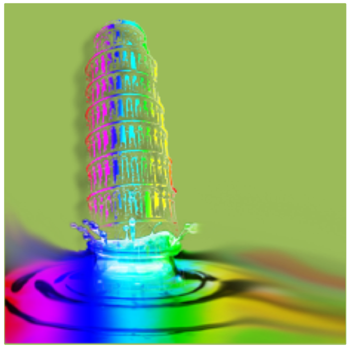
Centro E. Piaggio
bioengineering and robotics research center

Powder bed fusion processes



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Powder bed fusion processes

- AM process in which thermal energy selectively fuses regions of a powder bed
- First commercial example: Selective laser sintering (SLS), invented by Carl Deckard during his PhD in Texas University in 1987
- Basic set of characteristics:
  - one or more thermal sources
  - methods for controlling powder fusion
  - mechanism for adding and smoothing powder layers
- Laser is the most common thermal source (laser sintering)
  - polymer laser sintering (pLS)
  - metal laser sintering (mLS)

Laser Sintering

Baseline description

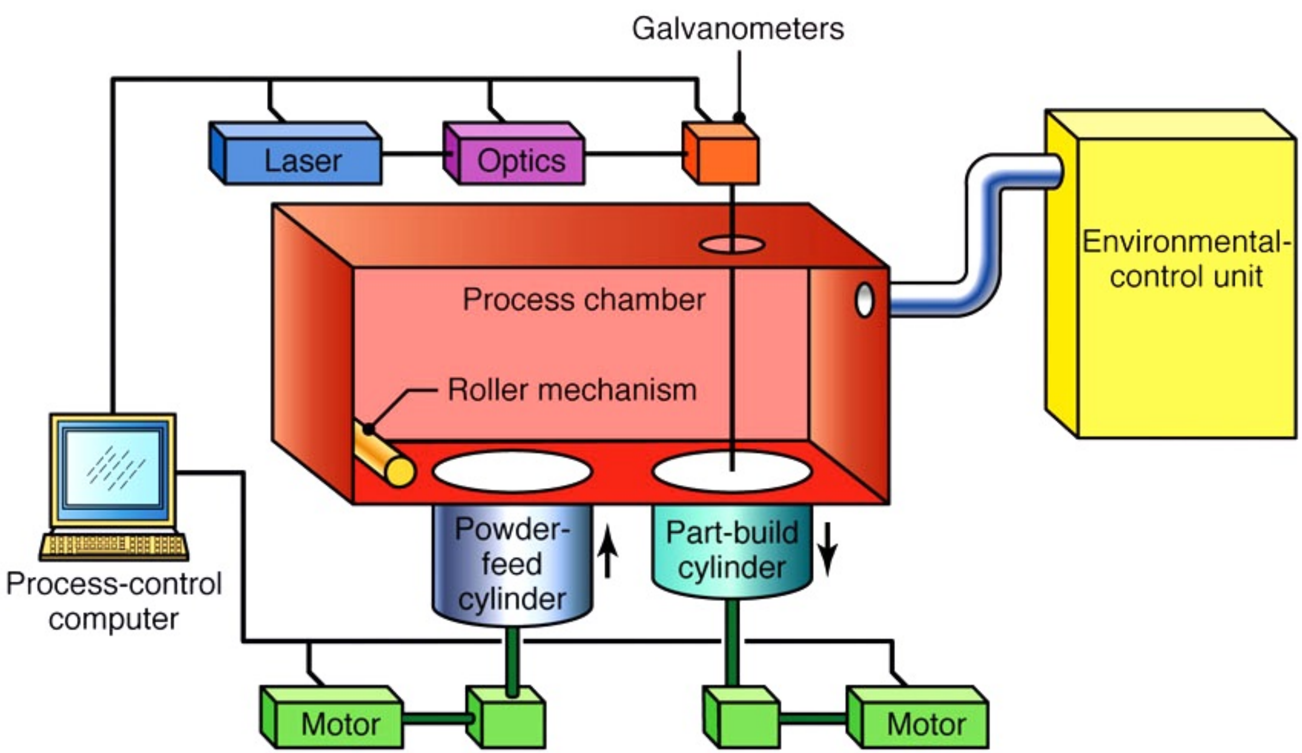


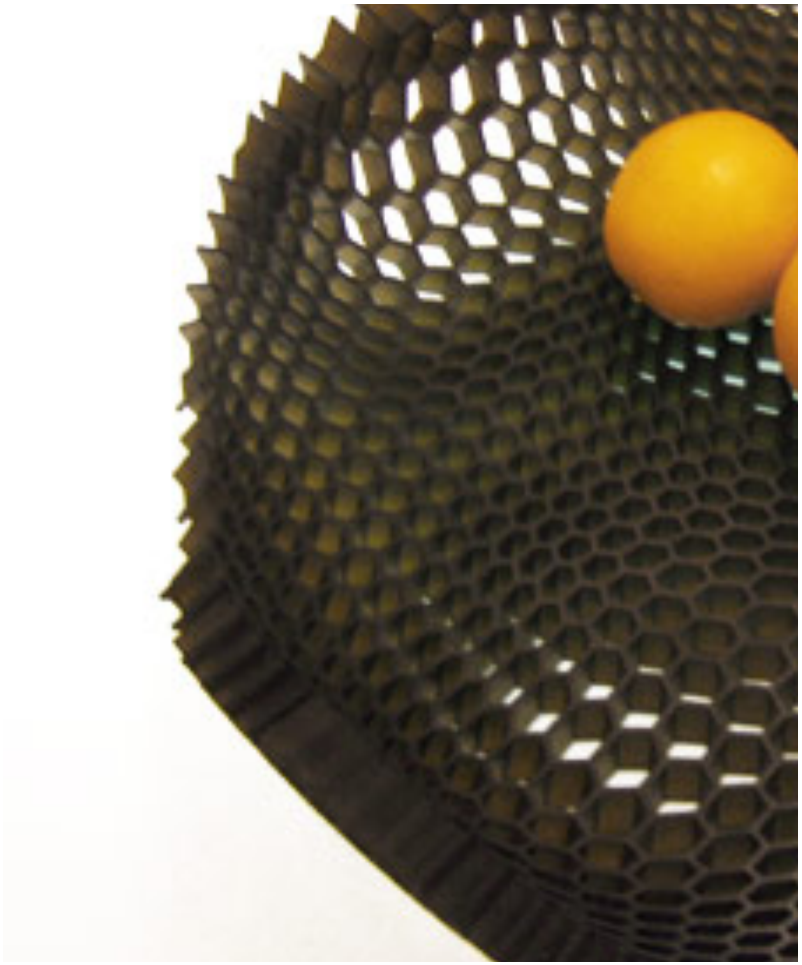
Figure 20.7 Schematic illustration of the selective-laser-sintering process. *Source*: After C. Deckard and P. F. McClure.

