EPFL

Additive manufacturing for metallic materials

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Gas turbine (Inconel 718) [8]

Contents

- Direct energy deposition (DED)
- Selective laser melting (SLM)
- Electron beam melting (EBM)
- Extrusion processes
- Micro and nano-scale AM of metals

Direct energy deposition

Emilien Ancey

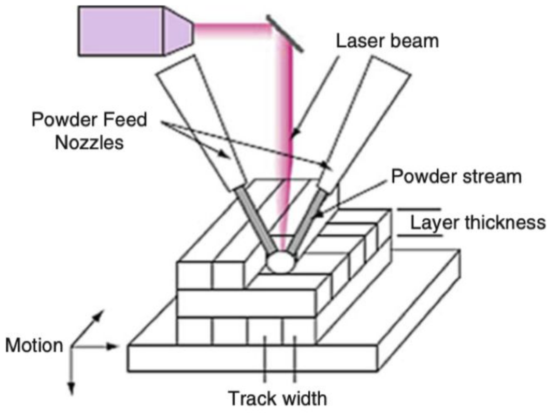
Direct laser deposited TC11/Ti2AlNb dual alloy blisk for aero engines

Y.Z. Zhang, Y.T. Liu, X.H. Zhao, Y.J. Tang,The interface microstructure and tensile properties of direct energy deposited TC11/Ti2AlNb dual alloy, Materials & Design, Volume 110, 2016, Pages 571-580, ISSN 0264-1275, https://doi.org/10.1016/j.matdes.2016.08.012. (https://www.sciencedirect.com/science/article/pii/S0264127516310747)

Direct Energy Deposition

- One general working principle, many trade names
  - Direct Metal Deposition (DMD)
  - Laser Based Metal Deposition (LBMD)
  - Laser Engineered Net Shaping (LENS)
  - …

- Focused on laser as a heat source

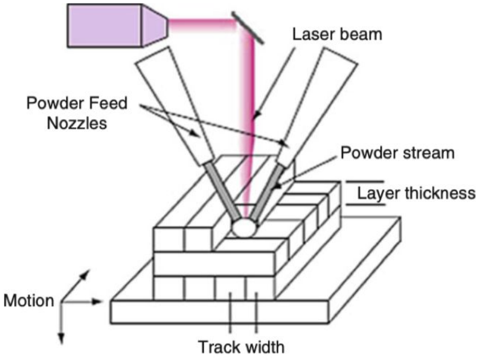


DED set-up [1]

[1] I. Gibson, D. Rosen, and B. Stucker, Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing. New York, NY: Springer, 2015. [Online]. Available: https://link.springer.com/10.1007/978-1-4939-2113-3

Direct Energy Deposition

- **Working principle**
  - A metallic powder or wire is feeded in a melting pool created by the focused laser beam
  - Many different nozzles: single-jet, co-axial and multi-jet + inert gas
  - Precision mainly comes from these systems: 40-1000 µm layer thickness + spot size high of 0.3-3 mm [2]
  - Very low losses: the good amount of material is melted everytime



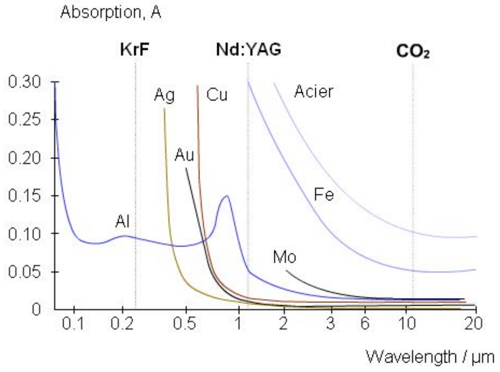
DED set-up [1]

[2] R. M. Mahamood, Laser Metal Deposition Process of Metals, Alloys, and Composite Materials, ser. Engineering Materials and Processes. Cham: Springer International Publishing, 2018. [Online]. Available: http://link.springer.com/10.1007/978-3-319-64985-6

Metallic feedstock: laser importance

- **Specific properties of materials required**
  - Decent absorption in wavelength of lasers (e.g. 1.064 µm Nd:YAG)
  - Low thermal conductivity
  - Typically: Ti-alloys, steels, Ni-superalloys are very easily doable
  - A good size distribution of powder is also key for properties

- **Technical parameters also play a role** [2]
  - Power of the laser: usually around 100W to a few kW
  - Scan speed: 0.15-1.5m/min
  - Spot size: 0.3-3mm



Absorption VS wavelength

Bajard, A. & Aubreton, O. & Eren, Gonen & Sallamand, Pierre & Truchetet, Frederic. (2011). 3D Digitization of Metallic Specular Surfaces using Scanning from Heating Approach. Proceedings of SPIE - The International Society for Optical Engineering. 7864. 10.1117/12.872467.

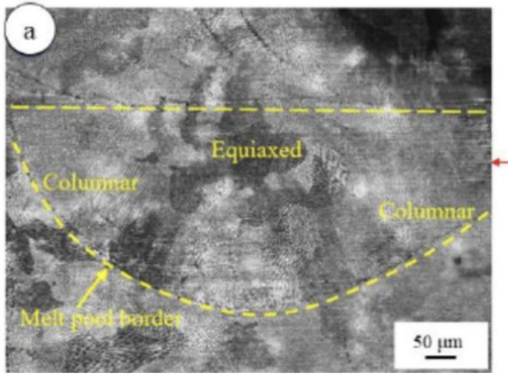
Process parameters: general impact

- **Laser power**
  - Direct impact on melt pool size → must be high enough to allow melting of powder, but not too large otherwise splattering could occur → chosen wisely
- **Scan speed**
  - Speed of displacement of feeding device + laser → inverse effect compared to laser power
- **Spot size**
  - Direct impact on track width
  - Also impact the focus of heat and thus melting
- **Powder flow rate**
  - Quantity of powder reaching melting pool every unit of time: 4-30 g/min [2]

→ These four parameters work in symbiosis and must be understood as a whole: must be optimized on a case-to-case basis

Resulting microstructures

- **Very complex thermal history**
  - Direct consequence of laser power and scan speed: high cooling rate
  - Up to 10^3 to 10^5 K/s → have a huge impact on microstructure and phase formation [2]
  - One layer can be remelted, heat affected many times
  - Impact on morphology of grains → also dependant on the layer
  - Impact on appearance of out of equilibrium phases



Light optical microscopy of the DED of steel

Saboori, Abdollah & Aversa, Alberta & Marchese, Giulio & Biamino, Sara & Lombardi, Mariangela & Fino, Paolo. (2020). Microstructure and Mechanical Properties of AISI 316L Produced by Directed Energy Deposition-Based Additive Manufacturing: A Review. Applied Sciences. 10. 3310. 10.3390/app10093310.

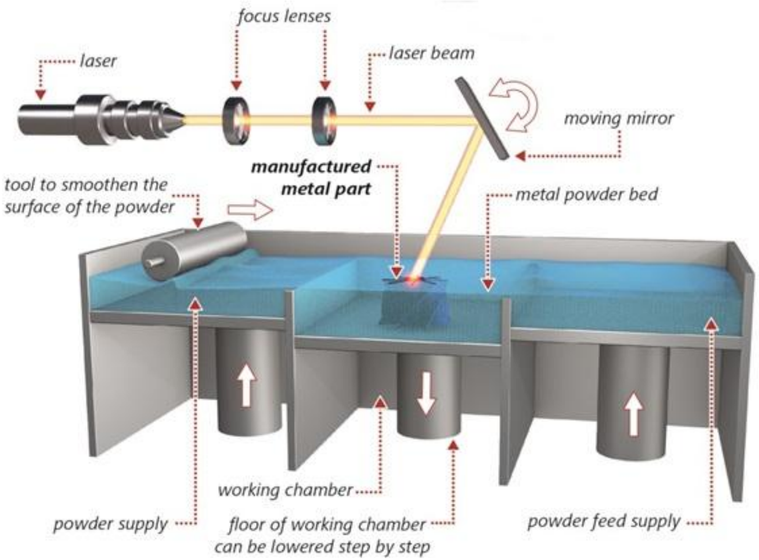
Typical example of DED

- **Multi-material part**
  - Very easy and tunable manufacturing of this part
  - Very high mechanical properties of the as-deposited material
- **Low precision part**
  - Near-net shape blanks: requires further finishing step

Direct laser deposited
TC11/Ti2AlNb dual alloy blisk for
aero engines

Pros and cons of DED

👍	👎
Low to zero losses	Very low precision
Manufacturing of multi-materials components	Quasi-always near net shape blanks → finishing step required
Direct printing on substrate: less joining problems like riveting	Large thermal stresses: heat-treatment can be useful
Possibility to repair parts	Very expensive equipment



Selective laser melting (SLM)

Noah Studer

Selective Laser Melting (SLM)

What is SLM ?

