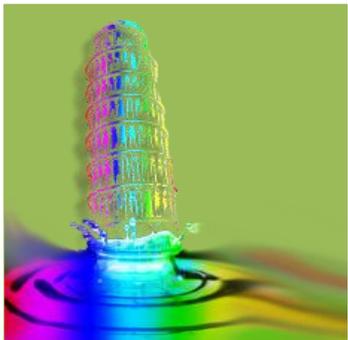




Centro E. Piaggio  
bioengineering and robotics research center

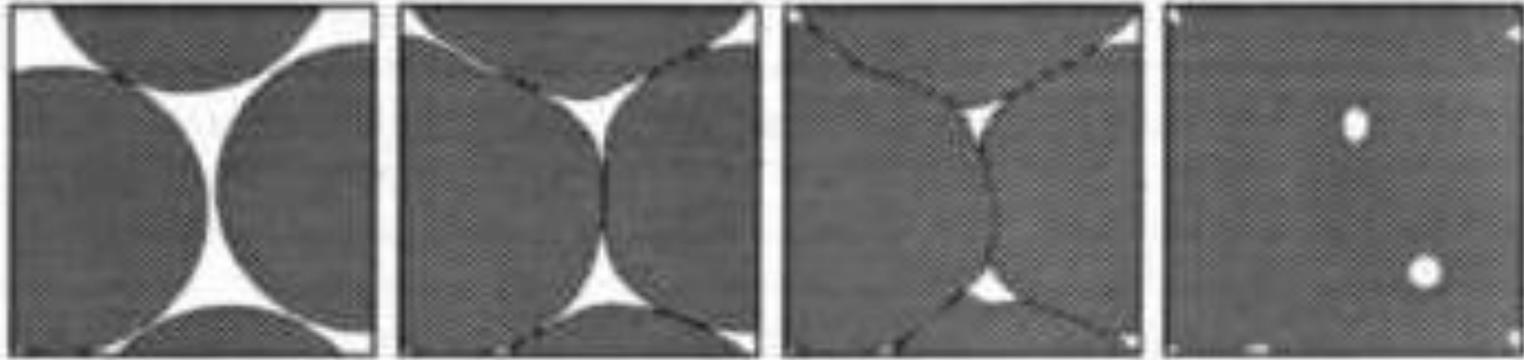
# Laser sintering

---



[carmelo.demaria@centropiaggio.unipi.it](mailto:carmelo.demaria@centropiaggio.unipi.it)

# + Sintering process



# + Sintering process

- bonding of the metal, ceramic or plastic powders together when heated to temperatures **in excess of approximately half the absolute melting temperature**.
- In the industry, sintering is mainly used for metal and ceramic parts (Powder Metallurgy).
- After pressing (compaction) of the powder inside mold for deforming into high densities, while providing the shape and dimensional control, the compacted parts are then sintered for achieving bonding of the powders metallurgically.



# + Sintering in additive manufacturing



- Sintering process used in additive manufacturing differs from the Powder Metallurgy, such as:
  - Plastic based powders, in addition to metal powders
  - Local sintering, not overall sintering
  - Very short sintering period
- Laser (heat source) is exposed to sections to be sintered for a very short time. Hard to achieve an ideal sintering.
- In some applications, for achieving the ideal sintering, the finished parts are heated in a separate sintering oven.

# + Sintering in Metallurgy vs AM



# + Laser Sintering

<https://www.youtube.com/watch?v=bgQvqVq-SQU>

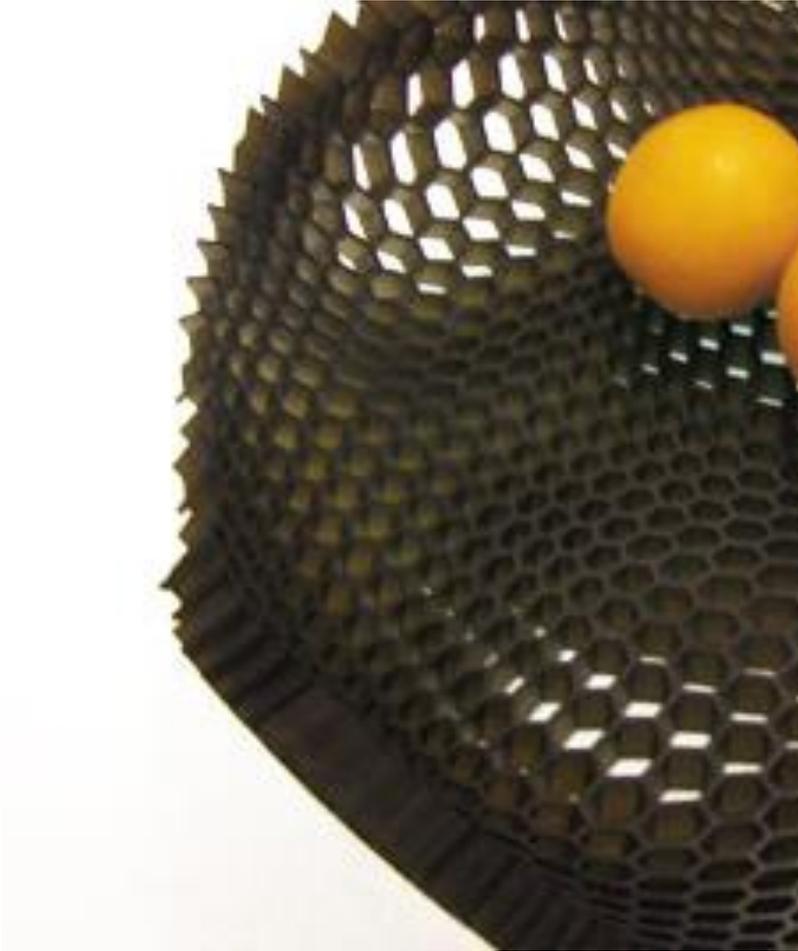


# + Selective Laser Sintering (SLS)

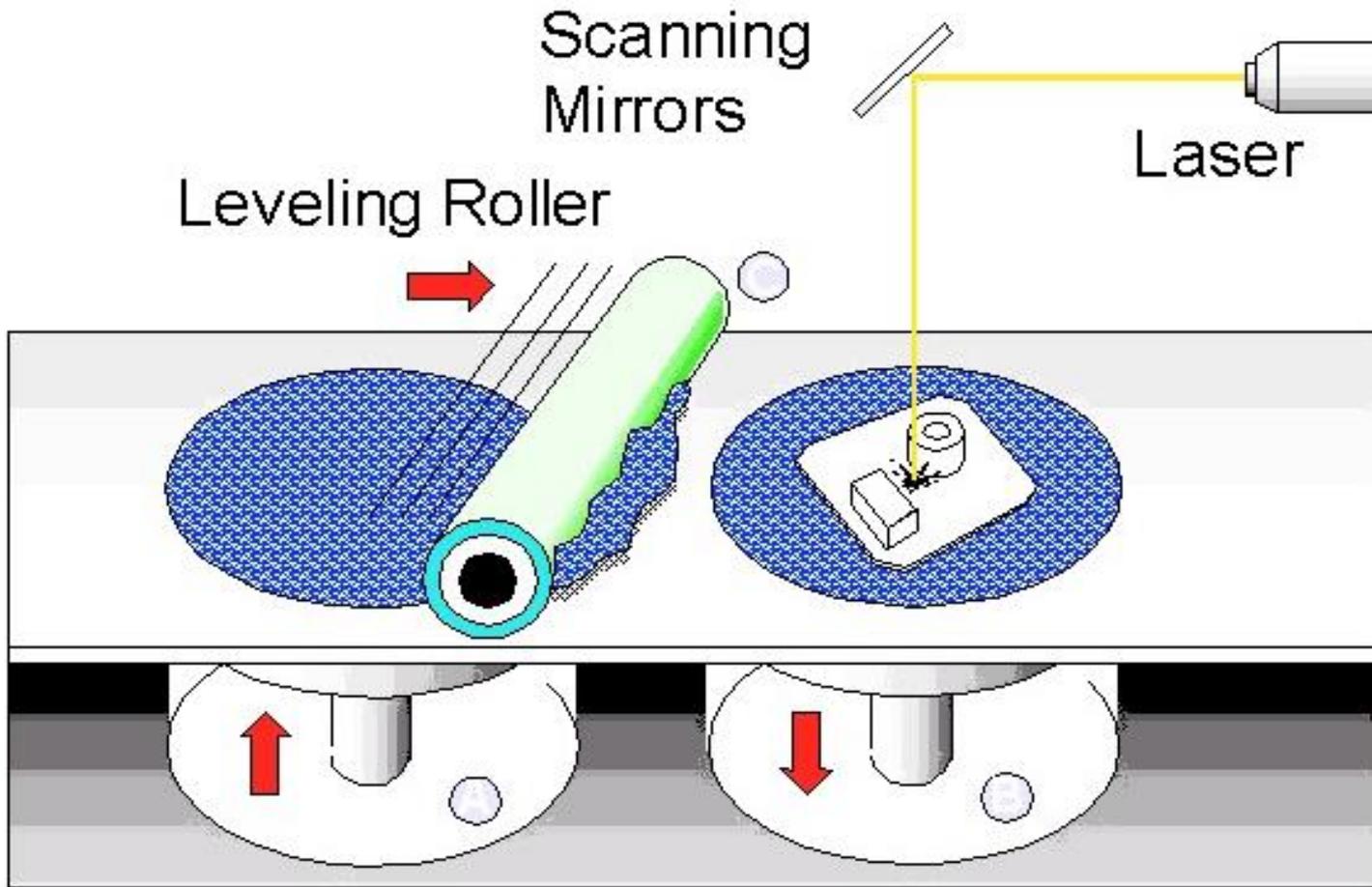
- Invented by Carl Deckard during his PhD. studies in Texas University in 1987.
- Offers the key advantage of making functional parts in essentially final materials.
- The system is mechanically more complex than stereolithography and most other technologies.
- A variety of thermoplastic materials such as nylon, glass filled nylon, polyamide and polystyrene are available. The method has also been extended to provide direct fabrication of metal and ceramic objects and tools.



# + SLS samples



# + Selective Laser Sintering



# + Selective-Laser-Sintering

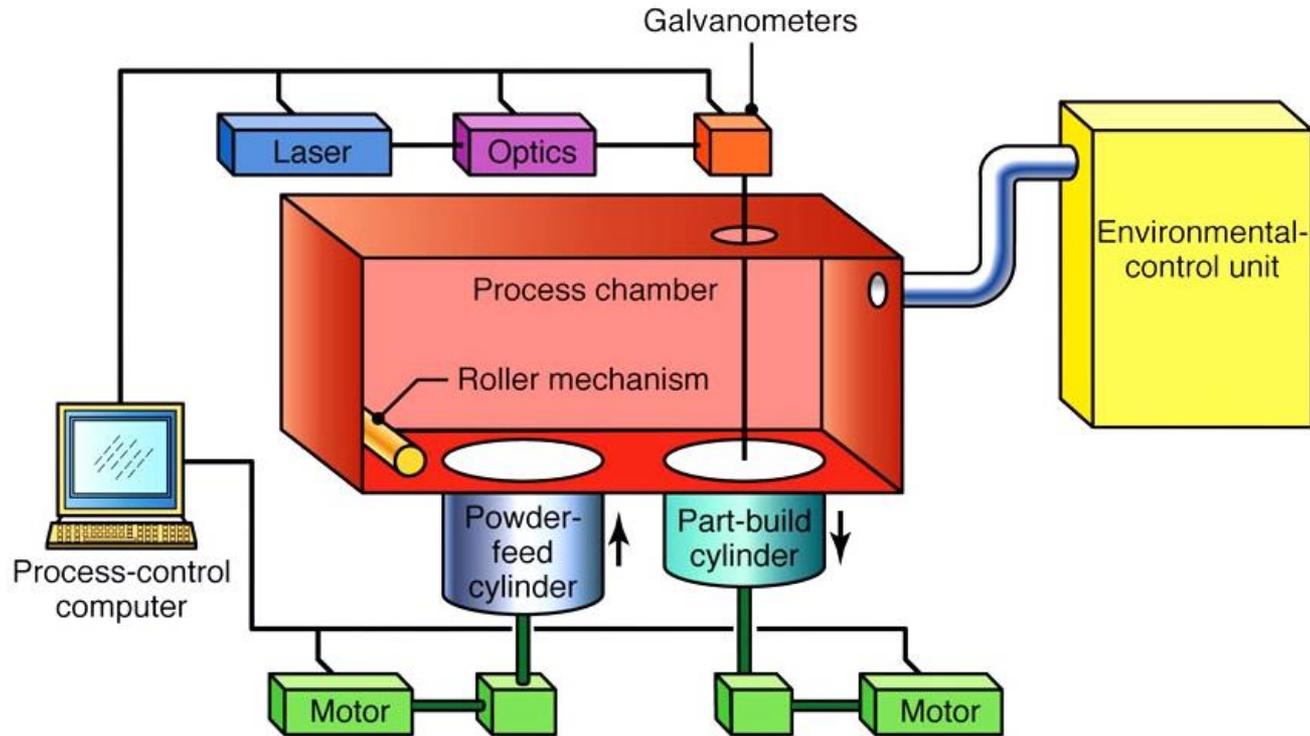


Figure 20.7 Schematic illustration of the selective-laser-sintering process. *Source:* After C. Deckard and P. F. McClure. Manufacturing, Engineering & Technology, Fifth Edition, by Serope Kalpakjian and Steven R. Schmid. ISBN 0-13-148965-8. © 2006 Pearson Education, Inc., Upper Saddle River, NJ. All rights reserved.

