INTRODUCTION TO AM
PART 1 – GENERAL AND PROCESS CHAIN

SEAMAC International Summer School 2024

SEAMAC International Summer School 2024, Freiberg, Germany
Technische Universität Bergakademie Freiberg (Germany)

Additive Manufacturing

Definition according to VDI 3405:

- Additive technologies, in contrast to conventional cutting, create parts not by removing, but by **adding material**.
- **Parts are created layer by layer** through adding material or by phase transition of a material from liquid or powder into solid state.
- Production does take place **without the requirement of moulds, dies or tools***.

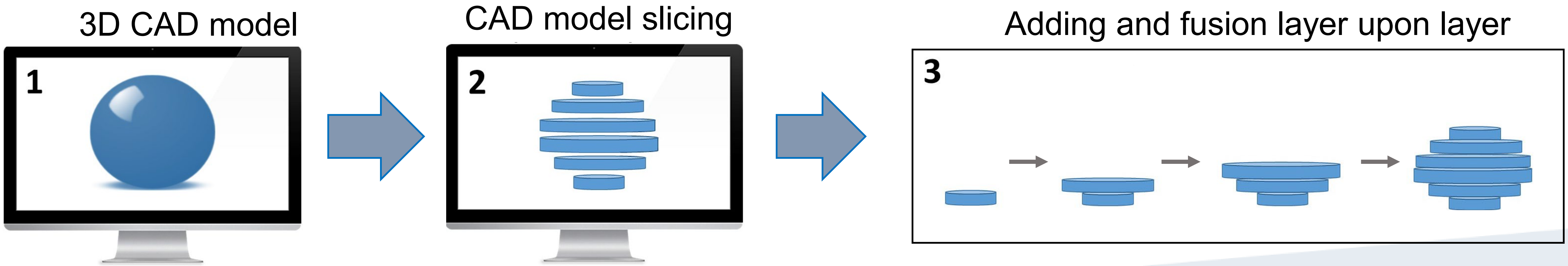
* I suggest to add „product specific".

Source: VDI Richtlinie 3405,Additive Manufacturingsverfahren - Grundlagen, Begriffe, Verfahrensbeschreibungen Verein Deutscher Ingenieure e.V., Düsseldorf 2014;

Definition of additive manufacturing (AM)

Additive manufacturing (AM) or 3D printing is the process of joining materials to make three-dimensional objects from three-dimensional (3D) CAD model data.

AM involves adding and fusion of layer upon layer until the product is completed.



Additive Manufacturing: many technologies

Stereolithography

Laser Beam Melting

Elektron Beam Melting

Liquid Deposition Modeling

Poly-Jet Modeling

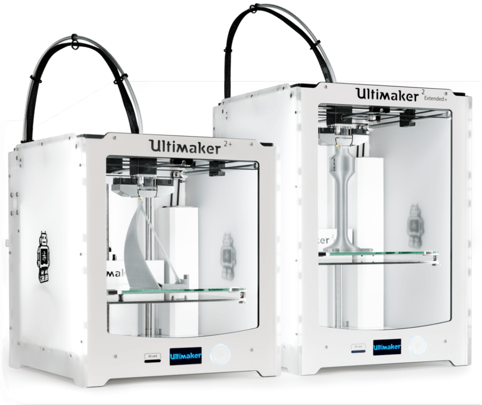
Wire Arc Additive Manufacturing

Digital Light Processing

Laser Powder Deposition Welding

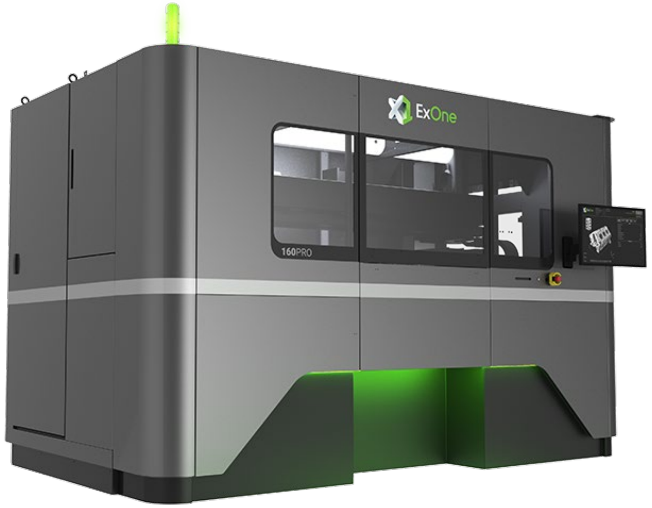
Laser-Sintering

Fused Filament Fabrication



[Ultimaker]

Binder Jetting



[ExOne]

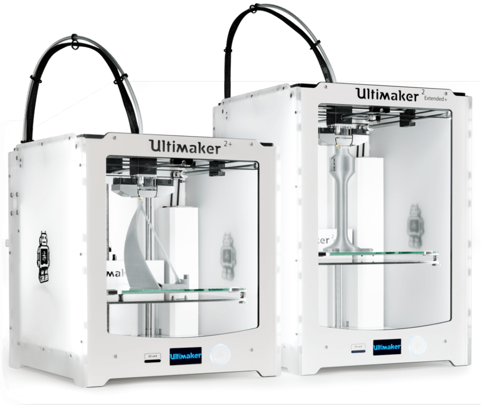
Additive Manufacturing: many technologies (DIN EN ISO/ASTM 52900)

VPP-UVL | PBF-LB/M | PBF-EB/M

MEX-CRB | MJT-UV/P | DED-Arc/M

VPP-UVM | DED-LB/M | PBF-LB/P

MEX-TRB



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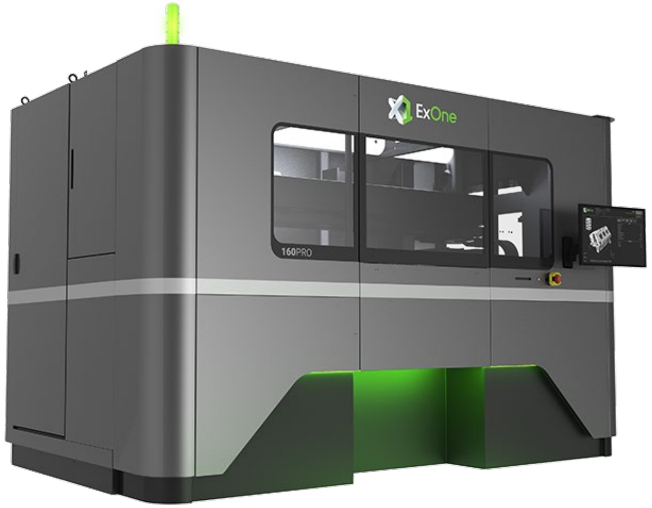
BJT

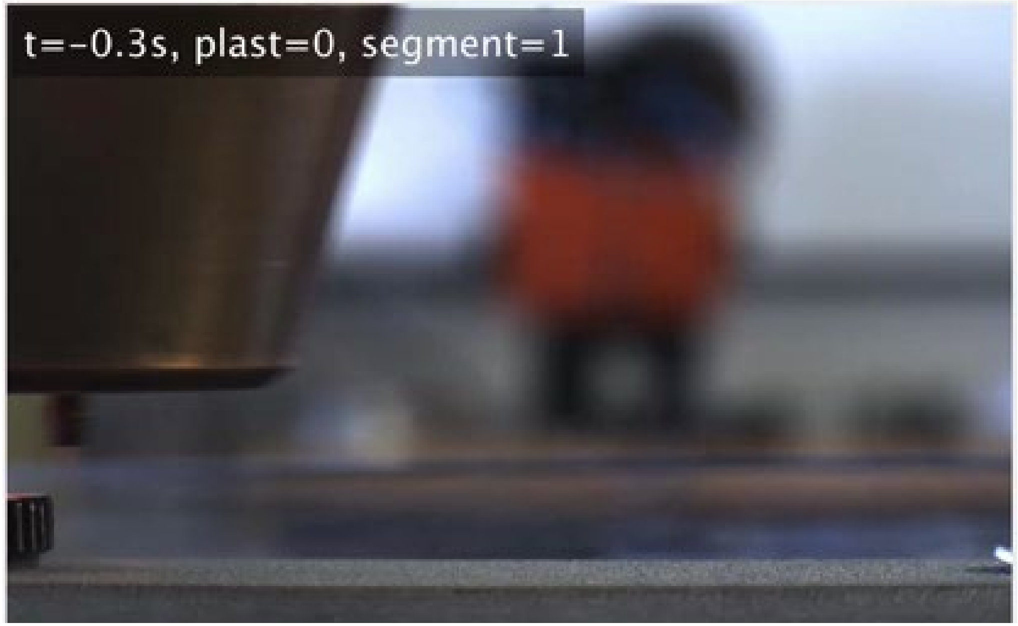


[ExOne]

Definition of additive manufacturing (AM)

Two basic AM system concepts for layer upon layer material adding and fusion

Direct deposition

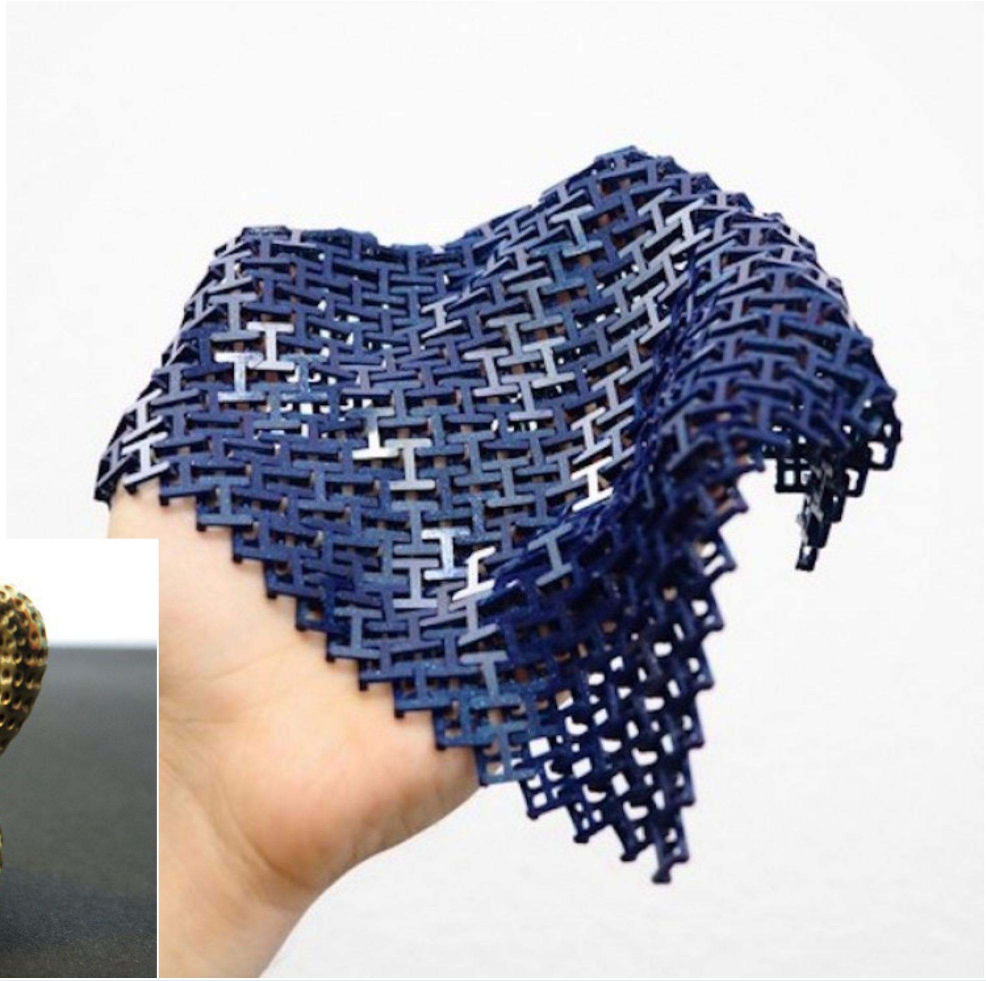


Selective fusion

Adding and fusion layer upon layer enables:

- **manufacturing of very complex** structures parts
- **without tooling** from the bottom up

Additive Manufacturing – what for?



Quelle: interestingengineering; sculpteo; QZ, allthat3d

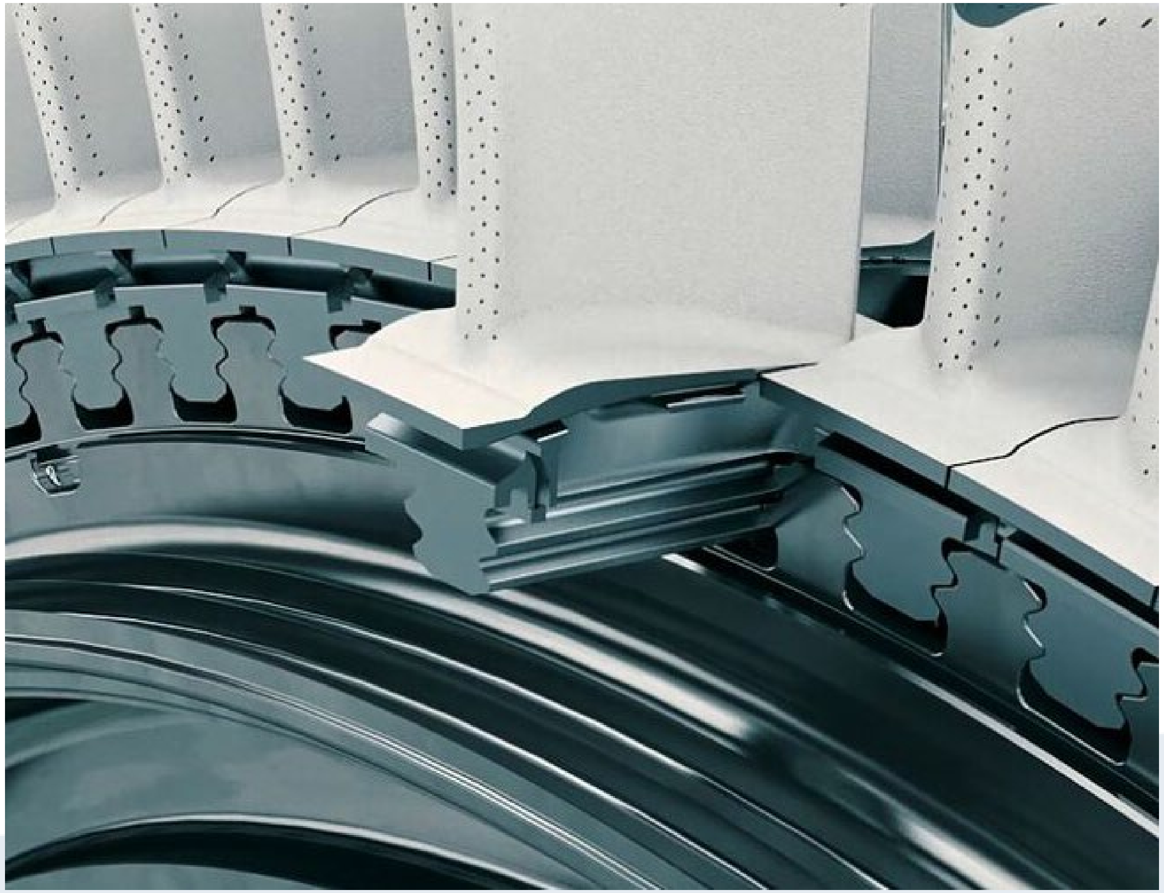
Additive Manufacturing – what for?

