Additive manufacturing (3d Printing) and application to micro-mechanics

Eric Boillat[1]

[1] Laboratoire de Métallurgie Thermomécanique
Institut de Science des Matériaux
EPFL

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Programm

Five parts

Part I

Additive processes

Additive processes
- Generalities
- Classification
- Historical remarks

1.1.1. Classification of production processes

The production processes fall into three main classes

- *The **subtractive** production processes where the part is manufactured by material **removal**:*
  - *milling, electrical discharge machining,*
  - *electrochemical machining,*
- *The **replicative** production processes where the part is manufactured by material **addition/deformation** in/on **a shape tool**. The shape tool has **a dedicated shape** and comes in contact with the part:*
  - *plastic injection,*
  - *sand-casting,*
  - *deep drawing,*
  - *classical sintering.*
- *The **additive** production processes where the part is manufactured by material **addition without use of shape tools**.*

Current names for additive processes

- *Rapid prototyping, Rapid tooling, Rapid manufacturing, 3d Printing.*

1.1.2. Some benefits of additive manufacturing

Direct from CAD to part, no tooling

- *They require **fewer steps** and most of the fabrication time can be hidden.*
- *Additive processes are **cheap in labor** due to a high degree of automation.*

Geometrical complexity for free

- *Additive processes enable the fabrication of almost any **kind of geometry**.*
- *They offer a solution to produce freely **optimized design** and parts with **integrated functions**.*

Fast, economical and fewer transportation

- *For a large class of applications (e.g. small and complicated parts) additive processes are **faster** than traditionnal processes.*
- *In general they also imply **less waste**. They do not produce chips and, in principle, only the material going into the part is used*
- *The additive processes are not based on highly dedicated equipments and use generic raw material. They are adapted to **localized production** (spare parts in aircraft carriers, space stations, machinery industry)*

(see Append. 3, 1,2, 4)

1.1.3. Some disadvantages of additive manufacturing

Inferior mechanical properties

- *The available materials to be applied in additive processes are **limited**.*
- *The consolidation might be problematic leading to **poor density/resistance or to anistropy**.*
- *Additive processes are still relatively random processes and they are **difficult to control**.*

Expensive and slow processes

- *Equipments and base material for additive processes are still **relatively expensive**.*
- *For large/uncomplicated parts or for very high series, there exist **traditionnal processes** which are **much faster**.*
- *In general, additive processes are not adapted to **low-end** applications.*

1.1.4. Classification of additive processes

Four main categories:

Material	***Further distinctions***	***Examples***
	Light deliver.	
Photoresist UV-curing	*laser* *flash + selective dep.* *structured flash*	*Stereolithography (SLA)* *Polymer jetting (PolyJet)* *Direct light processing (DLP)*
	material	
Extruded solid	*Amorph. thermoplastic* *Wax*	*Fused deposition model. (FDM)* *Ballistis part. model. (BPM)*
Jetted powder		*Direct metal Deposition (DMD)*
	consol. principle	
Powder bed	*Binding* *Thermal consolidation*	*Binder jetting (3dP)* *E-Beam direct manufacturing (EBDM)* *Sel. laser sintering/melting (SLS(M))*

1.1.5. History of additive processes

Main developments

Date	Inventor(s)	Process	Material
1979	R.Householder, H.Kodama, C.Hull	SLA	Photoresist
1989	S.Crump	FDM	ABS wire
1989	H.Marcus, C.Deckard (UTA)	SLS	Thermopl. powder
1991	EOS™	SLS-SLM	Metallic powder
2000	-	Objet Polyjet	(Jetted-)photoresist

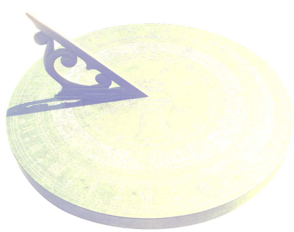
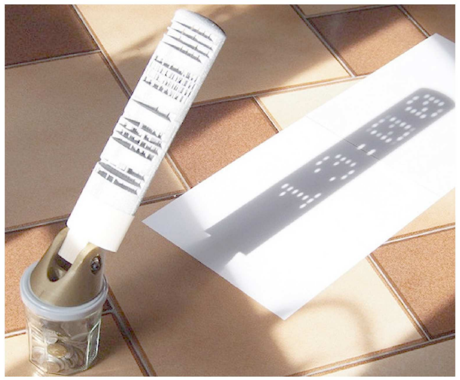
Milestones

Date	Event	and main consequences
2009	Stratasys patent about FDM in the public domain	
		Development of **inexpensive** jet- or extrusion- based machines
		Popularization of the name **3d-printing** instead of **AM**
2013	Obama, State of union	
		starting point of national competence centre on AM (NAMII)

APPENDICES

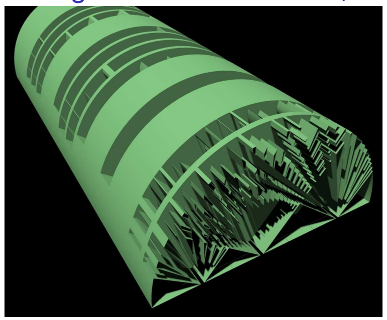
A 1: Integrated functions: innovation through AM

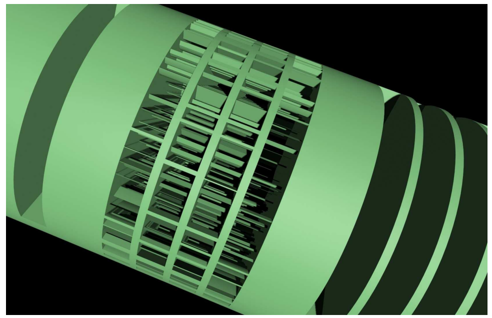
New generation of sundial.

Analog sundial (classic)	*Digital sundial (3d-printed)*
	

A 2: Integrated functions: innovation through AM

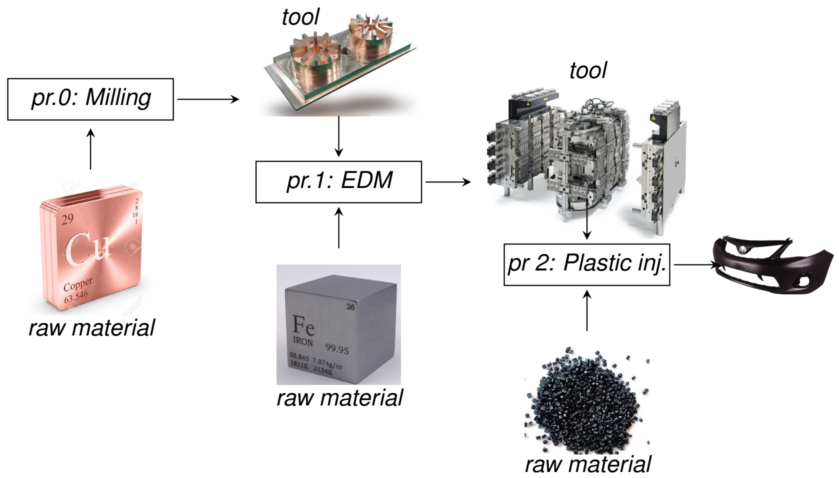
New generation of sundial, only possible by 3d-printing.





A 3: Process chain

Illustration of a process chain to get a part



- *The combination of process 0, 1 and 2 is called a **process chain**.*
- *The use of additive manufacturing may simplify a given process chain!*

A 4: Faster through additive manufacturing

3d printed (SLM) fuel nozzle

- *3 parts instead of $\simeq$ 237 to be assembled (mostly welding).*
- *Manufacturing time: **one day**.*
- *Material: **nickel based alloy**.*
- *Other benefits:*
  (i) *Fuel savings due to improved channels geometry ($ 3 millions per year and per aircraft).*
  (ii) *Increased lifetime due to fewer welds (=weak points).*

A 5: The NAMII National Additive Manufacturing Innovation Institute

A new industrial revolution

- *Additive manufacturing is seen as a way to maintain the **competitiveness** and the **sustainability** of our industry in the future:*
  "the 3-D printing has the potential to revolutionize the way we make almost everything. There's no reason this can't happen in other towns."

  Obama, State of Union address, 2013

National competence centers on additive manufacturing

America Makes
National Additive Manufacturing Innovation Institute

Fraunhofer
GENERATIV

$\Longrightarrow$ ***Towards Industry 4.0***

Part II

Photoresist processes

Stereolithography

2.1.1. Stereolithography, basic

Basic principle

- *A 3D part is built layer by layer from a photoresist.*
- *The resin is **selectively** consolidated by a UV laser deflected by galvanometric mirrors. The principle of consolidation is the curing of the photoresist molecules under the effect of UV light (UV-curing) .*
- *A chemical substance (inhibitor) prevents the UV-curing to diffuse to all the photoresist.*
- *The intelligence of the process goes through the management of the galvanometric mirrors displacements.*

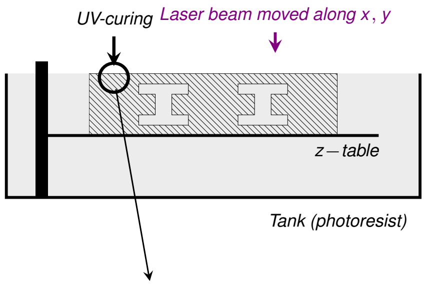
Etymology and acronym (3dPrinting before time!)

- ***-lithography** means writing (γραφη) on the stone (λιθος)*
- ***stereo-** is a reference to tri-dimensionnal reconstruction (στερεος=solid)*
- *The common acronym for this process is SLA.*

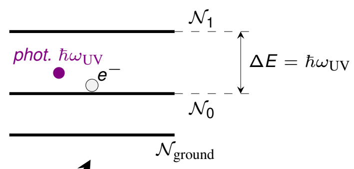
(see Append.6)