# + Selective Laser Sintering

## Process:

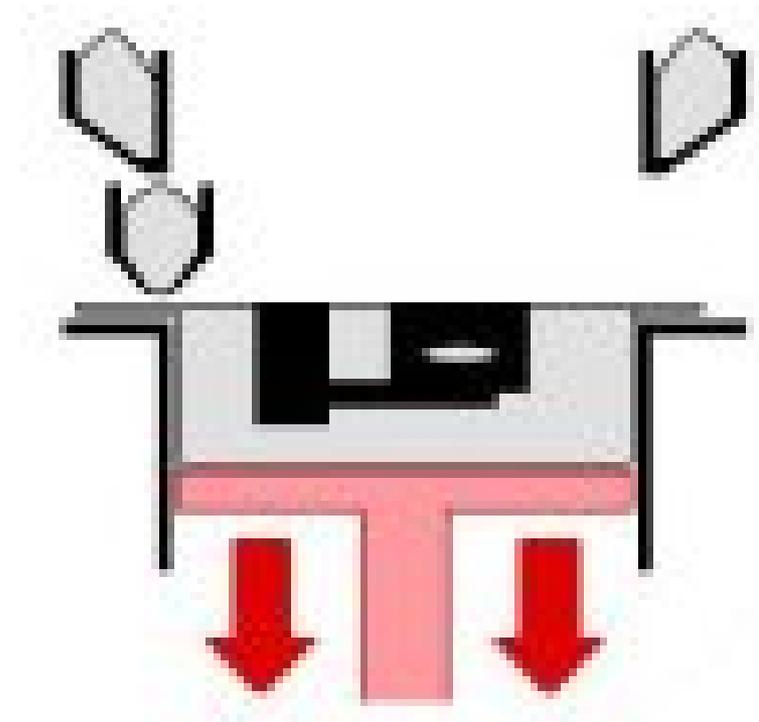
1) Laser beam is traced over the surface the tightly compacted powder to selectively melt and bond it to form a layer of the object.



# + Selective Laser Sintering

## Process:

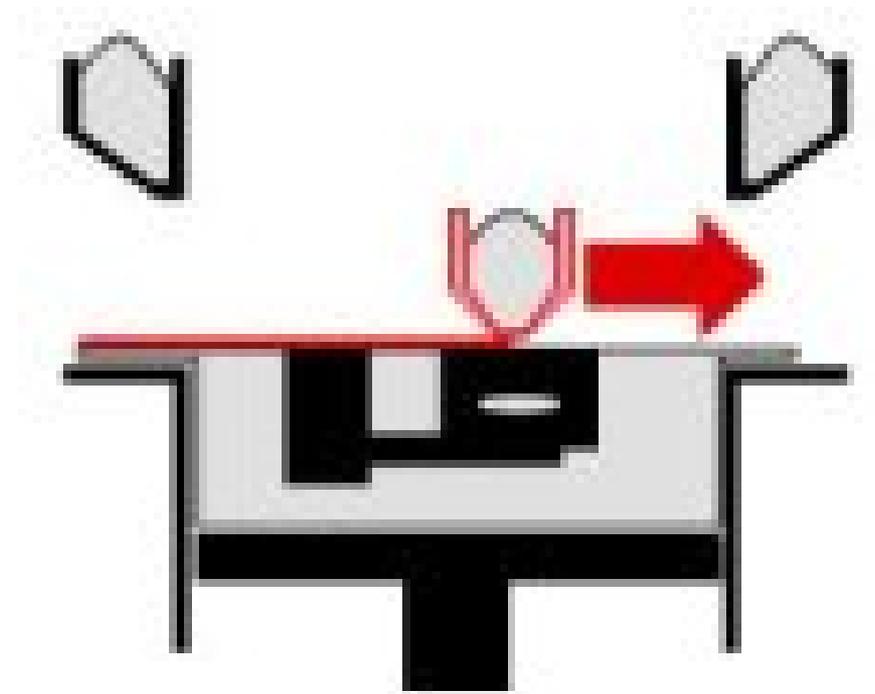
2) Platform is lowered down one object layer thickness to accommodate the new layer of powder



# + Selective Laser Sintering

## Process:

3) A new layer of powder is coated on the surface of the build chamber.

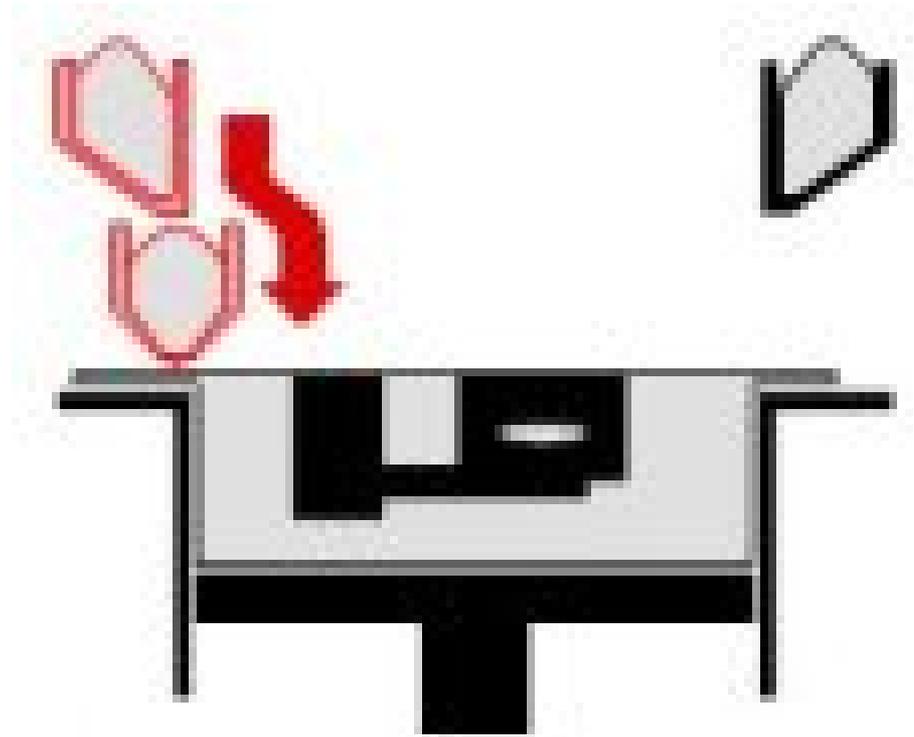


# + Selective Laser Sintering

## Process:

4) The powder is supplied from the powder bins to the recoater.

This process is repeated until the entire object is fabricated.



# + Selective Laser Sintering

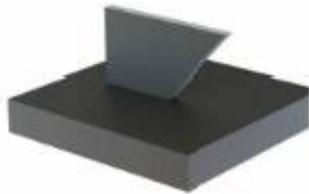


- The fabrication chamber is maintained at a temperature just below the melting point of the powder
- Heat from the laser need only elevate the temperature slightly to cause sintering. This greatly speeds up the process;
- No supports are required with this method since overhangs and undercuts are supported by the solid powder bed;
- Surface finishes and accuracy are not quite as good as with stereolithography, but material properties can be quite close to those of the intrinsic materials

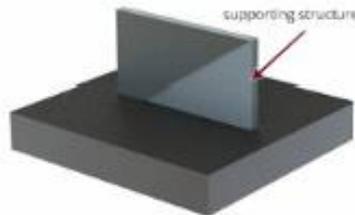
# + Selective Laser Sintering



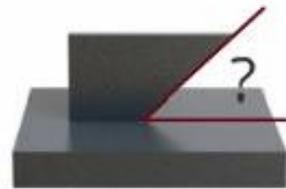
## Angled surfaces and holes



The powder in the build chamber does not provide any support to the part as it builds, so any angled surfaces will ideally be self-supporting

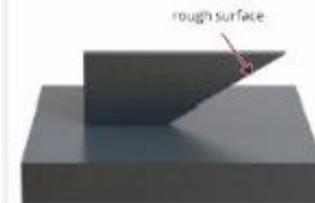


If the angle is too acute, the surface will need a supporting structure built in as part of the model. This supporting structure will then need to be removed by machining or wire cutting, increasing energy use



The minimum angles that will be self supporting are approximately:

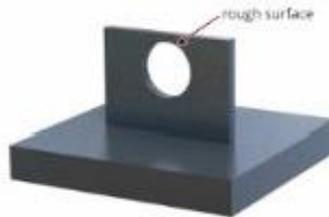
- Stainless steels: 30 degrees
- Inconels: 45 degrees
- Titanium: 20-30 degrees
- Aluminium: 45 degrees
- Cobalt Chrome: 30 degrees



If the angle is near the point where it needs supports, the downward facing surface will become rough and may require considerable post-finishing



Small holes can be accommodated easily. Holes of less than 6mm diameter are ideal



Larger circular holes will result in a roughened surface at the top which may need post-machining



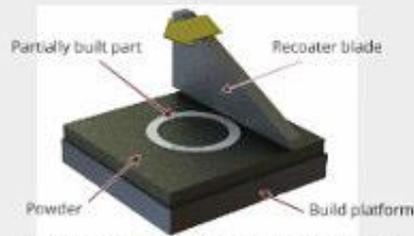
Large holes will require support structures to be added in the centre to prevent the part collapsing or becoming distorted during the build process. These supports will need to be removed by wire cutting or machining



If the hole has an angled or arched upper area it will probably not require any supports. This is one of the features of DMLS that can have a significant impact on the design process

# + Selective Laser Sintering

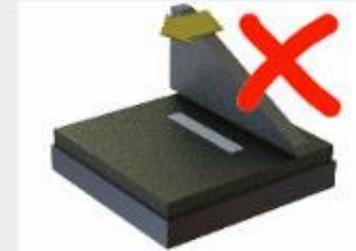
## Direction of build and cross sections



As the recoater blade passes over the part, depositing another layer of powder, it can touch the layer below, sometimes with some force. The orientation of the part is, therefore, important. The ideal geometry is a circular profile which provides a smooth lead in for the blade, and a stable cross section as it builds.



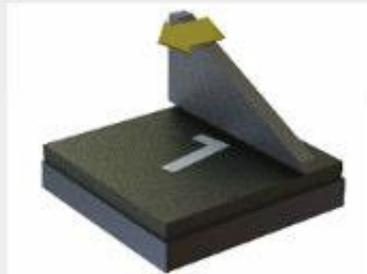
An open 'U' or similar shape is also ideal, as the lead in for the blade is again rounded, and the basic profile will be strong as it builds, resisting the force of the recoating blade.



The 'worst case' geometry would be a thin section parallel to the recoater blade. The blade will tend to 'bounce' off the parallel wall, and the section itself will not resist the force of the blade as it builds.



Any flat surfaces need to be at least 5 degrees from parallel with the blade to allow the blade to touch the part at a point, not a face



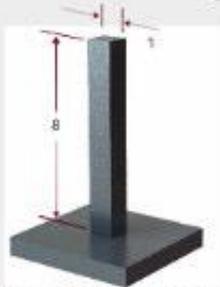
In addition to touching the part at an angle, it helps if the geometry is inherently stiff, which will resist bending forces as the recoater blade passes over the part.



Long, thinner parts with rounded ends will build well, as they also provide a smooth lead in for the blade and are inherently stiff. However, all these issues need to be considered in parallel with the other limits (build angles, etc) mentioned elsewhere in this section.

# + Selective Laser Sintering

## Part strength during the build process



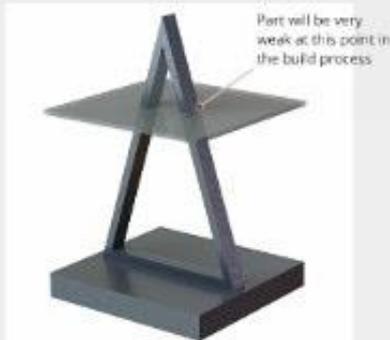
As the recoater blade passes over the building part, more force will be applied to the geometry as it gets taller. As a rule of thumb, the ratio between the section and the height should be approximately 8:1.