Quelle: natureworld/ EOS

Additive Manufacturing – what for?

Quelle: Porsche/911GT2RS

Additive Manufacturing – what for?



Quelle: Siemens, EOS

Additive Manufacturing – what for?

Quellen: 3T-AM/Launcher; Ariane6/ESA, Altair/Sulis

AM based complex shapes

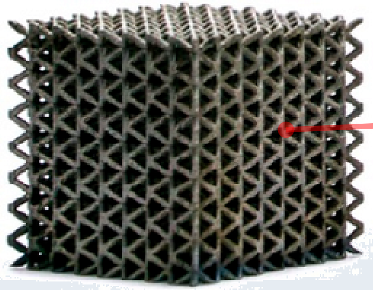
Adding layer upon layer enables fabrication of complex shapes not possible by other technologies

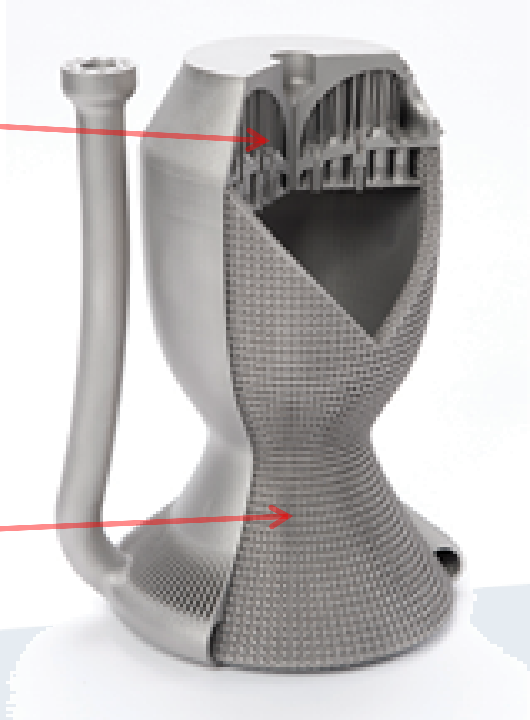
Rocket propulsion engine

Light weight, high stress and temperature resistant

Cavities

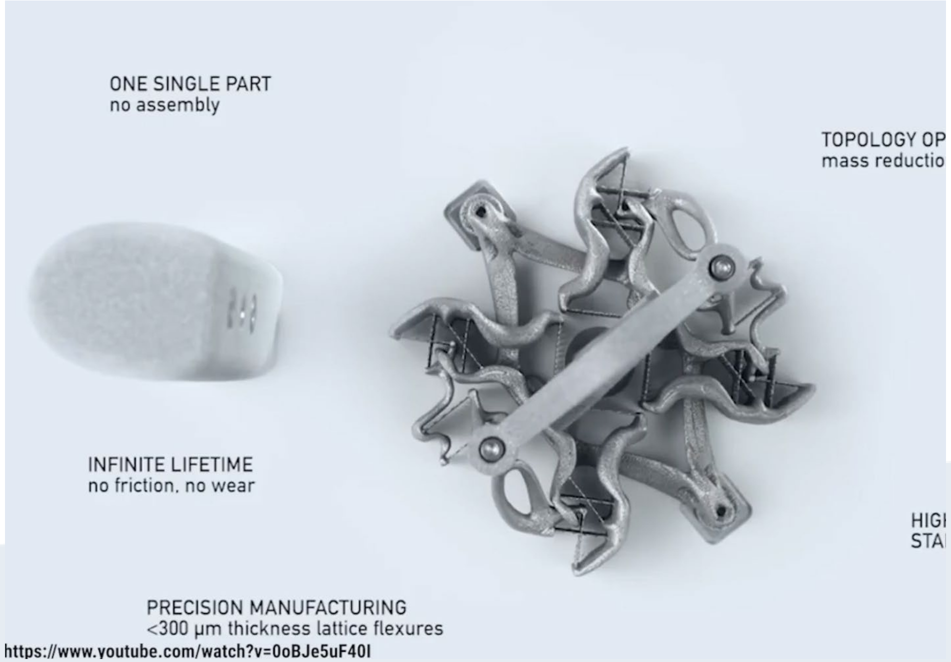
Lattice structure





Monolithic moving block

Light weight, component consolidation



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AM industry and some examples in use

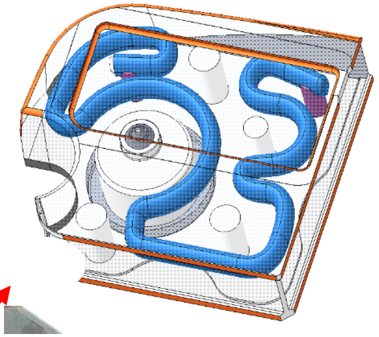
BMW - roadster
Roof bracket

→ topological weight minimisation

Audi
Spare parts on demand

→ storage cost minimisation

Kolektor
Tool insert conform cooling

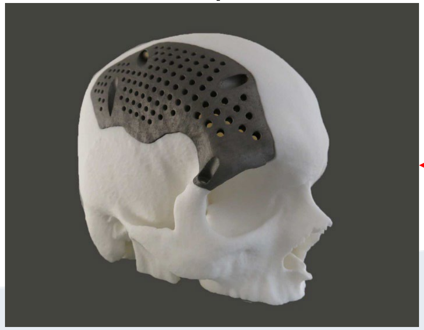


→ cooling optimisation

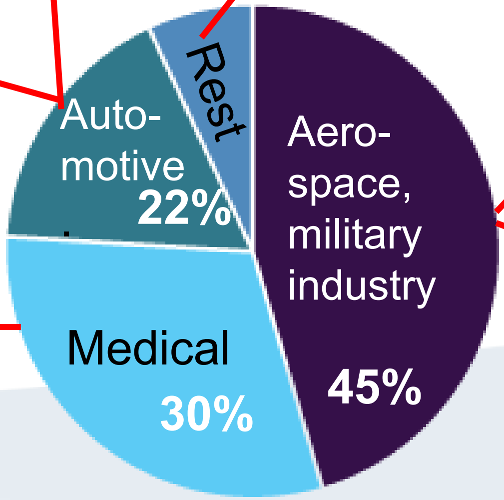
Lufthansa service
Turbine - Spare parts on demand

→ weight, functionality and storage cost optimisation

Sculpteo
Skull implant



→ 3D complex shape, customisation



Industry global market share (2022)

Avio - seat bracket

→ topological weight optimisation

AM examples in industry

Furniture

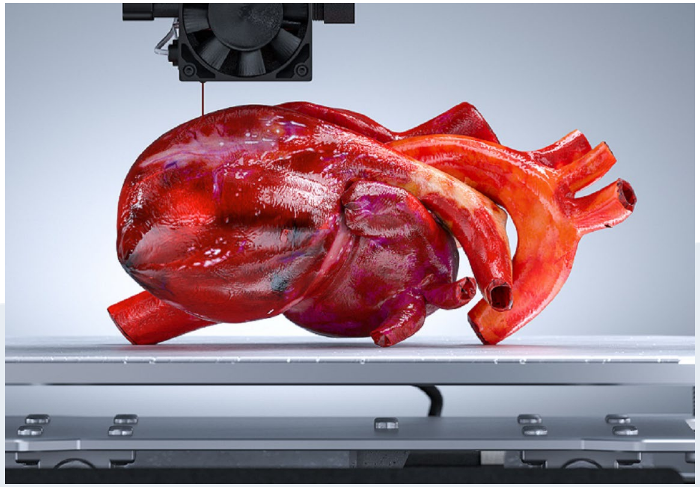
Fashion

Jewellery

Sport

Food

Medicine – tissues and organs



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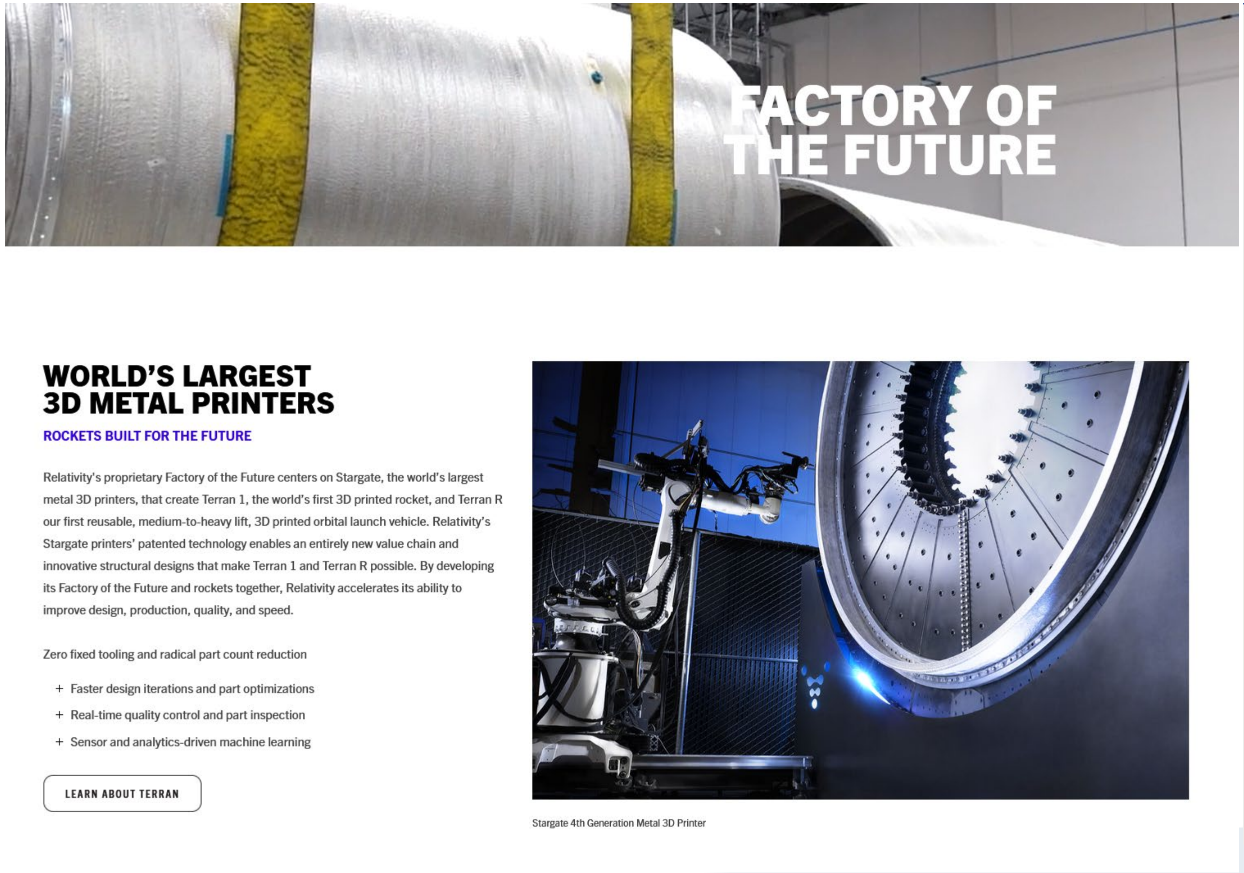
Additive Manufacturing – what for?

