Additive Manufacturing of Metals and Alloys

1. Introduction to AM of metals

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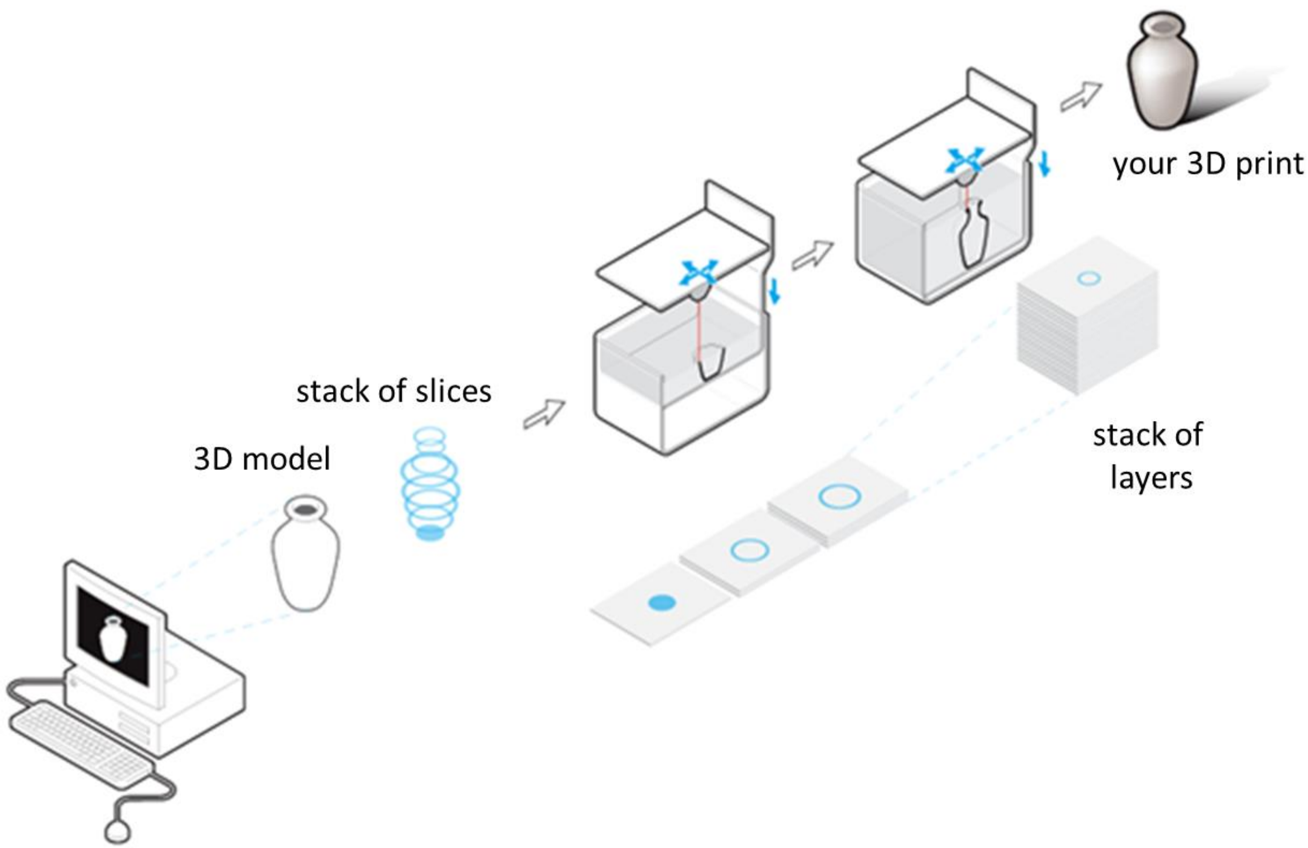
EPFL

Introduction to AM of metals

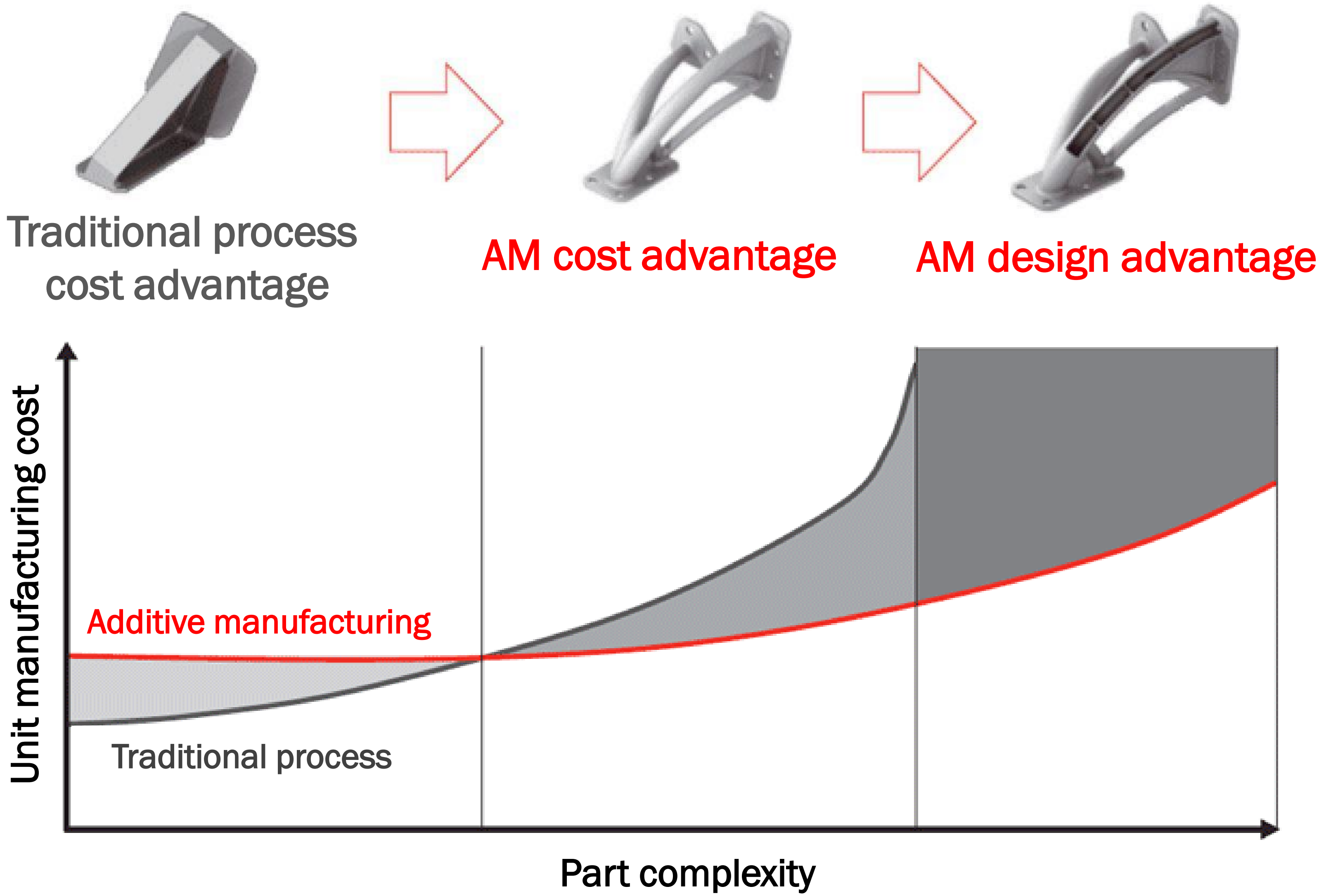
- Introduction
- AM of metals: examples of applications
    - aerospace
    - automotive
    - biomedical
    - others (sports, jewelry…)
- Palette of metals for AM
- AM processes for metals
    - Powder bed fusion
    - Directed energy deposition
    - Binder jetting

