tedata.com


Source: Raprotec GmbH


Source: Fabrisonic

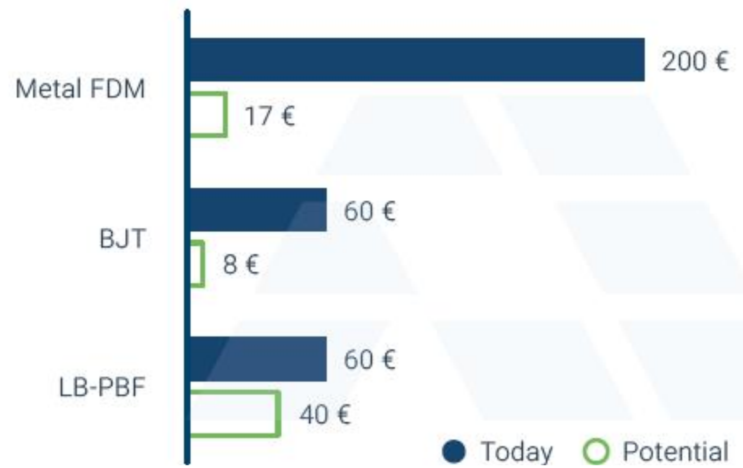
Sheet Lamination

- Advantages
  - Low cost
  - Parts can be used immediately after the process (no need for post curing)
  - High build rate 250 – 350 cm^3/h
  - Multimaterial systems possible

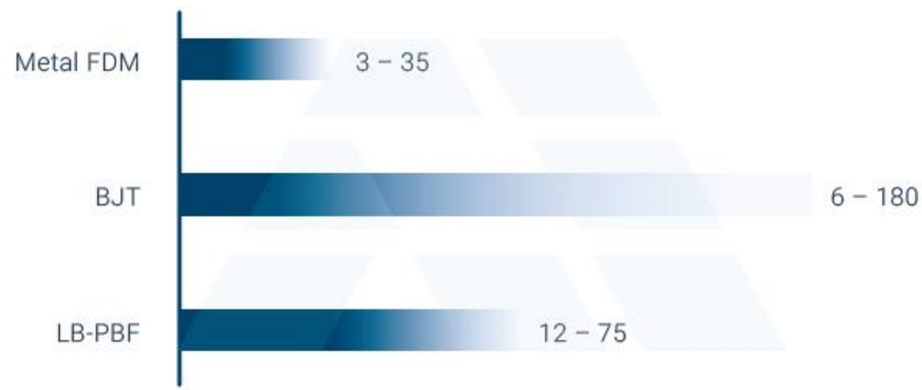
- Disadvantages
  - Material waste
  - Limited resolution (especially in z-direction)
  - No structural parts (low mechanical strength)

3. Summary / Technology Comparison

FEEDSTOCK COST PER KG FOR 316L



CURRENT PRODUCTION SPEED IN CM³/H



http://am-power.de/insights/

3. Summary / Technology Comparison

	LB-PBF	BJT	Metal FDM	MIM
Stainless steel	●	●	●	●
Tool steel	●	○	○	●
Super alloy	●	○	○	●
Titanium	●	●	○	●
Aluminum	●	◌	◌	◌
Copper/Bronce	○	○	●	●
Carbide	○	○	●	●

