Lecture Unit 08

Additive Manufacturing

Additive manufacturing Technologies within ISO-ASTM 52900

Powder bed fusion	Directed Energy Deposition	Material Extrusion	Material Jetting	Sheet lamination	Binder Jetting	Vat Photopoly-merisation
PBF-LB/M	DED-LB/M	MEX-MSt/M	MJT	SHL	BJT	VPP
PBF-LB/P		MEX-MSt/C				
PBF-EB/M		MEX-SSt/P				

Live-Survey

Consider airplanes could be manufactured by additive manufacturing technology, how long would this take for a modern system? (Expected build rate: 100 cm^3/h)

a) 10 days

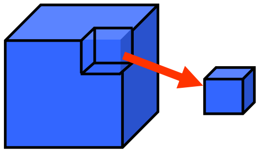
b) 36 months

c) 20 years

Result

Classification of manufacturing technologies

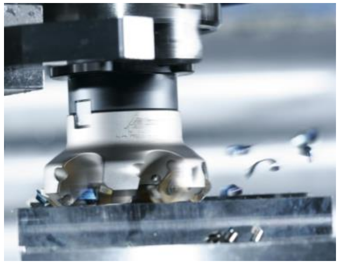
Alternative subdivision of manufacturing technologies (according to Burns):



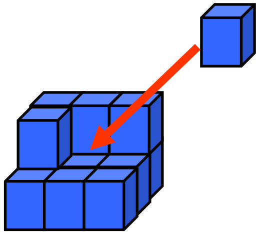
Subtractive

Subtractive Manufacturing:

→ Ablation of defined areas,
e. g. cutting or milling



sr-tech.de

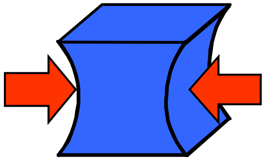


Additive

Additive manufacturing:

→ joining volume elements
e. g. PBF-LB/M or DED-LB/M

eos.info



Formative

Formative manufacturing:

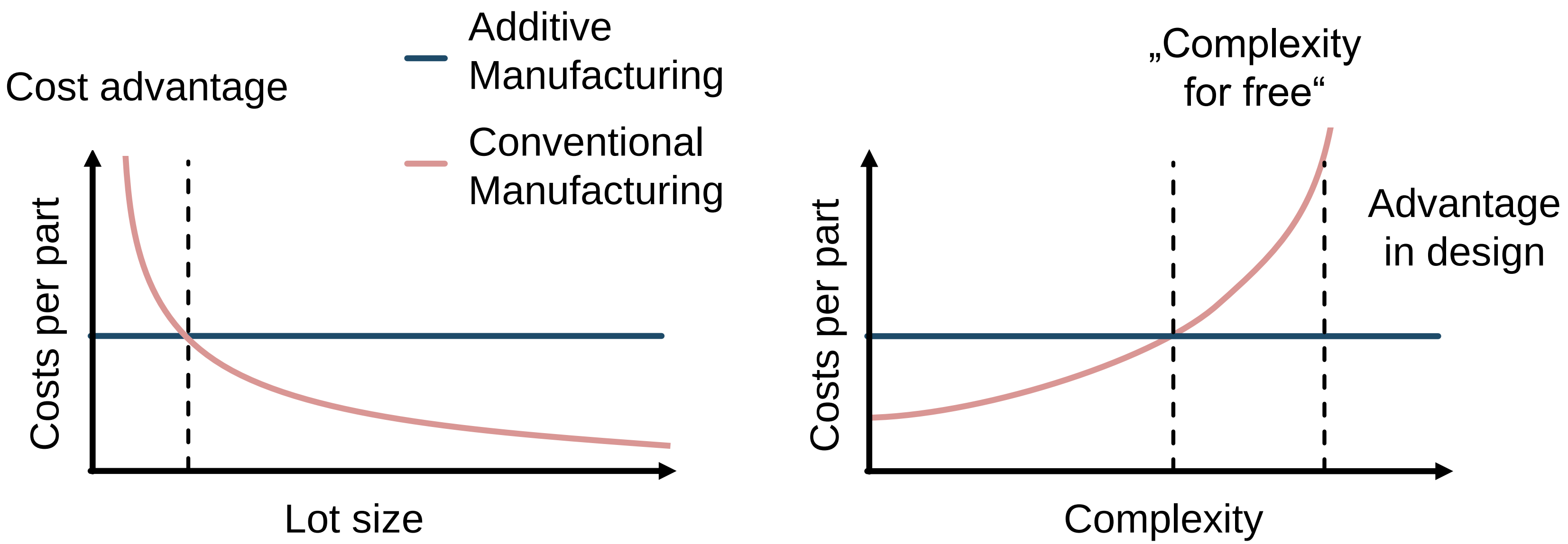
→ deforming of a given volume
e. g. deep drawing or bending

tracto-technik.de

Trends in production

Current trend: increasing amount of part variants and part complexity

Additive vs. conventional manufacturing



Economic efficiency of additive manufacturing technologies for small lot sizes and complex parts

Additive manufacturing – Potential

Additively manufactured parts: 10-50 times more expensive

Where lies the potential of AM processes?

Example: SAVING Project

Weight of a belt buckle:

Conventionally fabricated (steel):	155 g
Additively manufactured (titanium):	70 g

Airbus A-380:	max. 853 seats
Weight reduction:	max. 72.5 kg

→ Saving of 3.3 million liters of fuel or 2 million euro over the product life of an airplane

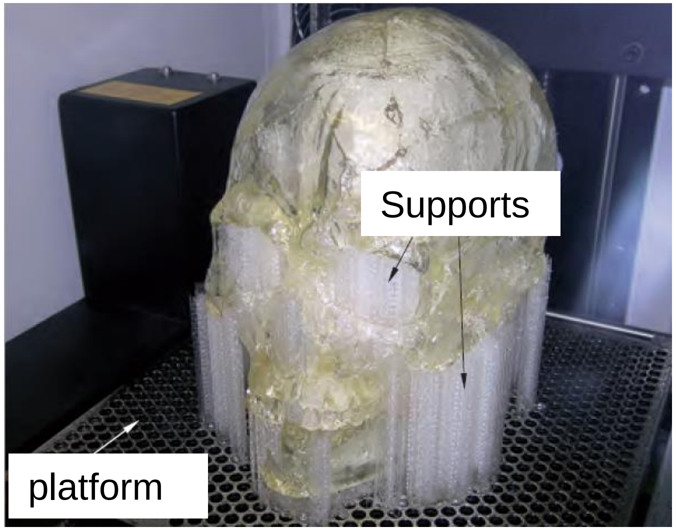
Conventionally fabricated belt buckle

Additively manufactured (PBF-LB/M) belt buckle

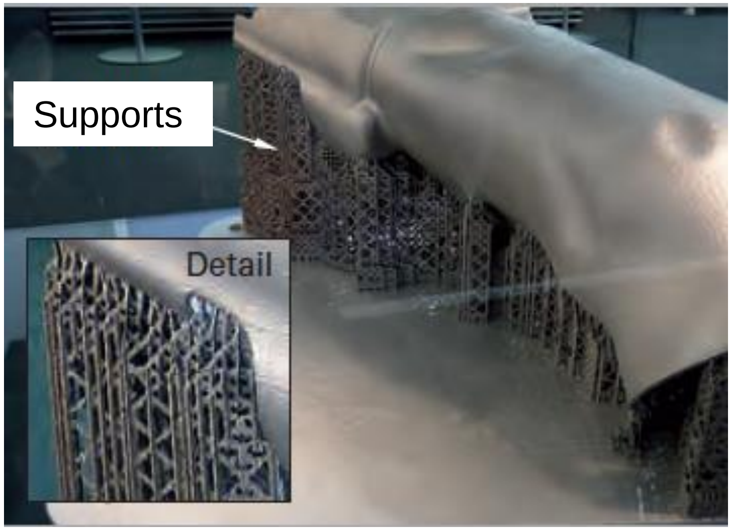
manufacturingthefuture.co.uk

Features of the additive manufacturing: Support structures

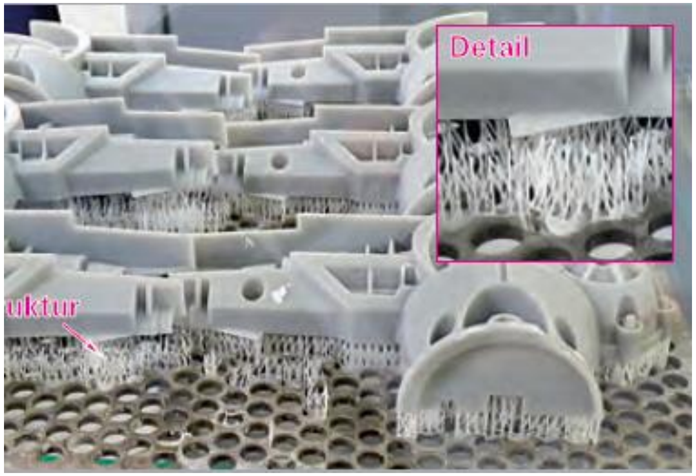
Vat Photopolymerization (VPP)