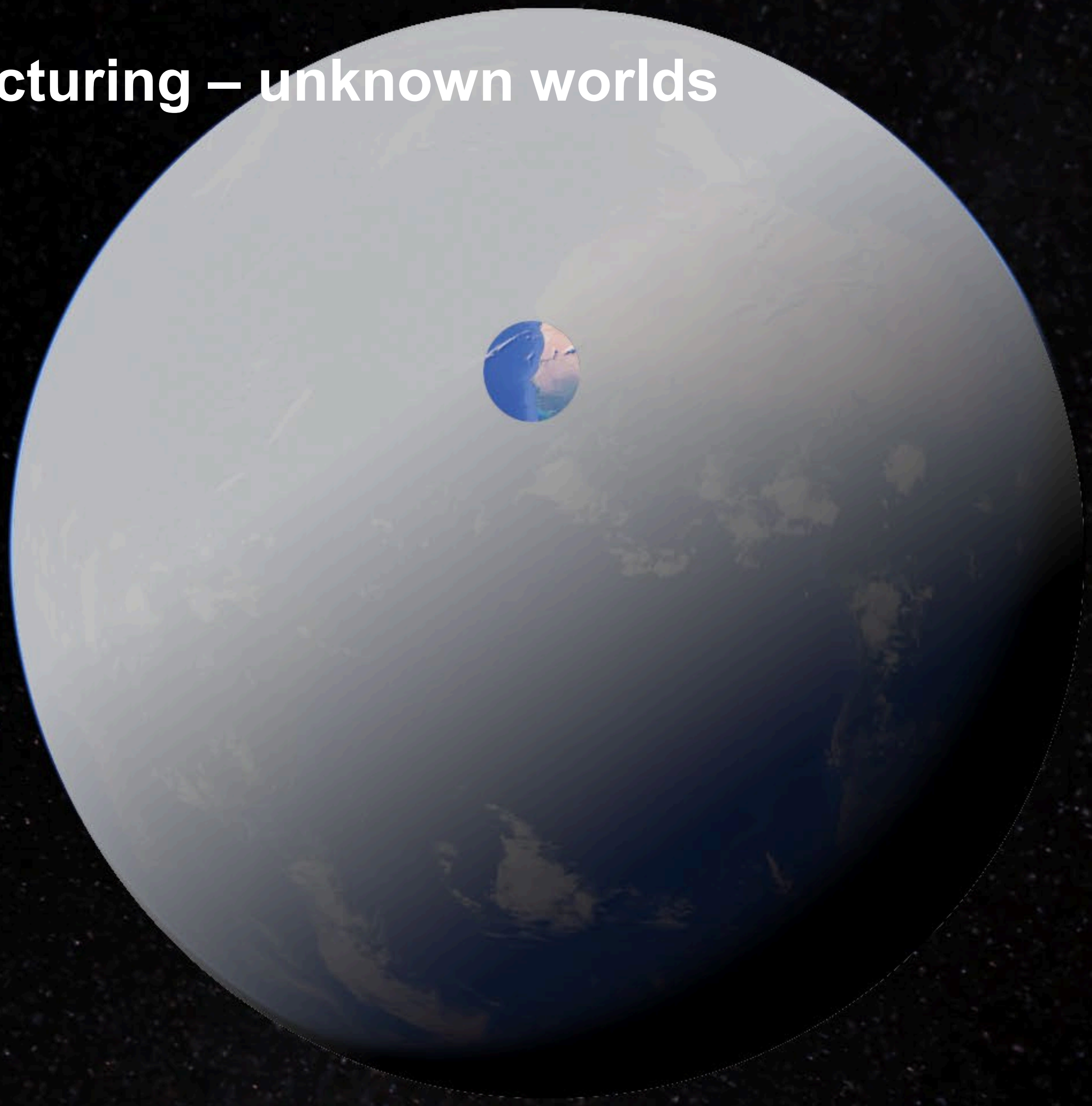


Quellen: relativity space, IEEE spectrum

Additive Manufacturing – what for?

Quelle: Twente, WASP/Wired

Additive Manufacturing – unknown worlds



Additive Manufacturing – discovery tools

Discover	Report	Apply
Research	Education	Transfer

Additive Manufacturing – where are the challenges?

- „Kinderkrankheiten“ / „teething troubles“
    - Process stability / Reproducibility / Process safety
    - Limited material selection
    - Largely proprietary technology
    - Comparably high cost
    - Developable knowledge of technologies
    - Demand for Post-Processing technologies and automatisation

➲ So far manageable amount of integration into process chains

➲ Limited competitive applications

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★ Utilise **extended possibilities**
★ Not (only) using other technologies, but **developing new approaches**

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BASICS

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Systematics of Additive Manufacutring

Specific features of AM processes:

- no need for product specific tools/dies/molds
- creation of layer geometry straight from CAD data
- files can – in principle – be built in any orientation (no clamping issues in building)

Also, all machine tools on the market today can run by the same (STL-)file format.

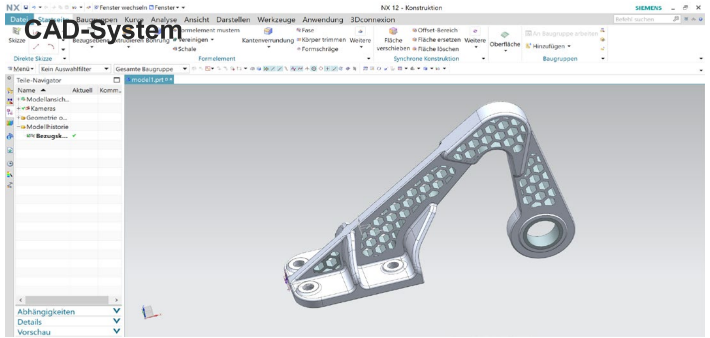
Technological process chain

CAD model → model preparation → process preparation → build process → post processing → follow up technologies

Process steps

1. 3D-CAD-model

- Starting point for production process
- 3D-CAD-data originates from engineering design, reverse engineering or medical data (computer tomography)
- Formats e.g.: STL, IGES, STEP

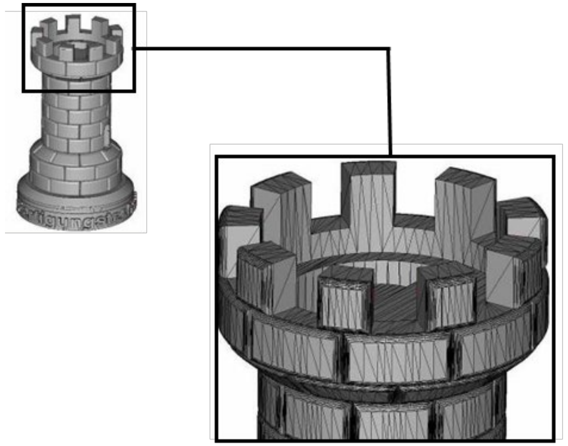


https://kuliahteknobiomedik.files.wordpress.com/2011/12/2007_computerized_tomography.jpg
https://amtech3d.com/einscan-pro-plus/

Process steps

2. Triangulation

- Best possible approximation of geometrical surface through triangles
- Triangulation errors appear especially on strongly curved freeform surfaces
  → Number of triangles as accurate as necessary, not as accurate as possible.
- Validation of geometry after triangulation is essential



Triangulated mesh

Final part

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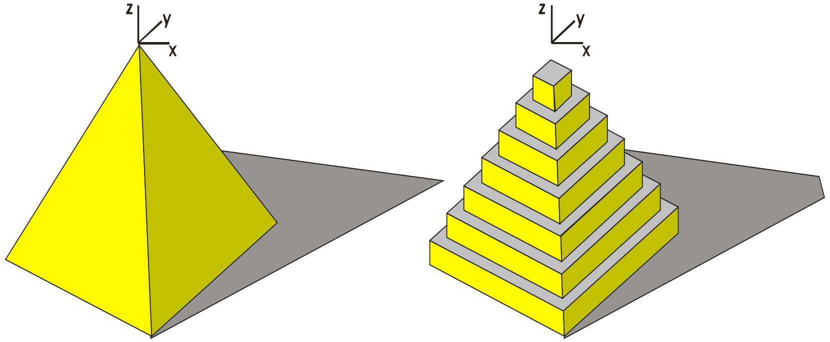
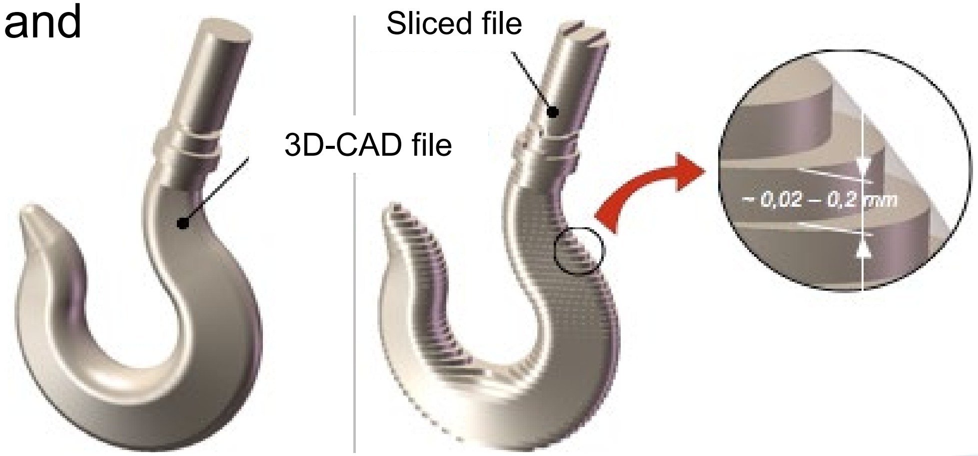
Process steps

3. Model preparation

- „slicing“ file (STL file) into layers
- build-process relevant geometrical information is created for each layer
- „staircase effect“ at curvatures, free form surfaces and obtuse angles
  → low surface quality





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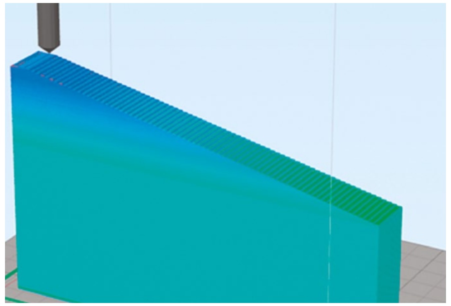
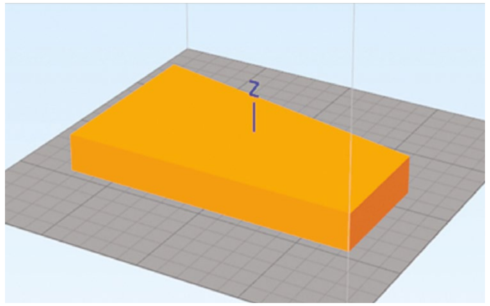
Process steps

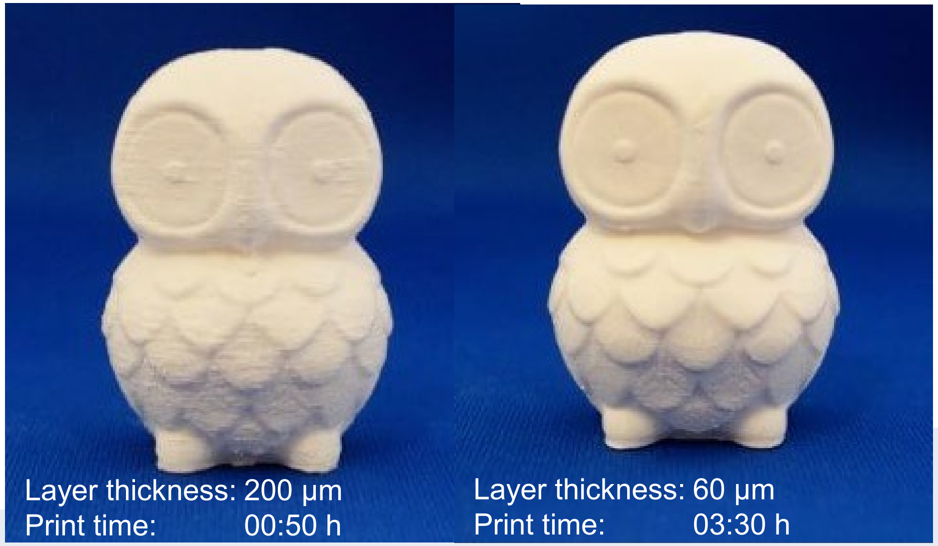
3. Model preparation

- For good surface quality, flat surfaces should be arranged *vertically* or *horizontally* in the build volume
  → minimising staircase effects

- The higher layer thickness the shorter is build time but staircase effect increases.
  → trade off quality against productivity





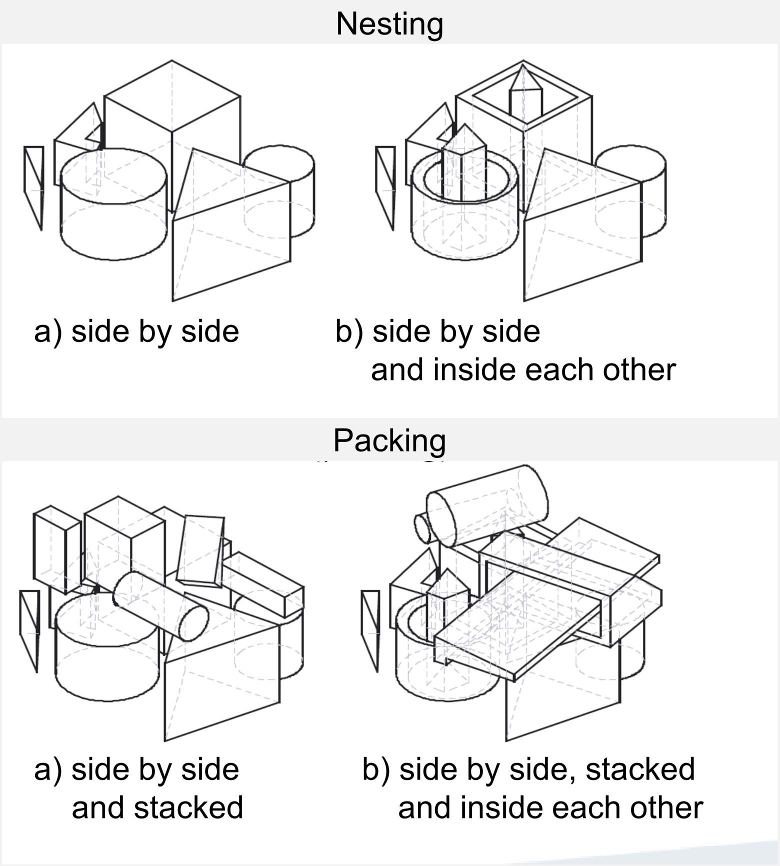


sourcen: https://3faktur.com, Zeitschrift: Make Magazin 1/2019

Process steps

3. Model preparation

- By optimal *nesting* and *packing* a higher productivity can be achieved while keeping quality
- Nesting and packing have different technology-dependent options