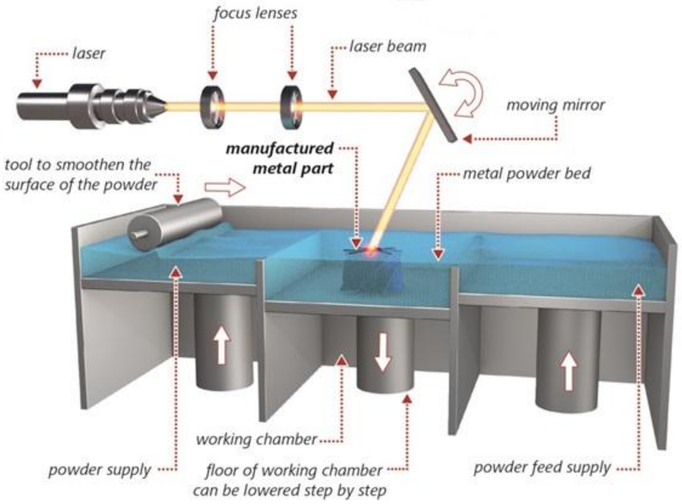
- Powder bed process using lasers to fuse metal layer by layer

History

- First commercial machine in 1998 (using a 12W laser)
- Modern machines (2014) now use laser up to 2800W (4x 700W) -> ⬇️ production time

Functioning

- Laser selectively melts powder on a build plate in an inert atmosphere → avoid oxidation + metal vapors
- Precision: Dimensional accuracy ~0.1-0.2% + layer thickness 20-100 µm (dep. on laser beam size)



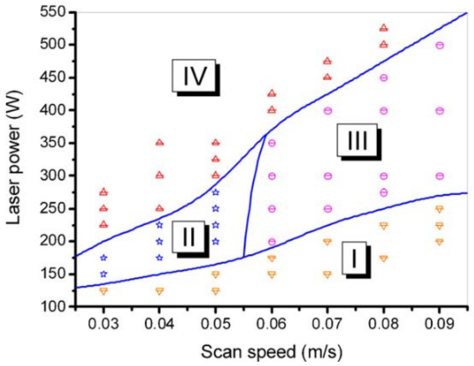
Selective laser melting mechanism scheme [1]

[1] Selective Laser Melting Technology: Benefits, Applications, and Best Models | Top 3D Shop." [Online]. Available: https://top3dshop.com/blog/selective-laser-melting-technology-benefits-applications-and-best-models

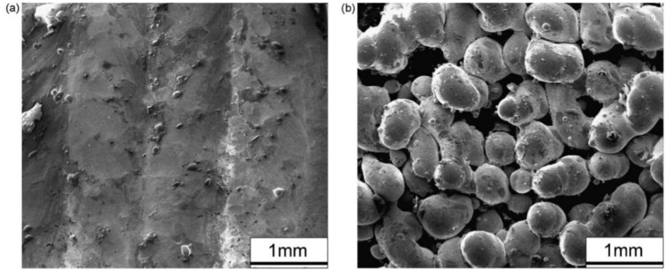
EPFL

Process parameters and impact on part properties

- **Laser Power & Scanning Speed**
  - Need of an optimal combination avoids defects
    - Zone I → Insufficient fusion
    - Zone II and III → Balling (Fig. b) = weak cohesion, need more penetration
    - Zones IV → Perfect melting (Fig. a)
- **Hatch angle**
  - Is laser scanning direction angle between two layers
  - E.g., 105° angle improves isotropy in 304 stainless steel



Influence of varying the laser power and scanning speed [2]



Microstructure : a) Complete melted surface; b) Surface with balling phenomenon [3]

[2], [3] D. Gu and Y. Shen, “Processing conditions and microstructural features of porous 316L stainless steel components by DMLS,” Applied Surface Science, vol. 255, no. 5, Part 1, pp.1880–1887, Dec. 2008. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0169433208015456

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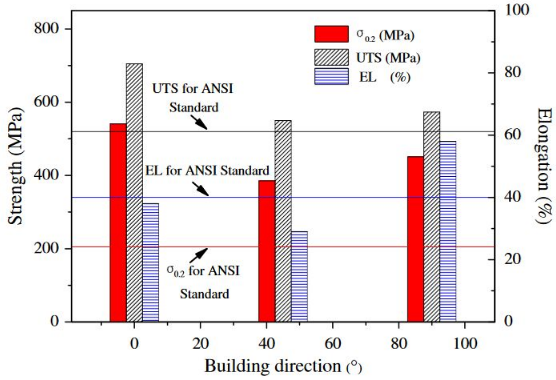
Process parameters and impact on part properties

Build Direction Influence

- Horizontal (0°) → Best for ductility
- Vertical (90°) → Good combin. strength + ductility
- 45° → Least favorable for mechanical properties

Additional Parameters

- Layer thickness → Affects precision and surface finish
- Overlap rate → Impacts density and strength



Mechanical properties in function of the build direction [4]

[4] K. Guan, Z. Wang, M. Gao, X. Li, and X. Zeng, "Effects of processing parameters on tensile properties of selective laser melted 304 stainless steel," Materials & Design, vol. 50, pp.581–586, Sep. 2013. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0261306913002562

Metals available for SLM technology

- **Common Materials**
  - Stainless steels, aluminum (e.g., AlSi10), titanium alloys (e.g., TiAl6V4), nickel alloys (Inconel 718), and Co-Cr alloys
- **Material Requirements**
  - Powder form with specific grain size
  - High laser absorption (e.g., near-infrared lasers = wavelength around 1000nm)
  - Limitations for reflective metals like copper → need laser with lower wavelength (around 500 nm) = more expensive
- **Emerging Materials**
  - Metal-ceramic Matrix Composites (e.g., Titanium and boron carbides in Inconel 718)
    - ⬆️ Hardness, wear resistance, strength, corrosion high-temperature resistance
  - Intermetallics (e.g., Al-La-Mg-Mn alloys)
    - ⬆️ mechanical properties at high temperatures while avoiding cracking

Post-processing of SLM parts

Initial Steps

- Remove excess powder
- Support removal (manual, bandsaw, EDM)

Heat Treatments

- To enhance mechanical properties
- Can be : stress relieving, hardening, or annealing
  → Can reduce residual stresses and/or improve ductility and toughness

Surface Treatments

- Electropolishing, bead blasting → Improves smoothness
- Spray painting → Corrosion protection
- Anodizing or electroplating → Strength and wear resistance

Pros and Cons of SLM

	
Production of complex parts	Residual stresses in the part (due to high cooling rate)
Reduction of weight (with infill) <-> cost	Post-processing almost mandatory
Recyclability of unmelt powder	Building size limited
Broad choice of materials	High equipment cost (from 50’000$ to 1’000’000$)

Industrial applications

- **Medical and dental industry**
  - Need of biocompatibility, high precision and corrosion resistance
    - Main materials : Titanium alloys, Co-Cr alloys and stainless steels
- **Automotive industry**
  - Light weight parts for high-performance vehicl and corrosion resistant
    - Main materials : Stainless steel and titanium alloys
- **Aerospace industry**
  - Need of high temperature and corrosion resistance
    - Main materials : Nickel alloys

Hip implant (Ti alloy) [5]

Exhaust system (stainless steel) [6]

Dental implants (Co-Cr alloy) [7]

Gas turbine (Inconel 718) [8]

[5],[7] https://www.slm-solutions.com/fileadmin/Content/Industries/Medical leaflet en web.pdf." [Online]. Available: https://www.slm-solutions.com/fileadmin/Content/Industries/ Medical Leaflet EN WEB.pdf, [6] SLM 3D Printing Stainless Steel Automobile Exhaust Pipe," Jun. 2023. [Online]. Available:https://be-cu.com/slm-3d-printing-stainless-steel-automobile-exhaust-pipe, [8] "China Customized Inconel 718 SLM 3D Printing Turbine Blade Suppliers, Manufacturers - Factory Direct Price - JR TECH." [Online]. Available: https://www.china-3dprinting.com/ metal-3d-printing/inconel-718-slm-3d-printing-turbine-blade.html