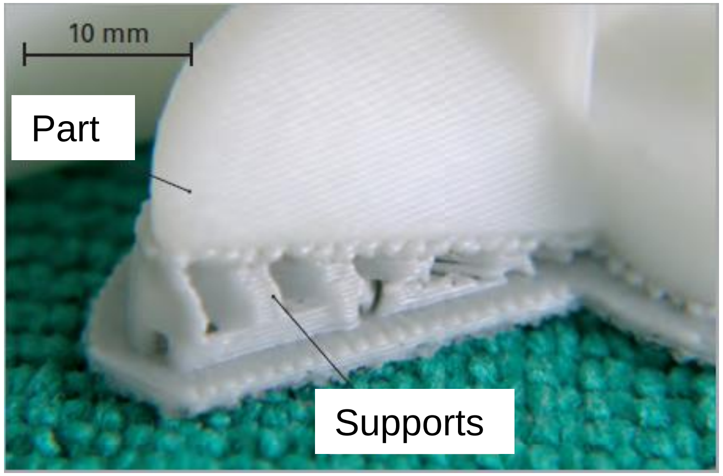
Powder bed fusion PBF-LB/M



Powder bed fusion PBF-LB/P



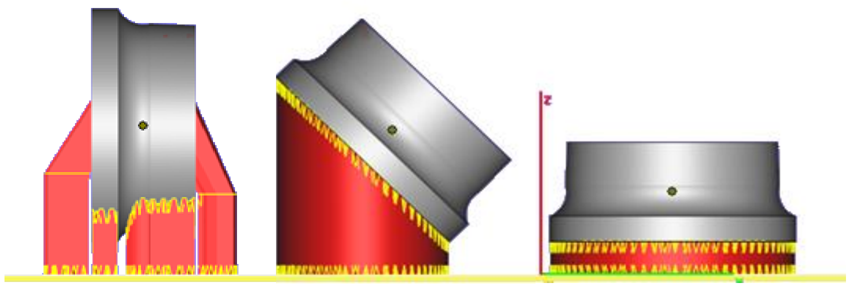
Material extrusion MEX-SSt/P

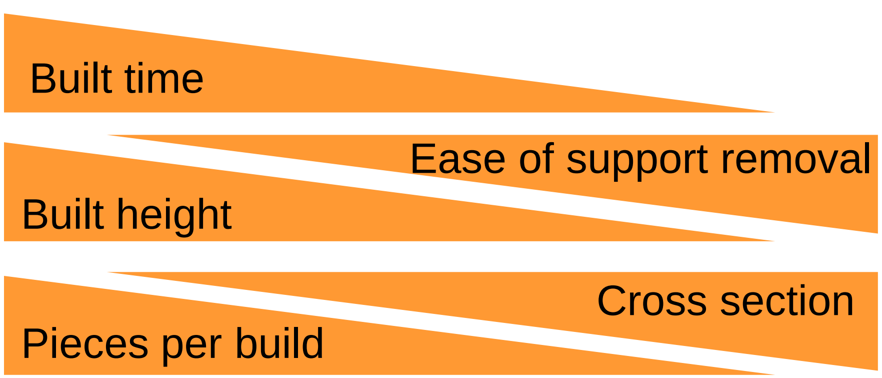


Need of support structures and consequences

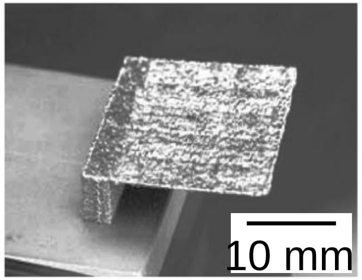
Support structures (e.g. for PBF-LB/M)

Consequences of the part placement on the support structure

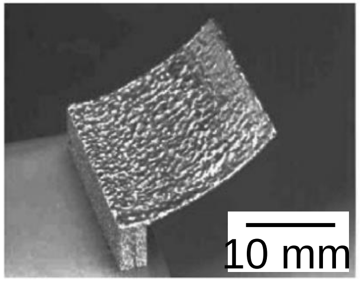




- Residual stress → deformation
- Restraint of powder recoating
- Supports reduce deformation
- After building:
  - Stress relief heat treatment
  - Removal of supports



first layer



second layer

Over, C.: Generative Fertigung von Bauteilen aus Werkzeugstahl X38CrMoV5-1 und Titan TiAl6V4 mit “Selective Laser Melting”. Dissertation, RWTH Aachen. Aachen: Shaker Verlag (2003)

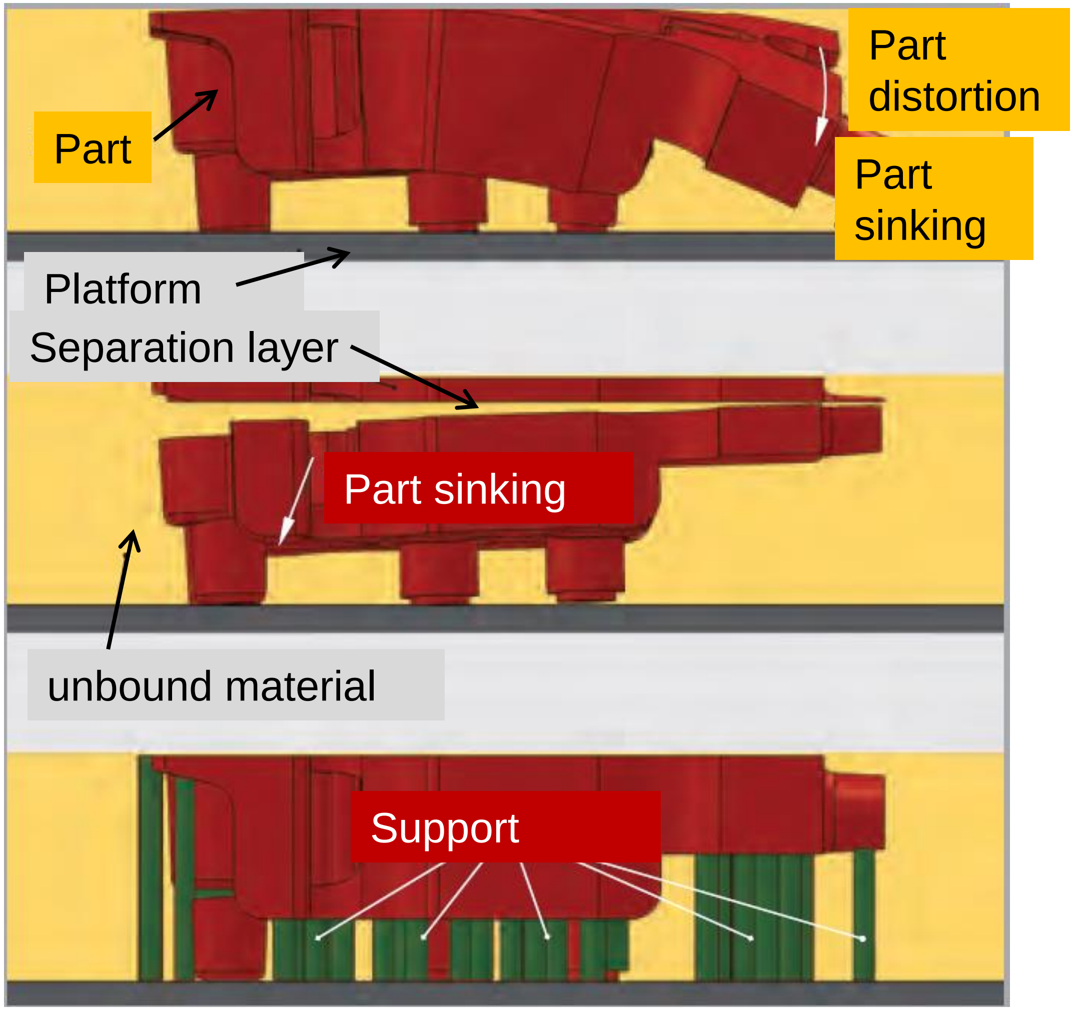
Support structure in additive manufacturing

Reasons for supports:

- Component distortion (Curling)
  - Irregular hardening of the material
  - Negatively affecting the dimensional accuracy
- Sinking of the component when the underlying powder cannot hold the component

  → Forming of a separation layer (interruption of the layer bonding)

Possible failures without support structures



europa-lehrmittel.de

File format: Surface Tesselation Language (STL)

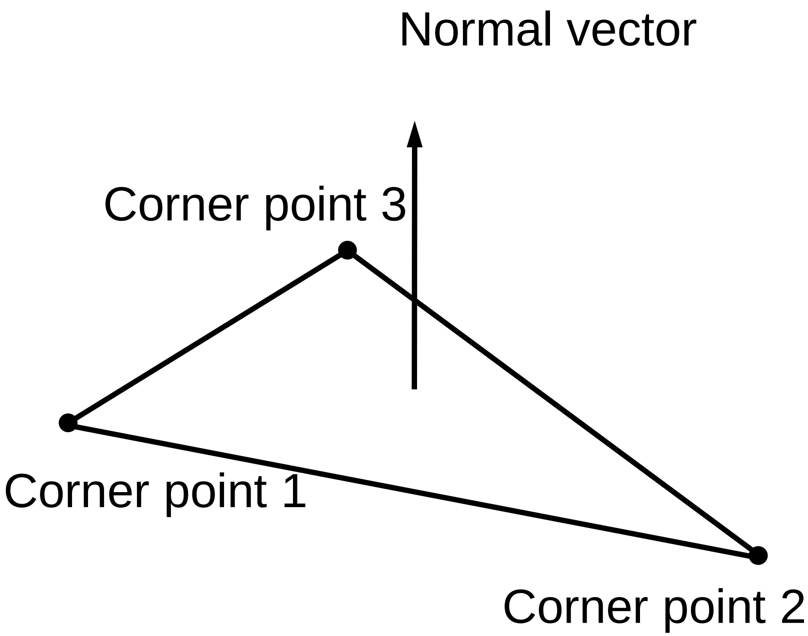
- STL-files consist of triangles with 12 coordinates each:

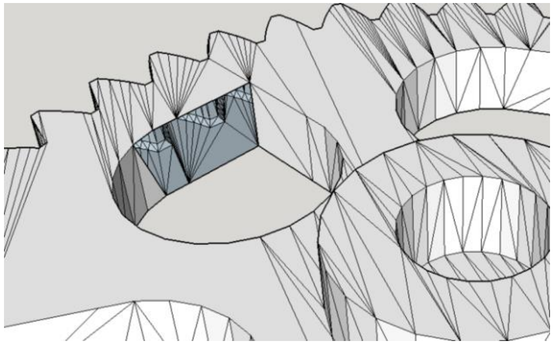
  → 3 vectors of the corner points

  → Normal vector

- Smaller triangles result in better approximation of curvatures
- More triangles are equivalent to larger file size
- *.STL file format has no consistency check

