# Additive Manufacturing and sustainability

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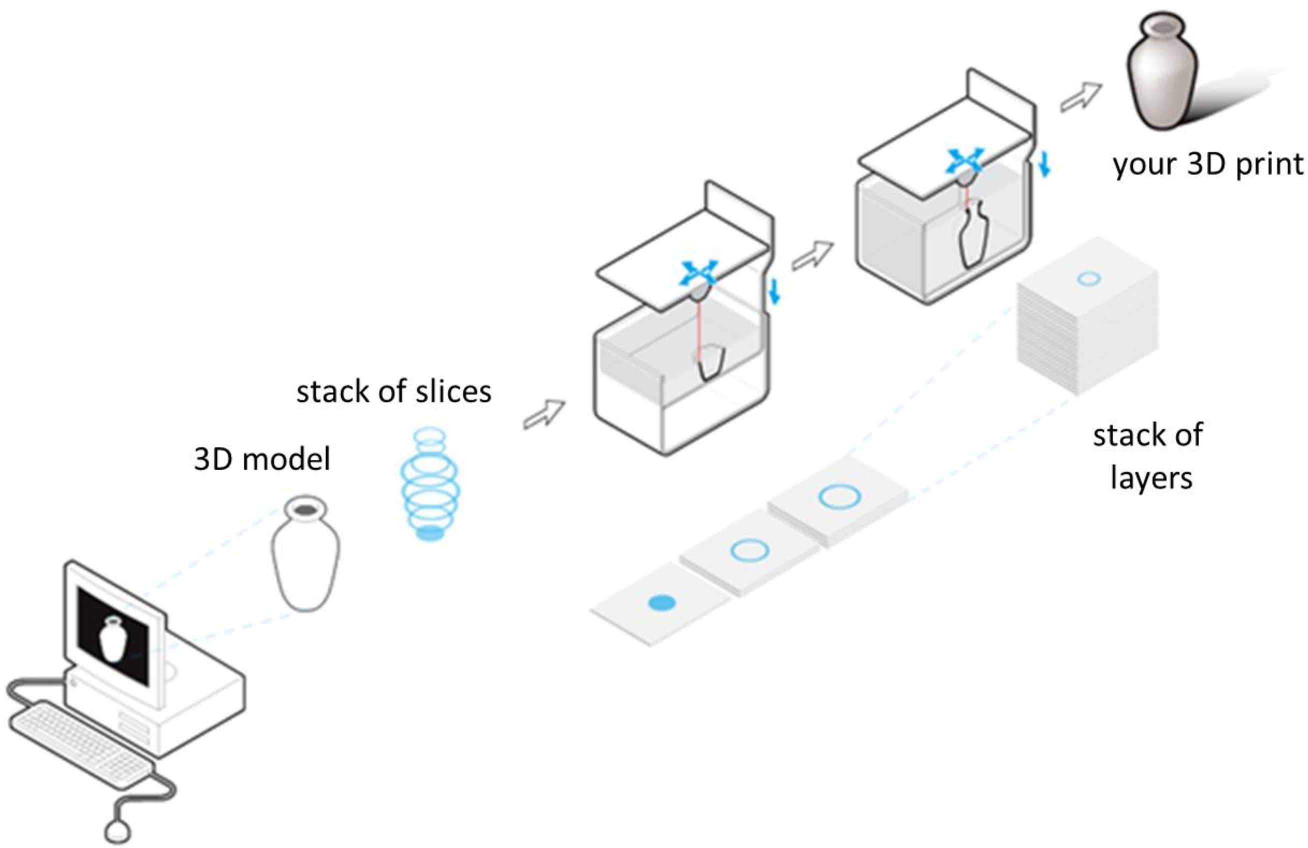
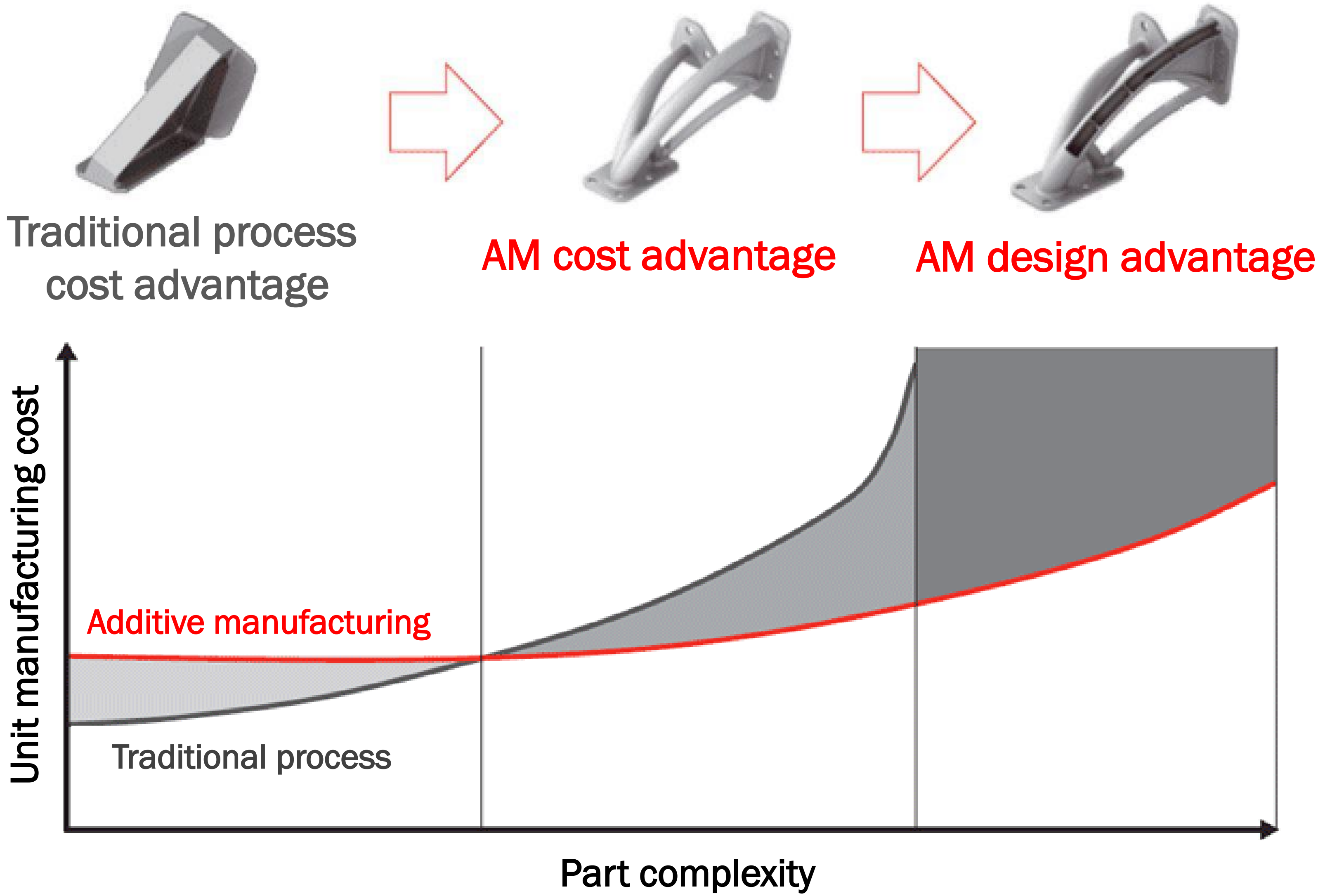
EPFL

# Additive manufacturing consists in building 3D objects by adding layer-upon-layer of material

AM is a **"bottom-up"** approach, in which parts are built layer-by-layer, so that **complex geometries** can be produced.



# AM processes enable the production of complex designs at an advantageous cost



# Part 1: Introduction to AM of metals

- **Examples of applications**
  - aerospace
  - automotive
  - biomedical
  - others (sports, jewelry…)
- **Palette of metals** for AM
- **AM processes** for metals
  - Powder bed fusion
  - Directed energy deposition

# Part 2 : L-PBF of metals – a brief overview

- Process overview
- Powder production
- Choice of process parameters
- Porosity
- Mechanical properties
- Energy efficiency

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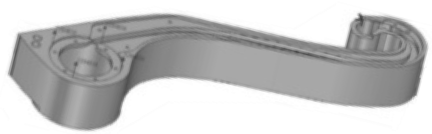
# Aerospace applications

**Weight reduction**: a major driver for AM in aerospace and automotive applications.

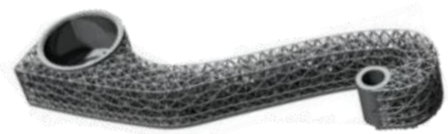
**1 kilogram** removed from every aircraft of a fleet of **600 commercial jet-liners** saves every year about 90 000 liters of fuel and avoids the emission of **230 tons of $CO_2$** in the atmosphere.

AM can be used to design **lightweight yet strong structures**:



0.8 kg – 100% $CO_2$

- **original design**



0.31 kg – 37% $CO_2$

- **lattice structures** : combination of material and space in a periodic cellular structure

0.37 kg – 46% CO2

- **topology optimization** : best distribution of material given an optimization goal (for instance mass minimization) while satisfying a set of constraints such as maximum stress or displacement.



Merkt, Altair Conference 2013.

# Saving raw material,
# Reducing weight & cost

## Use case: fuel nozzles for jet engines

**17 components** used to be necessary for the conventional manufacturing of the fuel injector.

A fully additively manufactured industrial fuel nozzle can be produced with just **4 components**.

*AM fuel nozzle*

### ADDITIVE MANUFACTURING

- fewer brazes and welds: increased durability
- 70% fewer operational steps
- 75% shorter lead time
- 10% **weight reduction**
- 80% **less raw material**

*The conventionally manufactured fuel nozzle showing the volume of raw material required for its production*

V. Vedula and V. Jagdale, *Metal AM*, 2019

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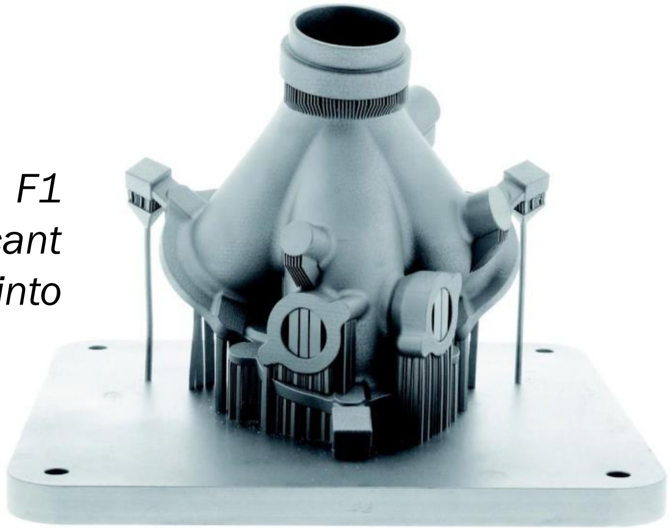
# Automotive applications

Mass production of automotive parts remains out of reach of current AM processes.

The main applications of AM in automotive are :

- Formula 1 race cars: rapid prototyping of functional test parts results in a competitive advantage. Cost is a secondary consideration compared to **weight reduction** and design freedom.

*Inconel exhaust manifold for Scuderia Ferrari F1 engines. This component is subjected to significant thermal and mechanical stresses and comes into contact with aggressive exhaust gases.*



Renishaw

- Vintage automotive restoration: production of rare replacement parts
- High-performance luxury automobiles

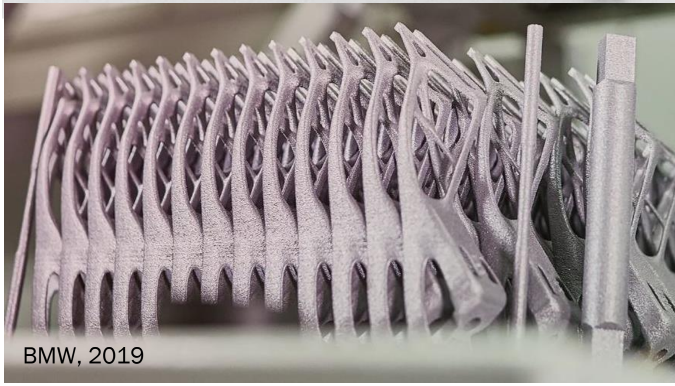
# Automotive applications


Scott, 2018

**Use case: roof bracket**

BMW incorporated an additively manufactured roof bracket in its 2018 i8 Roadster.

Topology optimization was used to design the part.


BMW, 2019


Jackson, 2018


Multistation Digital Manufacturing, 2018

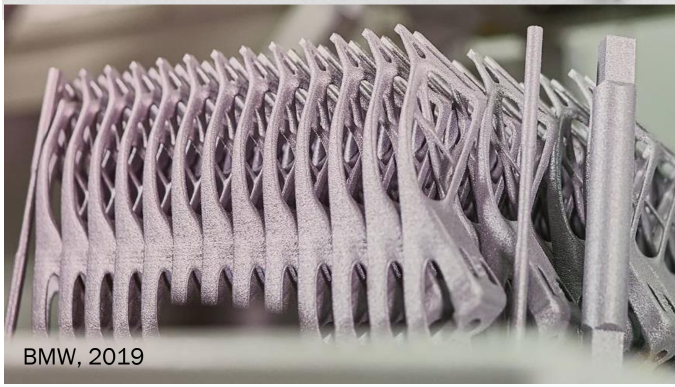
**Use case: brake caliper**

Bugatti designed an additively manufactured titanium brake calliper for its Bugatti Chiron.

This calliper is a critical part, used at speeds and temperatures up to 375 km/h and 1100°C.

# Automotive applications


Scott, 2018


BMW, 2019

ADDITIVE MANUFACTURING

- more than 600 brackets per batch
- 44% weight reduction

Jackson, 2018


Multistation Digital Manufacturing, 2018

ADDITIVE MANUFACTURING

- 40% weight reduction

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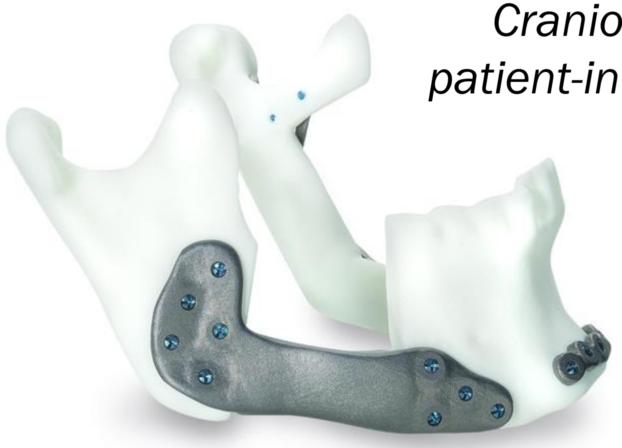
# Biomedical applications

Davies, 2017

*Skull implant*

*Craniomaxillofacial patient-individual implant*



Davies, 2017

ADDITIVE MANUFACTURING

- rapid availability
- less difficult surgical operations
- reduced surgical costs
- shorter and less painful recovery

*Custom-fit dental crowns and bridges*

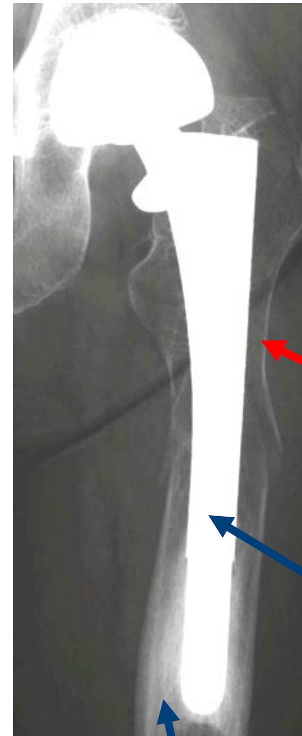
EOS

# Biomedical applications

Use case: hip prosthesis

Material requirements

- Corrosion resistance
- Biocompatibility
- Favorable mechanical properties
  - Sufficient strength
  - **Low elastic modulus** to avoid mechanical mismatch between bone and implant resulting in stress shielding and bone loss.