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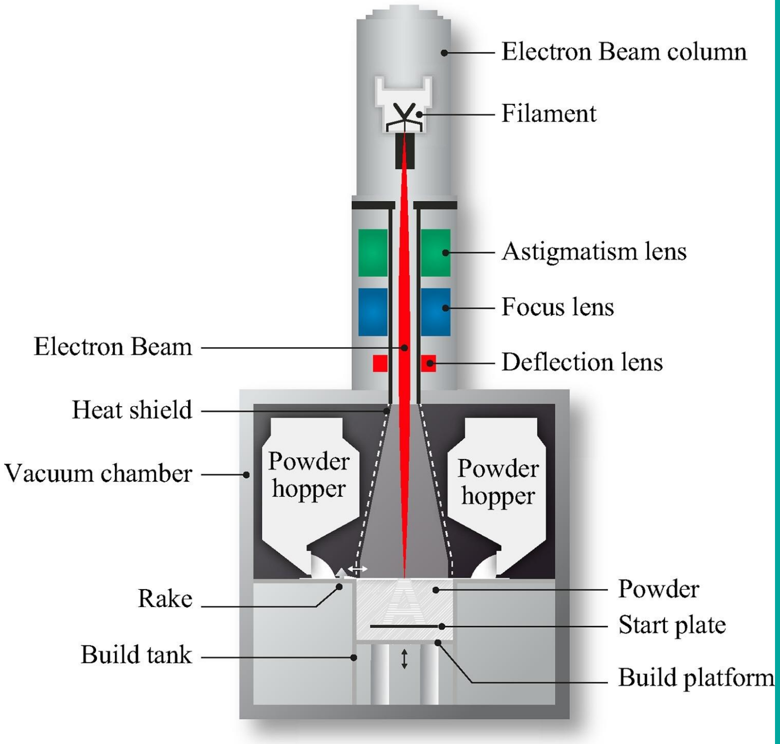


Electron-Beam Melting (EBM)

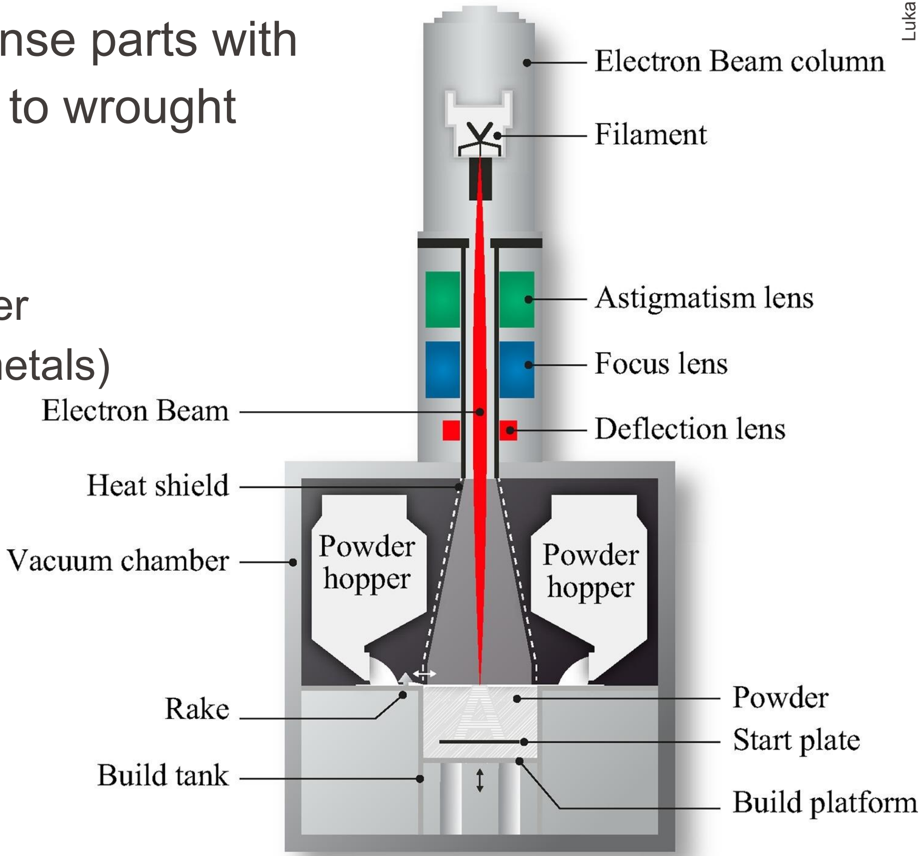
Luka Roche

M. Galati and L. Iuliano, “A literature review of powder-based electron beam melting focusing on numerical simulations,” Additive Manufacturing, vol. 19, pp. 1–20, Jan. 2018.[Online]. Available: https://www.sciencedirect.com/science/article/pii/S2214860417300635

Electron-Beam Melting (EBM)

Fast production of complex and dense parts with mechanical properties comparable to wrought metals

- **Background**
  - Electron beam instead of laser
  - Only conducting materials (metals)
  - Local melting of powder bed
  - Layer by layer
  - Vacuum environment
- **Marketing**
  - First and only by Arcam, General Electrics (GE)
  - Sweden, 2001

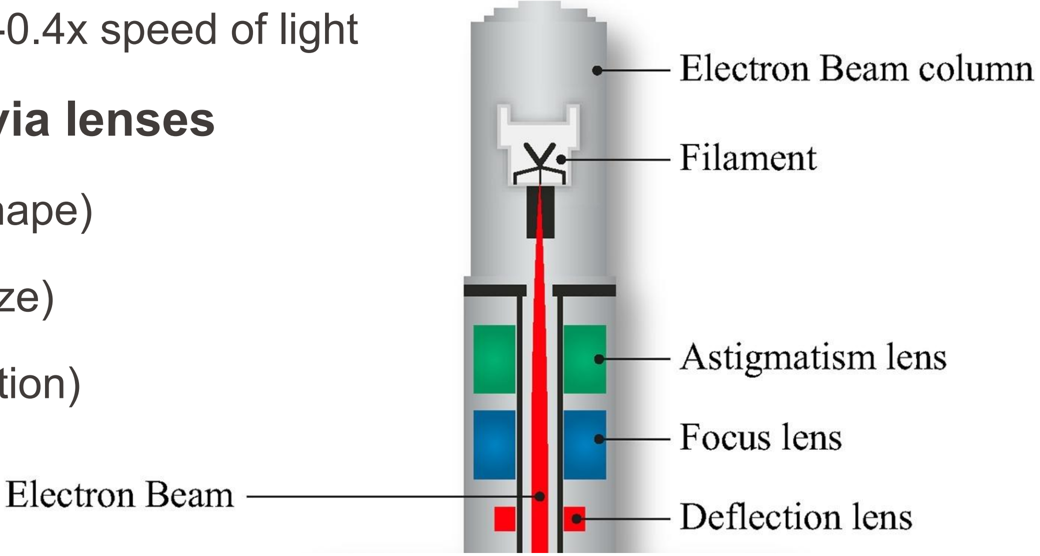


Components of an Arcam machine

M. Galati and L. Iuliano, “A literature review of powder-based electron beam melting focusing on numerical simulations,” Additive Manufacturing, vol. 19, pp. 1–20, Jan. 2018.[Online]. Available: https://www.sciencedirect.com/science/article/pii/S2214860417300635

Electron-Beam generation

- **Generation of electron beam**
  - 60 kV between filament and anode
  - Emitted electron 0.1-0.4x speed of light
- **Control of the beam via lenses**
  - Astigmatism lens (shape)
  - Focus lens (beam size)
  - Deflection lens (position)



Components of an Arcam machine, EB column

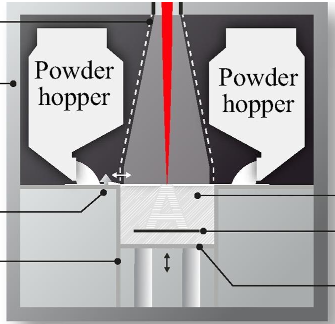
M. Galati and L. Iuliano, “A literature review of powder-based electron beam melting focusing on numerical simulations,” Additive Manufacturing, vol. 19, pp. 1–20, Jan. 2018.[Online]. Available: https://www.sciencedirect.com/science/article/pii/S2214860417300635