● Available ○ Under development ◌ Inherently difficult

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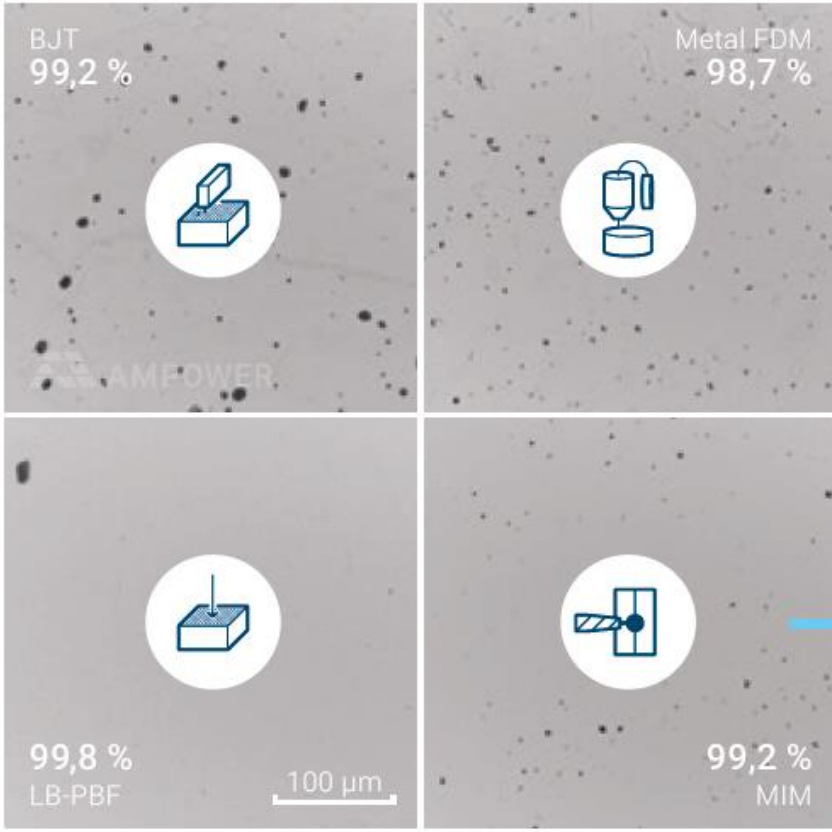
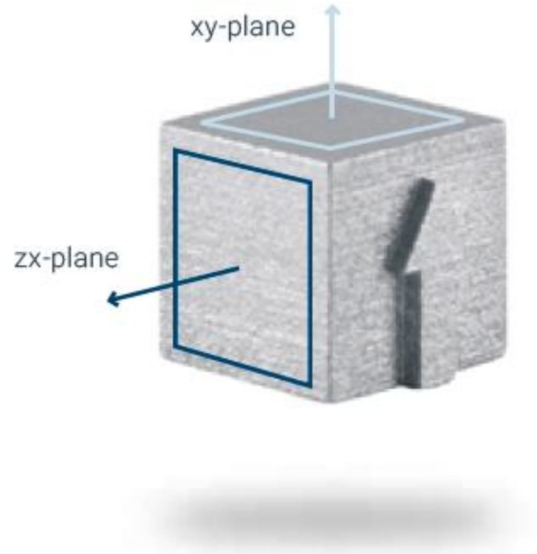
3. Summary / Technology Comparison