2.1.2. Stereolithography, basic design

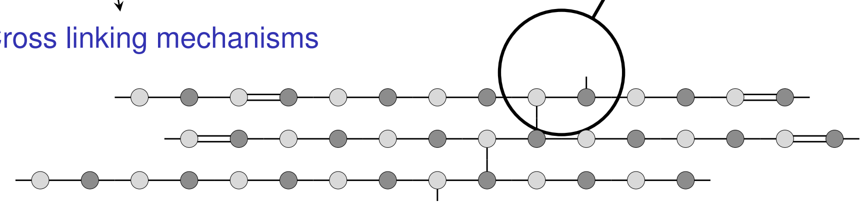
Diagram



Transition to excited level

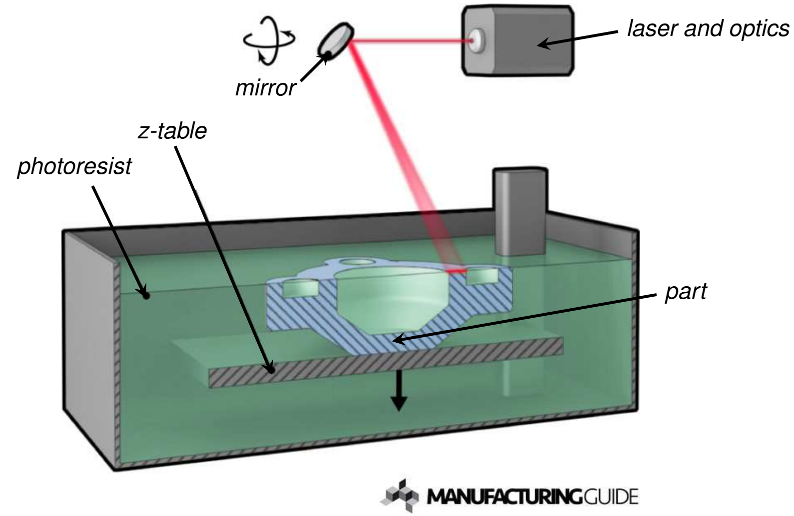


Cross linking mechanisms



2.1.3. Stereolithography, the machine

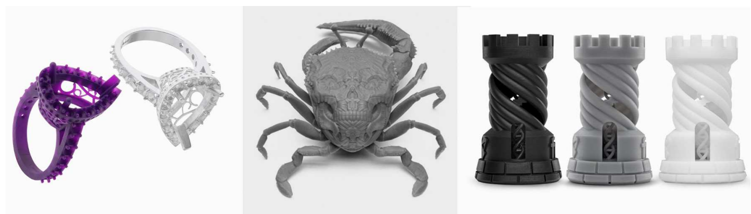
Details of the machine



2.1.4. Stereolithography, parts

Example of parts

lost patterns *prototypes/hobbies*



source: Formlabs™

occlusal protection *dental models* *surgical guides*

source: Formlabs™

2.1.5. Stereolithography, technical data

Mechanical properties of part (order of magnitude)

Material	E, GPa	R_m, MPa	ε_{rup}, %
VisiJet Flex	1.6	38	16
VisiJet HiTemp	3.4	66	6

Equipment (type, dimensions)

Laser	λ, μm	P, W	**Build volume**, mm^3
Helium-Cadmium (HeCd)	0.325	0.025	$250 \times 250 \times 500$

Performances

x-y resol., μm	**layer thick.**, μm	**build speed**, mm^3/s	**layering time**, s
$25 - 50$	$50 - 100$	$MCR = 5 - 10$	$10 - 20/1 - 2$[1]

(see Append. 7, 8)

[1] down-top or top-down

2.1.6. Stereolithography

Companies

- 3DSYSTEMS™ *(*PROJET *serie,* IPRO *serie,* SPRO *serie)*
- FORMLABS™.

Advantages and applications

- *Relatively precise (even better then 25 μm)*
- *Transparent materials, assembly of several parts (bonding),*
- *Master model for investment casting, for PUR molding (vacuum casting),*
- *Rapid manufacturing of parts in small series, fabrication of custom items.*

Disadvantages and issues

- *Technique limited to photoresists,*
- *Standard materials are expensive, toxic and difficult to store,*
- *Significant change in properties of the parts with time (aging),*
- *Post-processing required as well as supporting structures.*

(see Append 9, 10, 11, 12, 13, 14 15, 16)

Digital Light Processing (DLP)

2.2.1. Direct light processing

Basic principle

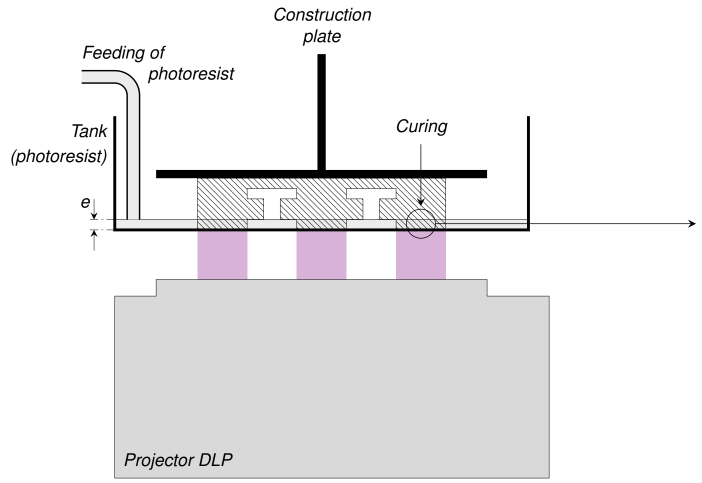
- *A 3D part is built layer by layer out of a* ***photoresist***
- *The resin is selectively consolidated by a UV flash deflected by a network of mirrors. The principle of consolidation is* ***photocuring****.*
- *The details of the part geometry are transferred into the process through the management of the deflecting mirrors.*
- *The acronym of this process is* ***DLP****.*

Direct light processing and stereolithography

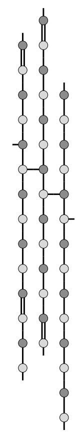
- *Direct light processing derives from the stereolithography by a modification of* ***the consolidation tool*** *and of* ***the intelligence transfer****.*

2.2.2. The DLP process

Diagram



Consolidation mechanism: cross-linking



2.2.3. Direct light processing

Typical equipments

Sisma EVE	Envisiontec™	B9 Creator™

source: Sisma™

source: Envisiontec™

source: B9 Creator ™

2.2.4. DLP (Envisiontec™), technical data

Use of material

Material	Application
Standard resin	*prototyping, master models (vacuum casting)*
Thermofusible resin	*lost patterns (investment casting)*
Charged resin	*mold cavity*

Equipment (type, dimensions)

Build volume, mm^3	*Low Precision (LP Mode)*	*High Precision (HP Mode)*
	$120 \times 90 \times 230$	$60 \times 45 \times 230$

Performances

DLP beamer with 1400×1050 pixels

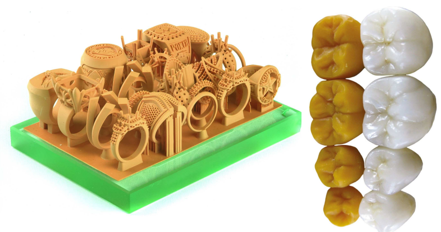
Mode	x-y resol.	layer thick.	build speed	layering time
LP	86 μm	50 μm	*n.a.* $(\infty)^2$	$< 10\,s$
HP	43 μm	25 μm	*n.a.* $(\infty)^2$	$< 10\,s$

[2] *the build time is not sensitive to part volume but only to part height: fab.time* $= \frac{height}{e}\frac{\tau_{layer}}{N}$ *with* e : *épaisseur de couche*, N : *taille de lot.*

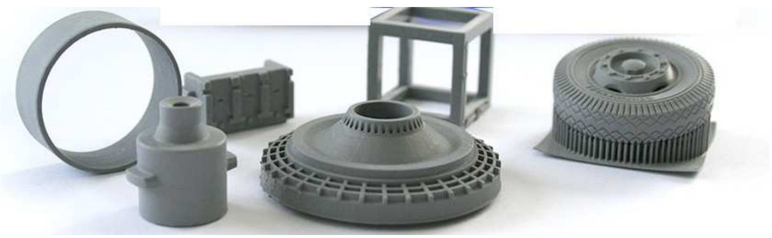
2.2.5. Direct light processing

Examples of parts

Thermofusible resist (PIC100)	Resist with ceramic filler(RC25)



Standard resist (R11)



source: Envisiontec™

2.2.6. Direct light processing

DLP characteristics/ providers

- *No DLP system is based on a down-top construction which has only drawbacks (more material, recoating, . . .) compared to the top-down strategy.*
- ***Providers**: Envisiontec™ , B9 Creator™ , Sisma™ , Carbon3d™ . . .*

Advantages (compared to stereolithography)

- *Price and simplicity of the machine, fabrication time possibly faster.*
- *Indirect production of ceramic parts (Lithoz™).*

Disadvantages compared to stereolithography

- *Less precise ($\simeq$ 45 μm against $\simeq$ 20 μm), lower productivity.*
- *Smaller work surface ($\simeq$ 60$\times$45 mm^2 against $\simeq$ 250$\times$250 mm^2).*
- *Achieving the productivity and accuracy of SLA would require to increase the resolution of the DMD by a factor $>$100 (175MPx against 1.5MPx now).*

Photopolymer jetting

2.3.1. Photopolymer jetting

Basic principle

- *A 3D part is built layer by layer out of a photoresist **selectively** deposited by an array of nozzles.*
- *The resin is consolidated by a UV flash and the principle of consolidation is UV-curing.*
- *The part geometry in transferred into the process through the management of the nozzles (displacement and feed rates).*

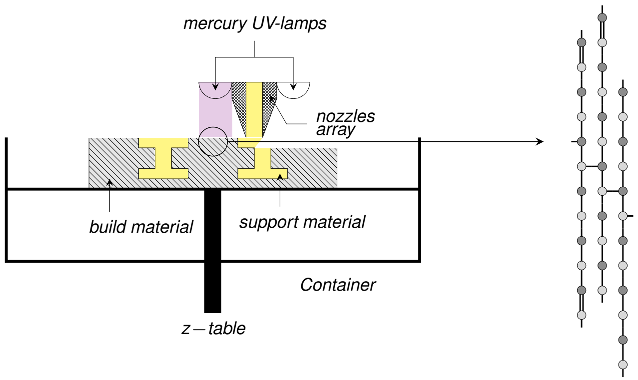
Remarks

- *Photopolymer jetting derives from stereolithography by a change in **the consolidation tool** and in **the way to transfer the part geometry**.*
- *Its recent development is due to the new nozzle technology for handling fluid with high viscosity.*
- *The nozzles deliver at least two different materials (construction/support).*

2.3.2. Photopolymer jetting

Diagram

Consolidation mechanism: cross linking

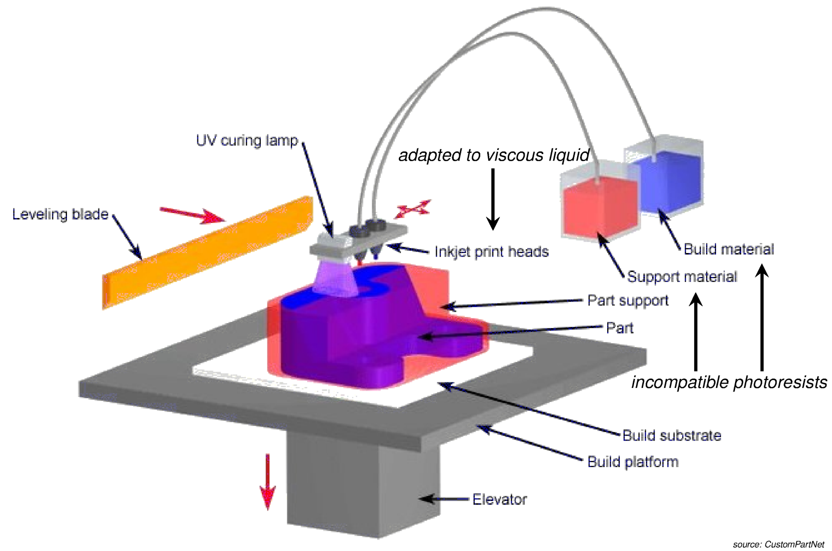


Remarks

- *The nozzles array translates along the x axis*
- *The build and support materials are two different photoresists. These materials are simultaneously cured by UV lamps.*