# Biomedical applications

**Use case: hip prosthesis**

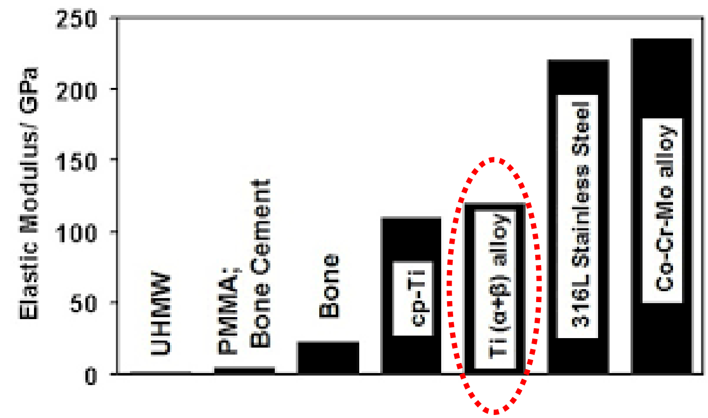
**Material requirements: Ti-6Al-4V**

- Corrosion resistance: **excellent** +
- Biocompatibility: **good** +
- Favorable mechanical properties
  - **High yield strength:** 900 MPa +
  - **Relatively low elastic modulus** ±

    $E_{steel}$ = 230 GPa

    $E_{Ti}$ = 110 GPa

  ... but still much higher than $E_{bone}$ = 30 GPa




- High cost −

| Form | Steel ($/pound) | Aluminium ($/pound) | Titanium ($/pound) |
|---|---|---|---|
| Ore | 0.02 | 0.01 | 0.22 |
| Metal | 0.1 | 1.1 | 5.44 |
| Ingot | 0.15 | 1.15 | 9.07 |
| Sheet | 0.3–0.6 | 1.0–5.0 | 15.0–50.0 |

Dutta and Froes, 2016

# Biomedical applications

Use case: hip prosthesis

Conventional manufacturing

Ti implants are typically shaped by investment casting or forging, followed by machining, polishing and coating.

Siemens, 2010

Machining

Main issues:

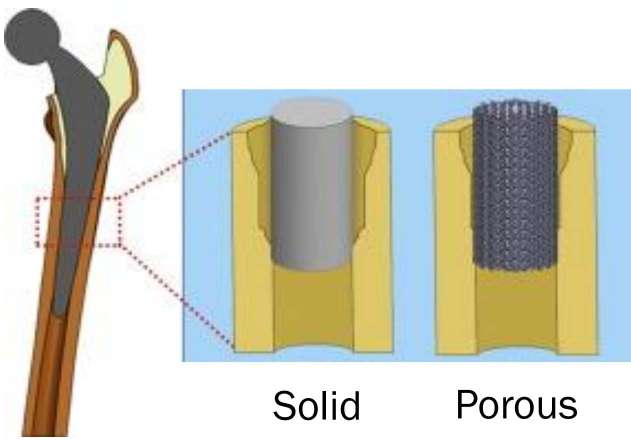
- High cost
- Time consuming process
- Tool wear and failure
- Material waste

# Biomedical applications

## Use case: hip prosthesis

### Additive manufacturing

AM allows to build porous parts : lattice structures

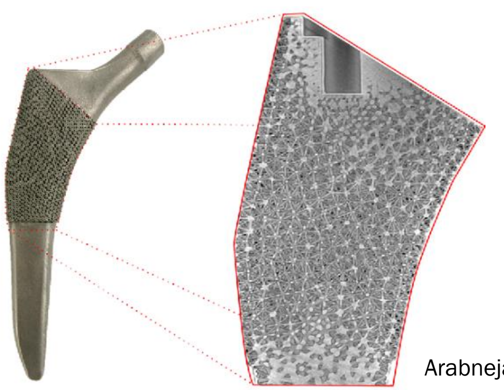



Limmahakhun, et al., 2017.

- **Solid implant**

mechanical mismatch between bone and implant ($E_{bone}$= 30 GPa, $E_{Ti}$ = 110 GPa)

$\Rightarrow$ stress shielding and bone resorption



Arabnejad et al., 2016

- **Porous implant**

architecture designed to mimic bone properties

$\Rightarrow$ reduced stress shielding

# Biomedical applications

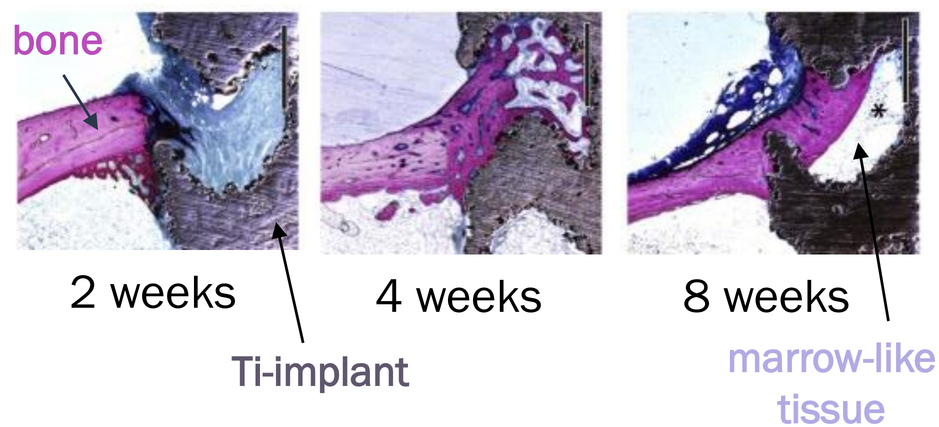
## Use case: hip prosthesis

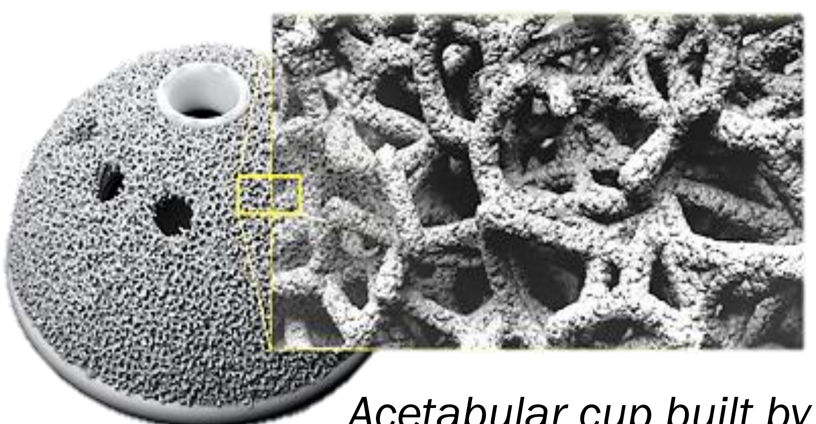
### Additive manufacturing

AM allows to build porous parts, which favor osseointegration

- Porous design favors bone ingrowth
- High surface roughness favors good fixation and cellular proliferation

Taniguchi, Naoya, et al., 2016



EOS

*Acetabular cup built by EBM*

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  - consumer products (sports, jewelry…)
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# Sports

## Use case: Ti bike frame


Maxey, 2014


Renishaw, 2015


Renishaw, 2015

### ADDITIVE MANUFACTURING

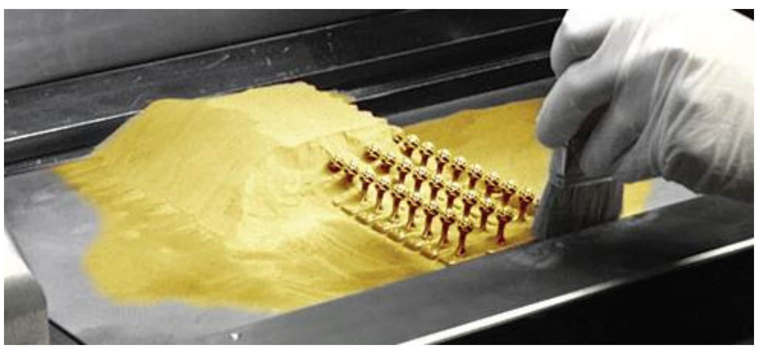
- 33% lighter than casted aluminium alloy version
- all components built on a single build plate, then assembled to create the frame

# Jewelry

Despite their high price, precious metals have been used for AM:
gold, platinum and palladium.

Dedicated powder bed AM machines with small build volumes and **optimized powder recycling** capabilities are available.

AM of precious metals can also be used in **dentistry** and **electronics**.



*As-built cufflinks on build platform*

EOS

*Post-processed and polished cufflinks*

# Watch industry

Use case: Ti watch case

Panerai built the lightweight titanium case of the Luminor Tourbillon GMT watch using additive manufacturing (L-PBF).

This allows the inside part of the case to be emptied, reducing the overall weight without compromising on the mechanical properties.

Panerai

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# Palette of metals for AM : overview

| | Aluminum | Maraging steel | Stainless steel | Titanium | Cobalt chrome | Nickel super alloys | Precious metals |
|---|---|---|---|---|---|---|---|
| Aerospace | X | | X | X | X | X | |
| Medical | | | X | X | X | | X |
| Energy, oil and gas | | | X | | | | |
| Automotive | X | | X | X | | | |
| Marine | | | X | X | | X | |
| Machinability and weldability | X | | X | X | | X | |
| Corrosion resistance | | | X | X | X | X | |
| High temperature | | | X | X | | X | |
| Tools and molds | | X | X | | | | |
| Consumer products | X | | X | | | | X |







# Palette of metals for AM

**Aluminum alloys:** low density, ideal for light-weight components in many industrial, aerospace and automotive applications, high thermal and electrical conductivity

- AlSi10Mg

**Tool steels and maraging steels:** alloys with very high strength and hardness, often used to manufacture tools and dies for injection molding or pressure casting

- H13 tool steel
- M300 maraging steel

**Stainless steel:** alloys with high strength and a moderate to high level of corrosion resistance

- Austenitic stainless steels
  - 304 and 304L stainless steel
  - 316 and 316L stainless steel

- Precipitation hardening stainless steel
  - 17-4 PH stainless steel
  - 15-5 PH stainless steel


*Antenna bracket for satellite*


*M300 die with integrated cooling channels*


*Chemical impeller (316L)*

# Palette of metals for AM

**Titanium**

- CP Ti : extreme corrosion resistance, ductility and weldability
- Ti-6Al-4V : excellent strength-to-weight ratio which makes it an ideal choice where weight saving load structures are required, good corrosion resistance, biocompatibility (can be used for a range of medical applications, particularly when direct metal contact with tissue or bone is required, due to its low stiffness).

Hendley, 2019

*Ti-6Al-4V acetabular cup*

- Grade 5
- Grade 23 (Extra Low Interstitial - ELI): reduced interstitial impurities O, C, N, leading to a higher ductility and fracture toughness

**Cobalt chrome alloys:** excellent biocompatibility (orthopaedics and dental applications), strength and wear resistance, high corrosion resistance and high temperature resistance (turbines and engine components).


*Patient-specific crowns and bridges on a dental building platform*

# Palette of metals for AM

**Nickel-based alloys:** high strength, excellent corrosion and oxidation resistance at high temperature. Applications in aeronautical, petrochemical and auto racing environments.

- Inconel 718
- Inconel 625
- Invar 36


Farinia Group

*Inconel 718 spinning wheel of a car turbocharger*

**Pure copper and copper alloys:** excellent thermal and electrical conductivity. Applications include thermal transfer components and electronic devices.


Scheithauer et al, 2018

*Heat exchanger*


EOS

*Ring made of 18 ct yellow gold*

**Precious metals**

- 18K yellow, rose and red gold alloys (Au-Ag-Cu)
- Pt alloys (950 Pt/Ru, PtIr20, Pt-Au)
- Pd alloys

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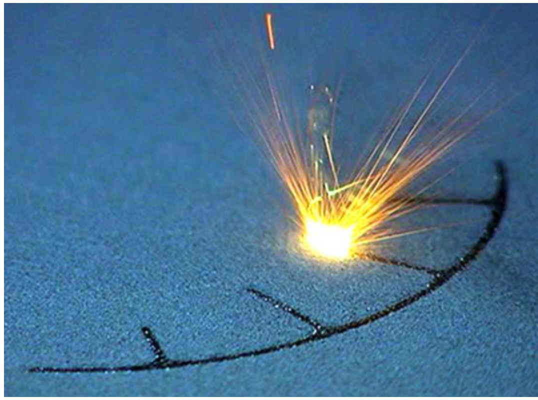
# AM processes for metals

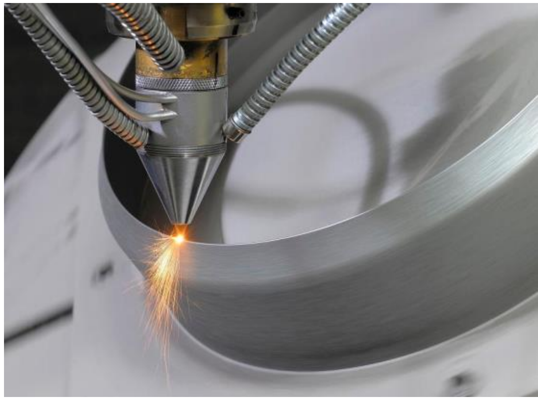
## Two families of AM processes for metals (ASTM standard terminology)

**Powder Bed Fusion (PBF):**
an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.



Vartanian, 2018

**Directed Energy Deposition (DED):**
an additive manufacturing process in which focused thermal energy (e.g. laser, electron beam, or plasma arc) is used to fuse materials by melting as they are being deposited.



Jackson, 2018

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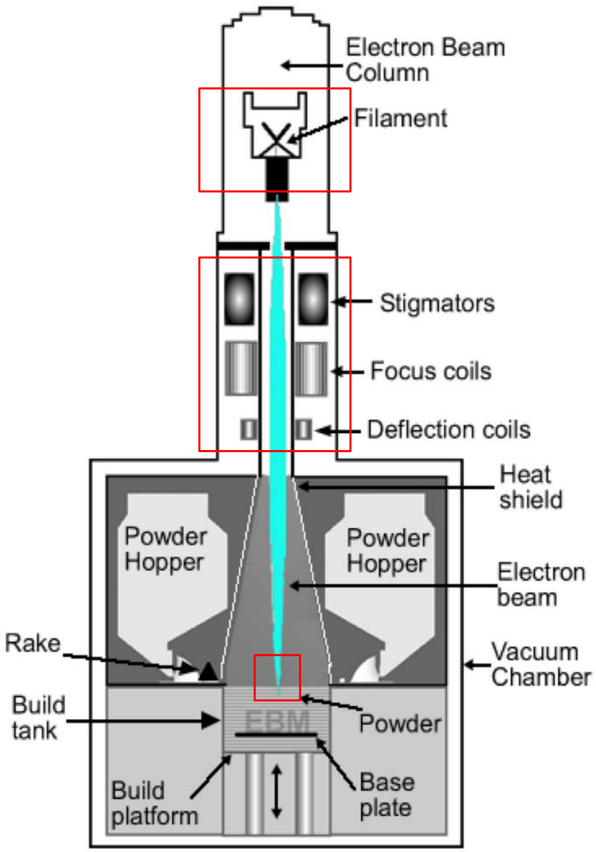
# Electron beam melting




Sidambe, 2014

**Low energy efficiency**

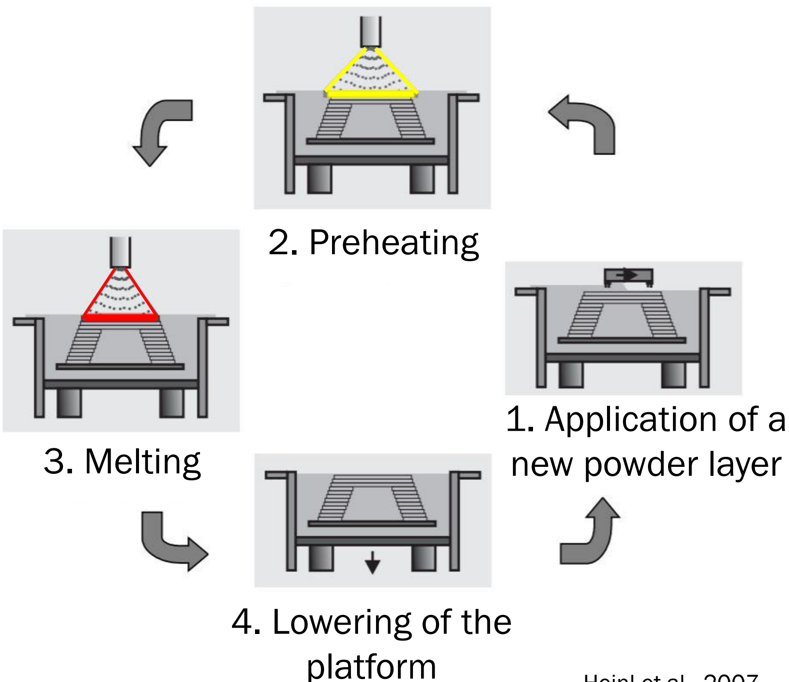
The high-power electron beam is generated by heating a tungsten filament.
Electrons are accelerated to a velocity between 0.1 and 0.4 times the speed of light using an accelerating voltage of 60 kV.