+ Laser Sintering

Baseline description

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

SLS samples



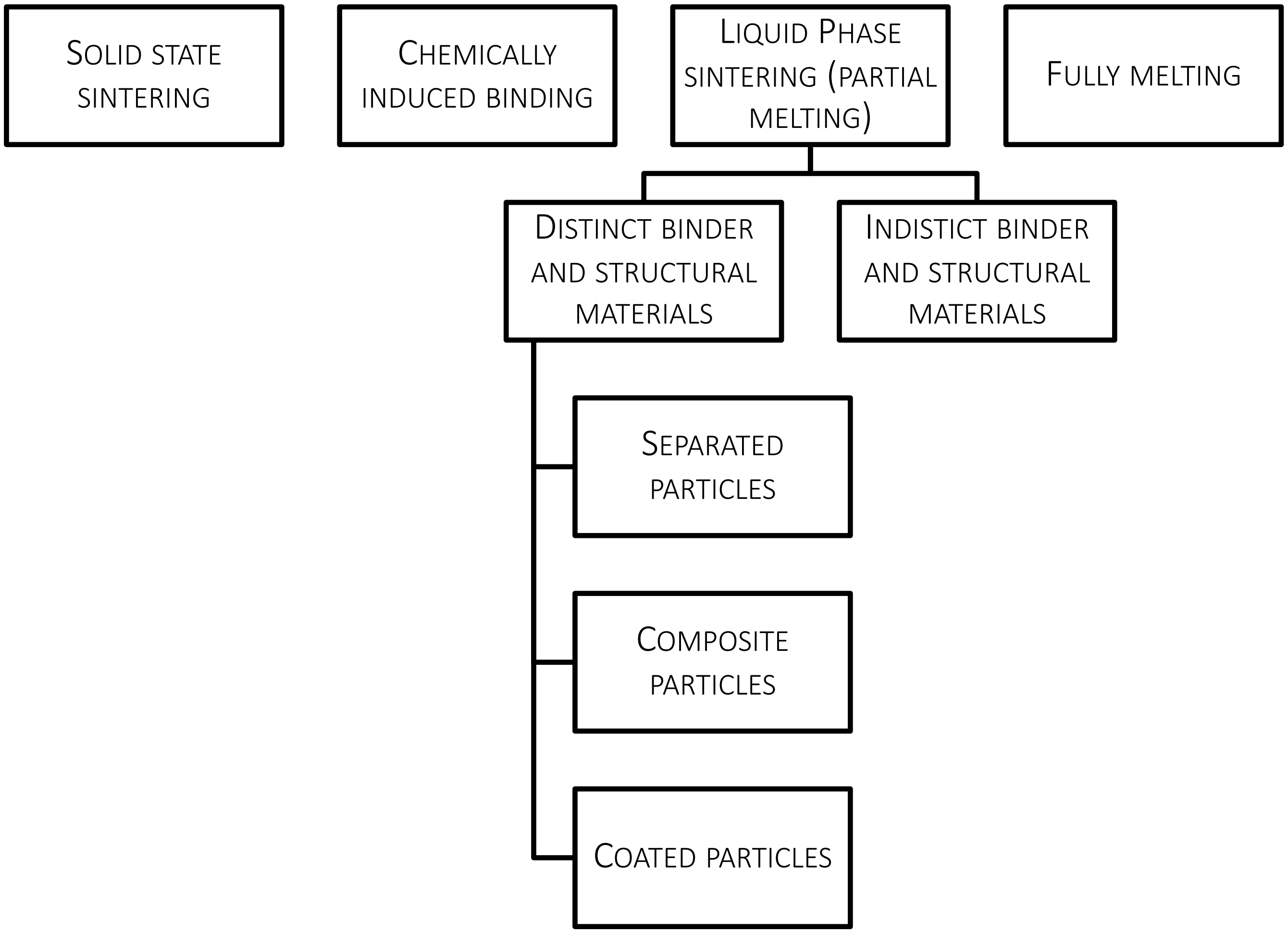
Laser Sintering

- 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

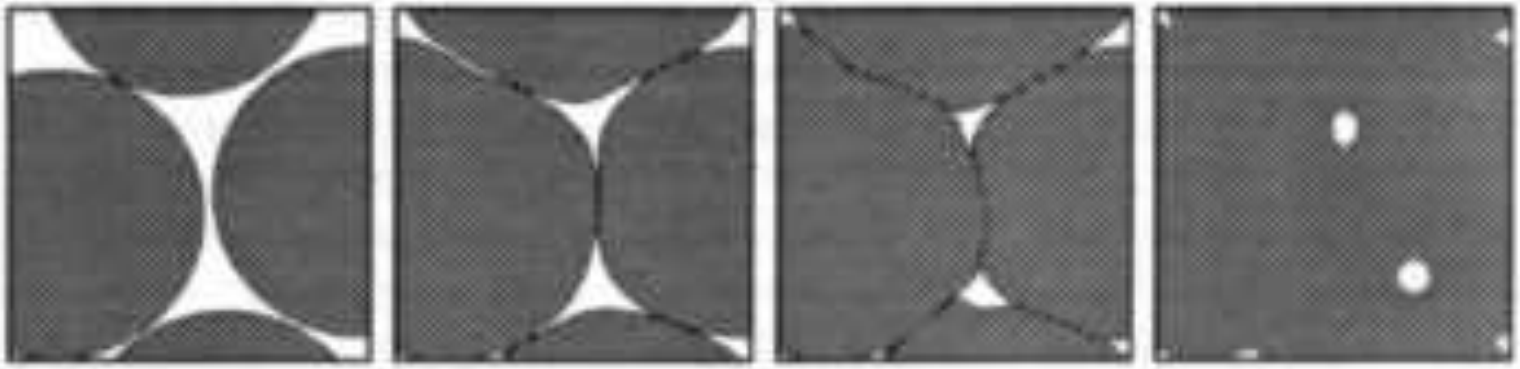
Materials

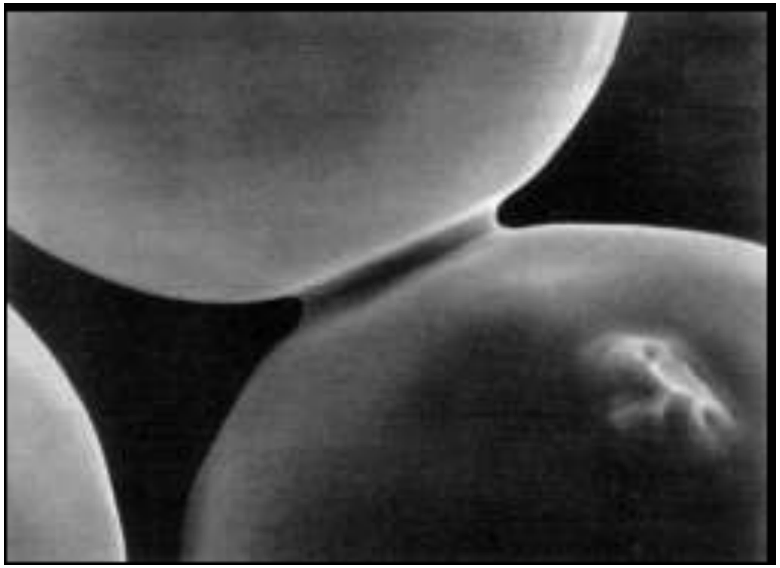
- Polymers and composites
  - amorphous vs (semi-)crystalline polymers
  - nylon (polyamide), ABS, PVC, and polystyrene, PCL, PLA
  - nylon/polycarbonate powders are health hazards (dangerous to breathe).
  - glass-filled or with other fillers
  - metals encapsulated in plastic.
- Metals
  - low melting metal alloys of nickel bronze, steel, titanium, alloy mixtures, and composites
- Ceramics and ceramic composites
  - Green sand (for sand casting), hydroxyapatite
  - Metal ceramic composites (chemically induced sintering processes)

Powder fusion mechanism



Solid state sintering process





Solid state 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.

Solid state sintering process

- Mechanism: diffusion between powder particles (intrinsically slow)
- Driving force: minimization of the total free energy $E_s = \gamma \times S$ (S=surface)
- Larger the surface to volume ratio, greater is the driving force (smaller particles sinter more rapidly)
- Diffusion rates depends on temperature with an Arrhenius law.

Solid state sintering process in AM

- Sintering process used in additive manufacturing (AM) differs from the Powder Metallurgy, such as:
  - Local sintering, not overall sintering
  - Very short sintering period
  - not use of isostatic pressure
- 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.
- Practically, the solid state sintering is not used as primary fusion mechanism in AM

Solid state sintering process in AM

- Side effects:
  - increase of average particle size of recycled powder
  - “part growth”: the final model results bigger due to solid state sintering of new powder at the shell of the model
    - compensation at building scanning strategy
    - removal during post processing
  - decrease of porosity

Chemically induced sintering

- It involves the use of thermally activated chemical reactions between
  - two types of powders or
  - powders and atmospheric gases

  to form a by-product which binds the powders together
- Primarly used for ceramic materials
  - SiC and O_2 to form composite SiC – SiO_2
  - Al and N_2 to form a link between Al and AlN particles
- Limited use in commercial application

Liquid phase sintering and partial melting

- Fusion of powder particles when a portion of constituentes within a collection of powder particles become molten, while other portions remain solid
- Molten constituentes act as "glue"
- Distinction between binder and structural materials
  - separate particles
  - composite particles
  - coated particles
  - no distiction (partial melting)

Liquid phase sintering

Separate particles

- Binder material is usually smaller in particle size than the structural material
  - Efficiency in packing
  - Less shrinkage
  - Lower porosity
- Polymeric binder with structural metal particles
- Usually for production of «green» parts

Black = binder

Liquid phase sintering

Composite particles

- Binder and structural materials agglomerated together, but distinct at microscopic level
- For «green» parts with higher density
- e.g. glass filled nylon

Black = binder

Liquid phase sintering

- Coated particles
- Better absorption of laser energy, more effective binding, better flow properties
- Less amount of binder is required
- Usually with a round shape

Partial melting

Indistinct binder and structural materials

- Very similar to liquid-phase sintering
- Important for noneutectic alloy compositions
- Firstly used in the Direct metal laser sintering (DMLS) machine by EOS

Full melting

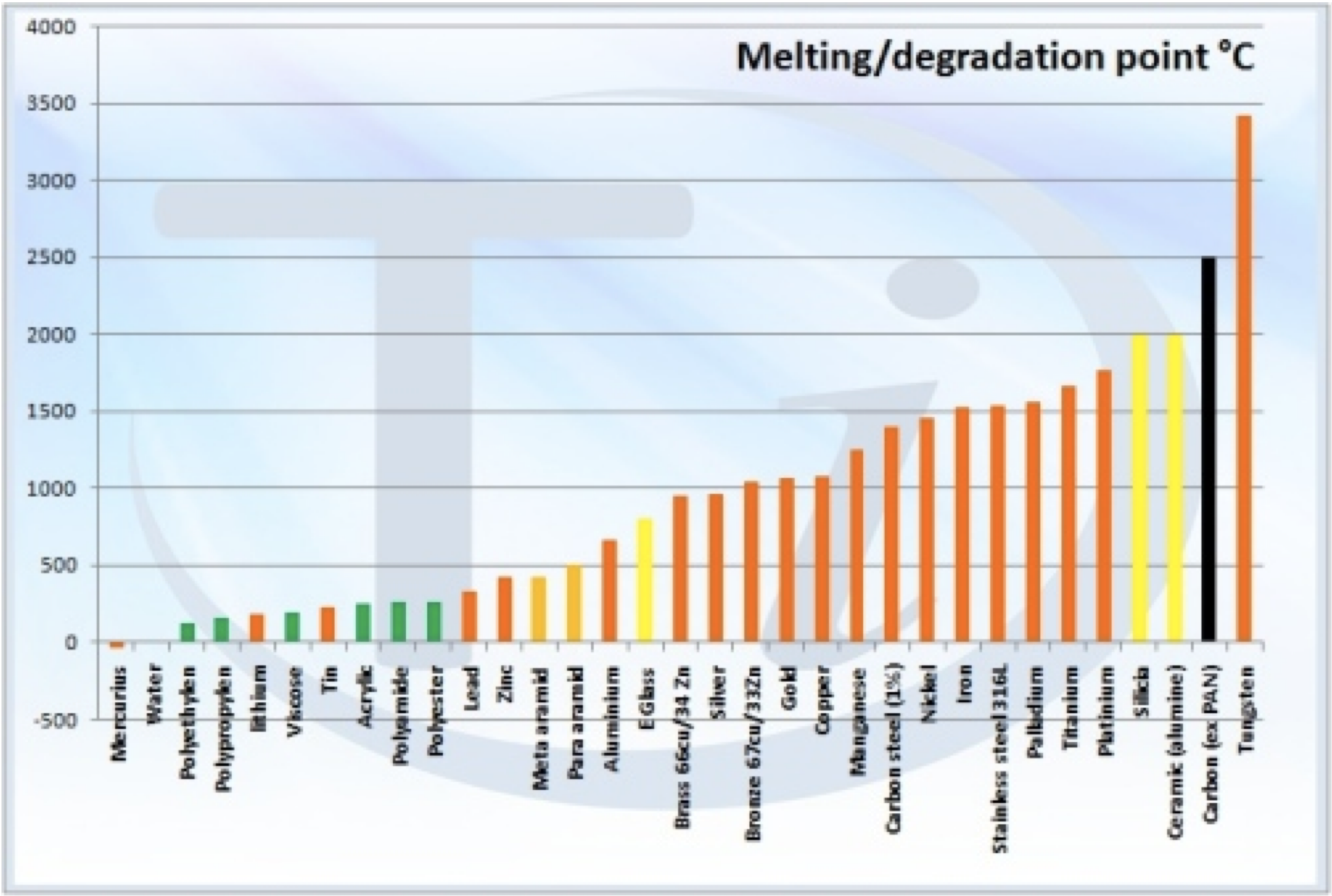
- Sintering mechanism most commonly associated with PBF processing for metal alloys and semicrystalline polymers
- Well-bonded, high density structures
  - Nylon polyamide
  - Ti, Stainless stell, CoCr