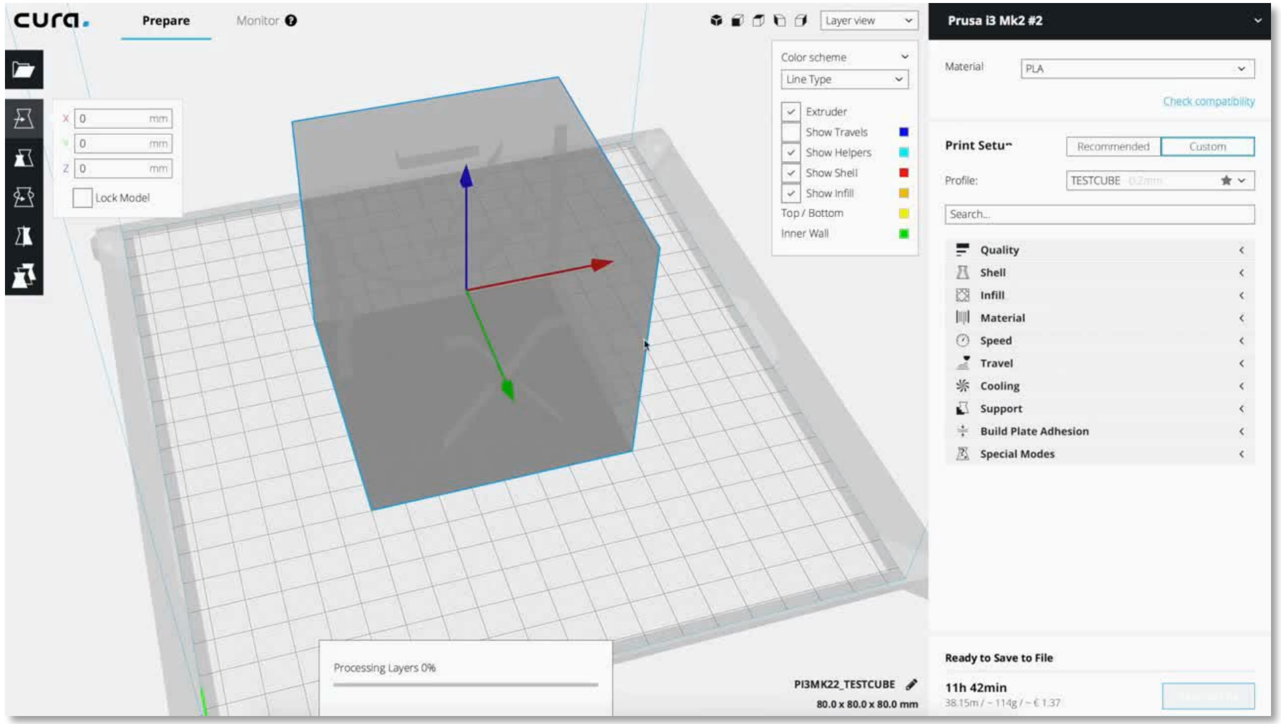


source: Martha, M. Optimierung des Produktentwicklungsprozesses durch CAD-CAM-Integration im Kontext der. Dissi., 2015

Process steps

4. Process preparation

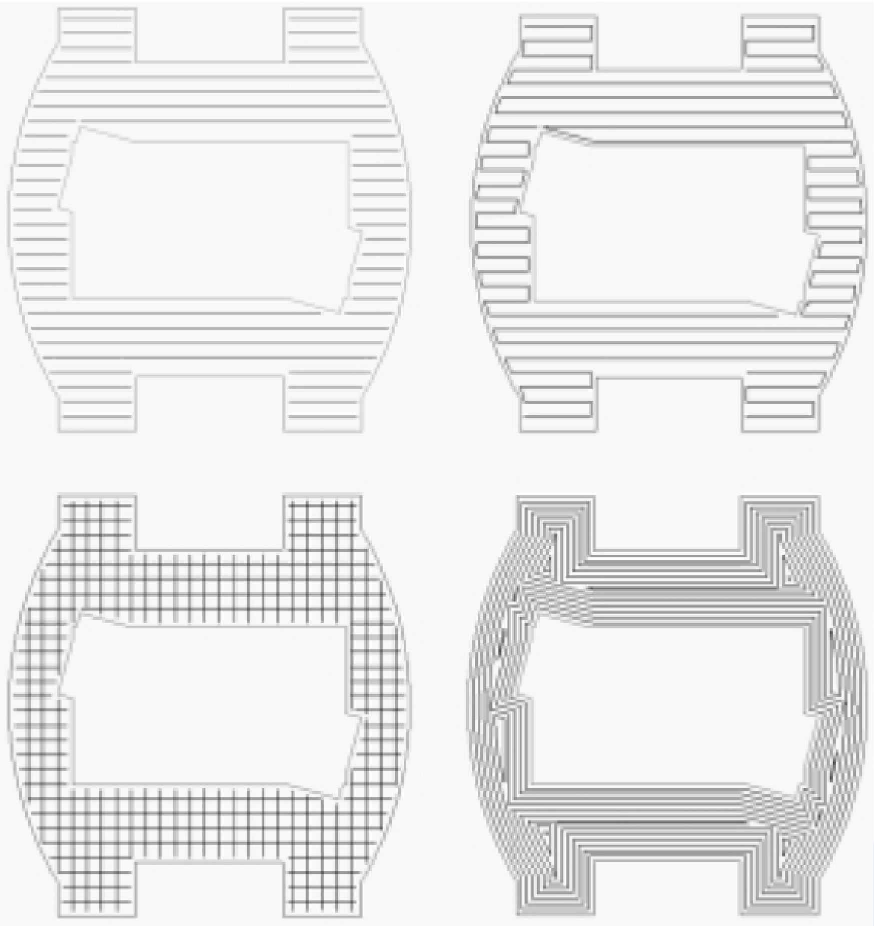
- Technology dependent, information on part *infill* is required (STL file only defines surfaces)
- Influence on amount of required material, part weight, build time and part stability



Process steps

4. Process preparation

- Layer information is converted to machine control information
- Material specific processing properties are to be respected
- Scanning: calculated paths which are followed during the build process
  - Influence on build time, energy- and temperature distribution on build platform and layer



Different scan strategies in PBF-LB

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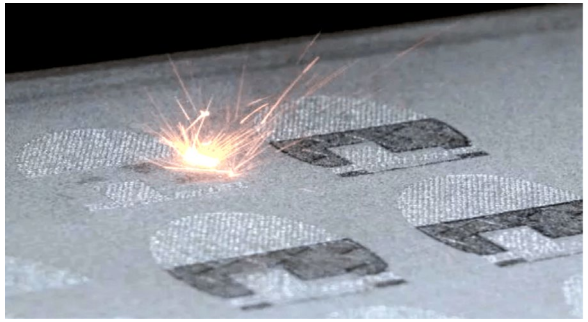
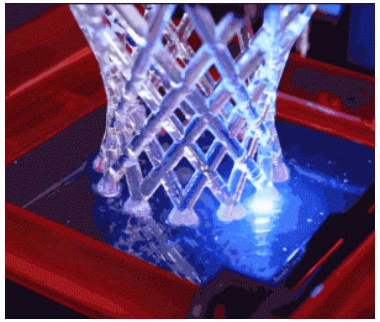
Process steps

5. Build process

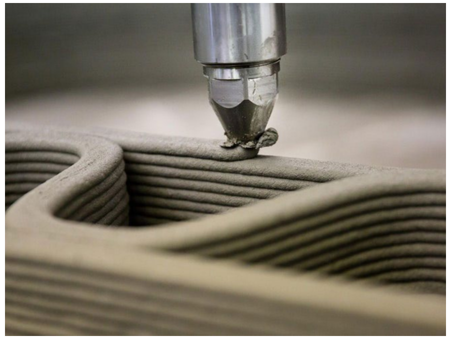
- Raw material is deposited on build platform (powder and vat based processes)
- Raw material is selectively shortly molten by an energy source, or solidified by a chemical activator
- Lowering the platform by one layer height and coating of another raw material layer



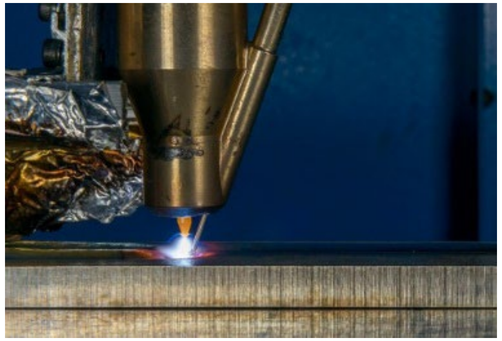
PBF-LB/M



VPP-UVM



MEX-CRB/C



DED-Arc/M

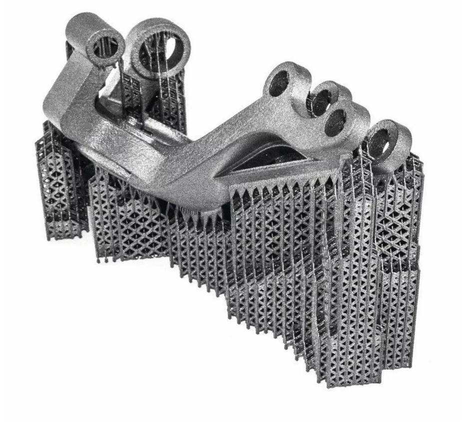
Source: https://waammat.com/about/waam

Process steps

6. Post processing

- Remove excess material
- Remove support structure (technology dependent)
- Curing of part (technology dependent)