The electrons are focused and deflected by electromagnetic lenses.

They hit the powder particles in the building chamber and release their kinetic energy mostly as thermal energy.

If an electron beam passes through a gas, the electrons interact with the gas atoms and are deflected. Therefore the process takes place in a vacuum chamber ($10^{-4}$ – $10^{-5}$ mbar) to ensure a clean and controlled build environment.

# Electron beam melting




Heinl et al., 2007

1. A layer of metal powder is spread homogeneously by the rake on the build platform.

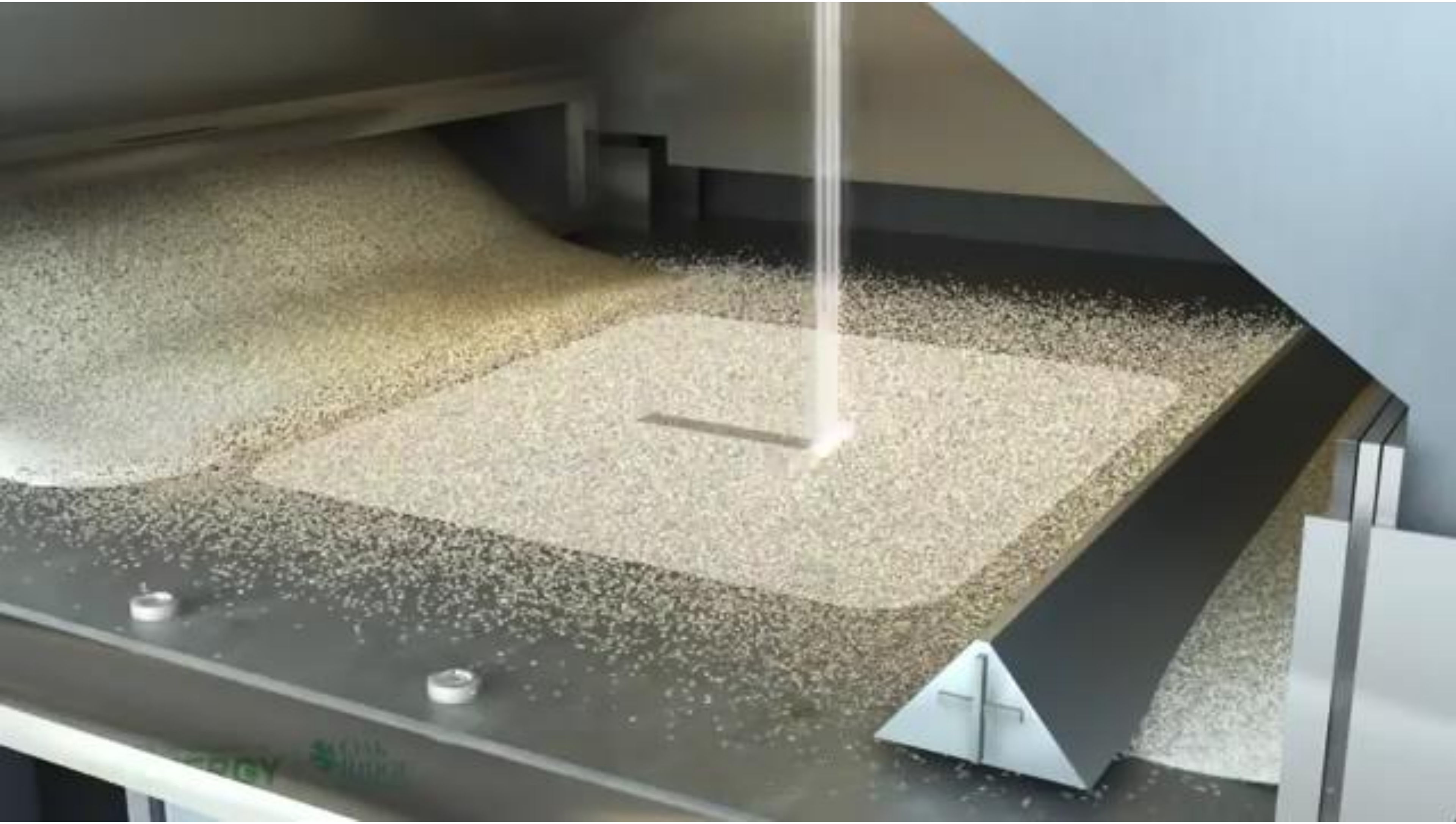
2. The powder layer is preheated using a relatively low beam current and a relatively high scan speed. The preheating lightly sinters the metal powder to hold it in place during subsequent melting.

3. The electron beam selectively scans the powder surface, at a higher beam power, line by line according to the layer data. The powder particles are melted and rapidly solidify to form a compact layer with the desired shape.

4. The build plate is lowered by one layer thickness and a new layer of powder is spread on top.

After the building stage, the part is cooled down. Cleaning of the parts from adherent partly molten powders is done by powder blasting, with the same powders as the one used for building. The removed powder can be reused after sieving.

# Electron beam melting



Oak Ridge, 2011

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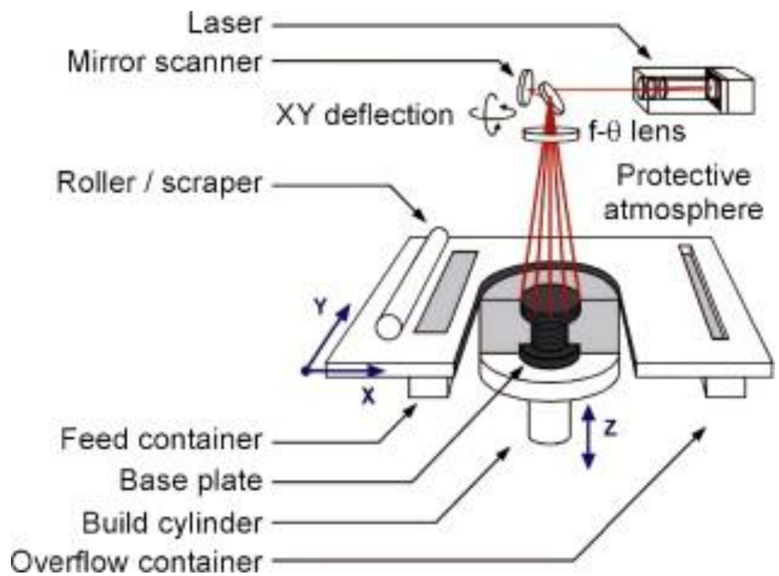
# Laser powder bed fusion

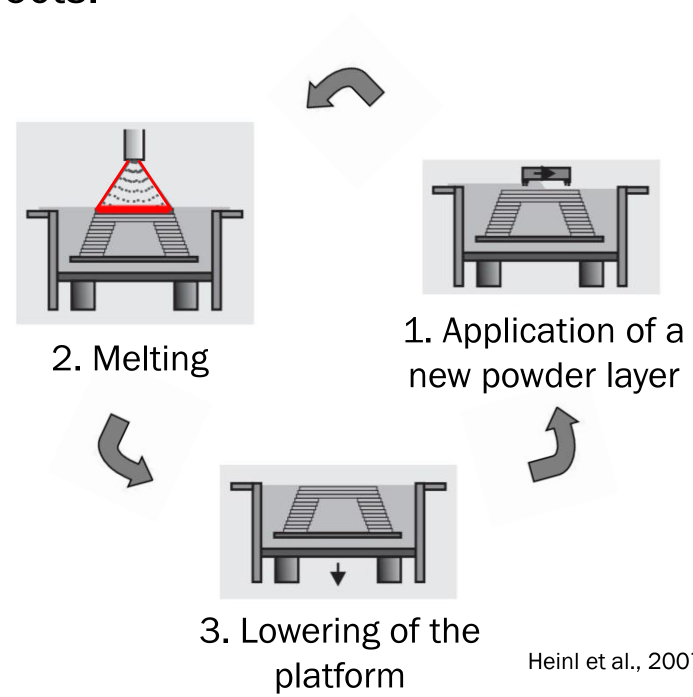
**also known as Selective Laser Melting**




PhD M. Rombouts, 2006

LPBF uses a high power laser ($CO_2$ or Nd-YAG) as a heat source.

The process is performed in an inert atmosphere (e.g. argon) to reduce oxidation effects.




Heinl et al., 2007

# Laser powder bed fusion

also known as Selective Laser Melting

Stratasys, 2017

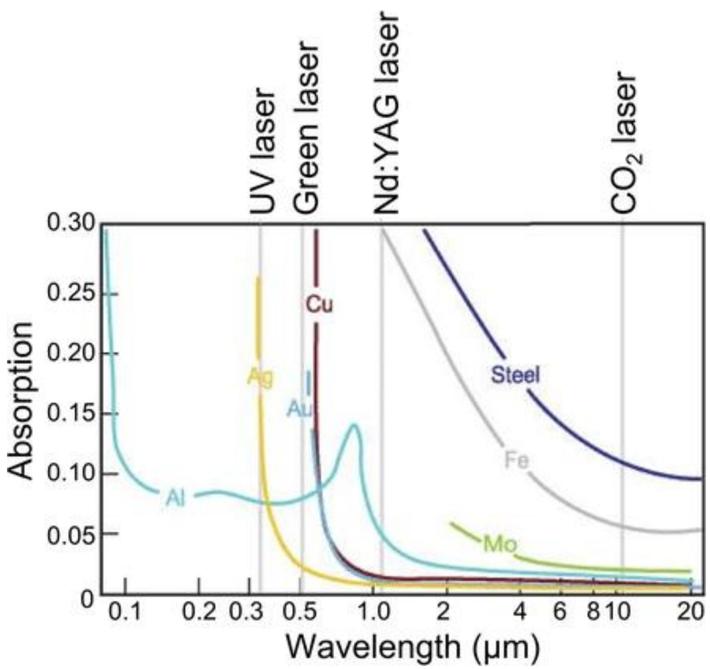
# EBM/LPBF comparison

| | EBM | LPBF |
|---|---|---|
| **Heat source** | Electron beam | Laser beam |

**Low energy efficiency**

Consequences :

- The materials used in EBM must be conductive.
- In LPBF the absorption of a given metal depends on the wavelength of the laser. The laser sources in commercial L-PBF machines are typically fiber or Nd:YAG lasers (wavelength 1064nm).




Oliveira et al., 2017

Alloys based on Fe, Ni, Al have a relatively low reflectivity for this wavelength.

Some reflective metals such as gold, copper, silver, are more difficult to process and may require the use of another wavelength, e.g. green laser (λ = 532 nm).

# EBM/LPBF comparison

| | EBM | LPBF |
|---|---|---|
| **Heat source** | Electron beam | Laser beam |
| **Atmosphere** | Vacuum | Inert gas |
| **Scanning** | Deflection coils | Mirror galvanometer |

Consequences :

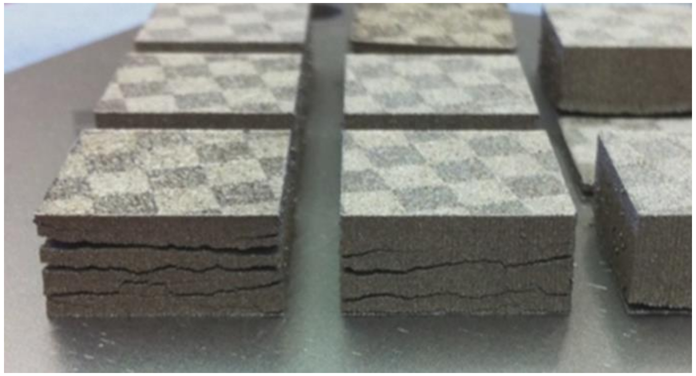
- In EBM, the electron beam is deflected magnetically, almost instantaneously, resulting in high positioning accuracy. In LPBF, the laser beam is optically deflected and the scan speed is mechanically limited by the movement of the mirrors. The scan speeds for the EBM system are orders of magnitude larger than laser melting systems.

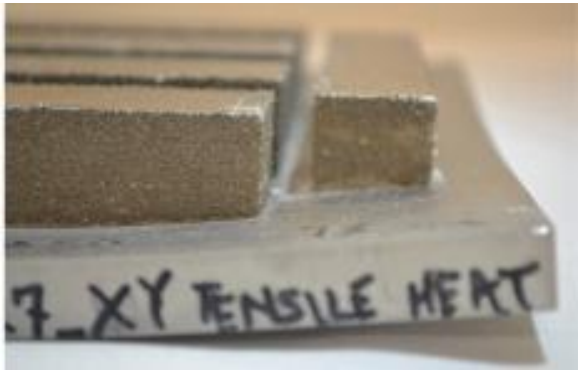
# EBM/LPBF comparison

| | EBM | LPBF |
|---|---|---|
| **Heat source** | Electron beam | Laser beam |
| **Atmosphere** | Vacuum | Inert gas |
| **Scanning** | Deflection coils | Mirror galvanometer |
| **Preheating temperature** | 700°C | 200°C |

Consequences :

- The cooling rate is much higher during LPBF than during EBM
- High residual stresses are generated in LPBF part resulting in cracking and warping






PhD K. Kempen, 2015

# EBM/LPBF comparison

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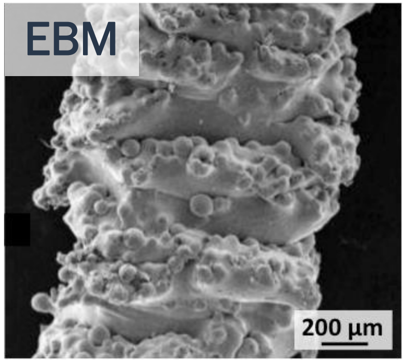
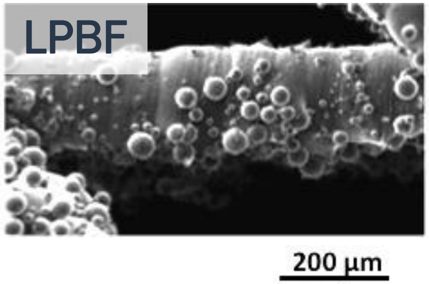
Consequences :

- The cooling rate is much higher during LPBF than during EBM
- High residual stresses are generated in LPBF part
- The surface finish is rougher in EBM ($R_a$ = 20-30µm) than in LPBF ($R_a$ = 5-10µm)




PhD M. Suard, 2015




Pyka et al., 2012

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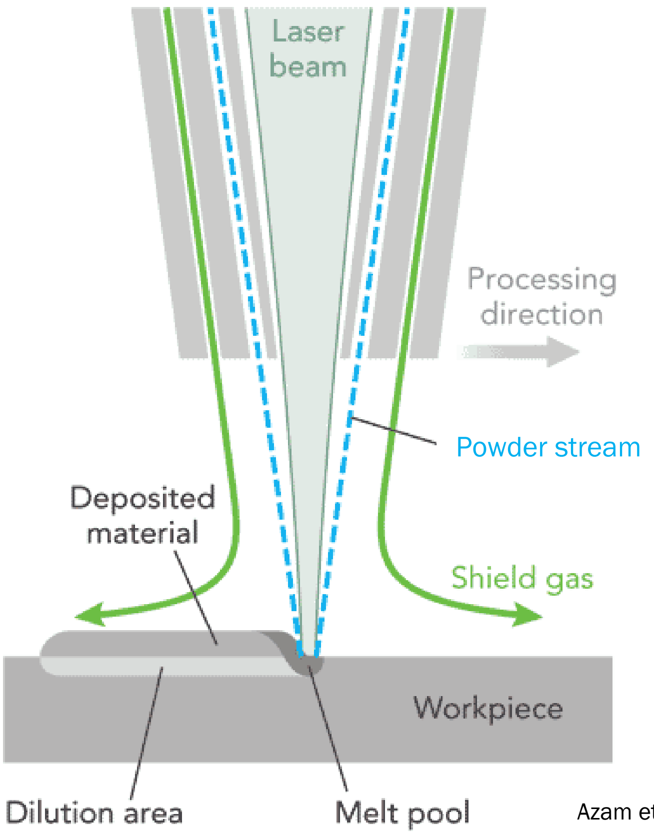
    - Laser powder bed fusion
  - Directed energy deposition
    - Powder fed
    - Wire fed

# Powder fed DED - laser

DED enables the creation of parts by melting material **as it is being** deposited.

