Dr. Alexander Katz

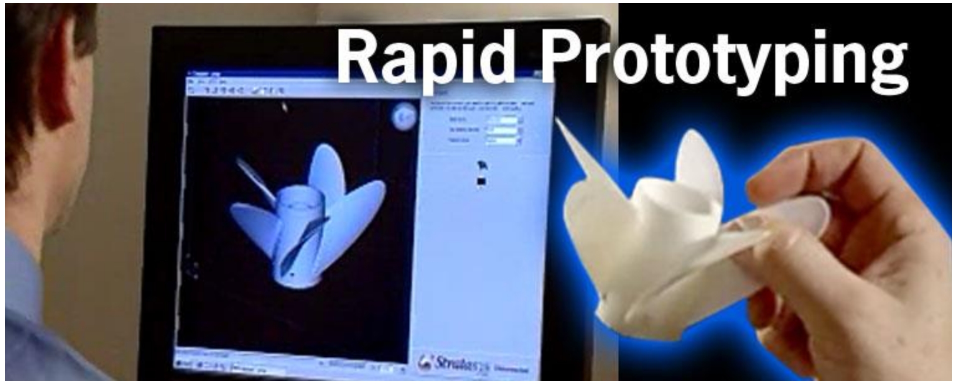
Selective Laser Melting (SLM) Additive Manufacturing as advanced welding: process, physics, joining mechanisms

AEAI Annual Israeli Welding Congress

2023, February 21

The world of 3D-Printing

3D printing is any of various processes in which material is joined or solidified under computer control to create a three-dimensional object, with material being added together (such as liquid molecules or powder grains being fused together). 3D printing is used in both rapid prototyping and additive manufacturing.



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A brief history of 3D-printing

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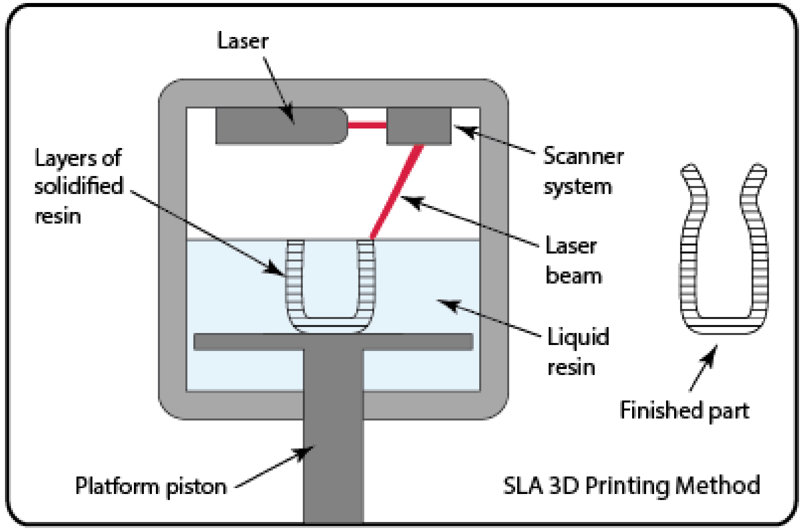
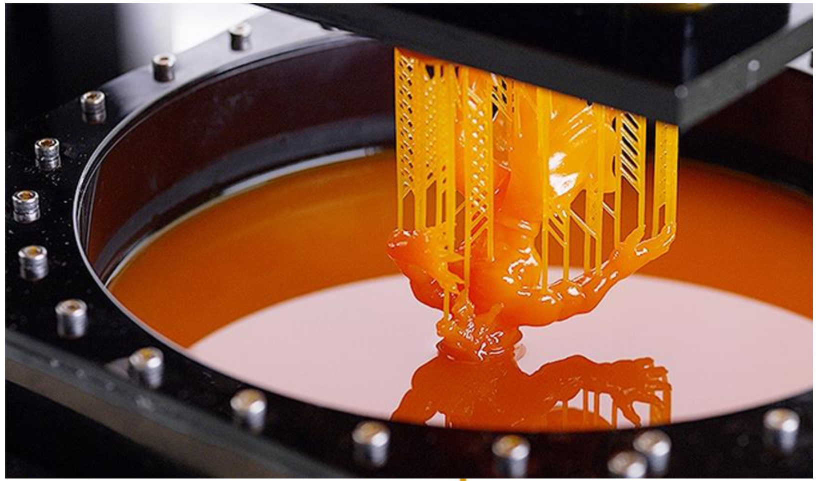
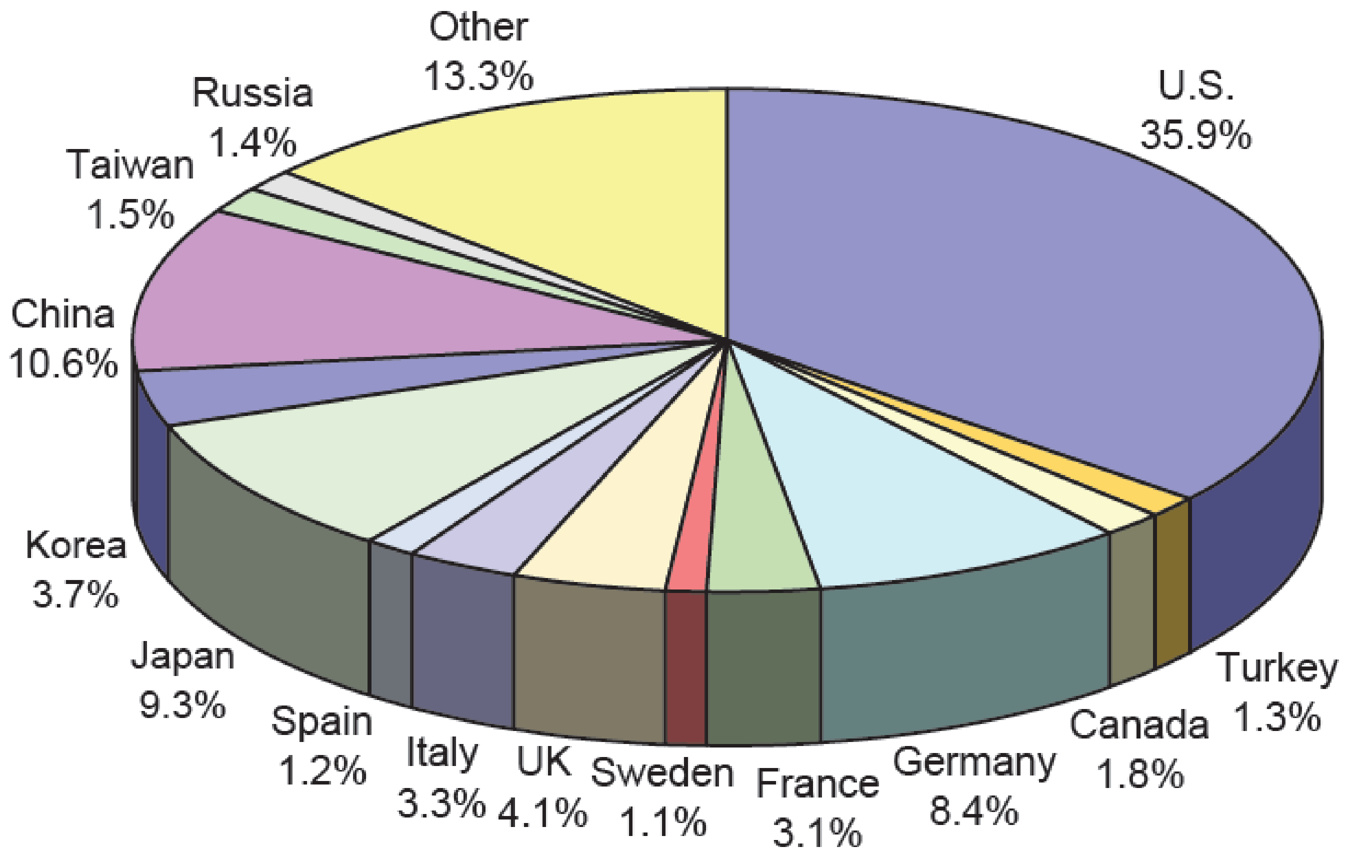
3D Printing in the late 1980s