2.3.3. Photopolymer jetting

Block diagram of the equipment



2.3.4. Photopolymer jetting

Equipments: Eden and Connec Serie (Objet™)

Eden 260 ***Connec 500***

source: Objet™

source: Objet™

2.3.5. Photopolymer jetting

Example of parts 1

source: Objet™

source: Objet™

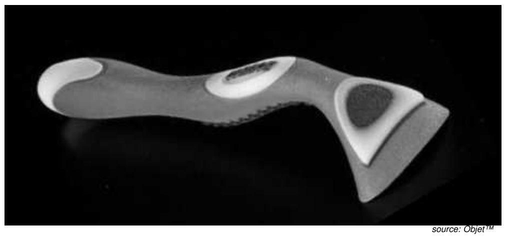
2.3.6. Photopolymer jetting

Example of parts 2

source: Objet™

source: Objet™

source: Objet™



source: Objet™

2.3.7. Photopolymer jetting

Example of parts 3

source: Objet™

source: Objet™

2.3.8. Photopolymer jetting, technical data

Mechanical properties of part (order of magnitude)

Material	*E, GPa*	*R_m, MPa*	*ε_{rup}, %*
RGD 515	*2.6-3.0*	*55-60*	*25-40*
RGD 525	*3.2-3.5*	*70-80*	*10-15*

Equipment (type, dimensions)

***Build volume**, mm^3*
from $260 \times 260 \times 200$ *to* $1000 \times 800 \times 500$

Performances

***x-y resol.**, μm*	***layer thickness**, μm*	***build speed**, mm^3/s*	***layering time**, s*
$40 - 50$	$15 - 80$	*MCR* $=$ *n.a.*(∞)[1]	$\simeq 20 - 15$ s

[1] *the build time is not sensitive to part volume but only to part height: fab.time* $= \frac{height}{e} \frac{\tau_{layer}}{N}$ *with* *e : épaisseur de couche, N : taille de lot.*

2.3.9. Photopolymer jetting

Characteristics of the jetted photopolymer process, providers

- *The construction material and the support material are solid photoresists. They are incompatible (i.e not connected after UV-flashing).*
- *The photopolymer jetting process is a consequence of a recent development of nozzles able to deliver high viscosity fluid without being blocked. Traditional printhead are designed for jetting only low viscosity fluid like ink.*

Compagnies

- *This process, developped by an Israeli company (Objet™) 15 years ago, is now commercialized by Stratasys™(USA).*

Advantages

- *Price and simplicity of the machine (from 50 kFrs to 250 kFrs).*
- *Precision (comparable to SLA).*
- *Simple management of the supports,*
- *Possibility of combining materials.*

APPENDICES

A 6: Lithography

Originally a printing process (Aloïs Senefelder, 1796, Bavaria)

(1) ***Drawing:*** *Fat wax on a smooth limestone.*

(2) ***Etching:*** *The stone is washed by a mixture of water and arabic gum:*
$\Longrightarrow$ *The gum is repelled by the fat parts and absorbed by others.*

(3) ***Inking:*** *The stone is inked:*
$\Longrightarrow$ *The ink is retained by the fat parts but slips on the gum.*

(4) ***Reproduction:*** *By pressing a paper sheet on the stone.*



- ***by extension,*** *one calls lithography any process where a part is partly protected (by fat, resine, ...) and then chemically etched (e.g fabrication of printed circuit board).*

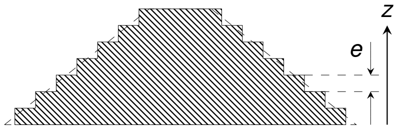
A 7: Resolution of an additive process

Resolution in different directions

- *Most of the additive processes build the part layerwise.*
- *Their resolution has to be considered differently in the build direction and in the layer plane.*

In the build direction (z)

- *The resolution is limited by a stair effect. It is proportional to the layer thickness e:*



In the layer plane (x, y)

- *the resolution is limited by two independant factors:*

(1) *the dimensions of the smallest matter element to be added:*
  - *UV-cured or molten volume, deposited liquid droplet,...*

(2) *the positionning accuracy of the system depositing or inducing the consolidation of that element:*
  - *nozzle, laser beam, binder jet.*

A 8: Build speed of an additive process

Build speed (material consolidation rate MCR)

- *In AM, the fabrication time is essentially* ***proportional*** *to the volume of the part and* ***does not depend*** *on its geometrical complexity .*
- *The ratio between the fabrication time of a part and its volume is called build speed (MCR) is (unit: mm^3/s):*

$$\textit{fab. time} \simeq \frac{\textit{volume}}{\textit{MCR}}.$$

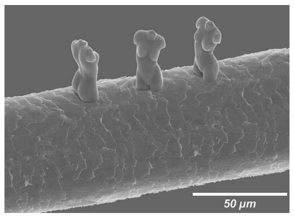
- *For a particular process, the build speed MCR varies between limits as a function of the used material.*
- *For most processes, the above formula only* ***underestimates*** *the fab. time. An accurate computation of the fabrication time of a part by an additive process also involves a term proportional to the construction height of the part :*

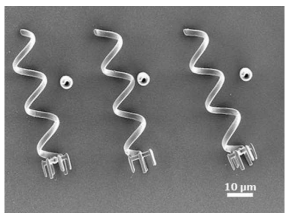
$$\textit{fab. time} \simeq \frac{\textit{volume}}{\textit{MCR}} + \frac{\textit{height}}{e} \times \frac{\tau_{layer}}{N}. \quad (1)$$

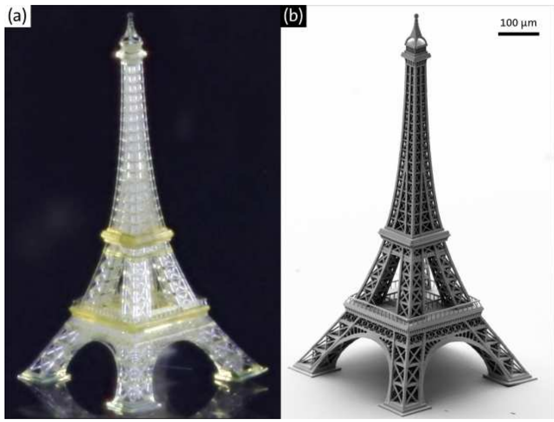
where e is the layer thickness and τ_{layer} the ***time to prepare a layer****: the ratio height/e represents the total number of layers. Note that the layering time can be* ***mutualized*** *between the N parts built in the same batch.*

A 9: Micro-stereolithography (μ−SLA)

Very small parts can be obtained by scaling down the process



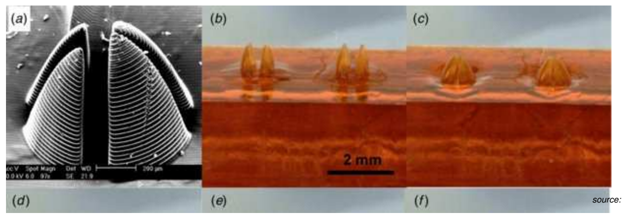




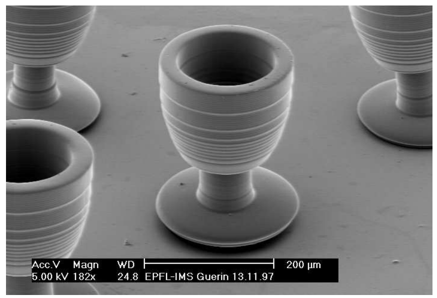
source: Fraunhofer-Institut für Lasertechnik Aachen

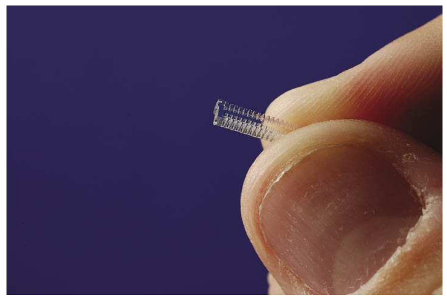
A 10: Micro-stereolithography (μ−SLA)

Very small parts can be obtained by scaling down the process



source: UniversityofWarwick



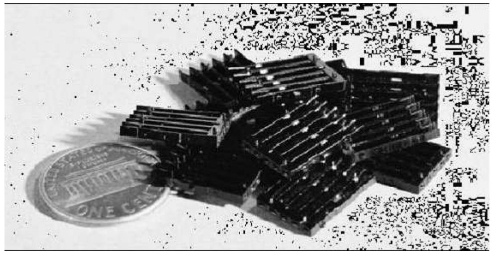


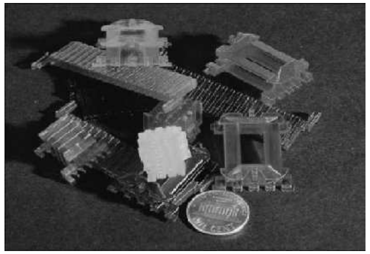
source: LMSi4

source: FineLinePrototyping

A 11: Manufacture of small series.

Electrical components





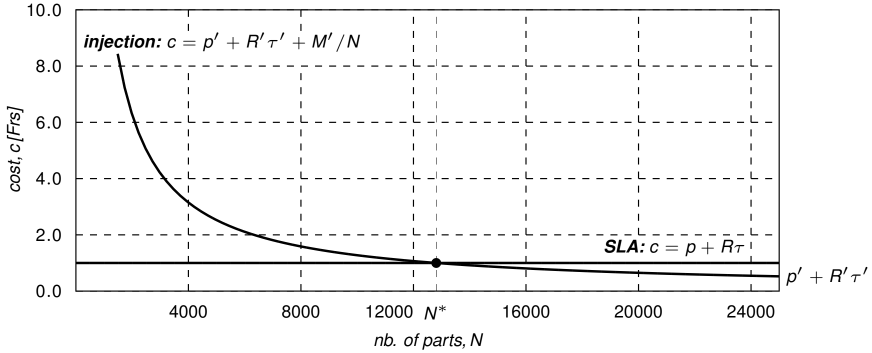
source: Fraunhofer-Institut für Lasertechnik Aachen

- *16'000 parts to produce*
  - *The **injection** and **SLA** processes are considered*
  - *SLA proves to be slightly more expensive*
  - *SLA is finally **chosen** due to shorter lead time (2 weeks against 2 month)*

A 12: Cost comparison SLA-injection.