**Laser-based DED** is also known as Laser Engineered Net shaping (LENS®) or Laser Metal Deposition (LMD)



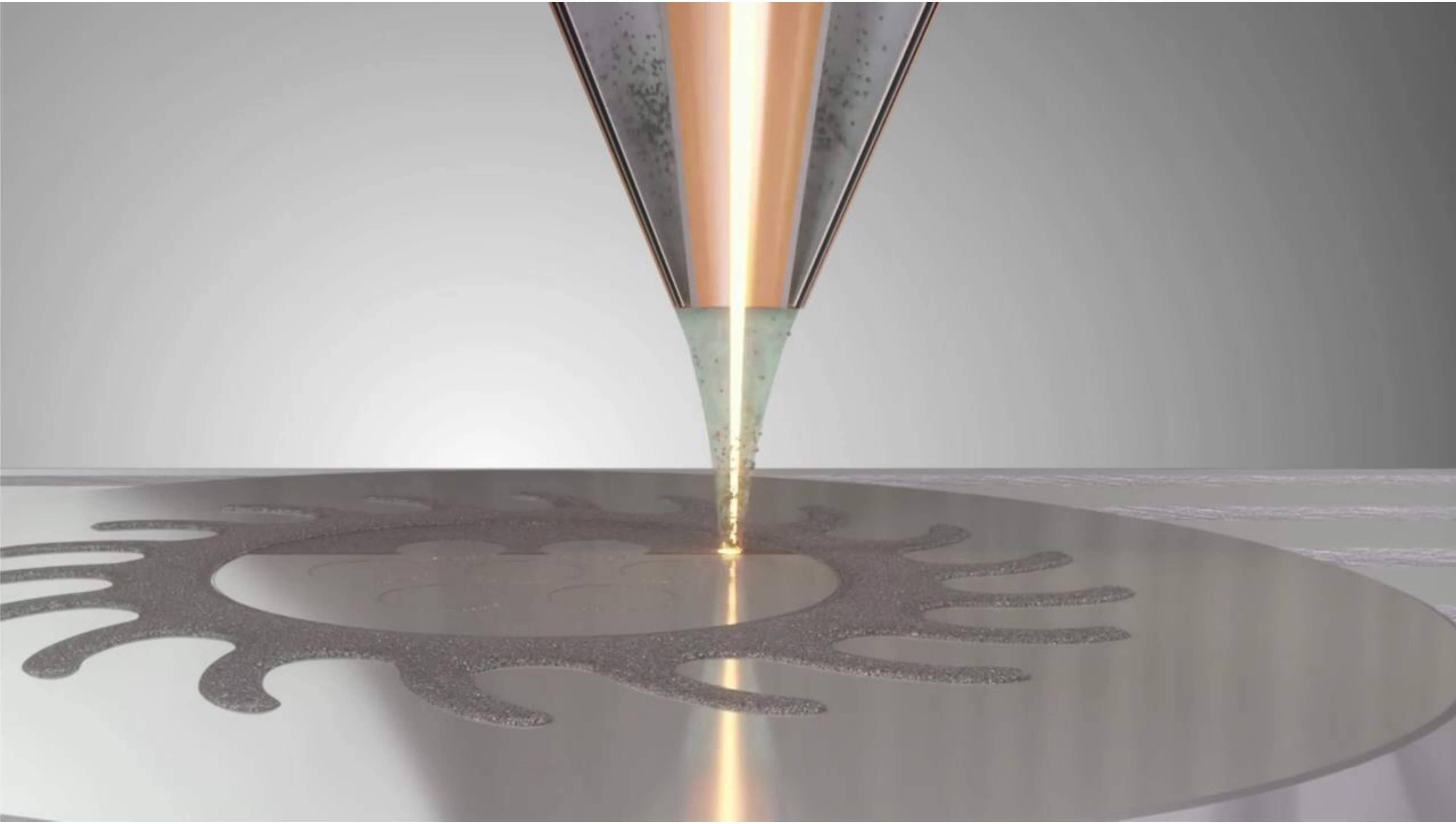

Azam et al., 2018

A high power laser is used to melt the metal powder that is supplied coaxially to the focus of the laser beam through a deposition head.

The X-Y table is moved in raster fashion to fabricate each layer of the object. The head is moved up vertically after each layer is completed.

An inert shielding gas such as argon is often used to protect the melt pool from atmospheric oxygen and to carry the powder stream into the molten pool.

# Powder fed DED - laser



OR LASER, 2016

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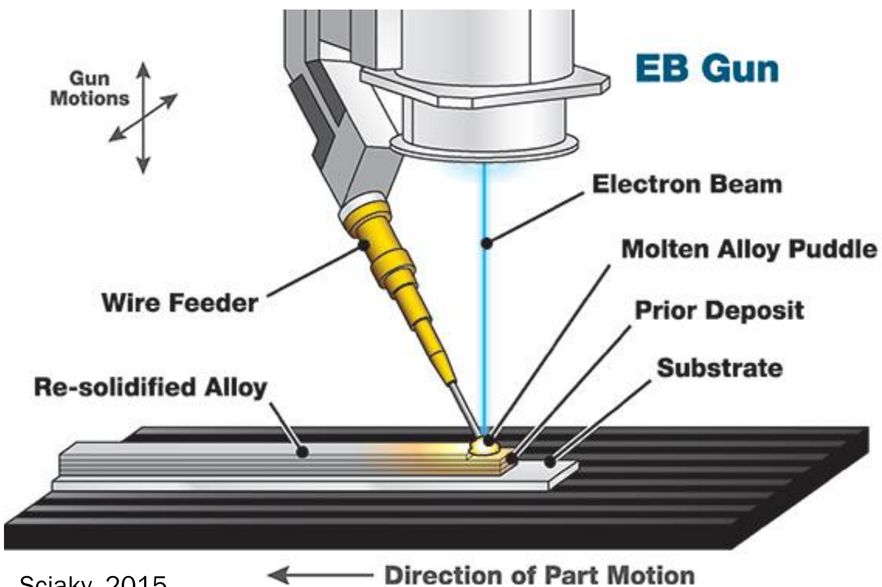
    - Powder fed
    - Wire fed

# Wire fed DED – electron beam

Electron Beam Additive Manufacturing (EBAM®) and Electron Beam Freeform Fabrication (EBF3) use wire feedstock and an electron beam heat source to produce a near-net shape part inside a large vacuum chamber, which provides a high-purity processing environment during the build and cooling.

Advantages of the technology are the very large build envelopes of 1850 x 1200 x 800 mm and the high deposition rates of 700–4100 $cm^3/h$.




Sciaky, 2015

# Wire fed DED – electron beam



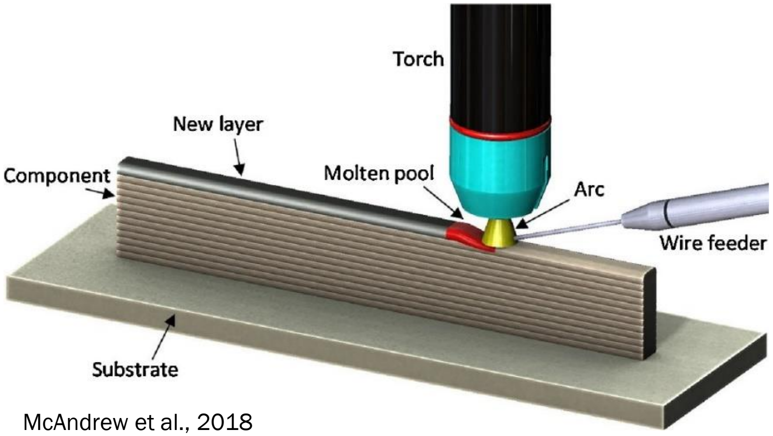
NASA, 2008

# Wire fed DED – arc

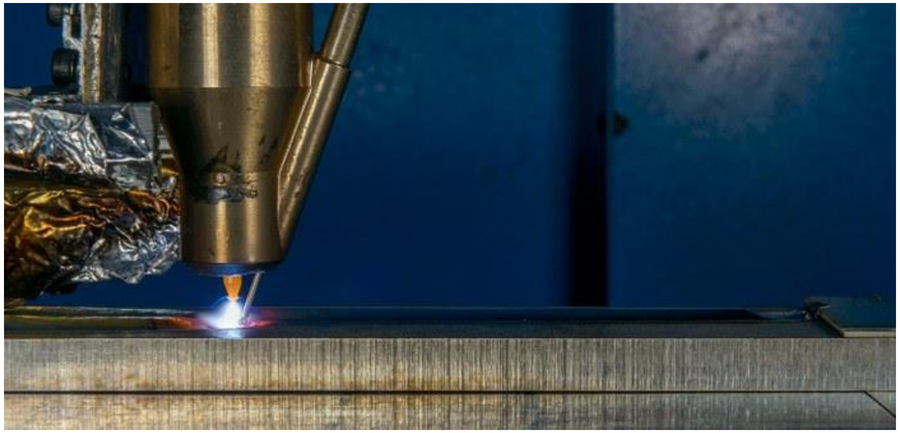
In DED-PA or DED-GMA, a plasma arc or gas metal arc is used as the heat source with filler wires as feedstock material similar to fusion welding.

An advantage of arc heat sources is the low equipment costs, but energy intensive.

A disadvantage is that the beam cannot be focused to below a few millimeters to allow the intricate detail required by many AM applications. Large melt pools and weld bead-shaped deposits typically require machining and finishing of the deposited near-net shape part.




McAndrew et al., 2018



WAAMMat

# DED – applications

DED is often used to repair or add additional material to existing components.

Examples of applications include repairing damaged turbine blades, propellers…

Listek, 2019

*Repair of broken teeth on a gear*

Qi et al., 2010

*Blisk airfoil repaired by laser DED*

# DED – applications

DED allows to build large parts, with a high productivity.

However, the geometrical accuracy is limited, and post-process machining is normally required.

Metal AM, 2019

*Manufacturing of a Lockheed Martin titanium satellite propellant tank using EBAM.*

Lockheed Martin

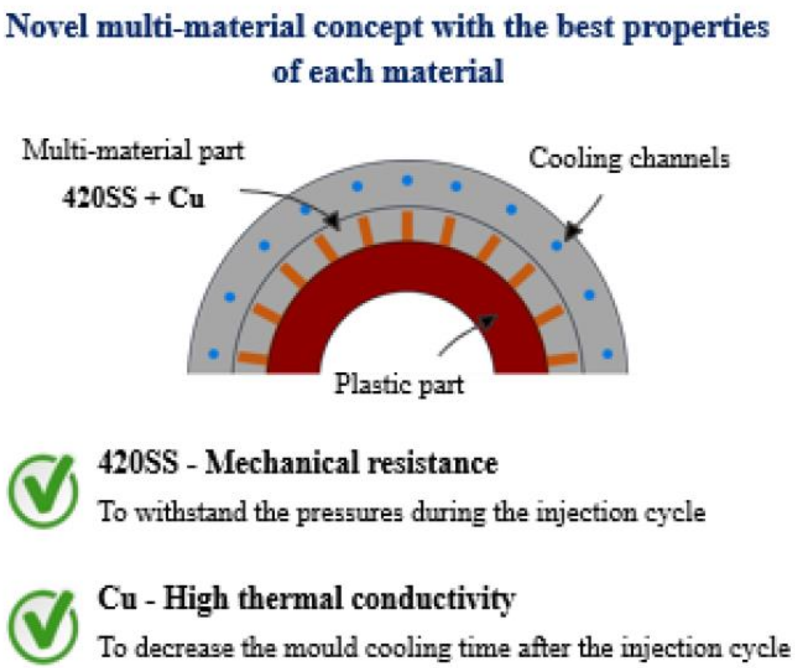
*Final part after post-processing*

# Powder-bed fusion/metal deposition – comparison

| Powder-bed fusion (EBM, LPBF) | Metal deposition (LMD, EBF3) |
| --- | --- |
| High to very high accuracy (0.04 to 0.2 mm)<br>LPBF : $R_a$ = 5-18 µm<br>EBM : $R_a$ = 10-30 µm | Low accuracy (0.5 to 1.5 mm)<br>LENS/LMD : Ra = 15-60 µm<br>EBF3/EBAM : Ra = 45-200 µm |
| Building of functional parts | Repair of damaged parts |
| Not suitable for large parts | Ability to build large parts |
| Low build rate<br>LPBF : 5 – 30 $cm^3$/h<br>EBM : up to 100 $cm^3$/h | Medium to high deposition rate<br>LENS/LMD: up to 400 $cm^3$/hr<br>EBF3/EBAM : 2500 $cm^3$/hr |
| Multi-material printing under development<br>→ Recycling of printed components ? | Multi-material printing :<br>functionally graded and hybrid parts |

**The choice of a given process is determined by the type of application.**

# Multi-material printing





Plastic injection molds
Steel + Copper
improved heat extraction + structural resistance