Powder removal



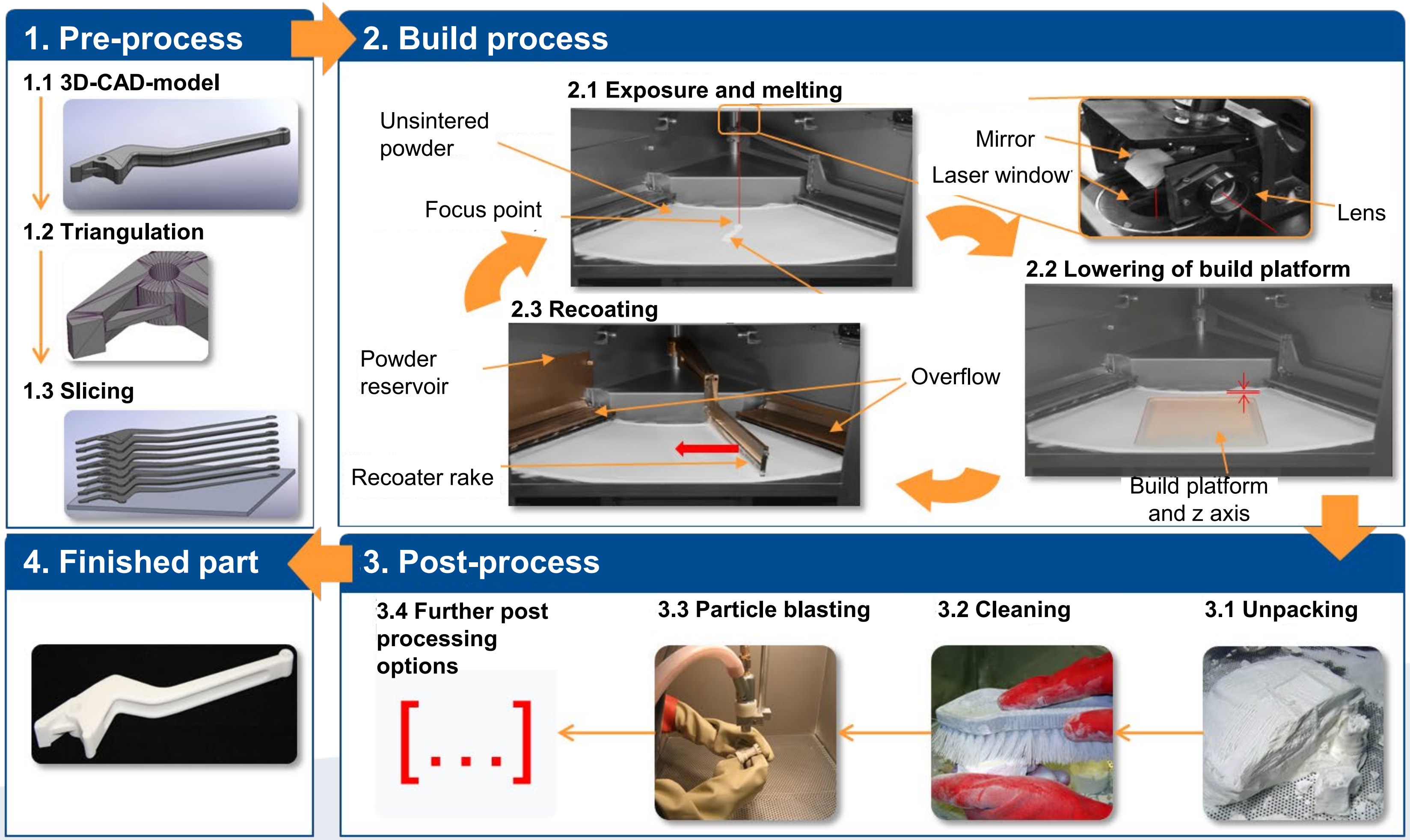
Metal part with support

VPP-UVM part

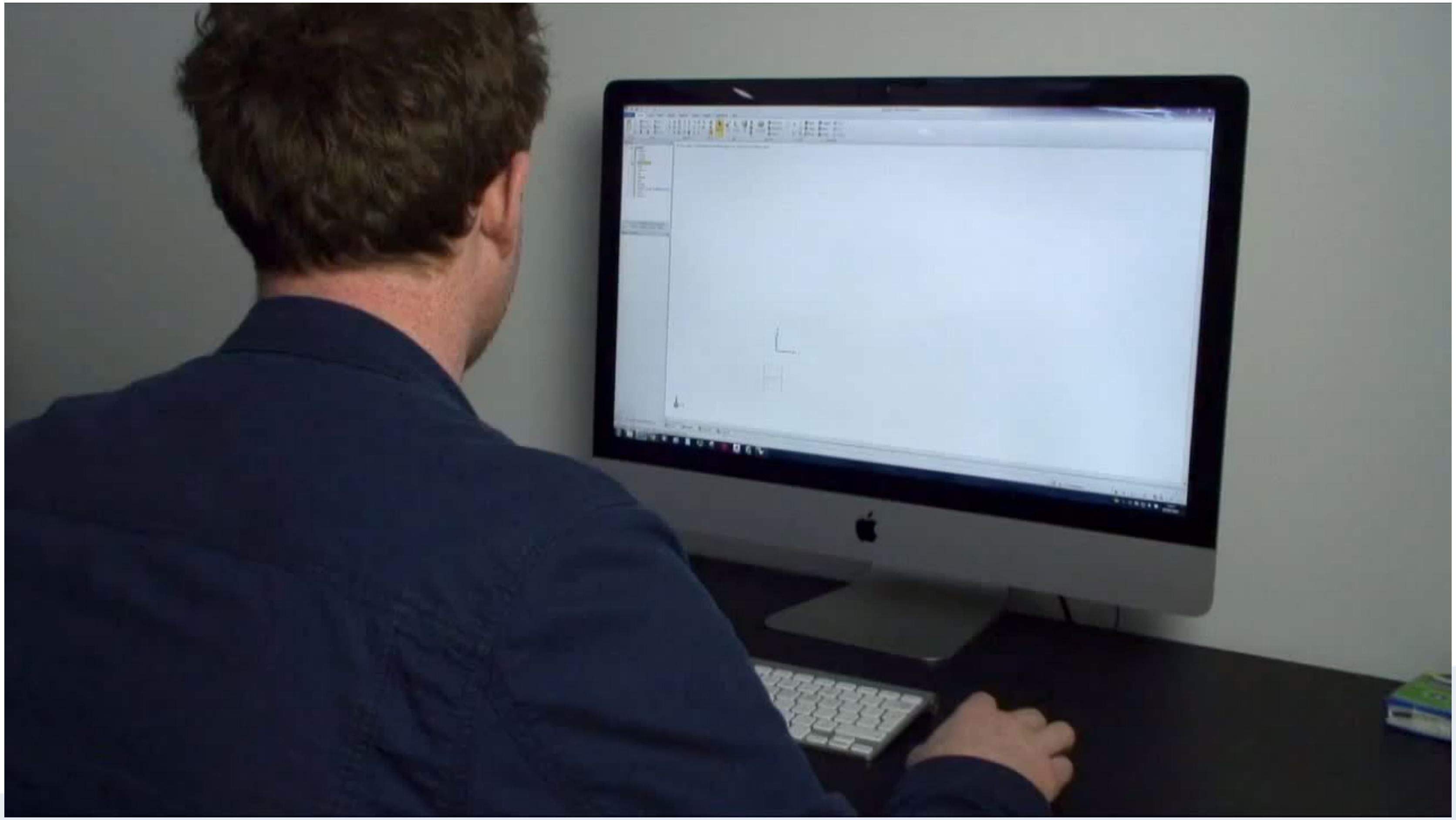
UV curing chamber

source: https://rookieelectronics.com

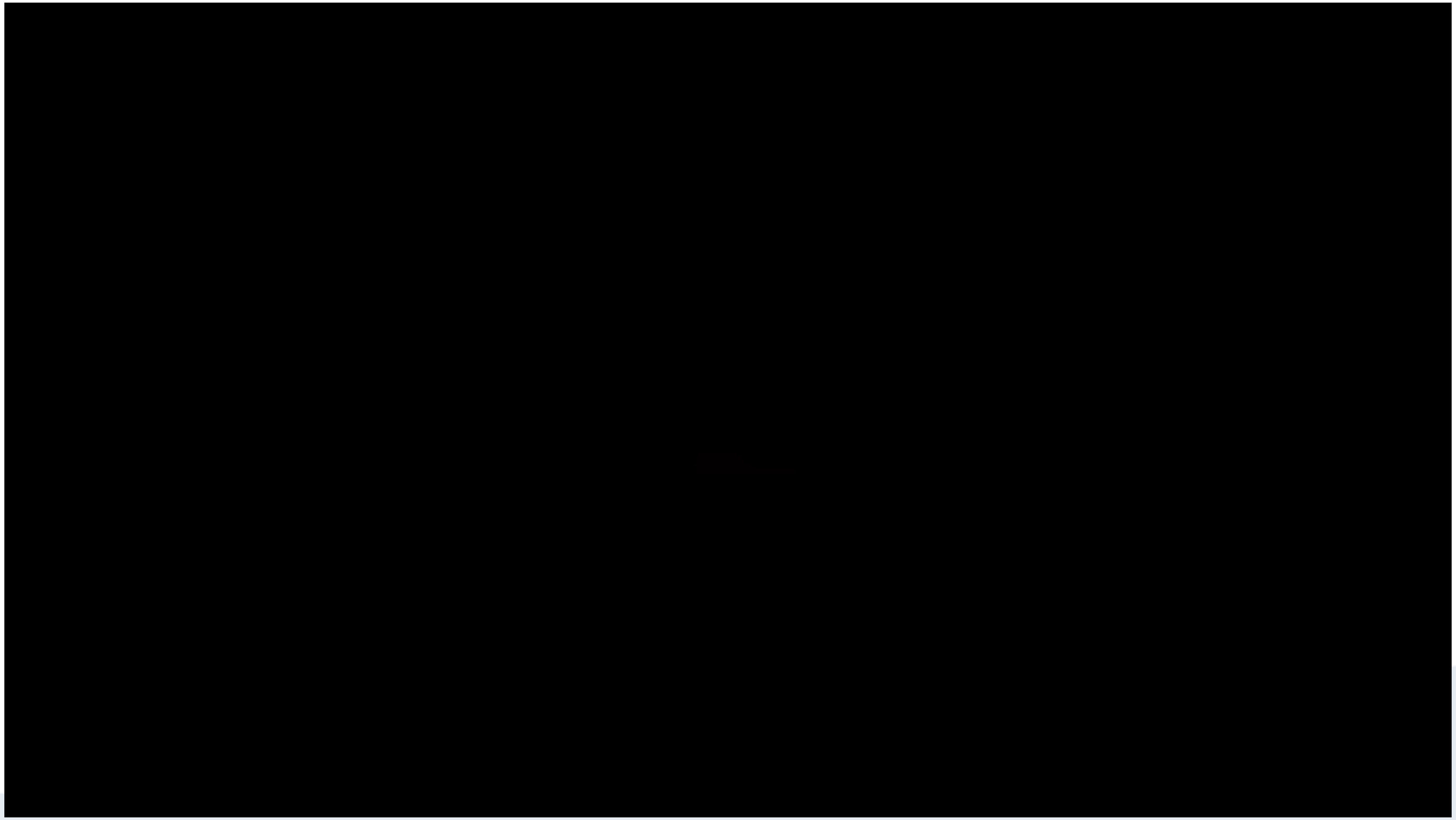
Process steps on the example of PBF-LB/P



Powder bed fusion – laser beam / polymer (PBF-LB/P)



Powder bed fusion – laser beam / metal (PBF-LB/M)



source: https://www.youtube.com/watch?v=8uiae6jYcmU

What manufacturing process is metal AM

Is it a “digital” casting ?
- in terms of AM part surface roughness → investment or sand casting

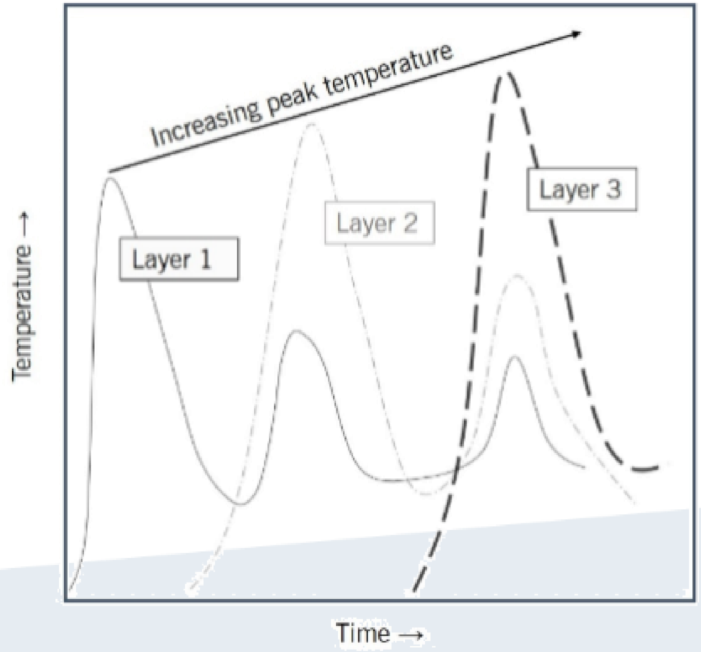
Is it a welding process ?
- in terms of heat loading → Arc or laser micro welding

It does not fit any of them.
- It has elements of every single one

→ AM of metals is a unique complex manufacturing process

Generated material mechanical properties?
- Generally can be substantially better than casted

Thermal cycles



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AM vs. conventional manufacturing

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Formative manufacturing (MIM)

best suited for:

- **high volume production of the same part**,
- requiring a **large initial investment** in tooling (molds),
- able to produce **parts at a very low unit price**.

Subtractive manufacturing (milling)

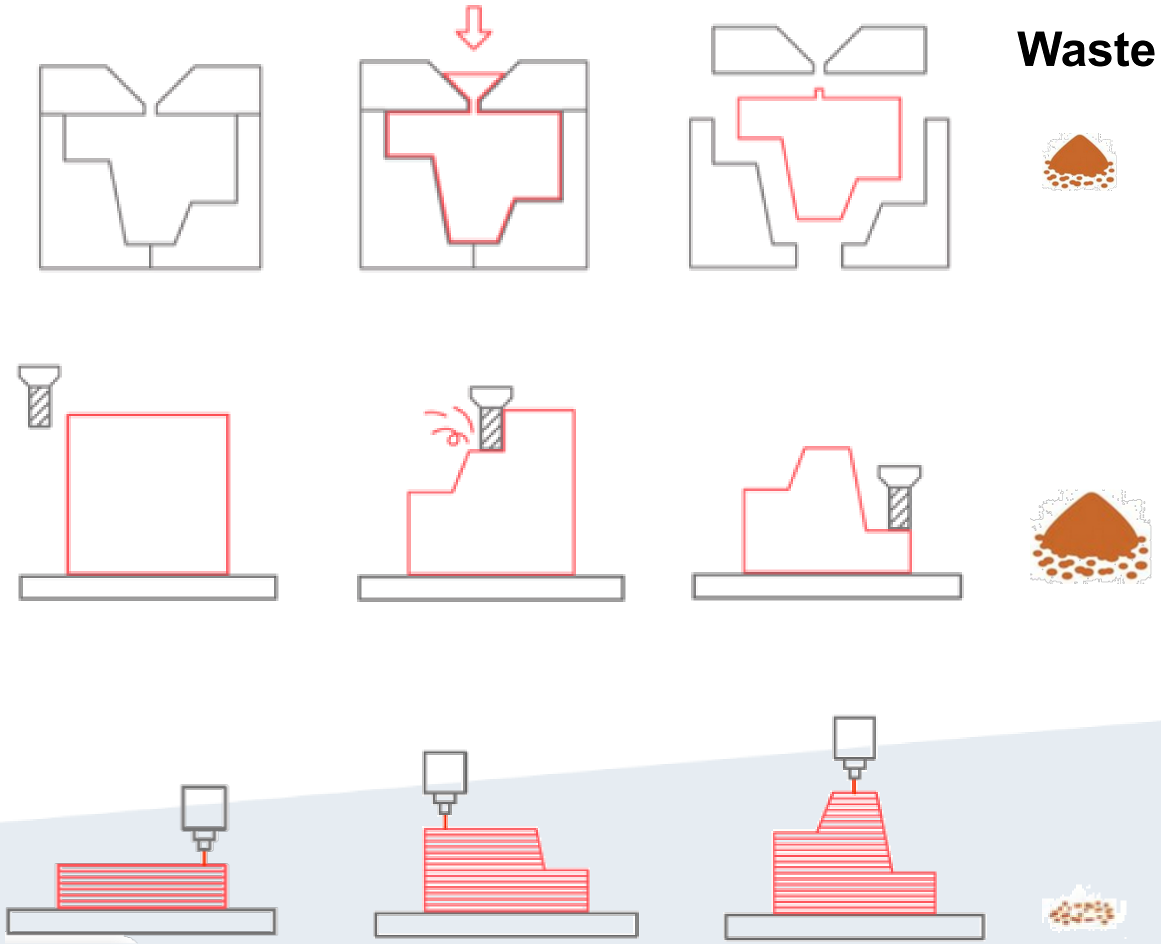
best suited for:

- parts with **relatively simple geometries**,
- produced **at low to mid volumes**.
- price increase with complexity

AM manufacturing (SLM)

best suited for:

- **high complex designs** that formative or subtractive methods are unable to produce,
- **low volume** production
- relative **high price**