The exact proportions will always depend on the specific geometry, but if the section gets too high, there is a danger that the recoater blade will bend the part, and possibly damage itself in the process, terminating the build sequence.



To prevent these problems, vertical sections need to be bridged at certain points. The best method of achieving this will be to use 'arches' to avoid the creation of downward facing flat surfaces.



Even a part that will be strong when it is finished may need some support during the build process. This triangular section will be very weak as the build gets close to the apex.



This kind of structure may need a simple support structure up the middle to provide some rigidity before the part is completed.



If the reason for the open structure is simply weight reduction, it may be easier to perforate it with holes (ideally less than 6mm in dia) that will reduce weight, but not require any supports.

# + Materials



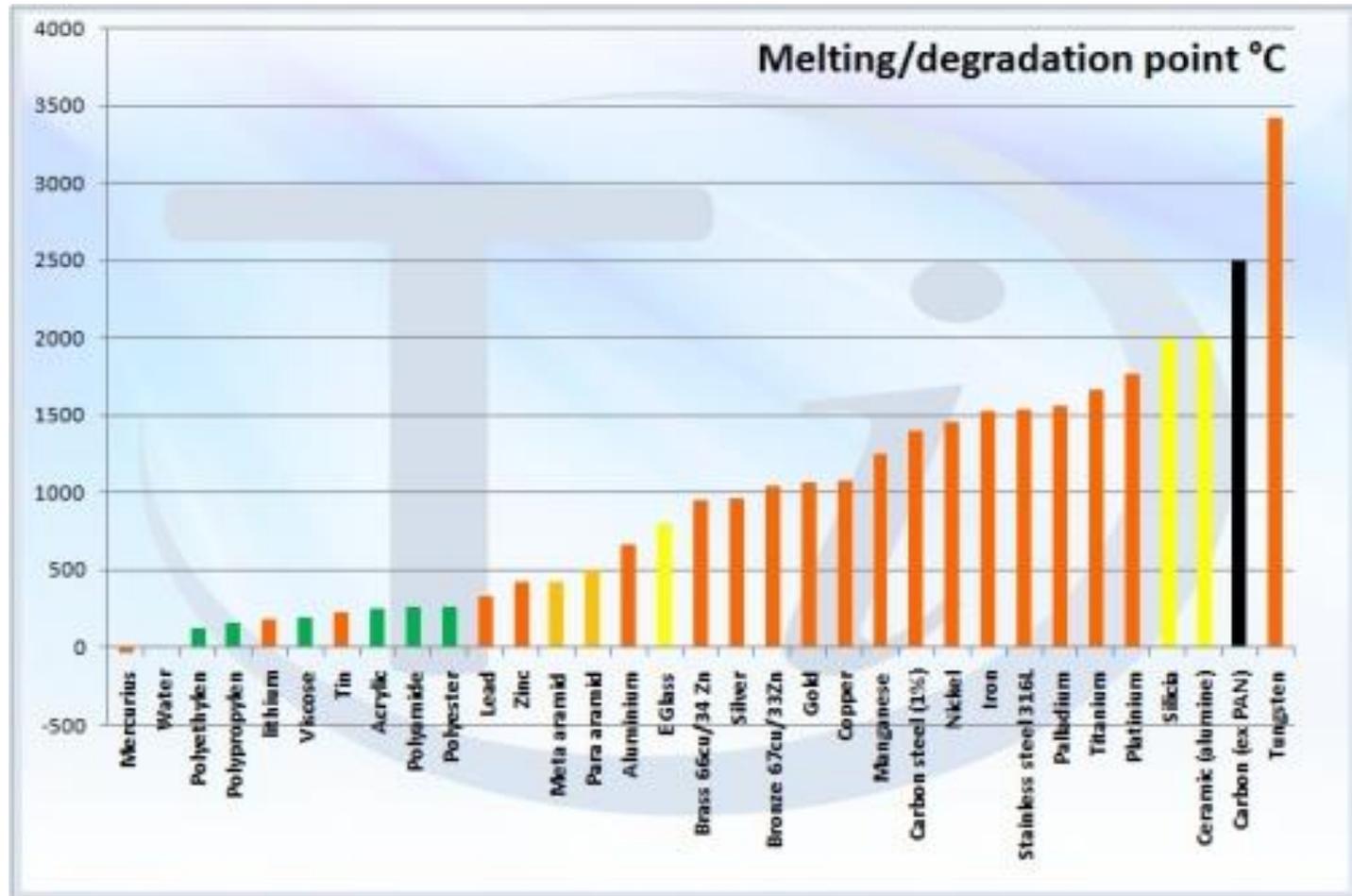
- Polymers
  - nylon, ABS, PVC, and polystyrene,
  - nylon/polycarbonate powders are health hazards (dangerous to breathe).
  - glass-filled or with other fillers
  - metals encapsulated in plastic.
- Metals
  - low melting metal alloys of nickel bronze, steel, titanium, alloy mixtures, and composites
- Green sand (for sand casting).

# + Relevant physical properties

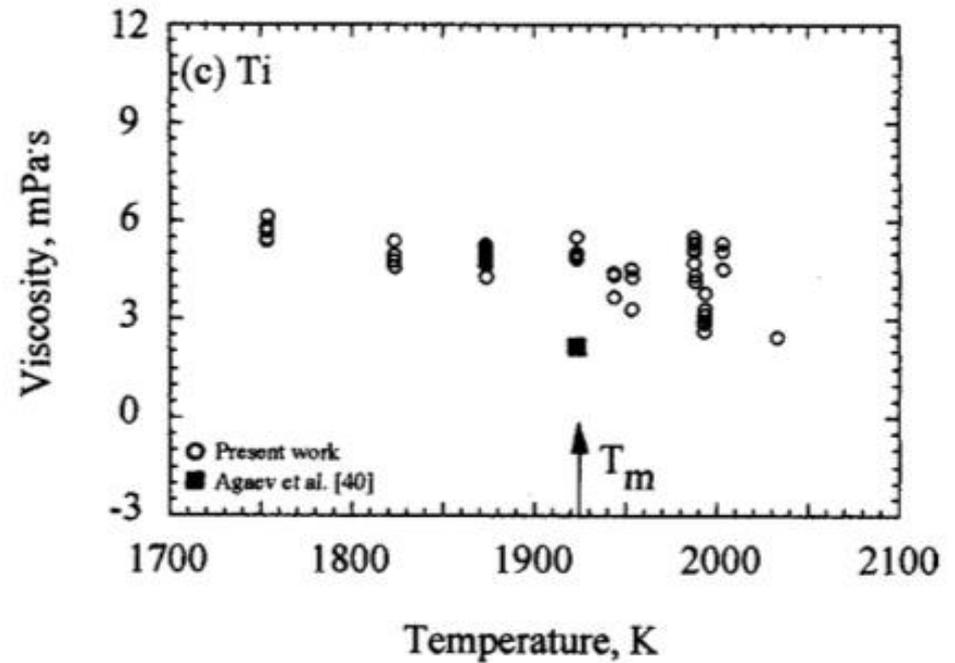
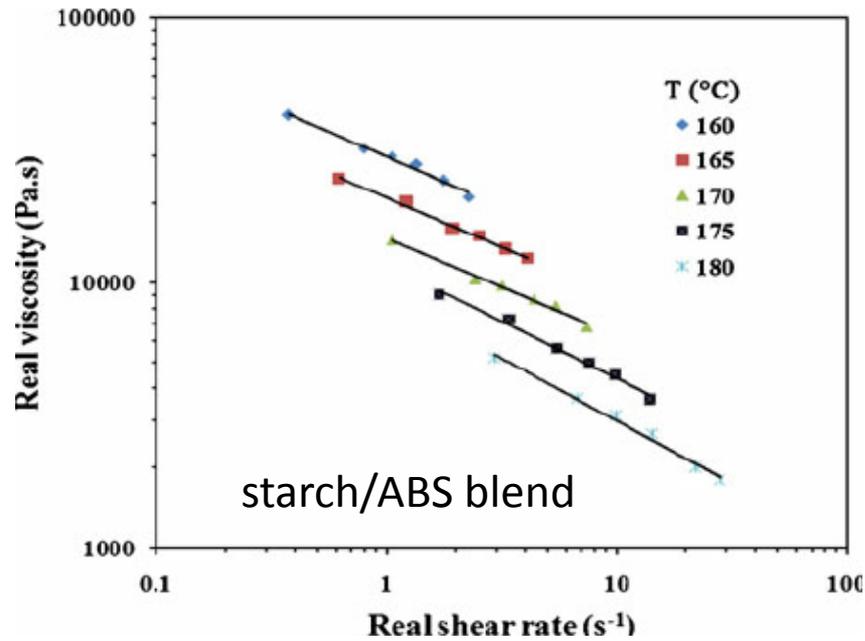
- Melting temperature
- Fluid Dynamic properties
  - Viscosity
  - Surface tension
- Heat conduction properties
  - Thermal conductivity
  - Specific heat
- Thermal expansion



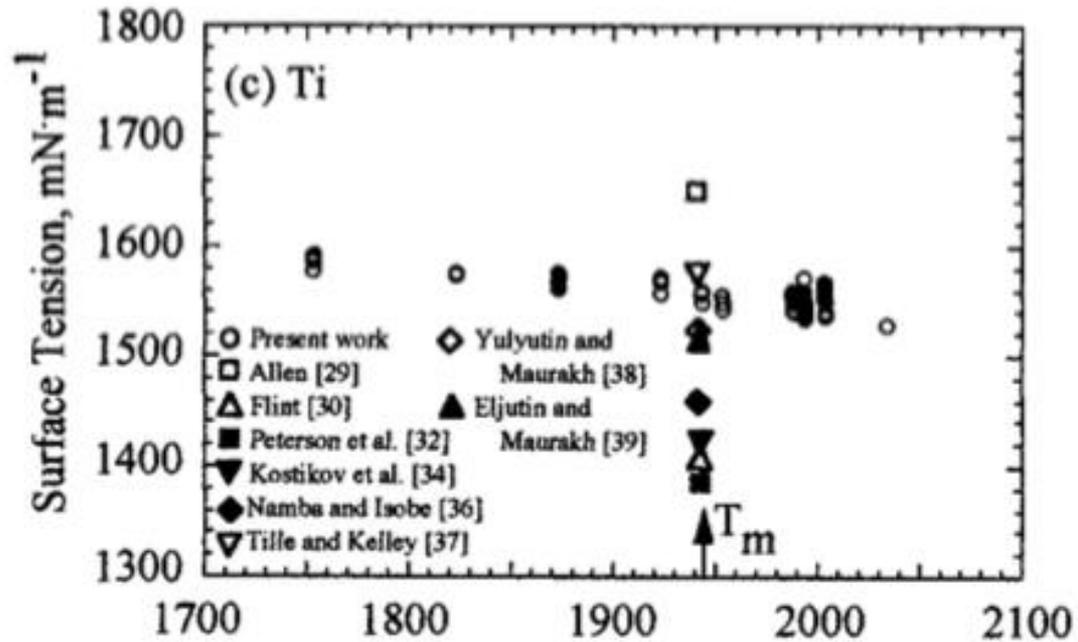
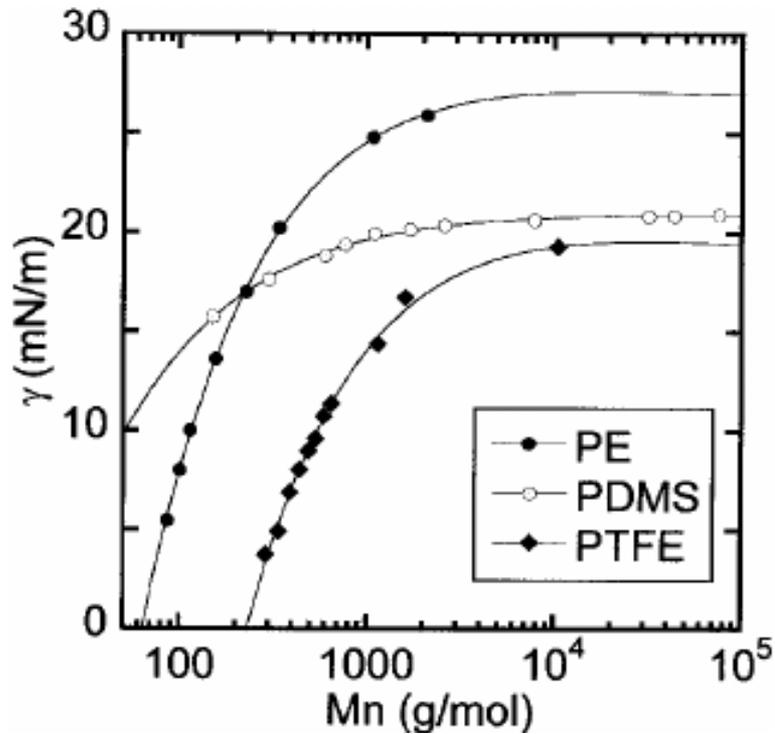
# + Melting temperature