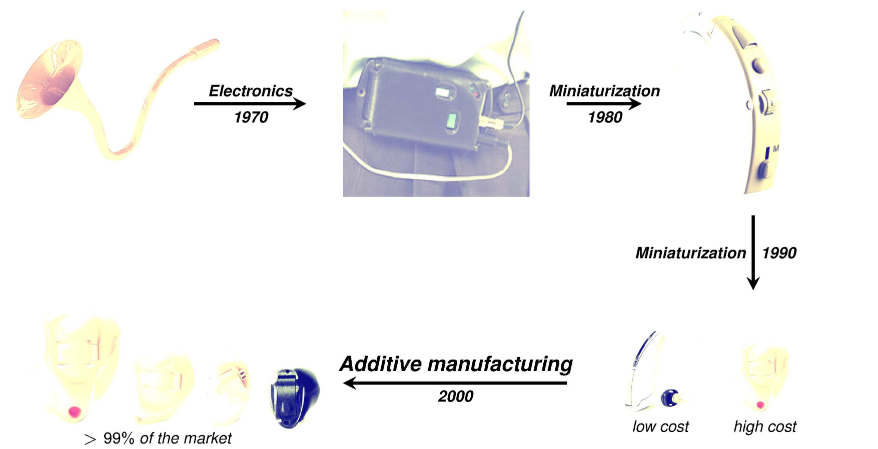
Determining parameters and cost comparison

	material cost, Frs	hourly rate (men+mach.), Frs/h	fab. time, h time, h	tool cost, Frs
SLA	p	R	τ	–
injection	p'	R'	τ'	M'



A 13: Custom items by SLA (Hearing aids)

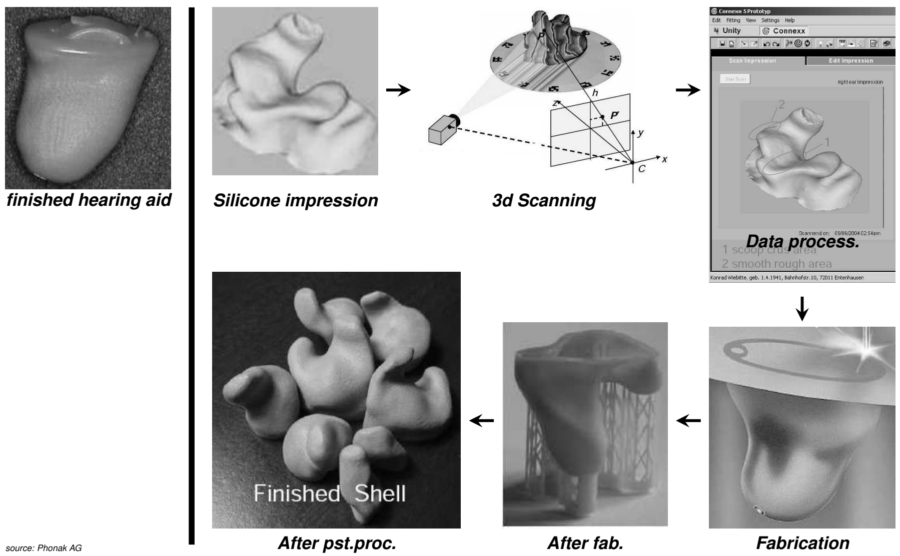
Transformation of an economical model



sources: Phonak AG, Siemens AG

A 14: Custom items by SLA (Hearing aids)

Hearing aids (Recent state of art)



source: Phonak AG

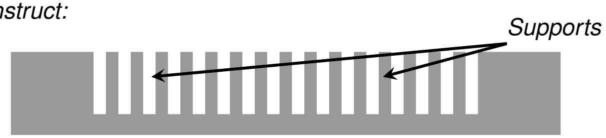
A 15: Support structures

Request of support structures

- *The polymerization decreases the specific volume of the resine and increases its density*
- *Large overhangs have a tendency to sink inside the uncured resine*

To fabricate a part with a large overhang:

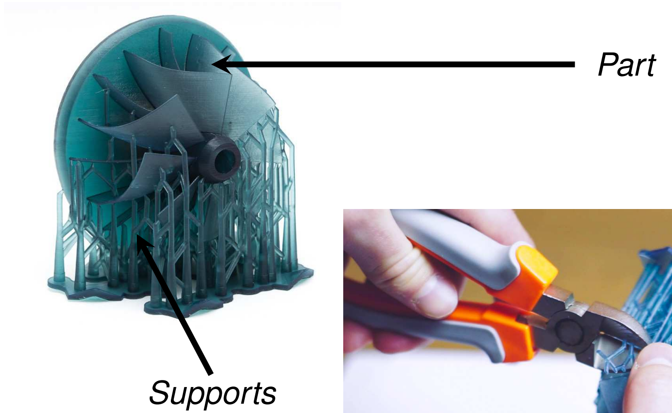
One has to construct:



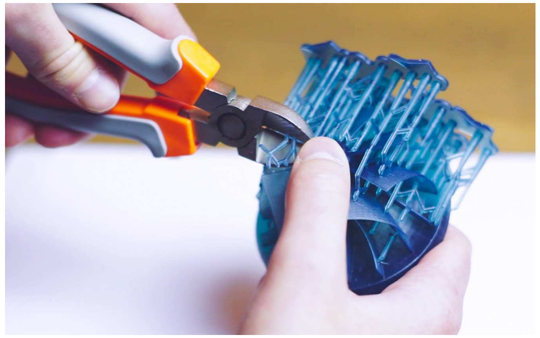
and to remove the supports afterwards

A 16: Support structures

Example of support structures



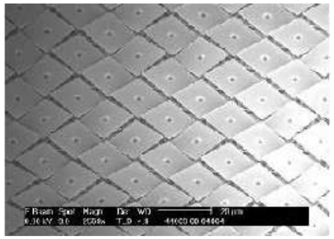
source: Proform SA



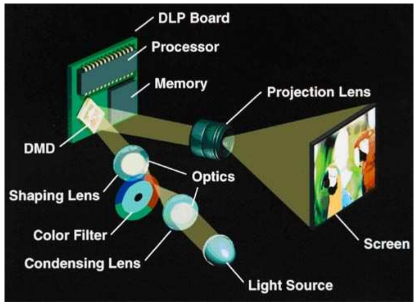
A 17: Digital micromirror devices (DMD)

A DMD acts as an optical switch of 1400 $\times$ 1050 pixels

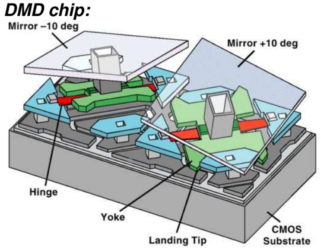
Mirrors network



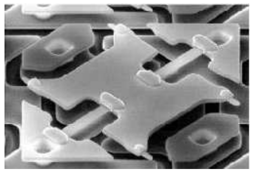
Detailed operation of a DMD cell



DMD chip:



Torsion hinge



DLP videoprojector in visible light

Dim. mirror: $\simeq 16\mu\text{m} \times 16\mu\text{m}$

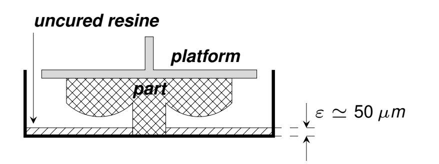
$t_{carac} \simeq 15\mu\text{s}$

source: Envisiontec™

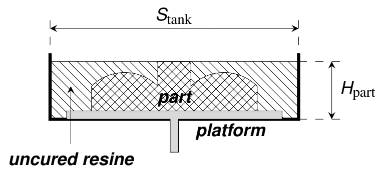
A 18: Some advantages to hang the part

Economy of resin and no need of recoating

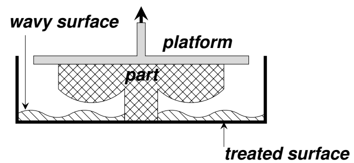
DLP process | *Stereolithography process*



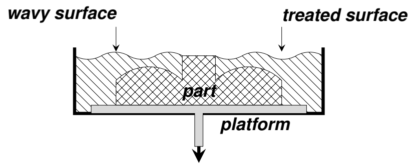
$V_{\text{resin}} \simeq V_{\text{part}}$



$V_{\text{resin}} \simeq S_{\text{tank}} \times H_{\text{part}}$



wavy surface $\neq$ treated surface



wavy surface $=$ treated surface

Part III

Extrusion processes

Fused Deposition Modelling (FDM)

3.1.1. Fused Deposition Modelling

Basic principle

- *A 3d part is built out of a molten amorphous thermoplastic wire extruded from a heated nozzle.*
- *The original and most suited material is ABS (**A**crylonitrile **B**utadiene **S**tyrene).*
- *The part is built lines by lines and layer by layer. The principle of consolidation is liquid phase bonding.*
- *The details of the part geometry are transferred into the process through the management of the nozzles (displacement and feed rates).*

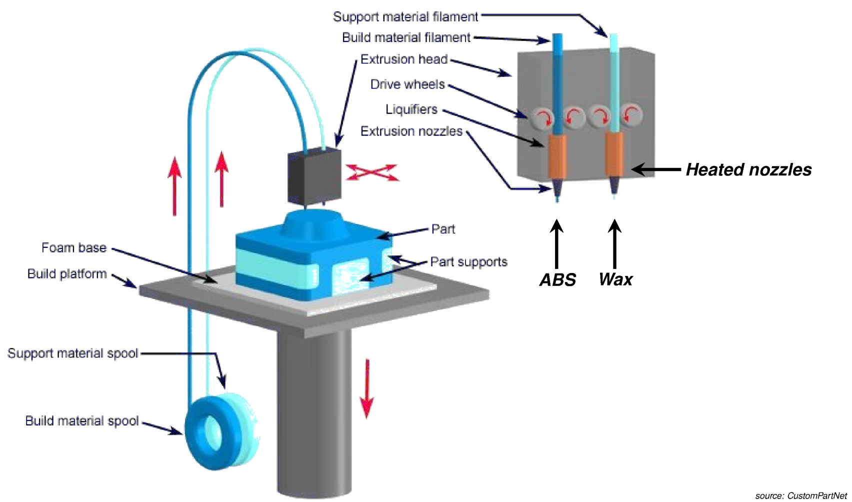
Acronym and remarks

- *This process is usually called FDM.*
- *FDM stations are generally equiped with two nozzles. The first one delivers the construction material (e.g. ABS) and the other a support material (typically wax).*

[1] Since they are less prone to shrinkage during re-solification, amorphous thermoplstics are better adapted to extrusion

3.1.2. Fused Deposition Modelling

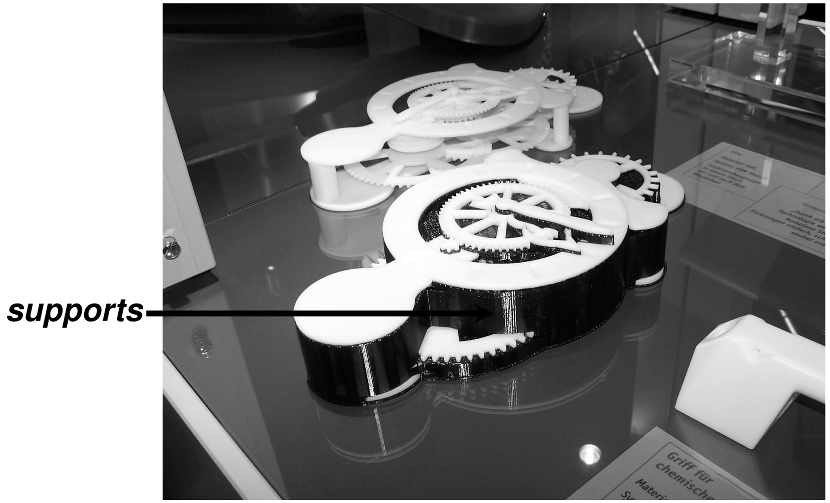
Block diagram



(see Append. 19)