PROCESS MODELLING

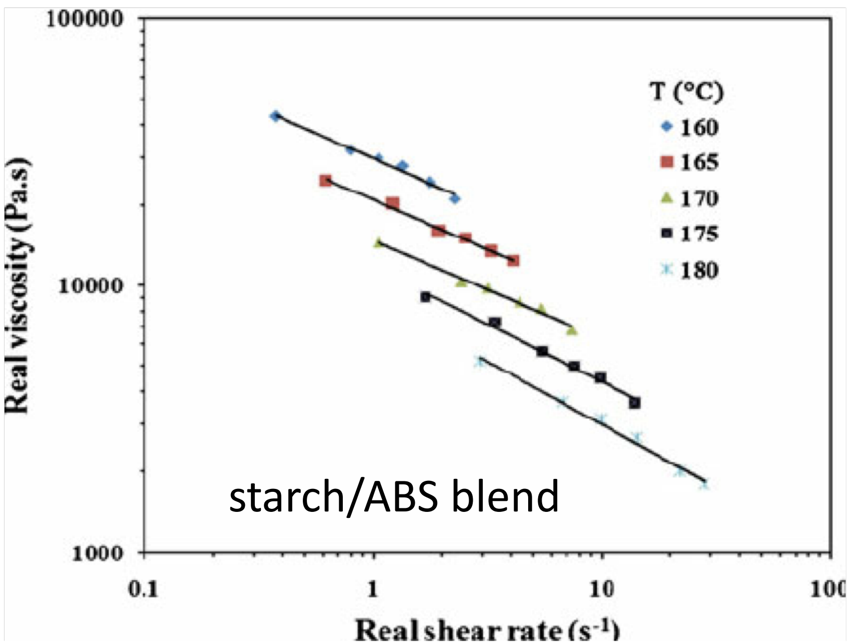
Relevant physical properties

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

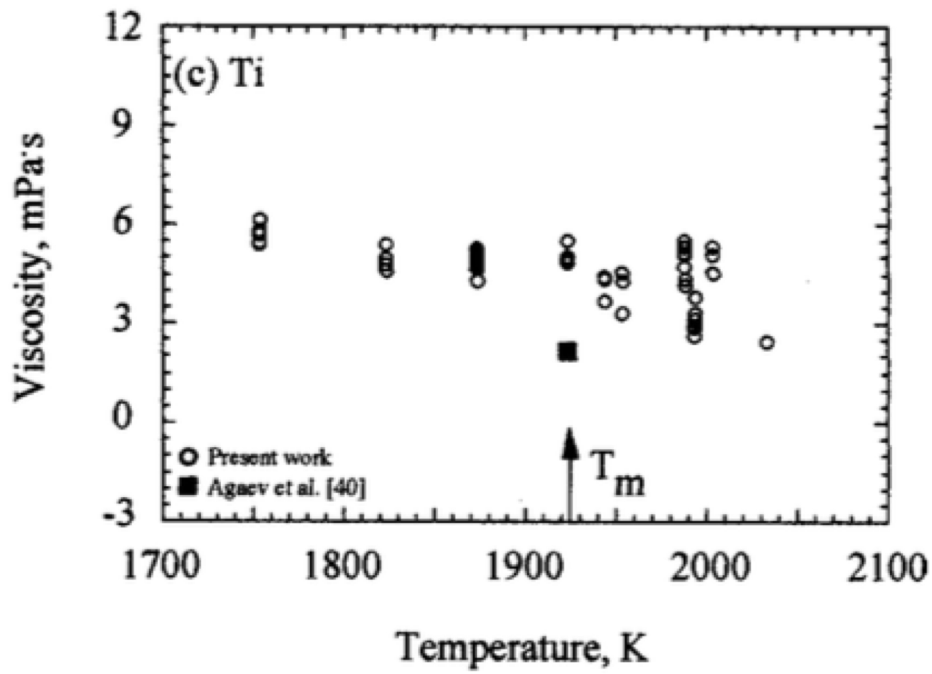
Melting temperature



Viscosity

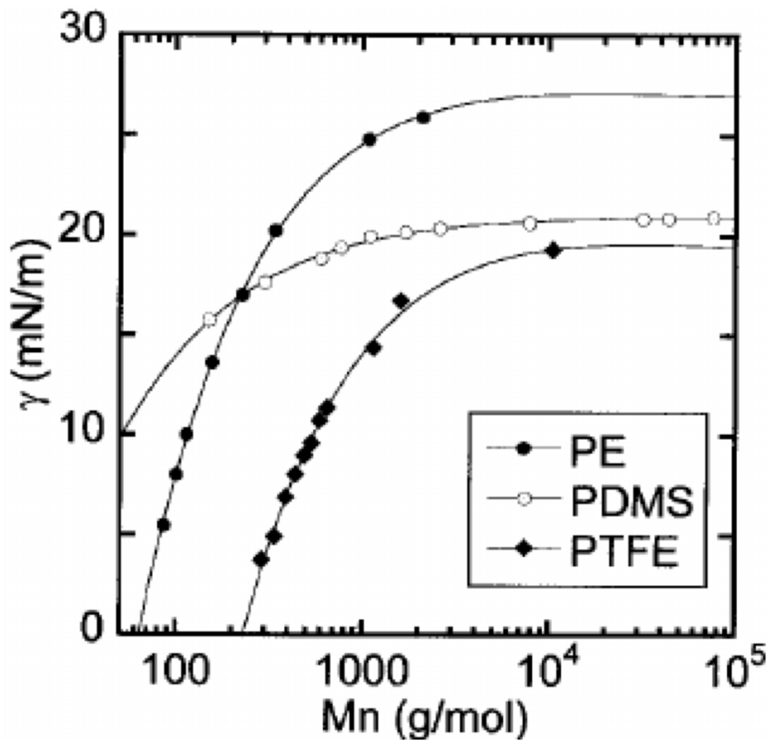


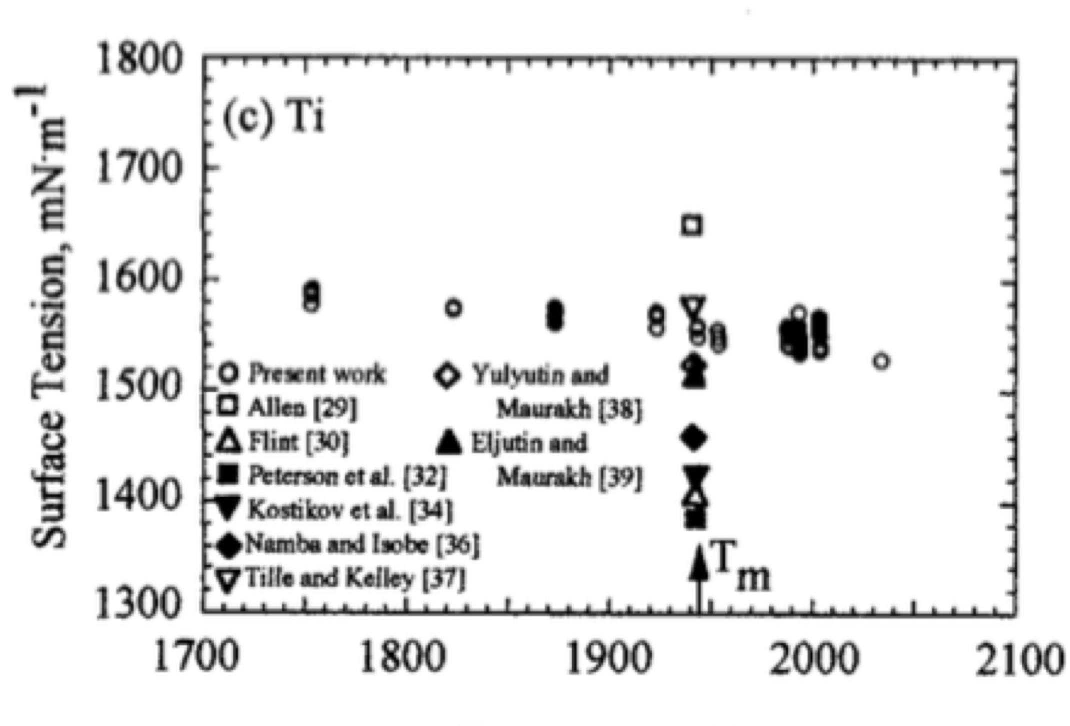
Real viscosity (Pa.s)
100000
10000
1000
0.1
1
10
100
Real shear rate (s-1)
T (°C)
160
165
170
175
180
starch/ABS blend



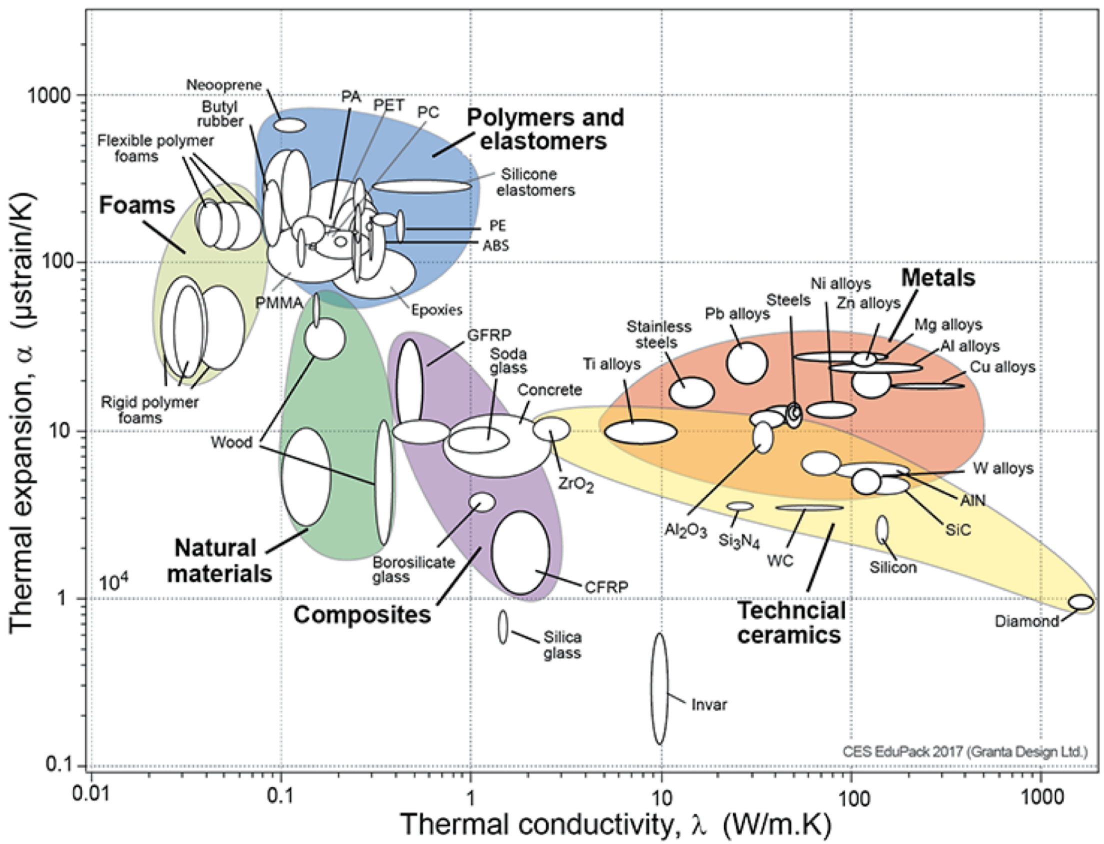
Viscosity, mPa·s
12
9
6
3
0
-3
(c) Ti
Present work
Agaev et al. [40]
Tm
1700
1800
1900
2000
2100
Temperature, K

Surface tension

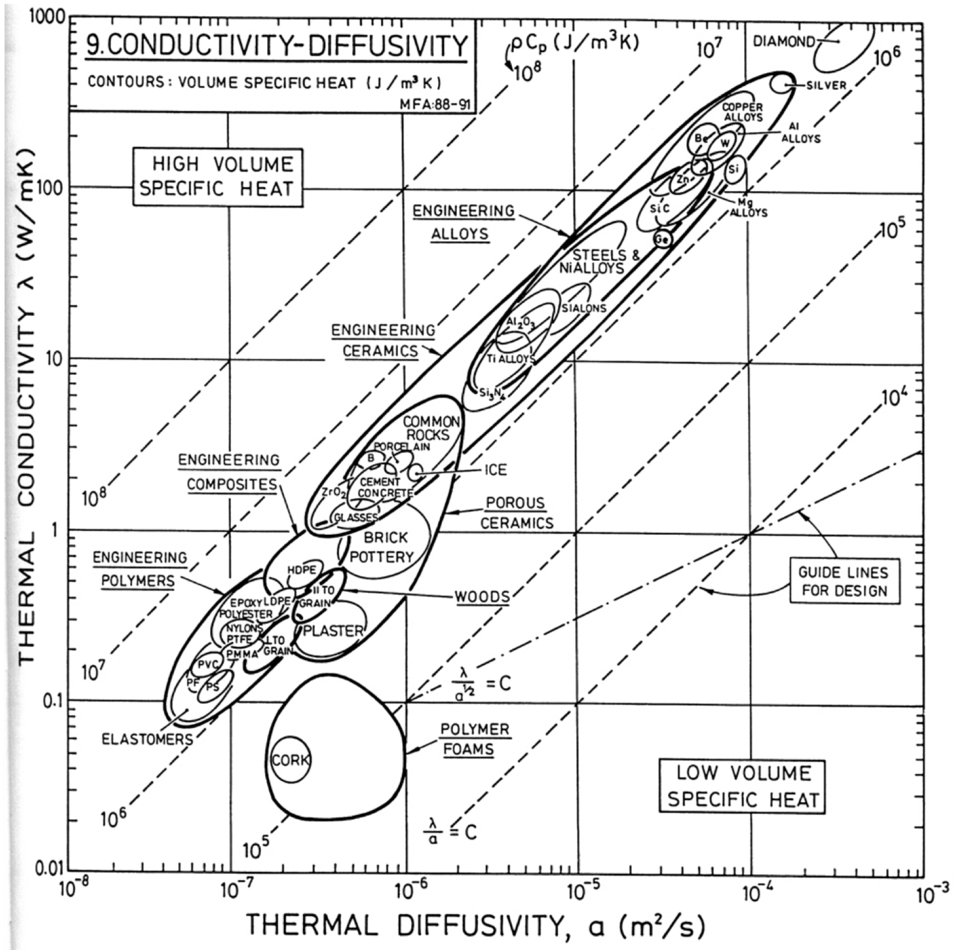




Thermal conductivity and expansion



Thermal conductivity



Heat capacity

increasing c_p

Material	c_p (J/kg-K) at room T
• Polymers	
Polypropylene	1925
Polyethylene	1850
Polystyrene	1170
Teflon	1050
• Ceramics	
Magnesia (MgO)	940
Alumina (Al_2O_3)	775
Glass	840
• Metals	
Aluminum	900
Steel	486
Tungsten	138
Gold	128