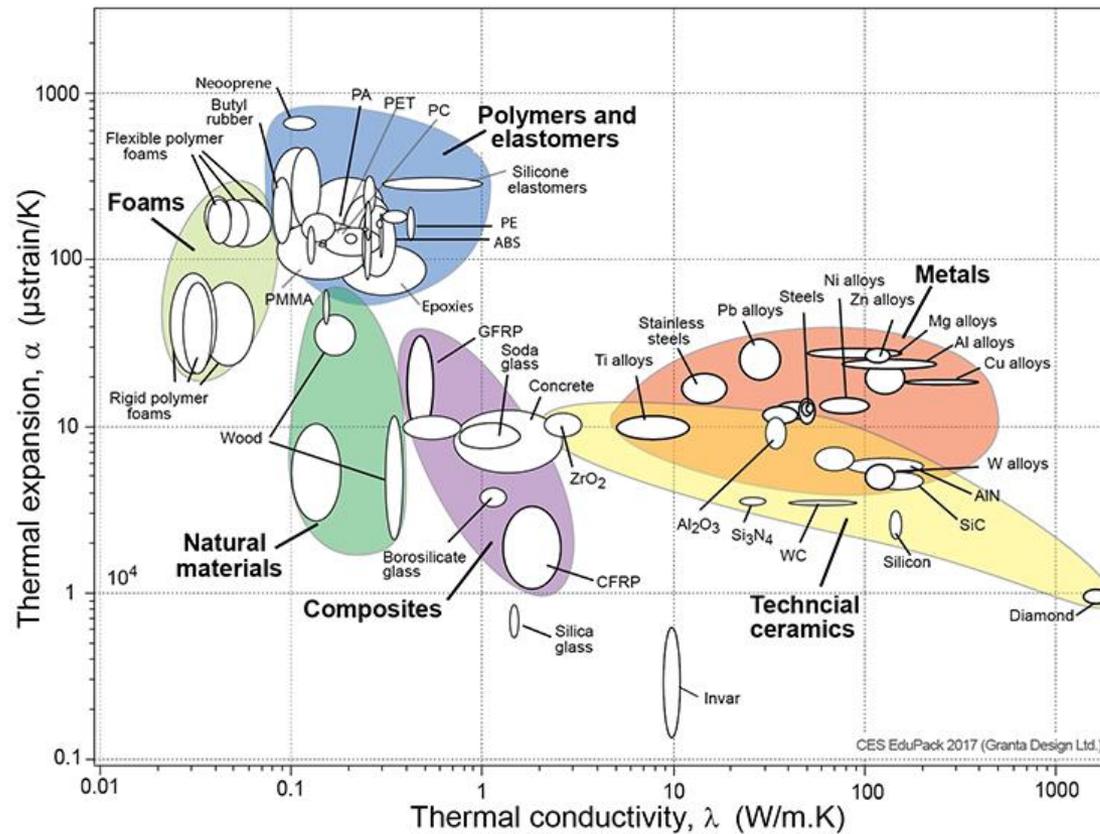
# + Viscosity



# + Surface tension



# + Thermal conductivity and expansion





# + Heat capacity



Material	$c_p$ (J/kg-K) at room $T$
<b>Polymers</b>	
Polypropylene	1925
Polyethylene	1850
Polystyrene	1170
Teflon	1050
<b>Ceramics</b>	
Magnesia (MgO)	940
Alumina (Al <sub>2</sub> O <sub>3</sub> )	775
Glass	840
<b>Metals</b>	
Aluminum	900
Steel	486
Tungsten	138
Gold	128

$c_p$  (specific heat): (J/kg-K)  
 $C_p$  (heat capacity): (J/mol-K)

- Why is  $c_p$  significantly larger for polymers?

Selected values from Table 19.1,  
*Callister & Rethwisch 8e.*

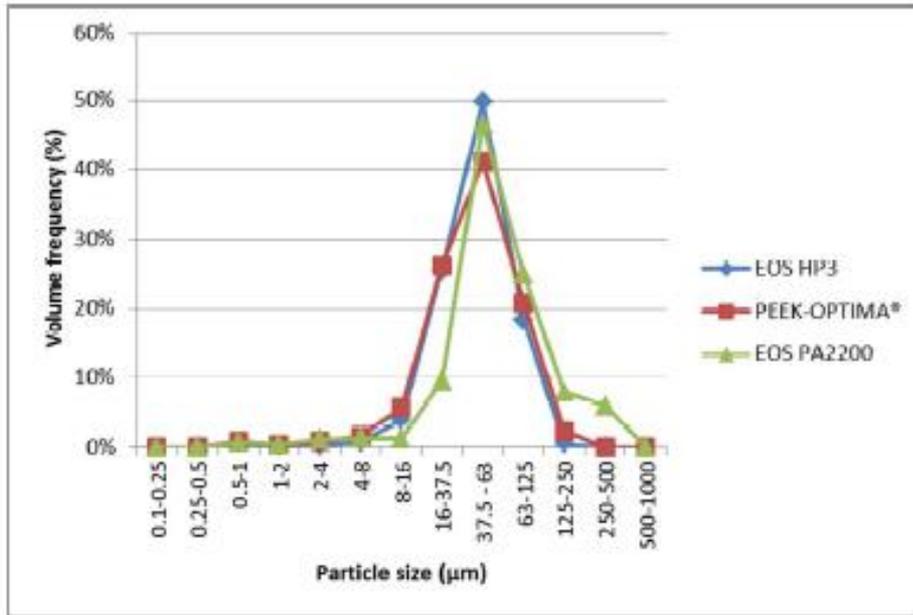
# + Plastic Laser Sintering

- For direct manufacture of styling models, functional prototypes, patterns for plaster, investment and vacuum casting, for end products and spare parts.

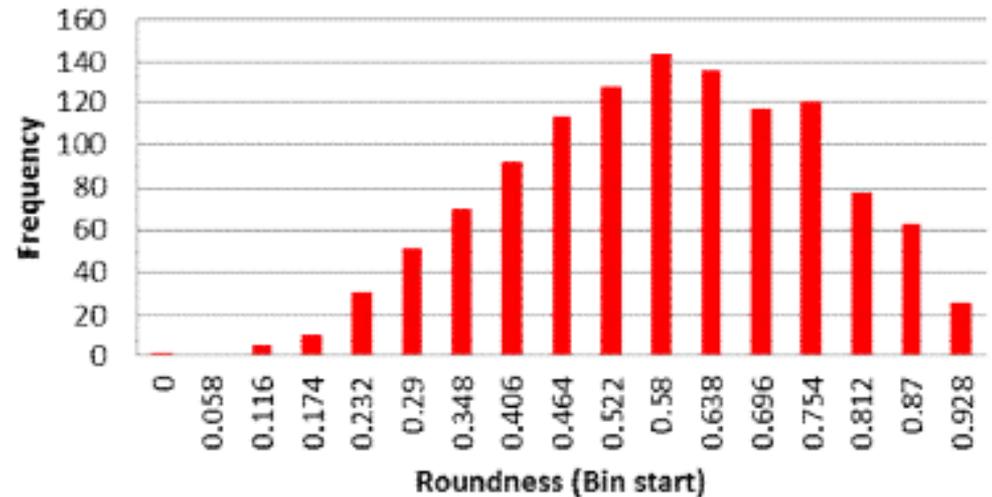
- Volvo Steering Wheel
- Engine Block Pattern
- Plaster Invest. Pattern



# + Plastic Laser Sintering



## Granulometry and roundness



# + Metal Laser Sintering

- For direct production of tooling, including for plastic injection molding, metal die casting, sheet metal forming as well as metal parts, directly from steel based and other metal powders.

- A gear for Volvo Corp.
- Die Cast Parts (500 Al parts produced)
- Motor Housing



# + Some available metals

Materiale EOS	R	Rp0,2	A	test di Fatica (*)	Durezza
	MPa	MPa	%	MPa	HRC
AlSi10Mg	405-445	230-275	3,5-6,5	97	n.d.
In718	980-1060	634-780	27-31	n.d.	30
SS PH1	1050-1150	650-850	16-17	30-35	>90 HRB
Ti6Al4V	1200-1230	1060-1070	10-11	n.d.	35-40
CoCr MP1	1200-1350	800-1060	11-24	560	35-45

Fonte: EOS

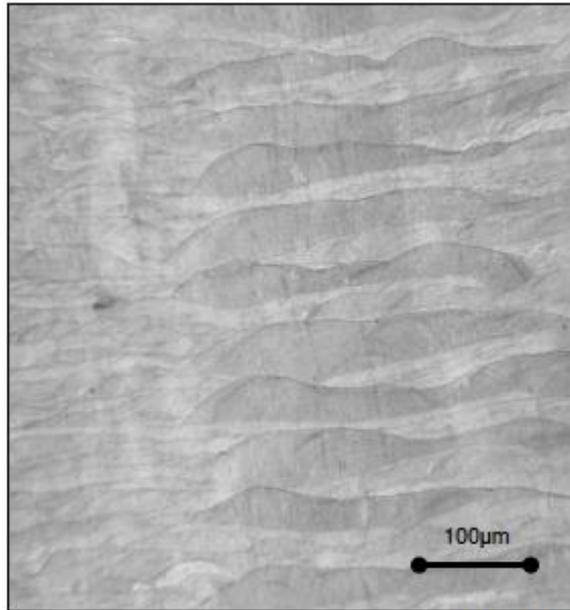
# + Some available metals

- Grana molto fine e distribuzione omogenea dei componenti stechiometrici
- Rispetto norme ISO e ASTM per la composizione chimica
- Proprietà meccaniche simili e superiori a prodotti equivalenti da barra, fusione e forgiatura a freddo (fonte EOS)
- Le caratteristiche metallurgiche sono migliori della fusione a “cera persa” (Investment casting). Infatti nella microfusione laser selettiva si arriva a fusione completa e risolidificazione in tempi brevissimi (frazioni di secondo) e non si dà tempo al “grano” di accrescere (cosa che avviene nell’investment casting)



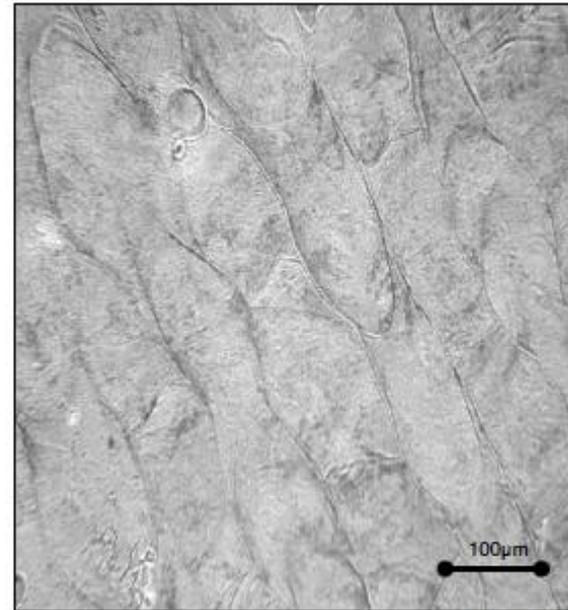
# + Some available metals

Micrografia di Stainless Steel GP1 mostra una struttura completamente fusa, densa. *Vista trasversale.*



Fonte: EOS

Micrografia di Stainless Steel GP1 *Vista da sopra.*

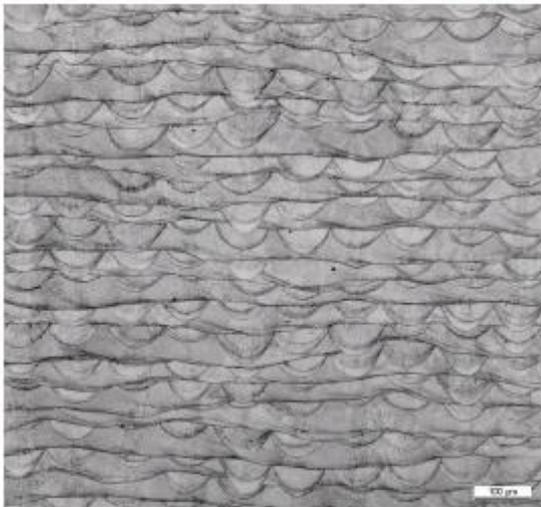


Fonte: EOS

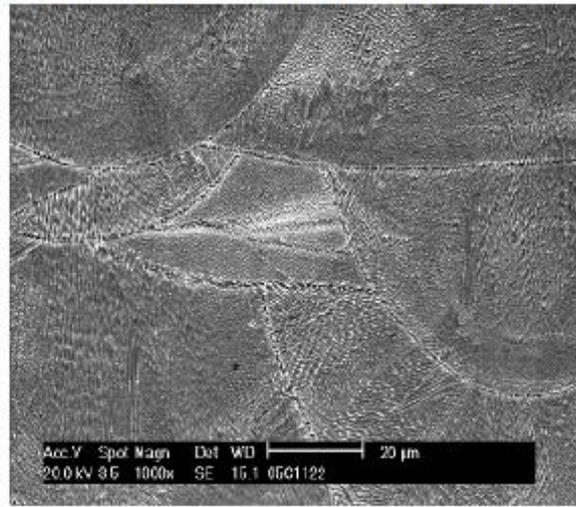
Si mostra una struttura completamente rifusa, densa