→ Potentially repair of the file required





reprap.org

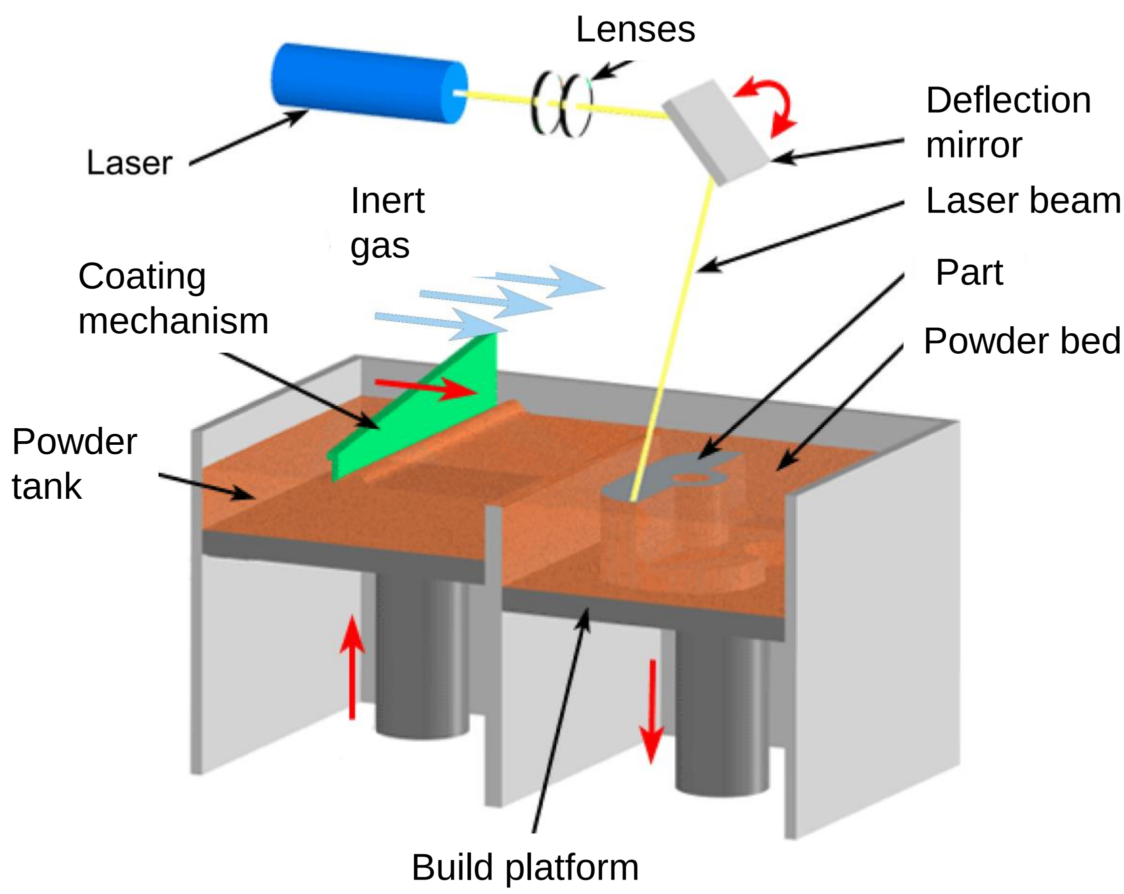
Powder Bed Fusion with Laser Beam of Metals

ISO-ASTM 52900:
PBF-LB/M

Process steps:

- Powder coating
- Melting of the applied powder layer by a focused laser beam
- Lowering of the build platform

→ Iteration of the 3 process steps until completion of the part



custompart.net

Powder Bed Fusion with Laser Beam of Metals

Energy input by the laser

Example: PBF-LB/M

Process parameter

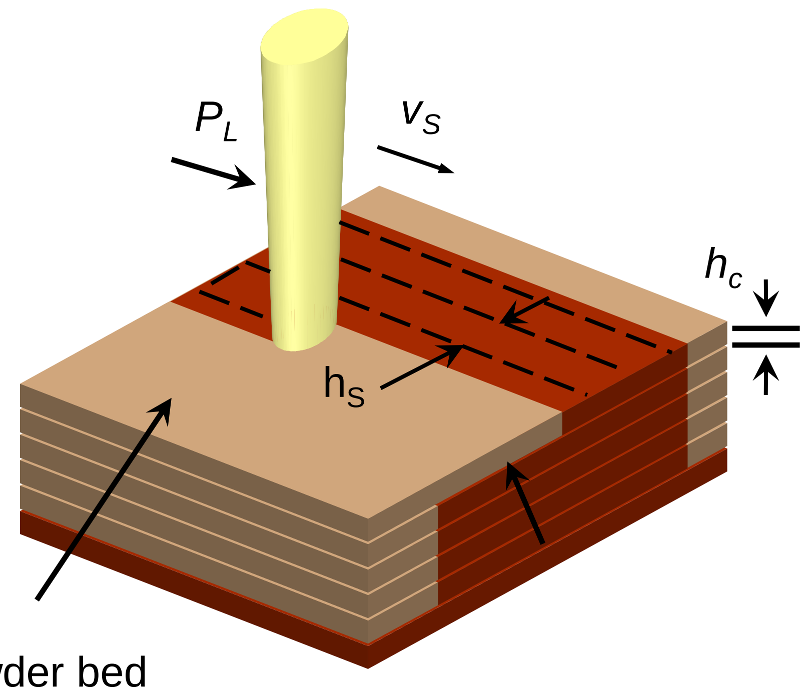
P_L: Laser power

v_S: Scan velocity

h_S: Line distance (Hatch)

h_c: Layer thickness

E_S: Energy per unit area



$$E_S = \frac{P_L}{v_S * h_S}$$ ***in J/m² (area energy density)***

$$E_S = \frac{P_L}{v_S * h_S * h_c}$$ ***in J/m³ (volume energy density***

Live-Survey

Which process is comparable to the melting of the layers in the PBF-LB/M process?

a) laser deep penetration welding

b) heat conduction welding

c) laser-based brazing

Result

PBF-LB/M: Pre-Process

Metal powder handling

- Powder particles are partly alveolar
- Powder is reactive

  → Explosion hazard (e. g. titanium powder)
- Fractionation of powder under protective atmosphere (Argon)

  → Particle size: 20 – 63 µm homogenous and reproducible powder layers

  → Avoidance of oxidation on powder surface
- Further quality control:
  chemical composition, particle form, particle size distribution

Sieving machine

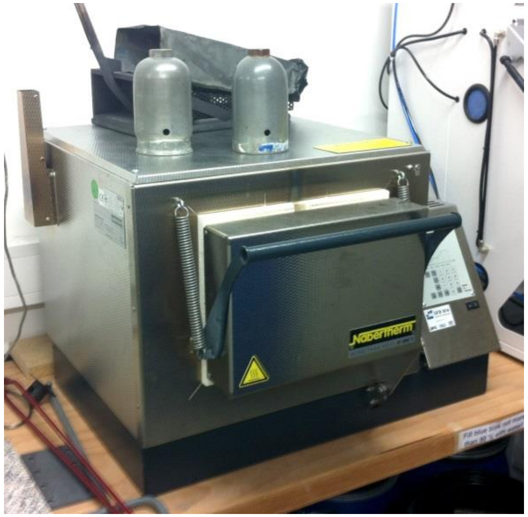
Haver & Böcker

Glovebox with Ar protective atmosphere

PBF-LB/M: Post-Processing

- Removal of non melted powder particles
  →Abrasive blast machine
- Heat treatment in a furnace
  → Annealing in order to reduce residual stress
  → Annealing and tempering in order to customize the microstructure and mechanical properties
- Removal of support structures
- Surface roughness: 50-150 µm
  → Often not sufficient for the end product application
  → Post-processing by milling or grinding
- Powder recycling / powder preparation

Furnace for heat treatment

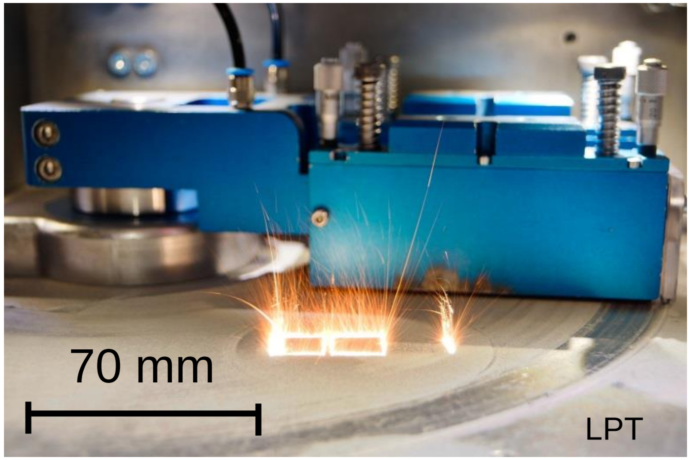


Tensile samples with supports

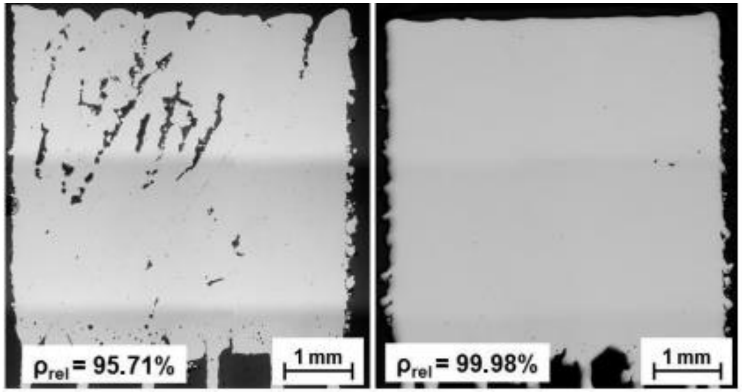
PBF-LB/M: Process features

- Relative density of parts:
  > 99,9 %
- Powder particle size:
  20 – 63 µm
- Typical layer thickness:
  20 – 100 µm
- High-performance laser
  (Fiber laser, disk laser)
- Mechanical properties of parts are comparable to conventionally fabricated parts
- Recoating mechanism:
  Ceramic or steel blade, rubber lip or roller