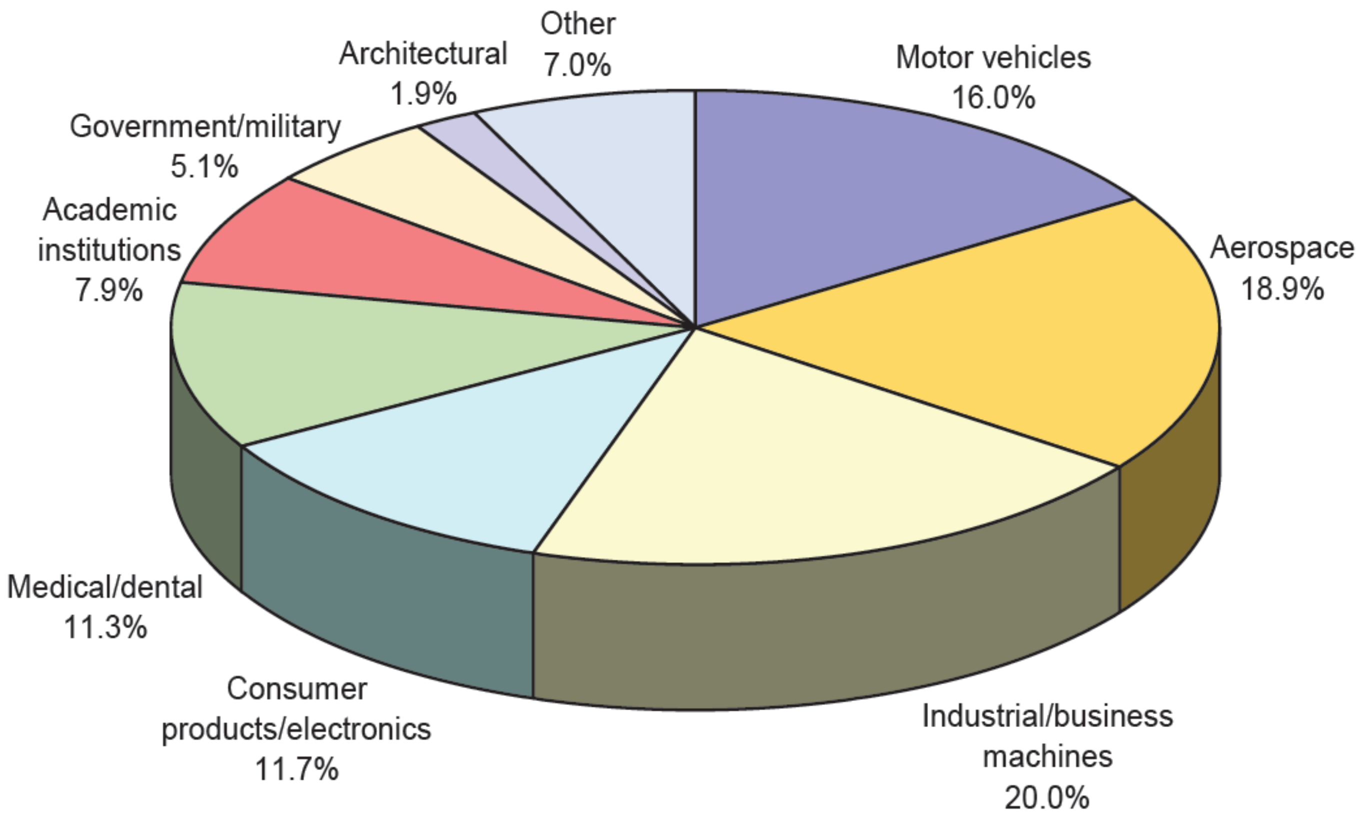




Additive Manufacturing Worldwide

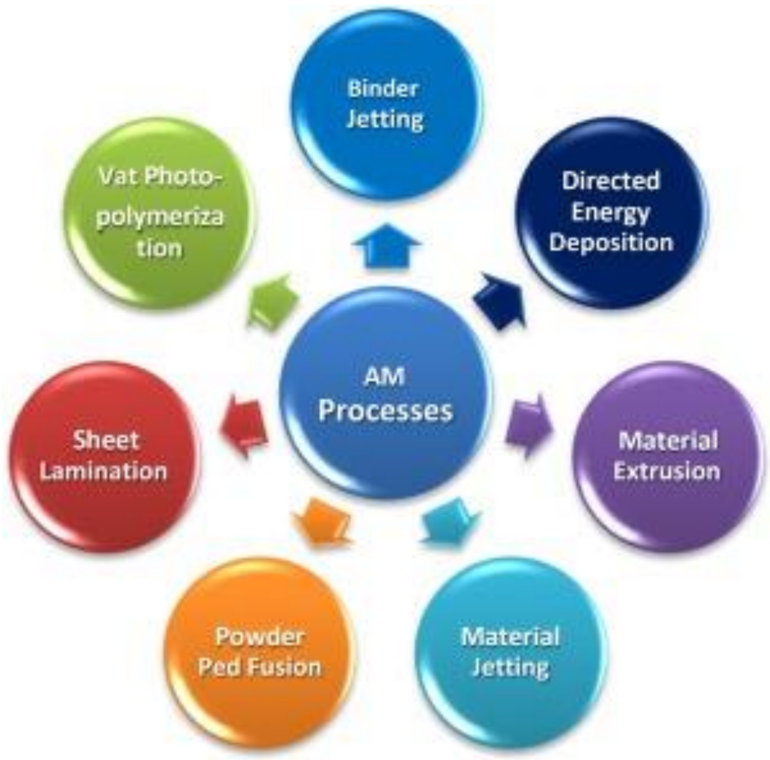


Additive Manufacturing at Different Industry Branches



Source: Wohlers Associates, Inc.

Variety of Presently Existing AM Technologies

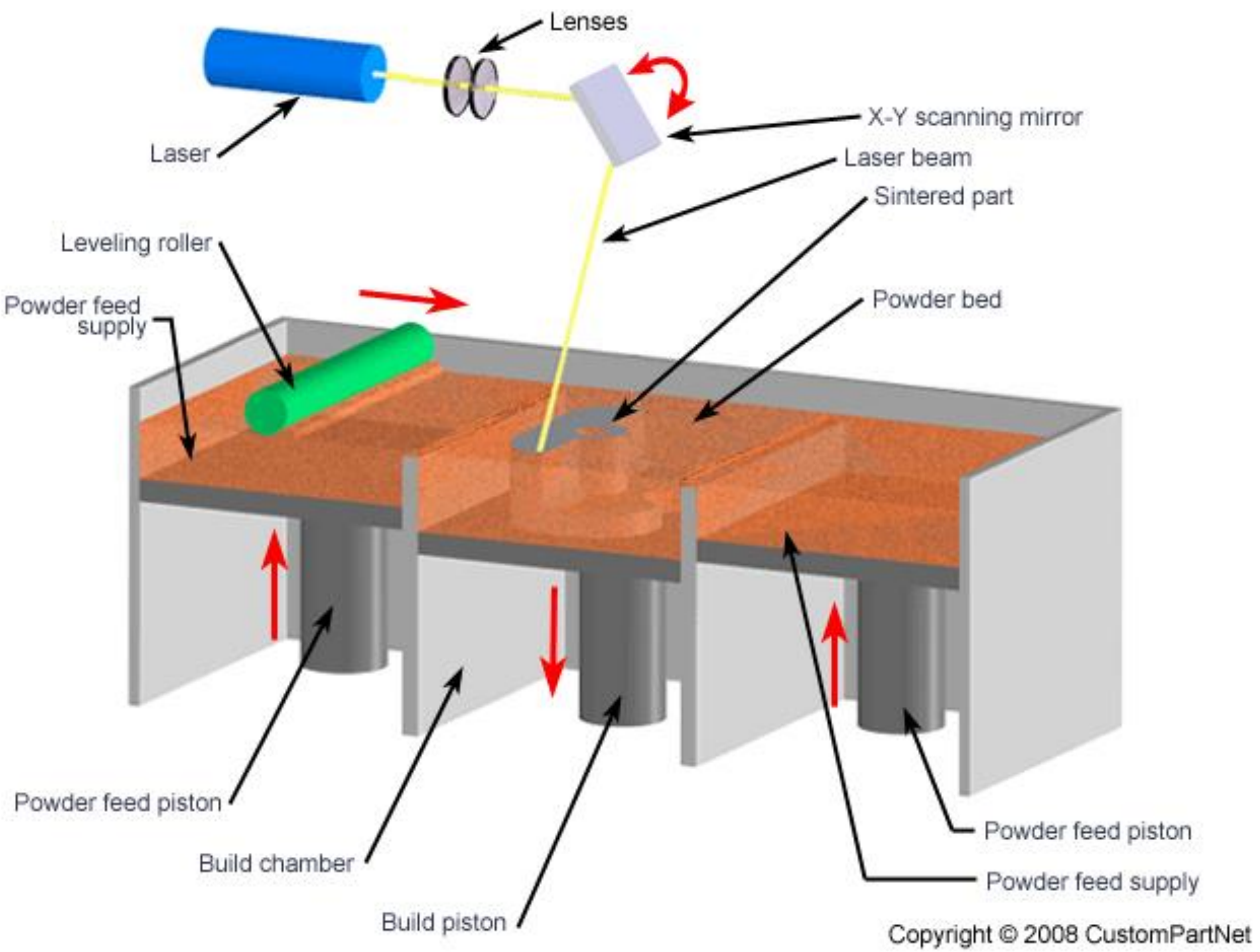


- Material extrusion—an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice
- Material jetting—an additive manufacturing process in which droplets of build material are selectively deposited
- Binder jetting—an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials
- Sheet lamination—an additive manufacturing process in which sheets of material are bonded to form a part
- Vat photopolymerization—an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization
- Powder bed fusion—an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed
- Directed energy deposition—an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited

New processes may develop in the future that do not fit into this system of categorization, so the standard would require revision to accommodate these new processes.