3.1.3. Fused Deposition Modelling

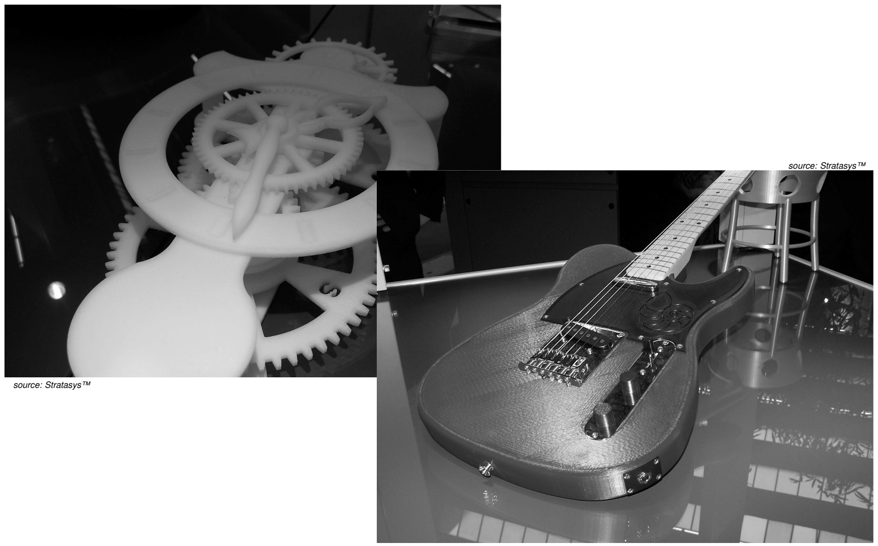
Examples of parts



source: Stratasys™

3.1.4. Fused Deposition Modelling

Examples of parts



source: Stratasys™

source: Stratasys™

3.1.5. Fused Deposition Modelling, technical data

Mechanical properties of part (order of magnitude)

Material	*E, GPa*	*R_m, MPa*	*ε_{rup}, %*
ABS plus P430	*2.3*	*37*	*3*
ULTEM 9085	*2.2*	*72*	*6*

Equipment (type, dimensions)

***Build volume**, mm^3*	
from $250 \times 250 \times 300$	*to* $915 \times 610 \times 915$

Performances

***x-y resol.**, μm*	***layer thickness**, μm*	***build speed**, mm^3/s*	***layering time**, s*
130	*130-300*	*MCR <5*	0[1]

[1] The fab. time only depends on the part volume: fab. time $= \frac{\text{volume}}{\text{MCR}}$

3.1.6. Fused Deposition Modelling

Companies

STRATASYS™, MAKERBOT™ , ULTIMAKER™, PRUSA™, REPRAP3D™, . . .

Advantages

- *Simple, clean and safe operation, parts with gradient of properties possible.*
- *Patterns for the vacuum casting process,*
- *Fabrication of different type of custom items (shoes).*

Disadvantages

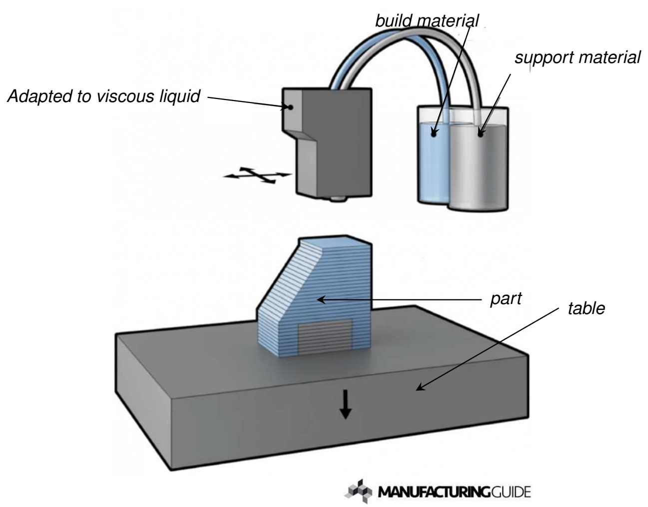
- *(Almost) exclusive use of ABS or PLA due to their particular ability to make hot bonds on top of already existing cold parts (this property is mostly connected to a favourable combination of wettability and viscosity in liquid phase).*
- *Anisotropy of the part properties, less accurate then SLA or Polyjet.*
- *Relatively low manufacturing speed.*

(see Append. 20)

"Ballistic Particle Manufacturing" (BPM)

3.2.1. Similar to FDM: the BPM™ process

Block diagram of the Ballistic Particle Manufacturing Process

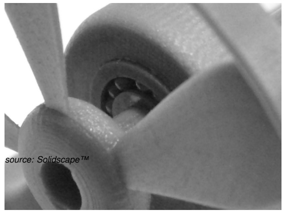
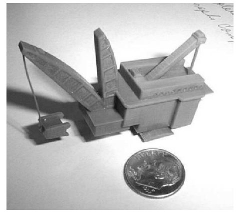


(see Append. 19)

3.2.2. Similar to FDM: the BPM™ process

Companies, example of parts and comments

Companies: SOLIDSCAPE ™ *(part of* STRATASYS ™*)* 3DSYSTEMS ™.

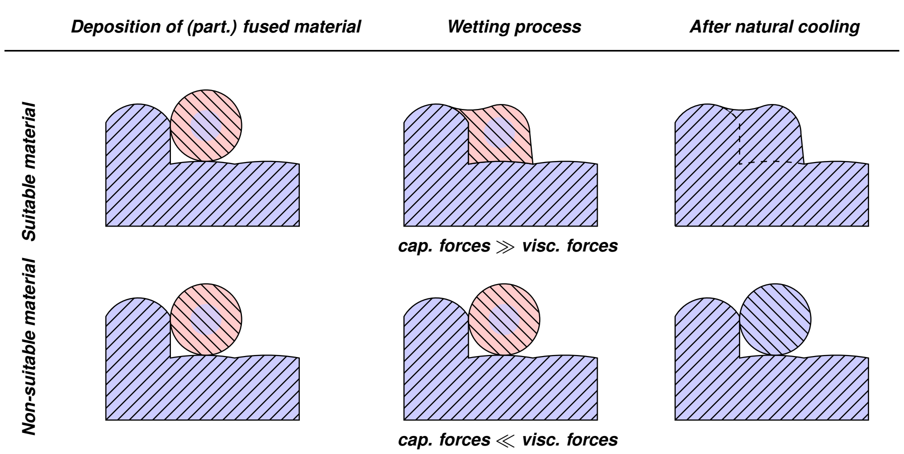

source: Solidscape™

- *Compare to FDM, the materials are cheaper and the process is faster for equivalent accuracy.*
- *Ideal for jewelry applications (lost patterns for the investment casting process).*
- *FDM-like plastic can also be processed by the* PROJET *machines developed by* 3DSYSTEMS ™*. The main issue is to avoid blocking the printer head with the viscous polymer liquid.*
- *This process is also commercialized as MJM (**M**ulti**J**et **M**anufacturing).*

APPENDICES

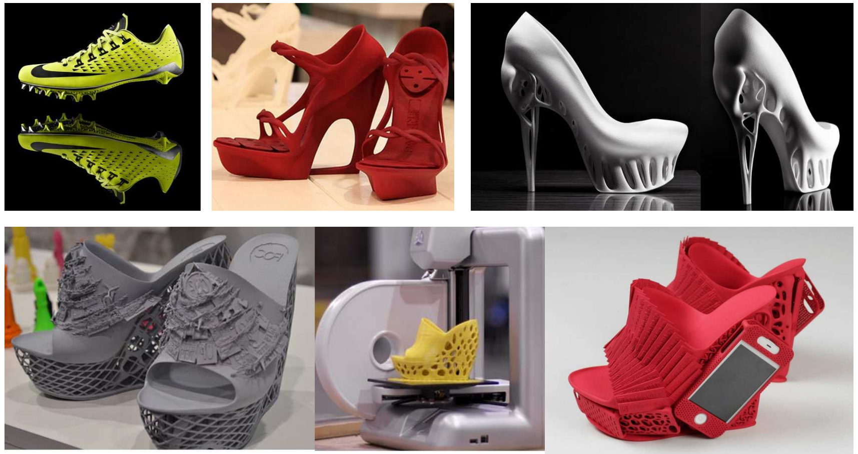
A 19: Liquid phase bonding

Different steps in the consolidation phase (view ⊥ to deposition)



A 20: Custom items (shoes) by FDM

Different types of shoes



Part IV

Powder processes

Binder jetting

4.1.1. Binder jetting

Principle

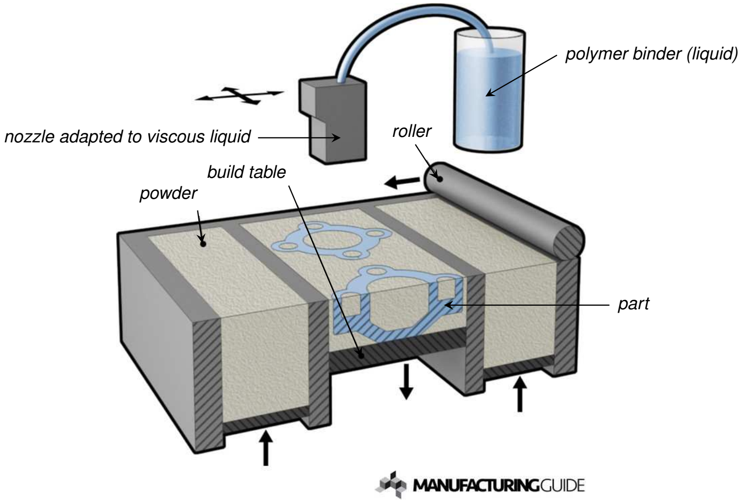
- *A 3d part is manufactured layer by layer by assembling solid particles with a liquid binder (usually of polymeric type).*
- *The liquid binder is distributed selectively using a inkjet print head and the consolidation principle is indirect bonding.*
- *The part geometry in transferred into the process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

4.1.2. Binder jetting

Block diagram



4.1.3. Binder jetting

Equipments: 3DSYSTEMS™ ZPrinter Serie

ZP-150	***ZP-350***	***ZP-650***


source: 3dSystems™


source: 3dSystems™


source: 3dSystems™

4.1.4. Binder jetting

Example of parts 1

source: 3dSystems™

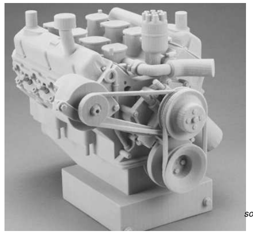

source: 3dSystems™


source: 3dSystems™


source: 3dSystems™

4.1.5. Binder jetting

Example of parts 2


source: 3dSystems™


source: 3dSystems™


source: 3dSystems™

4.1.7. 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 $200 \times 250 \times 200$	to $1200 \times 1200 \times 1600$

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

4.1.8. Binder jetting

Companies

3DSYSTEMS™, DIGITALMETAL™, EXONE™

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.*
- *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-P**rinting". 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 ,...*