Build chamber
(Realizer SLM 50 at LPT)



Cross-section of PBF-LB/M fabricated cubes (AlSi10Mg)



PBF-LB/M: Process challenges

- Porosity
- Heat accumulation
- High temperature gradients in space and time

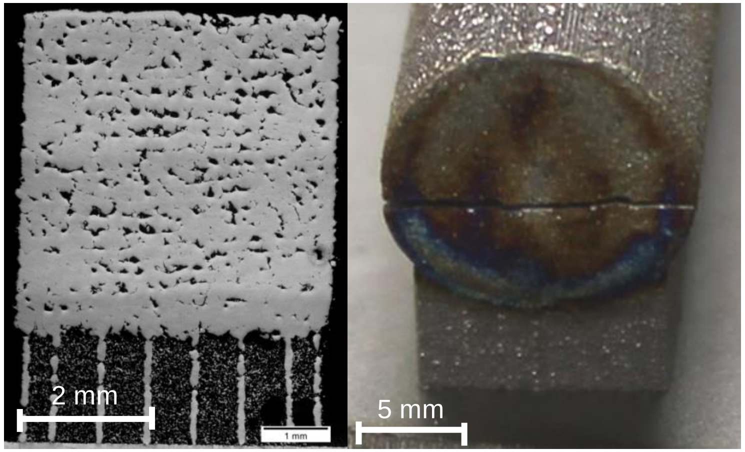
  → Crack formation

  → Deformation

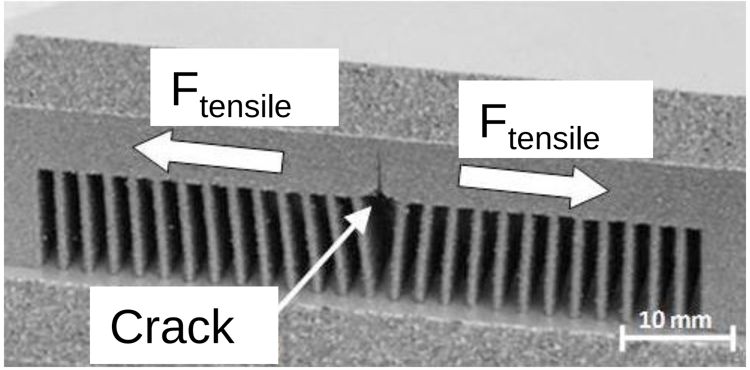
Subject of current research

- Development of specific process strategies (scan strategies, parameter studies for specific materials)
- Improvement of process understanding

Porosity and crack formation



Warpage of a part, fabricated by PBF-LB/M



Fraunhofer ILT

PBF-LB/M application: Medical engineering

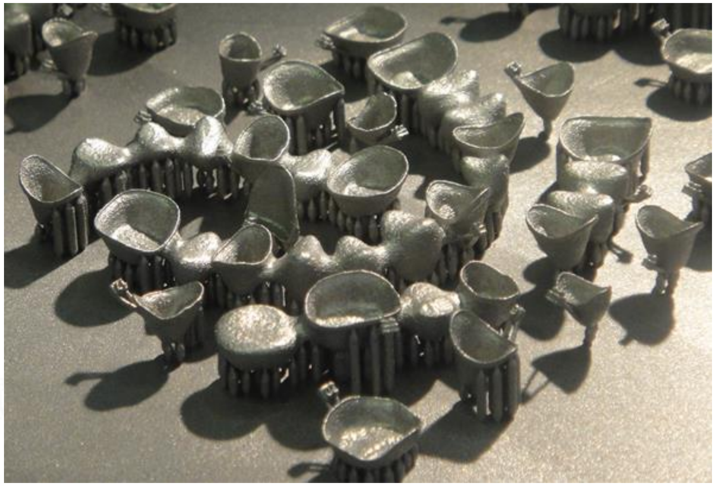
Advantages:

- Economical production of individualized implants
- Low weight of the implants (Lattice / hollow structure)
- Graded porosity → Osseointegration
- Adapted stiffness
- Low heat conductivity (sensitivity in cold weather)

Titanium screw for a dental crown

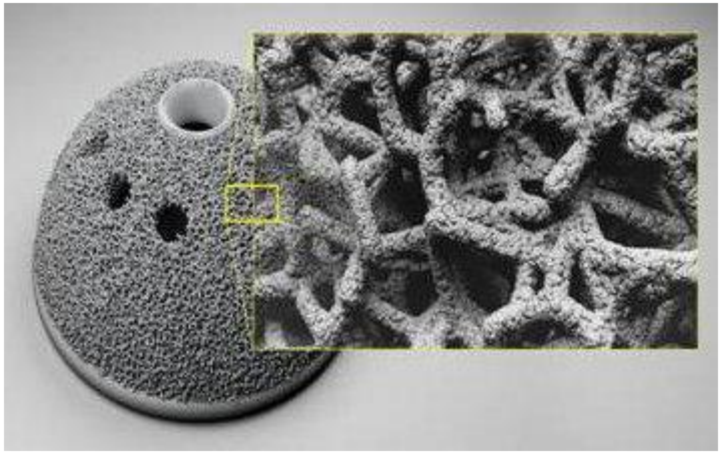
Leader Italia Tixos

Dental crown frames (CoCr alloy)



realizer.com

Titanium implant (acetabulum)



medicaldesign.com

PBF-LB/M application: Tool manufacturing

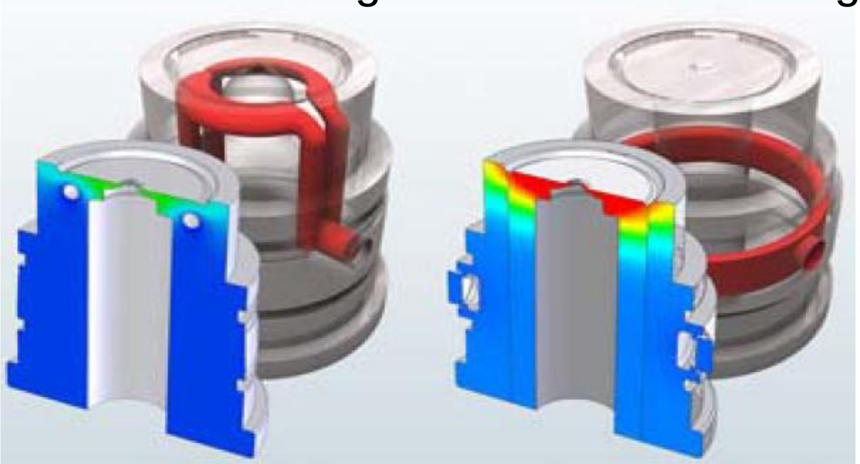
- Conformal cooling channels
  - → Reduction of cycle time
  - → Higher product life of the tool
  - → Fabricated products with better surface quality
- Fast production of injection molding tools (Time-to-market)

Conformal cooling channels

inglass.it

Fraunhofer ILT

Comparison of temperature
Conformal cooling and traditional cooling



rmit.edu

PBF-LB/M application: Lightweight construction / function integration

- Optimization with regard to function, weight and load for different parts
- Lightweight materials:
  Titanium, aluminium and other alloys

Example: Turbine injection nozzle

Advantages to the previous model:

- Integration of 20 single components to one part
- Design optimization:
  Fivefold higher product life
- 25 % weight reduction
- Lower production cost

Door hinge (Ti6Al4V)
(employed in aircrafts, EADS project)

mmsonline.com

Turbine injection nozzle
Manufactured by GE and used in LEAP Engine

industrial-lasers.com

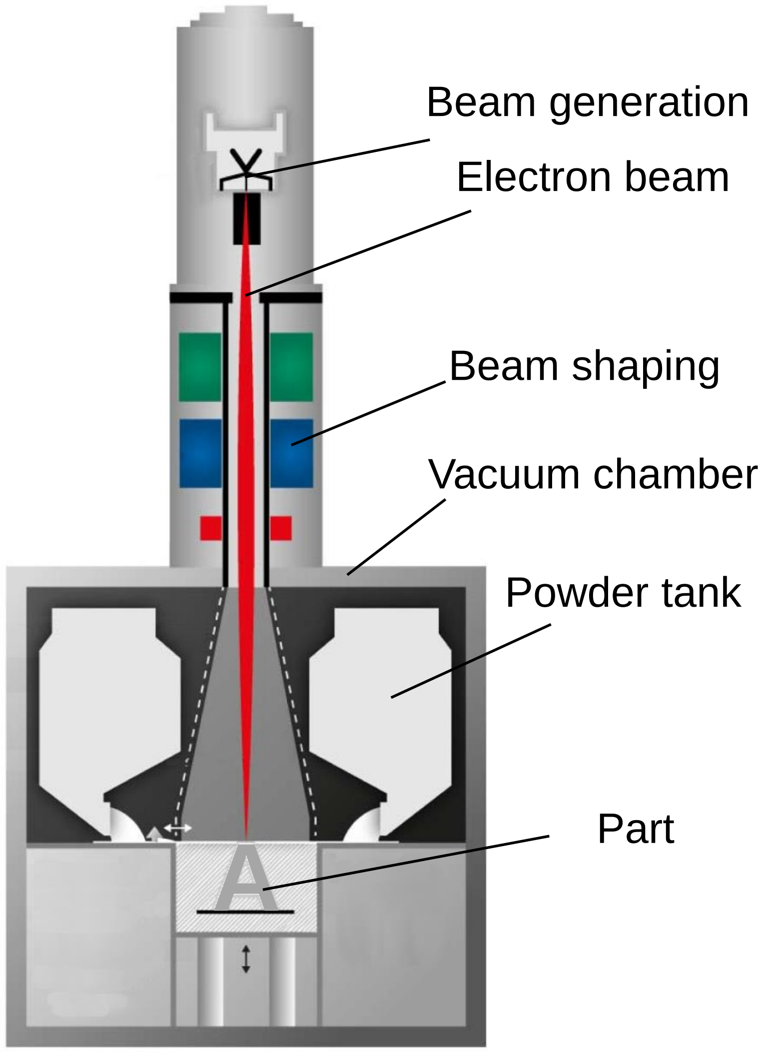
Powder Bed Fusion with Electron Beam of Metals