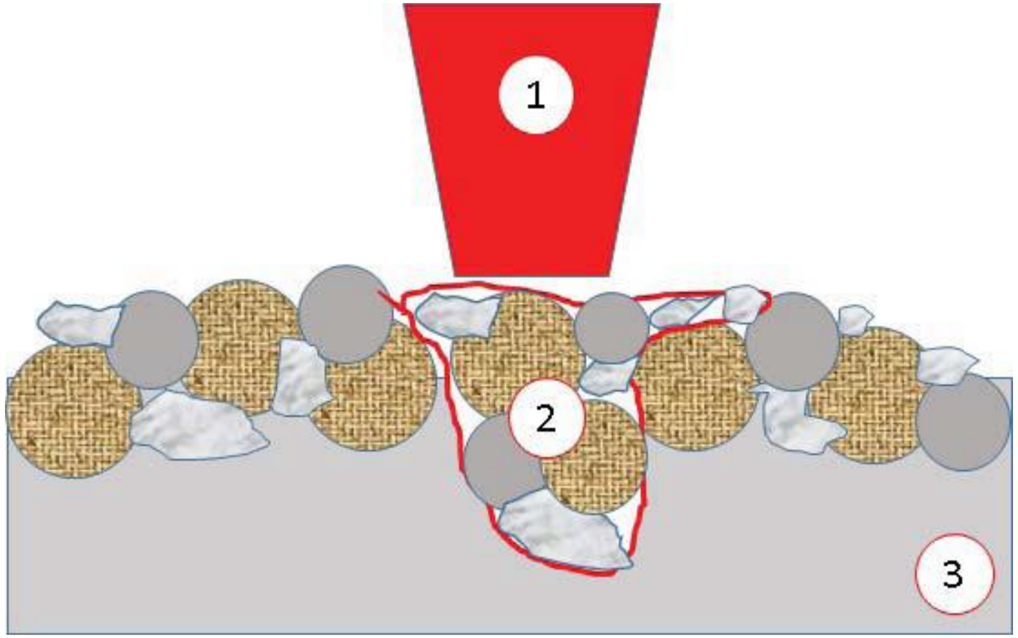
Selective Laser Melting Powder Bed AM

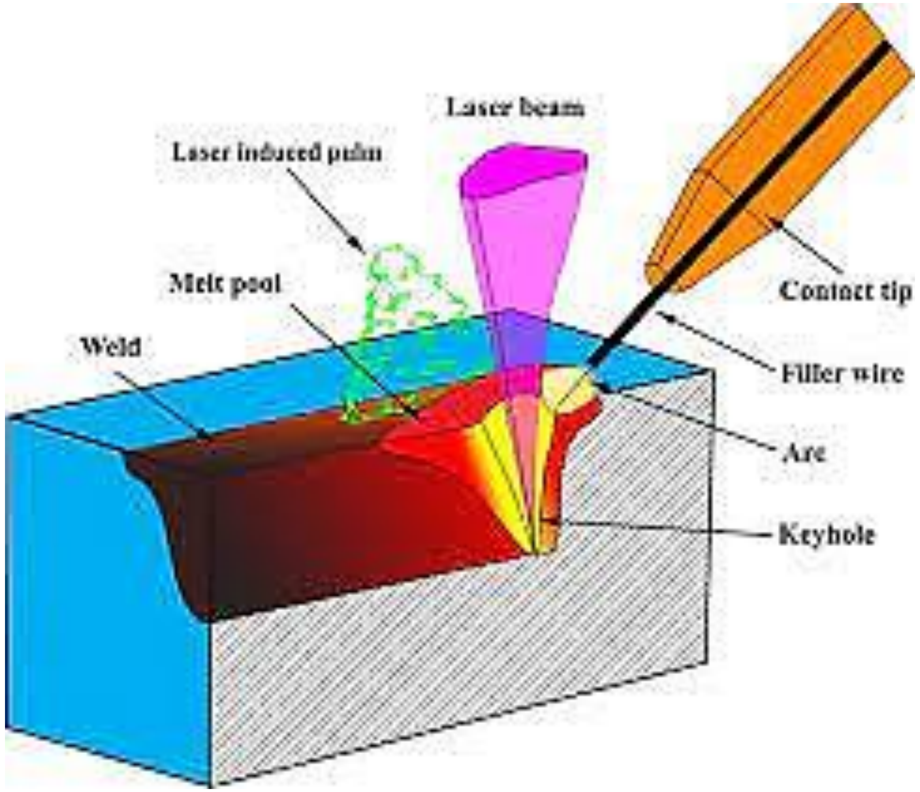
schematic



SLM AM vs. Laser Welding

schematic





SLM AM

Laser Welding

SLM AM vs. Laser Welding

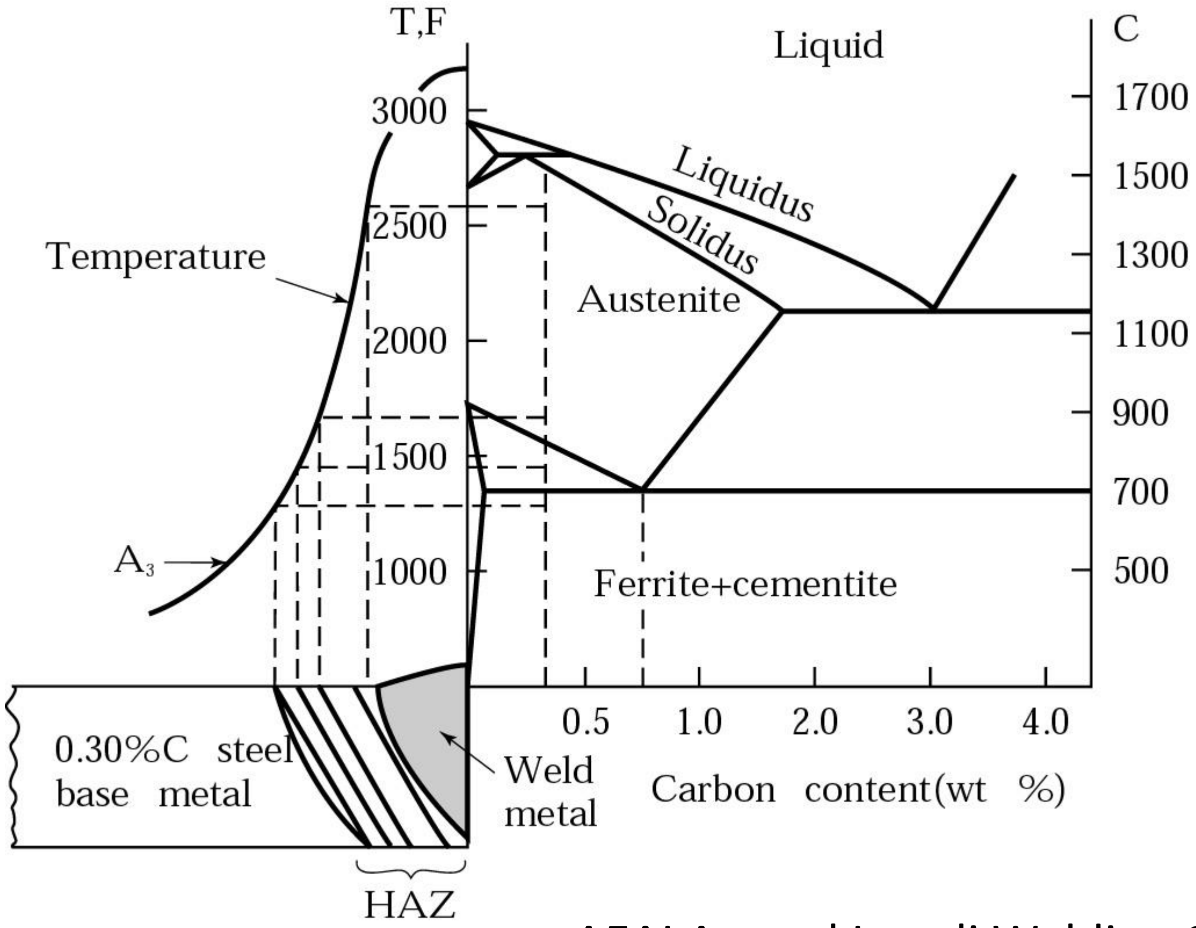
intrinsic restrictions

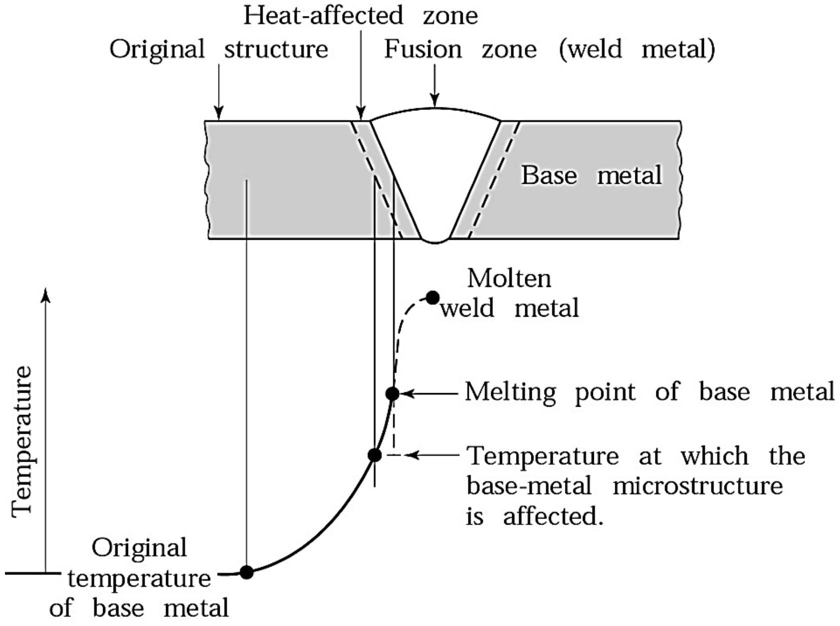
Different zones in welding joints / SLM built volumes

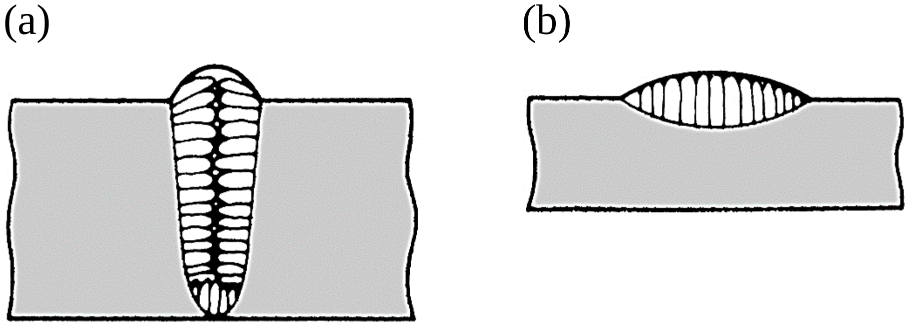
- ✓ Fusion zone (weld metal) – columnar (dendritic) structure, low strength, toughness and ductility
- ✓ Heat Affected Zone (HAZ) – zone which has been subjected temporarily to elevated temperature; its microstructure is different from that of the base metal
- ✓ Base metal

SLM AM vs. Laser Welding

intrinsic restrictions

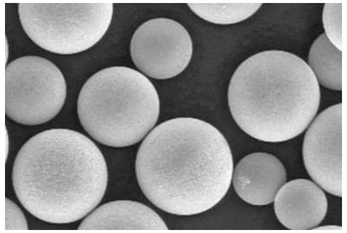






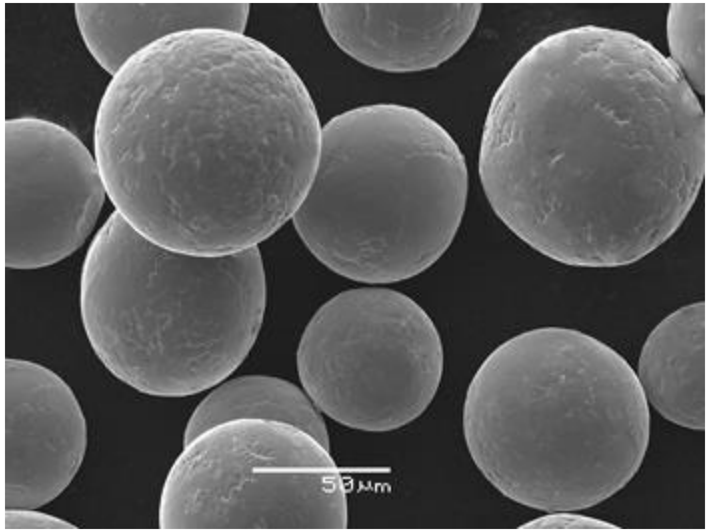
Materials for SLM

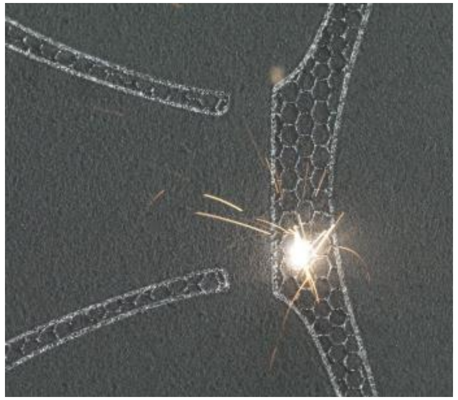
- ✓ Ti-6Al-4V (Grade5)
- ✓ Ti-6Al-4V-ELI (Grade23)
- ✓ Titanium CP (Grade2)
- ✓ Co Cralloy ASTM F75
- ✓ Gamma-TiAl, Ti-48Al-2Cr-2Nb
- ✓ Inco718, Ni-19Cr-19Fe
- ✓ Steels
- ✓ Copper alloys
- ✓ Refractory metals