Vacuum

- **Different purposes**
  - Necessary to avoid interaction with molecules
  - Minimise gas flow, reduce internal stresses -> avoid thermal cracks
- **Vacuum achievement**
  - Turbomolecular pumps
  - Generally ~10^{-3} Pa
  - Some helium added for better heat dissipation
  - In both, chamber and column
- **Drawback**
  - Equipment cost, time to reach vacuum

Powder and Materials

- **Powder particles**
  - Generally 45-105 µm size
  - Stored in powder hopper
- **Materials**
  - EB can reach higher temperatures (interesting for titanium)
  - Independent of the absorptivity
    - Example: Copper has a low absorption efficiency in the infrared domain



Components of an Arcam machine

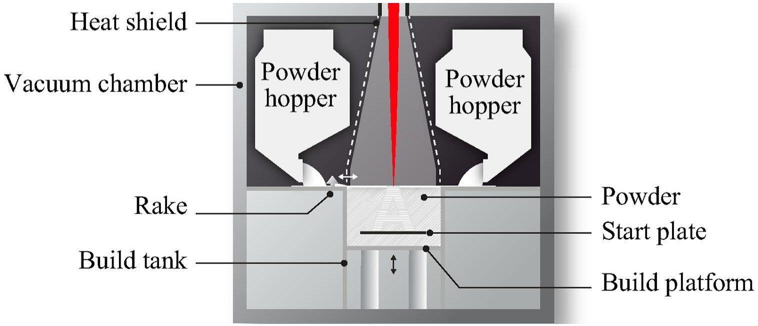
- According to GE, EBM works well with:

Stainless steel, nickel- and cobalt-based superalloys, Invar, aluminum, copper, titanium alloys…

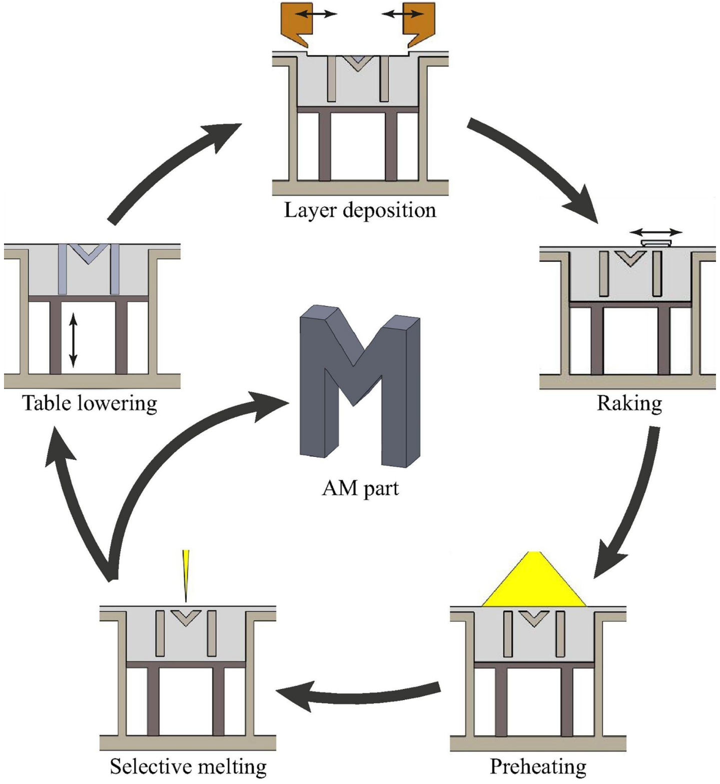
M. Galati and L. Iuliano, "A literature review of powder-based electron beam melting focusing on numerical simulations," Additive Manufacturing, vol. 19, pp. 1–20, Jan. 2018.[Online]. Available: https://www.sciencedirect.com/science/article/pii/S2214860417300635

Layer by layer production

- **Deposition of powder layer**
- **Raking** (homogeneous spreading)
- **Preheating**
- **Selective melting**
  - Form one “2D slice” of the part
  - Fusion with previous layer
- **Lowering of the build platform**
  - Production of next layer



Components of an Arcam machine, vacuum chamber

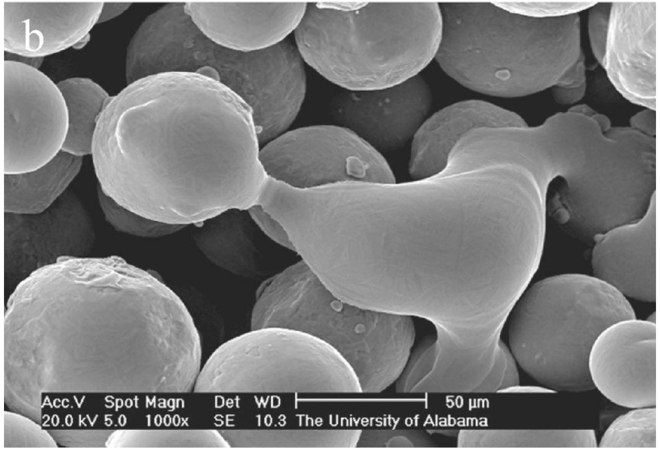


Steps of the EBM process [8]

M. Galati and L. Iuliano, “A literature review of powder-based electron beam melting focusing on numerical simulations,” Additive Manufacturing, vol. 19, pp. 1–20, Jan. 2018.[Online]. Available: https://www.sciencedirect.com/science/article/pii/S2214860417300635

Preheating

- **Preheating of the start plate and the powder**
  - Via an unfocused electron-beam
  - Temperature depends on metal
  - Sintering of particles (necking)
    - Increased thermal conductivity between particles
    - Reduced risk of powder spreading



SEM images of Ti6Al4V preheated particles, circular necks form

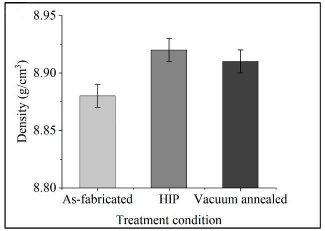
B. Cheng, S. Price, J. Lydon, K. Cooper, and K. Chou, “On Process Temperature in Powder-Bed Electron Beam Additive Manufacturing: Model Development and Validation,” Journal of Manufacturing Science and Engineering, vol. 136, no. 061018, Oct. 2014. [Online].Available: https://doi.org/10.1115/1.4028484

End of production

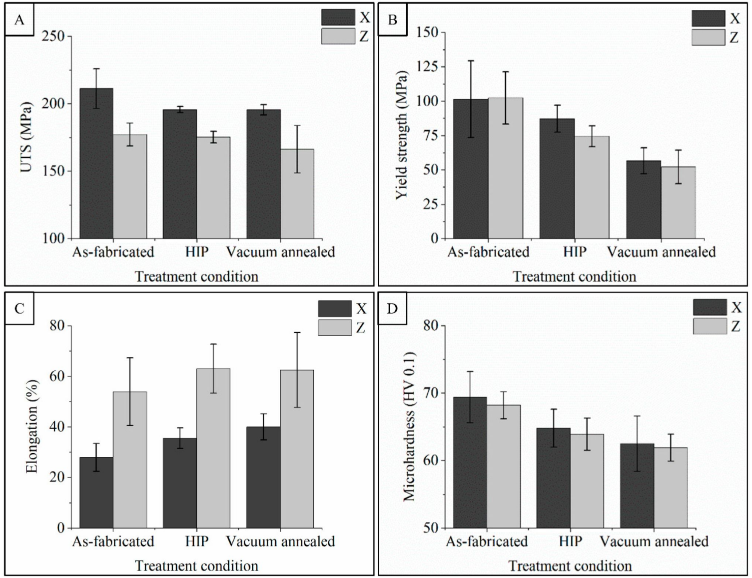
- **Cooling**
  - Increase pressure and helium
  - Easier heat dissipation
- **Recycling of unused powder**
  - Both volatile and agglomerated
  - Sand blasting
- **Post-processing**
  - Possible but not mandatory

Post-processing

- **Increase an already high density**
  - Isostatic pressing (HIP)
  - Vacuum annealing (VA)
- **Mechanical properties**
  - Anisotropy (regardless of post processing)
  - Both HIP and VA:
    - decrease ultimate tensile strength
    - decrease yield strength
    - decrease Vickers microhardness
    - increase elongation to failure