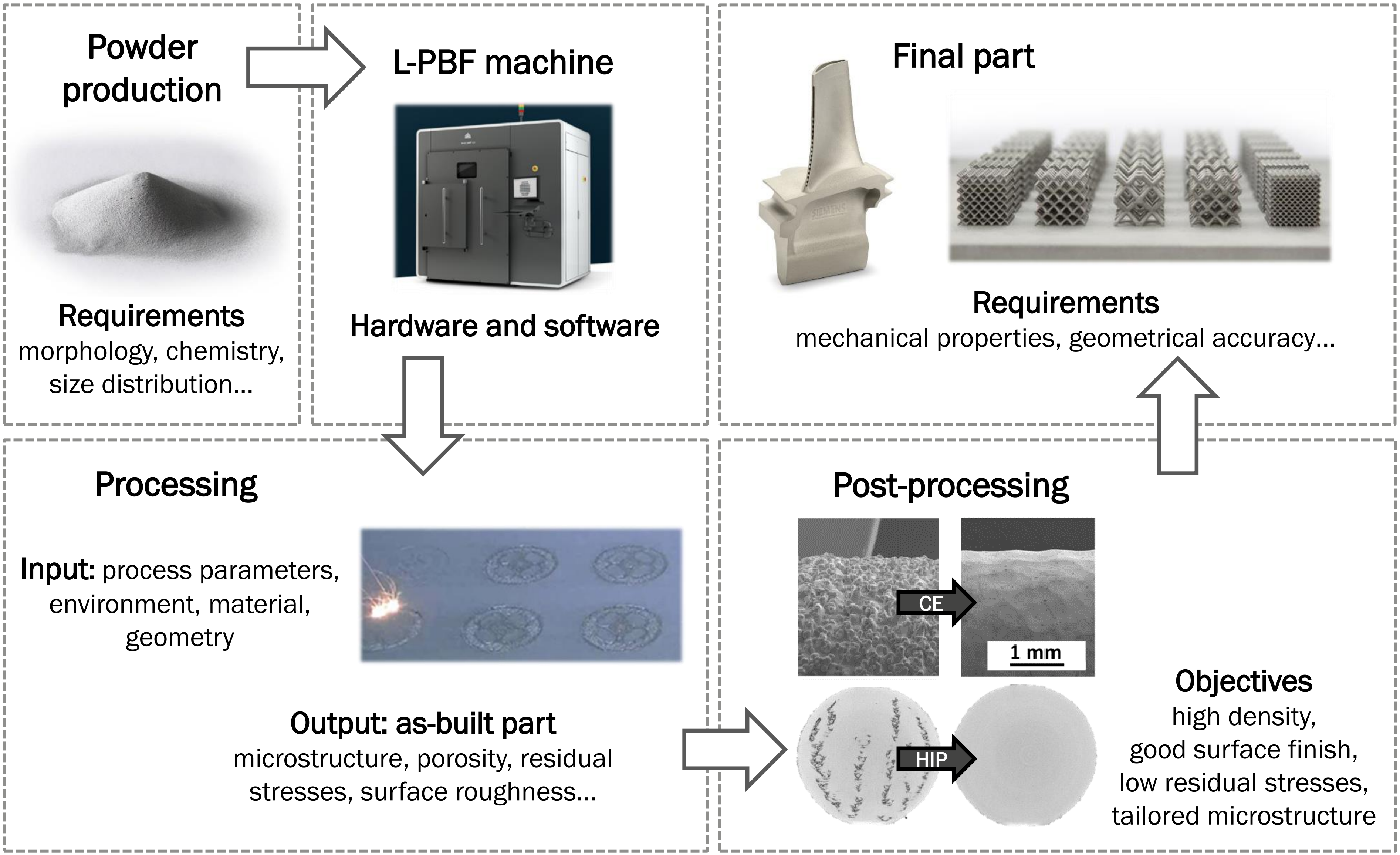
Gradient structure
316L steel – IN718

High T resistance

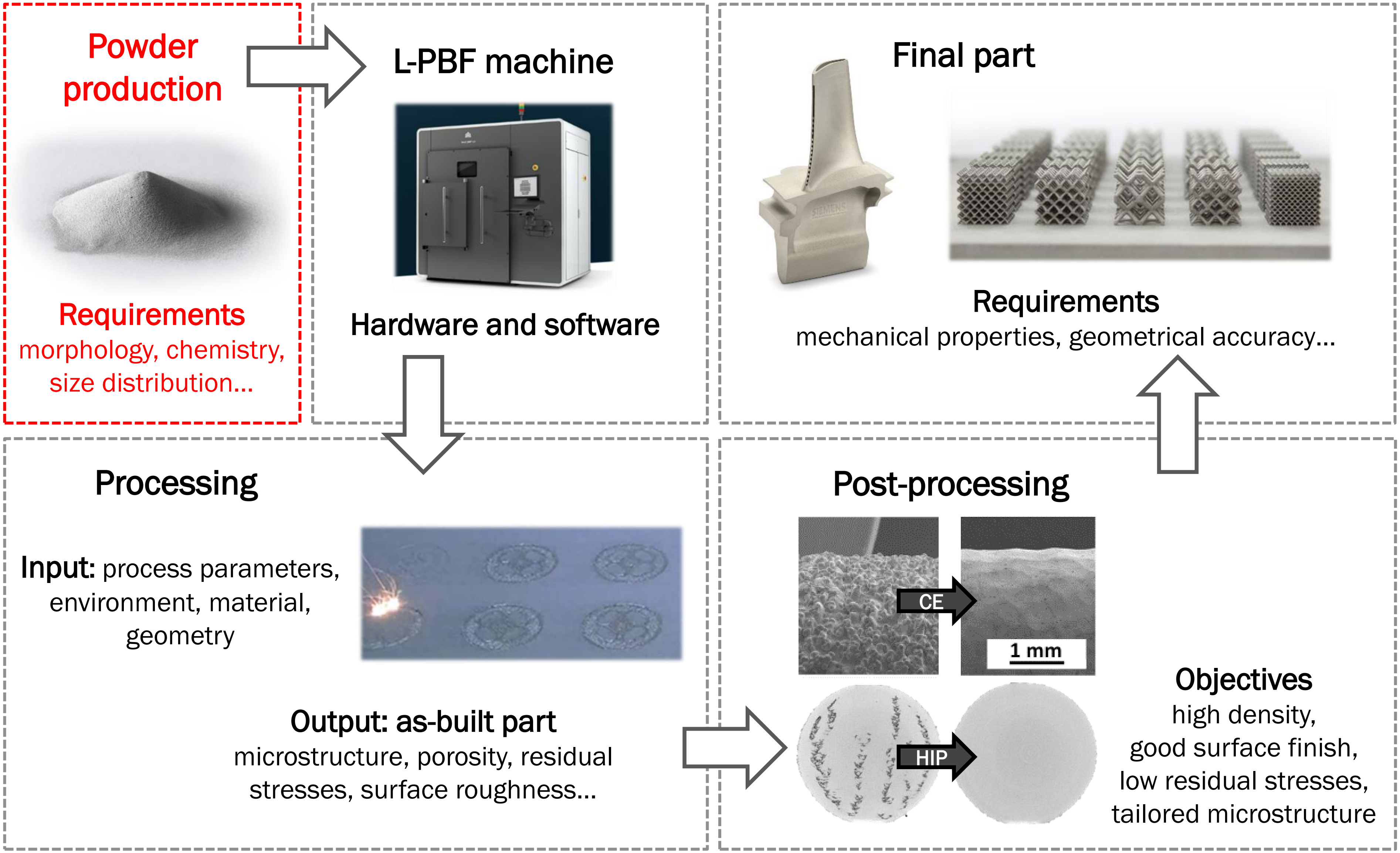
# Part 2 : L-PBF of metals – a brief overview

- Process overview
- Powder production
- Process parameters
- Porosity
- Mechanical properties
- Energy efficiency

# Process overview



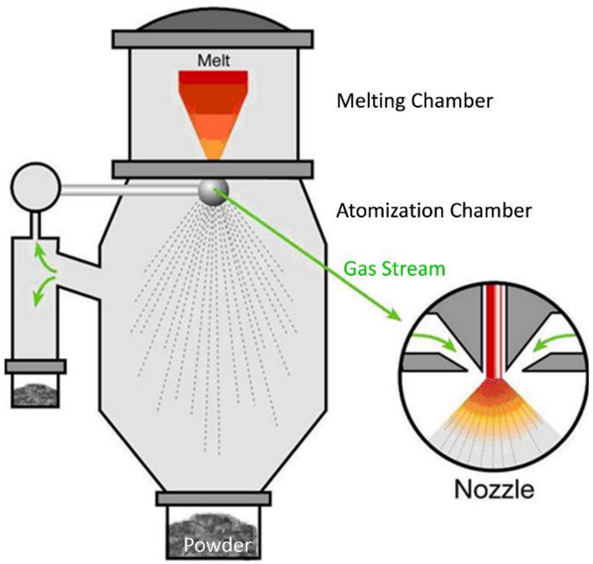
# Process overview

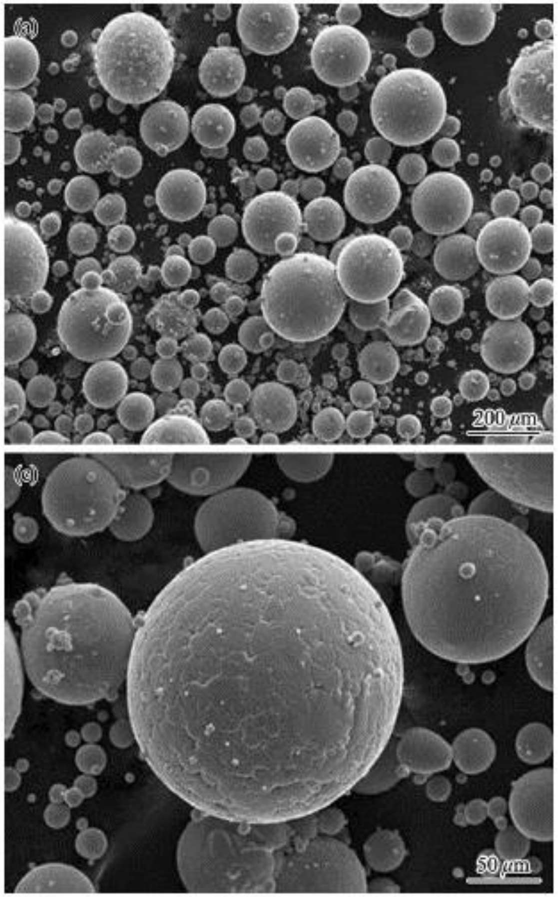


# Powder production

**Energy intensive**

## Gas atomization (GA)



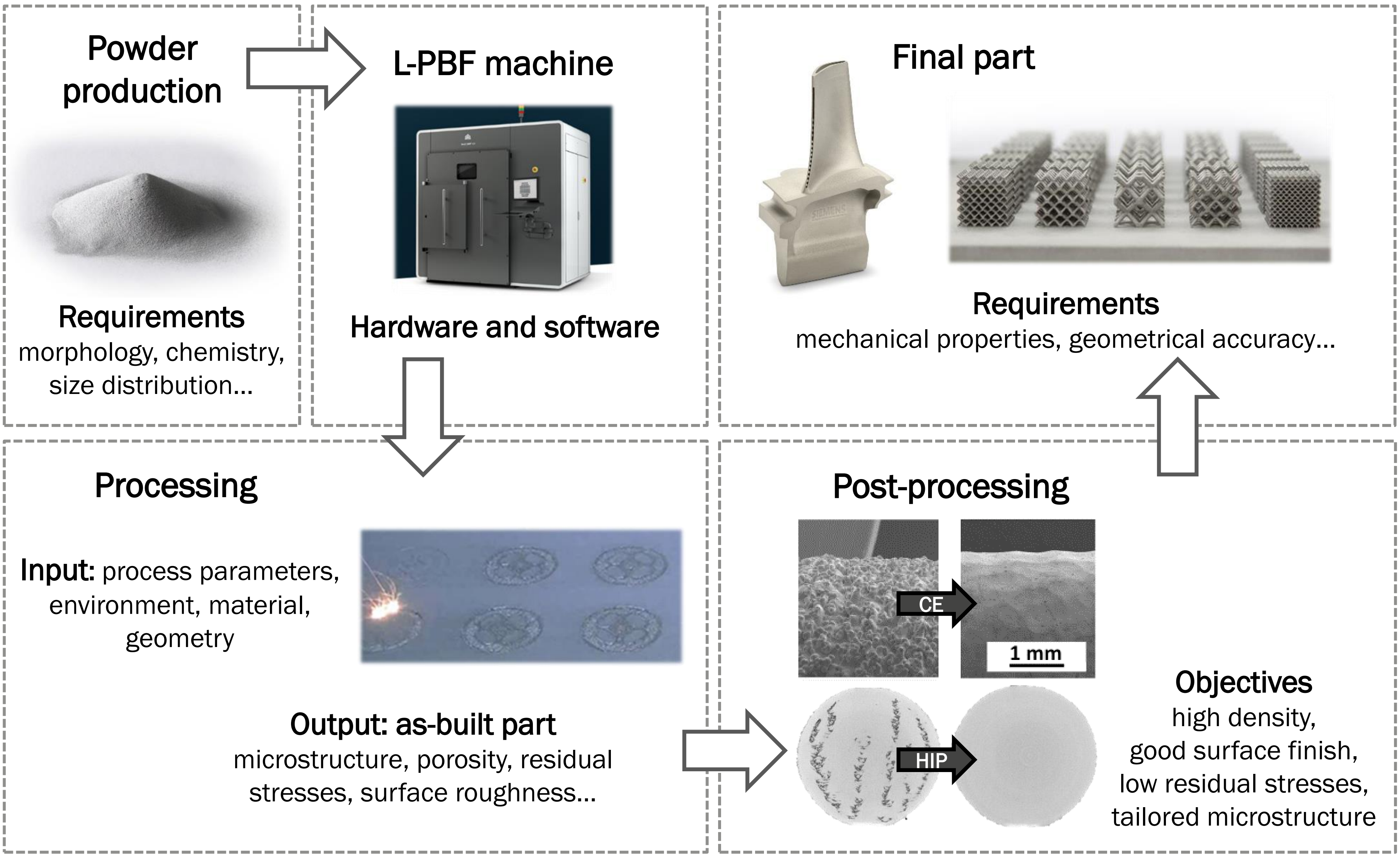

The molten alloy is forced through a nozzle where high velocity gas (e.g. Ar) impinges onto the flowing melt and breaks it up.

Powder is mostly spherical, with some asymmetric particles and satellites (smaller particle sticking to a larger one).



Guo et al., 2017

# Process overview



# Process overview

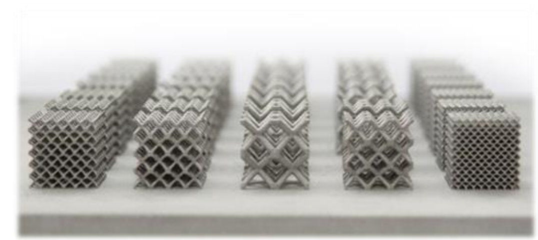
## Powder production

**Requirements**
morphology, chemistry,
size distribution…

## L-PBF machine

**Hardware and software**

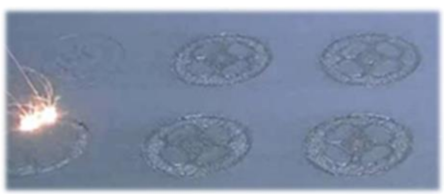
## Final part

**Requirements**
mechanical properties, geometrical accuracy…

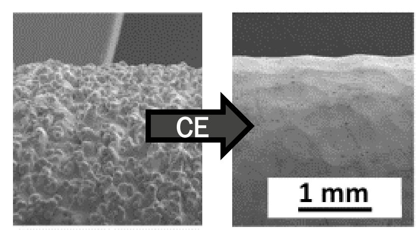
## Processing

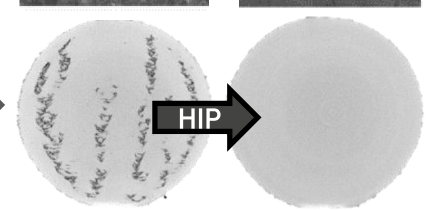
**Input:** process parameters,
environment, material,
geometry