Economy of AM vs. conventional manufacturing (Quantity

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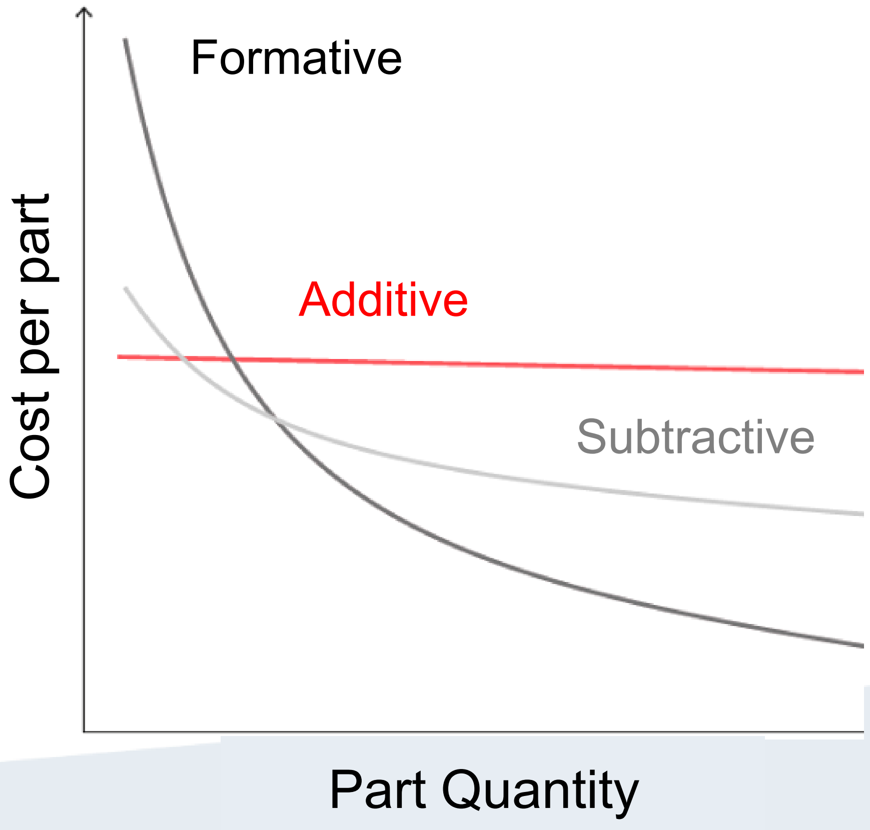
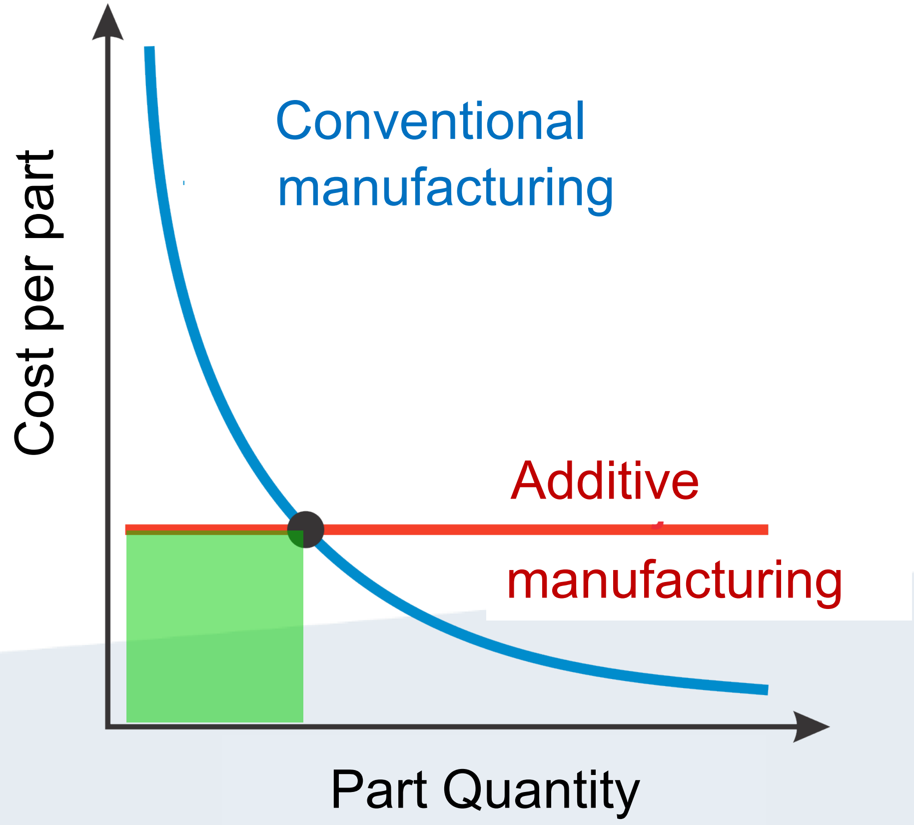
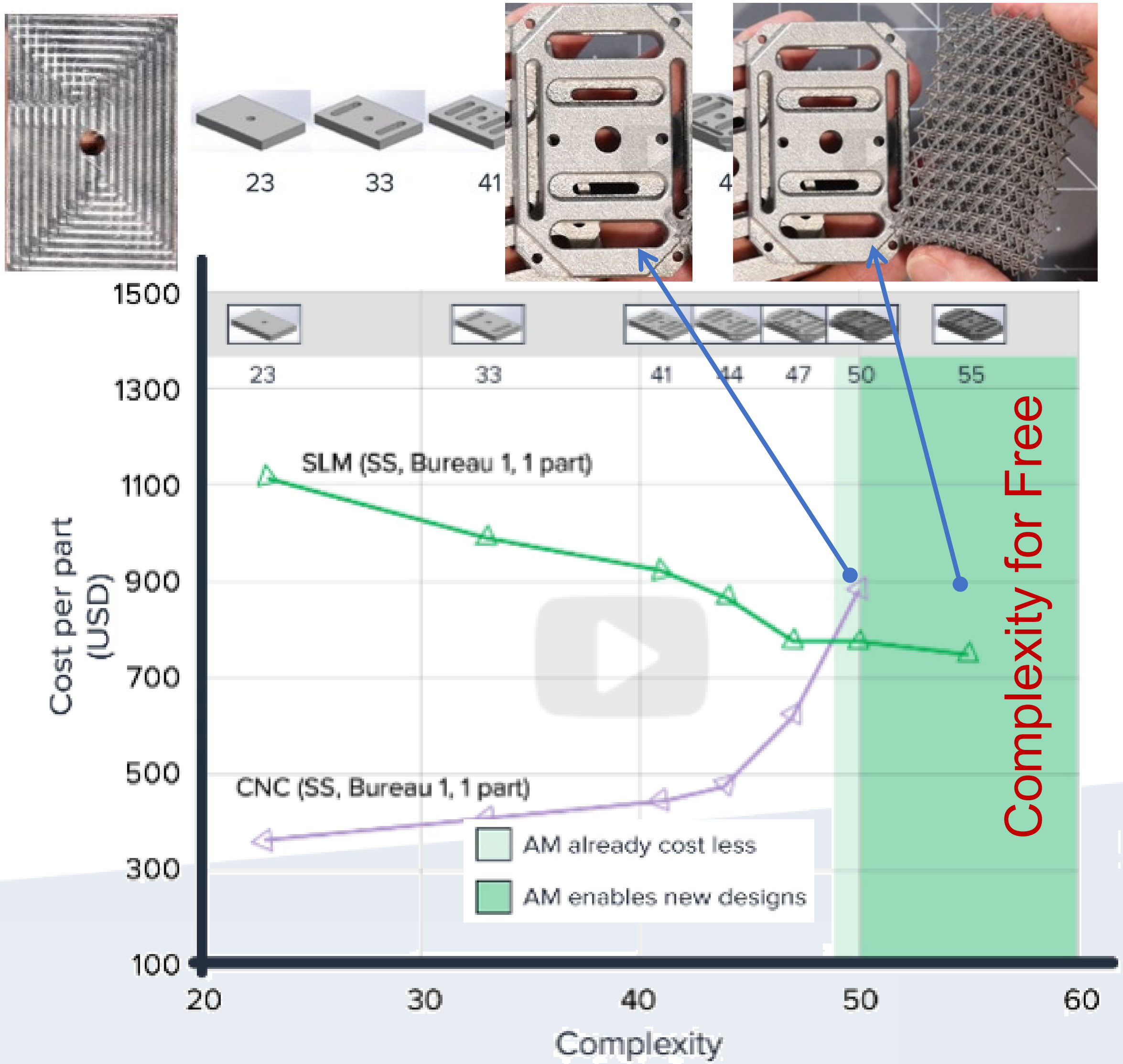
Part quantity

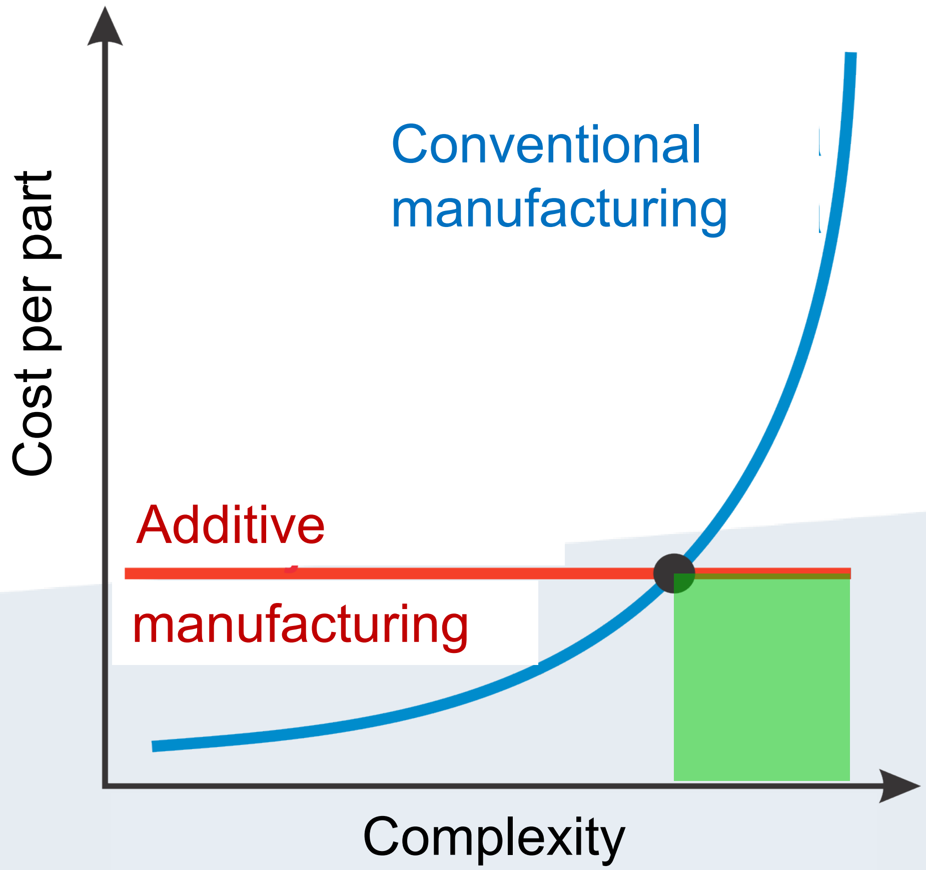




AM vs. conventional manufacturing

Part complexity





AM vs. convectional manufacturing – (Complexity)

Adapter 		
Material	Al 6061	AlSi10Mg 0,5
Fabrication process	5-axis milling	SLM
Mass 72,4 g	15,0 g	17,7 g
Price	203,58 EUR	190,66 EUR

AM Motivation, pro & contra

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AM - Motivation / Advantages	Prop.
Complex 3D geometry	16%
Faster prototype development	13%
Decrease of development costs	10%
Fabrication on demand	9%
Adaptation and faster redesign	9%
Reduction of mass	7%
Parts consolidation	7%
Conform inner channels, functionality opt.	6%
Lower (no) need for tooling at small batches	6%
Continues process of improvement	6%
Part customization and personalization	5%
Supply chain optimization	3%
Multilateral components, unique alloys	3%

Disadvantages
Limited material selection
Limited part volume (SLM)
Required post processing (thermal, machining)
High costs and constant cost /part
Anisotropic material properties
Increased possibility for copying
Low fabrication speed
Lower dimensional accuracy
Higher surface roughness

- Reduced waste compared to machining
- Part can be printed directly from the 3D model without the need for a drawing

Industrial application

Typical areas

- Small batches and/or custom made / bespoke parts
- Complex parts and designs which can not be produced by other technologies (lightweight design, functional integration…)
- Shortening iteration cycles in product development
- Manufacturing on demand, e.g. manufacturing of spare parts (e.g. for older series or stop-gaps)
- Local manufacturing with central engineering design

https://www.hacker-feinmechanik.de; www.arcam.com; https://www.rosswag-engineering.de;

AM based motivated improvement examples

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Ariane Group

Rocket motor injection head

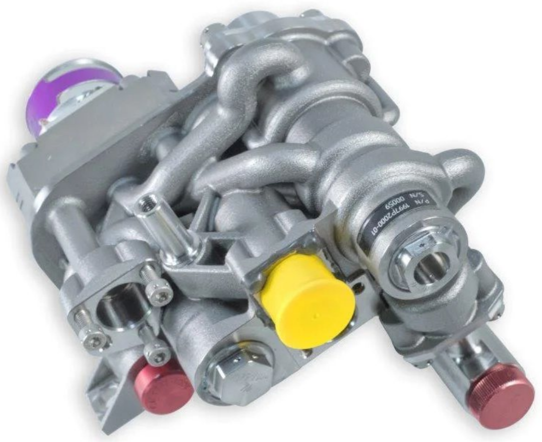
→ printed in one (before 248 parts)
→ production time 35 h (bf> 90 days)
→ 50 % less costs

GE Aviation

Fuel injection nozzle airplane LEAP

→ printed in one (before ~20 parts)
→ 25 % lower weight
→ 15 % higher efficiency
→ in 3 y. 30.000 printed parts

Liebherr



Hydraulic manifold (Airbus A380)

→ printed in one (before 10)
→ less tubes, less leakage points
→ 35 % less weight
→ 75 % shorter production time

AM based motivated improvement examples

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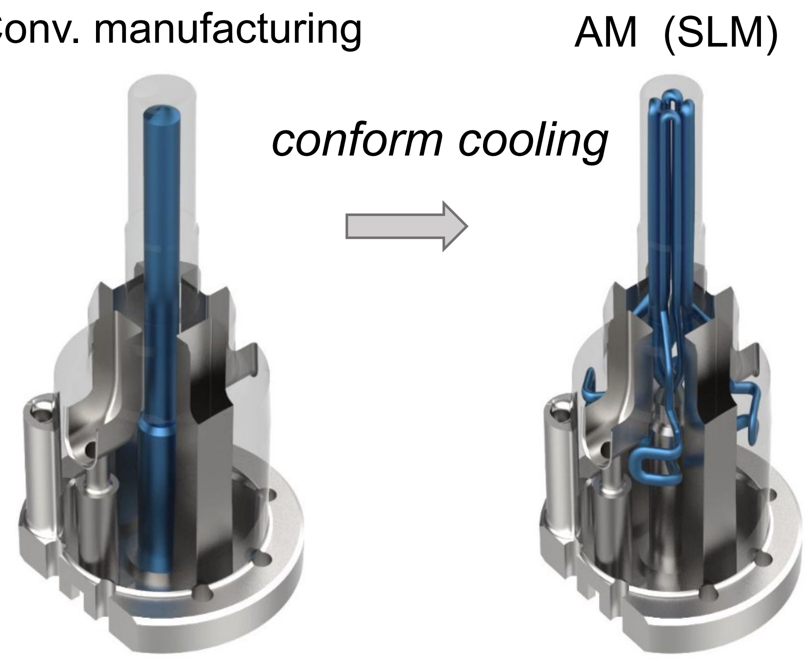
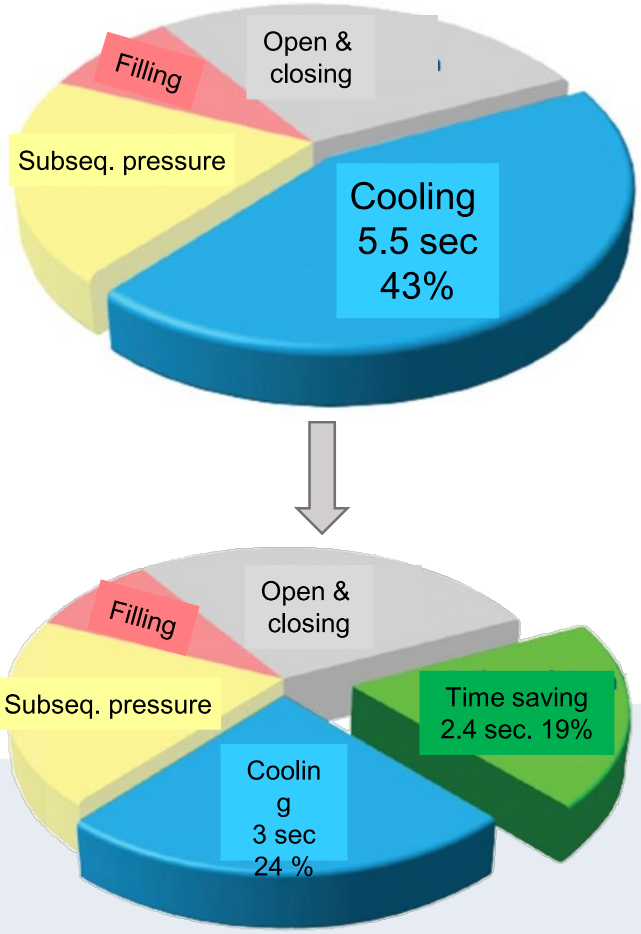
Insert of injection mold



→ *conform cooling optimization*
→ *19 % decrease of the total cycle time*
→ *uniform cooling – higher part quality*

IM phase time



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- AM provides endless possibilities for design and functionality improvement of components in various industries

- If not used correctly - it can be
  - a slow and
  - expensive process

  compared to conventional manufacturing methods

- If you can make it another way – you probably should.