Typical density values of MIM parts range between 95 to 97 %. The examined MIM specimen exhibits exemplary high quality with density of above 99 %.

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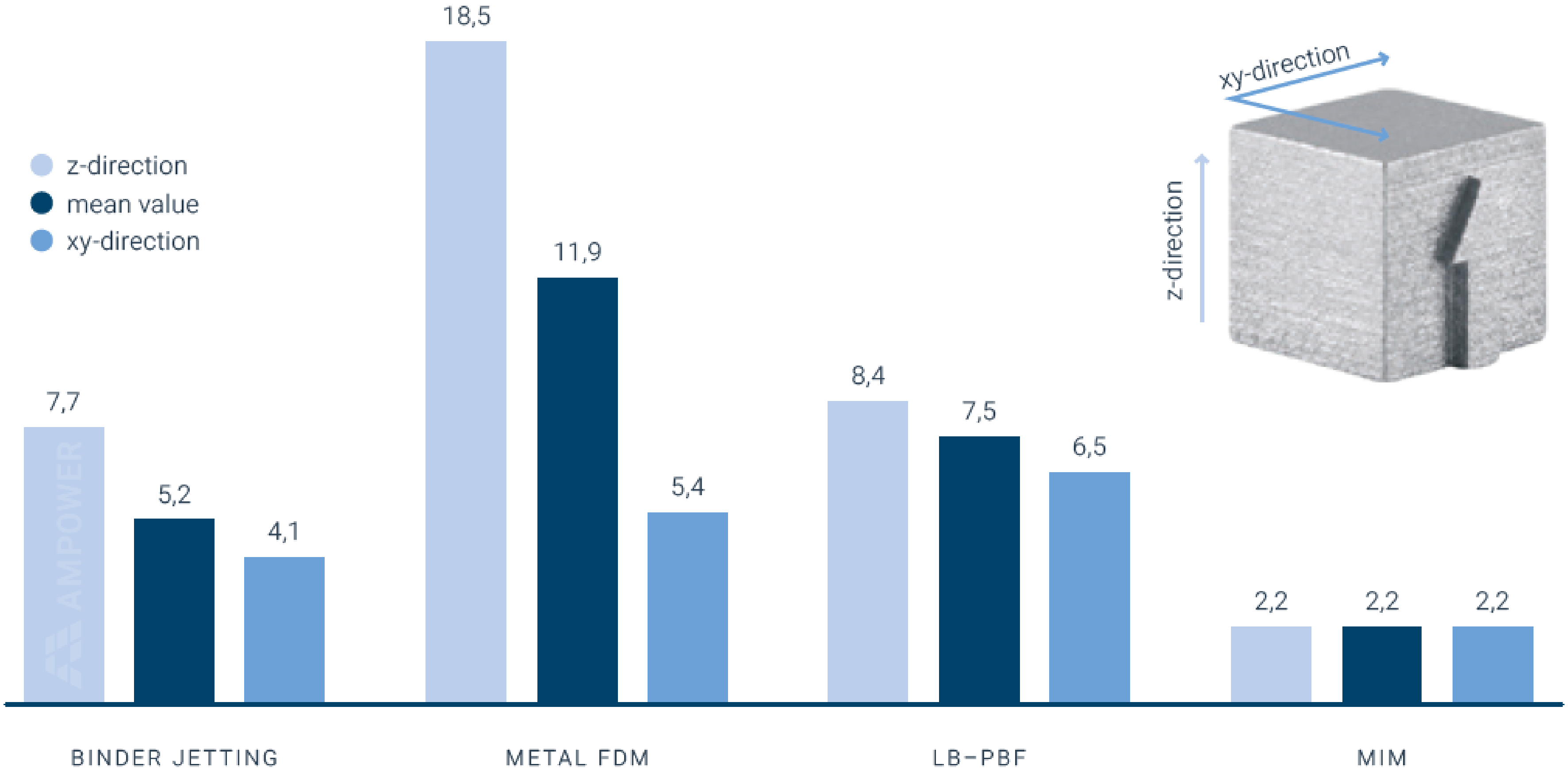
3. Summary / Technology Comparison