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

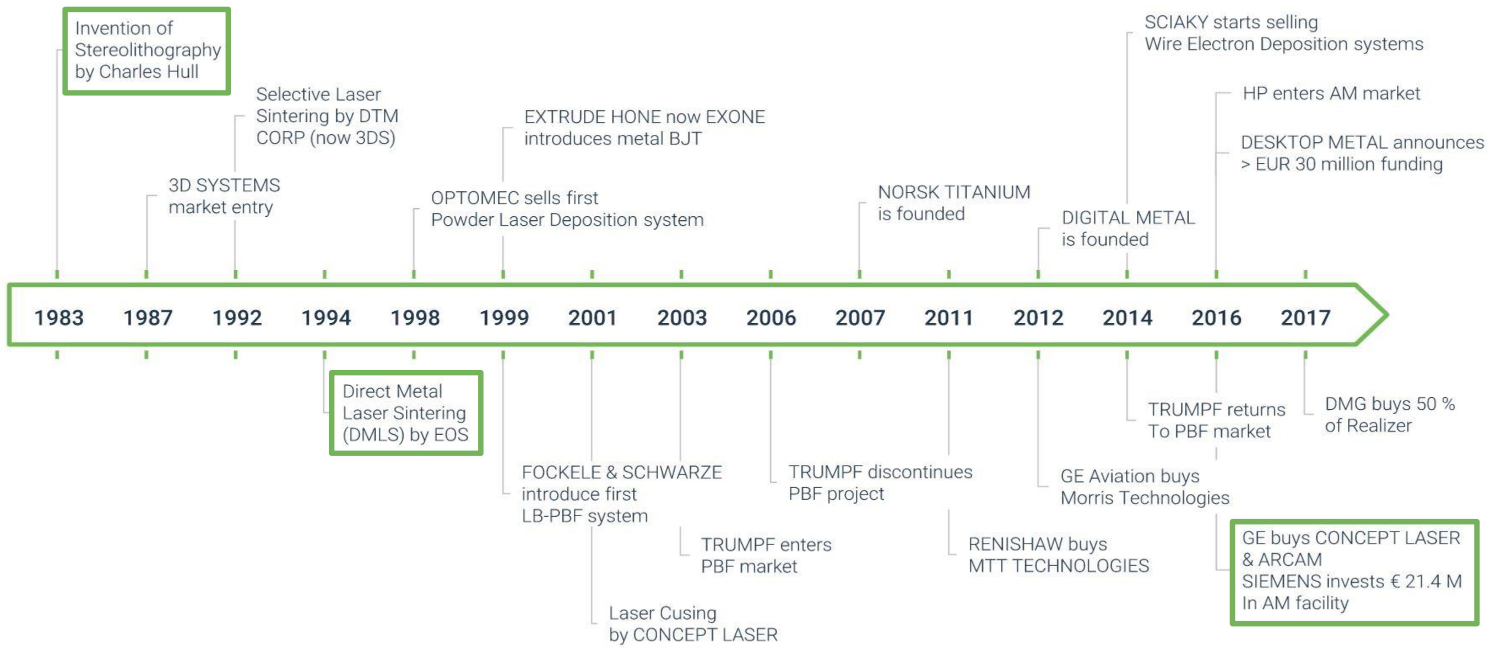
AM is a **"bottom-up"** approach, in which parts are built layer-by-layer, so that **complex geometries** can be produced.



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



Overview of AM history



60s and 70s: first experimental set-ups and early machine concept developments
80s: first Rapid Prototyping commercial systems.
90s: first commercial metal based AM systems (metal powder sintering)
90s-2000s: development and commercialization of several metal based AM methodologies
2010s: Major companies, such as HP, Lockheed Martin, Boeing and GE, extensively invest in AM.

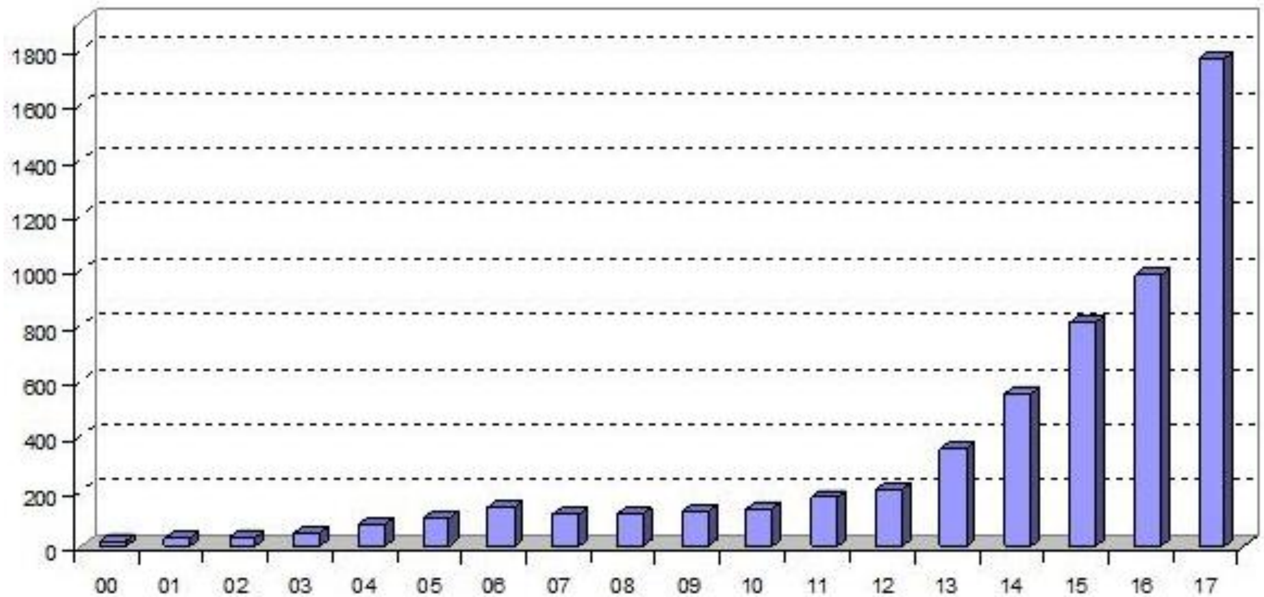
In 30 years, the metal AM industry has rapidly evolved from the production of prototypes to the manufacturing of finished parts, in some cases for critical applications.

https://additive-manufacturing-report.com/technology/additive-manufacturing-history/
https://www.metal-am.com/introduction-to-metal-additive-manufacturing-and-3d-printing/background-to-additive-manufacturing/

AM: a growing market

Significant rise in metal AM system installations worldwide

Number of metal AM system installations



Year

In 2019, the global metal AM market size is valued at EUR 2.02 billion including system, material and service sales.

Wohlers Report 2018.