Pre-alloyed powders

EOS - SLM process





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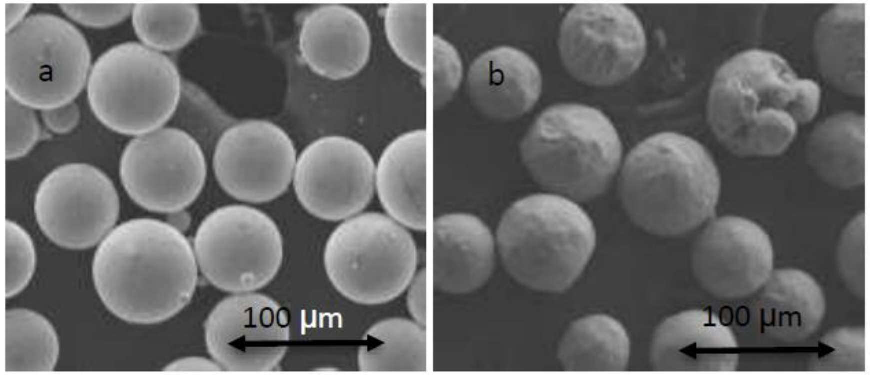
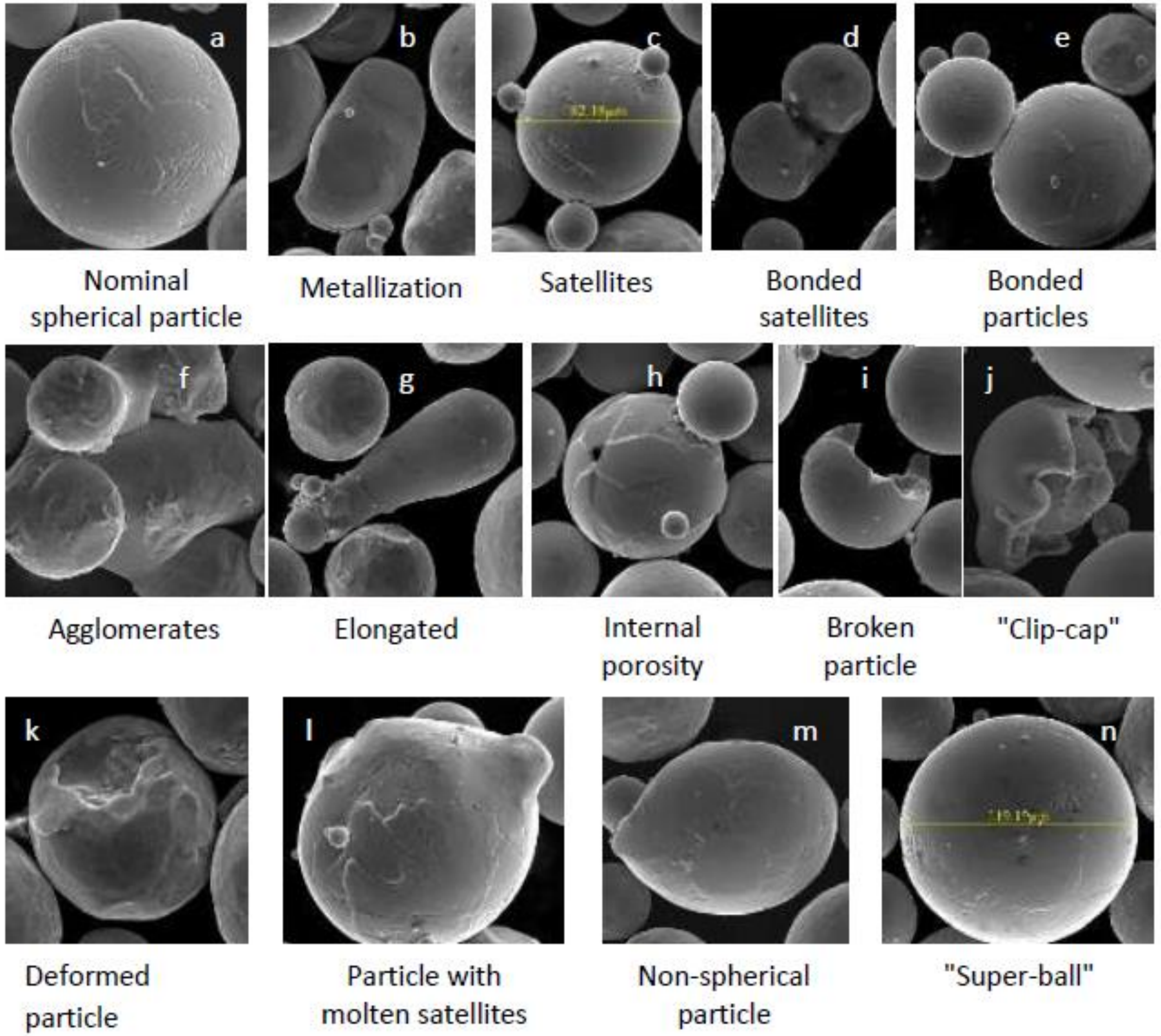
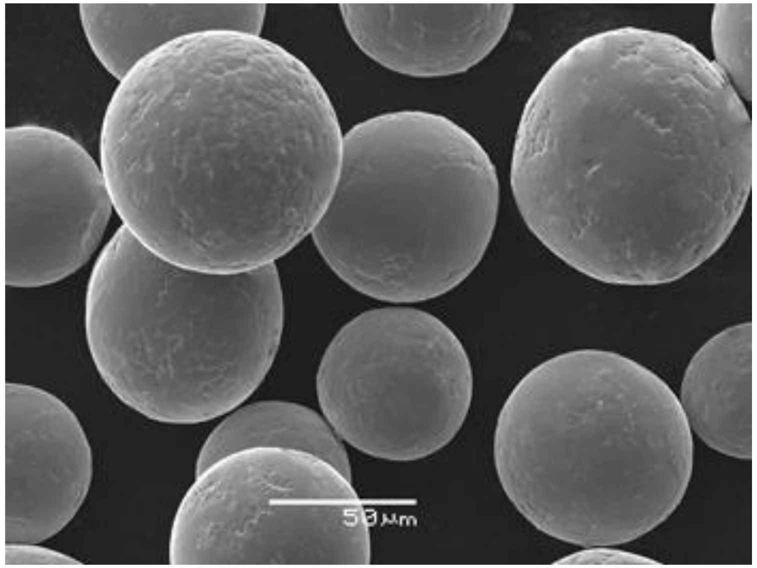
Selective Laser Melting:
Powder Recycling Effect

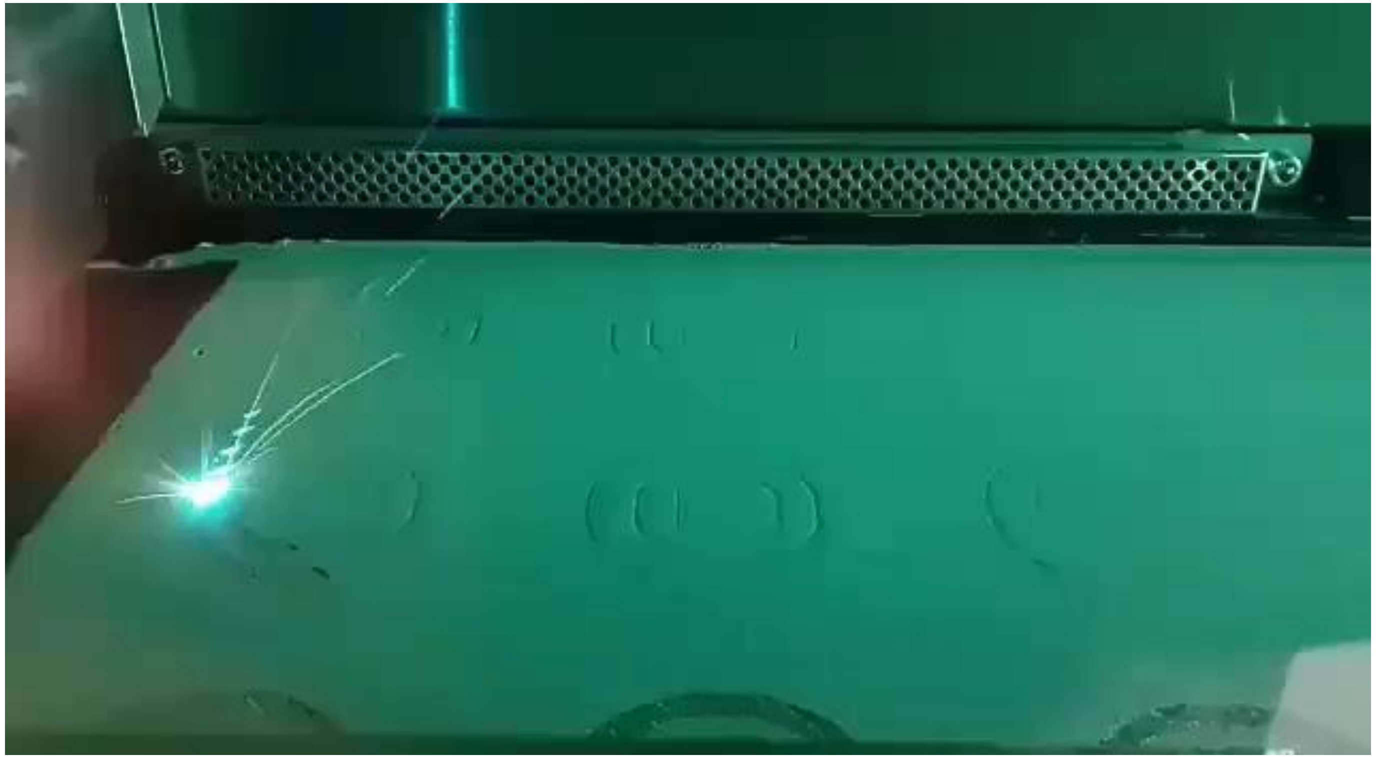




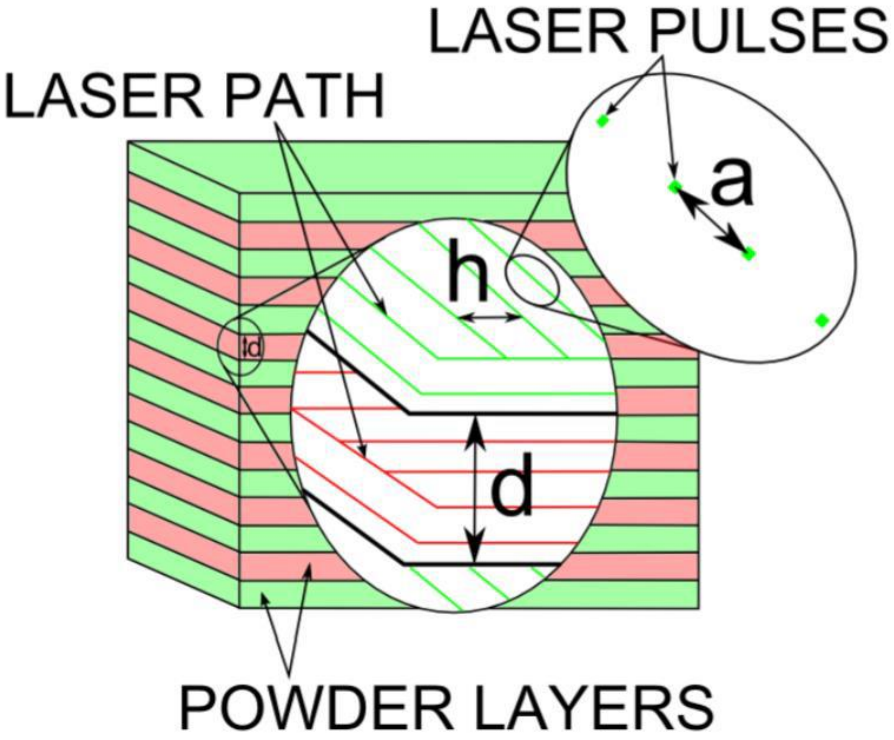
Popov V., Katz-Demyanetz A ,.Garkun A., Bamberger M. The Effect of Powder Recycling on the Mechanical Properties and Microstructure of Electron Beam Melted Ti-6Al-4V specimens. Journal: Additive Manufacturing (2018). (under review).

