

Chapter 4. Additive processes with powder base material

October 14, 2024

4.1 Binder jetting

4.2 Using light to machine materials

4.3 Selective Laser Sintering and Melting

4.4 Electron Beam Manufacturing

4.5 Direct Metal Deposition

4.6 Jet Fusion

3dP ●○○○○○○○○○	Laser ○○○○○○○○○○○○○	SLS/M ○○○○○○○○○○○○○○○	EBDM ○○○○○○○	DMD ○○○○○○○	Jet Fusion ○○○○○○○○○○○	3dP ○●○○○○○○○○○	Laser ○○○○○○○○○○○○○	SLS/M ○○○○○○○○○○○○○○○	EBDM ○○○○○○○	DMD ○○○○○○○	Jet Fusion ○○○○○○○○○○○
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4.1.1 Binder jetting

Principle

- A 3d part is manufactured layer by layer by assembling solid particles with a liquid binder (usually of polymeric type).
- The liquid binder is distributed selectively using a inkjet print head and the consolidation principle is indirect bonding.
- The part geometry is transferred into the process through the management of the print head (displacement and flow rates).

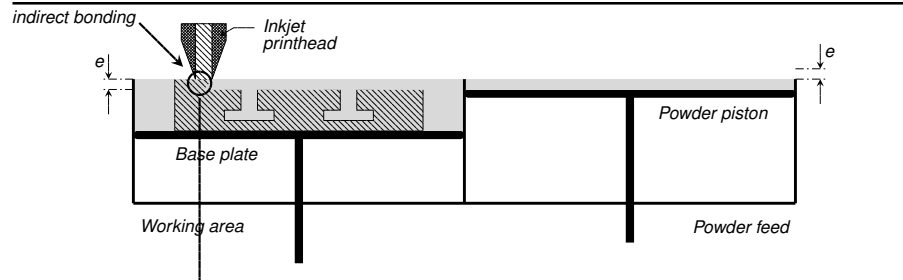
Remark

- The development of this process was connected to new technologies of printhead able to deliver viscous material

Binder jetting

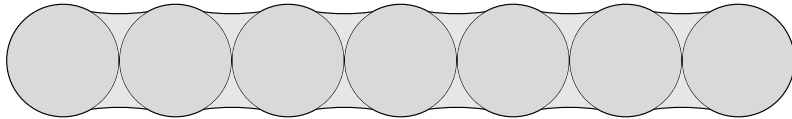
4.1.2 Binder jetting

Diagram



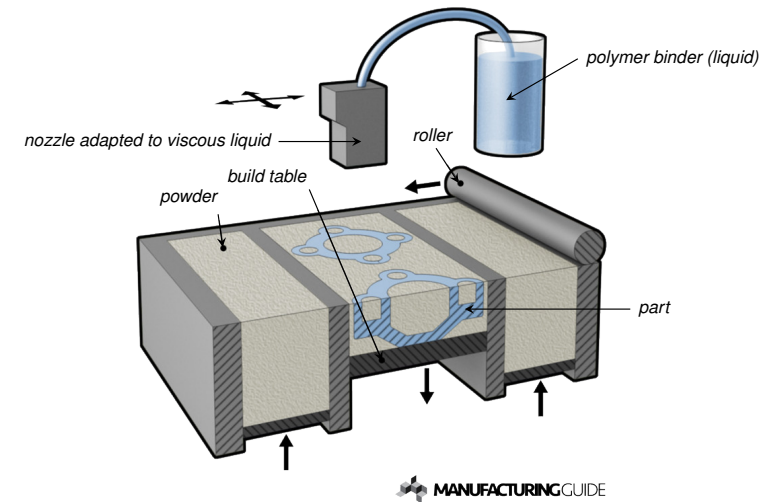
Consolidation mechanism

Indirect bonding



4.1.3 Binder jetting

Block diagram



4.1.4 Binder jetting

Equipments: 3DSYSTEMS™ ZPrinter Serie

ZP-150

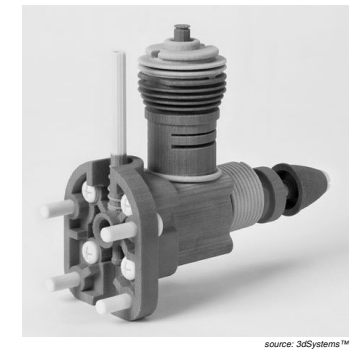
ZP-350

ZP-650



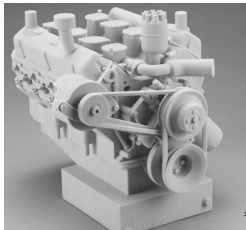
4.1.5 Binder jetting

Example of parts 1



4.1.6 Binder jetting

Example of parts 2



source: 3dSystems™



source: 3dSystems™



source: 3dSystems™

4.1.8 Binder deposition, technical data

Mechanical properties of part (order of magnitude)

Material	E, GPa	R _m , MPa	ε _{rup} , %
High Performance Composite	7	43	4.5

Equipment (type, dimensions)

Build volume, mm ³	
from 200 × 250 × 200	to 1200 × 1200 × 1600

Performances

x-y resol., μm	layer thickness, μm	build speed, mm ³ /s	layering time, s
50 – 80	100 – 200	n.a.(∞) ¹	2 – 5

¹ the build time is not sensitive to part volume but only to part height:

$$fab.time = \frac{height}{e} \frac{T_{layer}}{N}$$
with e : layer thickness, N : batch size.

4.1.9 Binder jetting

Companies

3DSYSTEMS™, DIGITALMETAL™, ExONE™, VOXELJET™

Advantages, applications and disadvantages

- Fast process (the specific consolidation time is $\simeq 0$) in average 5 to 10 times faster than SLA. Cheap machines and equipment.
- No need of supports (the powder is self-supporting).
- Possible coloration and use of many materials, parts (relatively) isotropic.
- Application to metallic and ceramic powder in combination with the classical post-processing chain: debonding-sintering-infiltration.
- Manufacture of molds and cores for sand casting.
- **Disadvantage:** Poor accuracy (compared to SLA or polyjet) and poor mechanical property without post-processing.

Denomination

- This process was originally named 3dP for "**3d-Printing**".
Today the name 3d-Printing refers almost to any additive process or at least, to those where a material is jetted like a photopolymer, ABS, wax, or a binder ,...

4.2.1 Foreword: light, heat and intensity

Heat generation

- In most cases, the interaction of light with matter generates heat. It leads to temperature elevation and phase transition (melting). Some powder based additive processes (SLS, SLM, DMD...) use this fact to achieve consolidation.

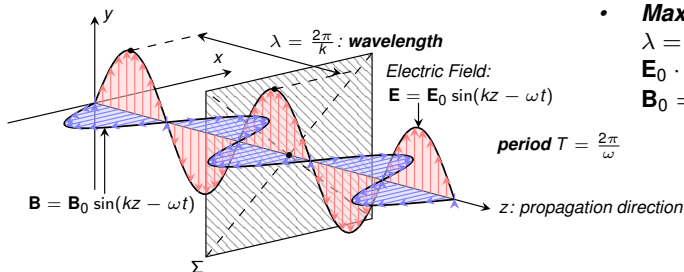
Electromagnetic wave and energy transport

- The emw's have been introduced in Chapter 2 has a particular distribution of the **electric field** in space and time. But emw's also **transport energy** (photons are energy quanta). The heat released during light-matter interactions actually corresponds to the **absorption** of the transported energy.
- The transported energy is quantified by a flux called **intensity**. The value of the light intensity can be tuned by the use of **focusing** optics (lenses). This possibility is essential for SLS and related processes where lenses are used to **concentrate** the intensity and achieve material melting.
- Program:** In the next slides we will introduce the notions of intensity and focalisation.

4.2 Intensities and focusing properties of different electromagnetic waves

4.2.2 Electric field distribution and energy transport

EMW are electric field distributions oscillating in space and time



- Maxwell equation:**
 $\lambda = cT$
 $E_0 \cdot e_z = 0$
 $B_0 = \frac{1}{c} e_z \times E_0$

EMW also transport energy in space

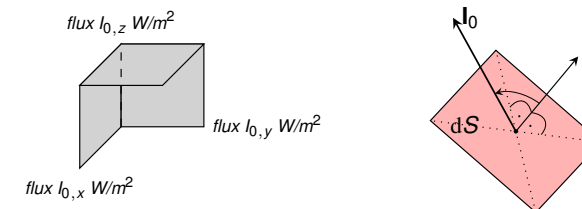
- Energy is **flowing** from one side of surface Σ to its other side.
- The flowing power (energy/per second) varies **periodically** in time with the same period as the electric field: period T .
- The period $T \simeq 10^{-15}$ s is **so small** compared to the characteristic time of most mechanical/thermal phenomena that only the **average power** P matters.
- If E is the energy transported through S during the period T , we have $P = \frac{E}{T}$.