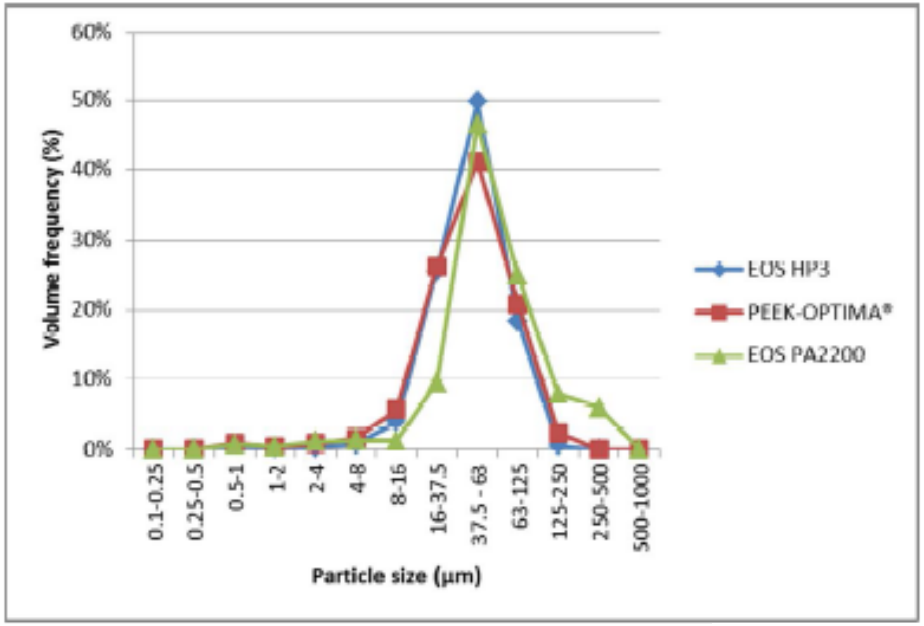
c_p (specific heat): (J/kg-K)

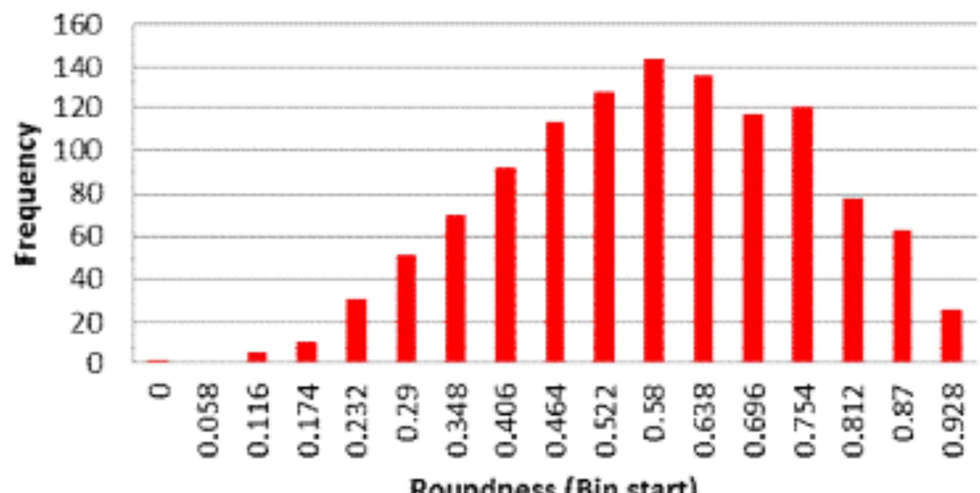
C_p (heat capacity): (J/mol-K)

- Why is c_p significantly larger for polymers?

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

Granulometry and roundness

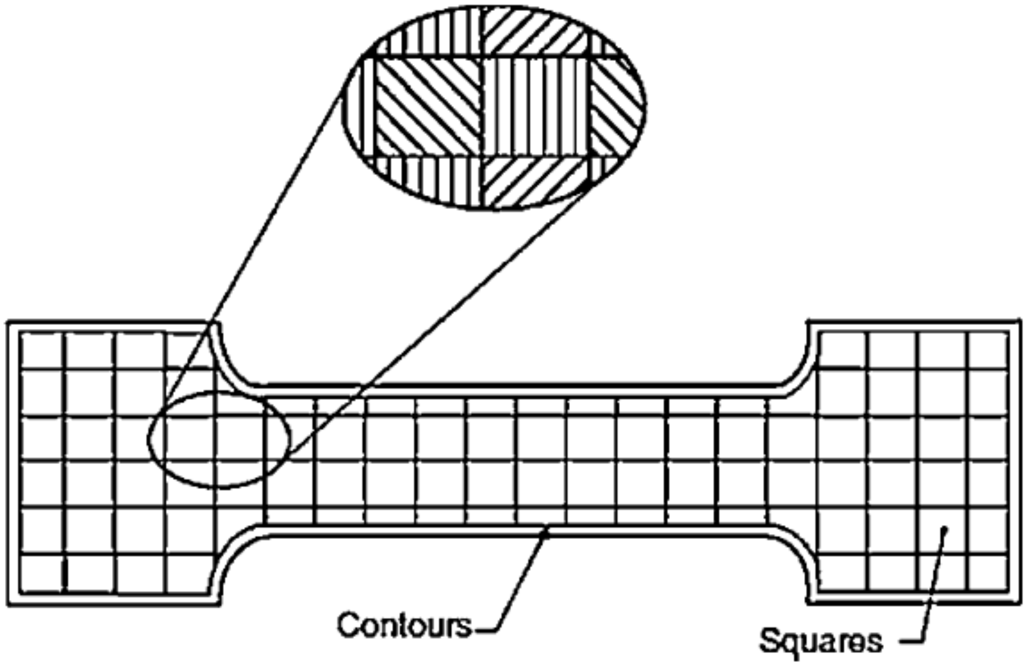




Process parameters

- Laser related parameters
  - laser power, spot size, pulse duration, pulse frequency, etc.
- Scanning relaterd paramters
  - scan speed, scan spacing, and scan pattern
- Powder related parameters
  - particle shape, size and distribution, powder bed density, layer thickness, material properties, etc ...
- Temperature related parameters
  - powder bed temperature, powder feeder temperature, temperature uniformity, etc ...

Scanning strategies

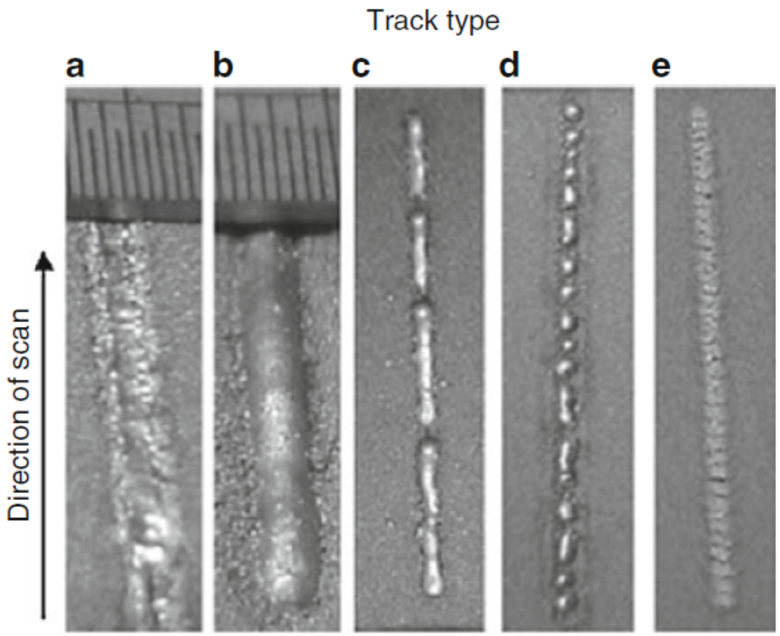


- Typical layer thickness are 0.02 to 0.15 mm
- Usually continuous wave laser are used

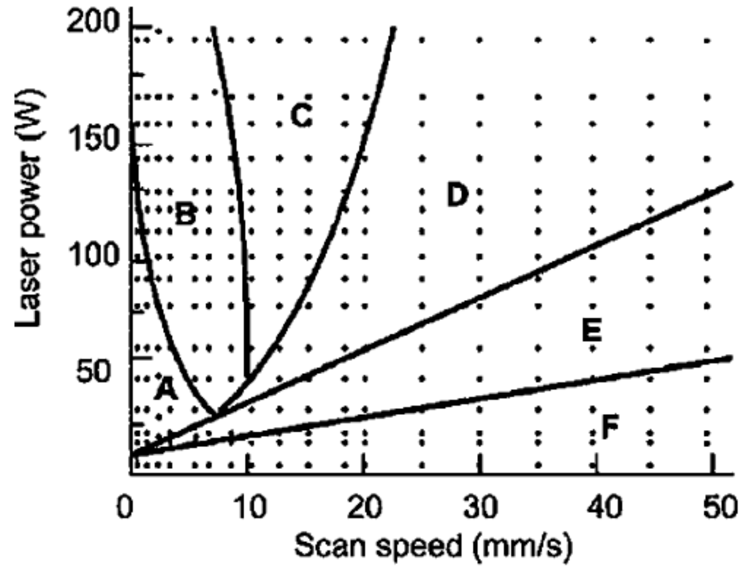
Applied energy density

- $E_A = P/(U \times SP)$
  - E_A = applied energy density (Andrews number) $[J/m^2]$
  - P = laser power [W]
  - U = scan velocity [m/s]
  - SP = scan spacing between parallel scan lines [m]