Selective Laser Sintering and Melting

4.2.1. Selective Laser Sintering and Melting

Principle

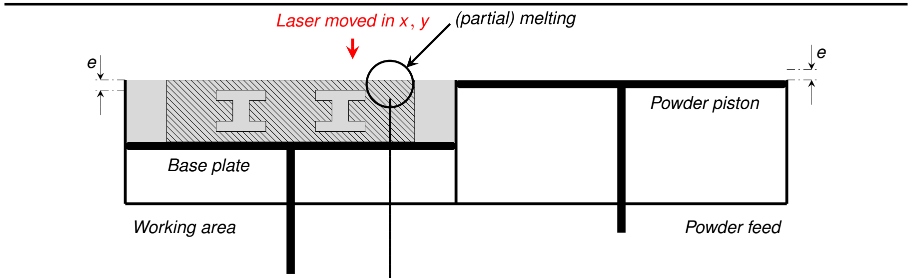
- *A 3d part is manufactured layer by layer from a metallic, polymer or ceramic powder.*
- *The powder is selectively consolidated by a laser beam moved by galvanometric mirrors. The physical consolidation principle is basically liquid phase sintering.*
- *The geometry of the part is transferred into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

Acronym

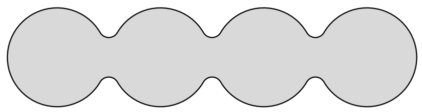
- *This process is usually called SLS for "**S**elective **L**aser **S**intering" or SLM for "**S**elective **L**aser **Melting**"*
- *Observe that the name **sintering** is used to qualify processes where the powder is only partly fused by the laser (e.g. in case of polymer or ceramic powders). Otherwise 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 LPBF for "**L**aser **P**owder **B**ed **F**usion".*

4.2.2. Selective Laser Sintering and Melting

Diagram



Consol. mechanism: liquid phase sint.



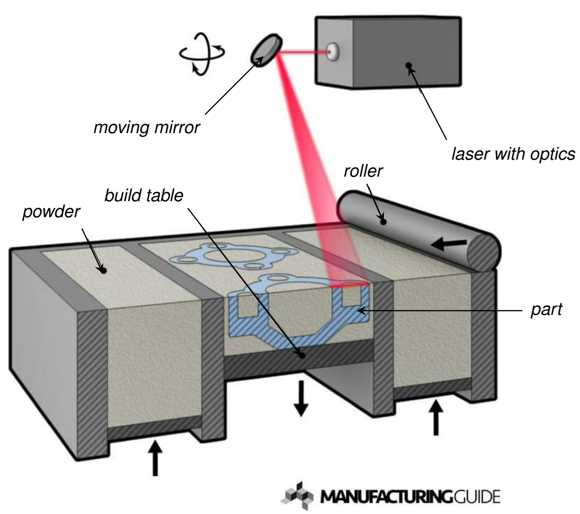
Remark

Easy recycling of unused powder

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

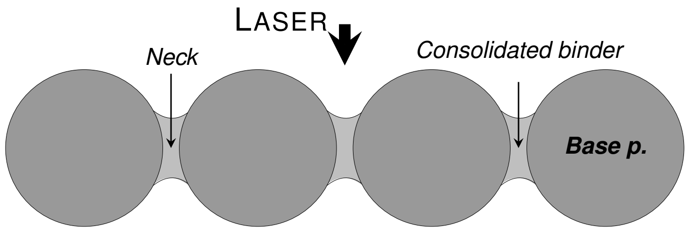
4.2.3. Selective Laser Sintering and Melting

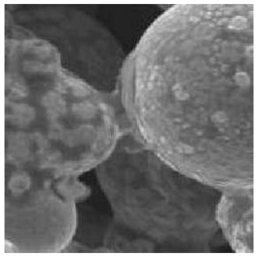
Block diagram



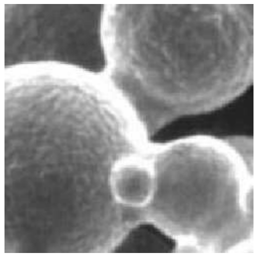
4.2.4. Selective Laser Sintering and Melting

Consolidation mechanism (details)





MEB micrographs

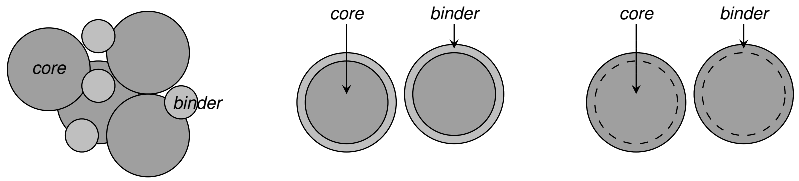


4.2.5. Selective Laser Sintering and Melting

Distinctions between different SLS(M) processes

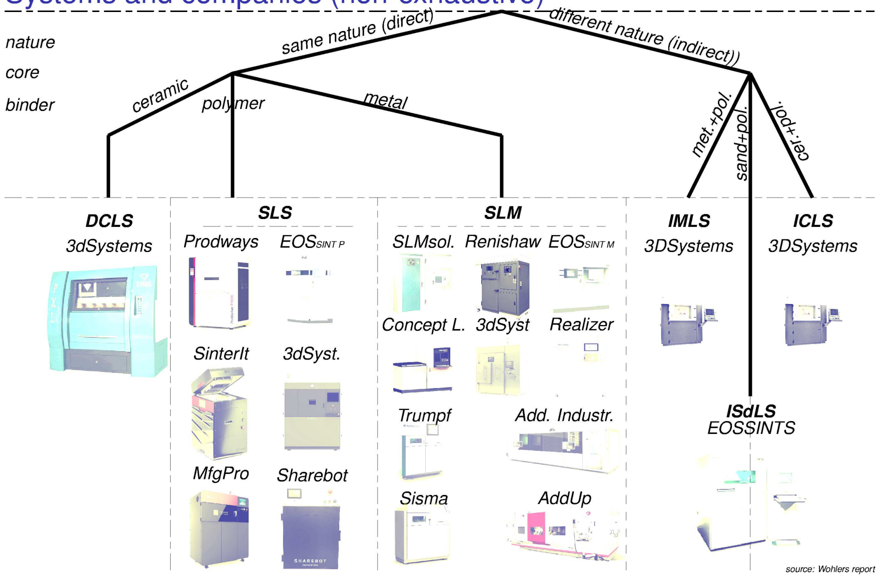
- *The SLS(M) processes are sub-categorized according to the chemical nature (metal, polymer or ceramic) of the binder and of the core particles:*
  - *if the natures of the core and binder are the same, then the process is said to be **direct**. Otherwise the process is said to be **indirect**.*
- *At the powder level, the binder/core materials might be mixed in different ways:*
  - *The binder might be the same as the core particles (direct process).*
  - *The binder and core particles are different (blended powders).*
  - *The binder is different but covers the core particles (coated powders).*
- *Observe that in indirect processes the binder is a polymer.*

Blended powder	***Coated powder***	***Homogeneous powder (direct process)***



4.2.6. Selective Laser Sintering and Melting

Systems and companies (non-exhaustive)



4.2.7. 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* $200 \times 200 \times 330$ *to* $700 \times 380 \times 560$

Performances

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

4.2.8. 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*	$250 \times 250 \times 300$

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

4.2.9. Selective Laser Sintering and Melting

Advantages, overview

- *Base material easy to recycle, especially for metals (SLM).*
- *Overhangs realizations without supports (the powder is self-supporting).*
- *Can be applied to many materials (≠ SLA).*
- *Free geometrical complexity (cost=f(Volume,Height)).*

Applications (summary)

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

(see Append. 33, 34, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30)

4.2.10. Selective Laser Sintering and Melting

Scaling down of the processes: μ−SLS

- *Limiting factor: the average size d_{50} 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** to form bigger grains and do not **flow**:*

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

- *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**.*

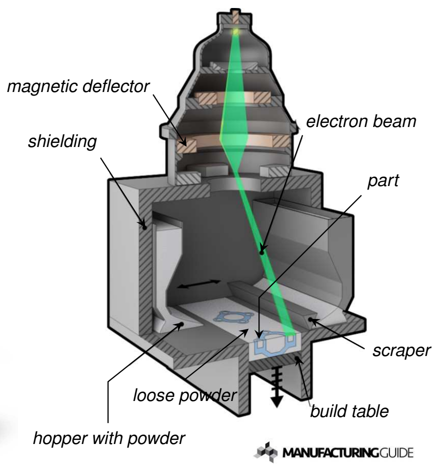
- *A μ−SLS machine has been developed by* EOS™ *in collaboration with* MicroMac™*.*

(see Append. 31, 32)

Electron Beam Direct Manufacturing

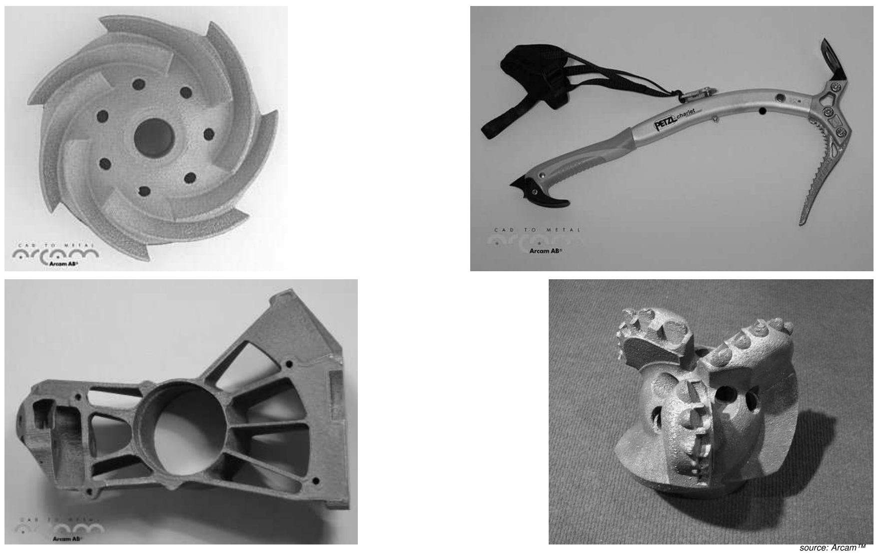
4.3.1. Similar to SLM: the EBDM process

Equipments: Arcam™machine



4.3.2. Similar to SLM: the EBDM process

Example of parts



4.3.3. Similar to SLM: the EBDM process

Example of parts

source: Arcam™

4.3.4. Similar to SLM: the EBDM process

Compagny

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

Advantages over SLS / SLM

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

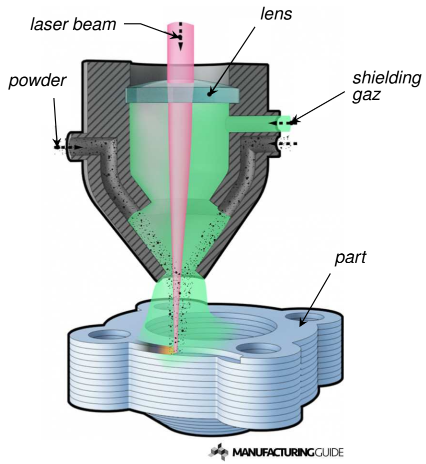
Disadvantages compared to SLS / SLM

- *EBDM stations are more expensive than SLS/SLM stations.*
- *The use of the machine is more complex:*
  - *X-ray emission,*
  - *fabrication under ultra high vacuum.*
- *EBDM is limited to metals.*
- *Less accuracy and resolution in EBDM.*
- *Potentially higher level of thermal stresses in EBDM.*