4.2.3 Transfer of energy and intensity

- The avg. power (over a time period) dP through a surface is proportional to the area dS but also depends on its orientation. It is actually proportional to the product $\mathbf{n} dS$ where $\mathbf{n}$ is the normal unit to the surface

$$dP = \mathbf{l}_0 \cdot \mathbf{n} dS$$

- The proportionality coefficient is a vector called intensity of the emw. It depends on the space coordinates x, y, z but not on time! Its unit is: W/m^2 .
- The x component of $\mathbf{l}_0$ is the ratio between the period T of the wave and the energy which is transported during the period through a unit surface $\perp$ to the Ox -axis. The y and z components of $\mathbf{l}_0(x, y, z)$ are defined accordingly.



- The power through a finite surface Σ is obtained by integr. $P = \int_{\Sigma} \mathbf{l}_0 \cdot \mathbf{n} dS$.

4.2.4 Intensity vector for different waves

Intensity of a plane emw

- The intensity vector of a plane emw is constant in space and oriented in the direction of propagation:

$$\mathbf{I}_0(x, y, z) = I_0 \mathbf{e}_z$$

- Poynting theory**

It is possible to connect I_0 to the three parameters characterizing the plane emw: the electric amplitude $\mathbf{E}_0$, the angular frequency ω and the wave number k :

$$I_0 = \frac{k}{2\mu_0\omega} \|\mathbf{E}_0\|^2 \quad \text{where} \quad \mu_0 = 4\pi \times 10^{-7} \text{ N/A}^2 \text{ (vacuum magnetic permeability)}$$

- The **propagation direction** of the plane emw is the direction in which energy travels.
- Plane emw are **unphysical**: the power transpt'd through a plane $\perp \mathbf{e}_z$ is ∞ :

$$\text{Power through the plane } z = 0: P_0 = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I_0 dx dy = \infty!$$

4.2.5 Intensity vector for different waves

Intensity of a gaussian emw traveling in the z direction

- The intensity of a gaussian emw is oriented in the propagation direction (e.g. $\mathbf{e}_z$) and has a gaussian distribution in the plane perpendicular to propagation:

$$\mathbf{I}_0(x, y, z) = \frac{P_0}{\pi w^2(z)} e^{-\frac{r^2}{w^2(z)}} \mathbf{e}_z, \quad r = \sqrt{x^2 + y^2} : \text{dist. to axis Oz}$$

- The parameter P_0 is the power transported in the z -direction.
- The gaussian decay radius w (called also beam waist) depends on z : $w = w(z)$: if λ is the wavelength and due to **Maxwell** equations $w(z)$ has the form:

$$w(z) = \sqrt{\frac{\lambda \Gamma}{2\pi}} \sqrt{1 + \frac{z^2}{\Gamma^2}}, \quad \text{for a distance } \Gamma > 0 \text{ called } \mathbf{Rayleigh range}.$$

- The intensity has a maximum value of $I_0 = \frac{P_0}{\pi w(z)^2}$ on the z -axis. It decays by a factor $1/e$ on the circle $r = w(z)$ and more than 63% of the energy is travelling through that circle.

(see Append. 8)

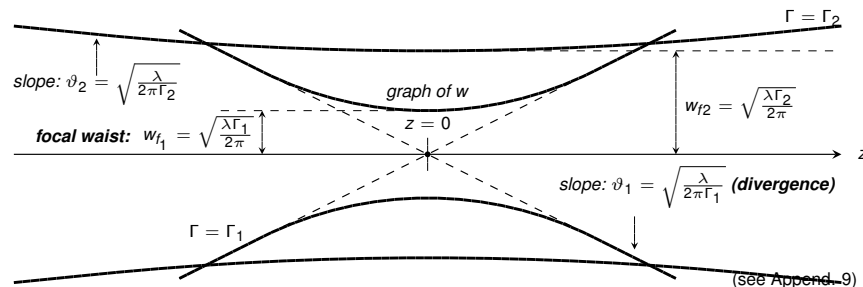
4.2.6 Caustic of a gaussian beam

Caustic, divergence, focal waist, Rayleigh range

- The volume $\mathcal{C}$ where the major part of energy is travelling is called **caustic** it is the set of points at a distance less then the waist from the propagation axis:

$$\mathcal{C} = \{(x, y, z) \in \mathbb{R}^3 \mid \sqrt{x^2 + y^2} \leq w(z)\} \quad \text{where} \quad w(z) = \sqrt{\frac{\lambda \Gamma}{2\pi}} \sqrt{1 + \frac{z^2}{\Gamma^2}}.$$

- For large $|z|$, $w(z) \simeq \sqrt{\frac{\lambda}{2\pi\Gamma}} |z| \Rightarrow \mathcal{C}$ is the union of two cones (axis Oz, divergence $\vartheta = \sqrt{\frac{\lambda}{2\pi\Gamma}}$) with a transition zone $z = 0$ (foc. waist $w_f = \sqrt{\frac{\lambda \Gamma}{2\pi}}$).
- The product of ϑ and w_f is **invariant** (not Γ -depending): $w_f \vartheta = \frac{\lambda}{2\pi}$

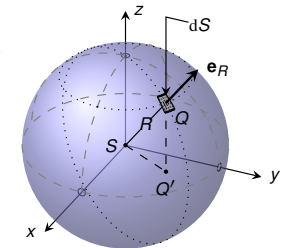


4.2.7 Intensity vector for different waves

Intensity of a spherical emw diverging and converging

- A spherical emw is associated to a source S of power P_0 . Its intensity at Q has spherical symmetry, is radially oriented:

$$\mathbf{I}_0(Q) = \frac{P_0}{4\pi R^2} \mathbf{e}_R$$



- the denominator $4\pi R^2$ compensates for the increase of the surface on which the power is distributed (a sphere!)
- The power P_0 might be negative. In that case S is an **e.m well** absorbing the power $-P_0 > 0$ and the intensity is directed towards S . The spherical wave is said to be **converging**.
- If P_0 is positive, the intensity is directed towards infinity, the spherical wave is said to be **diverging**.
- Spherical emw are good approximations of emw emitted by **far** thermal or fluorescent sources (like the sun). Converging spherical waves are generally produced by **lenses**.

4.2.8 Intensity vector for different waves (summary)

Plane, spherical and gaussian waves in the void

	Plane wave (dir. $\mathbf{e}_z$)	Gaussian wave (dir. $\mathbf{e}_z$)	Spherical wave
I_0	$\frac{1}{2\mu_0 c} \ \mathbf{E}_0\ ^2 \mathbf{e}_z$	$\frac{P_0}{\pi w(z)^2} e^{-\frac{r^2}{w(z)^2}} \mathbf{e}_z$	$\frac{P_0}{4\pi R^2} \mathbf{e}_R$
coord.	_____	$r = \sqrt{x^2 + y^2}$	$R = \sqrt{x^2 + y^2 + z^2}$
parameters	_____	$w(z) = \sqrt{\frac{\lambda \Gamma}{2\pi}} \sqrt{1 + \frac{z^2}{\Gamma^2}}$	_____
	$\mathbf{E}_0$: elec.amplitude	P_0 : transported power	
		λ : wavelength	
		$\Gamma > 0$: Rayleigh range	

- Collimated sources produced by lasers are well represented by gaussian waves
- Thermal (or fluorescent) emissions are well represented by spherical waves, especially far away from the source
- Plane waves are not physical, they correspond to an infinite quantity of energy!

$$\mu_0 = 4\pi \cdot 10^{-7} \text{ N/A}^2$$

4.2.9 Focusing far thermal/fluorescent sources

The lens transforms a diverging spherical emw into a converging one

- $\frac{1}{R} + \frac{1}{R'} = \frac{1}{f}$, $\frac{S'}{S} = \left(\frac{R'}{R}\right)^2$
- Image always after the focus: $R' \geq f$ (1)
- Construction limit for lenses: $f \geq 2\pi R_l$ (2)

The centers of emission/absorption are linked by geometrical optics

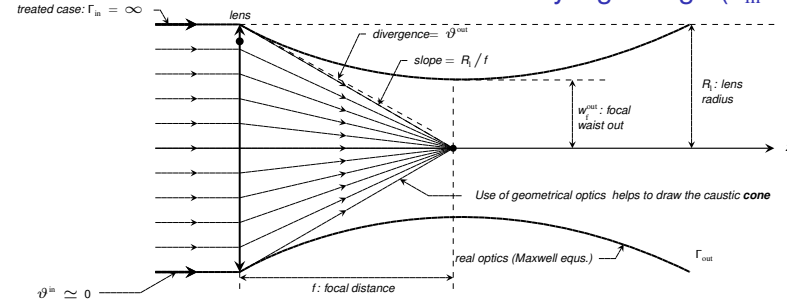
Computation of image intensity (order of magnitude)

- Intensity on the lens: $I_{\text{lens}} \simeq \frac{1}{4} P_{\text{source}} \frac{1}{\pi R^2} \mathbf{n}$
- Power collected by the lens: $P_{\text{lens}} = \frac{1}{4} P_{\text{source}} \left(\frac{R_l}{R}\right)^2$
- Intensity on the image: $I_{\text{image}} = \frac{P_{\text{lens}}}{S'} = \frac{1}{4} \frac{P_{\text{source}}}{S} \left(\frac{R}{R'} \frac{R_l}{R}\right)^2 = \frac{1}{4} \frac{P_{\text{source}}}{S} \left(\frac{R_l}{R'}\right)^2$
- Concl. (use of (1), (2)): $I_{\text{image}} \leq \frac{1}{4} I_{\text{source}} \left(\frac{R_l}{f}\right)^2 \leq \frac{1}{16\pi^2} I_{\text{source}}$