Applied energy density

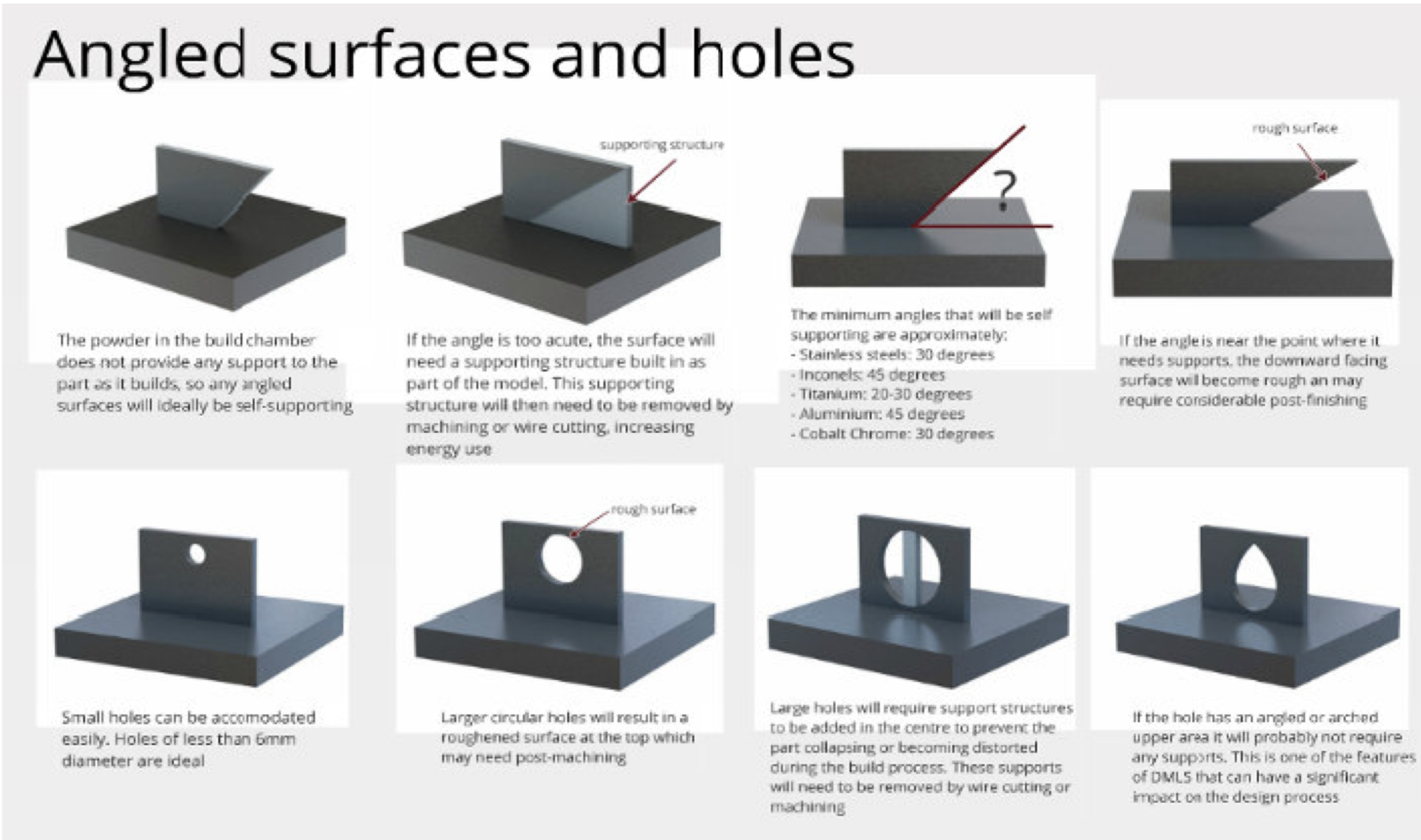


P(W)	110	110	110	110	77
U(mm/s)	0.5	2	15	25	40

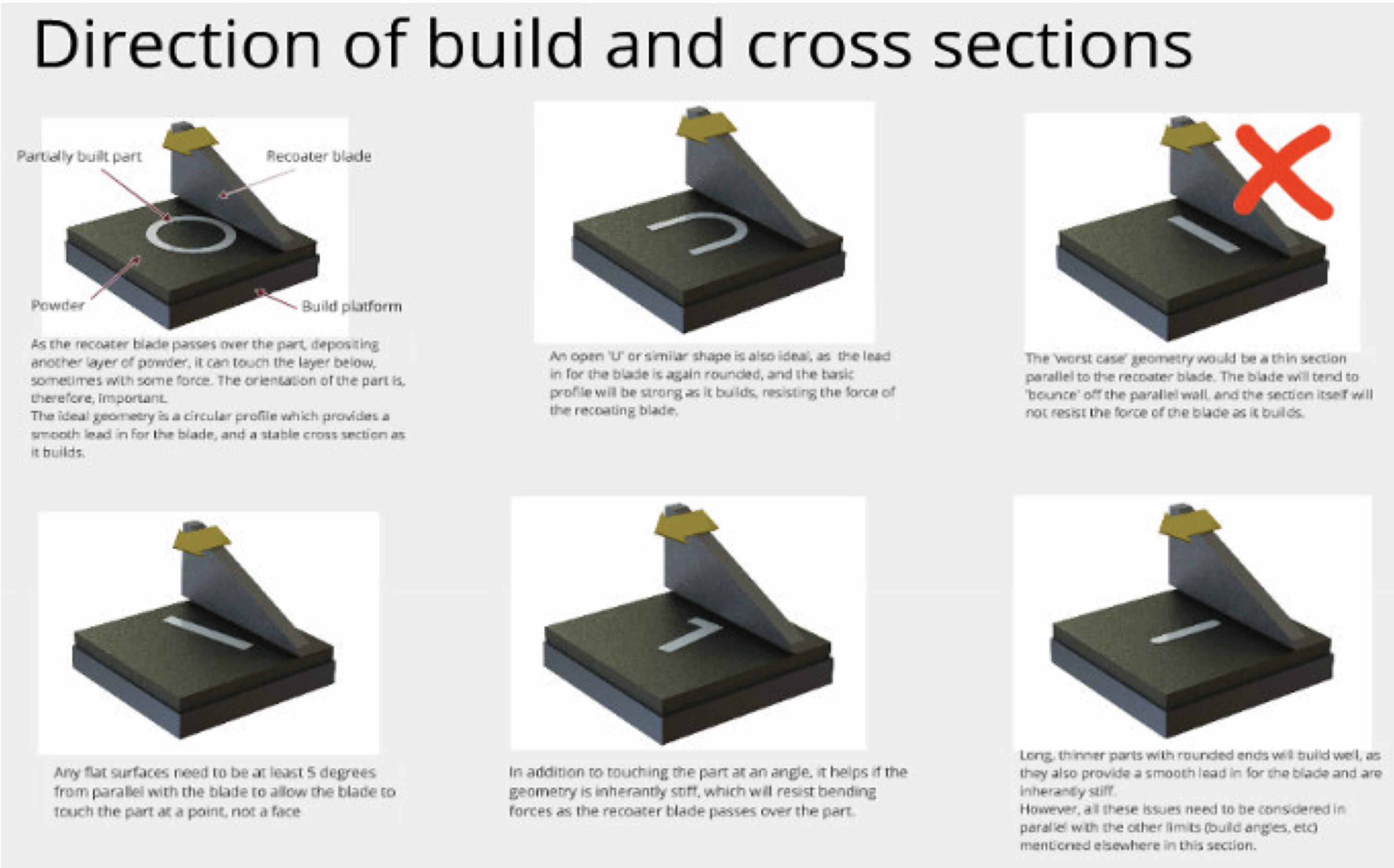


-150/+75 µm M2, 1.1 mm beam size

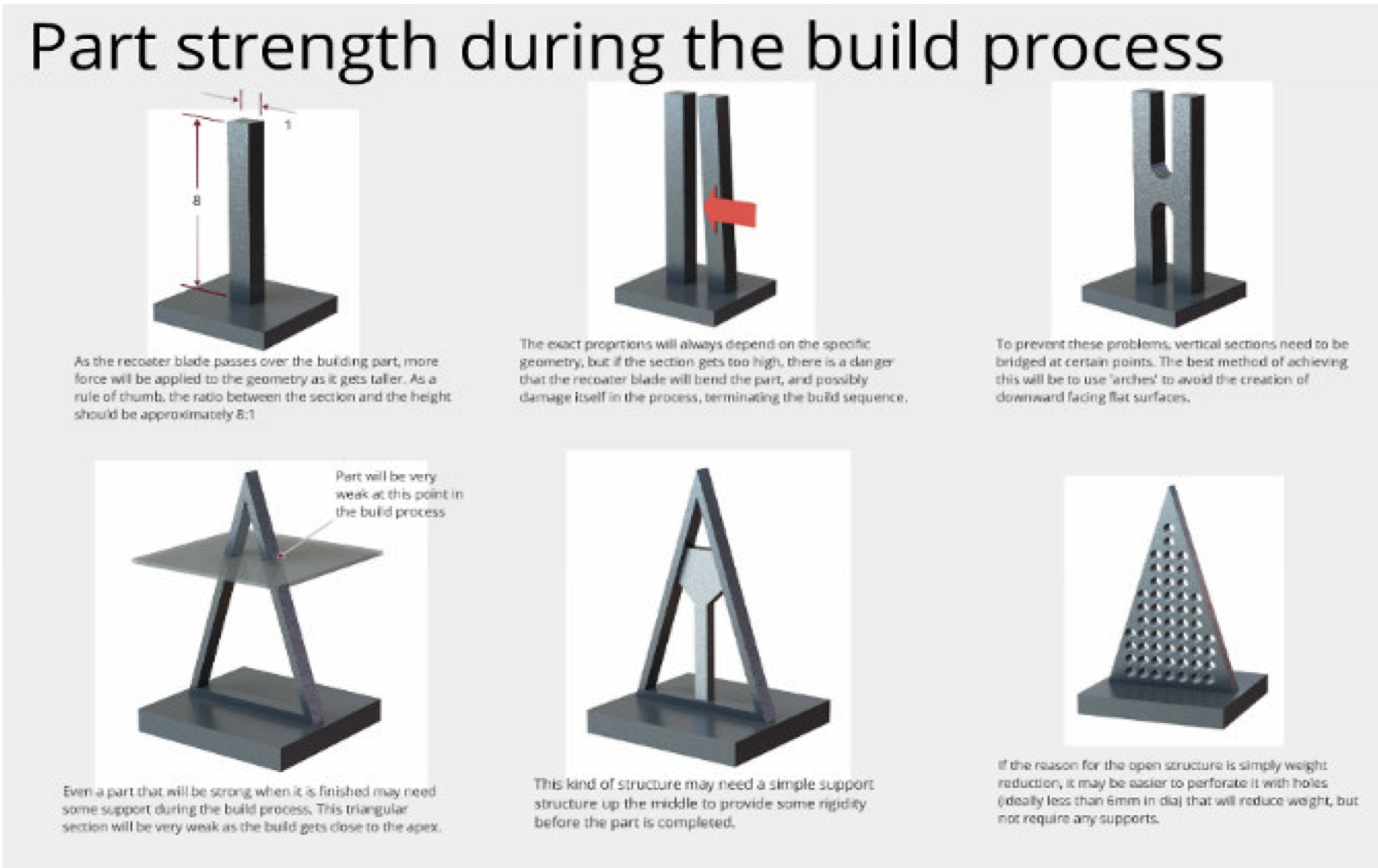
Laser Sintering – support strategies



Laser Sintering – orientation strategies



Laser Sintering – orientation strategies



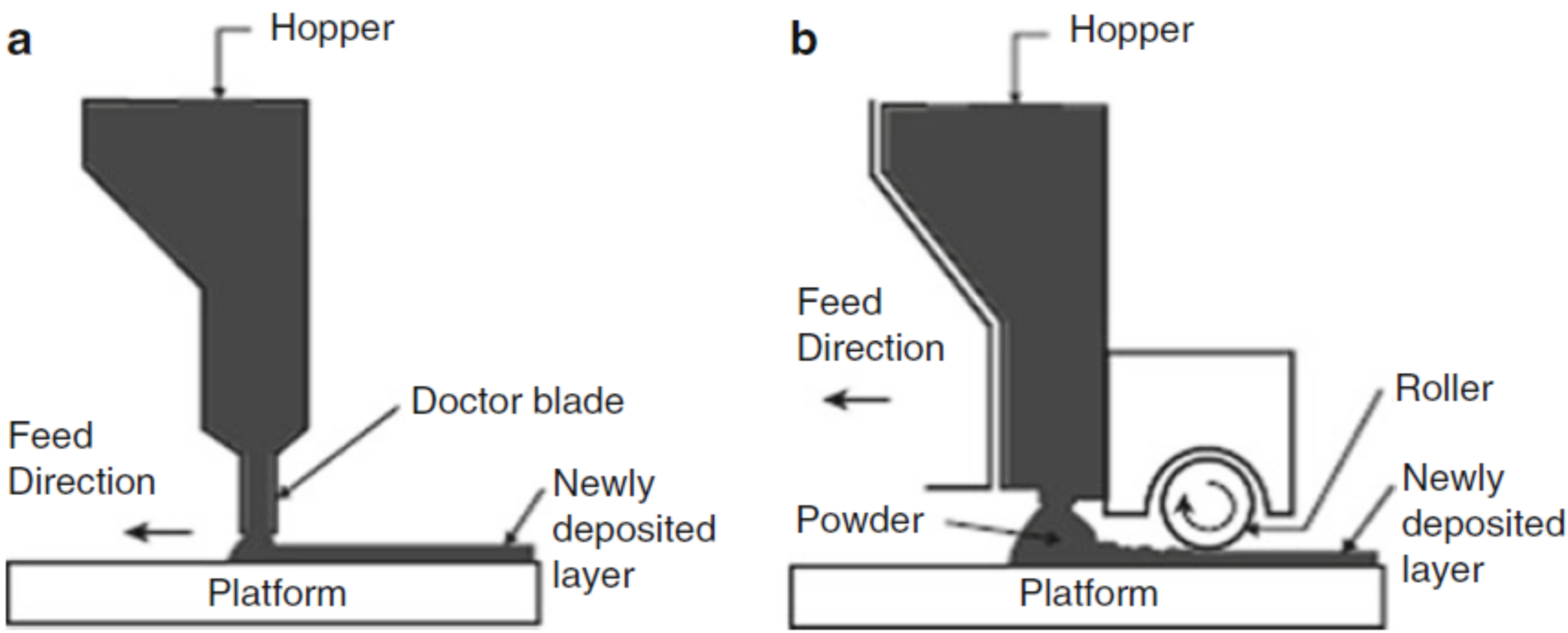
POWDER HANDLING

Powder handling systems

- Have a sufficient volume
- Deliver the right quantity of powder (without waste)
- Provide a smooth, thin, repeatable layer of powder
- Limit shear forces on previous layer
- As particle size decreases
  - Interparticle friction and electrostatic forces increases (limit flowability)
  - More reactivity (including explosion)
  - Airborne and clouding optics
  - More difficult to be handled