Arithmetic average roughness R_a as build in µm



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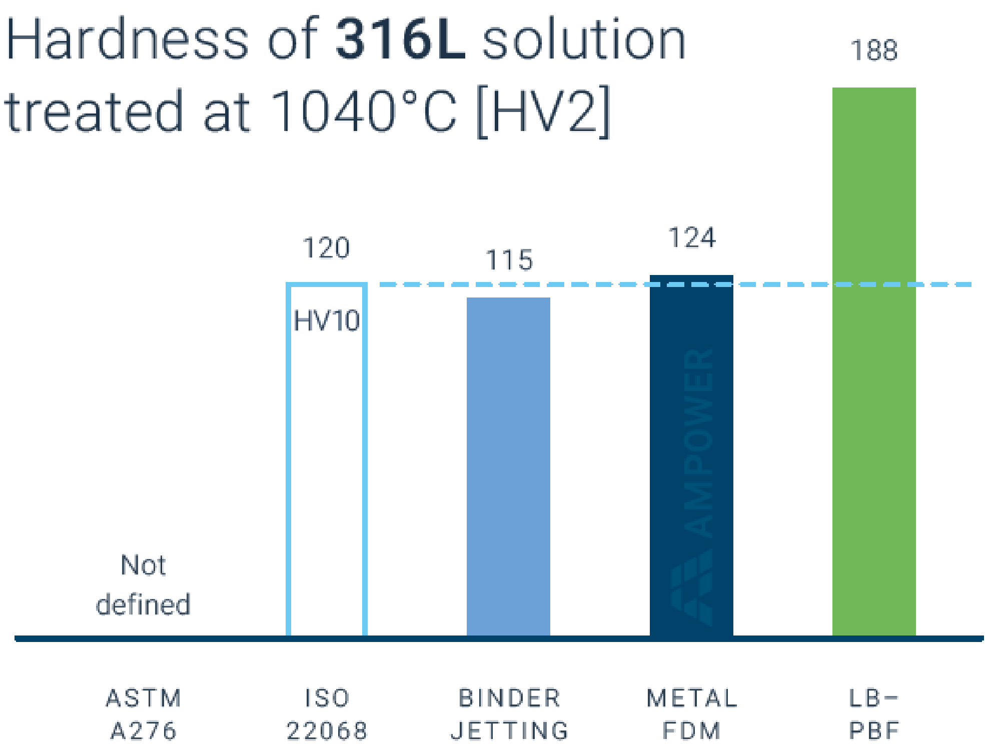
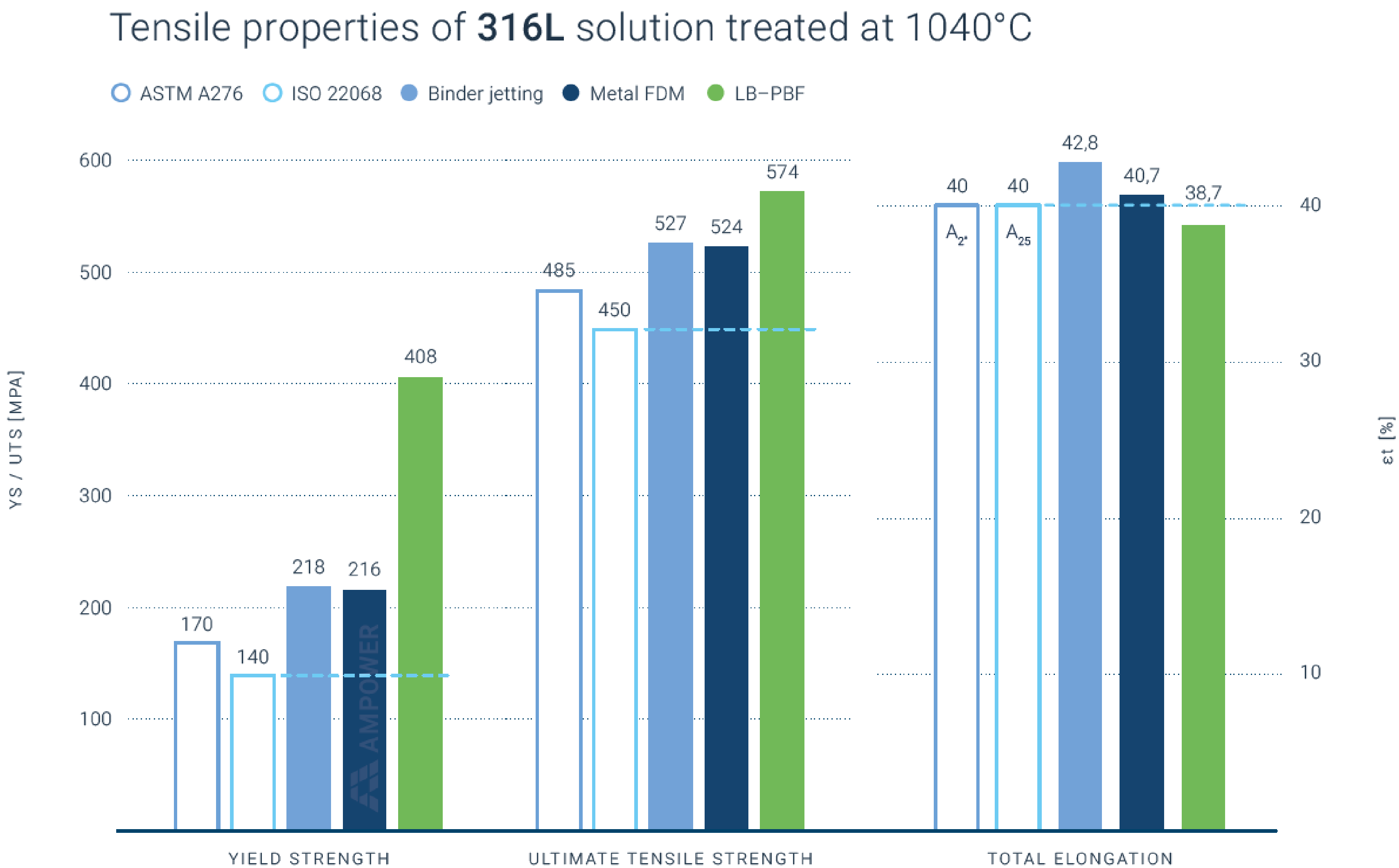
3. Summary / Technology Comparison



Sinter-based AM technologies achieve hardness close to the defined requirement for MIM alloys according to ISO 22068.

Decrease in hardness below the value described in the standard might be attributed to the additional solution treatment and/or accumulation of porosity.