(see Append. 11, 13)

4.2.10 Focusing collimated beams: Gaussian beam

Effect of the lens: transformation of the Rayleigh range ($\Gamma_{\text{in}} \rightarrow \Gamma_{\text{out}}$)



- When $\Gamma_{\text{in}} = \infty$, the transf. rule can be explained by using geometrical optics
- The divergence of the beam in real optics is the slope of the beam in geometrical optics: $\vartheta^{out} \approx \frac{R_l}{f}$ thus $w_f^{out} = \frac{\lambda}{2\pi} \frac{1}{\vartheta^{out}} \approx \frac{\lambda}{2\pi} \frac{f}{R_l}$. The conclusion is that

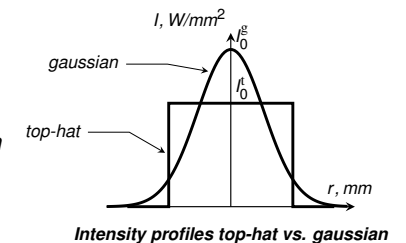
$$w_f \approx \lambda \cdot \frac{f}{2\pi R_l} \text{ in particular } w_f \geq \lambda \text{ since for any lens: } \frac{f}{2\pi R_l} \geq 1.$$

- The above inequality is called the **focusing limit equation**.

4.2.11 Focusing other beams: TEM, top-hat beams

TEM_{nm} modes, top-hat beams

- Lasers also have possibility to emit more general waves like: TEM (Transverse Electro-Magnetic) waves.
- They can also emit superpositions of such modes going to quasi top-hat waves.



Intensity profiles top-hat vs. gaussian

Focusing limit and beam quality

- Any TEM_{nm} modes or quasi top-hat mode has a focusing limit. It is expressed under the form of the focusing limit already obtained for gaussian modes:

$$w_f \geq M^2 \lambda \cdot \frac{f}{2\pi R_l} \quad \lambda : \text{wavelength and } f, R_l : \text{lens focal distance and radius.}$$

- The quantity $M^2 \geq 1$ is defined at the **beam quality**. We have $M^2 = 1$ for a gaussian beam and $M^2 = n^2 + m^2 + 1$ for a TEM_{nm} mode.

(see Append. 19)

Selective Laser Sintering and Melting

4.3.1 Selective Laser Sintering and Melting

Principle

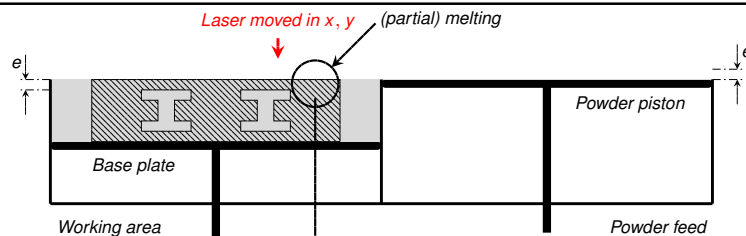
- A 3d part is manufactured layer by layer from a metallic, polymer or ceramic powder.
- The powder is selectively consolidated by a laser beam moved by galvanometric mirrors. The physical consolidation principle is basically liquid phase sintering or local fusion.
- The geometry of the part is transferred into the process by a coherent management of the galvanometric mirrors.

Acronym

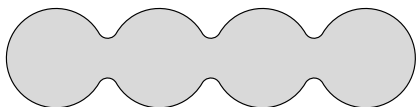
- This process is usually called SLS for "Selective Laser Sintering" or SLM for "Selective Laser Melting"
- Observe that the name **sintering** is used to qualify processes where the powder is only partly fused by the laser (e.g. in case of polymer or ceramic powders). Otherwise the name **melting** has to be used.
- According to new standardization rules, the names SLS and SLM should disappear in the future and be both replaced by L-PBF for "Laser Powder Bed Fusion".

4.3.2 Selective Laser Sintering and Melting

Diagram



Consol. mechanism: liquid phase sint.



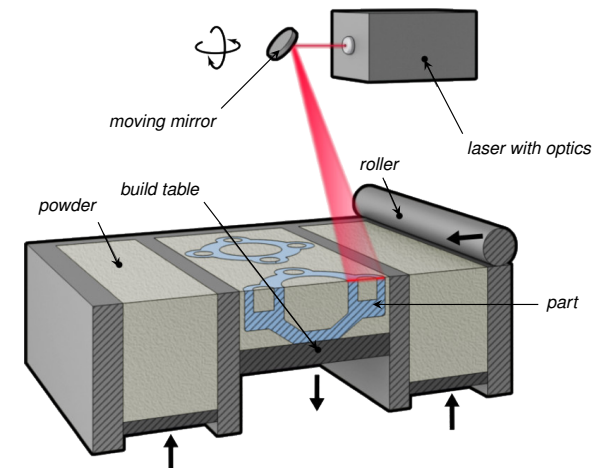
Remark

Easy recycling of unused powder

- mostly for metals (sieving operations required)
- less for polymers due to pre-heating

4.3.3 Selective Laser Sintering and Melting

Block diagram



4.3.4 Selective Laser Sintering and Melting

Equipment at EPFL: experimental platform



Technical data

Laser:	Nd:YAG (pulsed, 100W), Ytterbium fibre (cont., 500W)
Powder:	metal (Ti, Ni, Au, Ag, 316L, H13), blended ceram. (WC-CO)
Layers:	upto 20 μm
Workarea:	$\varnothing 120\text{ mm}$, $\varnothing 35\text{ mm}$, $z_{\text{max}} = 200\text{ mm}$
Miscellaneous:	On-line power beam and melt-pool control, beam-shaping

4.3.5 Needed laser intensity in SLS/M

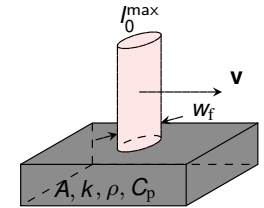
The maximal temperature under a non-moving light source

- A circular light source (focal waist w_f , peak intensity at center I_0^{max}) heats a material. The temperature elevation is estimated as

$$\Delta T_{\text{max}} \simeq \frac{A I_0^{\text{max}} w_f}{k} \times C_b$$

$$C_b = 1 \text{ for top-hat or } C_b = \frac{\sqrt{\pi}}{2} \text{ for g. beams}$$

- The coeff. A , k are the absorption and the thermal conductivity of the material.



The maximal temperature under a moving light source

- If the light source is moving (speed v), the temperature elevation is estimated as

$$\Delta T_{\text{max}} \simeq \frac{A I_0^{\text{max}} w_f}{k} \times C_b \times H\left(\frac{v}{v_{\text{diff}}}\right) \quad \text{where} \quad v_{\text{diff}} = \frac{2k}{\rho C_p w_f}$$

- ρ is the material density (g/cc), C_p its heat capacity (J/g $^\circ$ C), C_b is as above and $H(s) = \frac{1}{\pi} \int_0^\pi \frac{1 - e^{-s(1+\cos\vartheta)}}{s(1+\cos\vartheta)} d\vartheta$ for top-hat or $H(s) = \frac{1}{\pi} \int_0^\pi \text{erfcx}(s \frac{1+\cos\vartheta}{2}) d\vartheta$ for gaussian beams: $\text{erfcx}(y) = \frac{2}{\sqrt{\pi}} e^{y^2} \int_y^\infty e^{-t^2} dt$.

(see Append. 15, 16, 17, 18)

4.3.6 Needed laser intensity in SLS/M

Application: minimal intensity for metal selective laser sintering

- To sinter maraging steel the melting temperature has to be reached

Tab. Physical property of a typical maraging steel

k , W/mm/K	$A@ \lambda = 1064\text{ nm}$	ρ , g/mm 3	C_p , J/g/ $^\circ$ C	T_{melt} , $^\circ$ C
0.026	40%	8.04×10^{-3}	0.4	1413

- A gaussian IR-beam, $\lambda = 1064\text{ nm}$, is used with $w_f = 10\text{ }\mu\text{m}$ (for accuracy), with no pre-heating $\Delta T_{\text{max}} \simeq T_{\text{melt}} \implies$ the peak intensity to be used is at least:

$$I_0^{\text{max}} \geq \frac{k(T_{\text{melt}} - T_{\text{amb}})}{C_b A w_f} \simeq 1.04 \times 10^4 \text{ W/mm}^2.$$

- Productivity is achieved with high scan speed (e.g. $v = 3\text{ m/s}$) then we need:

$$I_0^{\text{max}} \geq \frac{k(T_{\text{melt}} - T_{\text{amb}})}{C_b A w_f} \times \frac{1}{H(\frac{\rho C_p w_f}{2k} v)} \simeq \frac{1.04 \times 10^4}{H(1.8554)} \simeq 2.6 \times 10^4 \text{ W/mm}^2.$$

- Such high intensity level can be obtained using laser, with efficient focusing!