Powder handling systems

- Hopper



Vibrating blade or roller

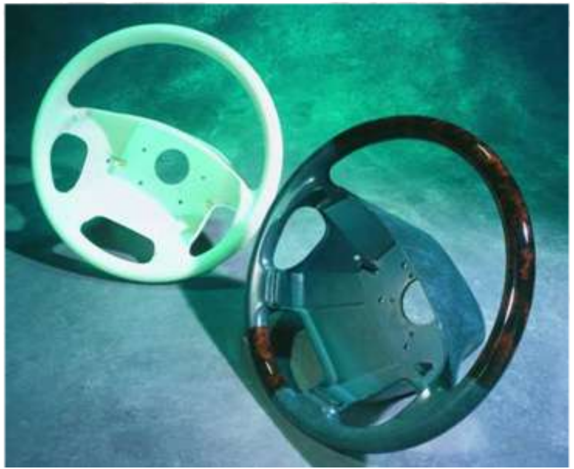
Powder recycling

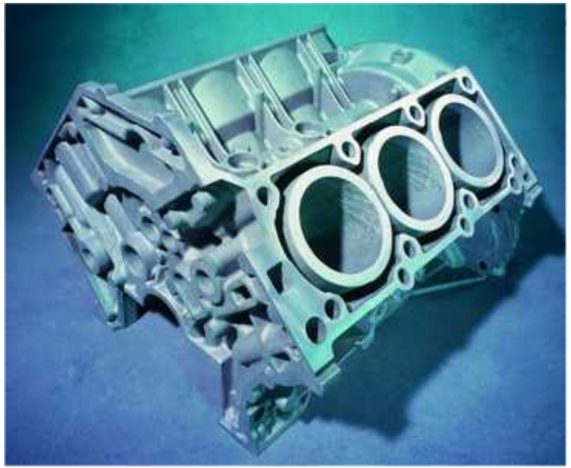
- Fraction based mixture might be
  - 1/3 unused powder,
  - 1/3 overflow/feed powder, and 1/3
  - build platform powder.

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

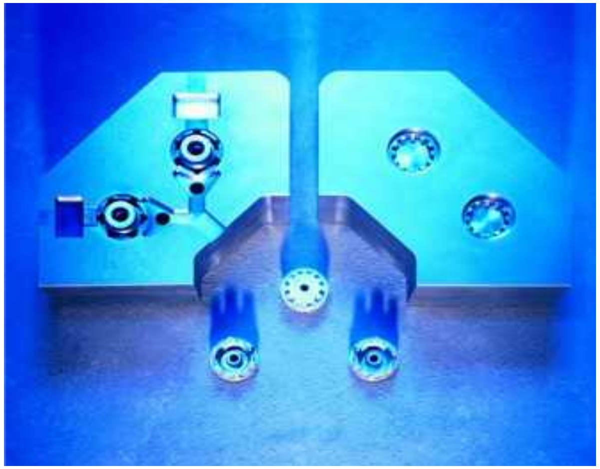


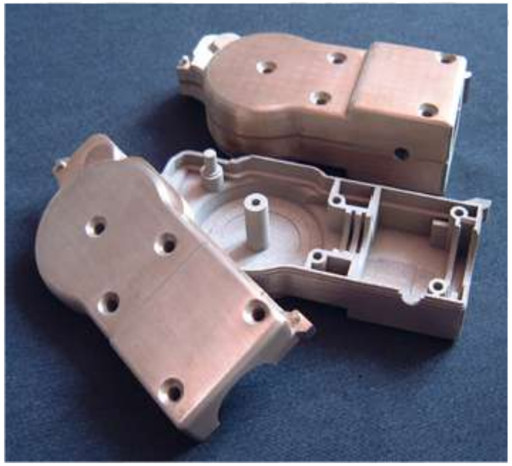


Metal Laser Sintering

- 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

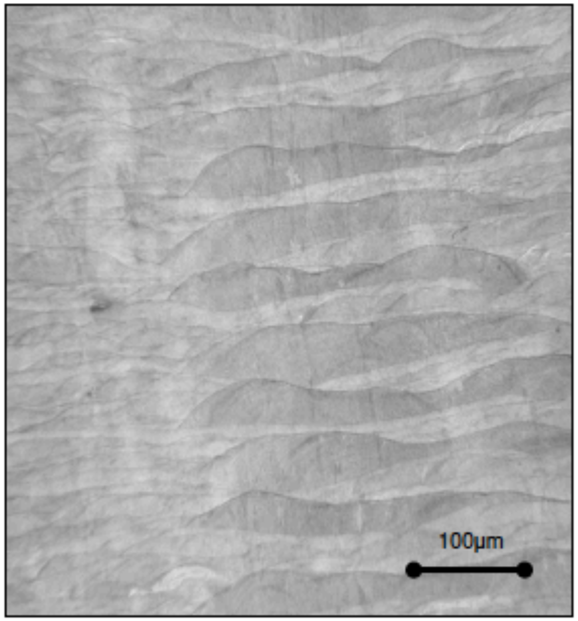
Fonte: EOS

Some available metals

- Grana molto fine e distribuzione omogenea dei componenti stechiometrici
- Rispetto norme ISO e ASTM per la composizione chimica
- Proprietà meccaniche similie 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)

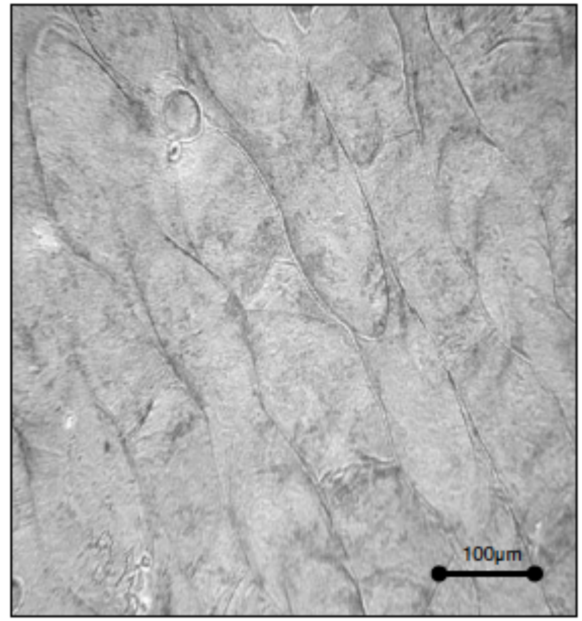
Some avaliable metals

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

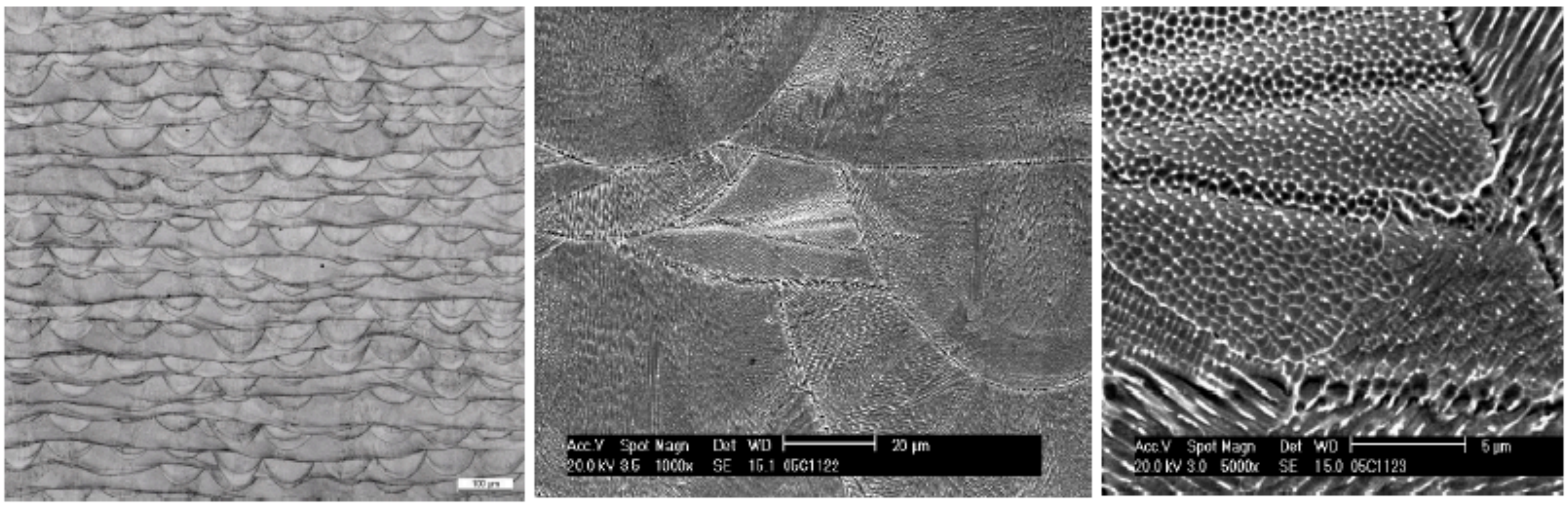
Si mostra una struttura completamente rifusa, densa

MET e-manufacturing

ASSOCIAZIONE ITALIANA DI METALLURGIA

Some avaliable metals

Micrografie di campioni di CobaltChromeMP1



10x   1000x SEM   5000x SEM   *Fonte: EOS*

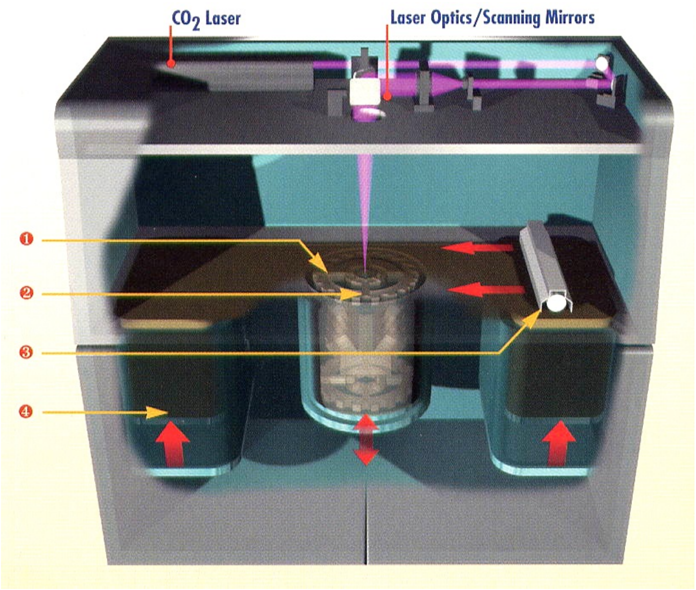
MP1 produce parti con strutture a grana molto fine e dimensioni tipiche di 0.3-0.6 µm

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



Volume di lavoro	380 X 330 x 460 mm
Laser	CO_2
Potenza	50 / 100 W
Spot	0.42 mm
Velocità di scansione	5000 mm/sec
Precisione di posizionamento	0.05 mm
Spessore layer	0.1 mm

METU SYSTEM

- EOS EOSINT P380 Rapid Prototyping System

General Properties
Plastic Laser Sintering System X,Y Axes Alternating Scanning
Technical Specifications
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
- Repeatibility of the process