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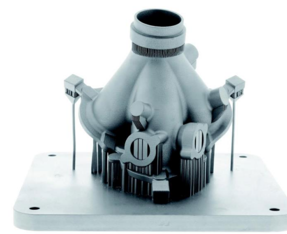
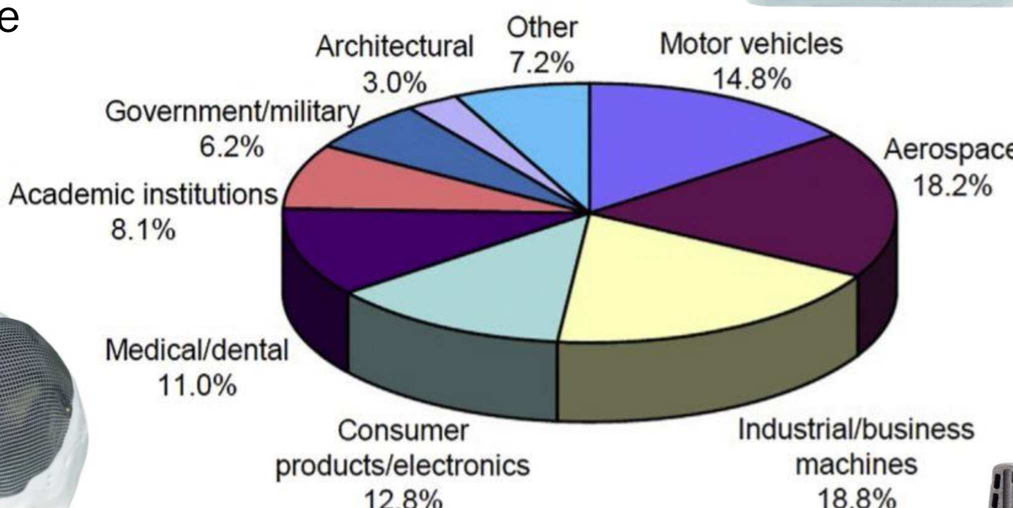
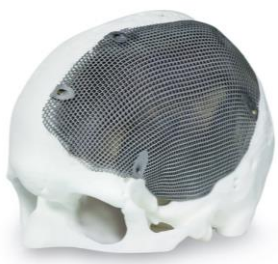
Applications: overview

Relevant industries

- industrial machines: e.g. tooling
- aerospace: e.g. lightweight structures
- medical/dental: implants, porous structures
- consumer goods: e.g. sports
- automotive







Wohlers Report 2017.

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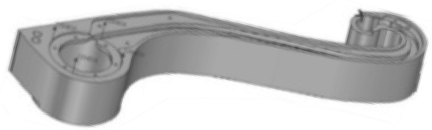
Aerospace applications

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

0.31 kg – 37% CO_2

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.

Aerospace applications

Use case: fuel nozzles for jet engines

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

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

ADDITIVE MANUFACTURING

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

AM fuel nozzle

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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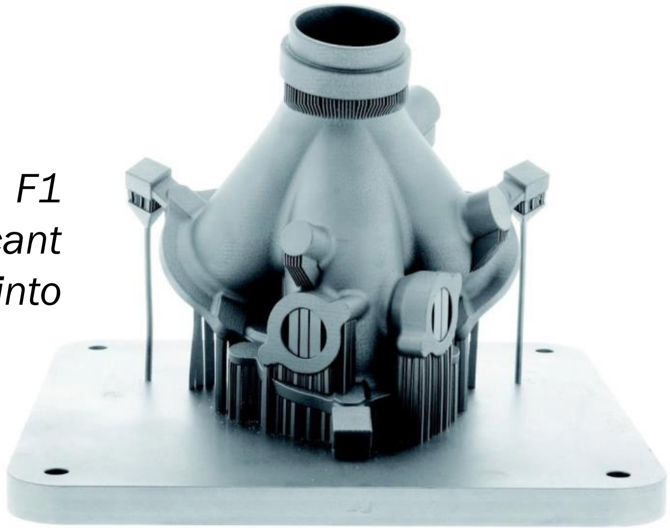
Automotive applications

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

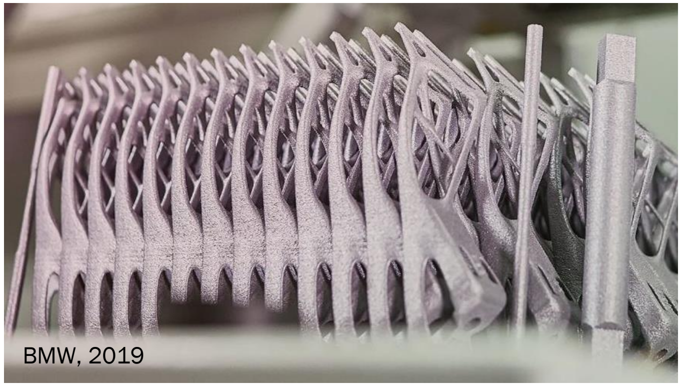
- Vintage automotive restoration: production of rare replacement parts
- High-performance luxury automobiles

Automotive applications

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


Scott, 2018

ADDITIVE MANUFACTURING

- more than 600 brackets per batch
- 44% 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

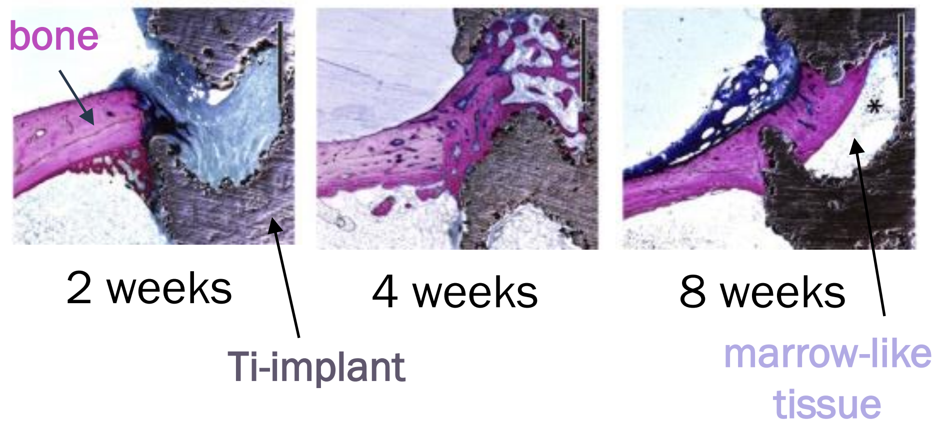
Biomedical applications

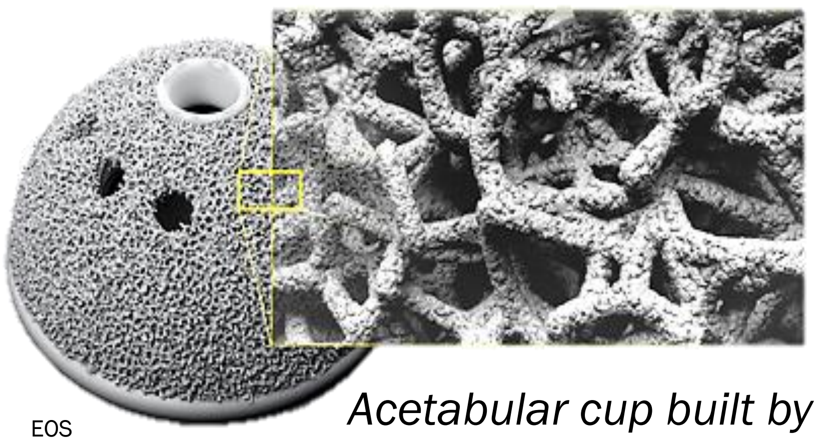
Additive manufacturing

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





Acetabular cup built by EBM

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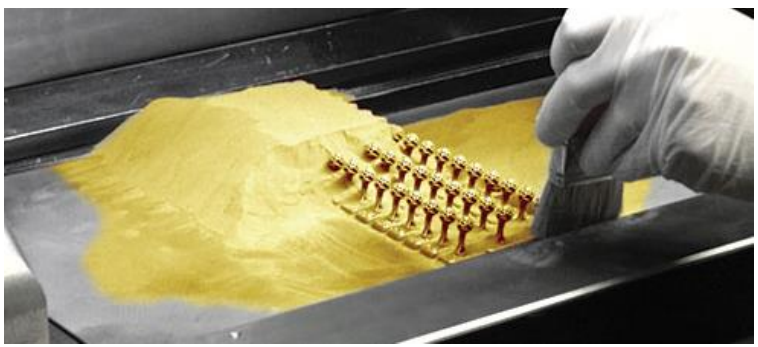
Jewelry

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**.