Effect of treatment condition on the density



Mechanical properties summary and selected statistical observations

P. Tarafder, C. Rock, and T. Horn, “Quasi-Static Tensile Properties of Unalloyed Copper Produced by Electron Beam Powder Bed Fusion Additive Manufacturing,” Materials, vol. 14, no. 11, p. 2932, Jan. 2021, number: 11 Publisher: Multidisciplinary Digital Publishing Institute. [Online]. Available: https://www.mdpi.com/1996-1944/14/11/2932

Comparison with SLM

Differences between EBM and SLM

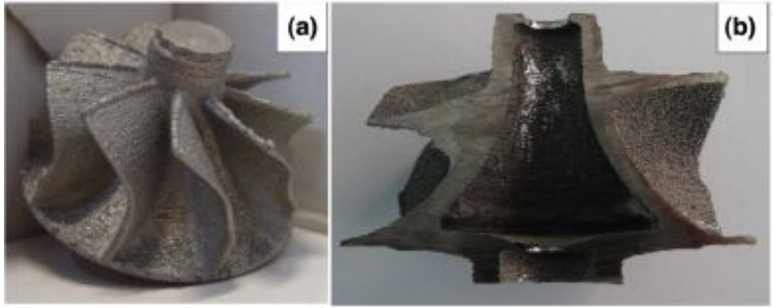
Characteristics	EBM	SLM
Thermal source	Electron beam	Laser
Production rate	3 kg/h	0.2 kg/h
Atmosphere	Vacuum	Inert gas
Energy absorption	Conductivity-limited	Absorptivity-limited
Energy costs	Moderate	High
Powder particle size	Medium	Fine
Feature resolution	Moderate	Excellent
Surface finish	Moderate to poor	Excellent to moderate

E. Sharabian, M. Leary, D. Fraser, and S. Gulizia, “Electron beam powder bed fusion of copper components: a review of mechanical properties and research opportunities,” The International Journal of Advanced Manufacturing Technology, vol. 122, no. 2, pp. 513–532, Sep. 2022. [Online]. Available: https://doi.org/10.1007/s00170-022-09922-6

Applications for EBM-parts

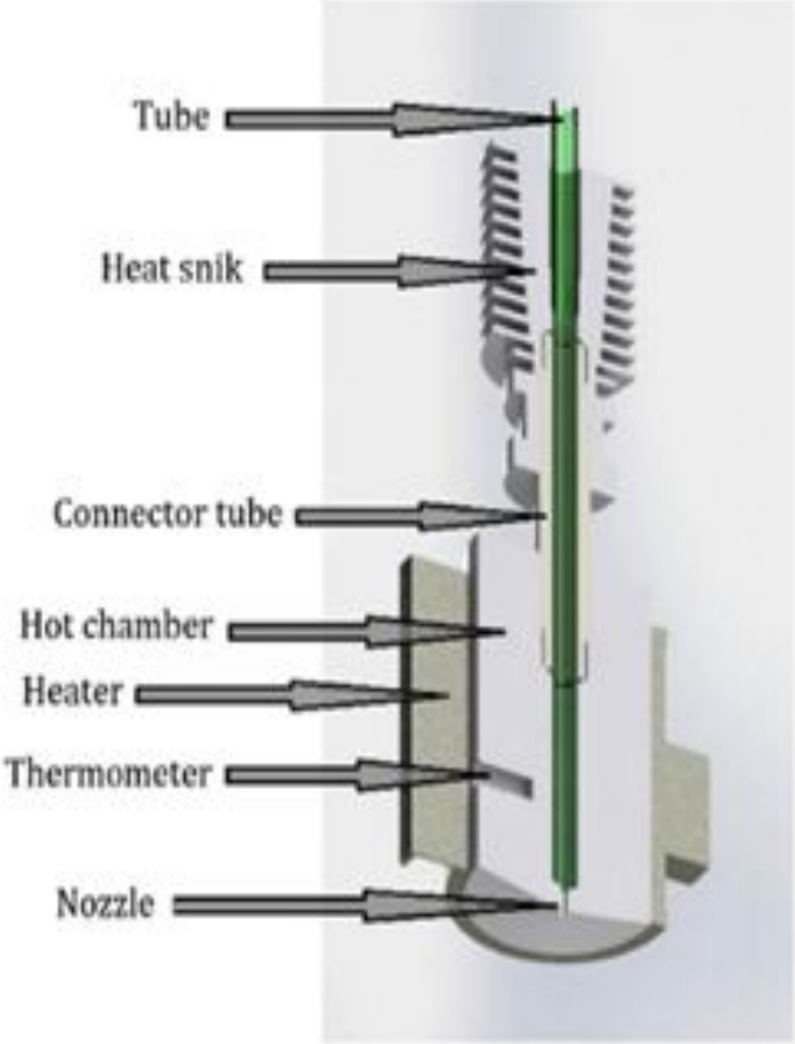
- **Biomedical industry**
  - Complex shapes
  - Cellular, meshed, and porous structures
  - Orthopedic metal implants
- **Aerospace industry**
  - Complex parts, titanium alloys
  - Enhanced mechanical properties
  - Reduced risk of heat cracking
  - Aircraft engine blades, automotive turbocharger wheels

Ti mandibular framework fabricated using EBM technology [1]



TiAl turbocharger wheel produced by EBM [2]

[1] M. Revilla-Le´on, K. IM, G.-A. J, and M. ¨Ozcan, "3D Metal Printing - Additive Manufacturing Technologies for Frameworks of Implant-Borne Fixed Dental Prosthesis," The European journal of prosthodontics and restorative dentistry, vol. 25, pp. 143–147, Sep. 2017.
[2] G. Baudana, S. Biamino, D. Ugues, M. Lombardi, P. Fino, M. Pavese, and C. Badini, "Titanium aluminides for aerospace and automotive applications processed by Electron Beam Melting: Contribution of Politecnico di Torino," Metal Powder Report, vol. 71, no. 3, pp. 193–199, May 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0026065716001600



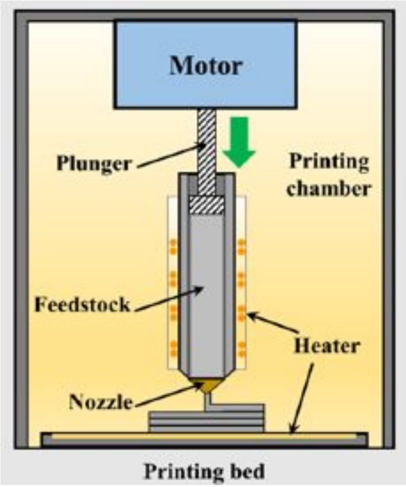
Material extrusion

Adrien Borgeat

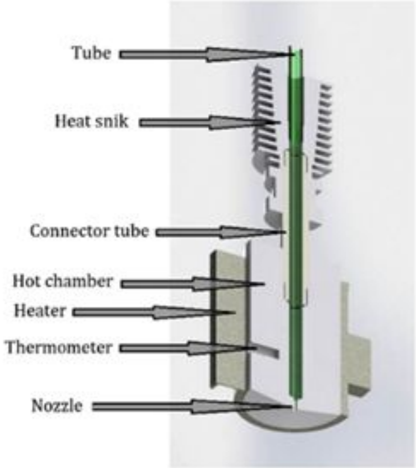
A. Jabbari and K. Abrinia, “A metal additive manufacturing method: semi-solid metal extrusion and deposition,” The International Journal of Advanced Manufacturing Technology, vol. 94, no. 9, pp. 3819–3828, Feb. 2018. [Online]. Available: https://doi.org/10.1007/s00170-017-1058-7

Material Extrusion

- Many possible processes (well-established or in development)
  - Metal extrusion (MEX)
  - Semi-solid material extrusion and deposition (SSMED)



MEX setup [1]



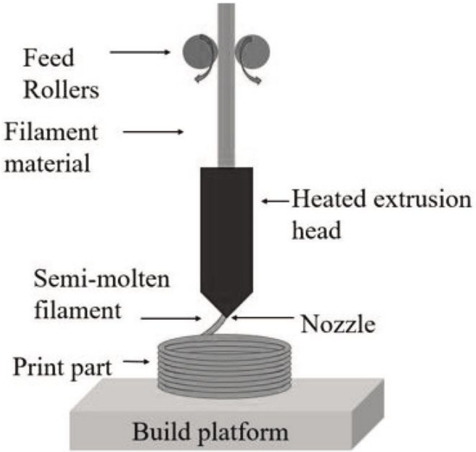
SSMED setup [2]

[1] Suwanpreecha, C., and A. Manonukul, Metals 12.3 (2022): 429.