(see Append.13, 18)

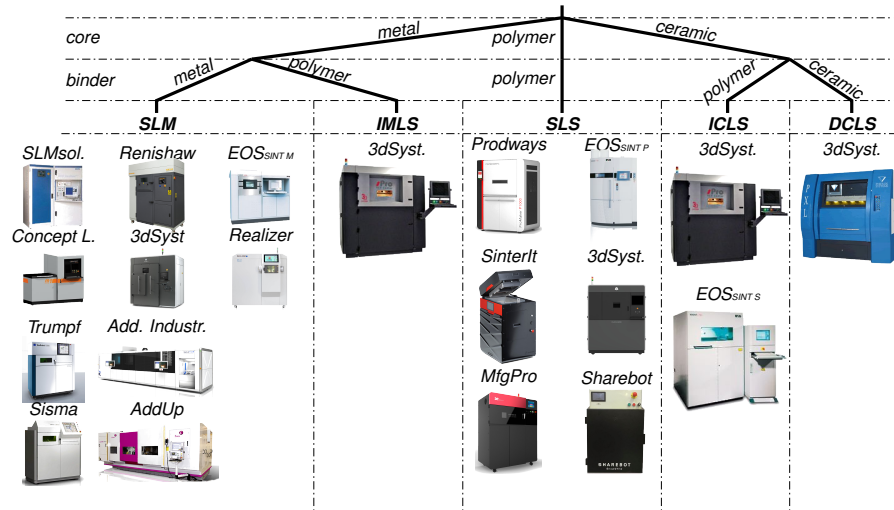
4.3.7 Selective Laser Sintering and Melting

Indirect and direct processes - Terminology

- The SLS(M) processes are sub-categorized according to the chemical nature (metal, polymer or ceramic) of the binder and of the core particles:
 - if the natures of the core and binder are the same, then the process is said to be **direct**. Otherwise the process is said to be **indirect**.
- The direct process for metal powders** is called acronym SLM (**S**elective **L**aser **M**elting). In this case, the laser is used to fuse almost all the powder. This solution avoids porosity and high density is achieved.
- In the direct process with polymer powders**, the preheating and the low thermal conductivity of the medium make too large melt pools problematic. Due to high capillary forces, too much liquid material would also impact badly the process resolution. For polymers, only a part of the powder will be fused and the consolidation principle will still be liquid phase sintering. To distinguish from the metal version, the acronym SLS (**S**elective **L**aser **S**intering) is maintained.
- The direct process for ceramic powder** is called **Direct Ceramic Laser Sintering** (DCLS).
- For indirect processes** using polymer binder, the prefix **Indirect** is used. The conventional acronyms are IMLS (**I**ndirect **M**etal **L**aser **S**intering) and ICLS (**I**ndirect **C**eramic **L**aser **S**intering).

4.3.8 Selective Laser Sintering and Melting

Systems and companies (non-exhaustive)

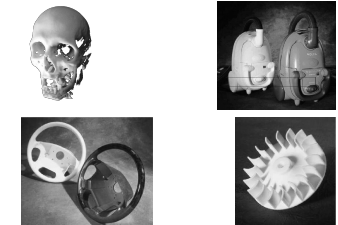


source: Wohlers report
(see Append. 20, 21, 22)

4.3.9 Selective Laser Sintering and Melting

Applications of direct processes -polymer (SLS)

High level models



Concept, funct. prototypes



Small series



Customized parts

(see Append. 23, 24, 25, 26)

4.3.10 Selective Laser Sintering and Melting

Applications of direct processes -metal (SLM)

Functional prototypes



Small series/unique parts



Customized parts



Moulds and cutting inserts

(see Append. 27, 28, 29, 30, 31, 32, 33, 34, 35)

4.3.11 SLS, technical data

Mechanical properties of part (order of magnitude)

Material	E, GPa	R _m , MPa	ε _{rup} , %
PEEK HP3	4.2	90	2.8
PA2201	1.7	48	15
PrimeCast101	1.6	5.5	0.4

Equipment (type, dimensions)

Laser	λ, μm	P, W	Build volume, mm ³
CO2	10.6	30-100	from 200 × 200 × 330 to 700 × 380 × 560

Performances

x-y resol., μm	layer thickness, μm	build speed, mm ³ /s	layering time, s
100	60 – 120	MCR = 10 – 100	10 – 30

4.3.12 SLM, technical data

Mechanical properties of part (order of magnitude)

Material	E, GPa	R _m , MPa	ε _{rup} , %	HRC
Ti6A4V	110	1'150	11	41
Inconel 718	170	980	31	30
Marag. steel	180	1'100	8	33

Equipment (type, dimensions)

Laser	λ, μm	P, W	Build volume, mm ³
Ytterbium Fiber	1.06	100-1000	250 × 250 × 300

Performances

x-y resol., μm	layer thickness, μm	build speed, mm ³ /s	layering time, s
40 – 60	50 – 80	MCR = 2 – 10	20 – 60

4.3.13 Selective Laser Sintering and Melting

Advantages, overview

- Base material easy to recycle, especially for metals (SLM).
- Can be applied to many materials (≠ SLA).
- Possible overhangs realizations without supports (the powder is self-supporting). Supports are however welcome:
 - In case of **metals**, the supports help to avoid thermal warpage. In the quasi-insulating powder, they behave like heat sinks: they regularize the thermal conditions and prevent problems connected to overheating and balling.
 - In case of **metals and polymers**, the supports stabilize the islands and avoid them to be moved by the rake.

Applications (summary)

- High level prototyping (functional prototypes, 1:1 models, ...).
- Small series of complex parts (robotics, fashion, jewelry, aerospace, ...).
- Customer fitted parts (medical, dental prostheses, ...).
- Rapid tooling (tools or prototype tooling for short runs).
- Tooling with conformal cooling.

4.3.14 Selective Laser Sintering and Melting

Scaling down of the processes: μ–SLS

- Limiting factor: the average size d₅₀ of the powder grains:

$$\text{resolution} \propto d_{50}.$$

- For most metallic powders the rule is:

$$d_{50} \gg 1\mu\text{m}.$$

- Finer powder cannot be handled. They agglomerate and do not **flow**:

$$\text{powder flowability} \simeq \frac{F_{\text{gravific}}}{F_{\text{cohesive}}} \propto \frac{V_{\text{gr.}}}{S_{\text{gr.}}} \propto d_{50} \rightarrow 0 \text{ if } d_{50} \rightarrow 0.$$

- Some exceptions: availability of nanometric powders for Mo, Ta, W ...
 - Those materials have relatively low cohesive forces. Unfortunately they are **refractory** materials and their consolidation process is **slow**.
- A μ–SLS machine has been developed by EOS TM in collaboration with MICROMAC TM.

Electron Beam Direct Manufacturing

4.4.1 Electron Beam Direct Manufacturing

Basic principle

- A 3D part is manufactured layer by layer from **metallic** powder .
- The powder is selectively consolidated by an **electron beam** moved by **magnetic deflectors**. The principle of consolidation is local fusion .
- The part geometry is transferred into the process through the control of the magnetic deflectors .
- To limit beam absorption, ultra void is needed inside the build chamber .
- To protect the surrounding against X-ray radiation emitted by the interaction between electrons and metal atoms, the build chamber also has to be heavily shielded .

Acronym

- The usual acronym is EBDM for "**E**lectron **B**eam **D**irect **M**anufacturing" .
- No to be confused with "**E**lectron **B**eam **M**achining" or EBM which is a subtractive process. It uses an electron beam to cut material !

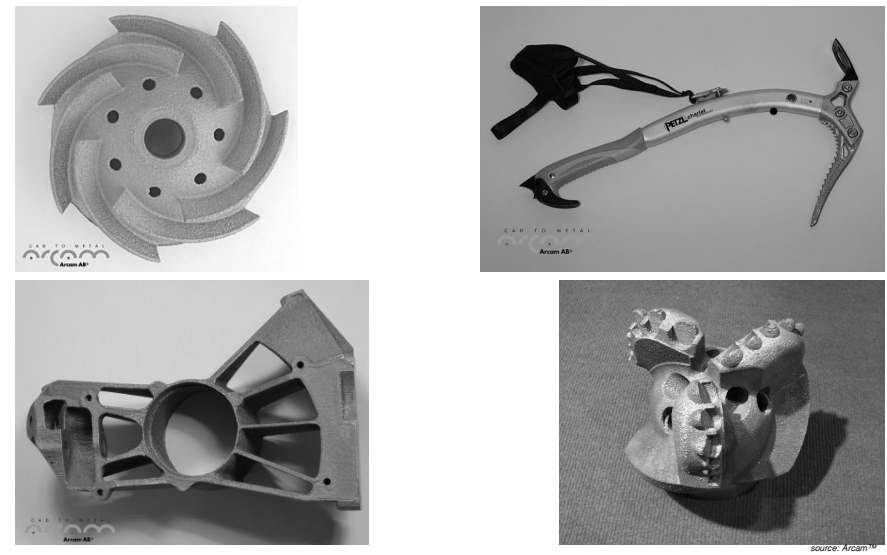
4.4.2 Electron Beam Direct Manufacturing

Equipments: Arcam™ machine



4.4.3 Electron Beam Direct Manufacturing

Example of parts 1



4.4.4 Electron Beam Direct Manufacturing

Example of parts 2



4.4.5 Electron Beam Direct Manufacturing

Compagny

Arcam AB™(Swedish company), now a part of General Electric (GE).