Nevertheless – there are many growing successful applications of AM in industry designed specifically for an AM process

Functional (graded) materials

Motivation: components that, depending on the location, require different material properties

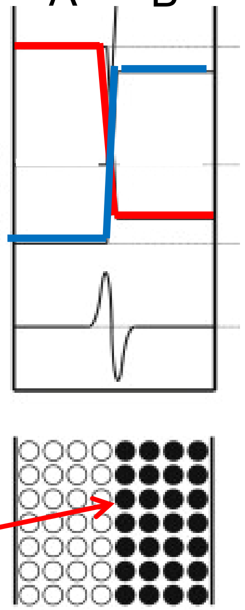
Problem: abrupt changes in material properties (metallurgical, technologically incompatible)

Functional material

A B

Heat conductivity

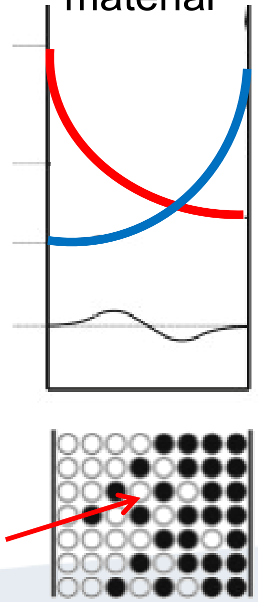
Thermal expansion



High thermo mechanical stresses
Cracking
Unwanted intermetallic phases

Sharp transition

FGM material



Low thermo-mechanical stresses

Gradient transition

Functional gradient materials (FGM) are materials built from different materials in which the **sharp transition** between the two materials is replaced by an **intermediate layer** or a **gradient transition of a mixture of the two**.

Functional graded materials

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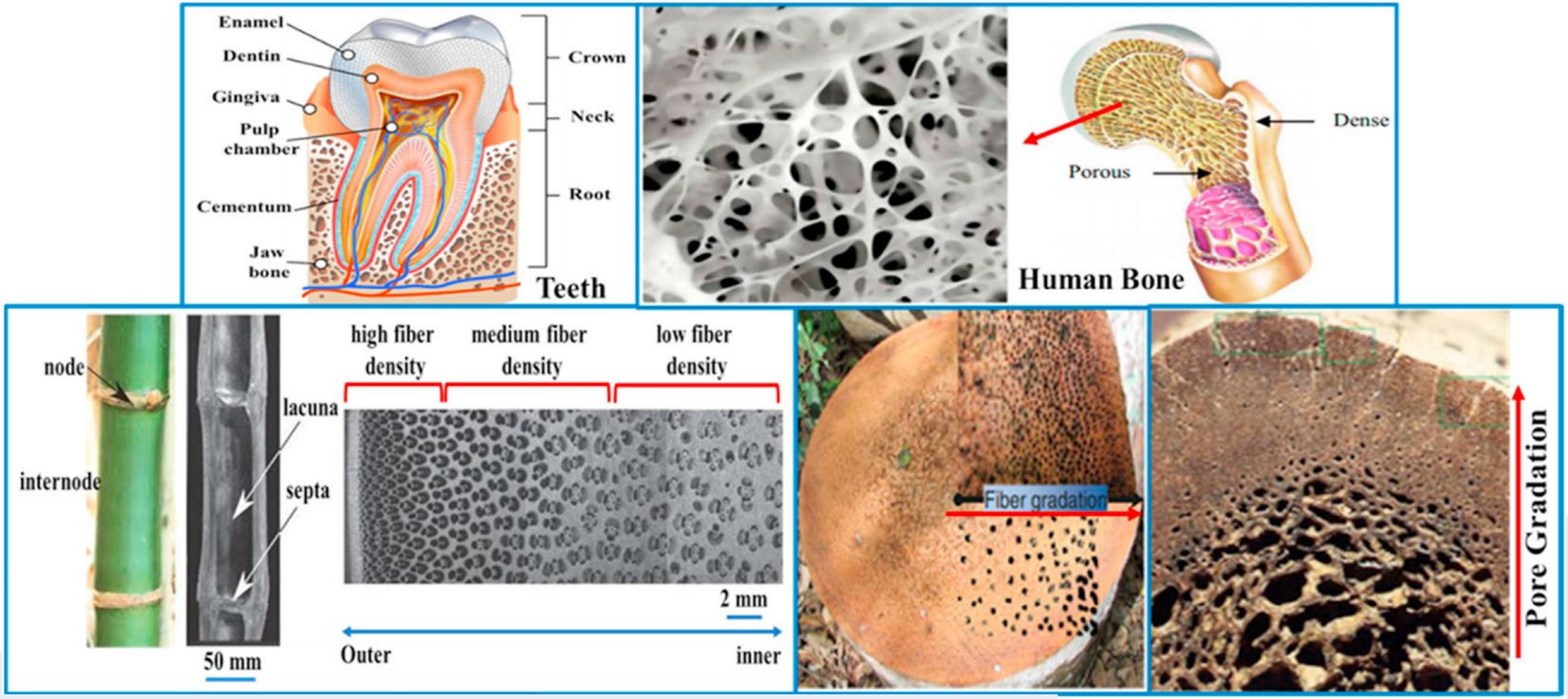
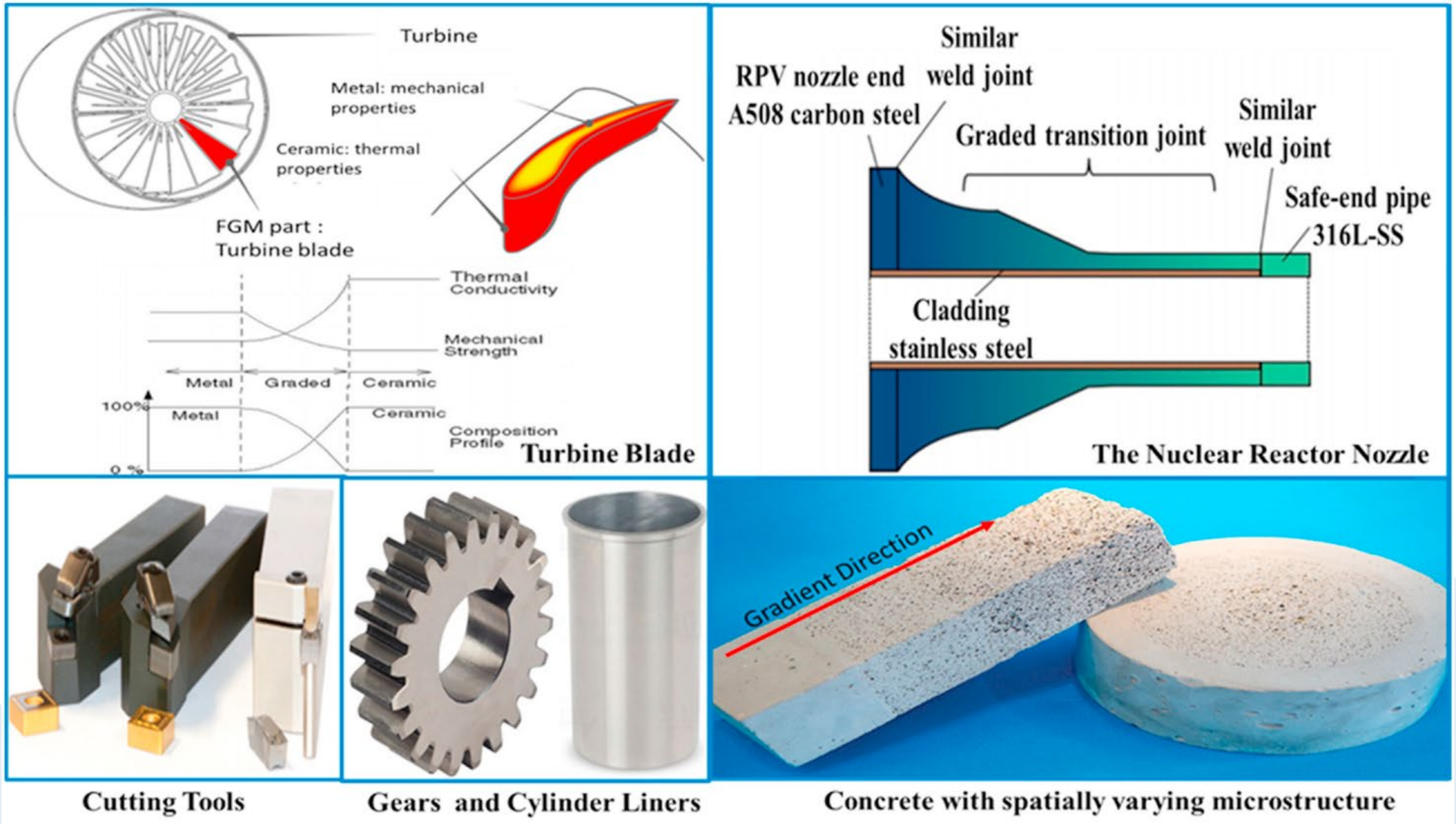
Examples from the nature



Cross Section of Dinosaur Bone

Functional graded materials

Engineering examples



https://www.sciencedirect.com/science/article/pii/S1359836820334247

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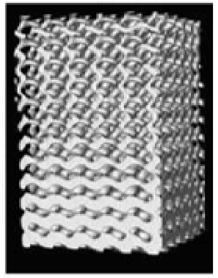
Functional graded materials