# + Some available metals

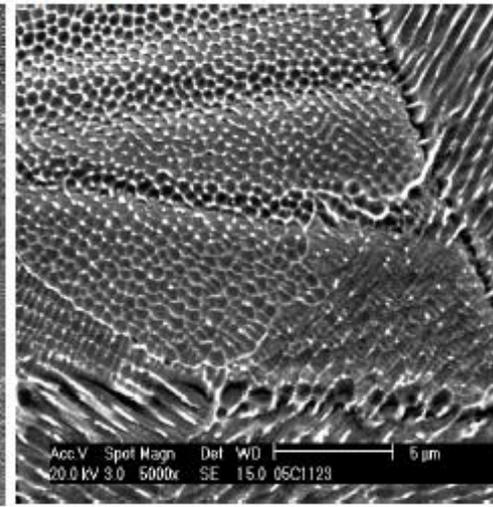
Micrografie di campioni di CobaltChromeMP1



10x



1000x SEM



5000x SEM

Fonte: EOS

MP1 produce parti con strutture a grana molto fine e dimensioni tipiche di 0.3-0.6 μm

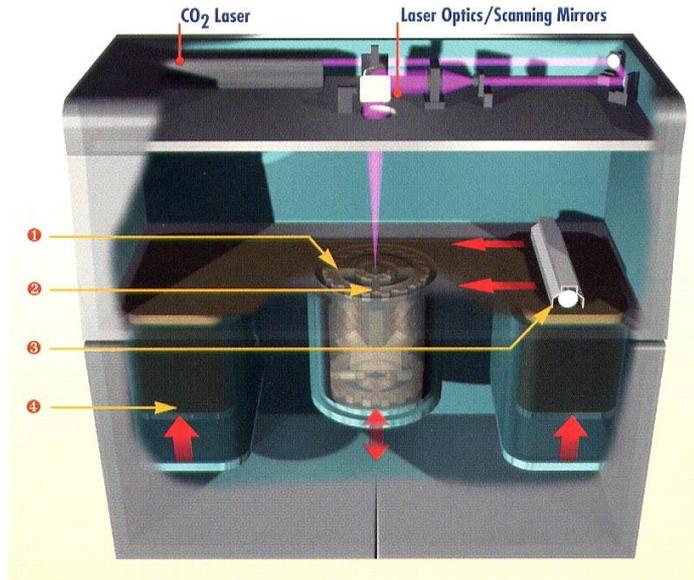
# + Sand Laser Sintering

- Laser Sintering System for direct, boxless manufacture of sand cores and moulds for metal casting.

- V6-24 Valve Cylinder Head.
- Impeller
- Steering Block for a car



# + DTM Sinterstation 2500



<b>Volume di lavoro</b>	380 X 330 x 460 mm
<b>Laser</b>	CO <sub>2</sub>
<b>Potenza</b>	50 / 100 W
<b>Spot</b>	0.42 mm
<b>Velocità di scansione</b>	5000 mm/sec
<b>Precisione di posizionamento</b>	0.05 mm
<b>Spessore layer</b>	0.1 mm



# METU SYSTEM



## ■ EOS EOSINT P380 Rapid Prototyping System

<i>General Properties</i>
Plastic Laser Sintering System X,Y Axes Alternating Scanning
<i>Technical Specifications</i>
Work Envelope:
-X Axis: 340 mm
-Y Axis : 340 mm
-Z Axis : 600 mm
Layer Forming Thickness:
0.15mm +/-0.05 mm
Max Laser Power: 50 W
Z Axis Production Speed: 30 mm / saat
Max Scanning Speed: 5 m/s



# + Eosint P360



# + Selective Laser Sintering

## Advantages:

- Cheap and no harmed healthy material,
- Large selection of used materials,
- Is not needed supported construction,
- Decreasing of destruction possibility of inside stresses.



# + Selective Laser Sintering



Disadvantages:

- Roughness surface after final modification it means “stairs” effect,
- Porosity of components,
- Different intensity in various parts of generated components,
- Material transformations are needing cleaning of the production device

# + Selective Laser Sintering

- Process is wall thickness dependent. (not suitable for massive parts)
- Process involving internal stresses in the parts need additional annealing
- Process requiring strong supports for parts fasten during the manufacturing (not only for heat transfer)
- Need to use build plates of the same material than the powder used in the machine (e.g.: more expensive for titanium powder)
- Cutting tool necessary (eg: a saw) in order to release the parts from the build plate



# + Selective Laser Sintering

- Surface finishing technologies
  - Tumbling
  - Blasting
  - Chemical and/or electrochemical polishing
  - Abrasive Flow Machining (AFM)
  - Thermal Energy Method (TEM)
  - Robotic and CNC polishing
  - Laser Polishing / Ablation
  - Electron-beam polishing (EBEST)



## + Future trends

- Increase of working volume with several laser heads
- Automatic recovery of unbounded powder
- Repeatability of the process



EBM

# **ELECTRON BEAM MELTING**

# + Electron Beam Melting (EBM)

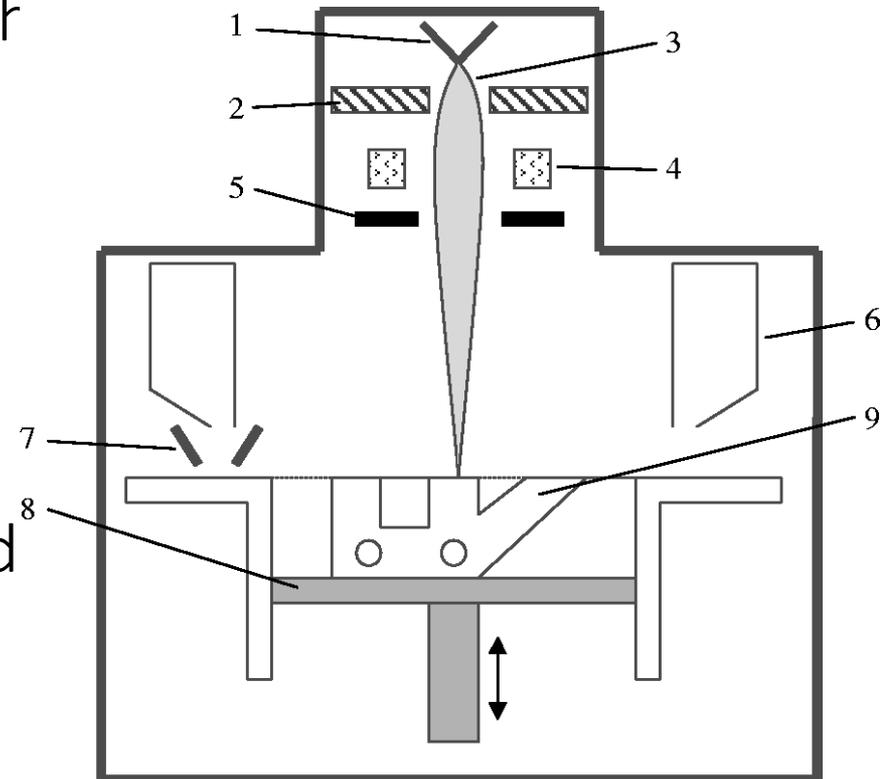
- Electron Beam Melting (EBM) is a type of rapid prototyping for metal parts. The technology manufactures parts by melting metal powder layer per layer with an electron beam in a high vacuum. Unlike some metal sintering techniques, the parts are fully solid, void-free, and extremely strong.
- EBM is also referred to as Electron Beam Machining.
- High speed electrons .5-.8 times the speed of light are bombarded on the surface of the work material generating enough heat to melt the surface of the part and cause the material to locally vaporize.
- EBM does require a vacuum, meaning that the workpiece is limited in size to the vacuum used. The surface finish on the part is much better than that of other manufacturing processes.
- EBM can be used on metals, non-metals, ceramics, and composites.



# + Electron Beam Melting (EBM)



- Dispensed metal powder in layers
- Cross-section molten in a high vacuum with a focused electron beam
- Process repeated until part is completed
- Stainless steel, Titanium, Tungsten parts
- Ideal for medical implants and injection molds
- Still very expensive process



# + Examples of EBM



From Computer Desktop Encyclopedia  
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© 2007 Arcam AB



ARCAM A2 machine for direct metal deposition



Components made of Ti and Co-Cr alloys



Biomedical components made of Ti alloys

# + EMB benefit

- High productivity
- Suitable for very massive parts
- No residual internal stress (constant 680-720°C build temperature)
- Less supports are needed for manufacturing of parts
- Possibility to stack parts on top of each other (mass production)
- Sintered powder = good for thermal conductivity = less supports
- Process under vacuum (no gas contaminations)
- Very fine microstructures (Ti6Al4V), very good mechanical and fatigue results (Ti6Al4V)



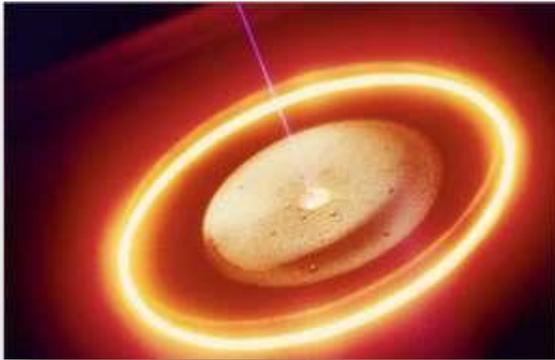
## + EBM drawbacks

- Powder is sintered -> tricky to remove (e.g. interior channels)
- Long dead time between 2 productions (8 hours for cooling – A2, A2X, A2XX systems)
- Tricky to work with fine powder
- Expensive maintenance contract



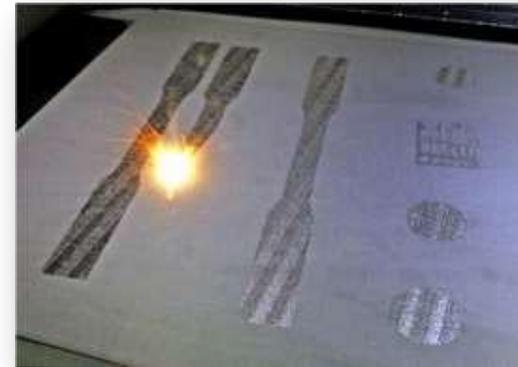
# + Comparison

- Electron Beam Melting (EBM)



- Metallic powder deposited in a powder bed
- Electron Beam
- Vacuum
- Build temperature: 680–720°C

- Laser Beam Melting (LBM)



- Metallic powder deposited in a powder bed
- Laser Beam
- Argon flow along Ox direction
- Build temperature: 200°C