Direct Metal Deposition

4.4.1. Similar to SLS: the DMD process

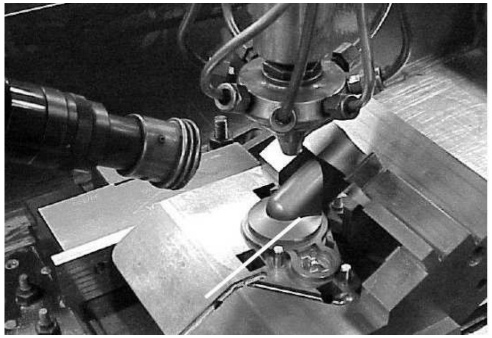
Equipments (a laser mounted on a five axes machine)

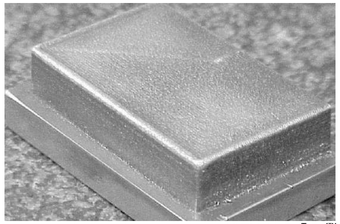


source: DMG-Mori™

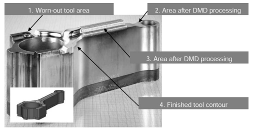
4.4.2. Similar to SLS: the DMD process

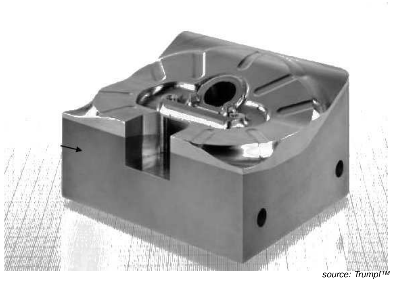
Example of parts


source: Trumpf™


source: Trumpf™

source: Trumpf™




source: Trumpf™

4.4.3. Similar to SLS: the DMD process

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 intgrate ablative processes inside the machine.*

Disadvantages compared to SLS/SLM

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

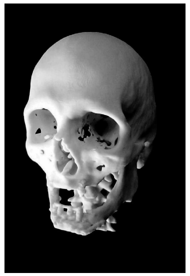
Companies and remarks

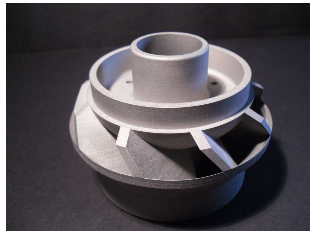
- *Optomec™, BeAM™ (Irépa Laser), DMG Mori™, Okuma™.*
- *The "Direct Metal Deposition" process is sometimes presented under the name "Laser engineered net shaping" (LENS) or "Laser cladding" when considered as a **reparation and coating** process only.*
- *The "Direct Metal Deposition" process only differs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

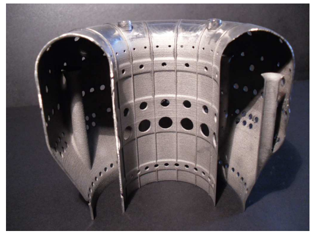
APPENDICES

A 21: High level prototypes by SLS_{plast}, DMLS or SLM

Prototyping: model for medical applications, functional prototyping



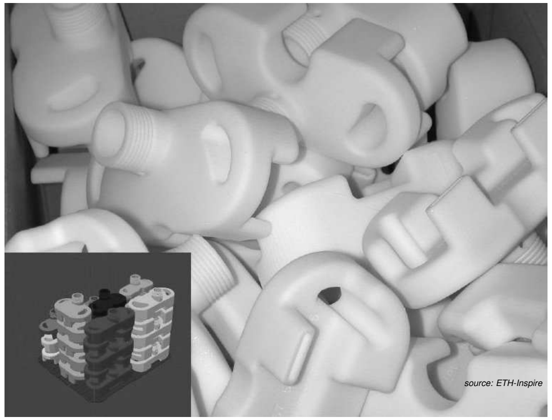




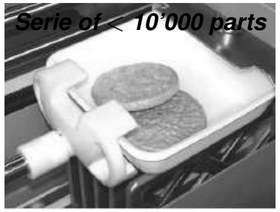
source: EOS™, ConceptLaser™, Phenix System™

A 22: Small series of parts by SLS$_{plast}$

Robotics: Trays handlers

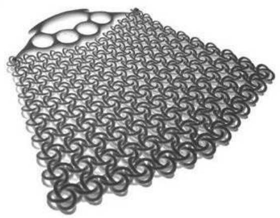


source: ETH-Inspire



A 23: Small series of parts by SLS$_{plast}$

Fashion: textiles manufacture



source: University of Loughborough

A 24: Small series of parts by DMLS/SLM

source: ConceptLaser™

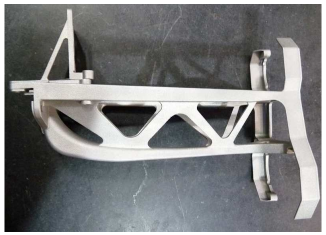
source: ConceptLaser™

source: EOS™

source: EOS™

A 25: DMLS/SLM parts for the aerospace industry

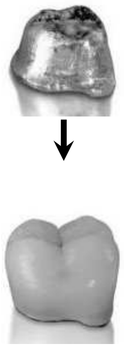
Aerospace: Antenna, hollow or optimized structures, spare parts

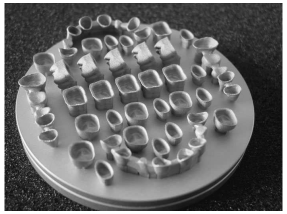


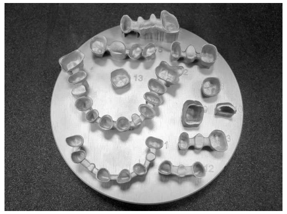
source: EOS™, ConceptLaser™

A 26: Fabrication of customized parts by SLM

Efficient manufacturing of dental implants by SLM





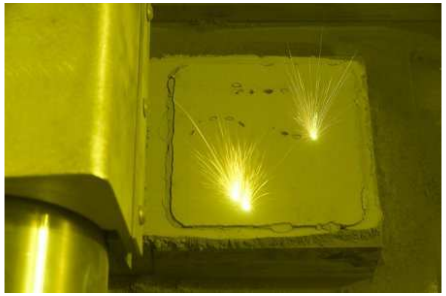


source: Phenix-Systems™

A 27: Fabrication of customized parts by SLM

Efficient manufacturing of dentures by SLM

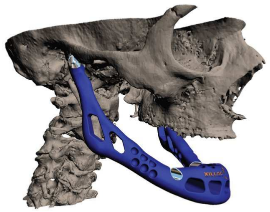
- *SLM is an alternative to the traditionnal processes:*
  - *it is faster,*
  - *it is cheaper.*

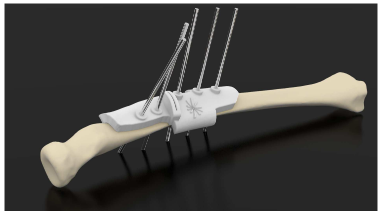


source: Phenix-Systems™

A 28: Customized parts by SLS_{plast} or SLM

Saw and drilling guides by SLS_{plast}, prostheses by SLM



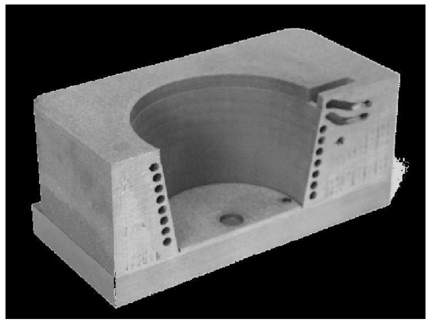


source: EOS™, ConceptLaser™

A 29: Fabrication of tools by SLM

Conformal cooling

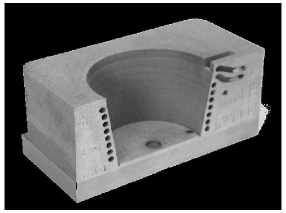
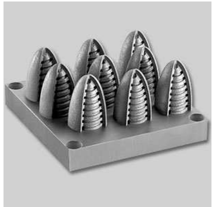
Optimised cutting tool (SLM)	*Optimised injection mould (SLM)*



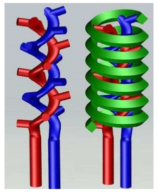
source: ConceptLaser™

A 30: Fabrication of tools by SLM

Conformal cooling (cutting tools / injection moulds)

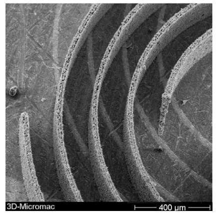


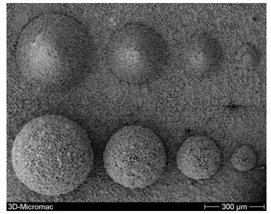


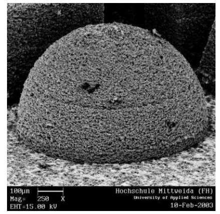
courtesy of ConceptLaser™ PhenixSystems™

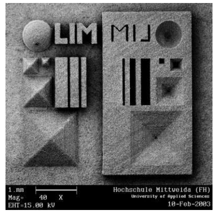
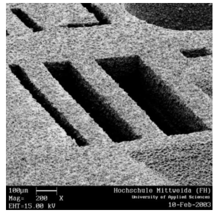
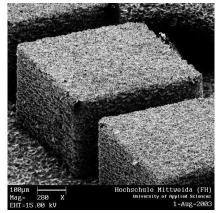
A 31: $\mu-$SLS(M) process: example of parts

$\mu-$SLS: example of parts (Tungsten)





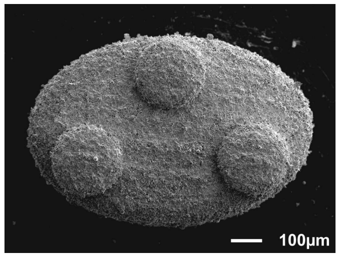


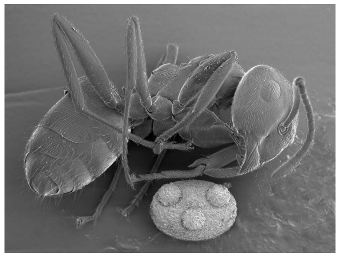




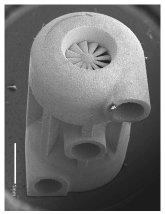
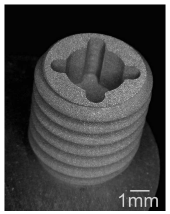
source: micromac™ TU Mitweida

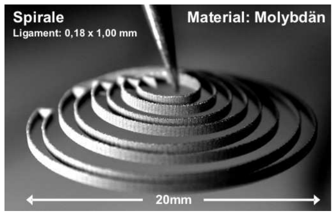
A 32: $\mu-$SLS(M) process: example of part (c'tnd)