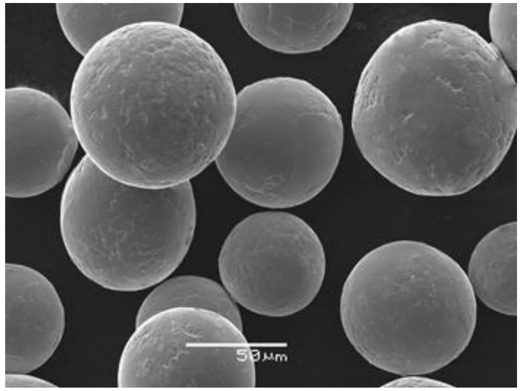
EOS - SLM process

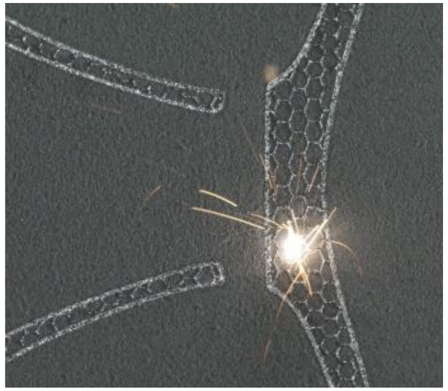


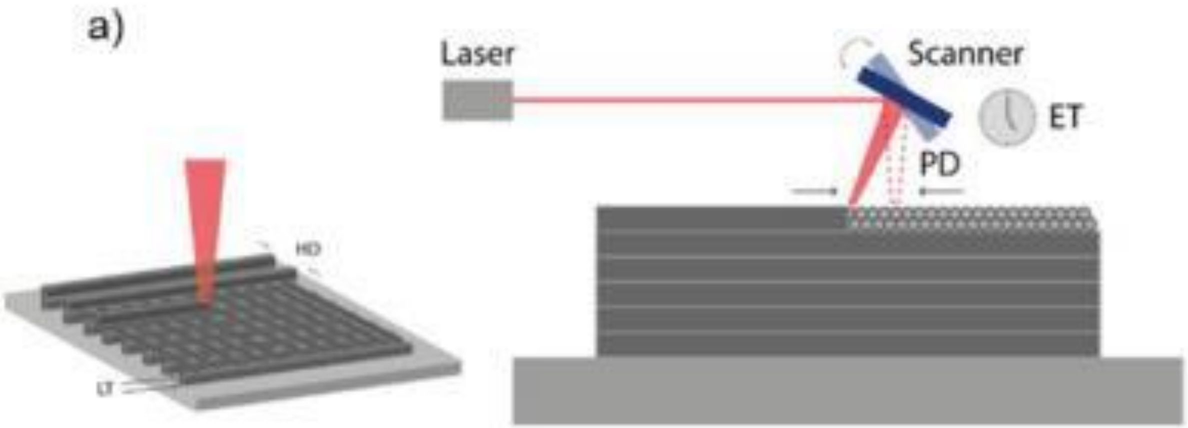


Process parameters









Heat post-treatment

Table 3 Common post-processing procedures for Ti–6Al–4V and Inconel 718

Treatment	Ti–6Al–4V	Inconel 718
Stress relief	2 hours, 700–730°C[197]	0·5 hours at 982°C[142] 1065 ± 15°C for 90 min (–5±15 min)[193]
Hot isostatic pressing (HIP)	2 hours, 900°C, 900 MPa[197] 180 ± 60 min, 895–955°C, >100 MPa[192]	4 hours at 1120°C, 200 MPa
Solution treat (ST)	Not typical	1 hour at 980°C[261]
Aging	Not typical	8 hours at 720°C Cool to 620°C Hold at 620°C for 18 hours total[261]

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Real-time monitoring possibilities

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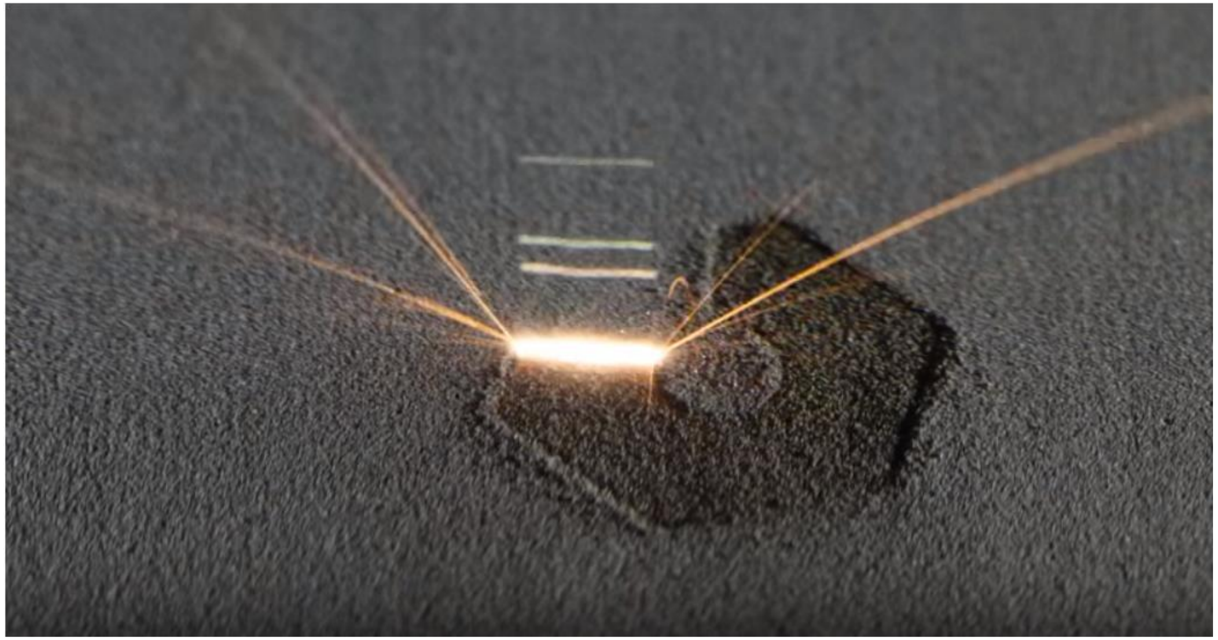
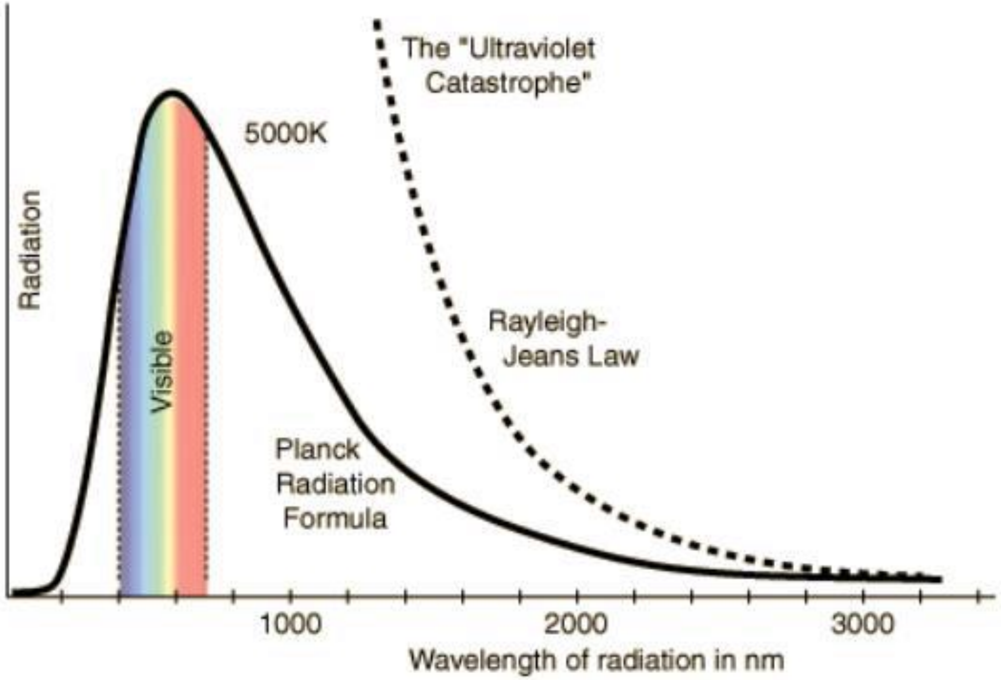
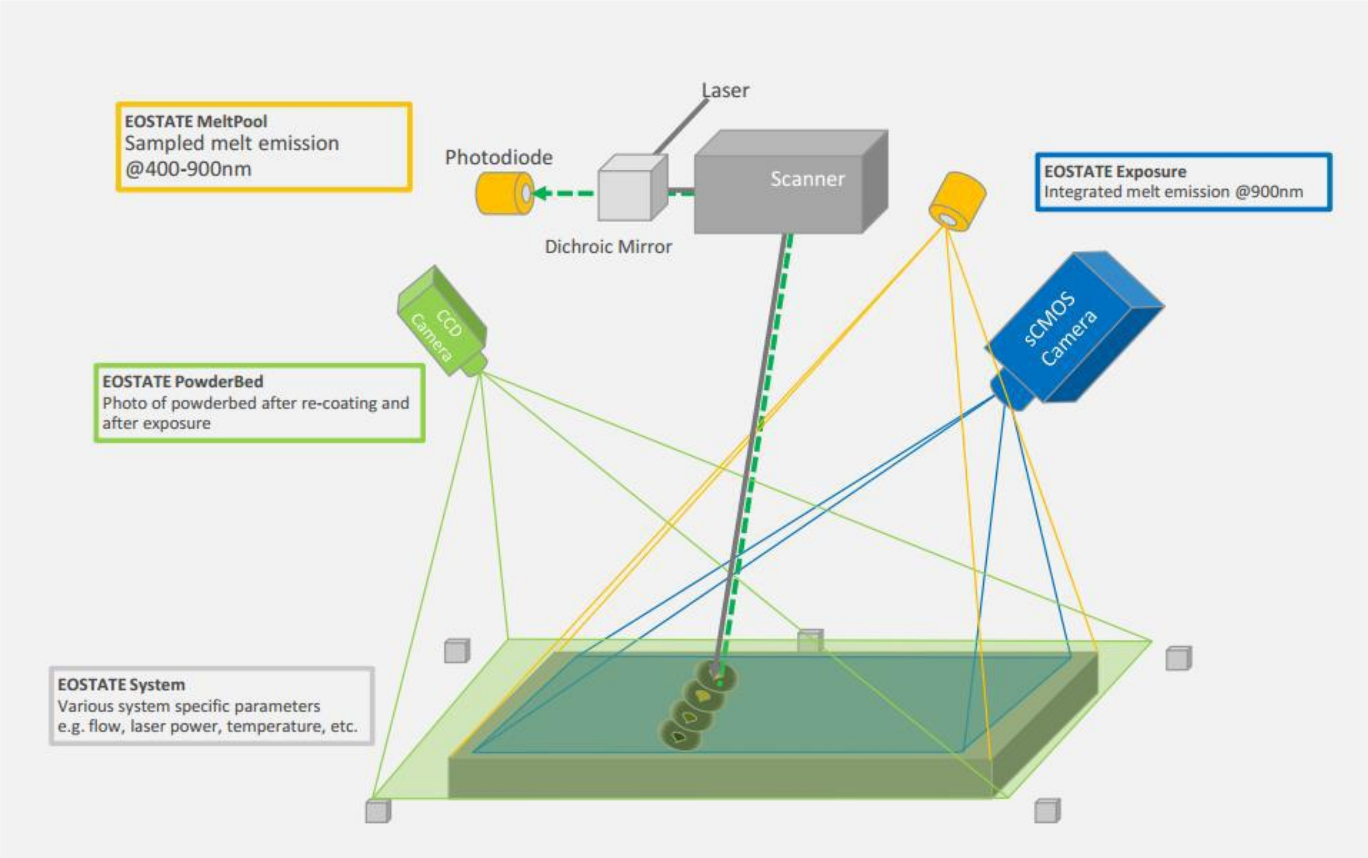
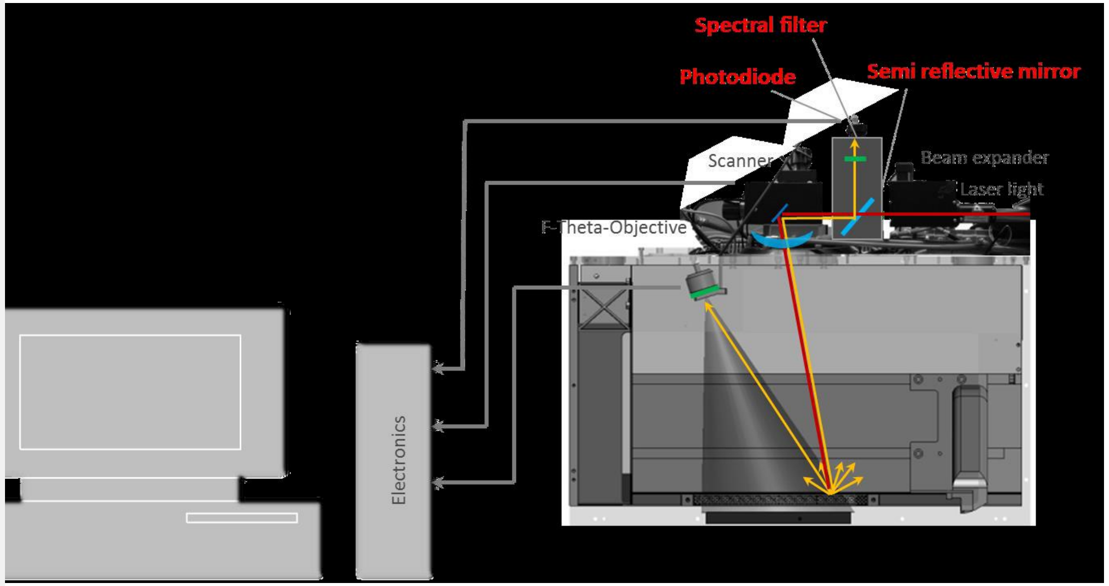