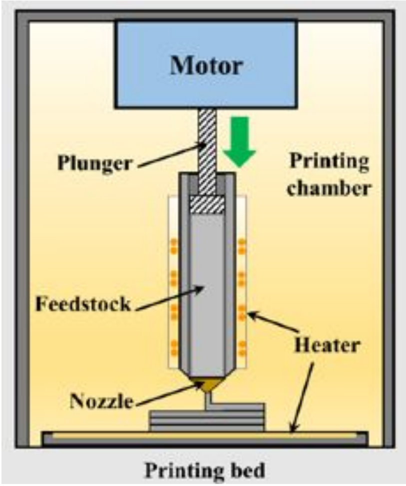
[2] A. Jabbari and K. Abrinia, “A metal additive manufacturing method: semi-solid metal extrusion and deposition,” The International Journal of Advanced Manufacturing Technology, vol. 94, no. 9, pp. 3819–3828, Feb. 2018. [Online]. Available: https: //doi.org/10.1007/s00170-017-1058-7

Metal Extrusion

- Based on a process efficient for polymers
- Comparison with Metal Injection Molding (MIM) because:
  - debinding and sintering needed
  - Same feedstocks can be used



Fused deposition modelling (FDM)
(since 1980s) [1]



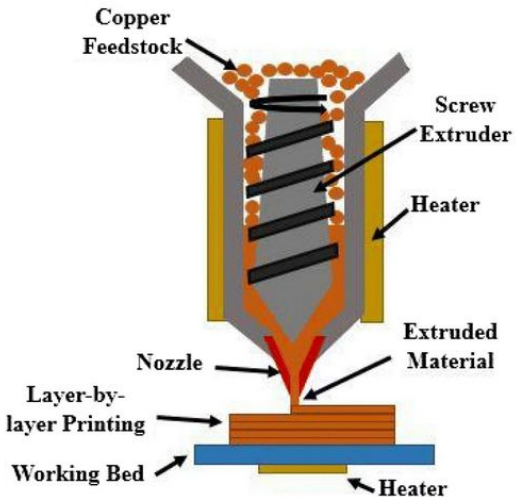
Metal Extrusion
(since 2000s) [2]

[1] Marciniak, M., Advances in Military Technology 18.2 (2023): 241–257.

[2] Suwanpreecha, C., and A. Manonukul, Metals 12.3 (2022): 429.

3 methods to produce green bodies

Screw-based

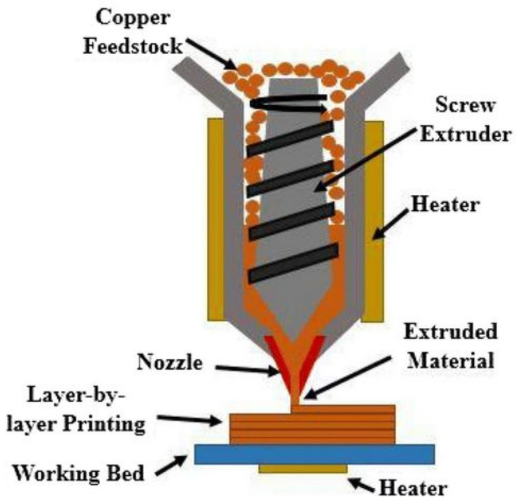


Same granules like MIM
Can be refilled (no stop)
Hard to control flow rate

Singh, G., J.-M. Missiaen, D. Bouvard, and J.-M. Chaix, The International Journal of Advanced Manufacturing Technology 115.1 (2021): 449–462.

3 methods to produce green bodies

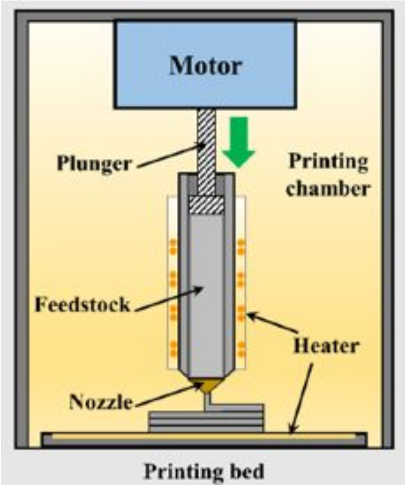
Screw-based



Same granules like MIM
Can be refilled (no stop)
Hard to control flow rate

Singh, G., J.-M. Missiaen, D. Bouvard, and J.-M. Chaix, The International Journal of Advanced Manufacturing Technology 115.1 (2021): 449–462.

Plunger-based

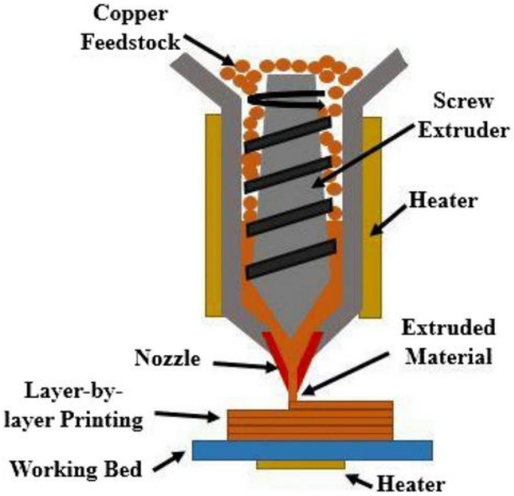


No screw => simplified head
Keep MIM feedstock
Not continuous

Suwanpreecha, C., and A. Manonukul, Metals 12.3 (2022): 429.

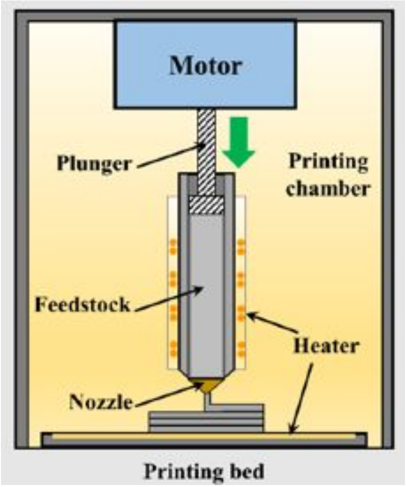
3 methods to produce green bodies

Screw-based



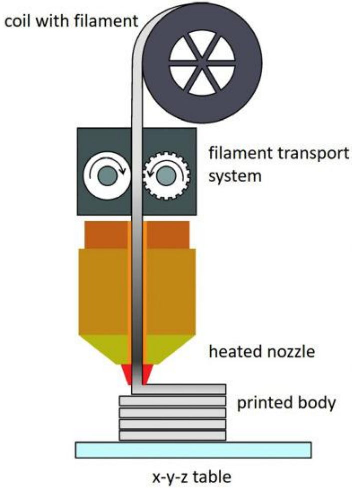
Same granules like MIM
Can be refilled (no stop)
Hard to control flow rate

Plunger-based



No screw => simplified head
Keep MIM feedstock
Not continuous

Filament-based



Cheaper (1 vs 5-10 kCHF)
Similar to FDM
Production of wires (one more step)

Singh, G., J.-M. Missiaen, D. Bouvard, and J.-M. Chaix, The International Journal of Advanced Manufacturing Technology 115.1 (2021): 449–462.

Suwanpreecha, C., and A. Manonukul, Metals 12.3 (2022): 429.

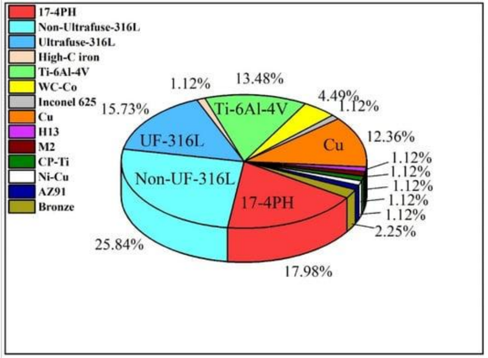
Lengauer, W., I. Duretek, M. Fürst, V. Schwarz, J. Gonzalez-Gutierrez, S. Schuschnigg, C. Kukla, M. Kitzmantel, E. Neubauer, C. Lieberwirth, and V. Morrison, International Journal of Refractory Metals and Hard Materials 82 (2019): 141–149.