3. Summary / Technology Comparison



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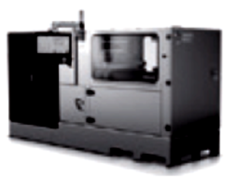
Technology	Machine hourly rate incl. consumables, excl. feedstock	Build envelope	Consumables
Metal FDM  Exemplary system Desktop Metal Studio	3-5 €/h	250 - 300 x 200 - 250 x 200 - 250 mm^3	Feedstock Electricity Compressed air
Binder jetting  Exemplary system Digital Metal DM P2500	35-50 €/h	170 - 400 x 150 - 250 x 60 - 250 mm^3	Metal powder Liquid binder Electricity
LB-PBF  Exemplary system SLM Solutions SLM 500 HL	35-50 €/h	250-500 x 250-280 x 200-380 mm^3	Metal powder Electricity Protective gas

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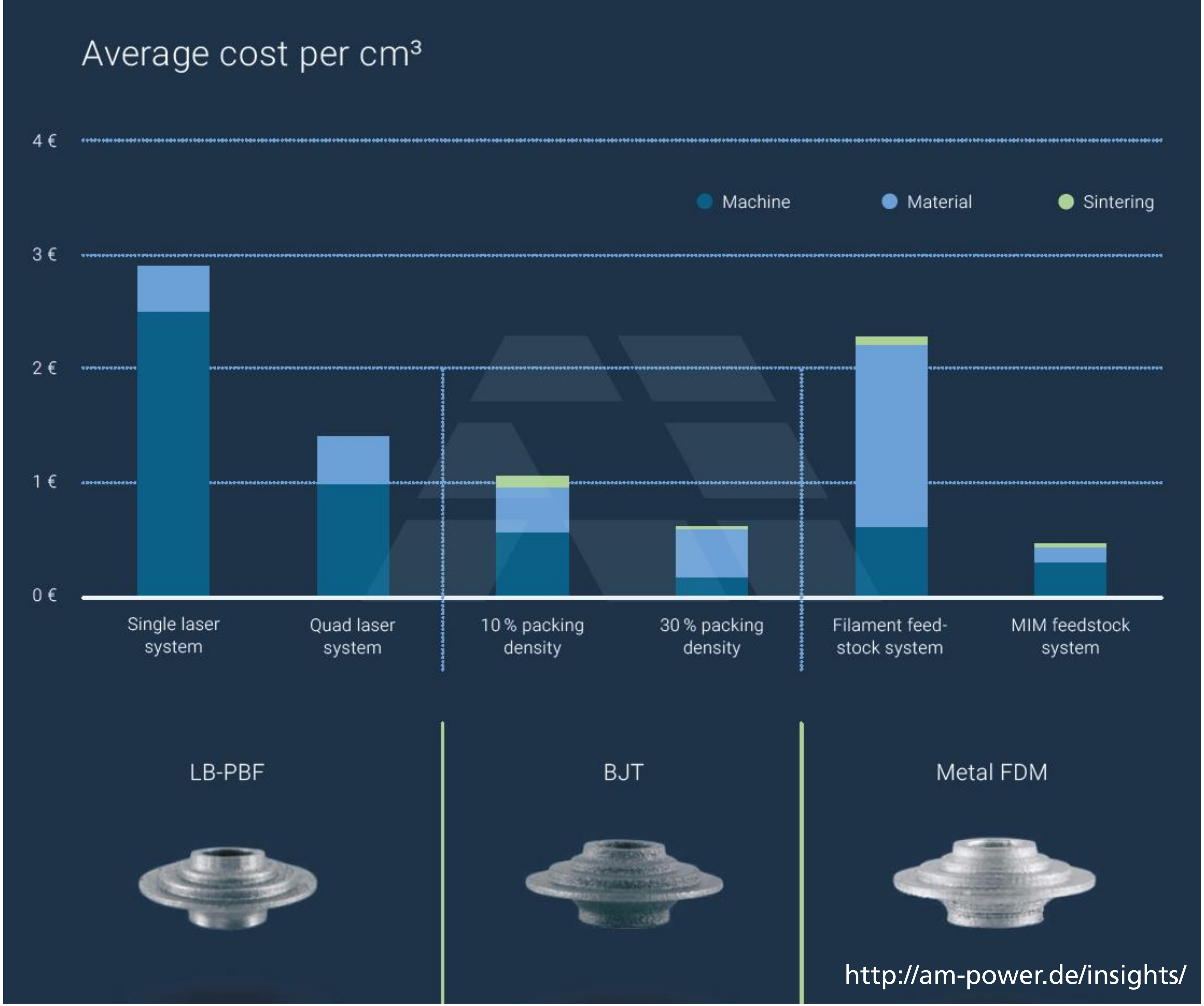

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