Advantages over SLS / SLM

- Slightly denser parts with somewhat higher mechanical properties.
- Higher building speed ($> 30 \text{ mm}^3/\text{s}$) due to higher nominal power.
- Less contamination (medical applications)

Disadvantages compared to SLS / SLM

- Compared to SLS/SLM stations, EBDM machines are more expensive and more complex:
 - a shielding is necessary to protect from X-ray emission,
 - a turbo-molecular pump is necessary to achieve ultra-void.
- EBDM is limited to metals.
- Less accuracy and resolution in EBDM.
- Potentially higher level of thermal stresses in EBDM.

Direct Metal Deposition

4.5.1 Direct Metal Deposition

Basic principle

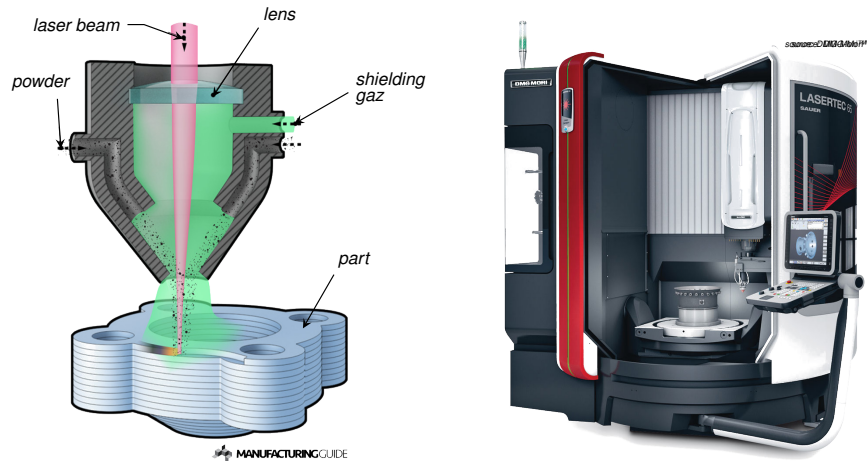
- A 3D part is manufactured from a **metallic** powder but not **layerwise**, the part grows in any directions .
- The powder is actually jetted selectively by a **nozzle** and molten by a laser beam. The principle of consolidation is local fusion .
- The part geometry is transferred into the process through the management of the nozzle displacements.

Acronym

- The usual acronym is DMD for "Direct Metal Deposition".
- The acronym DED for "Direct Energy Deposition" is used as well and tends to be even more popular .

4.5.2 Direct Metal Deposition

Equipments and technology



4.5.3 Direct Metal Deposition

Example of parts



- Mostly wired or shell-like parts, but with a rough surface finish.
- The main application is still to fabricate near net shape blanks.

4.5.4 Direct Metal Deposition

Advantages over SLS/SLM

- Machine with a lot of degrees of freedom (in theory: possibility to construct overhangs without supports).
- Possibility to mix materials in all directions.
- Possibility to combine with ablative processes.

Disadvantages compared to SLS/SLM

- More expensive (laser and a 5 axis machine), less resolution, thermal stresses.

Companies and remarks

- Optomec™, BeAM™ (Irépa Laser), DMG Mori™, Okuma™.
- The "Direct Metal Deposition" process is sometimes presented under the name "Laser engineered net shaping" (LENS) or "Laser cladding" when considered as a **reparation and coating** process only.
- The "Direct Metal Deposition" process only differs from "Laser Metal Wire Deposition" by the fact that the base material is a powder and not a wire.

4.6.1 The 'Jet Fusion' process

Principle

- A 3d part is built layer by layer by consolidating a polymer powder through a classical liquid phase sintering mechanism .
- An inkjet printer head selectively deposits a **fusing agent** where the powder needs to be consolidated and a **detailing agent** where it should not .
- A IR flash is globally applied onto the powder bed :
 - The fusing agent (usually charged with carbon particles) absorbs the radiation, heats up and melts the surrounding powder grains promoting liquid phase sintering .
 - The detailing agent (usually a greasy fluid) absorbs and heats up less. It also inhibits sintering even under high temperature .

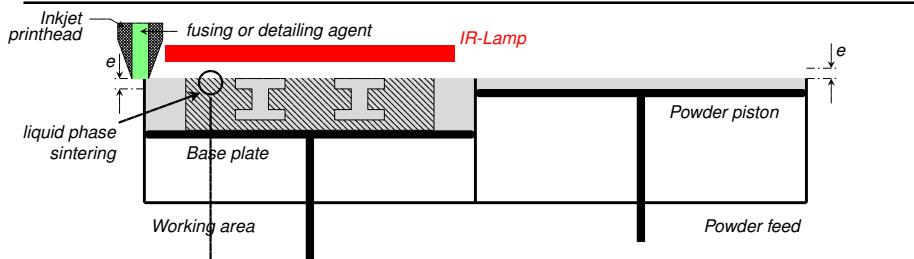
Remark

- The success of this process is linked to the development by HP™ of efficient and cheap fusing and detailing agents. It can be seen as a combination between the binder deposition and the SLS processes .

4.6 The 'Jet Fusion' process

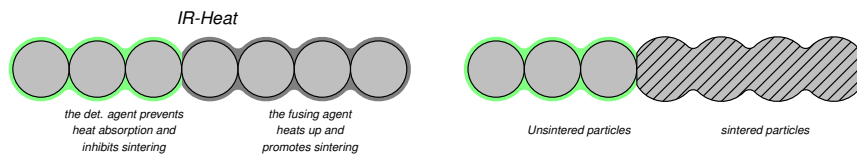
4.6.2 The 'Jet Fusion' process

Diagram



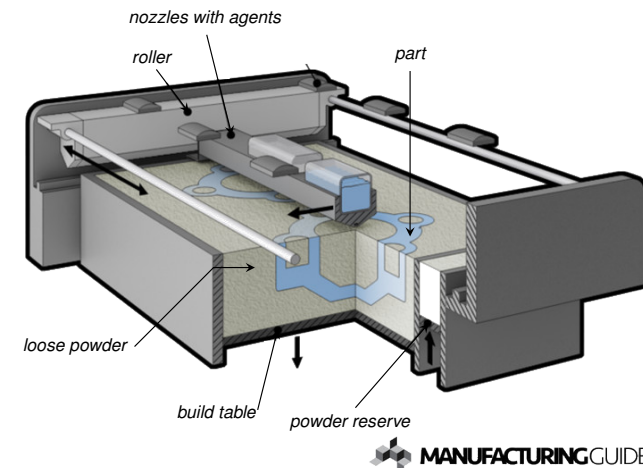
Consolidation mechanism

Liquid phase sintering



4.6.3 The 'Jet Fusion' process

Block diagram



4.6.4 The 'Jet Fusion' process

Equipements: HP™ Jet Fusion 580/380 Color Printer



Printing station

Cleaning station

source: HP™

4.6.5 The 'Jet Fusion' process

Example of parts 1



source: HP™ & LitePro™

4.6.6 The 'Jet Fusion' process

Example of parts 2



source: Nike™

source: Nike™

4.6.8 The 'Jet Fusion' process, technical data

Mechanical properties of part (order of magnitude)

Material	E, GPa	R _m , MPa	ε _{rup} , %
Nylon 12 (PA12)	1.7-1.8	48	15-20

Equipment (type, dimensions)

Printhead, dpi	Build volume, mm ³
1'200	from 332 × 190 × 248 to 254 × 190 × 248

Performances

x-y resol., μm	layer thickness, μm	build speed, mm ³ /s	layering time, s
50 – 80	80	n.a.(∞) ¹	2 – 5

¹ the build time is not sensitive to part volume but only to part height:

$$\text{fab.time} = \frac{\text{height}}{e} \cdot \frac{T_{\text{layer}}}{N}$$
 with e : layer thickness, N : batch size.

4.6.9 The 'Jet Fusion' process

Companies: HP™

Advantages, applications

- Fast process (the specific consolidation time is $\simeq 0$). For average parts this process can be considered to be 5 to 10 times faster than **SLS**.
- Better mechanical properties than **binder jetting**: the grains are not connected by binder but after sintering.
- High resolution and precision due to the effect of the detailing agent.
- Potential use of different type of agents (coloring agents,) to tune the part properties (color, mechanical properties, etc...).

Disadvantages

- Today the material portfolio is relatively narrow (limited to PA12?). The fusing and the detailing agents have to be developed specifically for each polymer.
- Very long cooling time before one can touch the parts.

A 1: Digital Metal: binder jetting in metal powders

Equipments: Digital Metal by Höganäs™



APPENDICES

- Indirect process: necessity to post-process the green parts in a sintering oven
- Similar to MIM process without the need of **tooling**

A 6: Prometal™ process: 3d printing of sand moulds

Applications:

- Molds for small series,
- Molds for prototypes series,

Remarks:

- Observe that no cores will have to be **installed manually** to cast parts with internal structures. Any cavity, any gate, and any riser can be directly manufactured. The only constraint is to maintain the possibility of removing the non-consolidated sand.
- Molds for large runs are still made by pressing/holding the sand around shape tools (master models) for the external shape and by installing kernels to cast parts with internal structures.