EOS

As-built cufflinks on build platform

Post-processed and polished cufflinks

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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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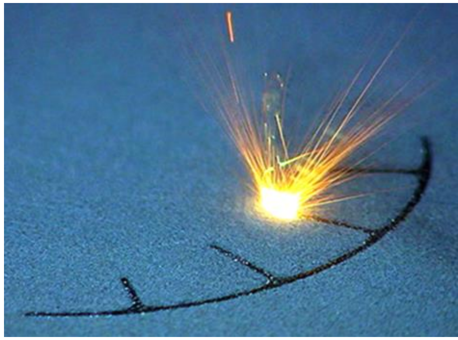
AM processes for metals

Three main families of AM processes for metals (ASTM standard terminology)

- **Powder Bed Fusion (PBF):**

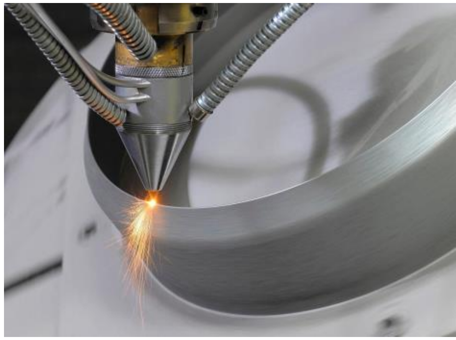
An additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.



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

- **Binder jetting or Binder Jet Printing (BJP)**

Liquid binding agent (binder) into a powder bed, followed by heating cycles in a furnace.

AM processes for metals

AM service providers

WIRE				POWDER							OTHER	
	Direct Energy Deposition				Powder Bed Fusion		Powder + Binder					
Joule Printing	E-Beam	Arc/Plasma	Laser	Laser	Laser	E-beam	Material Jetting	Material Extrusion	Binder jetting	Cold Spray	Friction Welding	Sheet Lamination
DigitalAlloys	Sciaky Inc	Norsk Titanium	GKN	BeAM	EOS	Arcam	XJET	Markforged	ExOne	SPEE3D	MELD	FABRISONIC
	Evobeam	WAAM	Mazak	TRUMPF	Concept Laser	JEOL		Desktop Metal	Digital Metal	Titomic		
		Gefertec		Optomec	SLM Solutions	freemelt		pollen	Desktop Metal			
		Prodways		FormAlloy	3D Systems				3DEO			
		Lincoln Electric		DMG Mori	Renishaw				hp			
				InssTek	AddUp				stratasys			
				Raycham	Additive Industries				GE Additive			
					Velo3D							
					Farsoon Technologies							
					TRUMPF							
					Aurora Labs							
					Coherent ORLaser							
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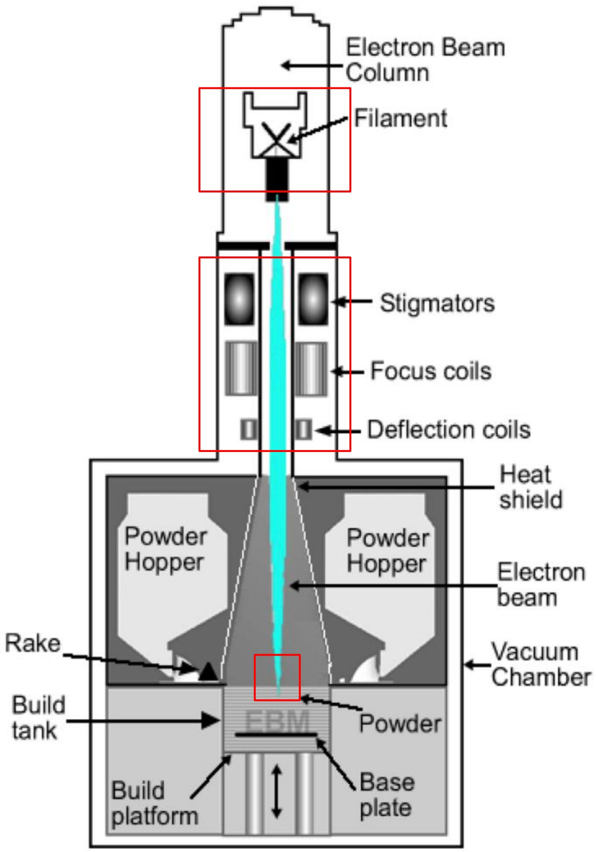
Electron beam melting



Sidambe, 2014

The high-power electron beam is generated by heating a tungsten filament.

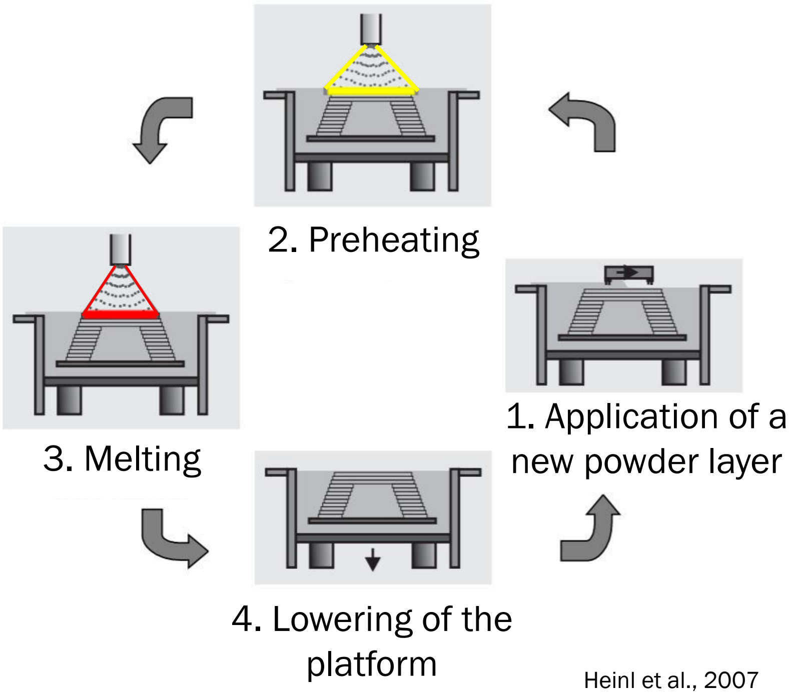
Electrons are accelerated to a velocity between 0.1 and 0.4 times the speed of light using an accelerating voltage of 60 kV.

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

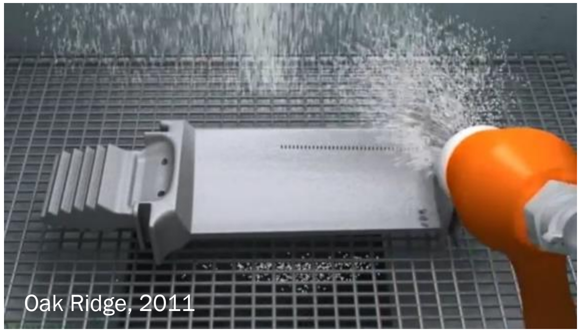
1. A layer of metal powder is spread homogeneously by the rake on the build platform.

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.