**Output: as-built part**
microstructure, porosity, residual
stresses, surface roughness…

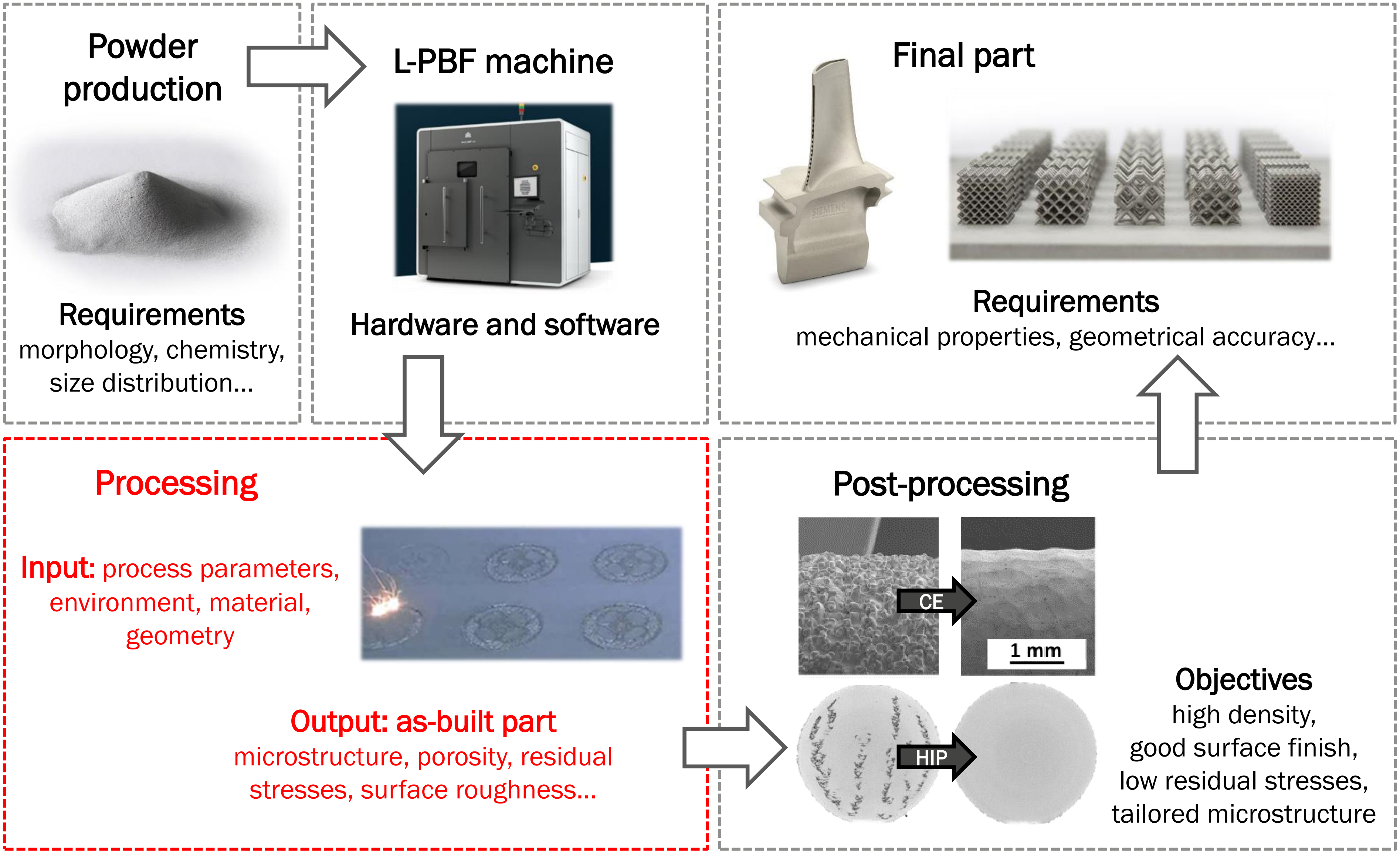
## Post-processing



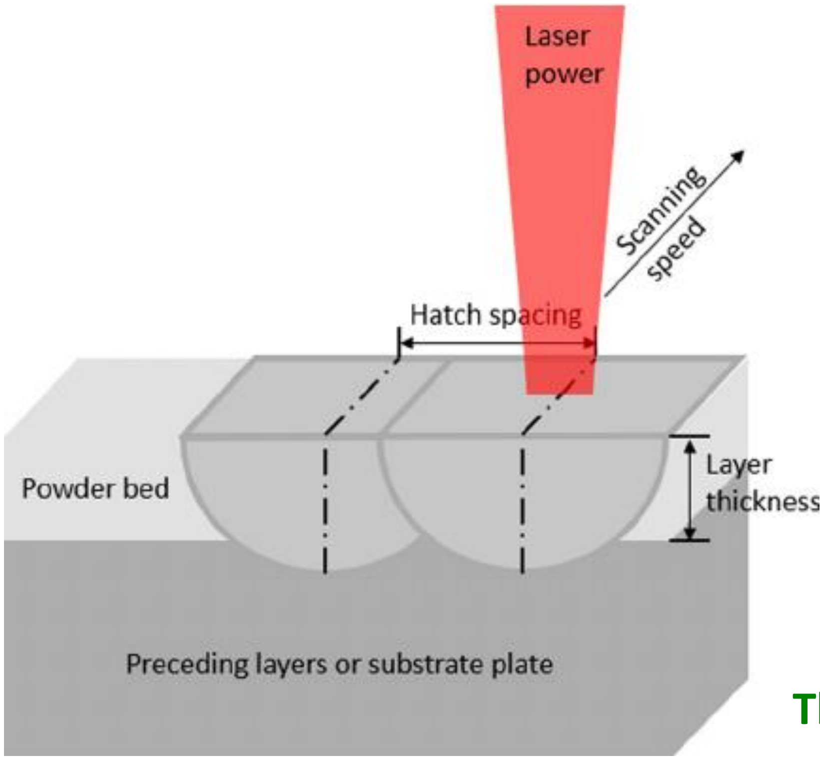




**Objectives**
high density,
good surface finish,
low residual stresses,
tailored microstructure

# Process overview



# Process parameters




Energy intensive

Laser power $P$ (W)
Scanning speed $v$ (mm/s)
Hatch spacing $h$ (µm)
Layer thickness $t$ (µm)

Energy density: $E = \frac{P}{vht}$

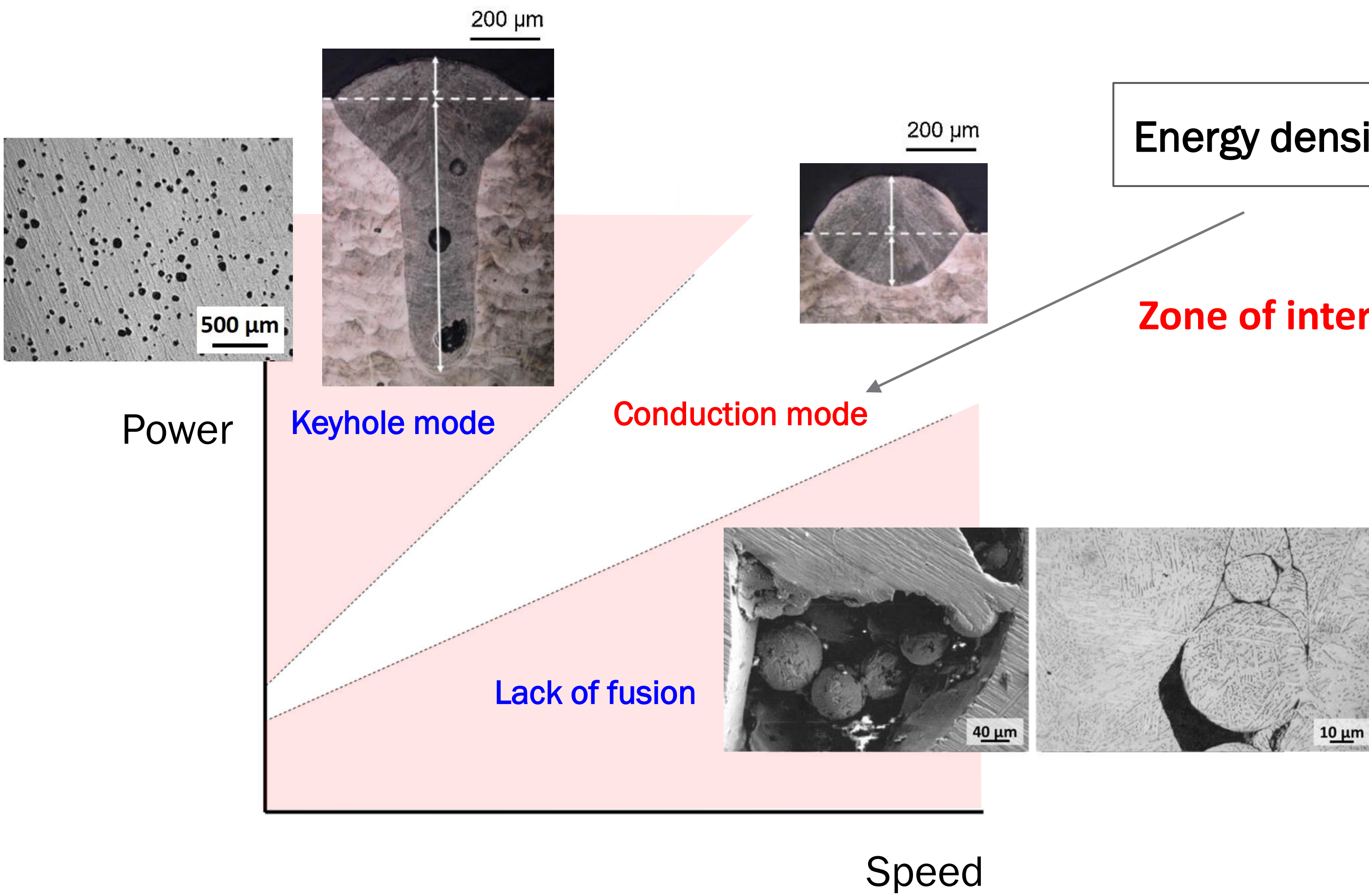
The material is melted more than once !

The energy density is a simple way to quantify the amount of energy provided to a certain volume of material during processing. It is widely used to determine the window of process parameters that lead to the production of fully dense parts.

Yap et al., 2015

# Porosity: processing map

## Process window for high density




Energy density: $E = \frac{P}{vht}$

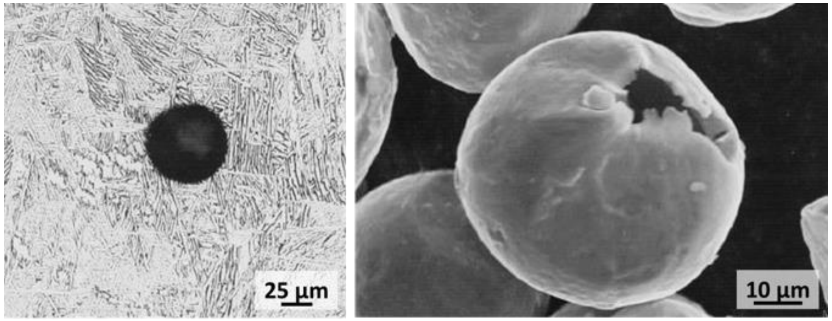
**Zone of interest**

# Porosity: origin

## Pores entrapped in feedstock powder

In the powder atomization process, gas can be introduced into the powder, and eventually remains in the fabricated part.

S.M. Gaytan et al., 2009




Small spherical pores resulting from gas entrapment during powder atomization

Also, if the packing density of metal powders is low, the gas present between the powder particles may dissolve in the molten pool. Because of the high cooling rate during the solidification process, the dissolved gas cannot come out of the surface of the molten pool before solidification takes place, and small gas pores remain in part.

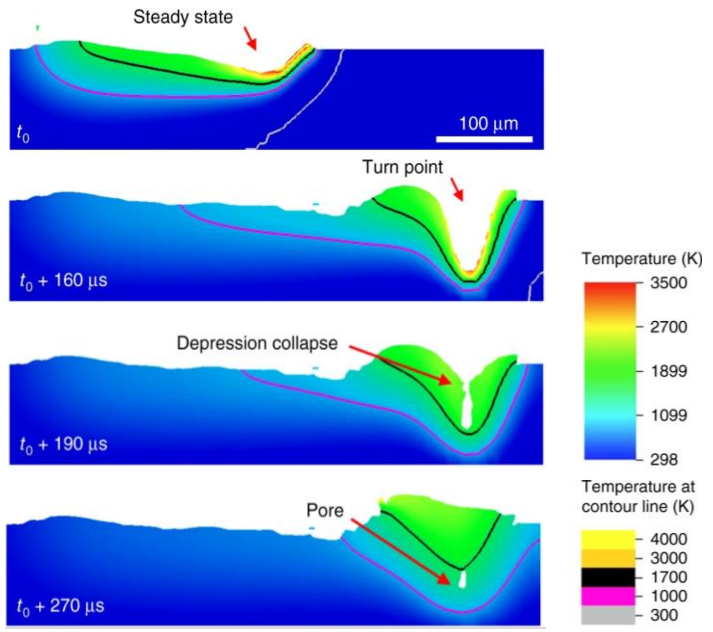
# Porosity: origin

## Keyhole mode

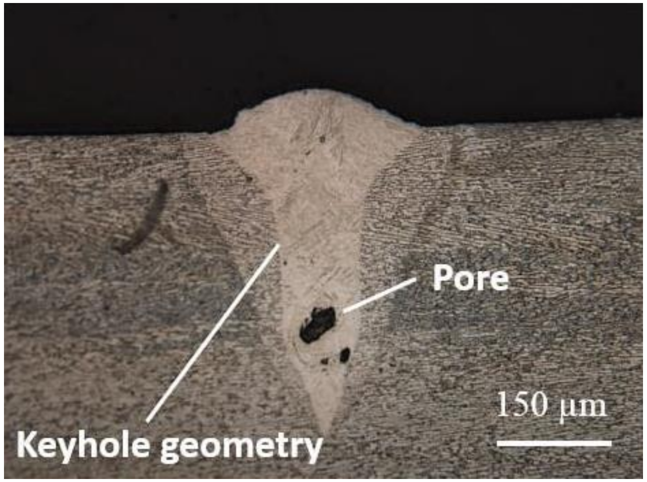
If the input of energy exceeds a threshold value (for example locally at the turn point of the laser), the melting mode changes from conduction mode to keyhole mode.

Vaporization of the metal creates a vapor cavity that increases the laser absorption. The resulting melt pool is no longer semicircular and the laser beam affects the metal much deeper than in conduction mode.

The collapse of the vapor cavity creates a void in the lower region of the melt pool.



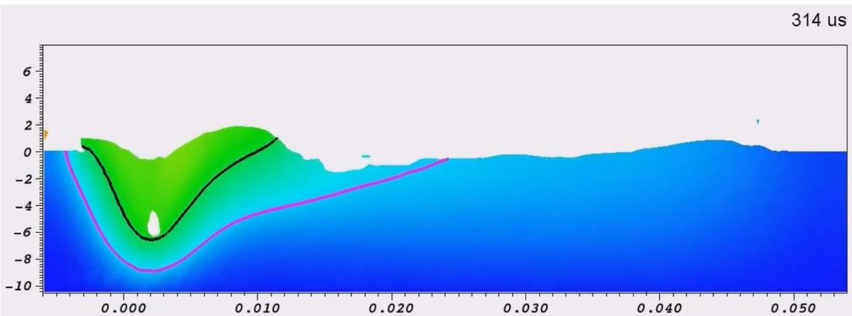

A. Martin et al., *Nature Communications*, 2019

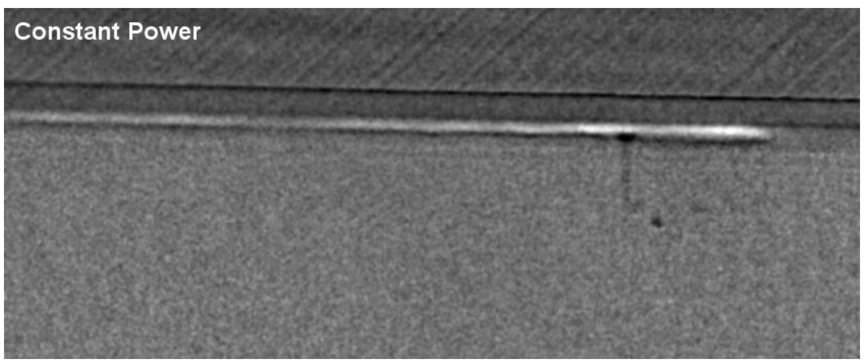



H. Gong et al., *Solid freeform fabrication symposium*, 2014

# Porosity: origin

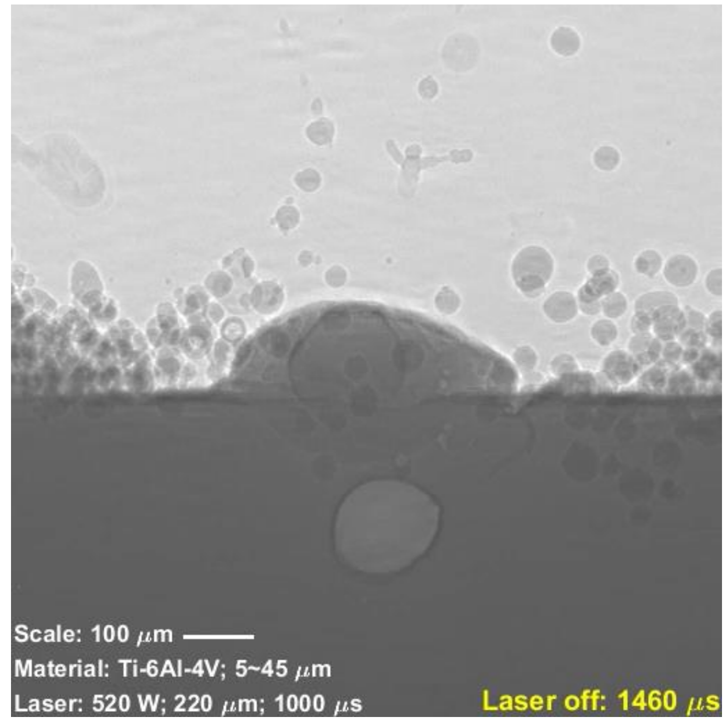
## Keyhole mode




A. Martin et al., *Nature Communications*, 2019

Formation of a keyhole pore at the turn point of the laser beam

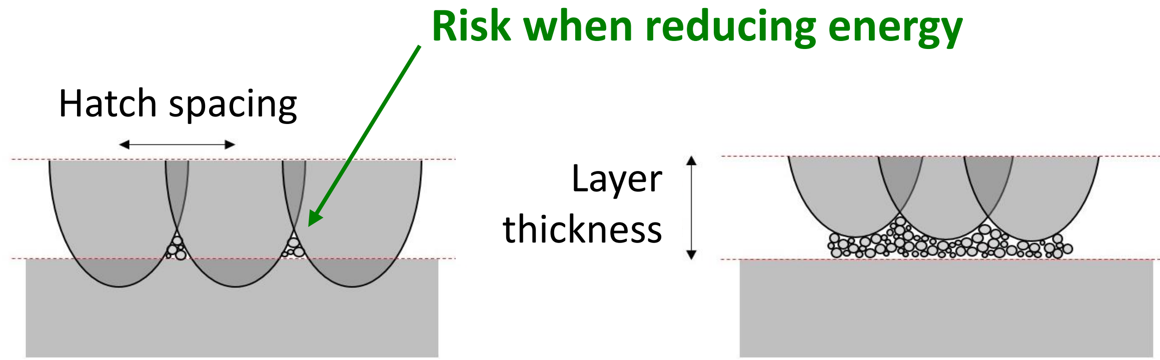



C. Zhao et al., *Scientific Reports*, 2017

High resolution X-ray imaging of the formation of a kehole pore

# Porosity: origin

## Lack-of-fusion

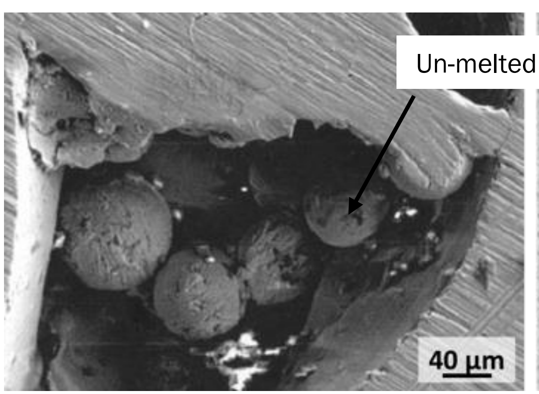



Lack-of-fusion (LOF) defects, are mainly due to insufficient energy input. The metal powders are not fully melted to deposit a new layer on the previous layer with a sufficient overlap. There are two types of LOF defects:

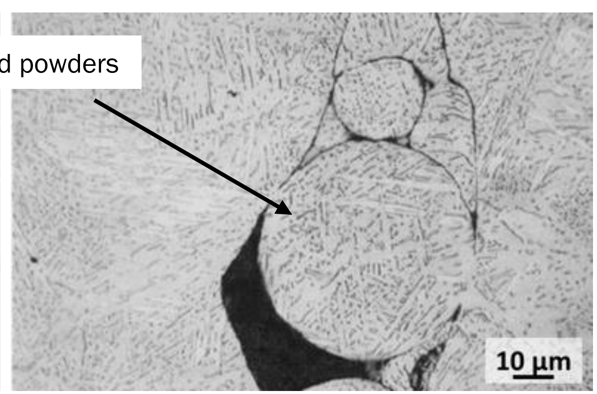
- poor bonding defects due to insufficient molten metal during solidification
- defects with un-melted metal powders

An LOF defect may contain numerous un-melted metal powder particles and reach large dimensions up to several hundred microns.