EBM

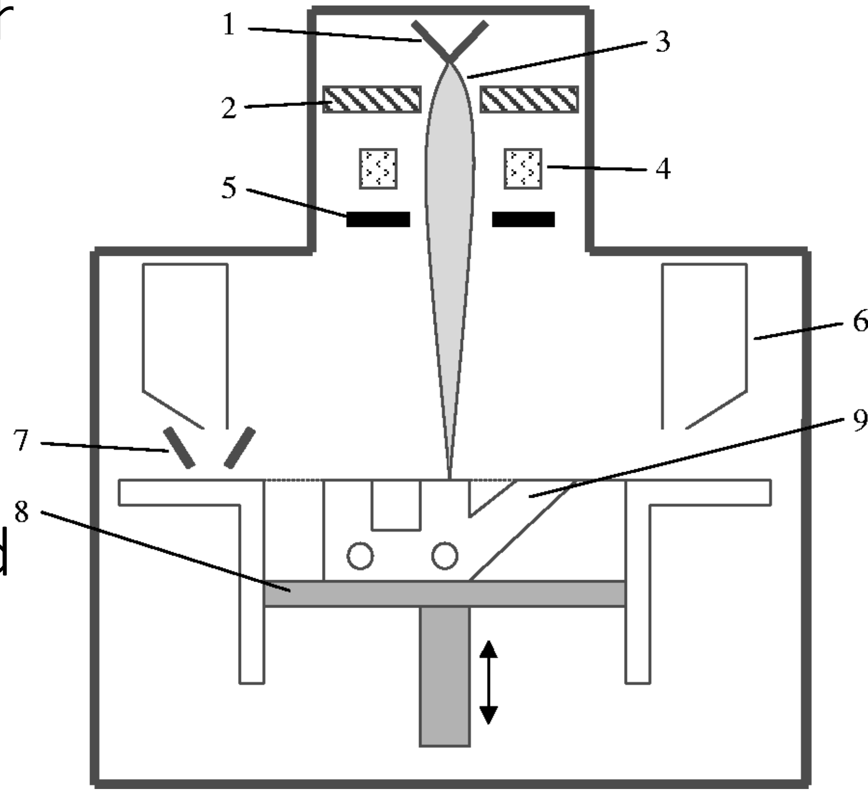
ELECTRON BEAM MELTING

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

ARCAM A2 machine for
direct metal deposition

Components made of Ti
and Co-Cr alloys

Biomedical components
made of Ti alloys

EMB benefit

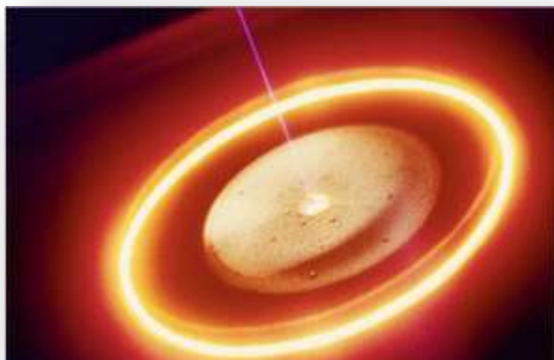
- High productivity
- Suitable for very massive parts
- No residual internal stress (constant 680-720°C build temperature)
- Less supports are needed for manufacturing of parts
- Possibility to stack parts on top of each other (mass production)
- Sintered powder = good for thermal conductivity = less supports
- Process under vacuum (no gaz 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

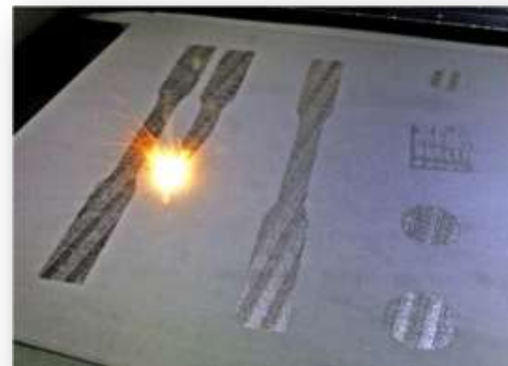
Comparison

- **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

Characteristic	Electron beam melting	Metal laser sintering
Thermal source	Electron beam	Laser
Atmosphere	Vacuum	Inert gas
Scanning	Deflection coils	Galvanometers
Energy absorption	Conductivity-limited	Absorptivity-limited
Powder preheating	Use electron beam	Use infrared or resistive heaters
Scan speeds	Very fast, magnetically driven	Limited by galvanometer inertia
Energy costs	Moderate	High
Surface finish	Moderate to poor	Excellent to moderate
Feature resolution	Moderate	Excellent
Materials	Metals (conductors)	Polymers, metals and ceramics
Powder particle size	Medium	Fine

Comparison

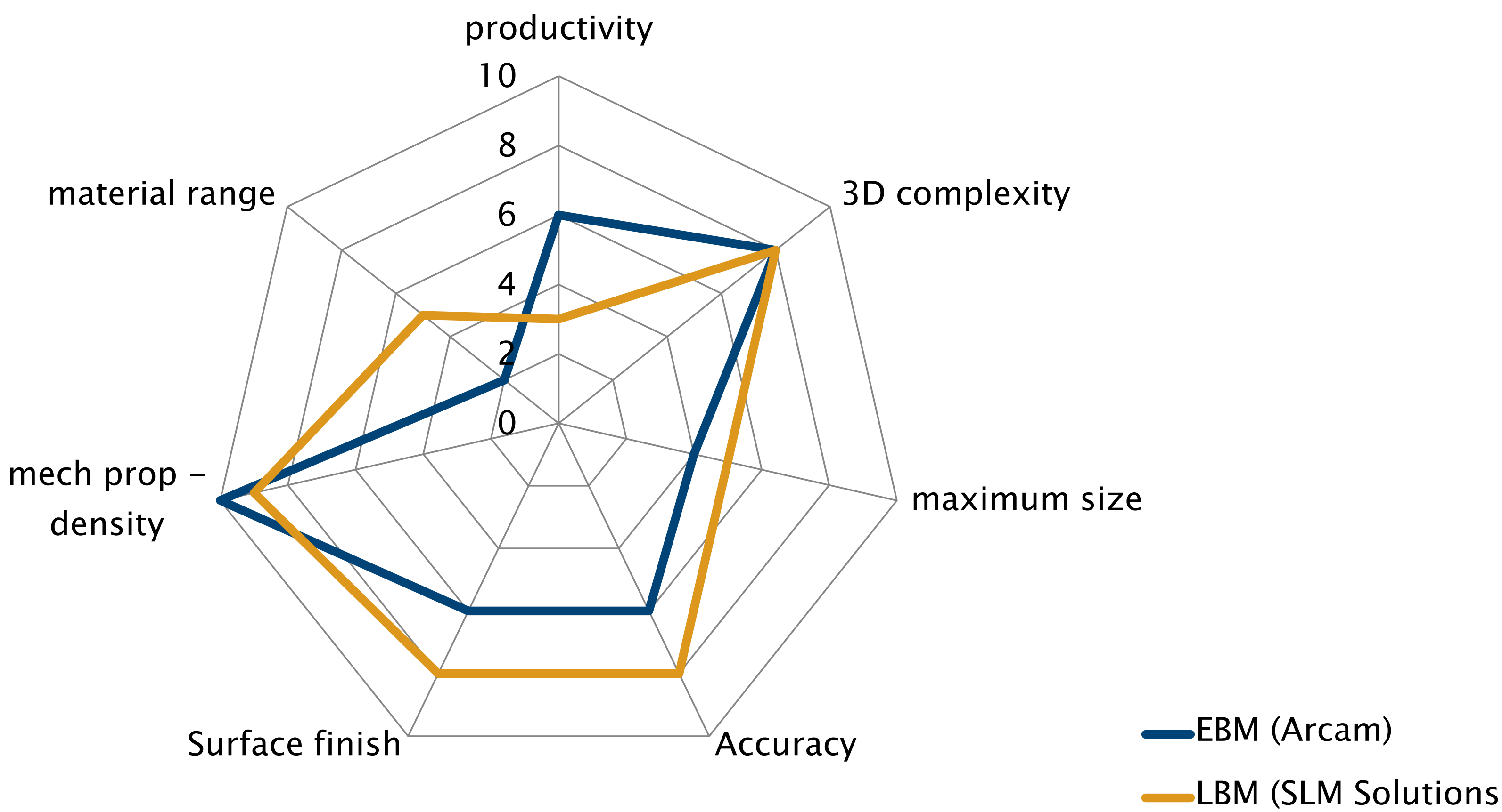
	LBM	EBM
Size (mm)	250 x 250 x 350*1	210 x 210 x 350*2
Layer thickness (µm)	30 – 60	50
Min wall thickness (mm)	0.2	0.6
Accuracy (mm)	+/– 0.1	+/– 0.3
Build rate (cm^3/h)	5 – 20	80
Surface roughness (µm)	5 – 15	20 – 30
Geometry limitations	Supports needed everywhere (thermal, anchorage)	Less supports but powder is sintered
Materials	Stainless steel, tool steel, titanium, aluminum,…	Only conductive materials (Ti_6Al_4V, CrCo,…)

*1 SLM Solutions 250HL

Comparison

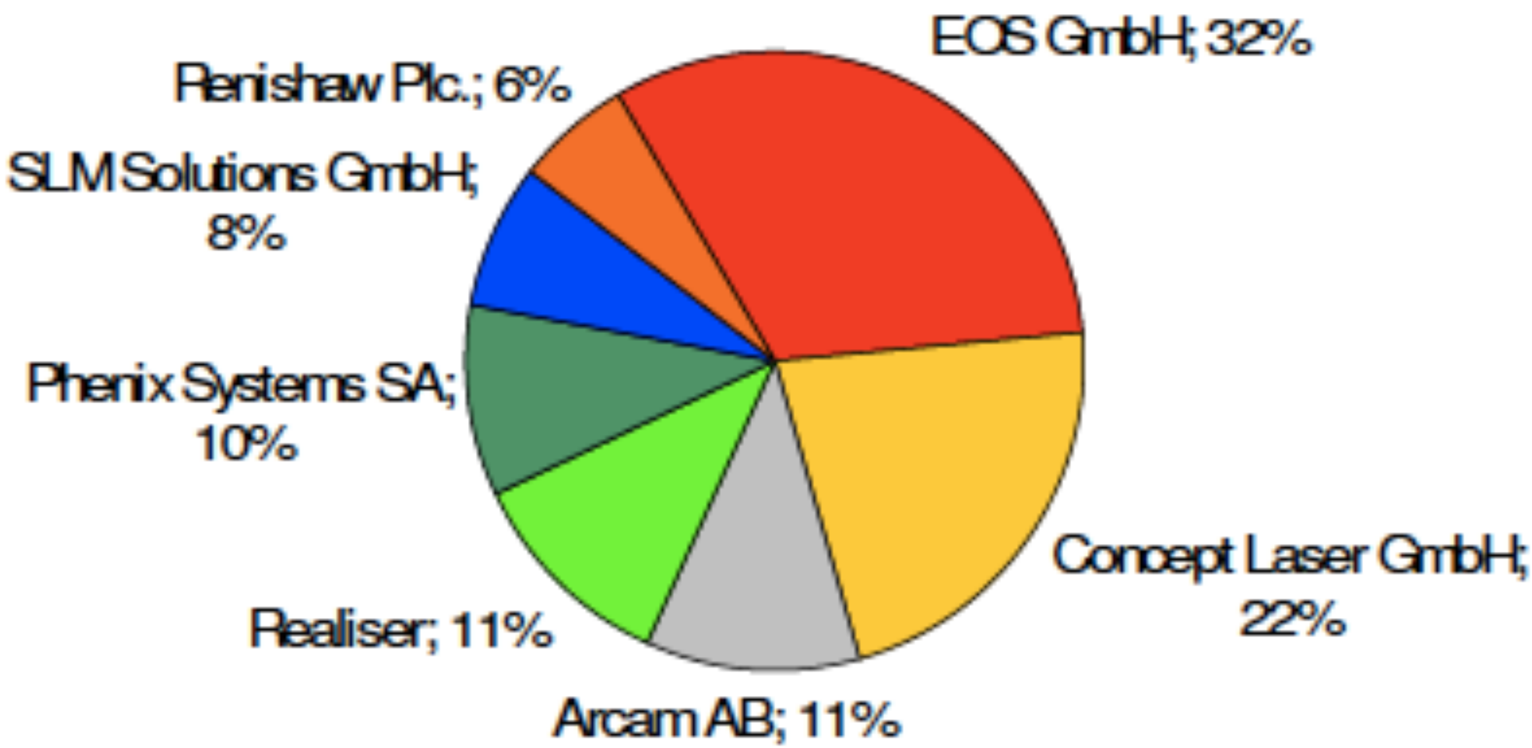
			EOS	SLM	Concept Laser	Renishaw	ARCAM
			M270	250HL	M1	AM250	A1
Gas di processo			Argon o Azoto	Argon o Azoto	Argon o Azoto	Argon o Azoto	
consumo di gas		Lt/h		90	1000	5-30	
Potenza del laser		W	200 - 400	200 - 400	200 - 400	200 - 400	50-3000
Max dimensione		mm	250 x 250 x 215	248 x 248 x 250	250 x250 x250	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 lase		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 ASTMF75	CoCr ASTMF 75	CoCr (F75), CrCo (dentale)	CoCr ASTMF75	CoCrMo ASTM F75
	Titanio		Ti6A4V	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