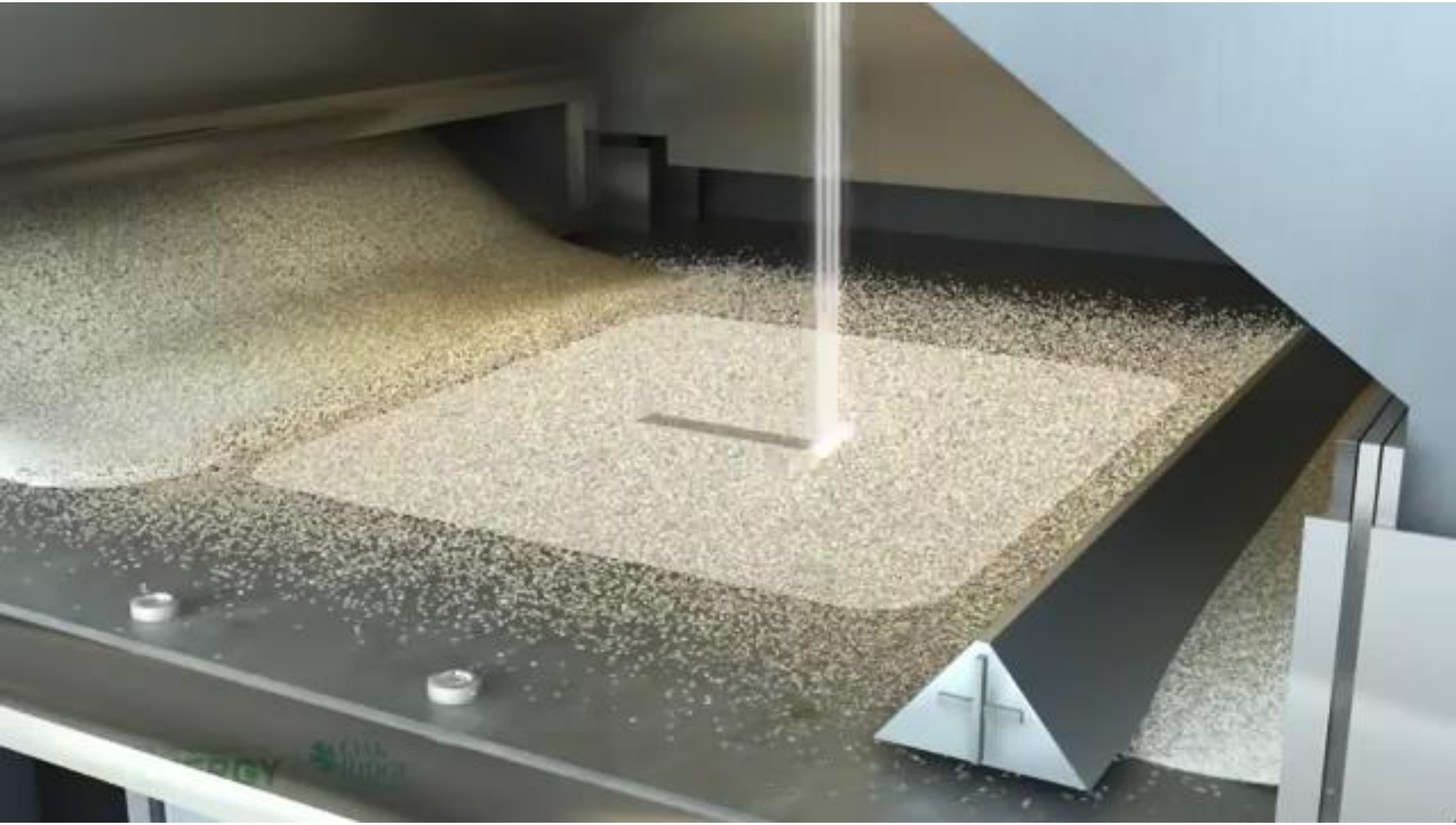
4. The build plate is lowered by one layer thickness and a new layer of powder is spread on top (step 1).

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.



Oak Ridge, 2011

Electron beam melting



Oak Ridge, 2011

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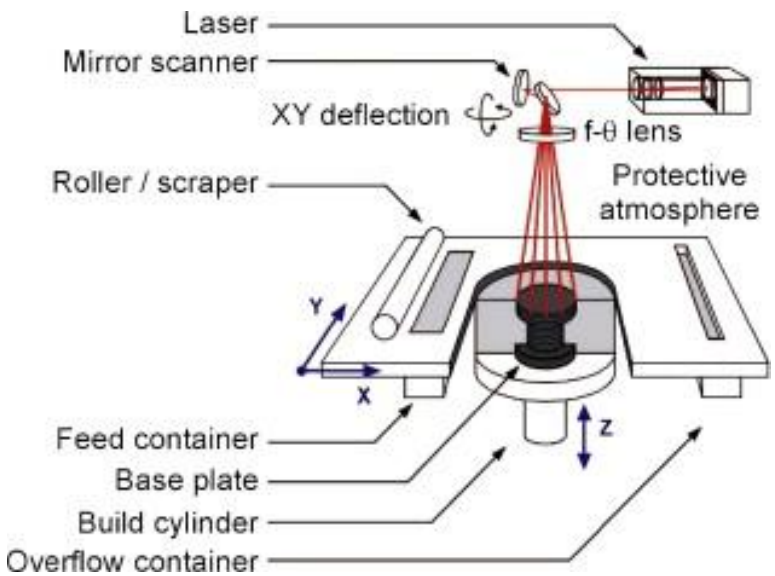
Laser powder bed fusion (LPBF)

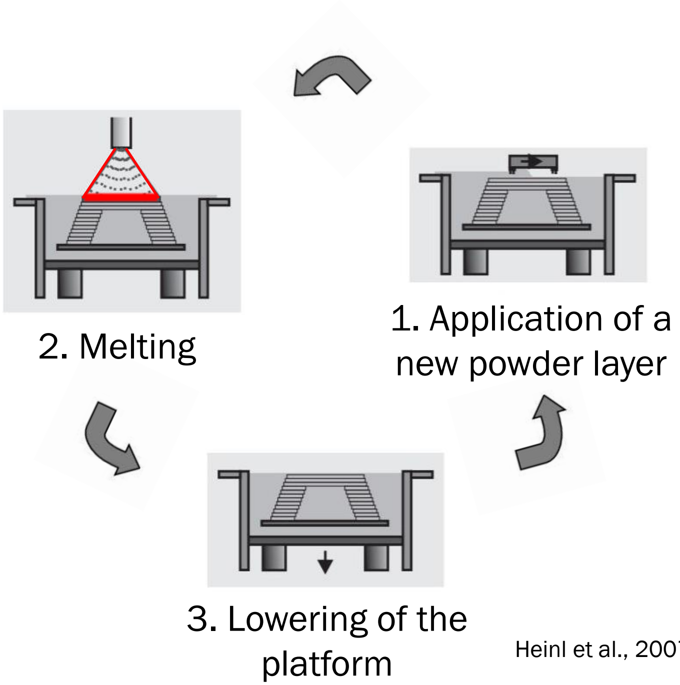
also known as Selective Laser Melting (SLM)



PhD M. Rombouts, 2006

LPBF uses a high power laser (fiber 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 (LPBF)

also known as Selective Laser Melting (SLM)

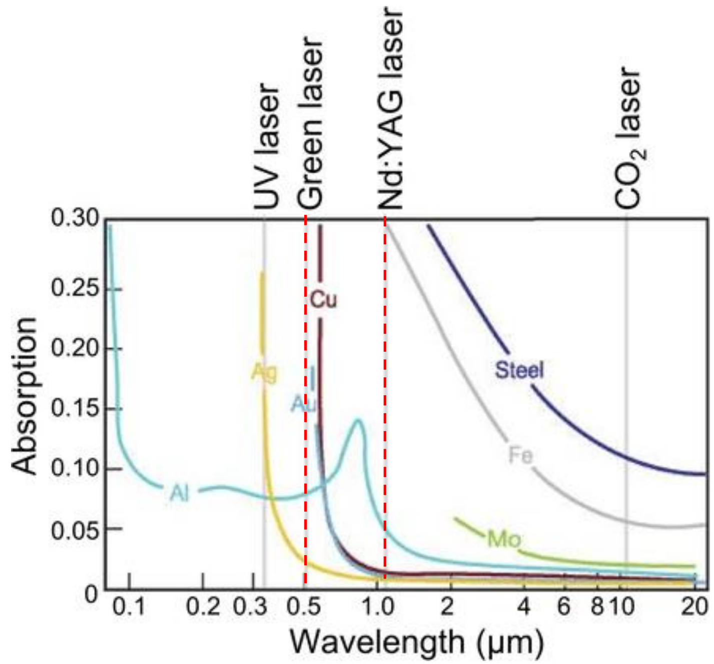
Stratasys, 2017

EBM/LPBF comparison

	EBM	LPBF
Heat source	Electron beam	Laser beam

<u>Consequences :</u>

- 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 LPBF 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.