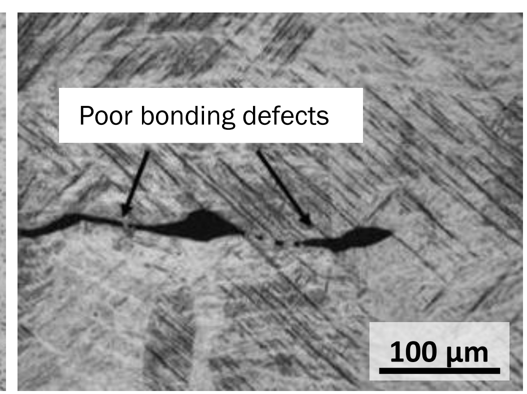
They are the most critical for the mechanical properties (local stress concentration and crack initiation)




S.M. Gaytan et al., 2009




S.M. Gaytan et al., 2009




B. Zhang, 2017

# Process overview

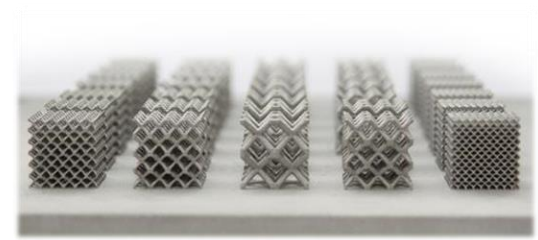
## Powder production

**Requirements**
morphology, chemistry, size distribution…

## L-PBF machine

**Hardware and software**

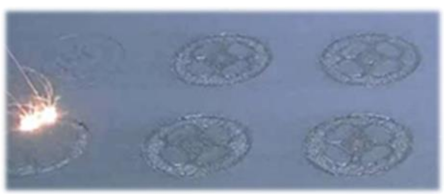
## Final part



**Requirements**
mechanical properties, geometrical accuracy…

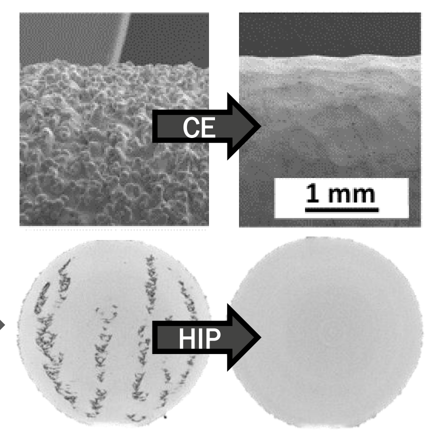
## Processing

**Input:** process parameters, environment, material, geometry



**Output: as-built part**
microstructure, porosity, residual stresses, surface roughness…

## Post-processing

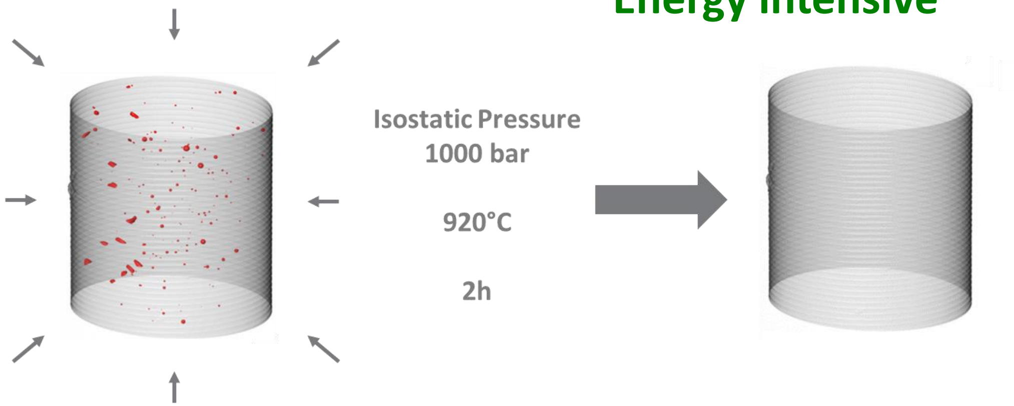



**Objectives**
high density,
good surface finish,
low residual stresses,
tailored microstructure

# Porosity: post-treatment

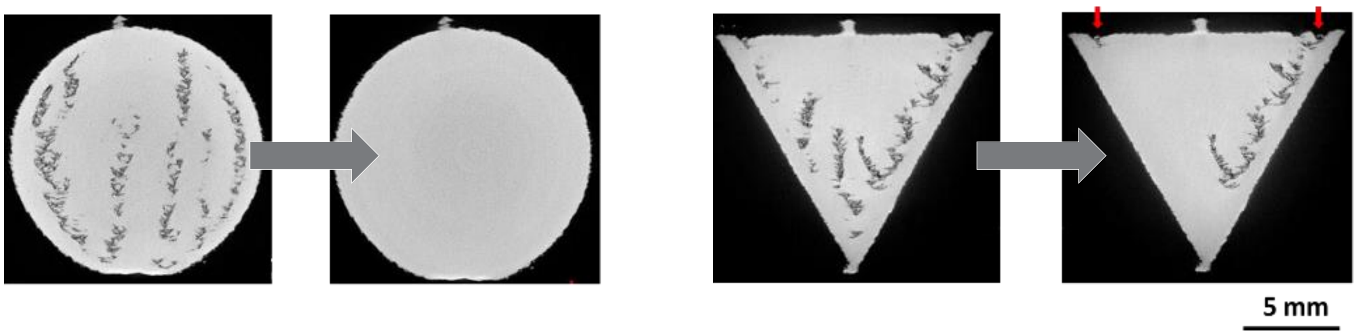
**Energy intensive**

## Hot Isostatic Pressing




Hot Isostatic Pressing (HIP) is a post-process thermo-mechanical treatment which consists in applying a high pressure and high temperature for several hours in order to close the voids that are present in the part.
Nearly fully dense parts (density > 99.9%) can be obtained after HIP.

However HIP is ineffective for open porosity and small gas-filled pores.






S. Tammas-Williams, *Metallurgical and Materials Transactions A*, 2016

# Process overview

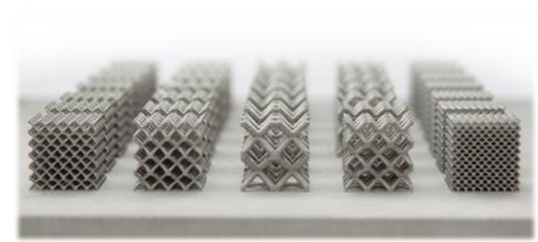
**Powder production**

**Requirements**
morphology, chemistry, size distribution...

**L-PBF machine**

**Hardware and software**

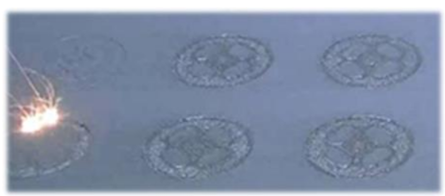
**Final part**



**Requirements**
mechanical properties, geometrical accuracy...

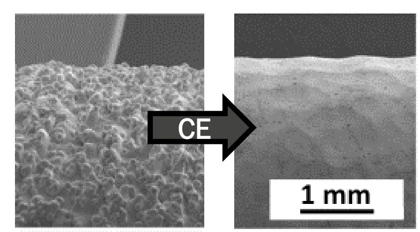
**Processing**

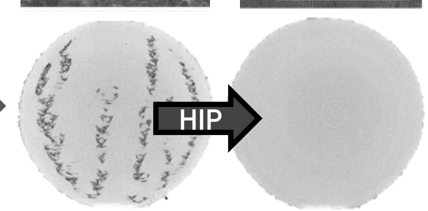
**Input:** process parameters, environment, material, geometry



**Output: as-built part**
microstructure, porosity, residual stresses, surface roughness...

**Post-processing**




**Objectives**
high density,
good surface finish,
low residual stresses,
tailored microstructure

# Mechanical properties

The mechanical properties of LPBF metals can vary substantially depending on a variety of factors: powder properties, process parameters, relative density of the material, geometry of the part, post-process treatments (surface treatments, HIP, heat treatments)…

In order to reach high mechanical properties, it is critical to:

- minimize the amount of porosity
- reduce surface roughness
- mitigate residual stresses
- perform material-specific **heat treatments** to optimize the microstructure

AM metal parts built with optimal process parameters and appropriate post-treatments exhibit high mechanical properties, comparable or superior to wrought material.

# Energy consumption

Energy consumption data of powder metallurgy processes found in the literature. (steels)

| Process | $SEC_{real}$ [MJ/kg] | Material | Reference |
|---|---|---|---|
| Additive manufacturing | 97 | 316L | [23] |
| | 112 | 316L | [24] |
| | 220 | 17-4 PH | [25] |
| Iron oxide reduction | 22.7 | Iron | [26] |
| Powder annealing | 3.6 | Iron | [26] |
| | 3.6 | Steel | [27] |
| | 5.8 | Iron | [28] |
| Pressing | 0.1 | Steel | [5] |
| | 0.1–0.5 | Iron | [26] |
| | 3.6 | Steel | [6] |
| Sintering | 2.4 | Steel | [29] |
| | 6.5 | Steel | [6] |
| | 7.1 | Steel | [30] |
| | 10.1 | Steel | [5] |
| Water atomisation | 3.6 | Steel | [30] |
| | 6.0 | Steel | [5] |
| | 11.7 | Iron | [28] |

**SEC = E/m**
Specific energy consumption

**m = mass output** of the process

**E = total energy** used by the process

J.M.C. Azevedo, A. Cabrera Serrenho, J. M. Allwood, Energy and material efficiency of **steel powder metallurgy**, Powder Technology 328 (2018) 329–336

# Energy efficiency (η)

Energy efficiency of the powder metallurgy processes (steels)

| Process | $SEC_{theo}$ [MJ/kg] | $SEC_{real}$ [MJ/kg] | $\eta$ |
|---|---|---|---|
| Induction melting | 1.3[a] | 2.2[b] | 59% |
| Gas atomisation | 0.3 | 2.7 | 11% |
| Water atomisation | 0.4[c] | 1.4[c] | 28% |
| Powder annealing | 0.5 | 3.6[d] | 14% |
| Sintering | 0.6 | 2.4[e] | 26% |
| Compaction | 0.1[c] | 3.6[c] | 2% |
| Hot isostatic pressing | 0.6 | 1.5 | 42% |
| Additive manufacturing | 1.3[a] | 97[f] | 1.3% |

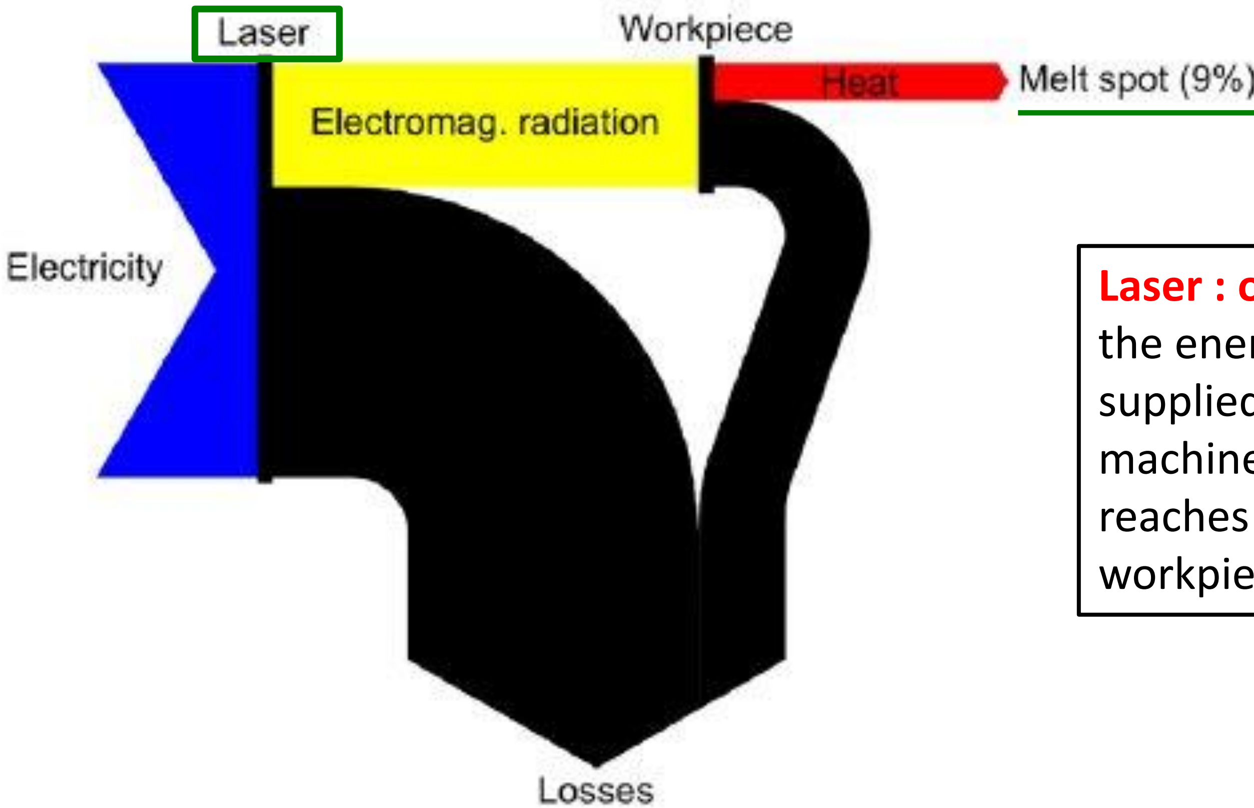
$$\eta = \frac{SEC_{theo}}{SEC_{real}}$$

$SEC_{theo}$ → Theoretical minimum energy consumption

$SEC_{real}$ → Actual energy inputs

J.M.C. Azevedo, A. Cabrera Serrenho, J. M. Allwood, Energy and material efficiency of **steel powder metallurgy**, Powder Technology 328 (2018) 329–336