# + Comparison

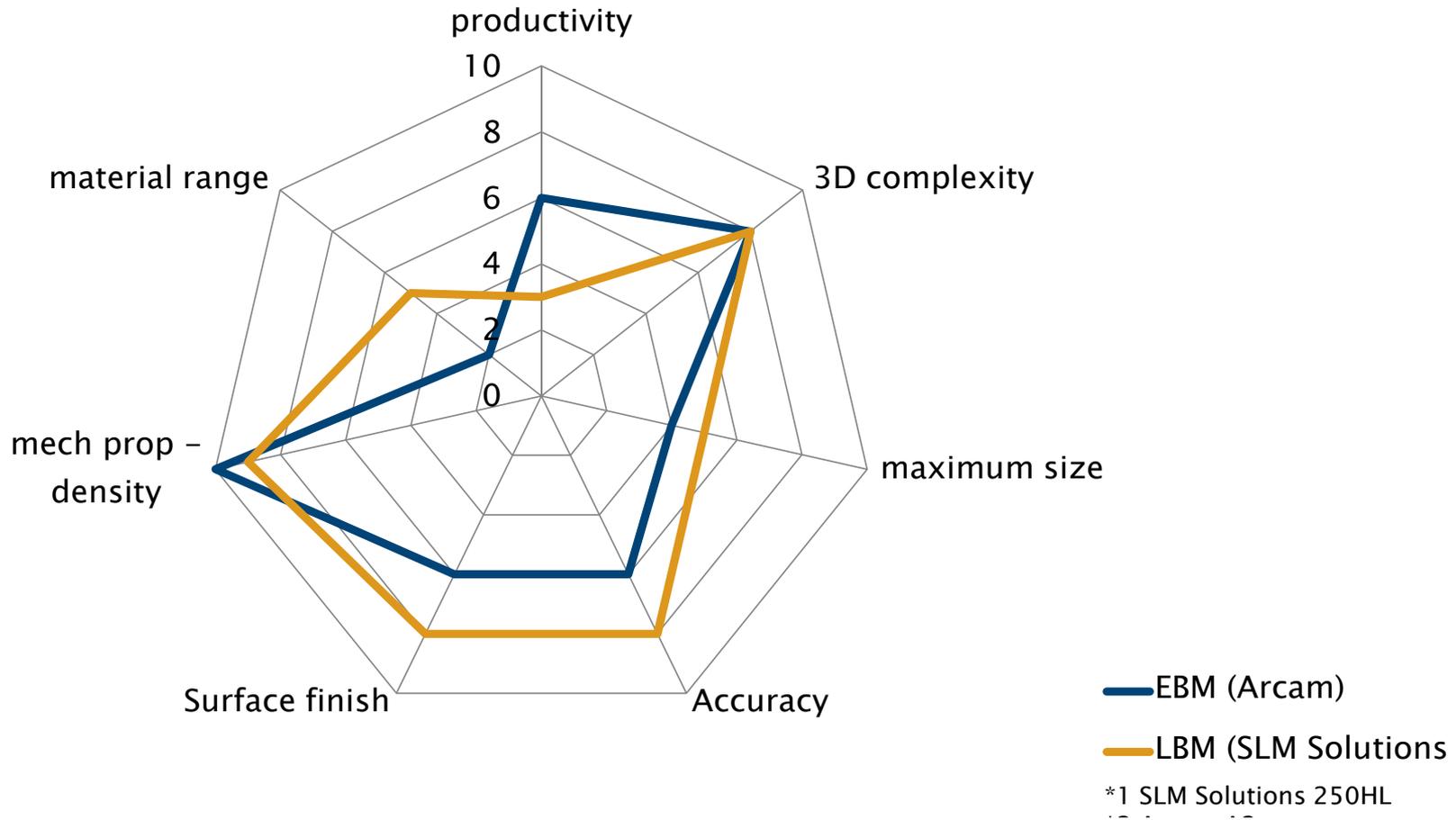
	LBM	EBM
Size (mm)	250 x 250 x 350* <sup>1</sup>	210 x 210 x 350* <sup>2</sup>
Layer thickness (µm)	30 – 60	50
Min wall thickness (mm)	0.2	0.6
Accuracy (mm)	+/- 0.1	+/- 0.3
Build rate (cm <sup>3</sup> /h)	5 – 20	80
Surface roughness (µm)	5 – 15	20 – 30
Geometry limitations	Supports needed everywhere (thermal, anchorage)	Less supports but powder is sintered
Materials	Stainless steel, tool steel, titanium, aluminum,...	Only conductive materials (Ti6Al4V, CrCo,...)

\*1 SLM Solutions 250HL

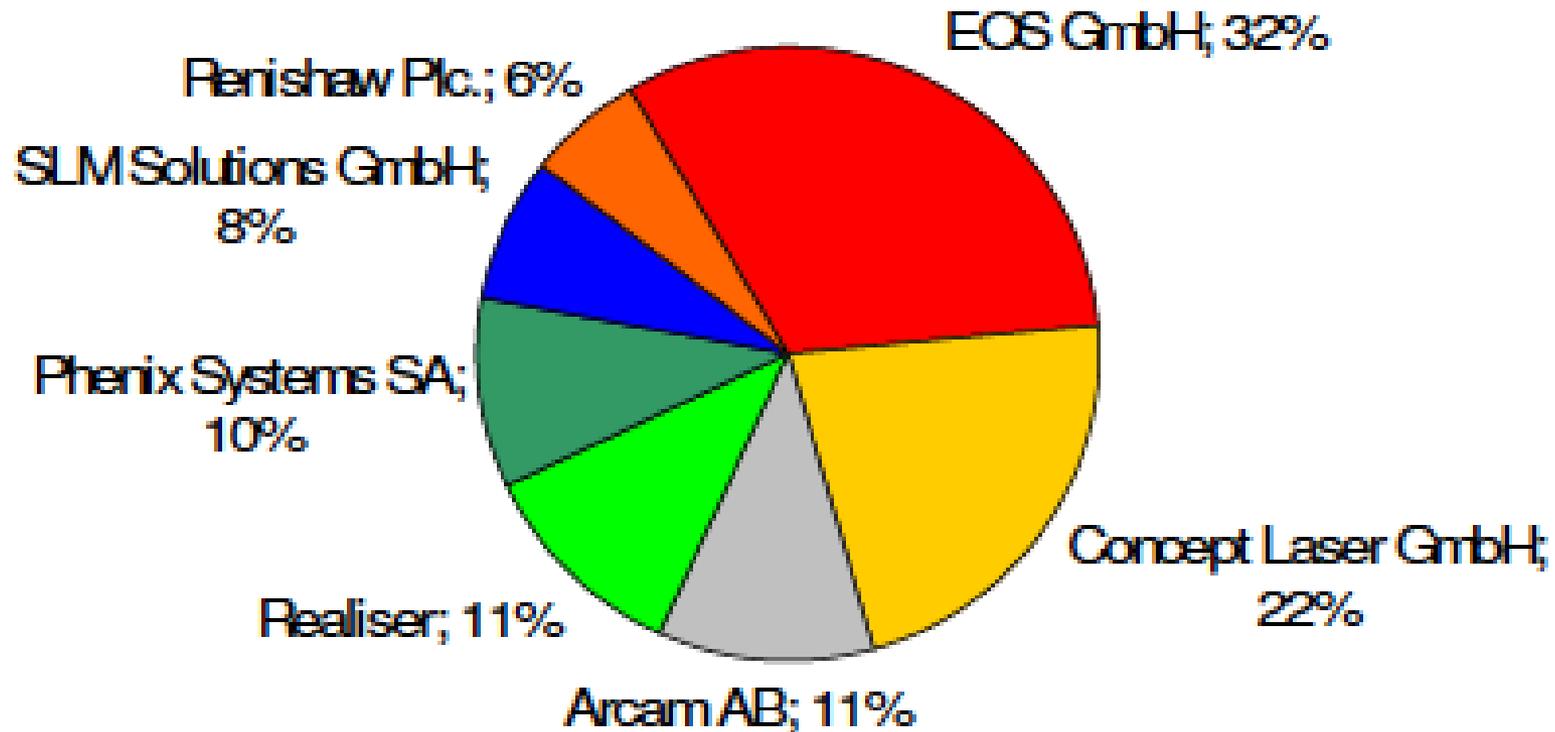
# + Comparison

		EOS	SLM	Concept Laser	Renishaw	ARCAM
		M270	250HL	M1	AM250	A1
Gas di processo		Argon o Azoto	Argon o Azoto	Argon o Azoto	Argon o Azoto	
consumo di gas	Lt/h		90	1000	5-30	
Potenza del laser	W	200 - 400	200 - 400	200 - 400	200 - 400	50-3000
Max dimensione	mm	250 x 250 x 215	248 x 248 x 250	250 x 250 x 250	245 x 245 x 300	200 x 200 x 180
Capacità produttiva	cmc/h	2 - 20	20	2 - 20	5 - 20	55-80
Velocità scansione laser	m/s		20	7	2	8000
Spessore layers	micron	20-60	20 -75	20-80	20 -100	
Formato file		STL	STL	STL	STL	STL
Precisione	mm	+/- 0,05		+/- 0,05		+/- 0,20
Rugosità	micron	4-6	4-6	4-6	4-6	25-35
Principali Materiali	Acciaio inox	17-4 PH1	1.4404 (316L) 1.4542 (17-4 PH)	1.4404	1.4404	
	Acciaio per stampi	Maraging	1.2344 (H13)	1.2709	1.2344	
	Superlega CoCr	CoCr ASTM F75	CoCr ASTM F 75	CoCr (F75), CrCo (dentale)	CoCr ASTM F75	CoCrMo ASTM F75
	Titanio	Ti6Al4V	Ti6Al4V, Ti6Al7Nb, Titanio puro	Titanium Grade 5	Ti-6Al-4V e Ti-6Al-7Nb	Ti6Al4V
	Leghe di Nickel	Inconel 625, 718	Inconel 625, 718	Inconel 625	inconel 718 e 625	
	Alluminio	AlSi10Mg	AlSi12	AlSi10Mg, AlSi12	AlSi12	