A 7: A way to measure intensity

GENTEC™ power-meter

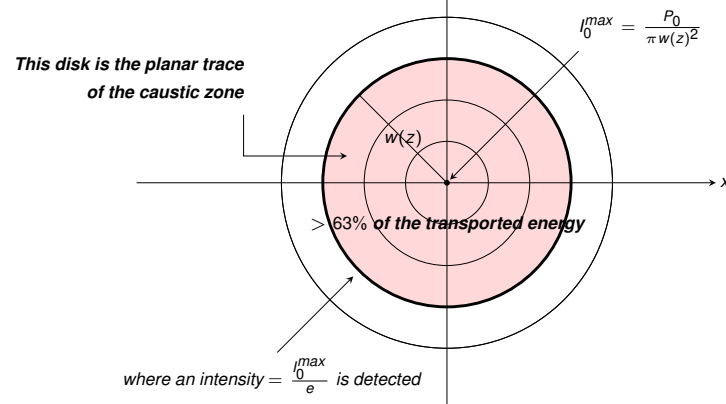


source: GENTEC™

A 8: Beam waist

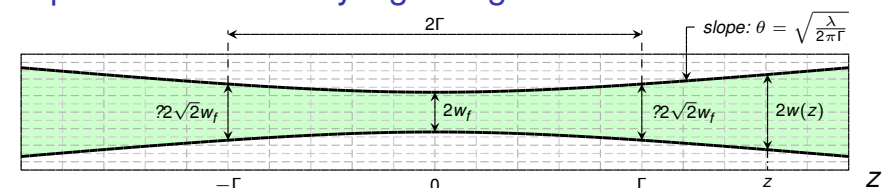
Isolines of the intensity in a plane $z = c^{ste}$ and max. intensity

Recall: $I_0(r, z) = \frac{P_0}{\pi w(z)^2} e^{-\frac{r^2}{w(z)^2}} e_z$



A 9: Rayleigh range

Interpretation of the Rayleigh range



- The waist depends on z : $w(z) = w_f \sqrt{1 + \frac{z^2}{\Gamma^2}}$ with $w_f = \sqrt{\frac{\lambda \Gamma}{2\pi}}$
 $w(0) = w_f$ and $w(\pm\Gamma) = \sqrt{2}w_f \Rightarrow$ interpretation of Γ

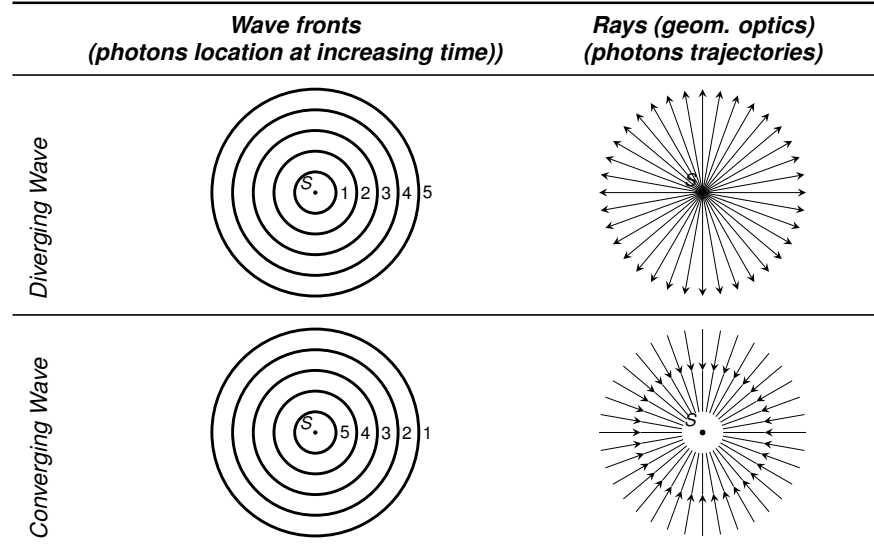
- **Example:** Take a UV-laser ($\lambda \simeq 450$ nm) beam:

$$w_f \simeq 10 \text{ mm} \Rightarrow \Gamma = 2\pi \frac{w_f^2}{\lambda} \simeq 2 \times 3.14 \times \frac{0.01^2}{450 \times 10^{-9}} \simeq 1'396 \text{ m}$$

- In that case, the Rayleigh range is more than 1 km.
- Large Rayleigh range corresponds to focal waist w_f which are large compared to λ , but to small divergence θ .

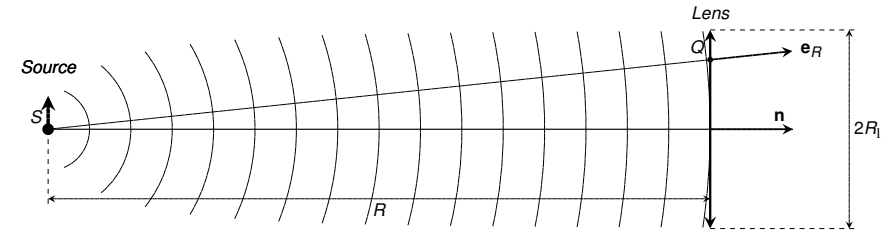
A 10: Spherical waves representation

Geometrical optics/photonic



A 11: Intensity on the lens

If the source and the lens are far way (compared to their dimensions)



Intensity at $Q \in \text{lens}$: $I_{\text{lens}} = \frac{P_{\text{source}}}{4\pi ||SQ||^2} \mathbf{e}_R$

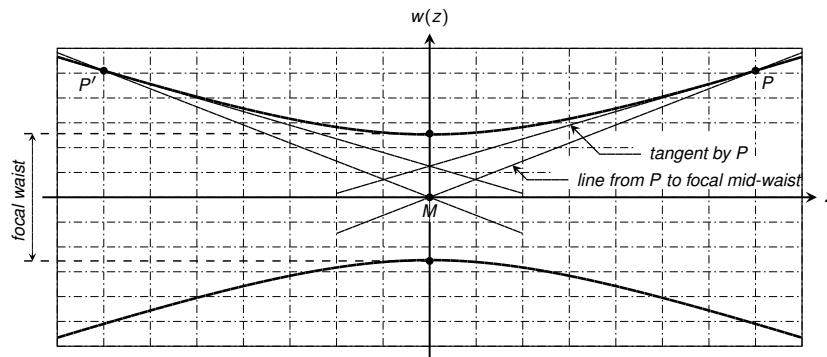
but $||SQ|| \simeq R$ and $\mathbf{e}_R \simeq \mathbf{n}$: $I_{\text{lens}} = \frac{P_{\text{source}}}{4\pi R^2} \mathbf{n}$

Power on lens: $P_{\text{lens}} = \int_{\text{lens}} \underbrace{I_{\text{lens}} \cdot \mathbf{n}}_{= \frac{P_{\text{source}}}{4\pi R^2}} d\sigma = \frac{P_{\text{source}}}{4\pi R^2} \pi R_l^2 = \frac{1}{4} P_{\text{source}} \frac{R_l^2}{R^2}$

A 12: A property of gaussian caustics

The gaussian caustic is $w(z) = \sqrt{\frac{\lambda \Gamma}{2\pi}} \sqrt{1 + \frac{z^2}{\Gamma^2}}$

- It has the property that $w(z) \geq zw'(z)$ for any $z \in \mathbb{R}$.
- The geometrical interpretation is that the tangent at any point P is always above the line joining P to the middle M of the focal waist.



A 13: Intensity to be reached: $I_0^{\text{max}} \simeq 10^5 \text{ W/mm}^2$

Thermal sources

The intensity emitted by a thermal source of emissivity ε is given by:

$$I_{\text{source}} = \varepsilon \sigma T^4, \quad \text{where } \sigma \simeq 5.670373 \times 10^{-14} \text{ W/mm}^2/\text{K}^4.$$

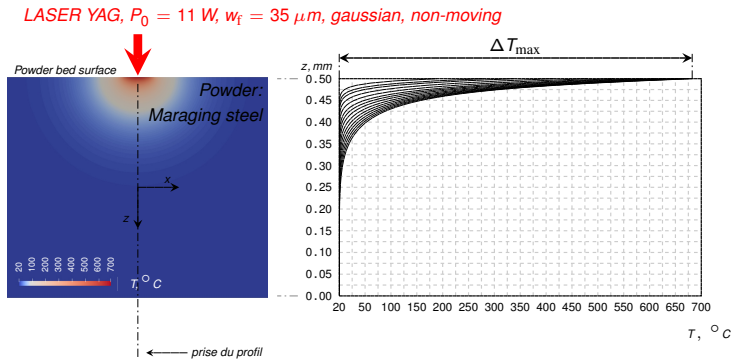
Source	Temp T , K	ε , -	I_{source} , $\frac{\text{W}}{\text{mm}^2}$	I_{image} , $\frac{\text{W}}{\text{mm}^2}$ (best)	effect
Wire(W)	$\simeq 2500$	0.35	$\simeq 0.77$	$\simeq 0.005$	none
Sun	$\simeq 5772$	1.0	$\simeq 63$	$\simeq 0.4$	burn pap.