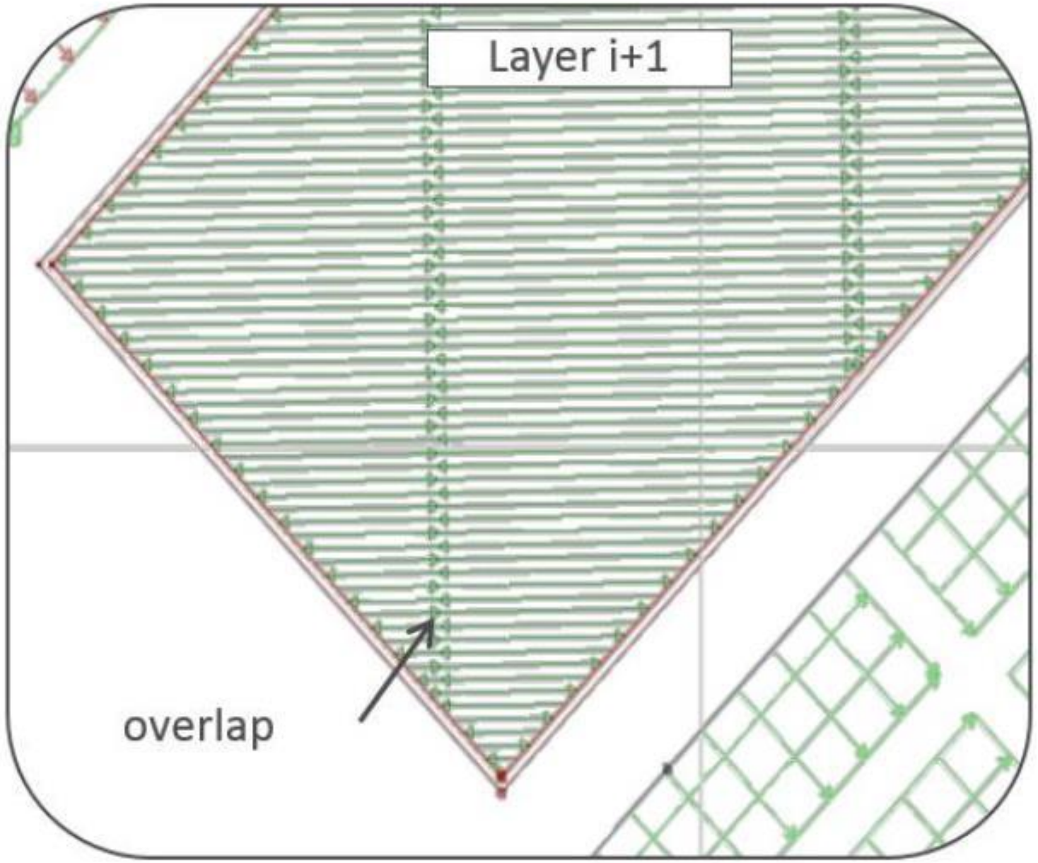


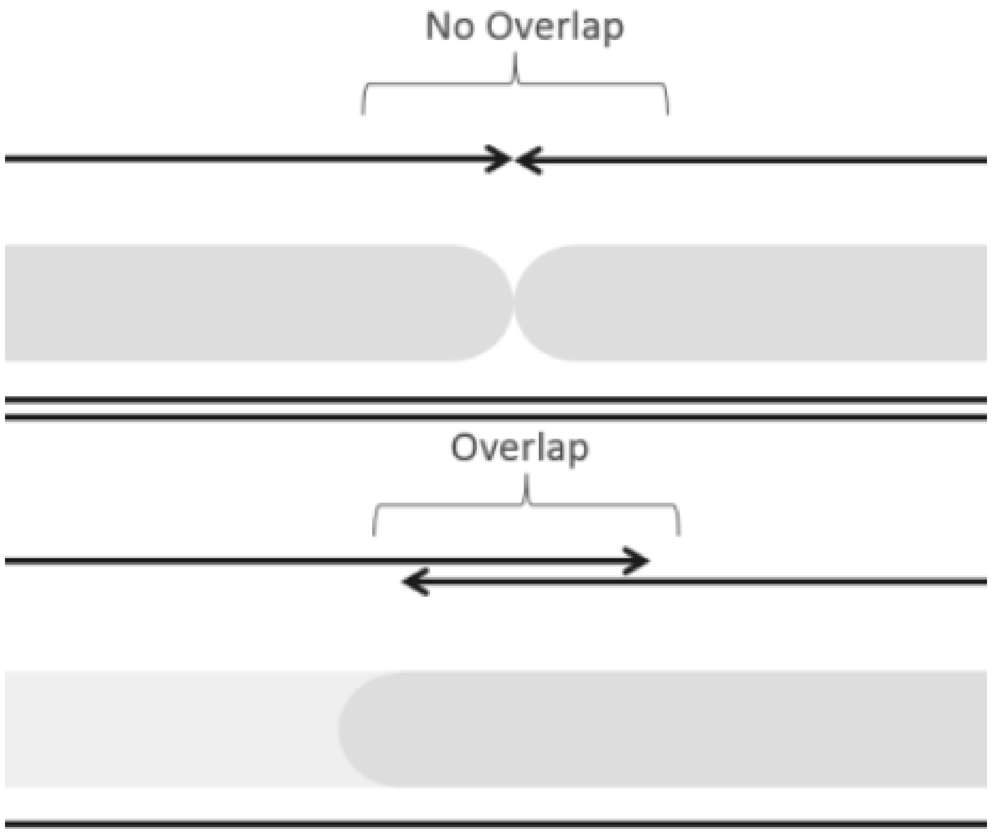
Real-time monitoring possibilities



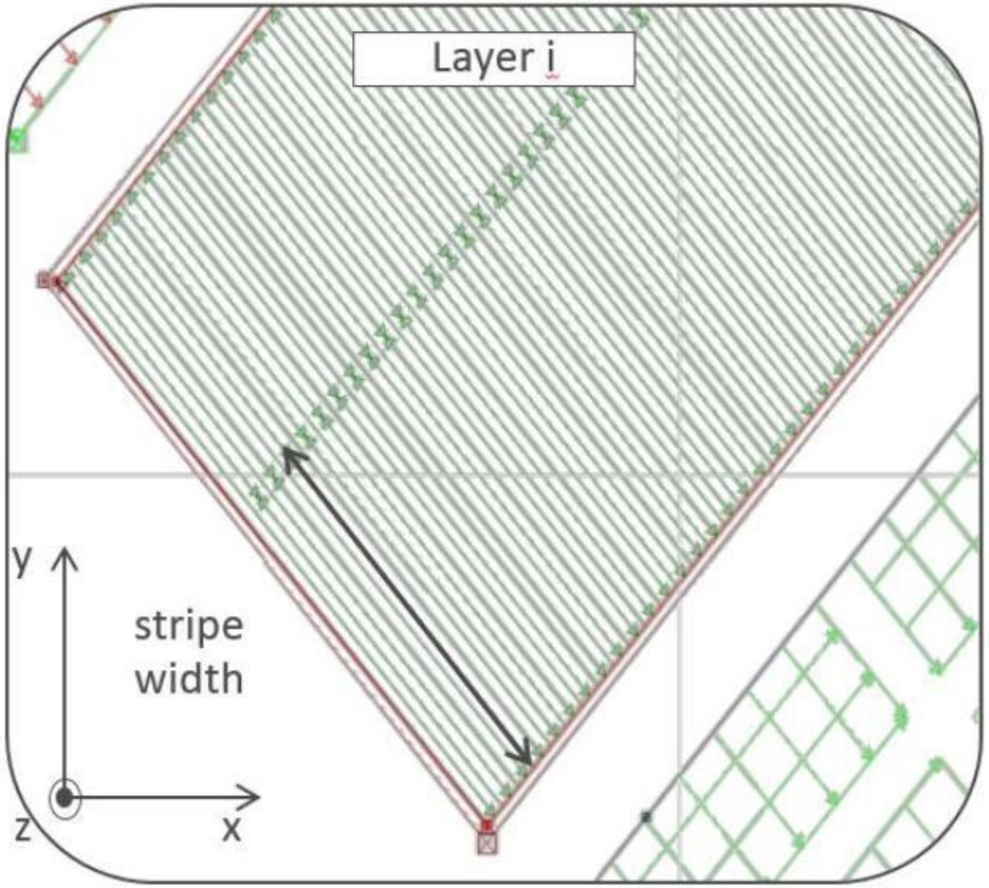


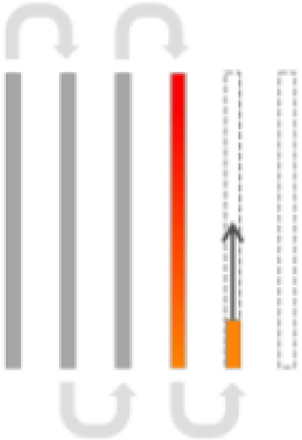
Printing strategies

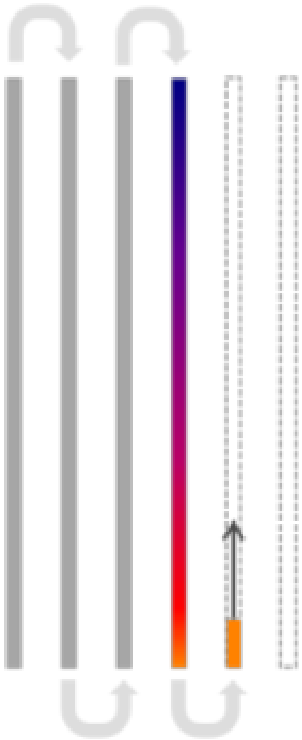




Printing strategies







Benefits and Limitations

	Advantages	Disadvantages
Material	No distinct binder and melt phases	Not suitable for well-controlled composite materials (*e.g.* WC-Co)
Cost and processing time	Elimination of time-consuming and costly furnace post-treatments for debinding, infiltration or post-sintering	High laser power and good beam quality (expensive lasers); smaller scanning velocities (longer build times)
Part quality	Suitable for producing fully dense parts in a direct way	Melt pool instabilities and higher residual stresses

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Part building and basic physical processes

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Physical processes involved in SLM

- ✓ Heat input and heat transfer
- ✓ Diffusion and mass transfer
- ✓ Solid state sintering at room temperature
- ✓ Phase transitions
- ✓ Nucleation and growth
- ✓ Evaporation/condensation
- ✓ Evaporation/condensation
- ✓ In situ alloying and in situ sintering

Heat transfer effects in SLM

- ✓ Heating/cooling rate and its effect on nucleation and growth of various phases and on phase transitions
- ✓ Re-melting of already printed layers
- ✓ Solidification/crystallization/amorphization of the as-printed layers
- ✓ Residual stresses and dimensional stability of the as-printed product

Interaction of incident beam with a sample and heat transfer equation

The main heat transfer mechanism through SLM is a thermal conduction induced by incident beam and resulted mainly in a sample electric current. Taking into account the linear scanning velocity v x the heat transfer equation in a non reactive sample can be written as:

$$\nabla \cdot q = -\rho C_p \left(\frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} \right)$$

q - heat flux, [W]
t - time, [s]
Cp - specific heat of i phase, [J/ kg K]

Rosenthal simplified solution

for moving point source, semi-infinite geometry,
no flux boundary conditions

$$T - T_0 = \frac{q}{2\pi k x} e^{\left[-\frac{\lambda v R}{2\pi}\right]}$$

$$\lambda = \frac{\rho C}{k}$$

λ - thermal resistance, [s/m^2]
q - heat flux, [W]
v - beam linear travel velocity, [m/s]
R - spot radius, [m]
x - depth from the heated sample s surface, [m]
C - specific heat, [J/ kg K]
k - is the coefficient of thermal conductivity, [W m $^{-1}$ K $^{-1}$]

Energy balance in laser heated non-reactive sample