$\mu-$SLS: example of parts (Molybdenum, tantalum)







source: micromac™ TU Mitweida

A 33: Fabrication cost

Parameters influencing the manufacturing costs

Related to	*Name*	*Symbol*	*Unit*
Material	*consolidation energy p.u.v*	e	$\mathrm{J/mm^3}$
	price p.u.v.	c	$\mathrm{frs/mm^3}$
Machine	*power*	P	W
	machine cost	C	frs/s
	layer thickness	ε	mm
	deposition time of one layer	τ	s

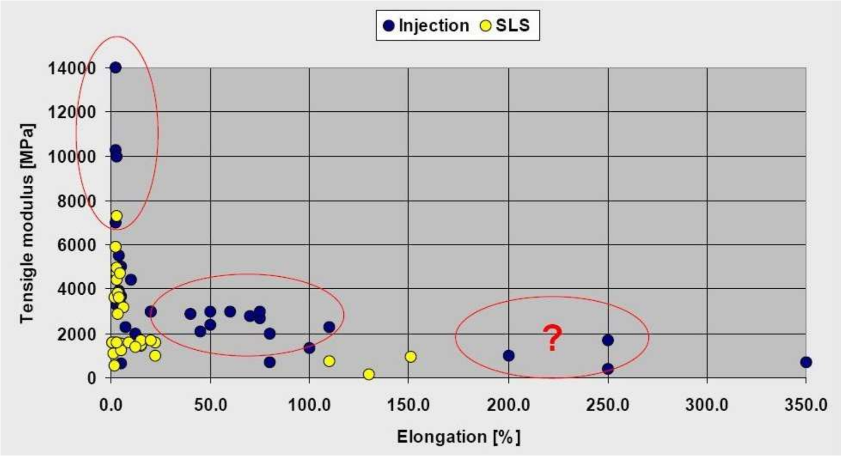
$$t_{lasing} = \frac{\text{Volume} \times e}{P} \quad \text{and} \quad t_{deposition} = \frac{\text{Height}}{\varepsilon} \times \tau$$

$$Cost = \left(\frac{\text{Volume} \times e}{P} + \frac{\text{Height}}{\varepsilon} \times \tau \right) \times C + \text{Volume} \times c.$$

Interest of sharing $t_{deposition}$ among many parts to diminish costs

A 34: Elastic properties of typical SLS plastic materials

Comparaison: plastic for injection **VS** plastic for SLS



source: ETH-Inspire

Part V

Computer aspects

Computer aspects of Additive manufacturing

Design for Additive manufacturing

5.1.1. Type of information

Layered manufacturing and .stl format

- *In additive manufacturing, the part is (generally) built layer by layer (layered manufacturing).*
- *Therefore it is necessary:*
  - *To get a computer description of each layer,*
  - *To define the tool path (laser, printhead, nozzle) to generate each layer.*
- *The standard procedure to produce the layers is to cut a .stl description of the part.*
- *The .stl description is an approximation of the* ***surface*** *of the part by a* ***polyhedron***

The Part

Its .STL representation

5.1.2. Example of .STL file

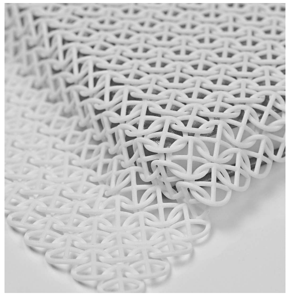
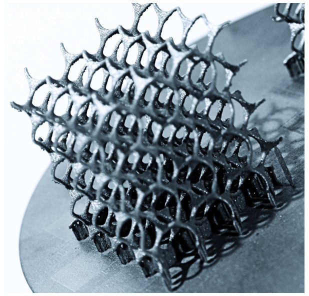
```
Triangle No 1   solid sample.stl
                    facet normal   -1.00000     0.00000     0.00000                               norm ext.
                                   outer loop
                                                vertex      140.502634  233.993075  -38.310362    1st vertex
                                                vertex      140.502634  229.424780  -38.310362    2nd vertex
                                                vertex      140.502634  242.525774  -27.097848    3rd vertex
                                   end loop
                    end facet
Triangle No 2       facet normal   0.903689     0.004563    0.428166
                                   outer loop
                                                vertex      134.521310  273.427837  30.342009
                                                vertex      134.521310  308.505852  30.715799
                                                vertex      140.502634  334.576026  18.369396
                                   end loop
                    end facet
Triangle No 3       facet normal   -0.903689    0.004563    0.428166
                                   outer loop
                                                vertex      140.502634  334.576026  18.369396
                                                vertex      140.502634  294.929752  17.946926
                                                vertex      140.502634  273.427873  30.342009
                                   end loop
                    end facet
                . . .
                end solid sample.stl
```

(see Append. 35)

5.1.3. Known problems related to .STL format

Parts with high aspect ratio, multimaterial parts

- *The STL format is not adapated to parts with large aspect ratio i.e large surface for small volume. They have very low local radius of curvature and their polyhedral approximation requests a lot of triangles. Popular examples of such situations are knitted fabrics, lattice structures, etc....*

knitted fabrics	***lattice structures***
 source: 3dSystems™	 source: SLMSolution™

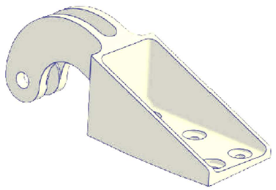
- *The STL format is not adapated to multimaterial parts either.*

(see Append. 36)

5.2.1. Design for additive manufacturing (DFAM)

Typical mistake to be avoided

(1) *The part is designed traditionally*
(2) *The part is eventually AM'd for some reasons*

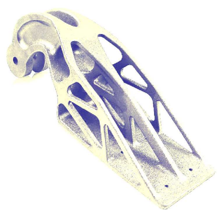


source: EADS innovation team

→ *The reasons could be: small serie, high complexity, etc..*

A more efficient solution exists:

(1) *AM is choosen for some reasons (same as above)*
(2) *The part is designed for AM.*



source: EADS innovation team

(see Append. 37, 38, 39)

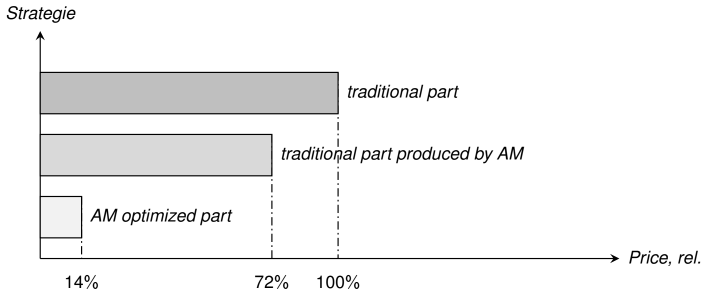
5.2.2. Design for additive manufacturing (DFAM)

Expected gains

- *For the same functions and mechanical properties, an AM optimized part*

(1) *is lighter and uses less material than the traditional part,*
(2) *is much cheaper than the traditional part when it is produced by AM:*
(3) *makes additive manufacturing even more profitable (see Fig. below).*

Price analysis over an average part - aerospace application

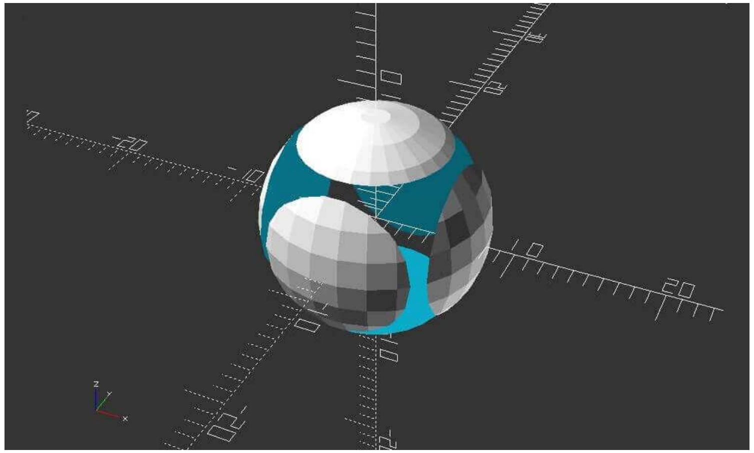


source: EADS innovation team

APPENDICES

A 35: Origin of the .STL format

The .STL format has been developped for rendering purposes



- *The external normal was necessary to determine the brightness level of each triangles.*

A 36: Multimaterial applications

Possible solution: consider different parts

- *Produce **two** .STL files:*

(1) *one for the bones,*
(2) *one for the soft tissue.*

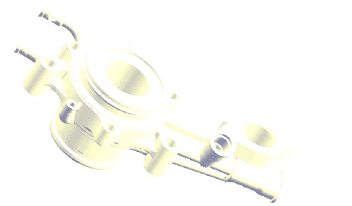
- *Slice the **two** .STL independently to get **two** .SLI files.*
- *Hatch the **two** .SLI files independently to get **two** .CLI files.*

- *Construct the part layer layer by moving the print-head according:*

(1) *to the info in the first .CLI file with the bone material,*
(2) *to the info in the second .CLI file with the soft tissue material.*

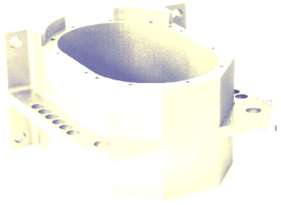
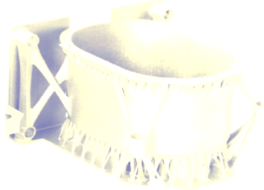
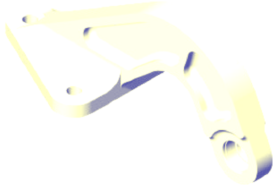
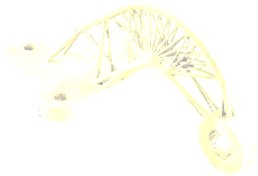
A 37: Other examples of part designed for AM

New design, new fonctions

	Traditional design	***AM design***
Airducts (aircraft).	 courtesy:IRCCyN	 courtesy:IRCCyN
Pump system	 courtesy:IRCCyN	 courtesy:IRCCyN

A 38: Other examples of part designed for AM

New design, new fonctions

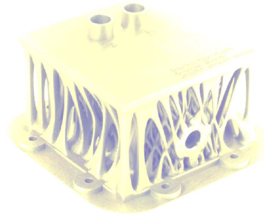
	Traditional design	***AM design***
Gear box	 *courtesy:3T RPD*	 *courtesy:3T RPD*
Hinge	 *courtesy:University Of Sheffield*	 *courtesy:University Of Sheffield*

A 39: Other examples of part designed for AM

New design, new fonctions

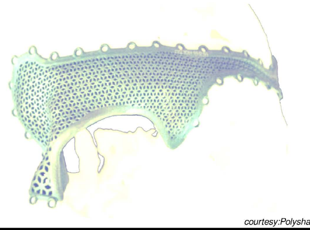
Design for AM only

courtesy:Polyshape™



courtesy:Polyshape™

courtesy:ConceptLaser™



courtesy:Polyshape™