Feedstock composition

- Metal alloy: **stainless steel**, Cu, Ti, Ni -> any sinterable alloy
  - Small and spherical particles (increase green density)
  - Fraction of feedstock: 60-70 vol.% (50-60 vol.% for filament-based)

- Plasticiser: wax, paraffin, low molecular weight polymer
  - Reduces viscosity
  - 50-90 vol.% of polymers added

- Backbone: PP, PE, higher molecular weight polymer
  - Gives strength when plasticiser is removed
  - 10-40 vol.% of polymers added



Metals used as feedstock for MEX [1]

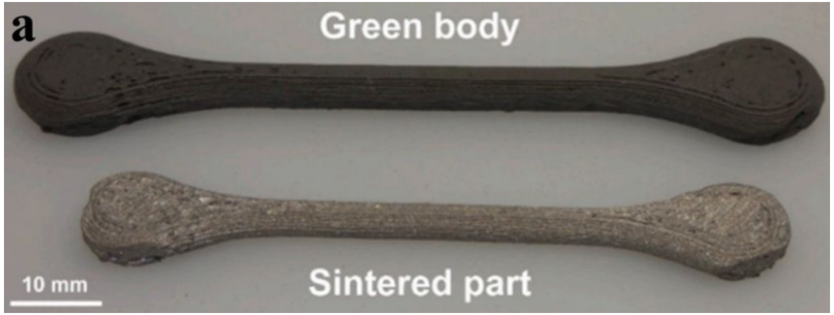
Suwanpreecha, C., and A. Manonukul, Metals 12.3 (2022): 429.

Debinding & Sintering

- Elimination of plasticizer
  - Most common: through solvent (hexane, acetone)
  - More rarely: evaporation -> big bubbles damaging the structure

- Elimination of backbone
  - Thermally removed
  - Under protective atmosphere

- Sintering
  - Temperature and time depend on metal
  - 12-20% size reduction



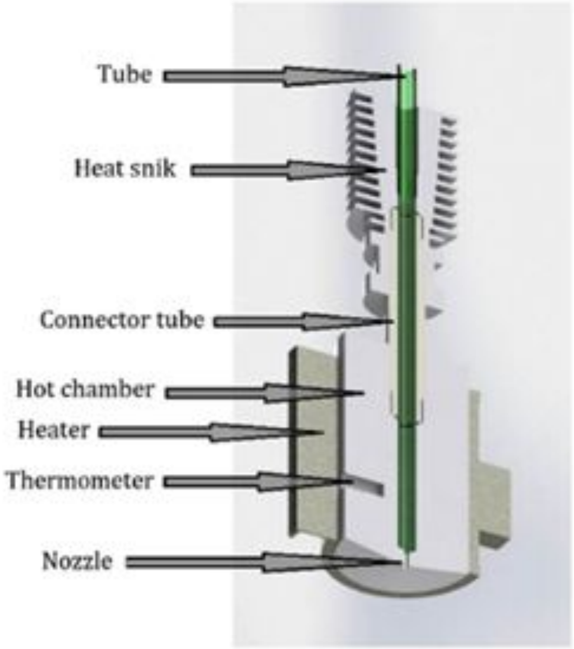
As-printed through MEX and as sintered Ti-6Al-4V piece

Suwanpreecha, C., and A. Manonukul, Metals 12.3 (2022): 429.

Pros and Cons of MEX

👍	👎
Same feedstock like MIM => wide range of possible metals	Nozzles suffer from high wear
No loose powder => better for health	Low mechanical properties
Lower power sources needed as the metal is not completely melted	Many steps (printing, debinding, sintering)
Multiple nozzles => multi-material printing	Lower resolution that SLM (250-400 µm)
Applications for prothesis	

Semi-solid metal extrusion and deposition (SSMED)



Jabbari, A., and K. Abrinia, The International Journal of Advanced Manufacturing Technology 94.9 (2018): 3819–3828.

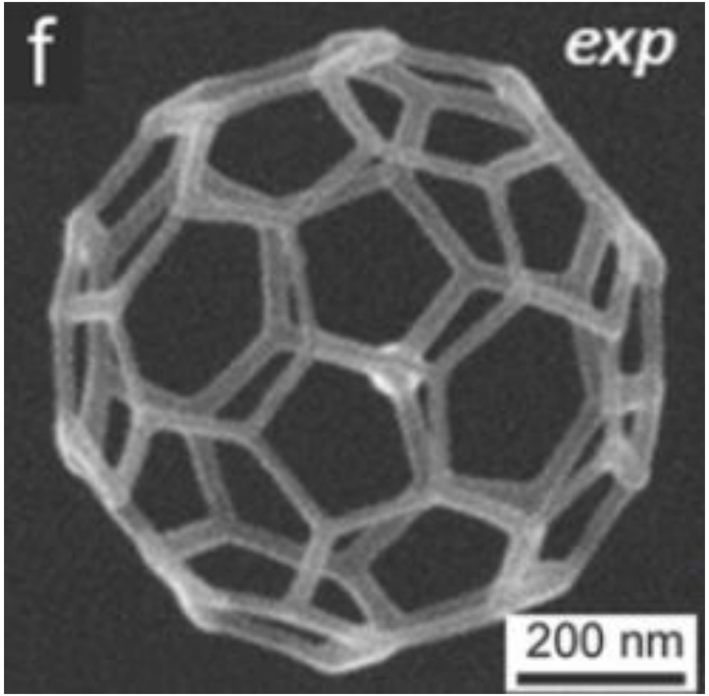
- Solid fraction: 30-50%
- More possible materials (lower temperature)
- Feedstock: globular grains to ensure better properties
- Printer similar to Fused Deposition Modeling (polymers)

Pros and Cons of SSMED

👍	👎
No powder at all	Rheology of semi-solid metal badly understood
Better deposition rate and repeatability than powder based processes	Difficult to ensure globular microstructure of feedstock
Density: 100%	Different printer head for different solid fraction
Lower temperature => less shrinkage, new possible materials	Lower resolution that SLM (250-400 µm)
Only one process (no need of sintering)	

Micro and nano-scale AM of metals

Arnaud Sansonnens

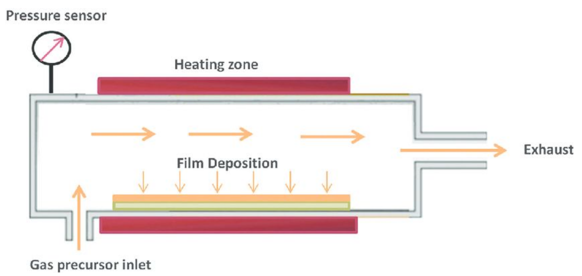


Complex FEBID Structur [1]

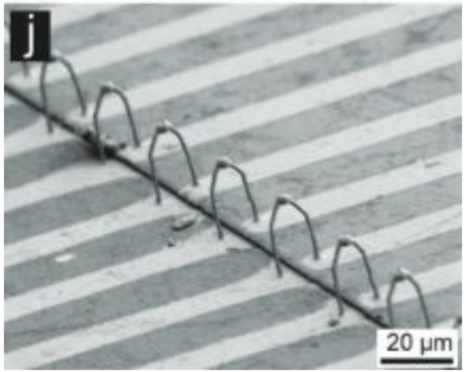
[1] L. Hirt, A. Reiser, R. Spolenak, and T. Zambelli, “Additive Manufacturing of Metal Structures at the Micrometer Scale,” Advanced Materials, vol. 29, no. 17, p. 1604211, May 2017.

Micro and Nanoscale AM for metals

- Metal often use in microstructure
  - Microsystem, Microfluidic, Quantum Application
  - Electrical Conductivity, Thermal Conductivity, Magnetism Properties, Mechanical Durability, Chemical Resistance, Superconductivity
- Industrial 2D application with Electroplating, CVD, PVD
- AM allows 3D structures
  - Complex Shape (freeform, internal channel)
  - Layer by Layer or Out of Plane Geometry



CVD Process [2]



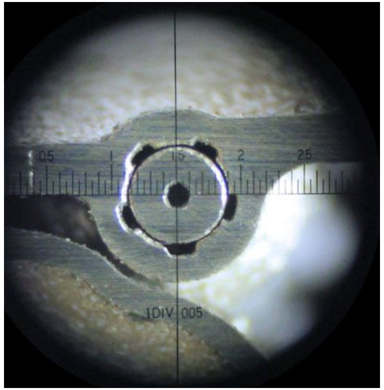
3D silver interconnect [1]

[2]Zhang, Qi & Sando, Daniel & Valanoor, Nagarajan. (2016). Chemical Route derived Bismuth Ferrite Thin films and Nanomaterials. J. Mater. Chem. C. 4. 10.1039/C6TC00243A.