$$q \cdot t = \sum_{i=1}^{n} C_i m_i \Delta T$$

q – machine's power, [W]
t - time, [s]
C_i - specific heat of i phase, [J/ kg K]
m_i - mass of i phase, [kg]

Applied heat input

$$H = \frac{\eta E I}{v}$$

η - beam efficiency
E - voltage, [V]
I - current, [A]

Energy for heating a non-reactive sample

$$Q = \sum_{i}^{N} c_i m_i \Delta T$$

Q - required heat input, [J]
C_i - specific heat of i phase, [J/ kg K]
m_i - mass of the i phase, [kg]

Energy for melting a sample

$$Q = \sum_{i}^{N} k_i m_i$$

Q - required heat input, [J]
K_i - heat of fusion of i phase, [J/kg]
m_i - mass of the i phase, [kg]

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Heat transfer effect

example

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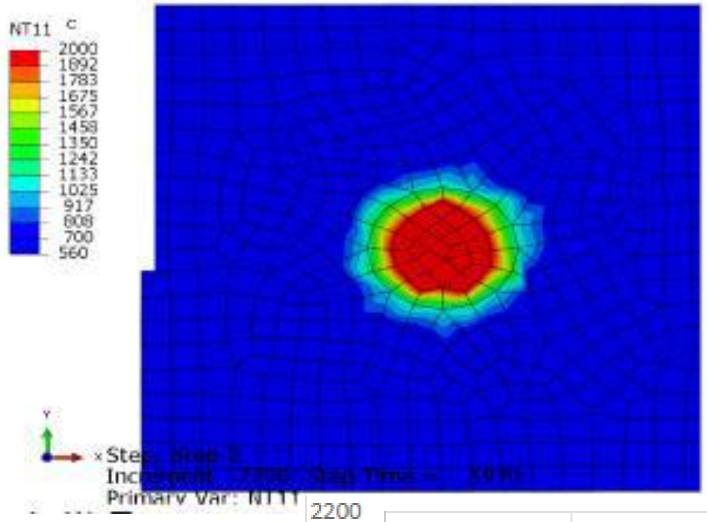

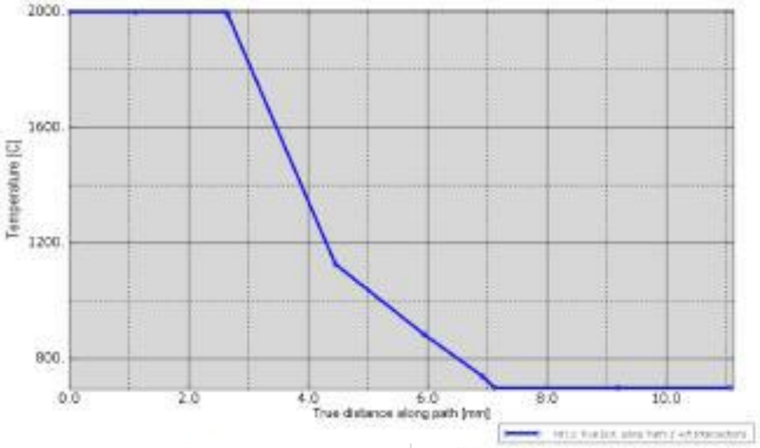

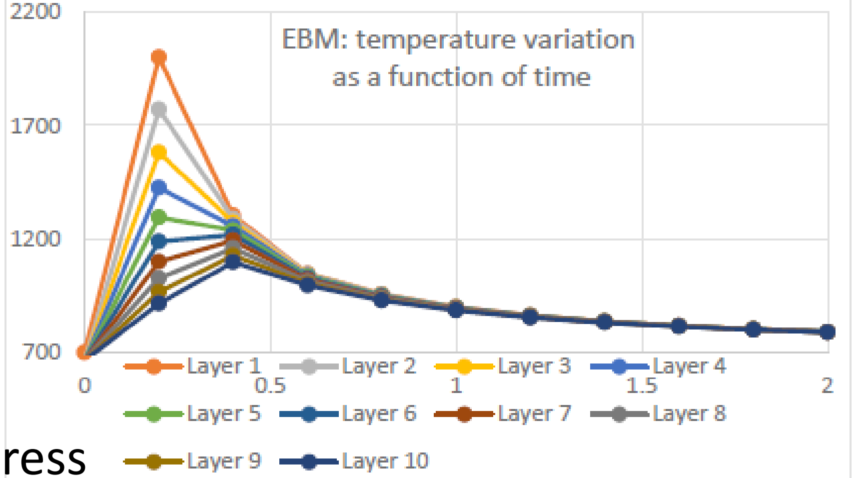

Diffusion governed processes in SLM

- ✓ Dissolution
- ✓ Grain growth
- ✓ Precipitation
- ✓ Segregation
- ✓ Porosity closure
- ✓ Evaporation

Basic diffusion mathematics

$$\frac{\partial \mu}{\partial t} = D\left(\frac{\partial^2 \mu}{\partial x^2} + \frac{\partial^2 \mu}{\partial y^2} + \frac{\partial^2 \mu}{\partial z^2}\right)$$

diffusion equation in 3D Cartesian system

$$D = D_0 \exp\left(-\frac{E_a}{RT}\right)$$

diffusion coefficient’s
Arrhenius-type temperature dependence

$$x \sim 2\sqrt{Dt}$$

characteristic diffusion distance

Examples of diffusion equation's solutions

$$\frac{\Delta C}{\Delta x} = \frac{C_A - C_B}{x_A - x_B}$$

diffusion from infinite body to infinite body via thin membrane (steady state solution)

$$c(x,t) = \frac{N}{\sqrt{4\pi Dt}} e^{-x^2/(4Dt)}$$

diffusion into a thin film

$$\frac{C_x - C_0}{C_s - C_0} = 1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)$$

diffusion from infinite material's source to infinite body

$$c(x,t) = \frac{4c_0}{\pi} \sum_{j=0}^{\infty} \left(\frac{1}{2j+1} \sin\left[(2j+1)\pi \frac{x}{L}\right] \exp\left[-\frac{(2j+1)^2 \pi^2}{L^2} Dt\right] \right)$$

degassing a thin plate in vacuum

Diffusion governed processes

example of alloy depletion

Sample	Phase description	Element content, at. %				
		Al	Cr	Mo	Nb	Ta
Initial powder	Overall	12.0	25.0	25.0	25.0	13.0
As-built	Overall	8.4	25.8	25.7	26.5	13.6
	TaMoNbCr s.s.	1.4	9.4	39.1	29.9	20.2
	$(TaMoNbCr)_{Al}$ s.s.	11.8	27.6	24.8	24.3	11.5
HT 1000 °C	Overall	8.0	24.7	26.3	26.4	14.6
	TaMoNbCr s.s.	1.3	9.3	38.7	29.7	21.0
	$(TaMoNbCr)_{Al}$ s.s.	11.7	27.4	24.3	24.2	12.4
HT 1300 °C	Overall	7.8	23.2	26.7	27.3	15.0
	TaMoNbCr s.s.	1.3	9.9	37.5	30.9	20.4
	$(TaMoNbCr)_{Al}$ s.s.	11.8	28.5	23.4	23.8	12.5