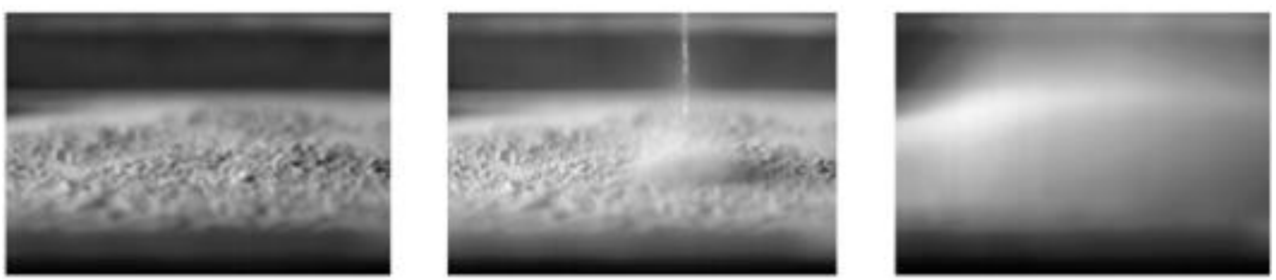
Some reflective metals such as gold, copper and silver, have very high reflectivity at λ = 1064 nm, and may require the use of a green laser (λ = 532 nm) to be processed.

EBM/LPBF comparison

	EBM	LPBF
Heat source	Electron beam	Laser beam

<u>Consequences :</u>

- The materials used in EBM must be conductive.
- In LPBF the absorption of a given metal depends on the wavelength of the laser. Some reflective metals such as gold, copper, silver, require the use of a green laser to be processed.
- In EBM the accumulation of electrostatic charges can generate a “smoke” effect if the electronic repulsive forces overcome the gravitational and frictional forces. Therefore, in EBM, very fine powders are not suitable.



PhD T. Mahale, 2009

20 mm

EBM/LPBF comparison

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

Consequences :

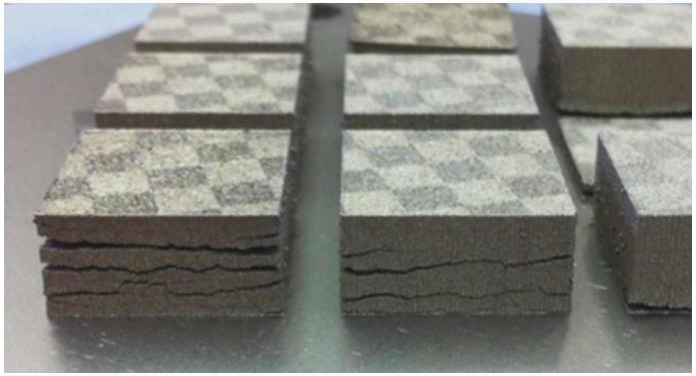
- In EBM, the electron beam is deflected magnetically, almost instantaneously, resulting in high positioning accuracy. In LPBF, the laser beam is optically deflected and the scan speed is mechanically limited by the movement of the mirrors. The scan speeds for the EBM system are orders of magnitude greater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

EBM/LPBF comparison

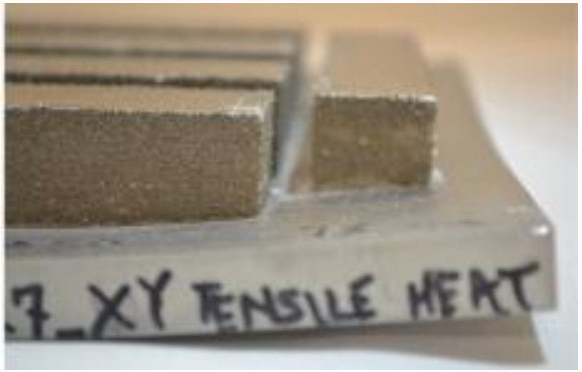
	EBM	LPBF
Heat source	Electron beam	Laser beam
Atmosphere	Vacuum	Inert gas
Scanning	Deflection coils	Mirror galvanometer
Preheating temperature	700 °C	200 °C

Consequences :

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



PhD K. Kempen, 2015

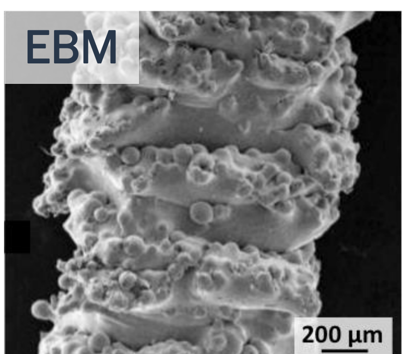


EBM/LPBF comparison

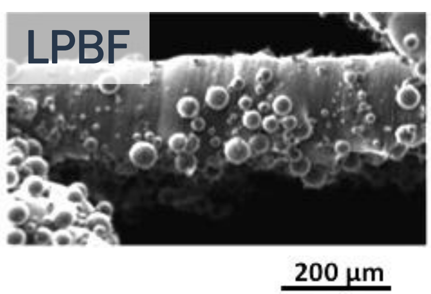
	EBM	LPBF
Heat source	Electron beam	Laser beam
Atmosphere	Vacuum	Inert gas
Scanning	Deflection coils	Mirror galvanometer
Preheating temperature	700 °C	80 °C

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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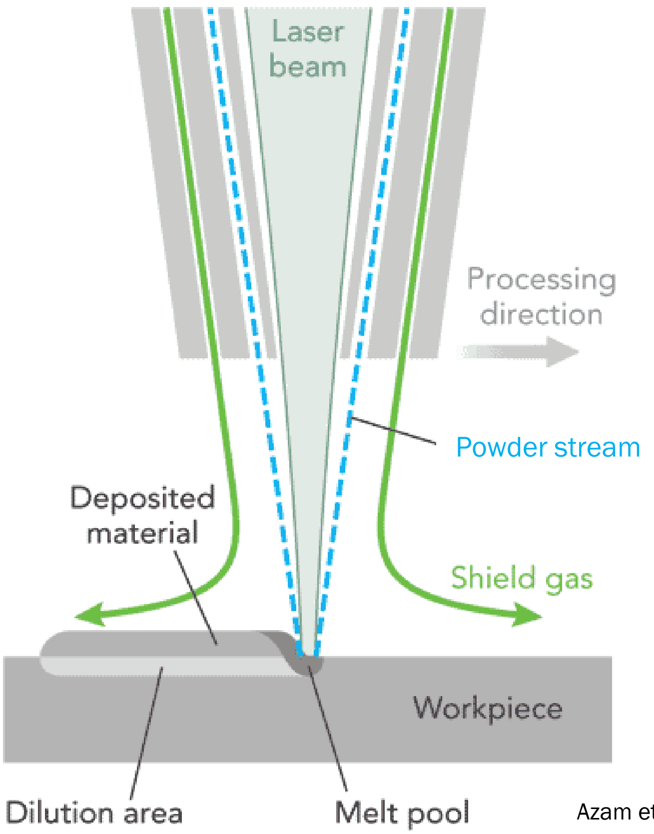
  - Directed energy deposition
    - Powder fed
    - Wire fed
  - Binder jetting

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)