Gaussian sources (laser)

wavelength $\lambda = 1.064 \mu\text{m}$	power $P_0 = 100 \text{ W}$	lens focal $f = 800 \text{ mm}$	lens radius $R = 25 \text{ mm}$
foc. waist $w_f \simeq 5.41 \mu\text{m}$	peak intensity $I_0^{\text{max}} = 1.08 \times 10^6 \text{ W/mm}^2$		

A 14: Heat diffusion

Heat diffusion in a powder bed after 90 ms



- After some ms, the maximal temperature stops increasing and stabilizes at a value

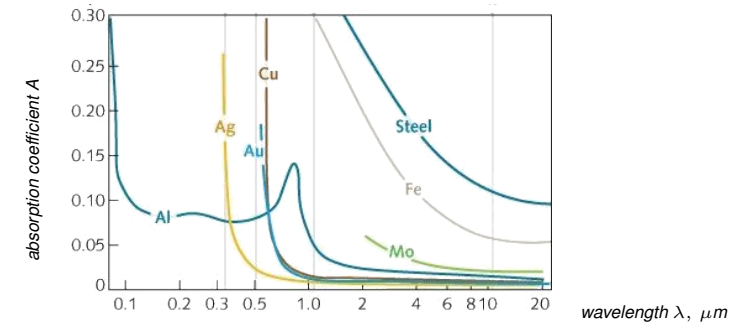
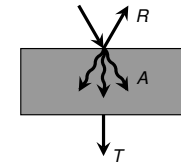
$$\Delta T_{\max} \rightarrow \frac{AP}{\pi k w_f} C_b, \quad C_b = \begin{cases} \sqrt{\pi}/2 & \text{gaussian beam} \\ 1 & \text{top-hat beam} \end{cases}$$

- The delay for stabilization depends on the therm. diffusivity $\eta = \frac{k}{\rho C_p}$ of the mat.

A 15: Absorption coefficient

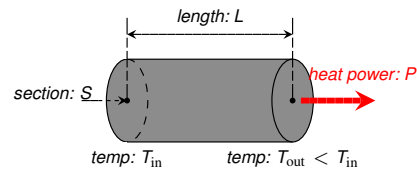
Definition of the absorption coefficient A

- Consider light in incidence onto matter. A part R of the transported energy is reflected, a part T is transmitted and a part $A = 1 - (R + T)$ is absorbed.
- The number $A \in [0, 1]$ is called **absorption coefficient**.
- The abs. coefficient A is a material property. It also depends on the wavelength:



A 16: Thermal conductivity (definition)

Thermal conductivity describes the ability to conduct heat



- temp. gradient: $\frac{T_{\text{in}} - T_{\text{out}}}{L} > 0, ^\circ\text{C}/\text{m}$
- heat flux: $\frac{P}{S}, \text{W}/\text{m}^2$

- Fourier:** The heat flux is proportional to the temperature gradient.
- The proportionality coefficient is material dependent. It is called thermal conductivity and denoted k:

$$\frac{P}{S} = k \frac{T_{\text{in}} - T_{\text{out}}}{L} \quad \text{unit of } k: \text{W}/\text{m}/\text{K} \text{ or } \text{W}/\text{mm}/\text{K}.$$

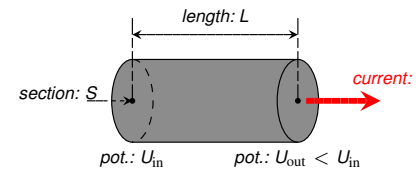
- Typical values of k (around room temperature) are given below:

material	k, W/m/K	material	k, W/m/K	material	k, W/m/K
Silver	419	Copper	385	Gold	301
Tungst.	163	Mar. Steel	14 – 25	Titanium	17
Alumina	25	Epoxy	0.5	ABS	0.1 – 0.2

(source: matweb)

A 17: Electrical conductivity

Electrical conductivity describes the ability to conduct charges



- potential gradient: $\frac{U_{\text{in}} - U_{\text{out}}}{L} > 0, \text{V}/\text{m}$
- specific current: $\frac{I}{S}, \text{A}/\text{mm}^2$

- Ohm:** The specific current is proportional to the potential gradient.
- The proportionality coefficient is material dependent. It is called electrical conductivity and denoted σ :

$$\frac{I}{S} = \sigma \frac{U_{\text{in}} - U_{\text{out}}}{L} \quad \text{unit of } \sigma: \text{A}/\text{m}/\text{V} \text{ or } \text{A}/\text{mm}/\text{V}.$$

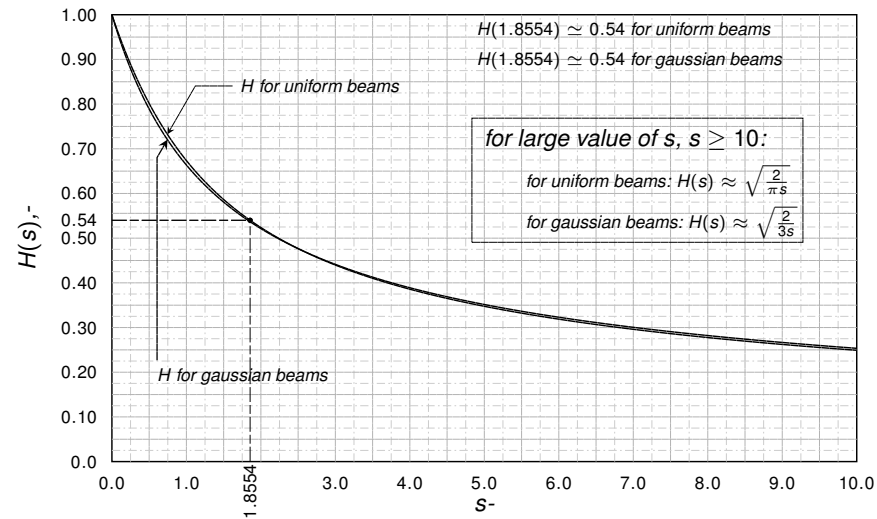
- Typical value of σ (around room temperature) are given below:

material	$\sigma, \text{A}/\text{m}/\text{V}$	material	$\sigma, \text{A}/\text{m}/\text{V}$	material	$\sigma, \text{A}/\text{m}/\text{V}$
Silver	$6.4 \cdot 10^7$	Copper	$5.8 \cdot 10^7$	Gold	$4.5 \cdot 10^7$
Tungst.	$1.7 \cdot 10^7$	Mar. steel	$\simeq 0.4 \cdot 10^7$	Titanium	$0.18 \cdot 10^7$
Alumina	$< 10^{-12}$	Epoxy	$< 10^{-10}$	ABS	$< 10^{-7}$

(source: matweb)

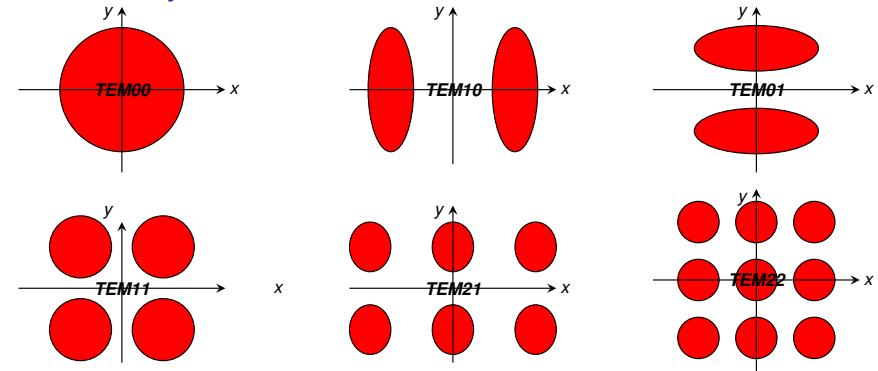
A 18: Graphical representation of the H functions

Functions $s \rightarrow H(s)$ for uniform and gaussian beams



A 19: Profiles of TEM_{nm} beams in the plane Oxy

Iso-intensity lines



TEM_{nm} and gaussian mode

- The TEM₀₀ mode is actually identical to the **gaussian mode**.

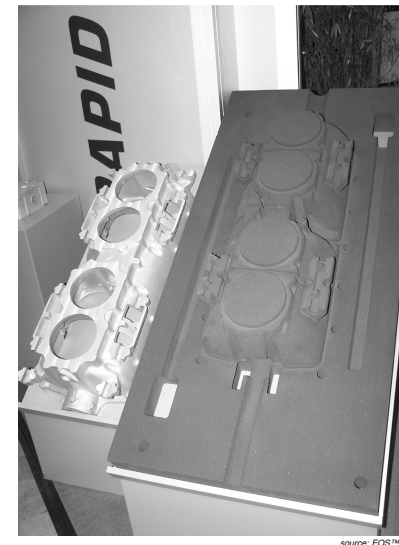
A 20: Sand moulds by ICLS

Sand moulds: ICLS



A 21: Sand moulds by ICLS

Sand molds: ICLS

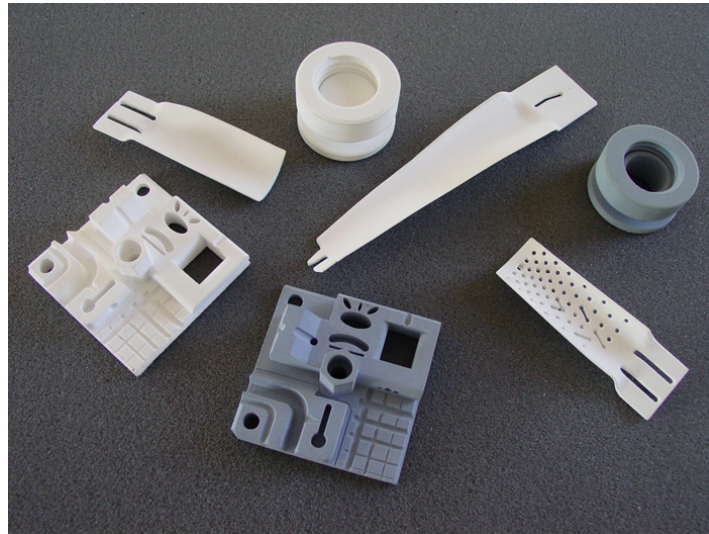


Remark:

- This process integrates the kernel fabrications and is adapted to prototype moulds or to moulds for unique parts (or small series).
- It is in direct competition with the 3dP Prometal™ process. The last one is preferred today.