Element	Evaporation temperatures at different pressures, °C		
	At 10^{-2} mbar	At 10^{-3} mbar	At 10^{-4} mbar
Al	1209	1087	982
Cr	1383	1254	1144
Mo	2466	2258	2080
Nb	2669	2439	2256
Ta	3025	2776	2567

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Post treatment and basic physical processes effect on formation of SLM as-built product's properties

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Heat Treating

Physics of nucleation

$$\Delta F = f(\Delta F_\gamma, \Delta F_v, r)$$

$$\frac{\partial \Delta F}{\partial r} = 0 \rightarrow r_c$$

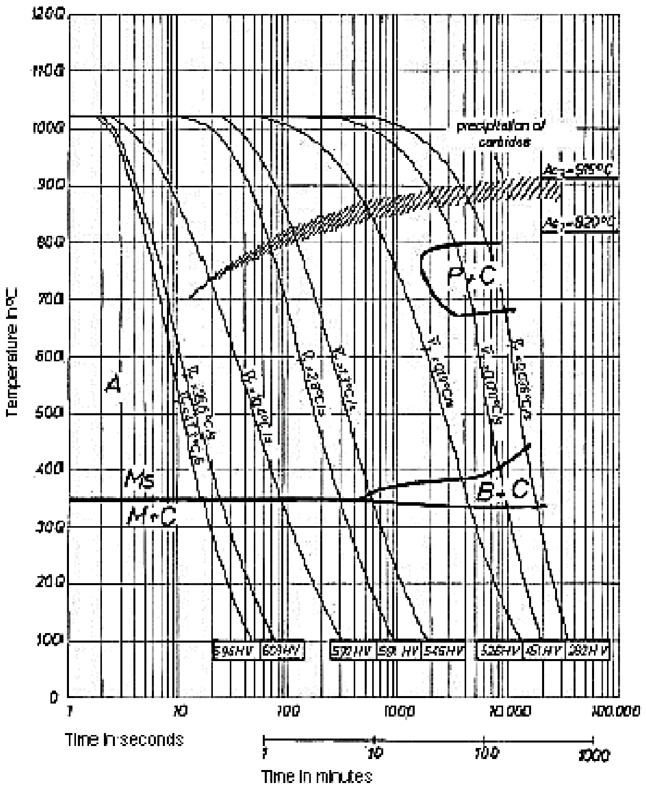
$$\Delta F = \Delta F_\gamma + \Delta F_v = 4\pi r^2 \gamma + \frac{4}{3}\pi r^3 F_v$$

$$\frac{\partial \Delta F}{\partial r} = 8\pi r \gamma + 4\pi r^2 F_v = 0$$

$$\rightarrow r_c = \frac{-2\gamma}{F_v}$$

$$\Delta F_{r_c} = \frac{16\pi\gamma^3}{F_v^{\,2}} - \frac{32\pi\gamma^3}{3F_v^{\,2}} = \frac{16\pi\gamma^3}{3F_v^{\,2}}$$

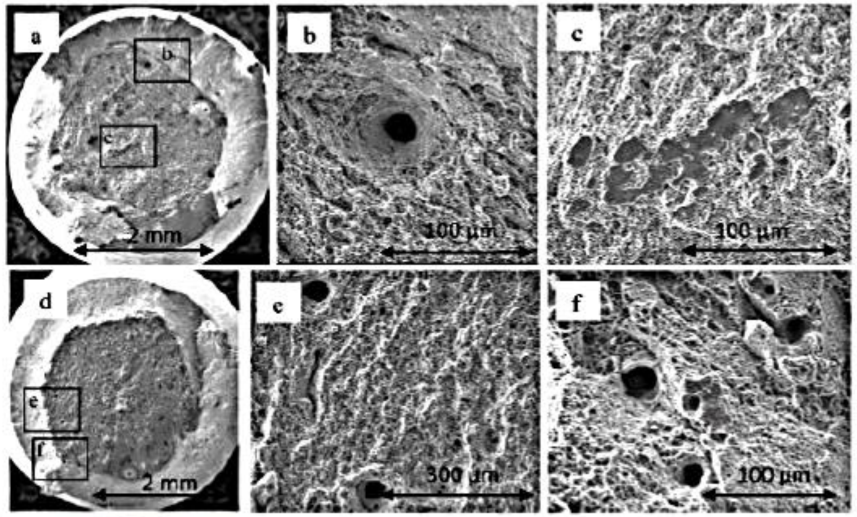
Example: printing of steel H13 made part



Carbides formation decreases quenching ability of the as-printed material and then prevents thermal cracking while the building process

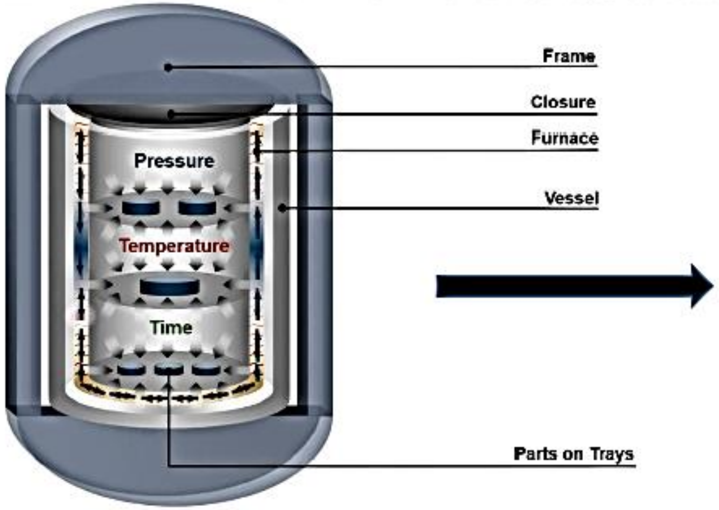
Example

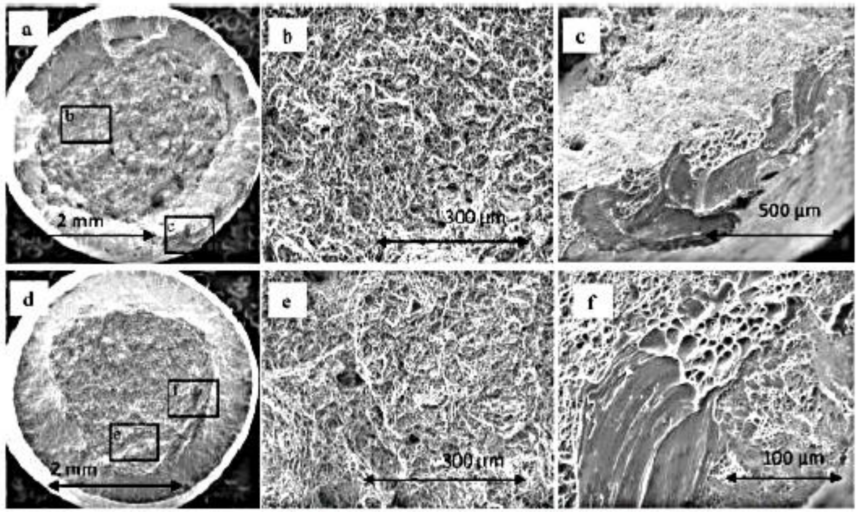
effect of HIP on porosity



as-printed

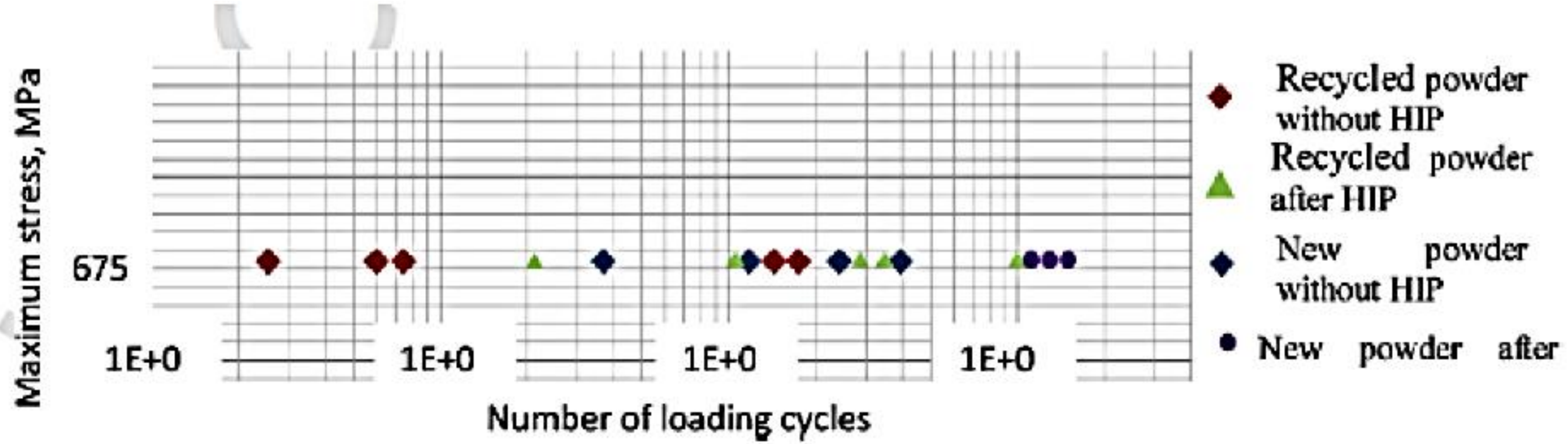
as-printed and then HIPed





Example

effect of HIP on fatigue resistance



Summary

1. Selective Laser Melting (SLM) is a strongly promising highly digitalized Additive Manufacturing (AM) method permitting to produce metallic and composite high-performance parts for aerospace, automotive, medicine, defense, etc. industries.

2. From the technological point of view, SLM may be considered as advanced welding process permitting not only joining, but also volume manufacturing of metallic parts.

3. SLM AM route is governed by a group of complicated physical and chemical processes leading to layer by layer addition and then joining of material resulting in building of the desired part.

4. Microstructure and properties formation of the as-print product are formed as a result of wide variety of the acting physical processes, namely heat and mass transfer, nucleation and growth, strengthening, etc.

5. Knowledge and smart management of acting physical and chemical processes are the keys for successful SLM Additive Manufacturing of high-performance parts with desired properties and with the highest quality.