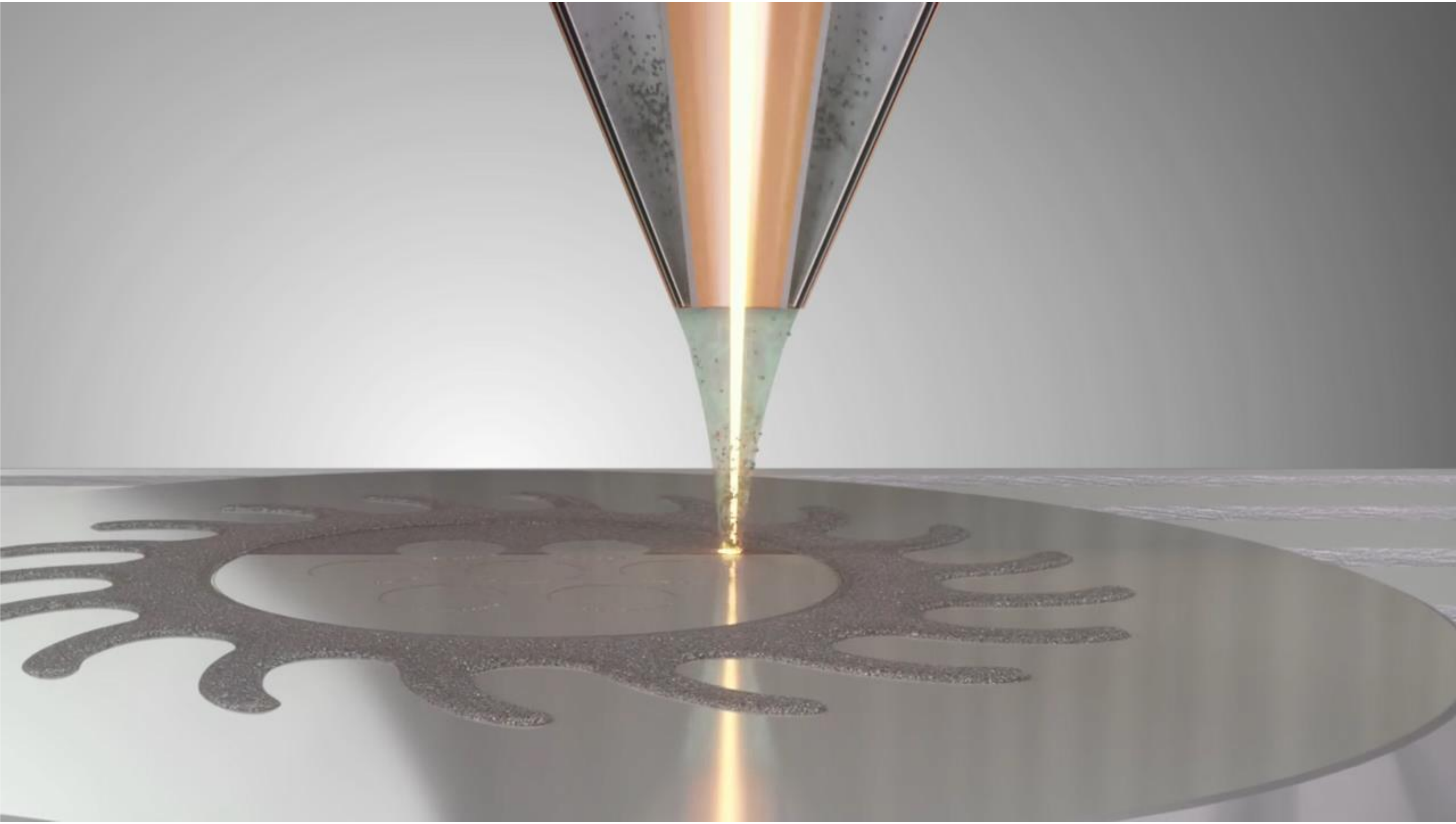
Azam et al., 2018

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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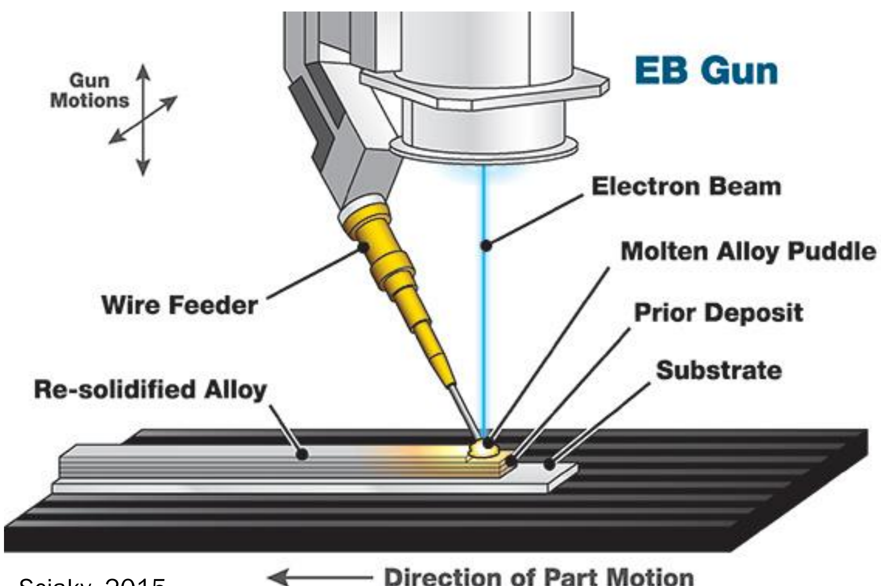
Wire fed DED – electron beam

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

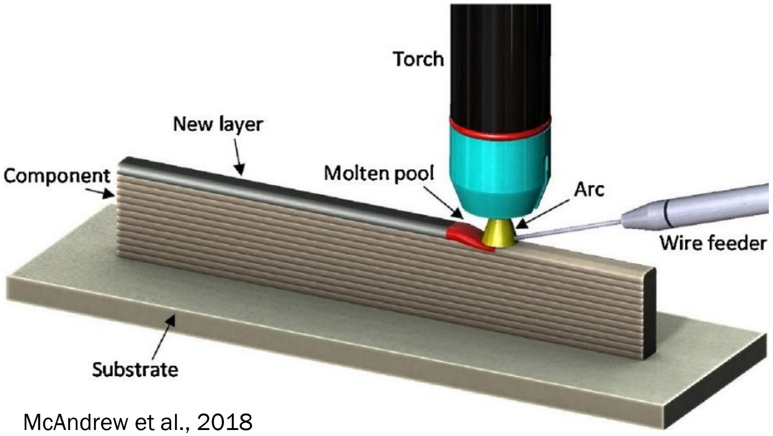
NASA, 2008

Wire fed DED – arc

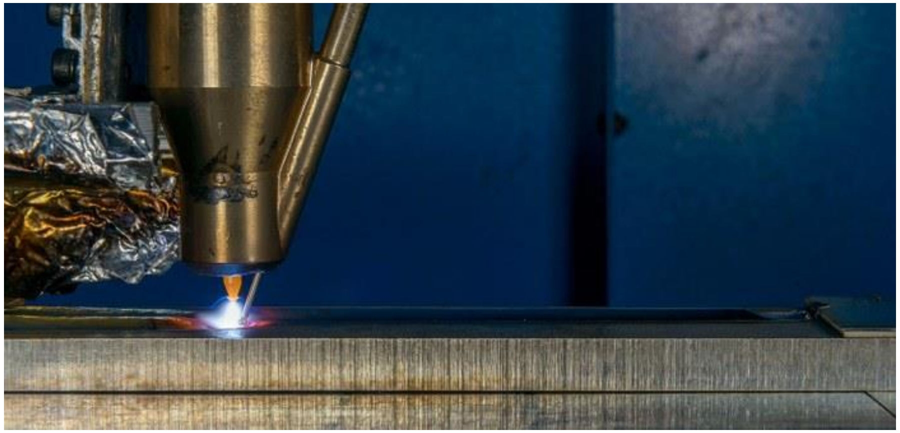
In DED-PA or DED-GMA, a plasma arc or gas metal arc is used as the heat source with filler wires as feedstock material similar to fusion welding.

An advantage of arc heat sources is the low equipment costs.