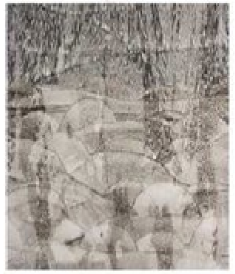
FGM gradient type classification

Composition

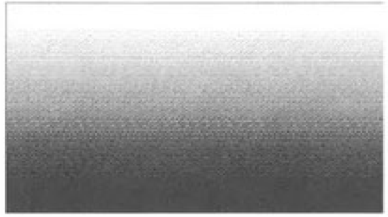
Porosity



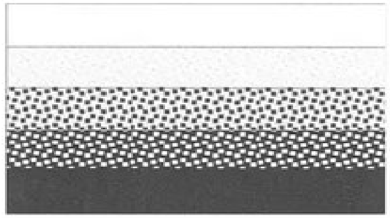
Microstructure



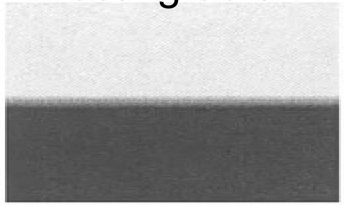
Continuous



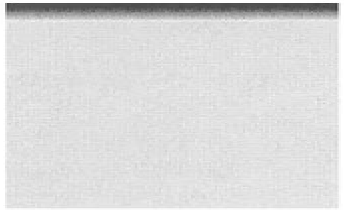
Stepwise

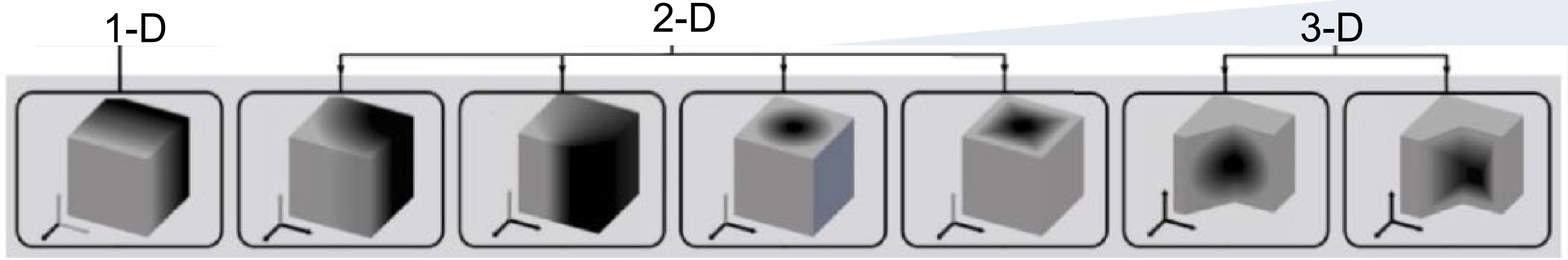


Intermediate
local gradient



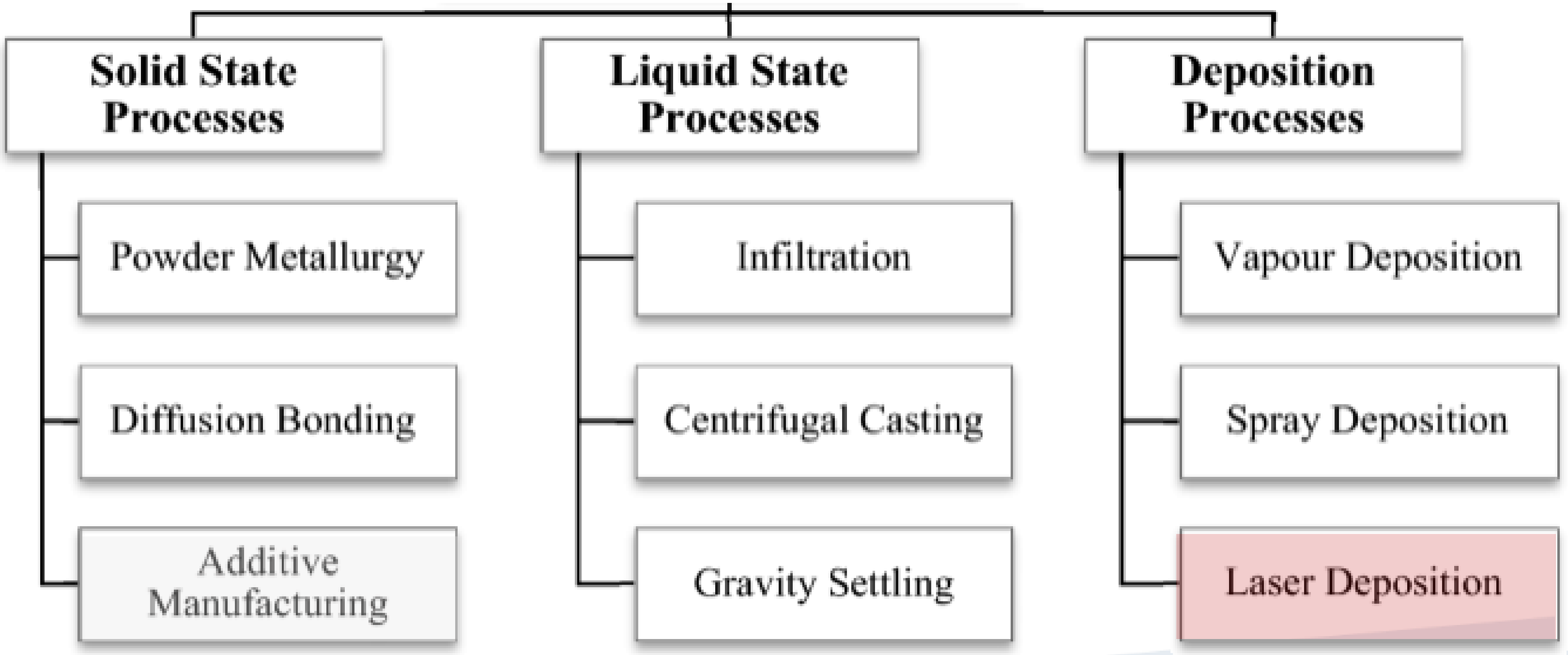
Surface
local gradient





Functional graded materials

FGM fabrication methods



SLM , EBM → Porosity FGM

DED (DLD, DEBD) → Composition FGM

L-DED fabrication of FGM

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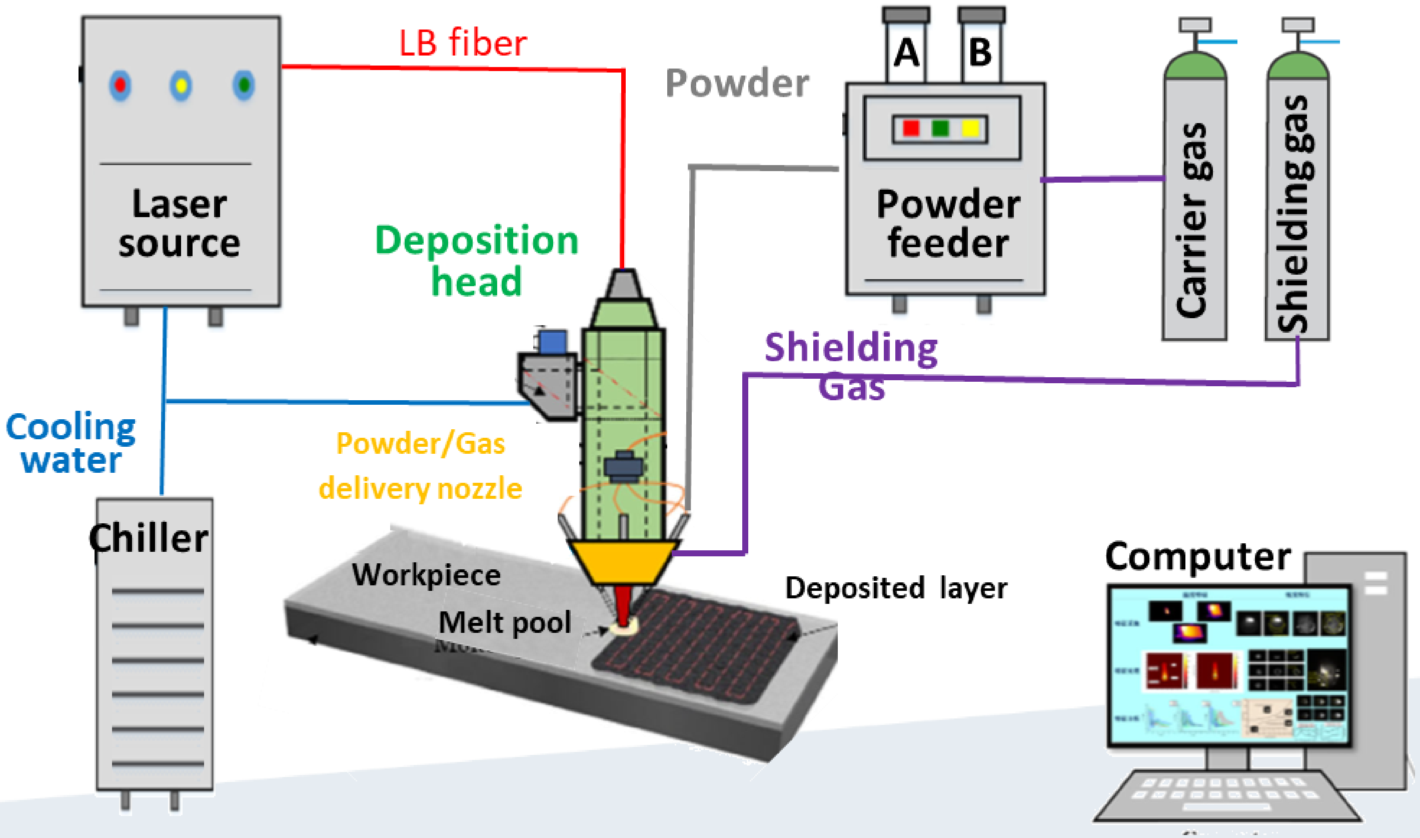
AM L-DED system - POWDER



L-DED fabrication of FGM SS316 – Inc 718

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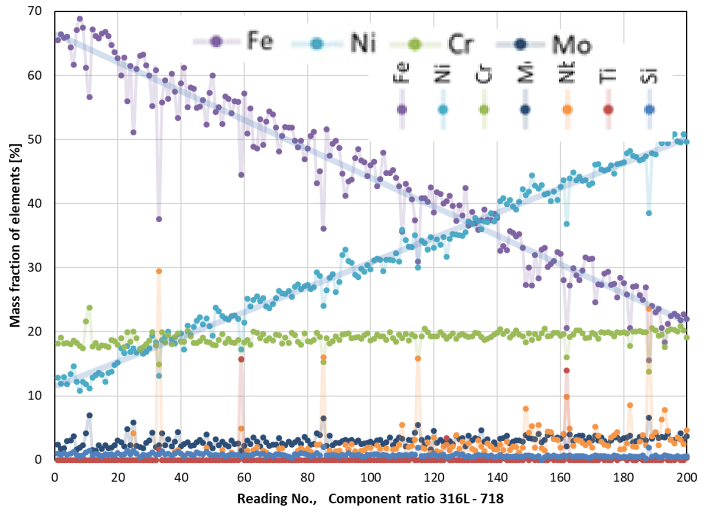
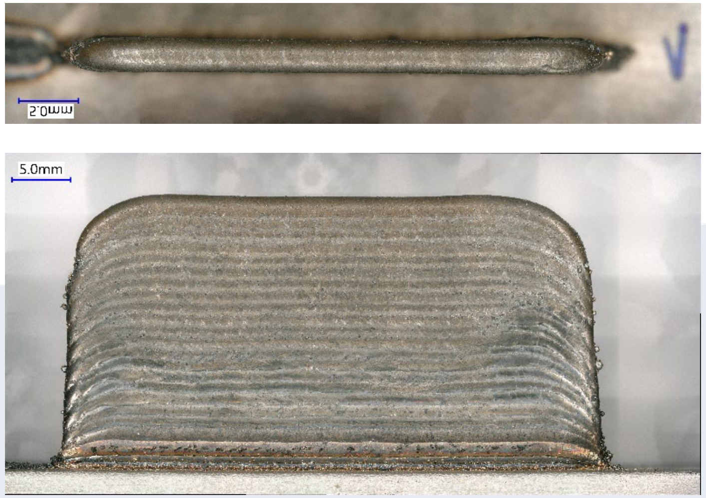
FGM – Fabrication strategy

Deposition path	Interlayer dwell time (Cooling time)	Material gradient function	Material gradient orientation
- Unidirectional - Bidirectional - Segmented	- No dwell - Dwell till *T* = konst.	- Linear - Progresive (e.g. power) - Degresive (e.g. root)	- Transverse - Longitudinal

FGM - Metallurgical defects

FGM: SS316-Inc718





DLD fabrication of FGM SS316 – Inc 718

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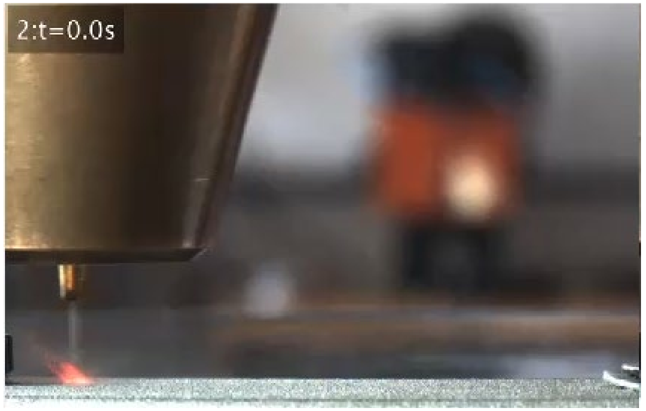
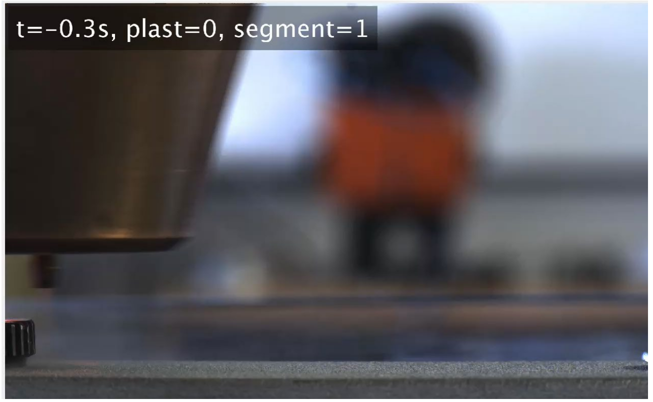
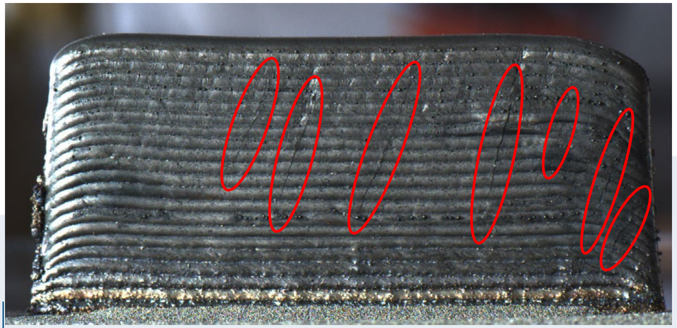
FGM – functional graded material and component fabrication (SS316L – Inconel718)

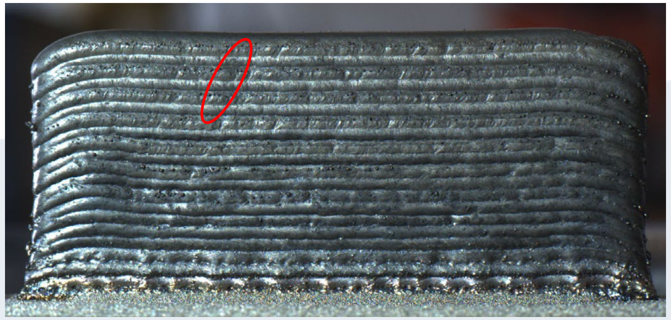
P_L = 1500 – 800 [W], h=1mm, # 21 Liner gradient 10%/ layer

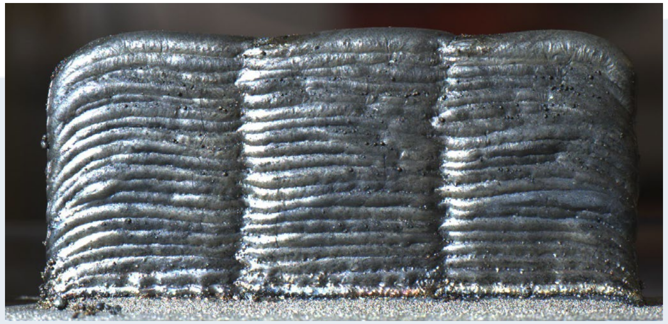
Uni-directional | Bi-directional | Segmental











Now go, discover!