ISO-ASTM 52900:
PBF-EB/M

Process steps:

- Powder recoating
- Pre-Sintering of the whole powder layer
- Melting of the metal powder by an electron beam
- Lowering the build platform

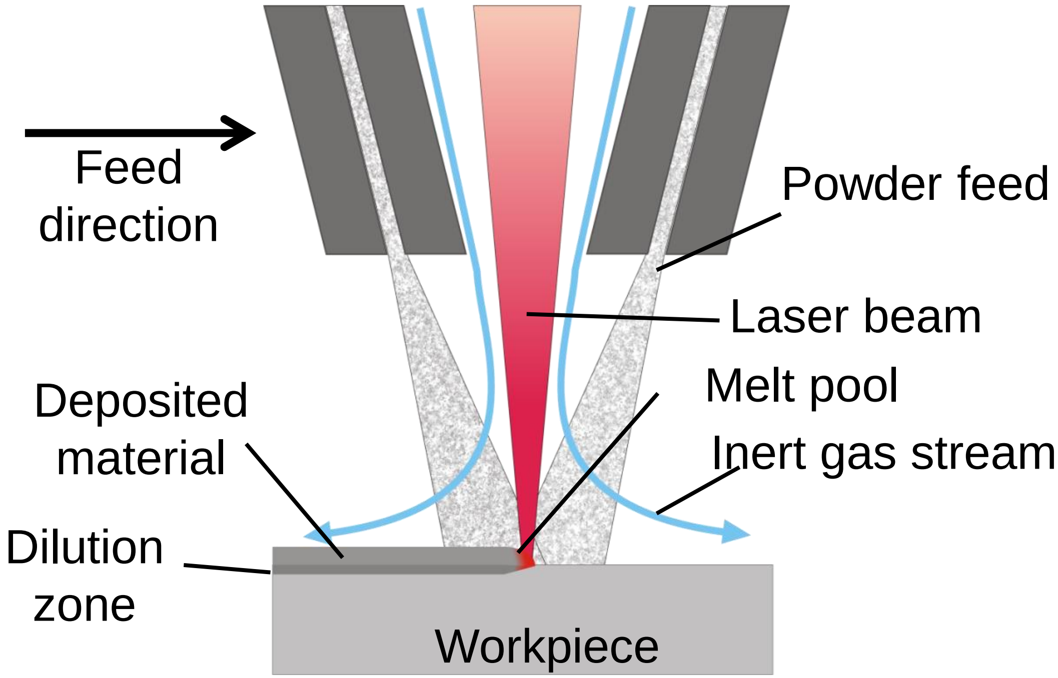
→ Repetition of the four process steps until the part is finished



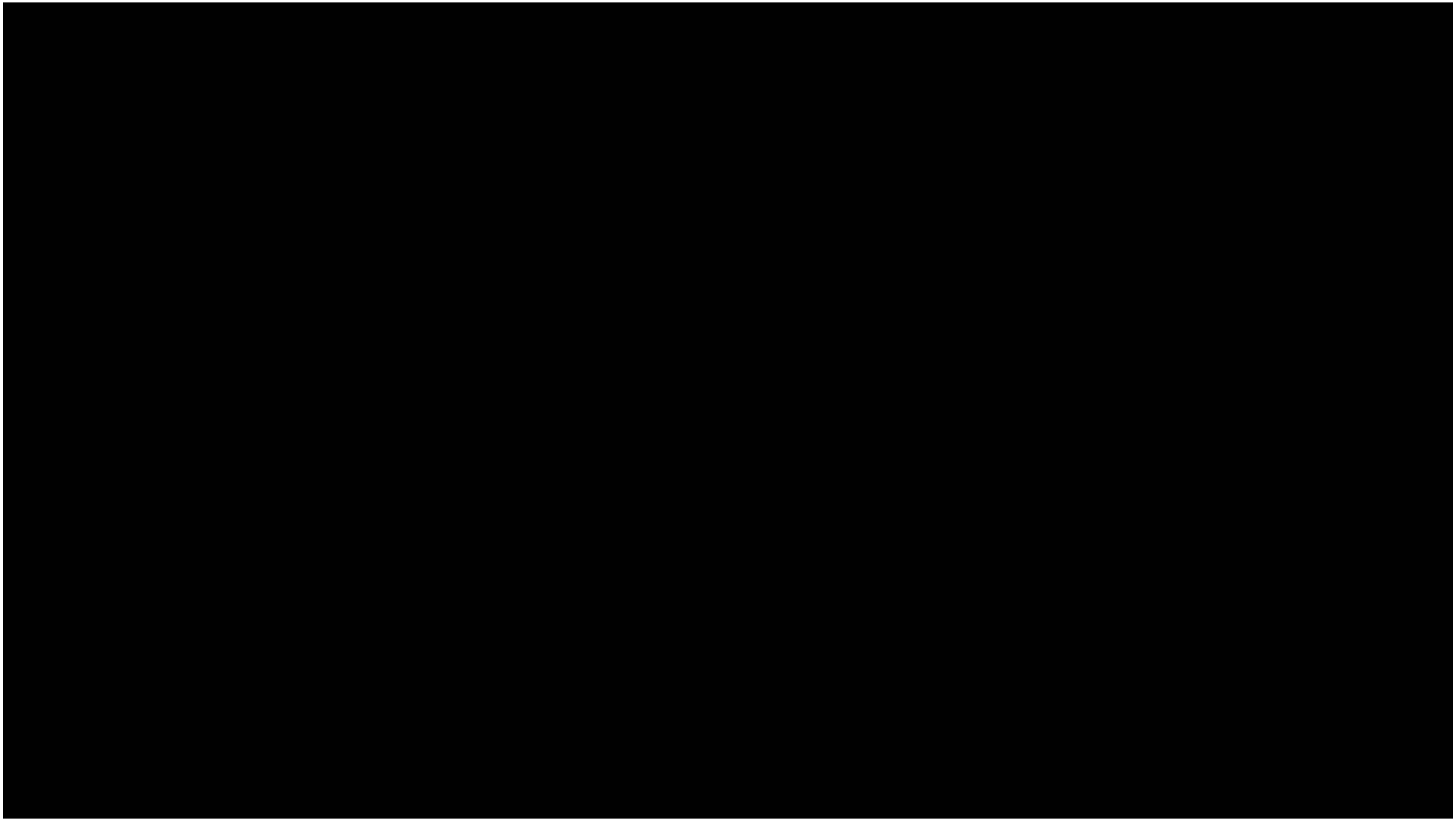
arcam.com

Directed Energy Deposition with Laser Beam of Metals

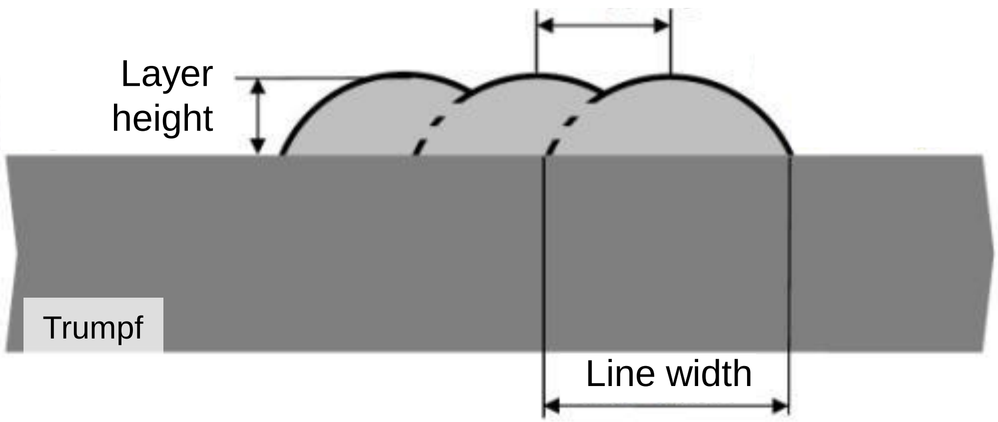
- ISO-ASTM 52900:
  DED-LB/M
- Generation of a melt pool on the workpiece surface
- Supply of an additional material (powder or wire) to the melt pool and complete melting of the supplied material
- Generation of a metallurgical joint
- Near-Net-Shape geometries possible (mechanical post-processing required)



DED-LB/M: Process visualization



DED-LB/M: Geometry of the weld tracks

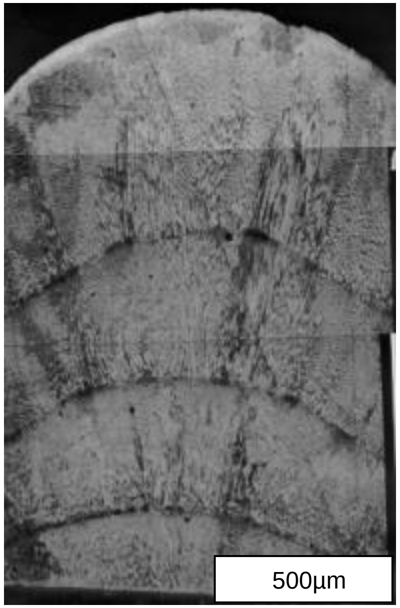


→ Sufficient overlap to obtain a completely dense structure

	Min.*	Max.*
Line width	0,3 mm	7 mm
Layer height	0,1 mm	2 mm
Overlap	0,15 mm	3 mm

*) depending on the material and the laser parameters

Stainless steel
(4 layers;
Layer height 0.5 mm)