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) LPBF : R_a = 5-10 µm EBM : R_a = 20-30 µm	Low accuracy (0.5 to 1.5 mm) LENS/LMD : Ra = 15-60 µm 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 LPBF : 5 – 30 cm^3/h EBM : up to 100 cm^3/h	Medium to high deposition rate LENS/LMD: up to 400 cm^3/hr EBF3/EBAM : 2500 cm^3/hr
Multi-material printing : *under development* (multiple powders in powder bed)	Multi-material printing : functionally graded and hybrid parts

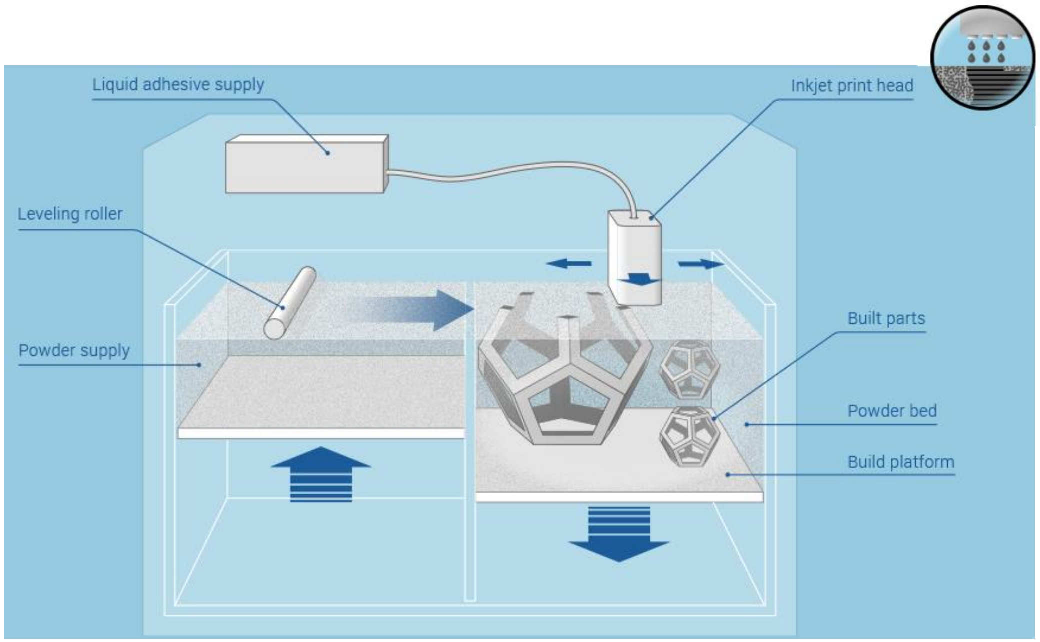
The choice of a given process is determined by the type of application.

Part 1 : Introduction to AM of metals

- AM of metals: examples of applications
- Palette of metals for AM
- AM processes for metals
  - Powder bed fusion
    - Electron beam melting
    - Laser powder bed fusion
  - Directed energy deposition
    - Powder fed
    - Wire fed
  - Binder jetting

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.



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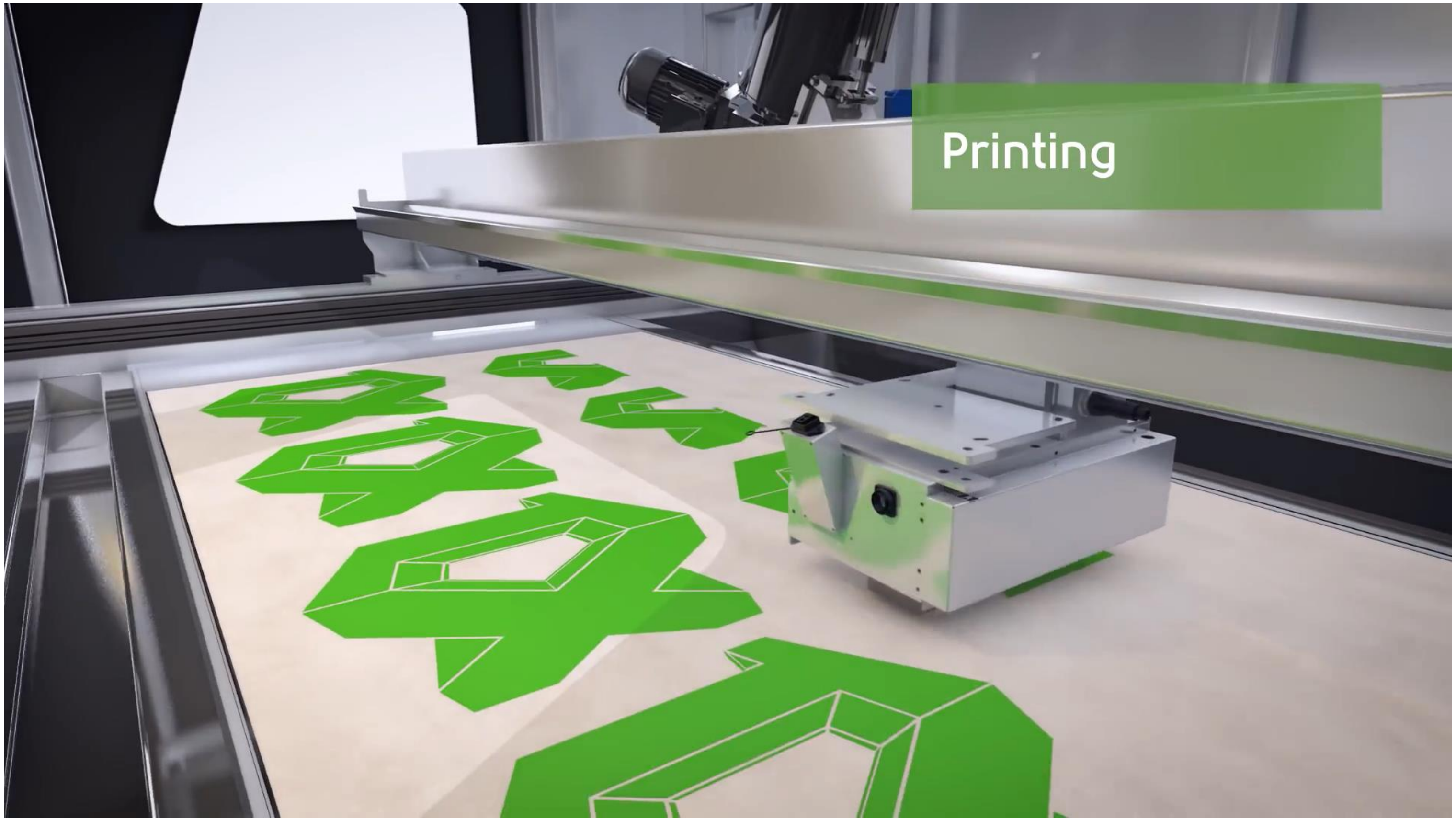


https://www.exone.com/en-US/case-studies/what-is-binder-jetting

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.

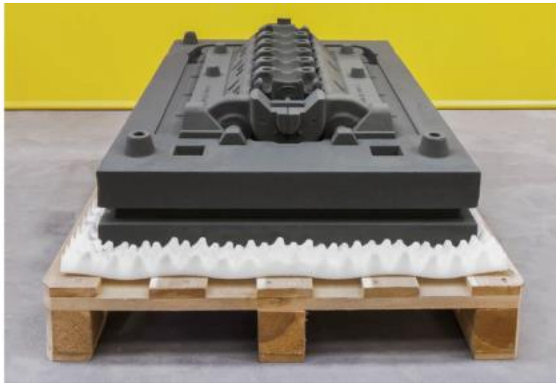
Binder jetting

Advantages

- fast and cheap technology
- no requirement for support structures during printing
  - ⇒ very few geometric restrictions
- 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



Casting mold block

Heavy equipment and machinery part

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