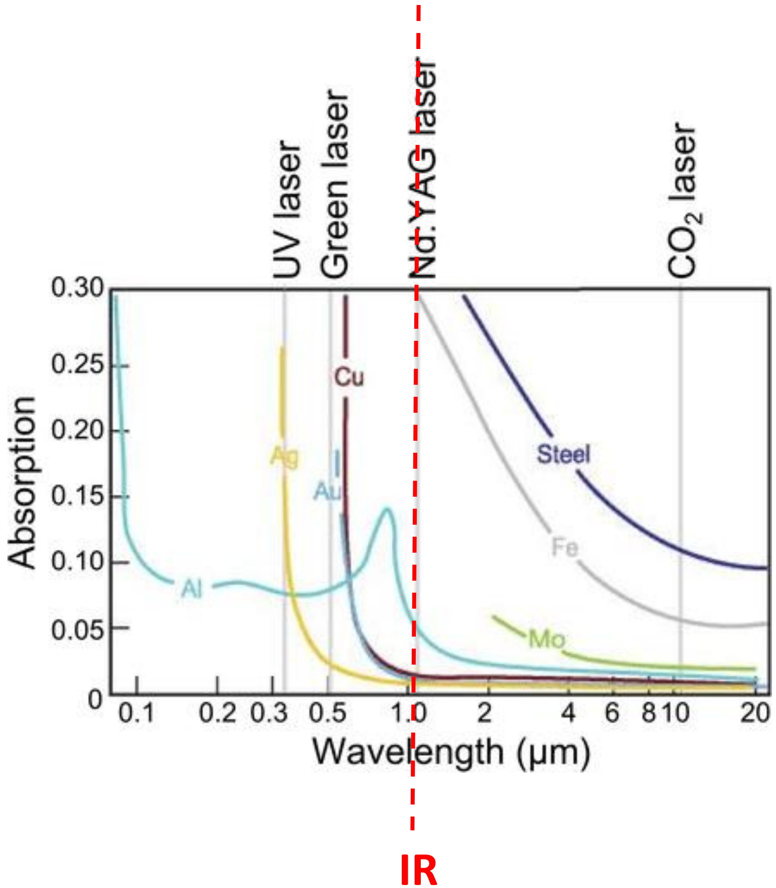
# Causes for low energy efficiency in AM




**Laser : only 9%** of the energy supplied to the machine actually reaches the workpiece.

J.M.C. Azevedo, A. Cabrera Serrenho, J. M. Allwood, Energy and material efficiency of **steel powder metallurgy**, Powder Technology 328 (2018) 329–336

# Causes for low energy efficiency in AM



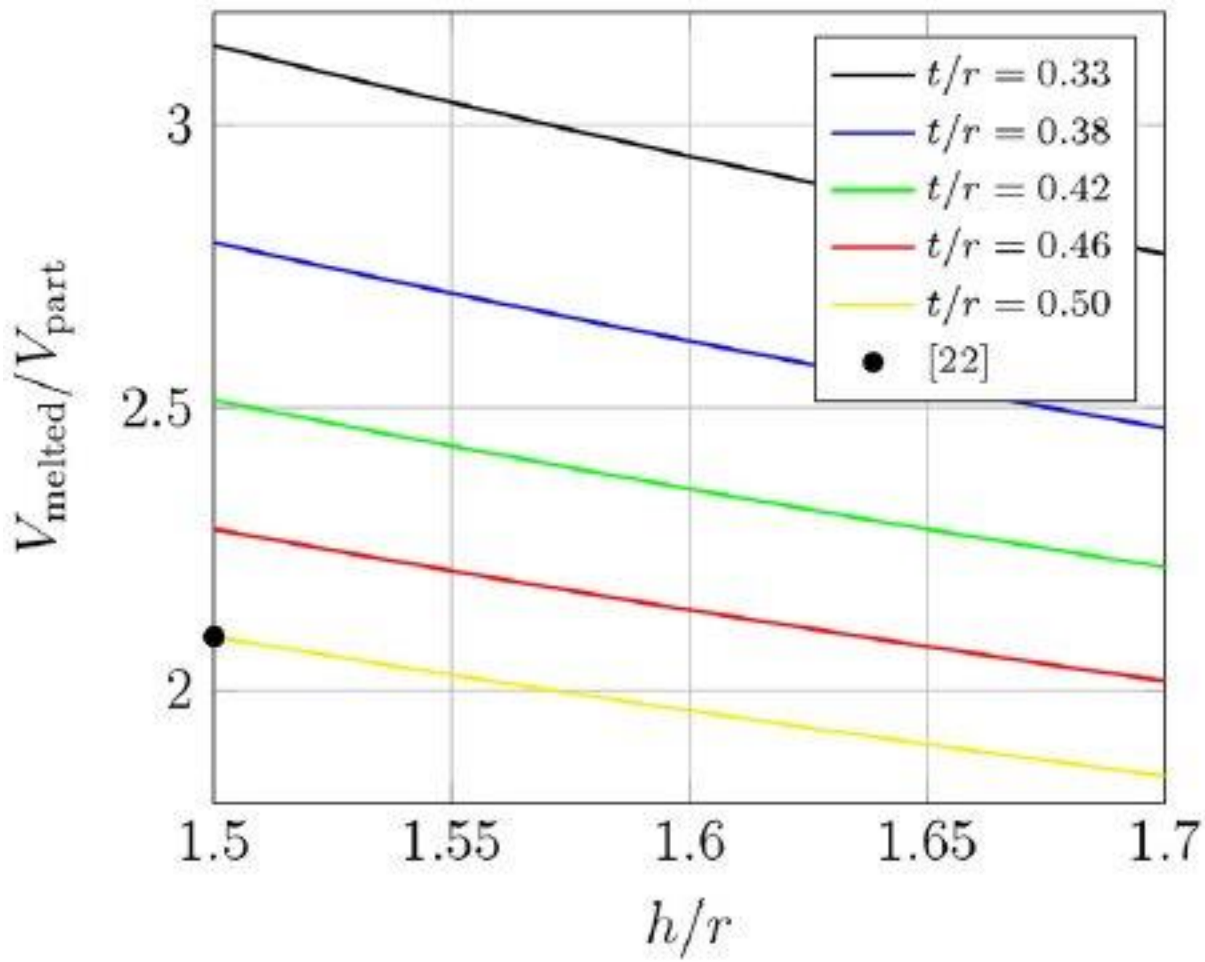

**Absorptivity**

Alloys based on **Fe**, Ni have a relatively high **absorption** at IR wavelengths (~ 30%).

Some metals such as gold, copper, silver, and even <u>aluminium</u> are **very reflective** :

**Absorption < 5%**

# Causes for low energy efficiency in AM




*h* = hatch spacing
*t* = layer thickness
*r* = melt pool size

**LPBF : the material is melted more than once**

J.M.C. Azevedo, A. Cabrera Serrenho, J. M. Allwood, Energy and material efficiency of **steel powder metallurgy**, Powder Technology 328 (2018) 329–336

# Recommandations for improved efficiency

- Increase efficiency of the gas atomization processes

- Avoid using lasers as heat sources
  → example : the binder jetting process

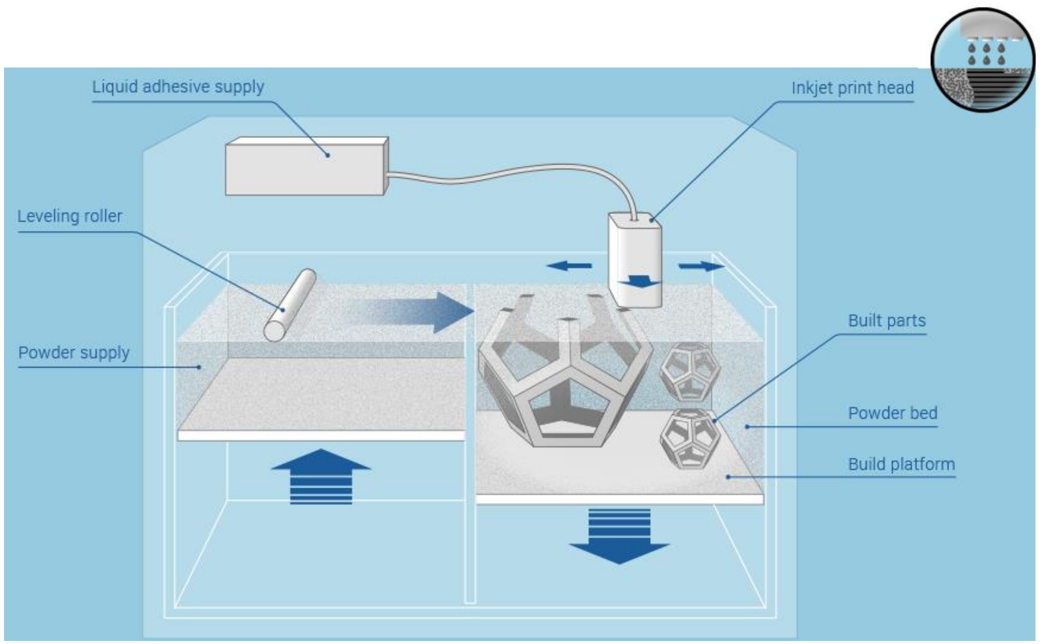
⇩

**Binder jetting or Binder Jet Printing (BJP) :**
Liquid binding agent (binder) into a powder bed, followed by heating cycles in a furnace.

J.M.C. Azevedo, A. Cabrera Serrenho, J. M. Allwood, Energy and material efficiency of **steel powder metallurgy**, Powder Technology 328 (2018) 329–336

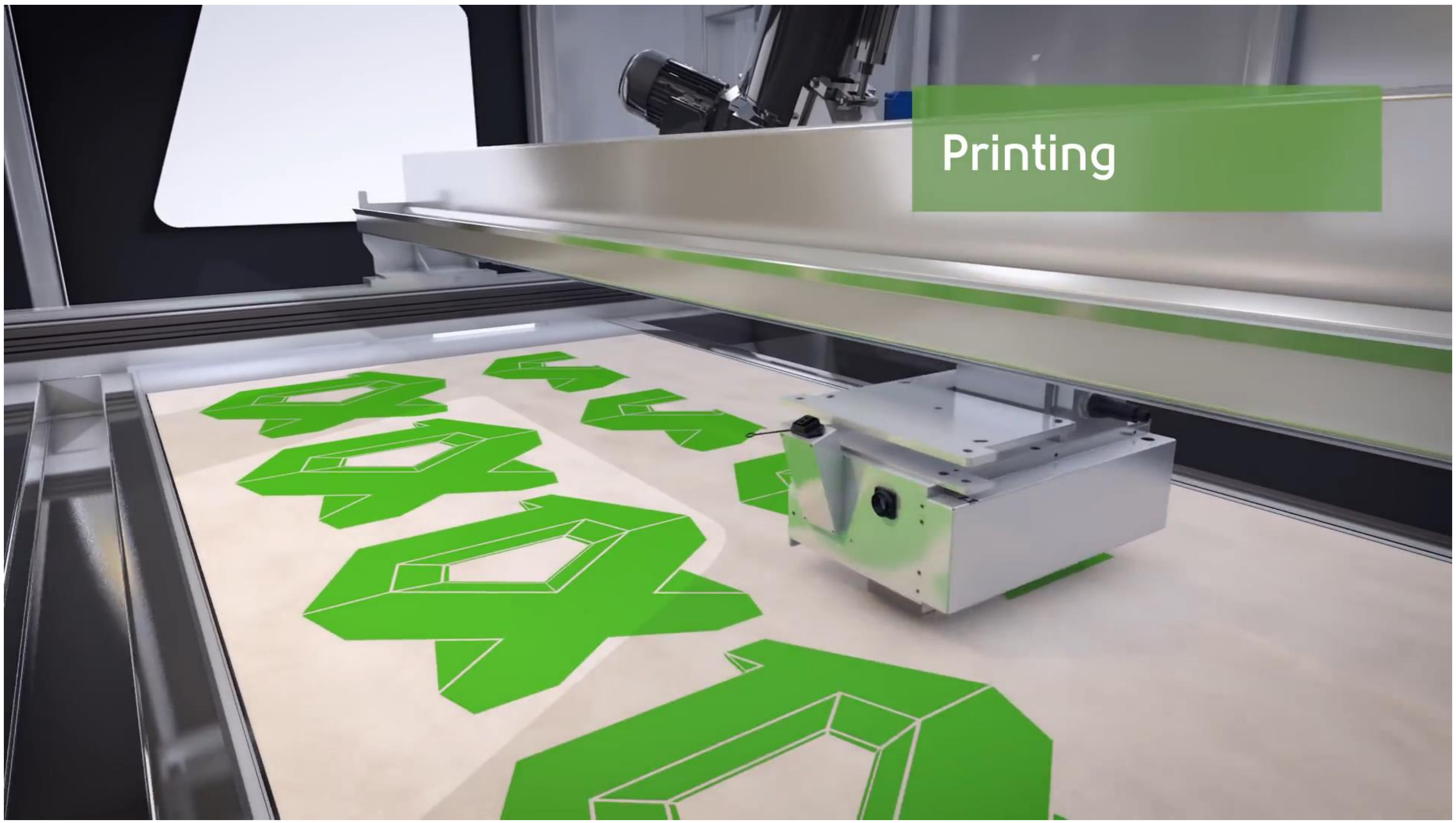
# Binder jetting (BJP)

**Binder jet printing** is an additive manufacturing technique that dispenses a liquid binding agent (the binder) into a powder bed to fabricate a "green" part.
Hence, in BJP, only a small portion of the part material is delivered through the print head. Most of the part material is comprised of powder in the powder bed.
Binder droplets form spherical agglomerates of binder liquid and powder particles and provide bonding within and between layers.
BJP does not employ heat to melt the metal powder particles during the build process and prints rapidly each layers using a wide printhead with many inkjet nozzles.




# Binder jetting (BJP)

**Binder jet printing** is an additive manufacturing technique that dispenses a liquid binding agent (the binder) into a powder bed to fabricate a part.






https://www.exone.com/en-US/case-studies/what-is-binder-jetting

# Binder jetting (BJP)

**Post-processing**

After fabrication, the "green" part is removed from the AM machine and subjected to 2–3 furnace cycles.

In the **first cycle**, low temperature is used for several hours to burn off the polymer binder.

In the **second cycle**, high temperature is used to sinter the metal particles together. At this stage, the part is approximately 60% dense.

In the **third cycle**, a bronze ingot (or other alloy with a lower melting temperature than the powder alloy) is placed in the furnace in contact with the part so that bronze infiltrates into the part's pores, resulting in parts that are greater than 90% dense.

In some cases, the infiltration step is skipped and the part is sintered to near-full density, leading to **considerable shrinkage and distortion**. Careful control of this distortion is very difficult for complex geometries



Gibson, Ian, et al. "Binder jetting." *Additive manufacturing technologies*. Springer, Cham, 2021. 237-252.

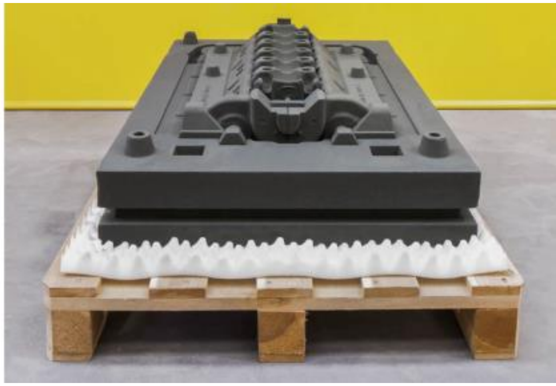
# Binder jetting

**Advantages**

- fast and cheap technology
- bonding occurs at room temperature
  - ⇒ no thermal effects during printing (e.g. residual stresses, distortion, cracks…)
  - ⇒ suited for large parts

**Disadvantages:**

- low density
- low mechanical properties
  - ⇒ typically not suitable for structural applications
- Challenging post-processing steps (distortions)



*Casting mold block*

*Heavy equipment and machinery part*

# Conclusions

**AM provides new design opportunities for metal parts but several aspects remain critical**

The choice of the manufacturing process is highly dependent on the end application.

In order to obtain high quality parts for critical applications, a thorough optimization of the process is an absolute pre-requisite. Additionally, post-process treatments are often required, typically a combination of surface treatments and heat treatments.

**AM of metals is much more than "making nice geometries", the material science behind it is crucial**

# Conclusions

## Sustainability aspects remain controversial

Some features play **in the good direction**

- Reduced weight and associated $CO_2$ emission
- Reduced material waste
- Recyclability of powders (only for a single material)

While others indicate **low energy efficiency**

- Atomization process
- Lasers inefficient heat sources
- Multiple melting of the material

New processes emerge, but sustainability is often associated with low performance (geometrical accuracy, material properties)

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