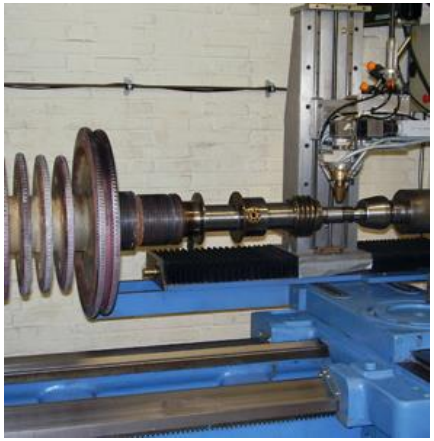
University of Liverpool

DED-LB/M: Applications

Wear resistant cutting edge

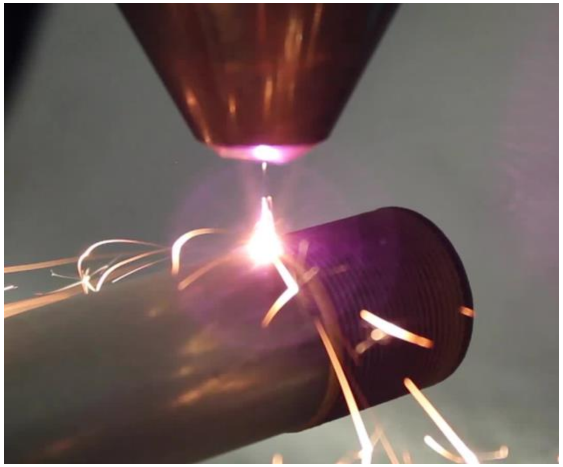
eifeler-lasertechnik.de

Turbine rotors



stork-gears.com

Coating of a shaft



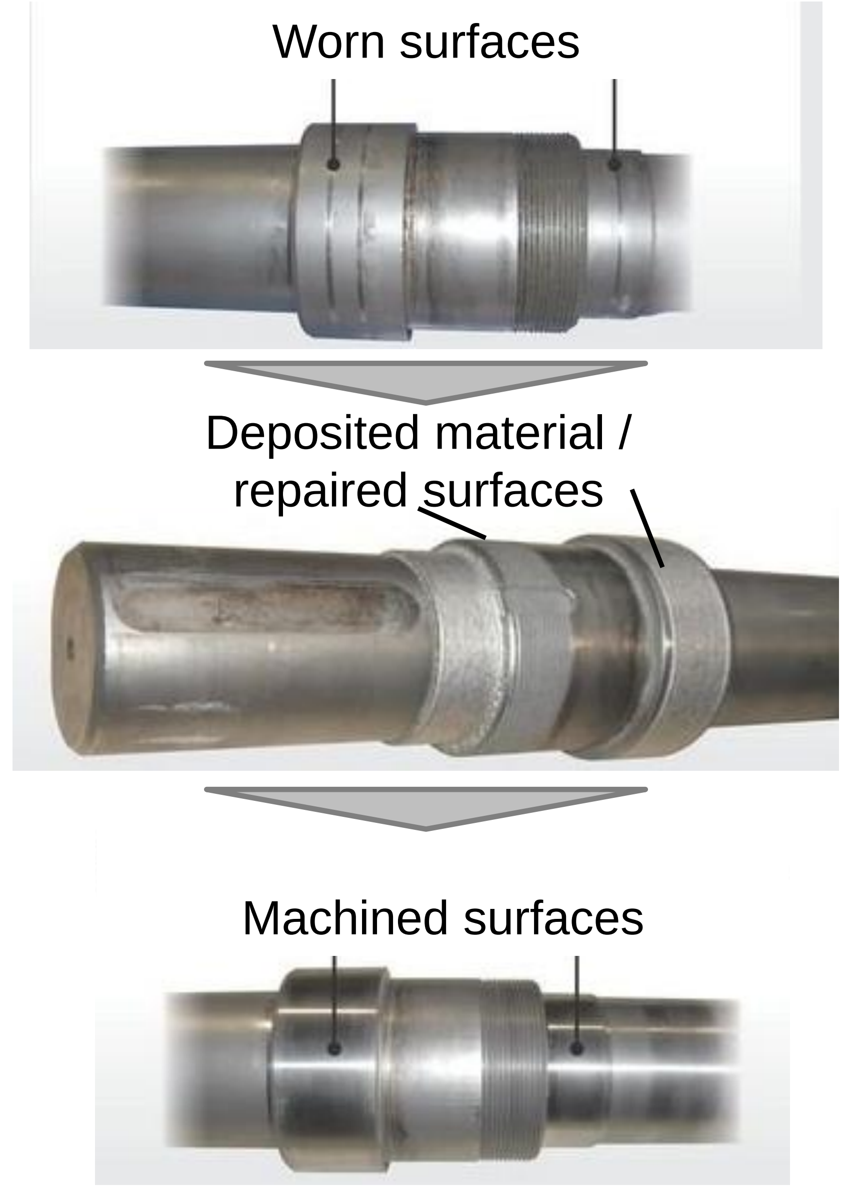
LPT; FAU Erlangen

repair of a gas turbine blade

industrial-lasers.com

DED-LB/M: Repair of a steel shaft

- Repair of costly high-performance components
  - → Thermal damage
  - → Chemical abrasion
  - → Mechanical abrasion
- Examples: Turbine blades, engine components, etc.
- Reconstitution of the surface geometry
  - → High requirements in terms of the microstructure of the deposited material, e.g. orientation, crystallite size and growth



reitze.com

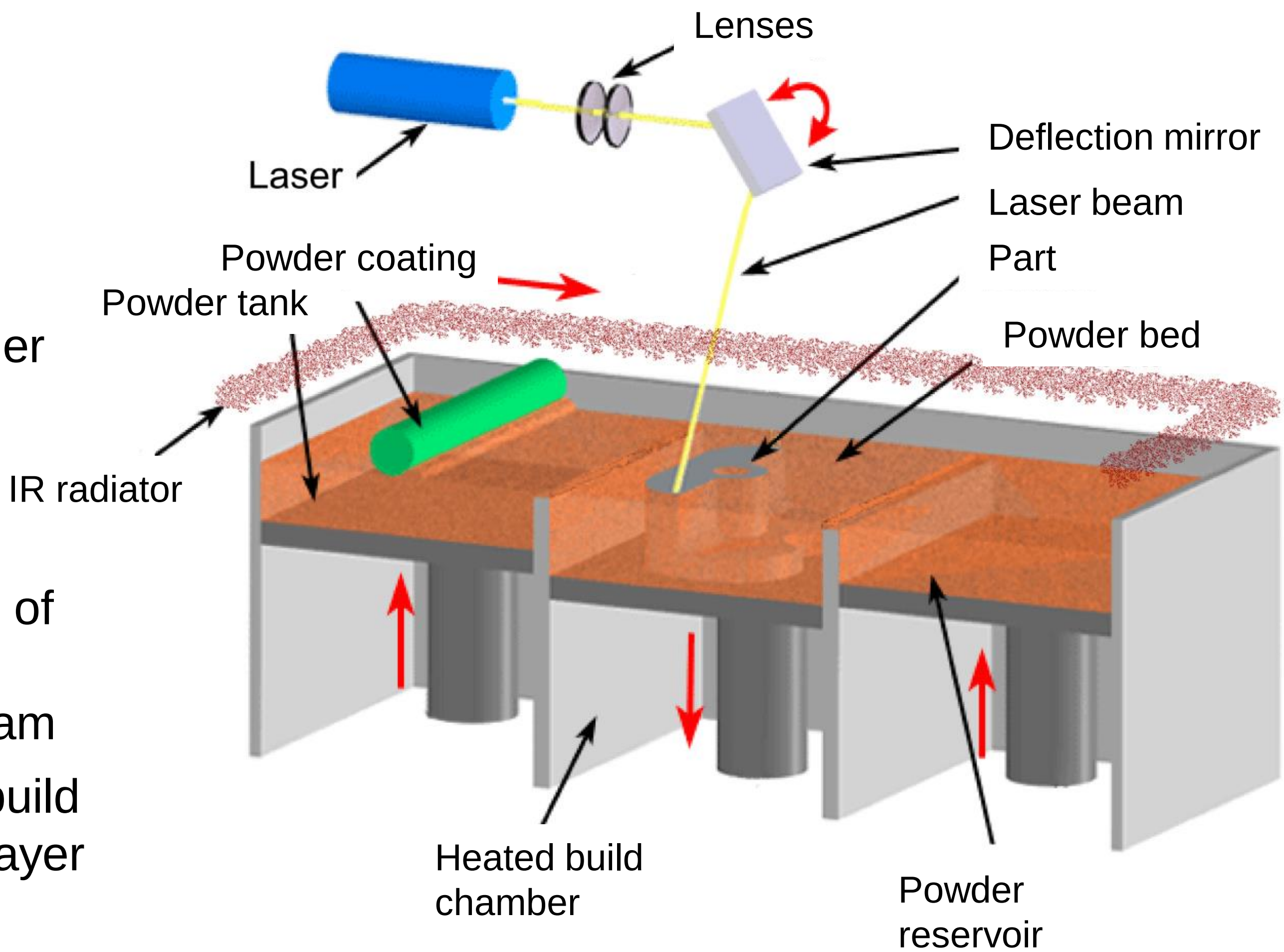
Powder Bed Fusion with Laser Beam of Polymers

ISO-ASTM 52900:
PBF-LB/P

Process steps:

- Preheating and holding the powder near melting temperature
- Powder coating
- Selective melting of the powder by focused laser beam
- Lowering of the build platform by one layer height