A 22: Ceramic parts by ICLS

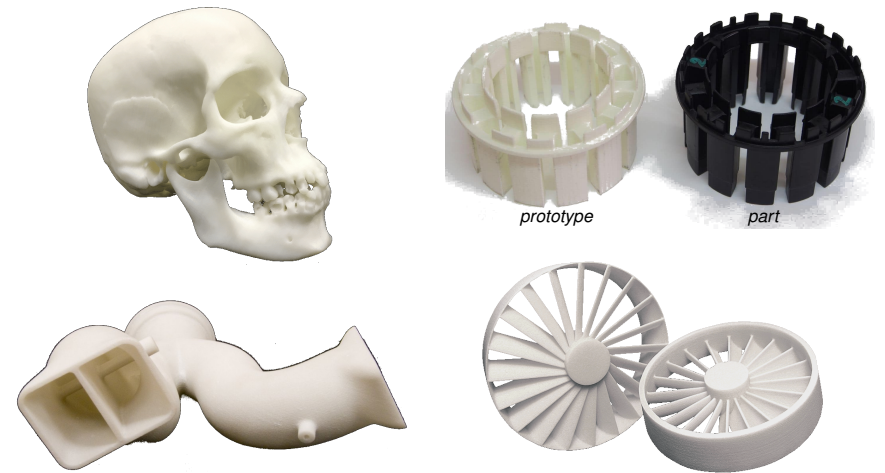
Parts ICLS and DCLS



source: Phenix-Systems™

A 23: High level prototypes by SLS

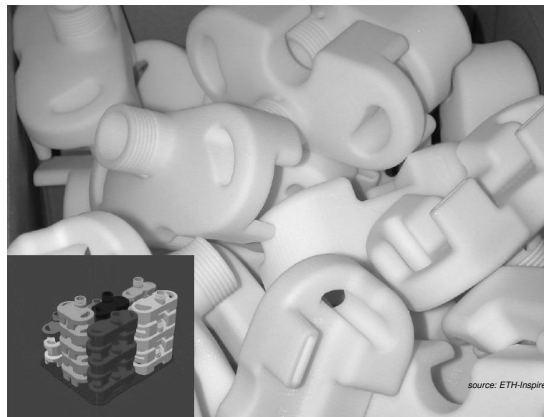
Prototyping by SLS



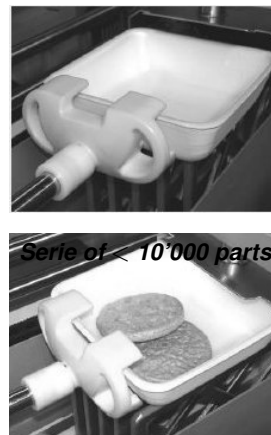
source: EOS™, 3dSystems™

A 24: Small series of parts by SLS

Robotics: Trays handlers



source: ETH-Inspire

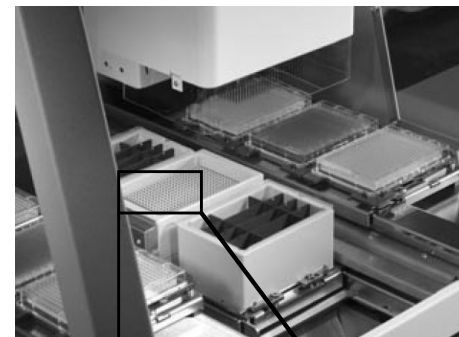


Historical use of powders processes

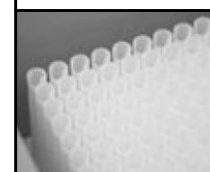
⇒ This application request particular elastic properties

A 25: Small series of parts by SLS

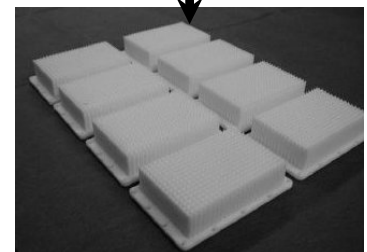
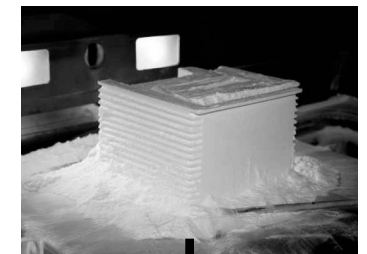
Robotics: Washing devices for pharmaceutical pipettes



source: ETH-Inspire



Fabrication



A 35: Fabrication of tools by SLM

Conformal cooling

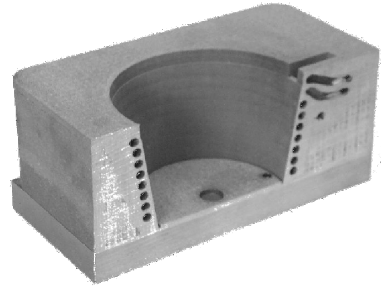
Optimised cutting tool (SLM)



source: ConceptLaser™

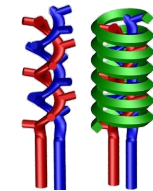
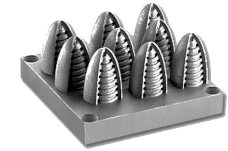
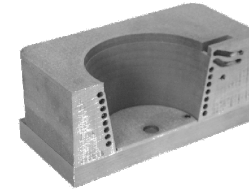
Improved cutting speed and tool life
Improved lubricant distribution

Optimised injection mould (SLM)



Reduced cycle time
Less injection constraints
⇒ Injection of parts with thinner walls

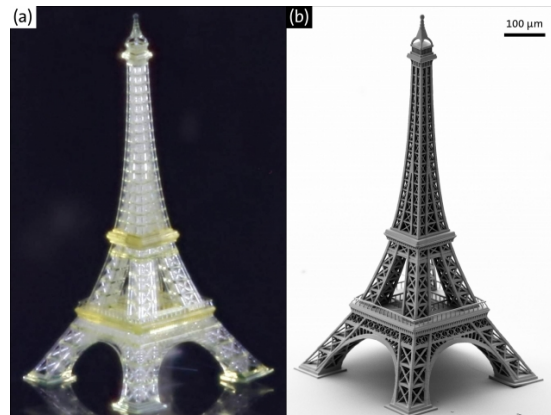
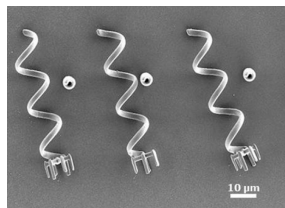
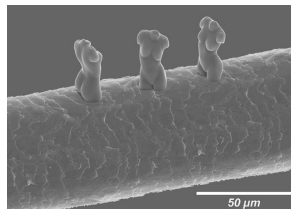
Conformal cooling (cutting tools / injection moulds)



courtesy of ConceptLaser™ PhenixSystems™

A 36: Micro-stereolithography

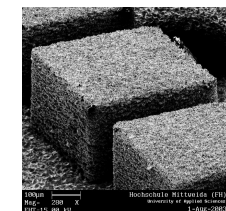
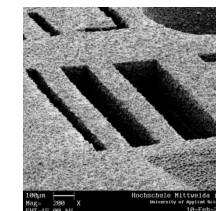
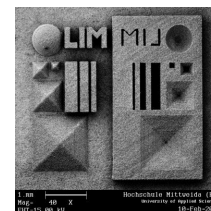
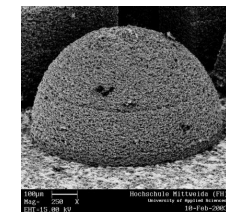
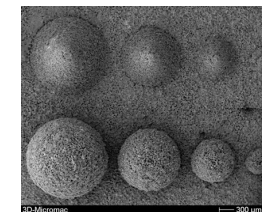
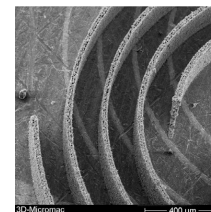
Very small parts can be obtained by scaling down the process



source: Fraunhofer-Institut für Lasertechnik Aachen

A 37: μ -SLS(M) process: example of parts

μ -SLS: example of parts (Tungsten)



source: micromac™ TU Mitweida