Micro Selective Laser Melting (μSLM)

- Improvement from SLM
  - smaller particles size (< 1μm)
  - layer thickness (μm range)
  - Laser Spot Diam. (< tens μm)
  - Laser Source (in range of 100W)
- One of the most common and advanced commercialized machines for μSLM is DMP74 [5]

Stents manufactured with μSLM[3]



Pivot Join [4]

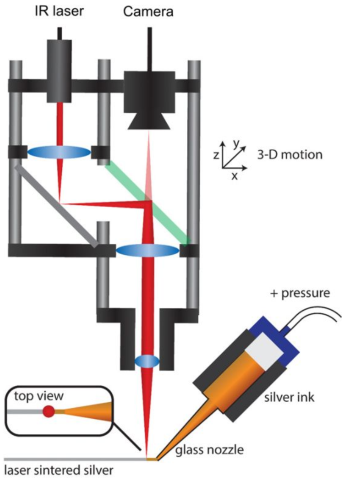
[3] https://additive.industrie.de/news/micro-slm-hybrider-3d-druck-pu-schaum-metal-coating-fit-additive-manufacturing/#1

[4] https://www.3dmicroprint.com/files/2016/12/Case-study-grabber.pdf

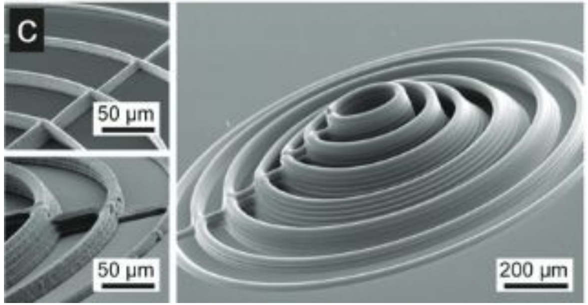
[5] https://www.3dmicroprint.com/files/2024/03/Maschine DMP.pdf

Direct Ink Writing (DIW)

- Depose Ink with metal nanoparticle inside
  - similar to macro. filament extrusion
- Importance of viscosity of it's ink (solid core, fluid shell)
- Laser-DIW enable in situ annealing
- Capabilities [1] :
  - Deposition Size : DIW = 2µm, Lazer-DIW = 600nm
  - Deposition Rate : DIW = 20-500 µm/s Lazer DIW = 0.5-1 mm/s



Laser-DIW Process [6]

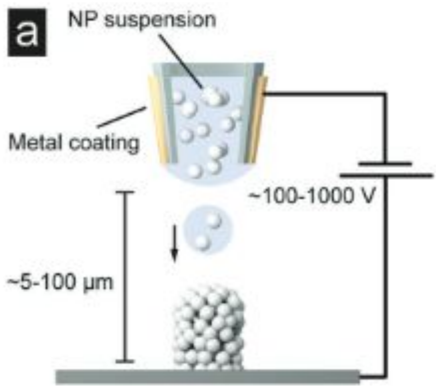


SEM image of 3D Silver-Structure [1]

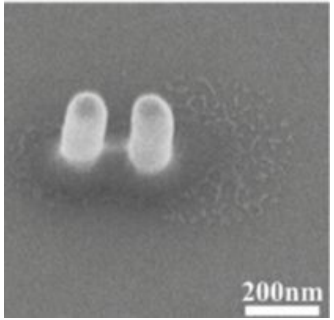
[6] M. A. Skylar-Scott, S. Gunasekaran, and J. A. Lewis, "Laser-assisted direct ink writing of planar and 3D metal architectures," Proceedings of the National Academy of Sciences, vol. 113, no. 22, pp. 6137–6142, May 2016

Electrohydrodynamic (EHD) printing

- Use electrostatic fields to eject tiny droplets
- Ink Deposition Modes
  - Cone Jet : continuous jet of ink from the nozzle, very useful to create continuous track
  - Microdripping : pulsed electric field release periodically tiny droplets
- Feature Sizes
  - Cone Jet : few µm
  - Microdripping : tens of nm



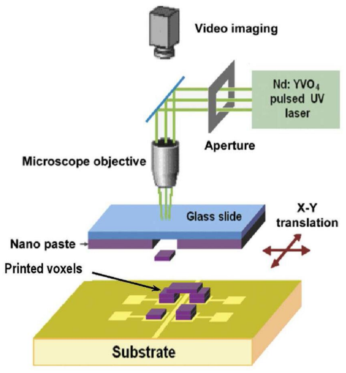
EHD Process [1]



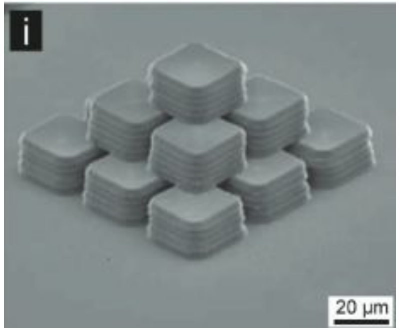
2 pillars manufactured by EHD [1]

Laser-Induced Forwar Transfer (LIFT)

- Use laser ablation to transfer material from a donor layer to a substrate
- Often need surface pre-treatment to improve adherence
- Minimal Feature Size = 0.5 µm [7]
- Often use to produce vertical and layered structure



Lift Process [7]

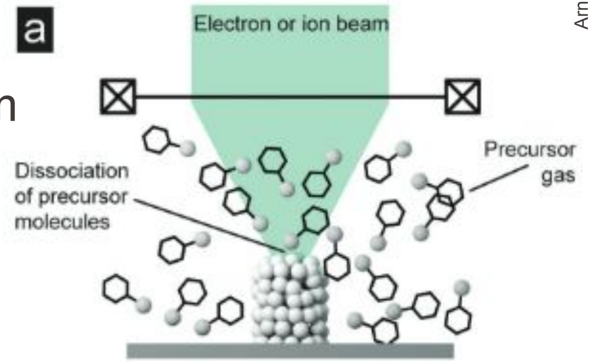


Structure with stacked layer [7]

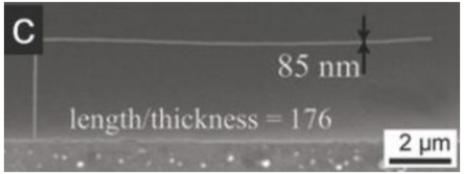
[7] A. Piqué, R. C. Y. Auyeung, H. Kim, N. A. Charipar, and S. A. Mathews, "Laser 3D micro-manufacturing," Journal of Physics D: Applied Physics, vol. 49, no. 22, p. 223001, Jun. 2016.

Focused Electron/Ion Beam Induced Deposition (FEBID/FIBID)

- Most precise AM methods for metal
- Precursor gas dissociates upon electron/ion beam interaction, depositing solid material onto substrate
- FIBID has higher deposition rate but risk of contamination
- Resolution of 0.7–2 nm achievable, it depends on interaction volume [8]
- SEM feedback enables precise 3D structures with control



FEBID/FIBID Process [1]



Standing Wire [1]

[8] W. F. Van Dorp, B. Van Someren, C. W. Hagen, P. Kruit, and P. A. Crozier, "Approaching the Resolution Limit of Nanometer-Scale Electron Beam-Induced Deposition," Nano Letters, vol. 5, no. 7, pp. 1303–1307, Jul. 2005

EPFL

Comparison between all the techniques at the macro scale (added after the presentation)

Methods	Resolution [µm]	Printing speed [mm/s]	Printer cost [kCHF]	Loose powders ?	More than one material at a time?
DED	300-1000	2.5-25	~500	Yes	Yes
SLM	20-100	10-50	50-1000	Yes	No
EBM	50-200	200-1000*	100-250	Yes	No
MEX	250-400	1-80**	1-10	No	Yes

*without time to achieve vacuum
**Only to print green bodies. Debinding (8 hours for standard pieces) and sintering (2-4 hours) are not considered here

Questions
&
Answers