→ Iteration of the last three process steps



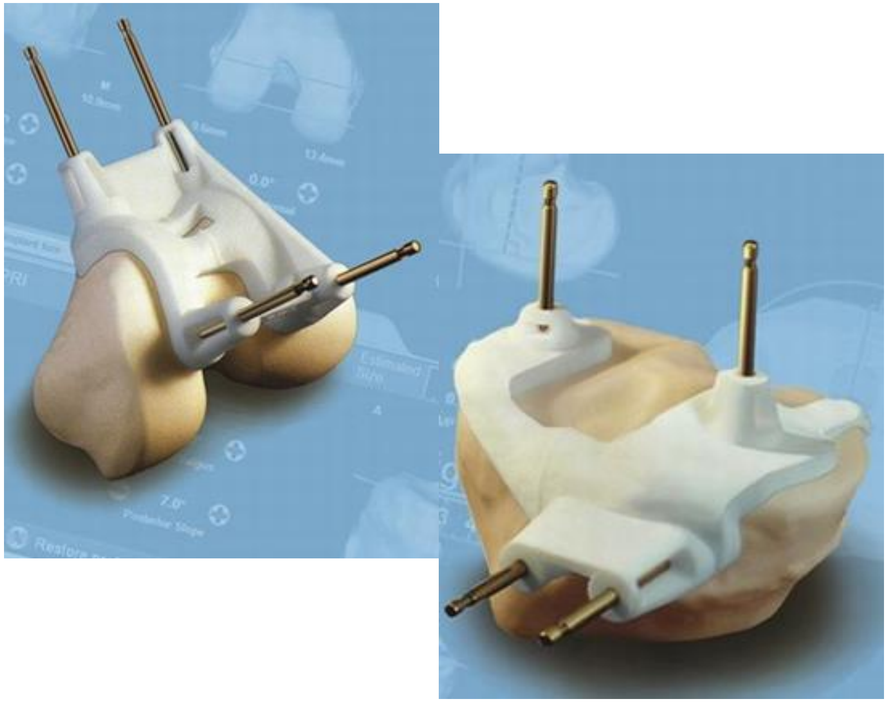
custompartnet.com

PBF-LB/P application: Medical engineering

Knee prosthesis with patient specific drilling guide:

- Drilling, guided by PBF-LB/P PA12 drilling template
- Removal of drilling guides and insertion of fixing pins
- Reusable sawing guide put on fixing pins
- Guided cutting of the bone and removal of the support instruments
- Insertion of the knee implant

Drilling template for knee-surgery



Materialise, Zimmer

Bracers:

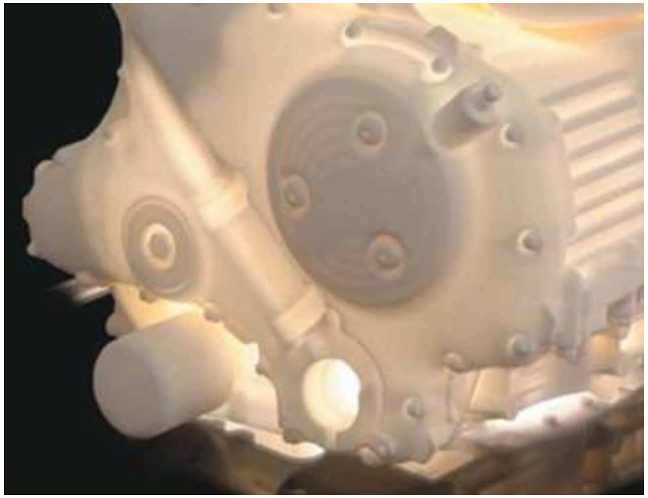
- Adaption to the bone structure
- Optimized, local support for the injured area

Exoskeleton (prototype) for fracture of the arm

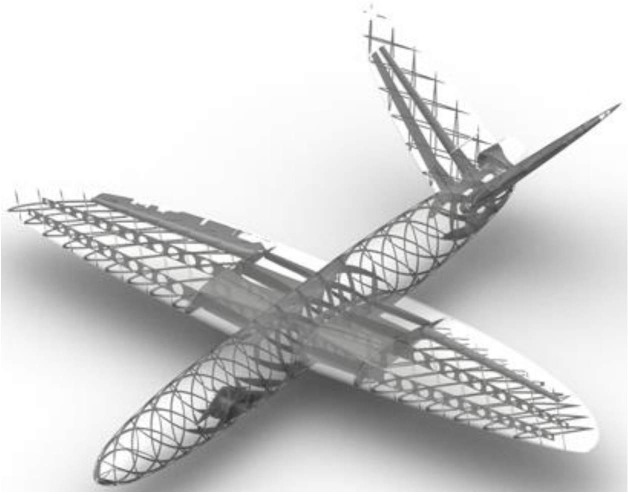
3druck.com

PBF-LB/P: Application

Gear housing (Design-Prototype)



UAV „SULSA“

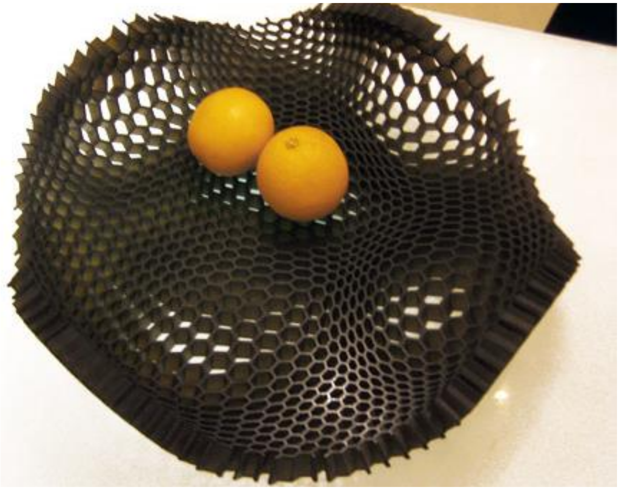


SULSA

Manifold (Functional prototype)

iopscience.iop.org

Fruit bowl (design product)

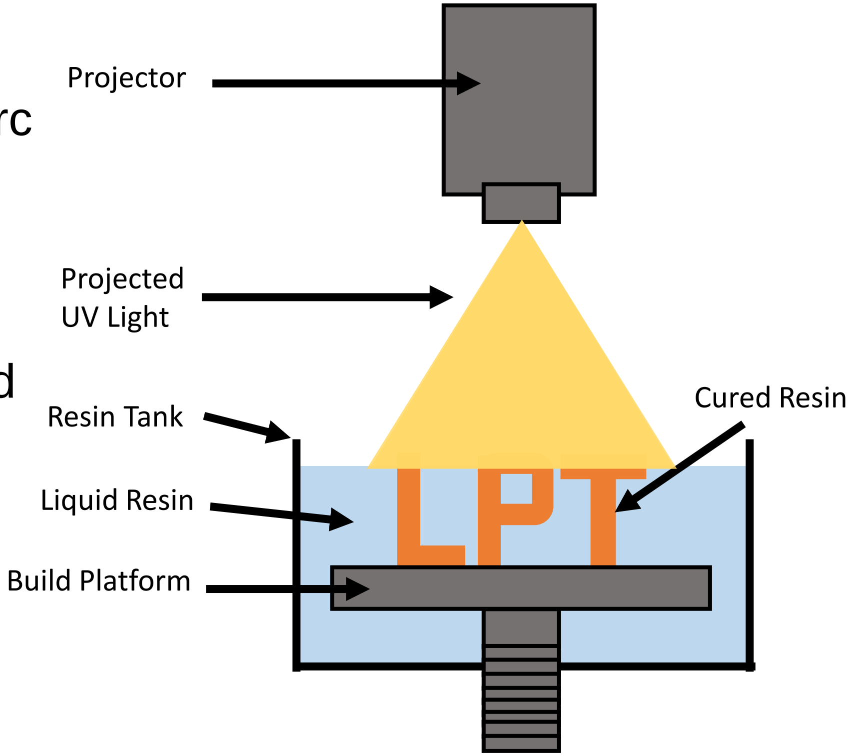


cribcandy.com

Vat Photopolymerization (VPP) - Digital Light Processing

Process steps:

- Uses a conventional light source e.g. arc lamp with liquid crystal display panel
- Build projector displays image of 3D model onto resin layer
- Exposed liquid resin cures and the build plate moves down
- Repeated until part is built
- Optional: Post heat treatment to fully cure resin



Pros:

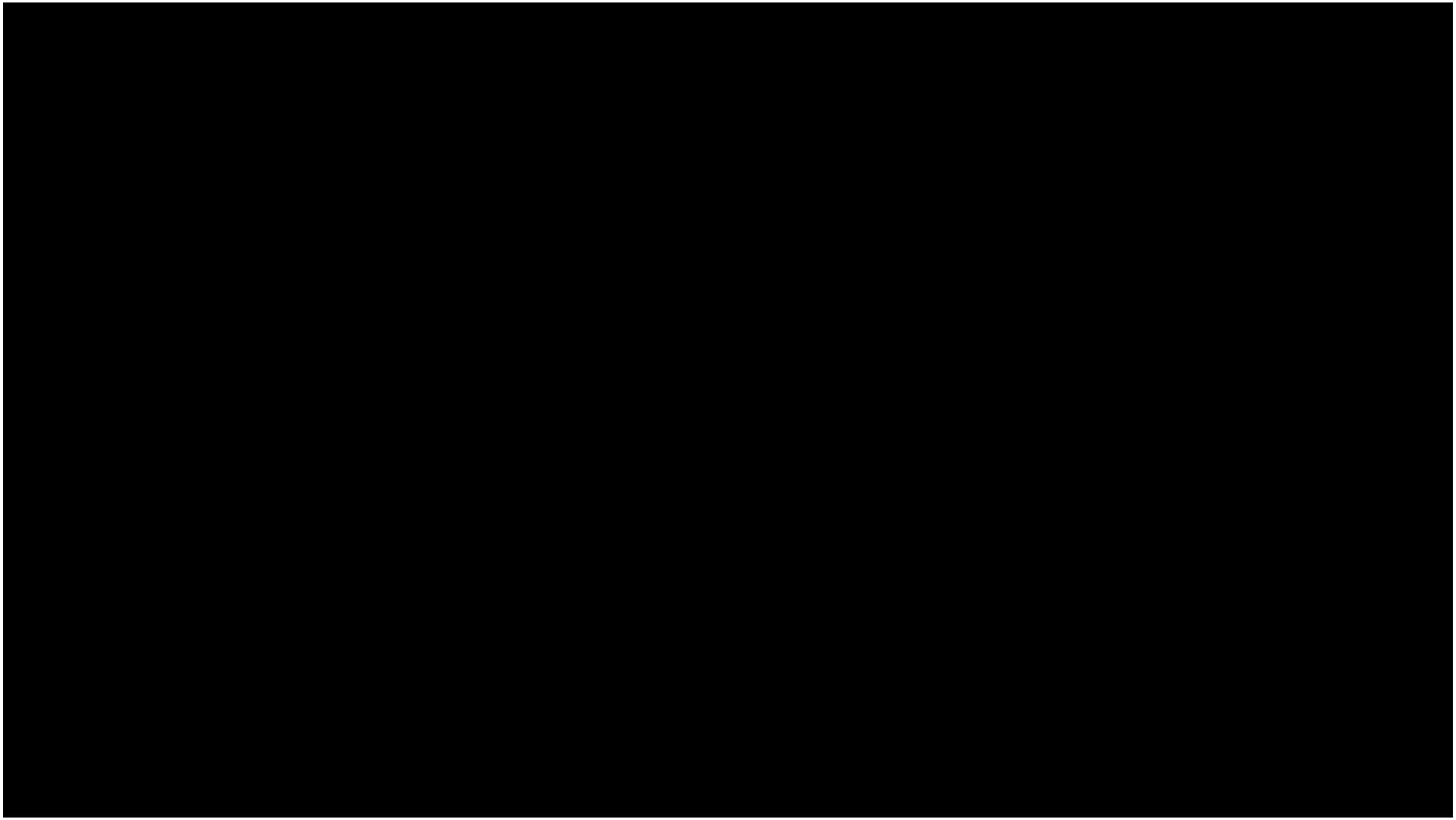
- Short printing time
- UV light source is cheaper than a laser

Cons:

- Accuracy
- Projector housing requires a lot of space

quickparts.com

Vat Photopolymerization (VPP) - Digital Light Processing

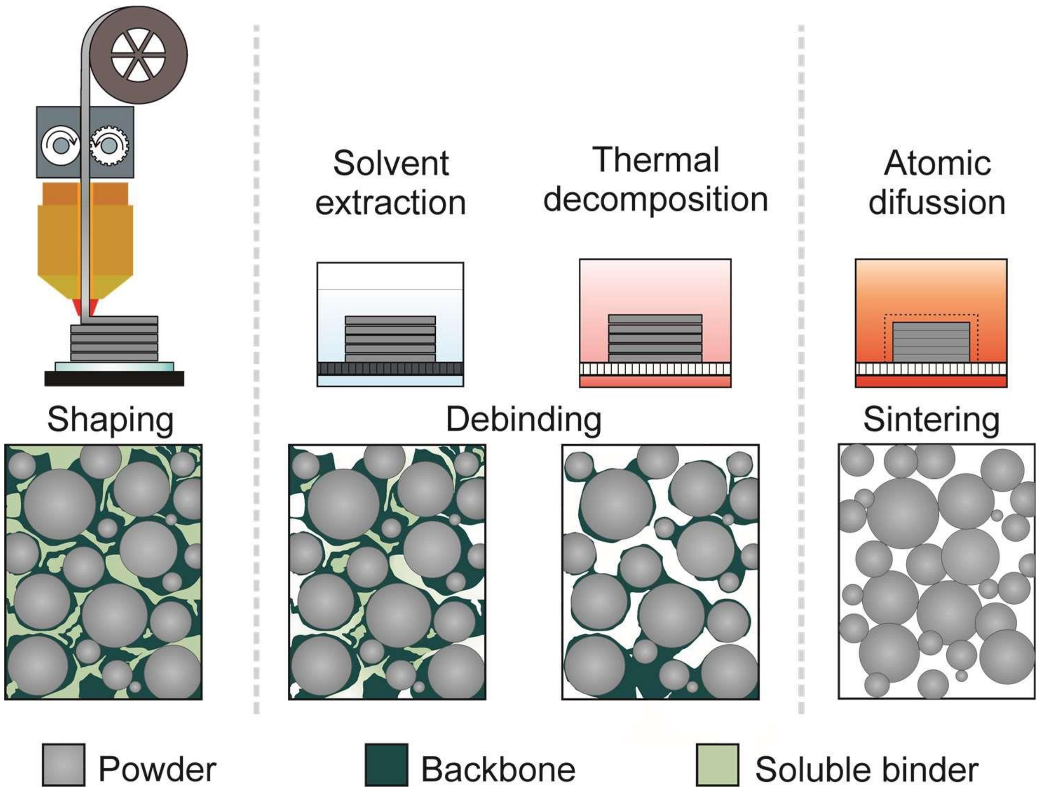


Handwerkskammer Koblenz

Material Extrusion of Metals / Ceramics – Process Steps

1. Shaping: Extrusion of a powder filled polymer mixture through a heated nozzle -> green part
2. Solvent extraction: Debinding of the green part in a solvent
3. Thermal decomposition: Debinding of the insoluble binder
4. Sintering to reduce porosity and obtain the final material properties

Shrinkage during sintering: consideration of an oversize for the part before printing



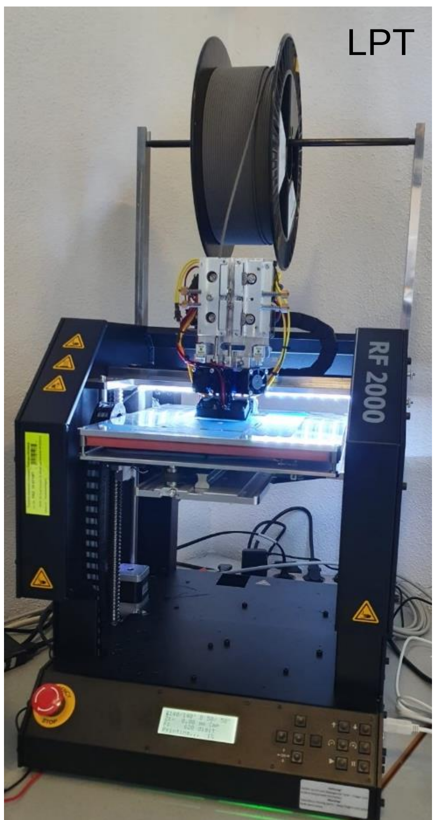
Gonzalez-Gutierrez et al.
Materials 2018, 840; doi:10.3390/ma11050840

Material Extrusion (Metals, Ceramics)

ISO-ASTM 52900: MEX-MSt/M or MEX-MSt/C
Material **Ex**trusion in a **M**ulti **St**ep Process of **M**etals
Material **Ex**trusion in a **M**ulti **St**ep Process of **C**eramics

PT+A

Printer for green part generation



LPT

Facility for solvent debinding

LÖMI

Furnace for thermal debinding and sintering

Carbolite Gero

Material Extrusion (Metals, Ceramics) – Pros and Cons

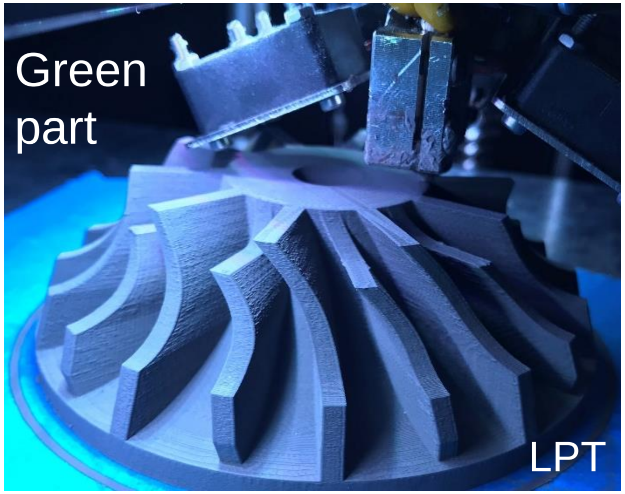
Advantages (compared to powder bed fusion)

- Diverse materials: numerous thermoplastic polymers, metals, ceramics and composite materials processable
- Good scalability of the process due to moderate costs of the required systems
- Few safety issues: no free powder and no laser radiation required
- Multi material parts possible
- Low thermal gradients due to the isothermal sintering process

  -> beneficial for brittle materials susceptible to cracking

Disadvantages

- Only for moderate wall thicknesses of <10 mm and part mass <1 kg
- High linear shrinkage during sintering (15-20 %)
- Filaments cost-intensive due to limited number of suppliers
- Frequently residual porosity in the final parts



Material Extrusion (Polymers)

ISO-ASTM 52900: MEX-SSt/P
Material **Ex**trusion in a **S**ingle **St**ep of **P**olymers

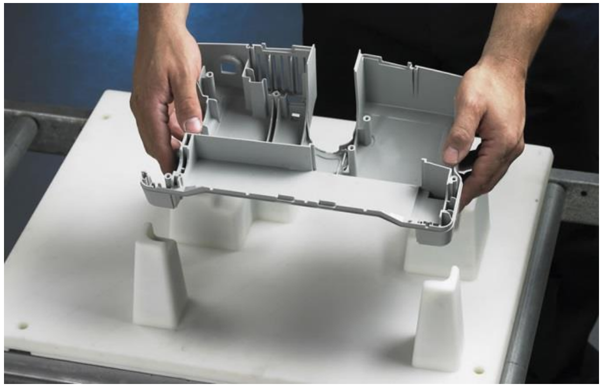
Controller (Design prototype)

amazonaws.com

Battery box (Function prototype)

studiofathom.com

Positioning aid



javelin-tech.com

Air conditioning channel (in aircrafts)

studiofathom.com