# + Comparison



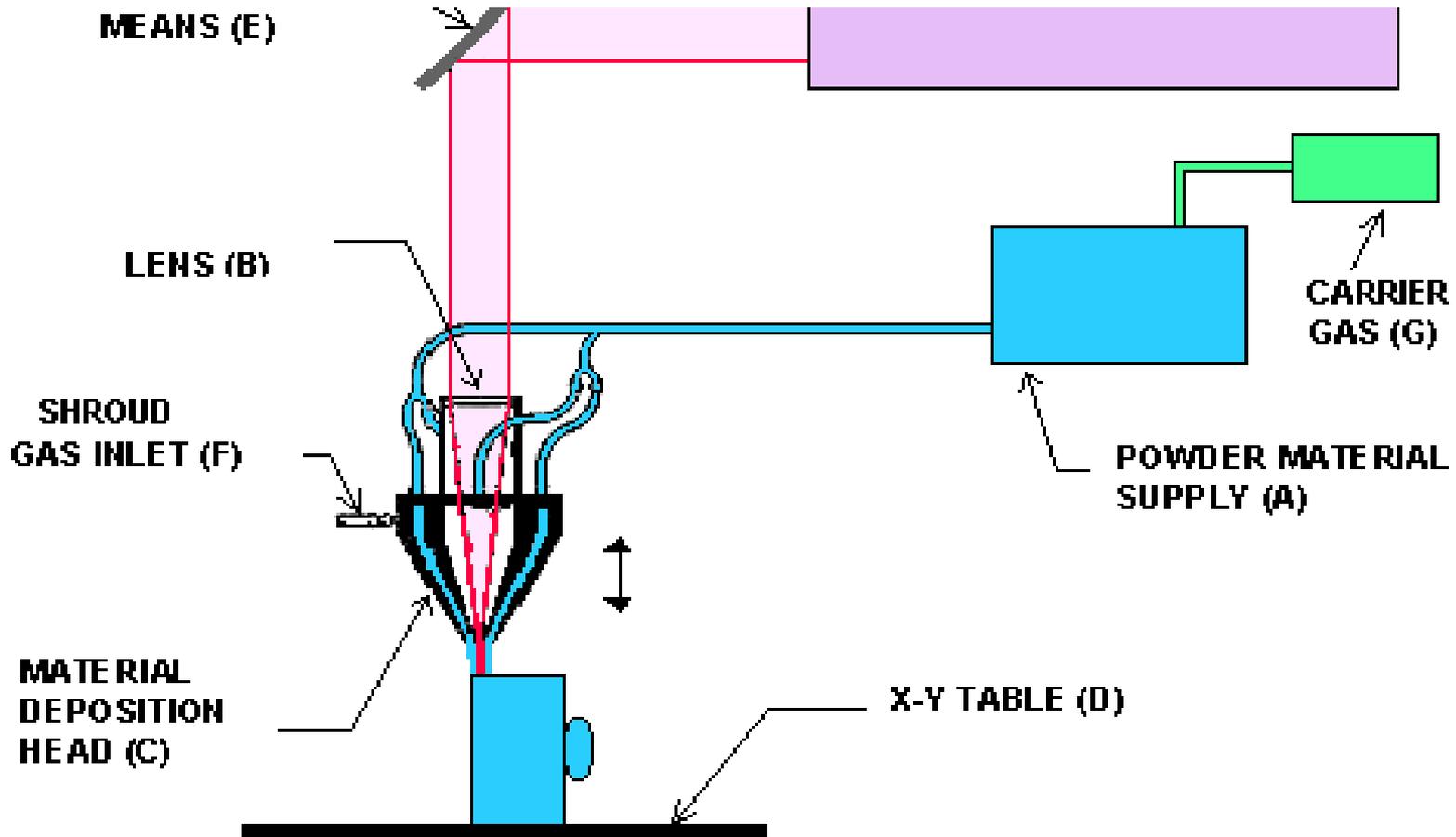
# + European Market 2011



Lens

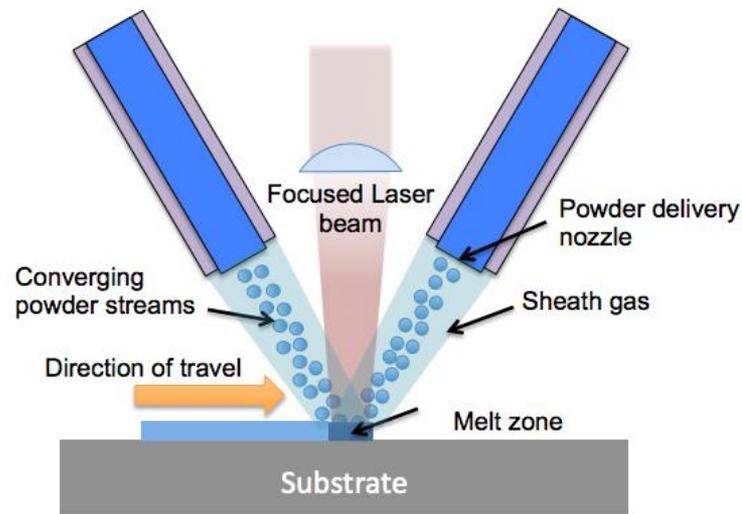
# **LASER ENGINEERED NET SHAPING**

# + Laser Engineered Net Shaping



# + Laser Engineering Net Shaping

- Direct energy deposition



# + Laser Engineered Net Shaping

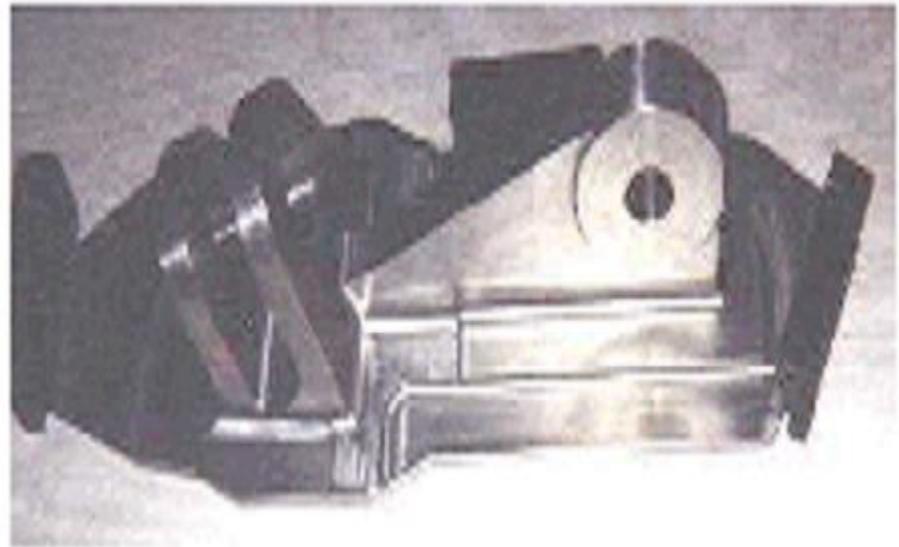
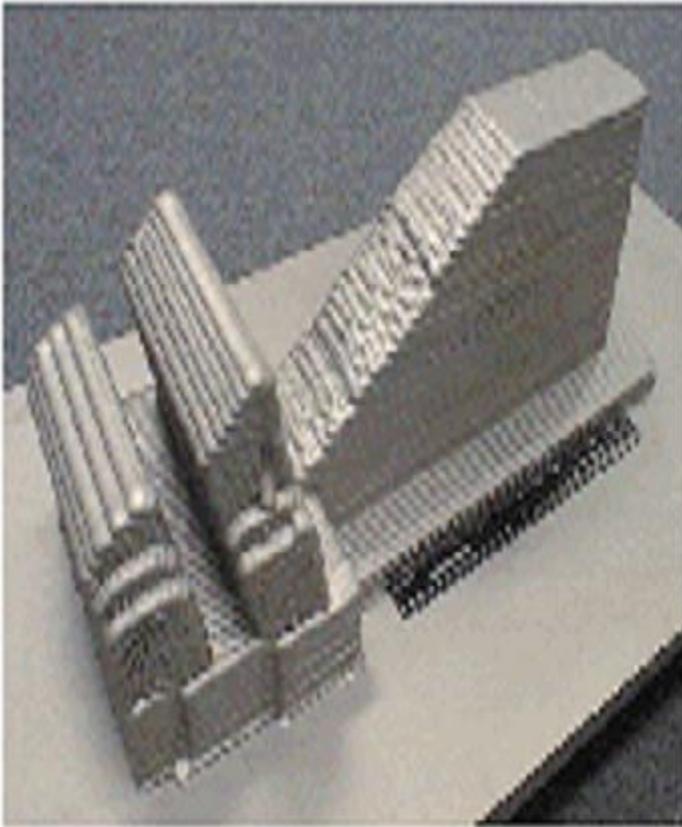
- Fully Dense Metal parts with good metallurgical properties
- Laser melts metal powder
- Powder delivered coaxially with laser
- Inert gas protects weld pool
- Near net shape with some finish machining

# + Laser Engineered Net Shaping

- In addition to titanium, a variety of materials can be used such as stainless steel, copper, aluminum etc.
- Materials composition can be changed dynamically and continuously, leading to objects with properties that might be mutually exclusive using classical fabrication methods.
- Has the ability to fabricate fully-dense metal parts with good metallurgical properties at reasonable speeds;
- Objects fabricated are near net shape, but generally will require finish machining.



# + Laser Engineered Net Shaping



Before and after finish machining

# + Laser Engineered Net Shaping



120x120x120 cm LENS Machine

# + LENS (Other names)

Capability of in situ repair



# + Laser Engineered Net Shaping

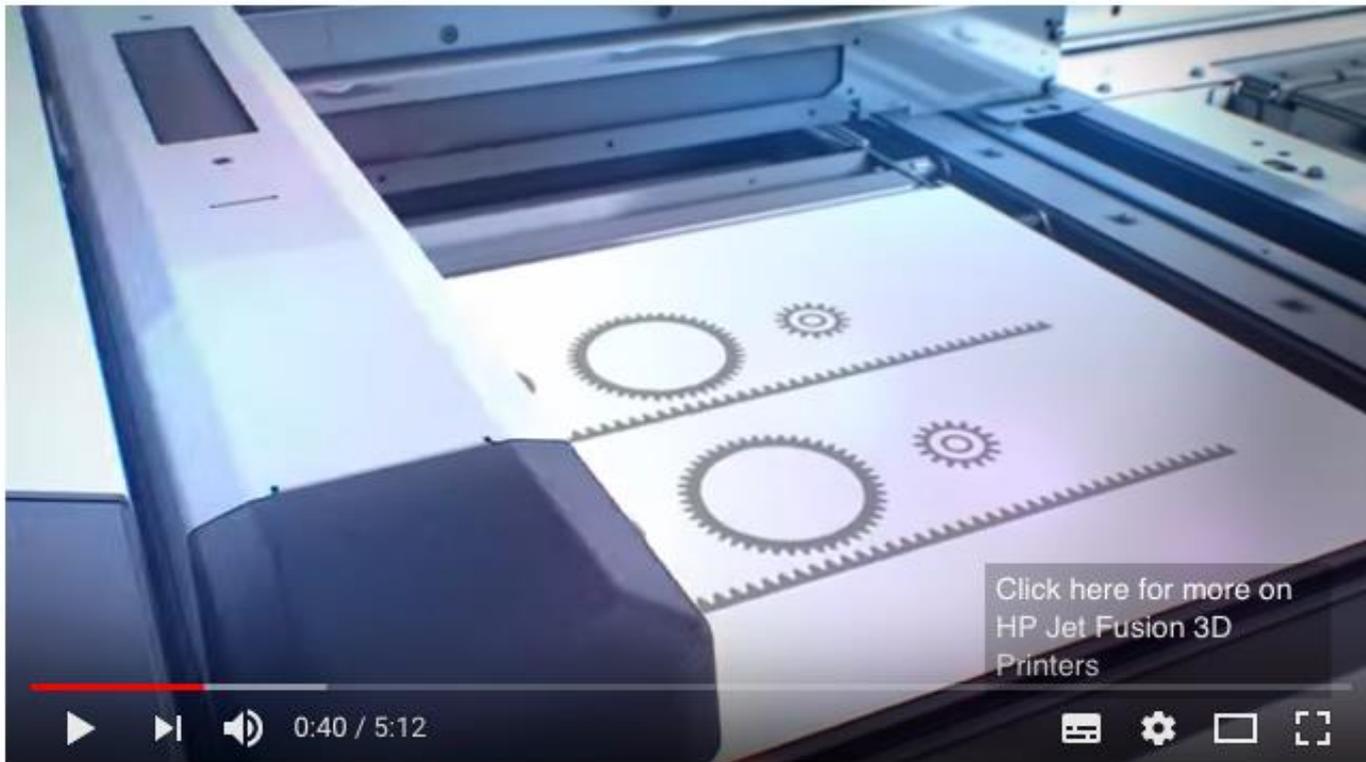
<https://www.youtube.com/watch?v=d2foaRi4nxM>



# **MULTIJET FUSION**

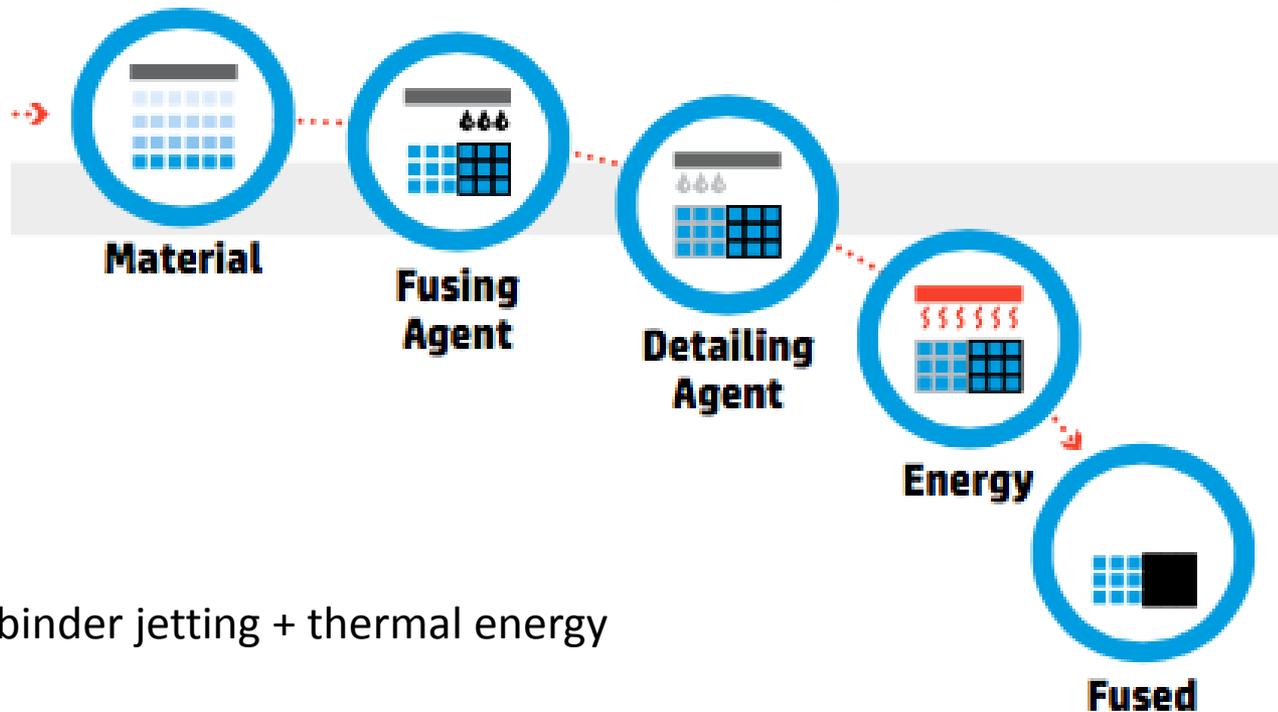
# + MultiJet Fusion

- [https://www.youtube.com/watch?time\\_continue=1&v=VXntl3ff5tc](https://www.youtube.com/watch?time_continue=1&v=VXntl3ff5tc)
- <https://www.youtube.com/watch?v=qEPqIVs11KM>

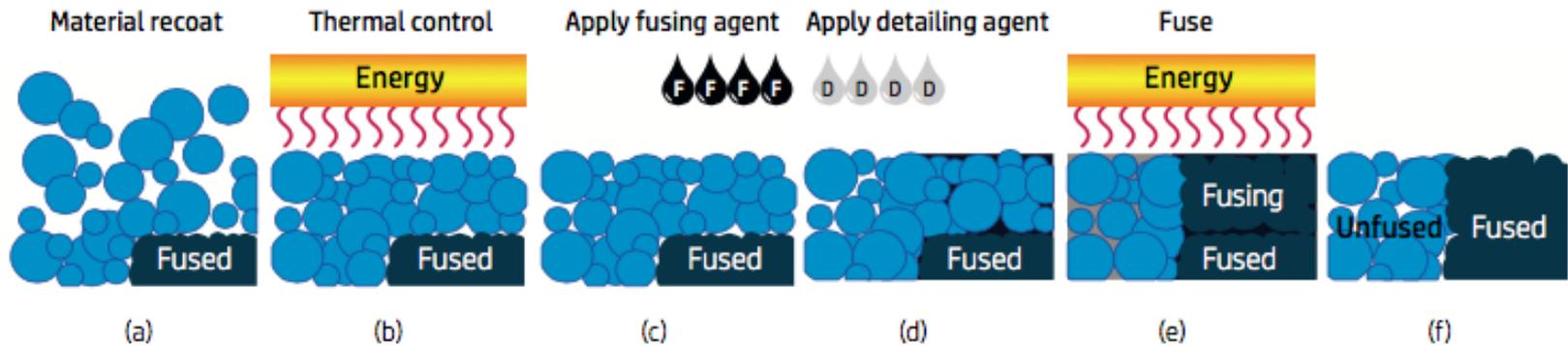
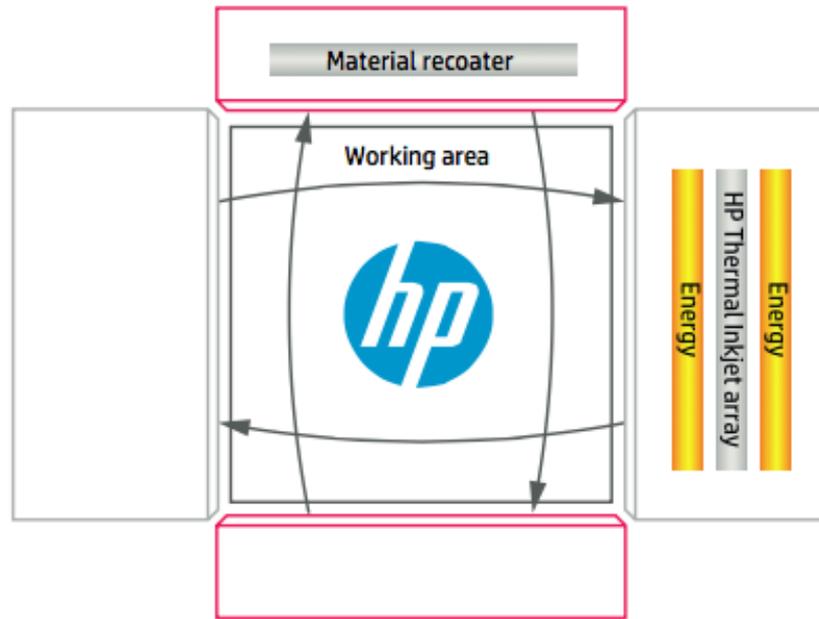


# + Multijet Fusion

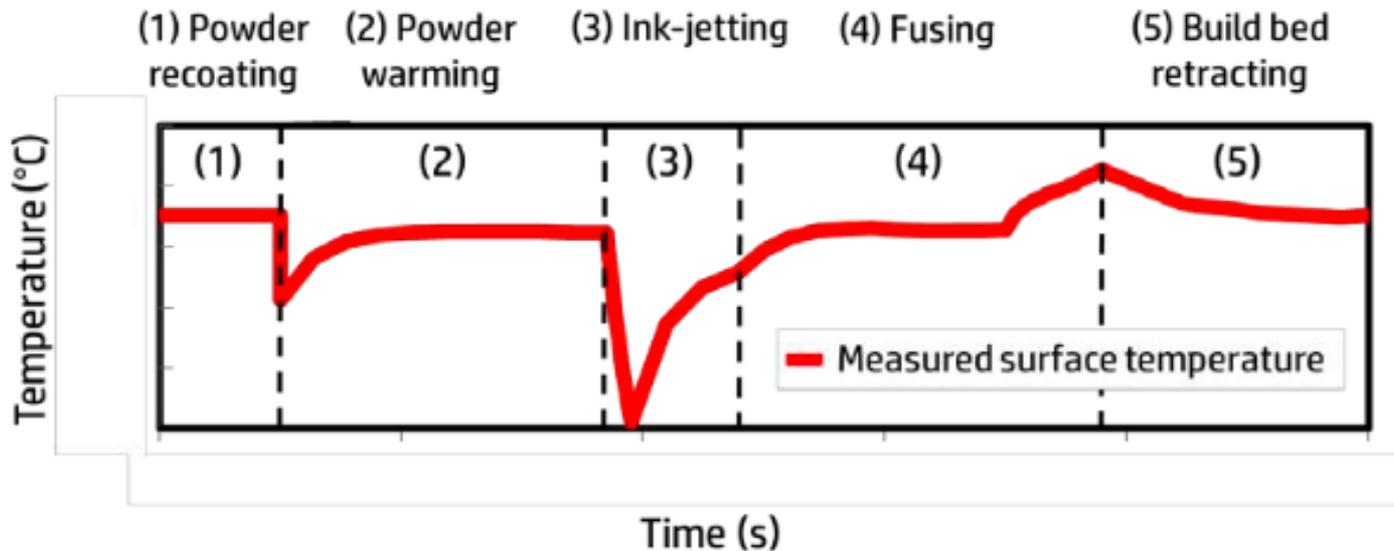
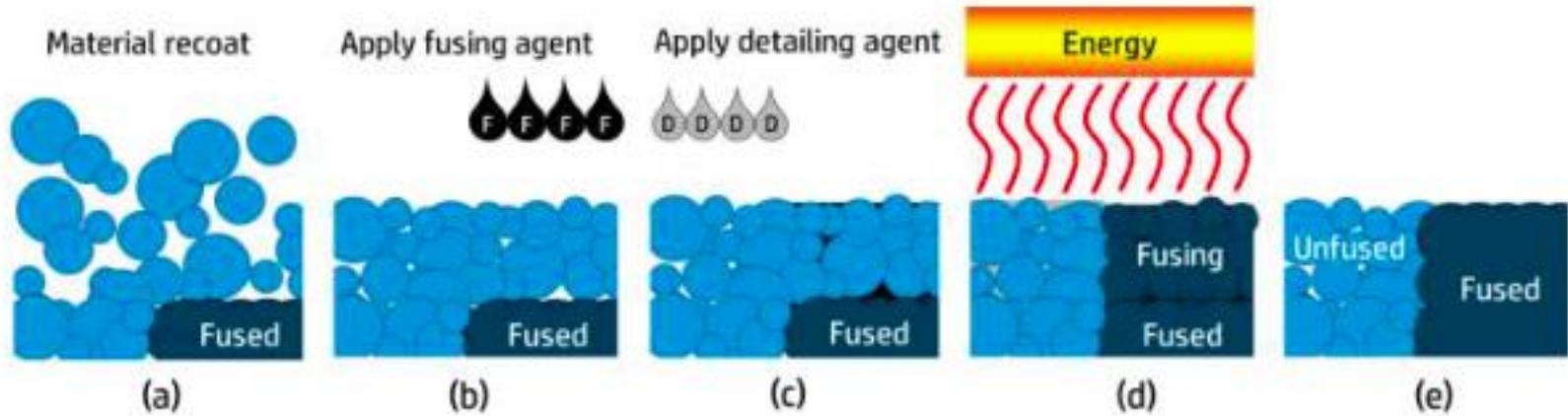
**7** **Printing with voxel-level control:**  
Just press Start to get extreme dimensional accuracy and fine detail,<sup>3</sup> thanks to HP's unique Multi-Agent printing process.



# + Multijet Fusion



# + Multijet Fusion



# + MultiJet Fusion - Materials



HP 3D printing materials provide optimal output quality and high reusability at a low cost per part. Engineered for HP Multi Jet Fusion technology, these materials test the limits of functional part creation, optimizing cost and part quality, while also delivering high<sup>10</sup> and, in many cases, industry-leading reusability<sup>8</sup> at the lowest cost per part.<sup>2</sup>

## **HP 3D High Reusability PA 12**

HP 3D High Reusability PA 12 produces strong, functional, detailed complex parts and helps reduce total cost of ownership.<sup>11</sup> This robust thermoplastic is ideally suited for complex assemblies, housings, enclosures, and watertight applications. It provides the best balance between mechanical properties and reusability,<sup>12</sup> and provides biocompatibility certifications.<sup>13</sup> It also delivers consistent performance—while achieving 80% surplus powder reusability<sup>8</sup>—at the lowest cost per part.<sup>2</sup>

Thermoplastics

## **HP 3D High Reusability PA 12 Glass Beads**

Ideal for applications requiring high stiffness like enclosures and housings, fixtures and tooling, HP 3D High Reusability PA 12 Glass Beads is a 40% glass bead filled thermoplastic material with both optimal mechanical properties and high reusability.<sup>10</sup> It provides dimensional stability along with repeatability.<sup>14</sup> Customers experience quality results at a low cost per part and get consistent performance while achieving 70% surplus powder reusability.<sup>15</sup>

Thermoplastics +  
glass beads

## **HP 3D High Reusability PA 11**

HP 3D High Reusability PA 11 is designed for the production of strong, ductile,<sup>16</sup> functional parts including prostheses, insoles, sports goods, snap fits, living hinges, and more. Providing the lowest cost per part,<sup>2</sup> HP 3D High Reusability PA 11 is a cost-efficient material offering industry-leading surplus powder reusability,<sup>8</sup> and is made from renewable sources.<sup>17</sup> It offers excellent chemical resistance<sup>18</sup> and enhanced elongation-at-break.<sup>16</sup>

# + MultiJet Fusion



## HP Jet Fusion 3D 4210/4200/3200 Printer

<b>Printer performance</b>	Technology	HP Multi Jet Fusion technology
	Effective building volume	380 x 284 x 380 mm (15 x 11.2 x 15 in)
	Building speed	<b>3200 Printer:</b> 2800 cm <sup>3</sup> /hr (170 in <sup>3</sup> /hr) <sup>21</sup> <b>4210/4200:</b> 4500 cm <sup>3</sup> /hr (274 in <sup>3</sup> /hr) <sup>22</sup>
	Layer thickness	<b>3200 Printer:</b> 0.08 mm (0.003 in) <b>4210/4200:</b> 0.07 to 0.08 mm (0.0027 to 0.0031 in)
	Print resolution (x, y)	1200 dpi
<b>Dimensions (w x d x h)</b>	Printer	2210 x 1200 x 1448 mm (87 x 47 x 57 in)
	Shipping	2300 x 1325 x 2068 mm (91 x 52 x 81 in)
	Operating area	3700 x 3700 x 2500 mm (146 x 146 x 99 in)
<b>Weight</b>	Printer	750 kg (1653 lb)
	Shipping	945 kg (2083 lb)

# **A BRIEF RECAP**

# + A(nother) possible classification

## ASTM/ISO 52900 classification

- **Binder jetting:** AM process in which a liquid bonding agent is selectively deposited to join powder materials
- **Directed energy deposition:** AM process in which focused thermal energy is used to fuse materials by melting as they are being deposited
  - Note: “Focused thermal energy” means that an energy source (e.g. laser, electron beam, or plasma arc) is focused to melt the materials being deposited.
- **Material extrusion** AM process in which material is selectively dispensed through a nozzle or orifice
- **Material jetting:** AM process in which droplets of build material are selectively deposited
  - Note: Example materials include photopolymer and wax.
- **Powder bed fusion:** AM process in which thermal energy selectively fuses regions of a powder bed
- **Sheet lamination:** AM process in which sheets of material are bonded to form a part
- **Vat photopolymerisation:** AM process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

# + A(nother) possible classification

Materials	Example materials	Process categories						
		Vat photo-polymer-ization	Material jetting	Binder jetting	Powder bed fusion	Material extrusion	Directed energy deposition	Sheet lamination
Thermoset Polymers	Epoxies and acrylates	X	X					
Thermo-plastic polymers	Polyamide, ABS, PPSF		X	X	X	X		X
Wood	paper							X
Metals	Steel, Titanium alloys, Cobalt chromium			X	X		X	X
Industrial ceramic materials	Alumina, Zirconia, Silicone nitride	X		X	X			X
Structural ceramic materials	Cement, Foundry sand			X	X	X		

Note: Combinations of the above material classes, e.g. a composite, are possible