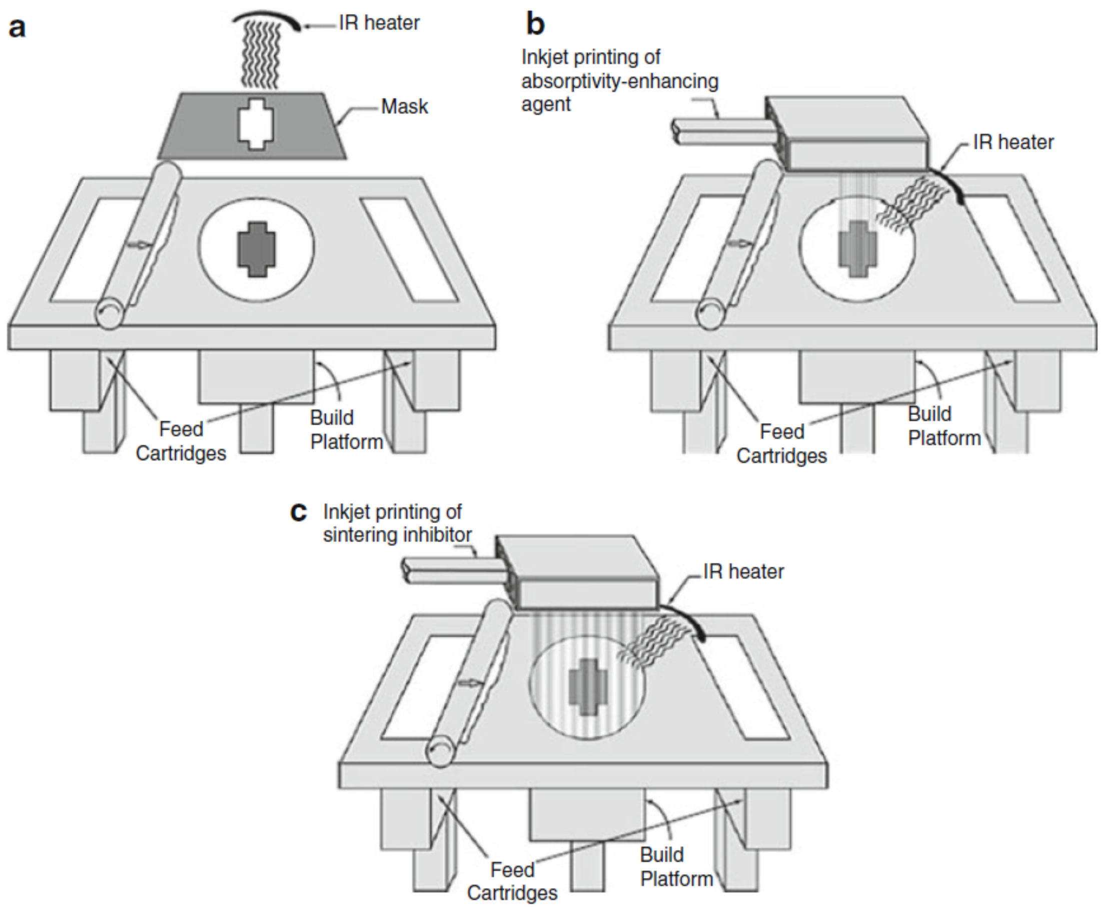


*1 SLM Solutions 250HL

European Market 2011



PBF process variant

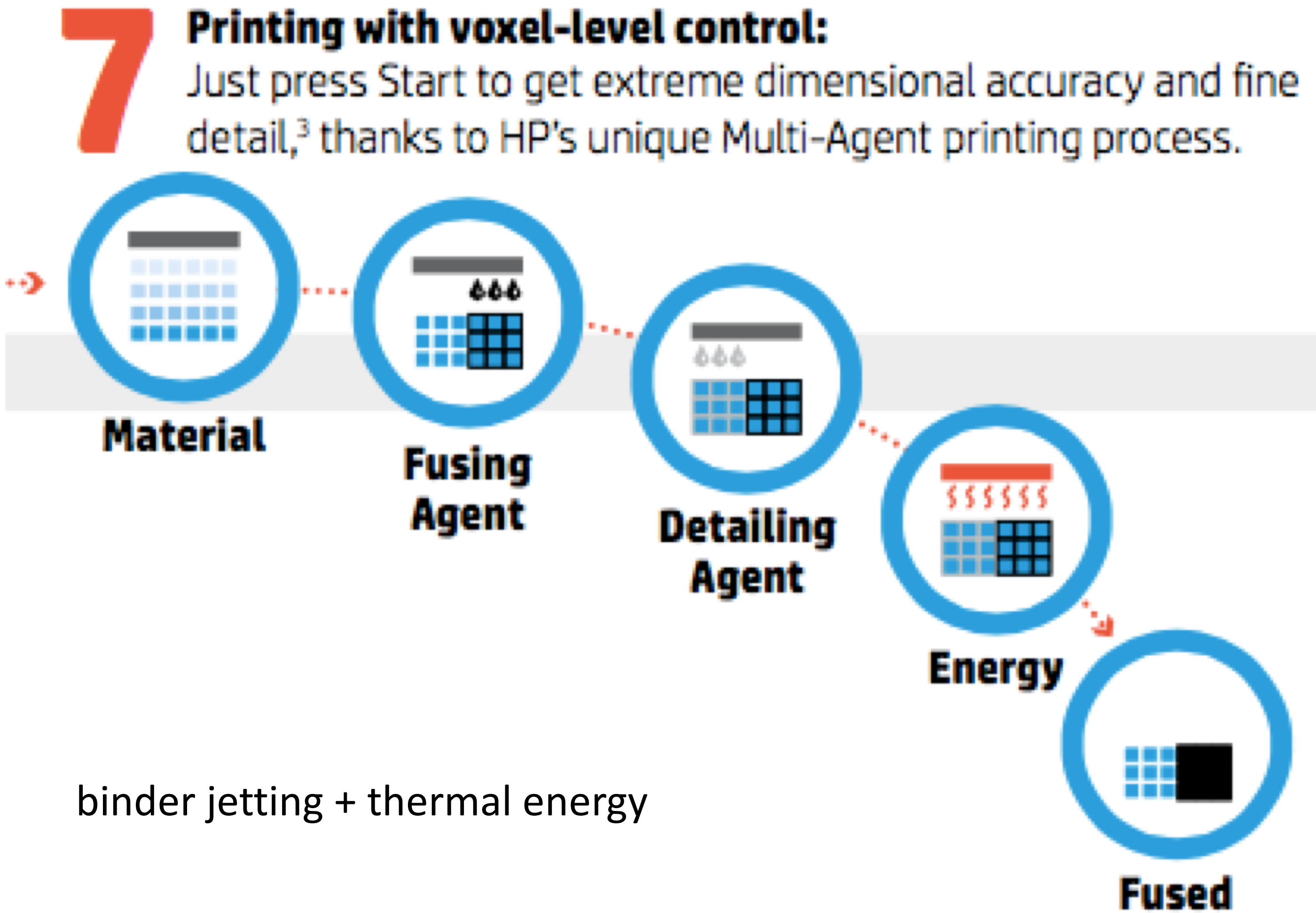


MULTIJET FUSION

Multijet Fusion

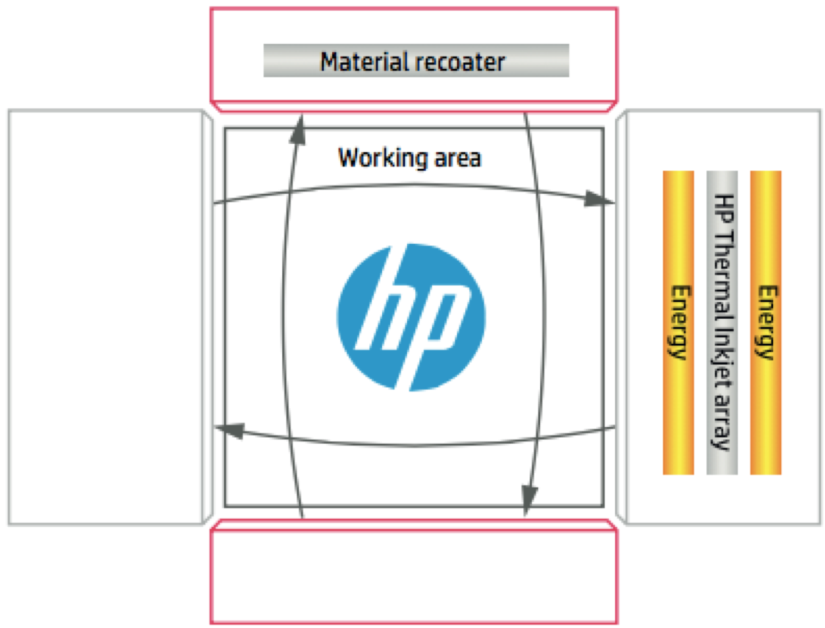
- https://www.youtube.com/watch?time_continue=1&v=VXntl3ff5tc
- https://www.youtube.com/watch?v=qEPqlVs11KM

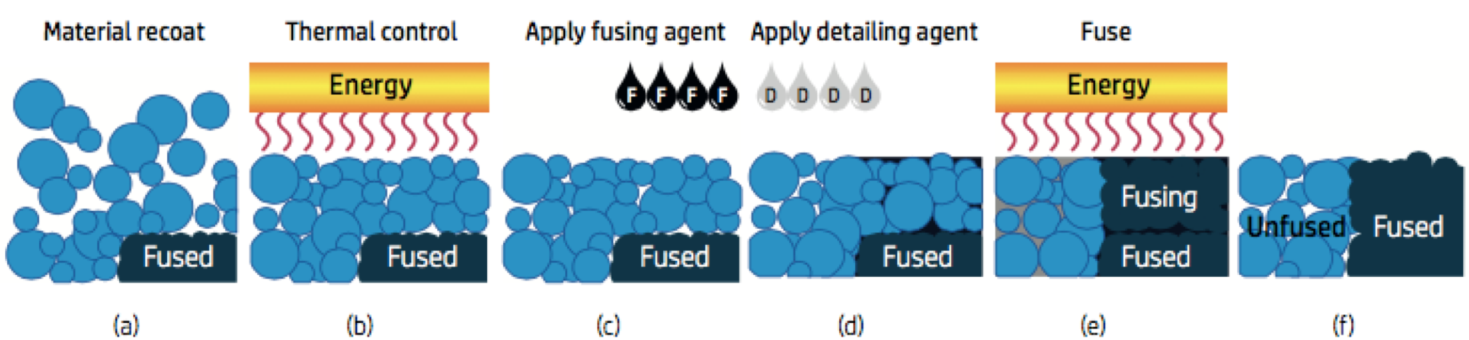
Multijet Fusion



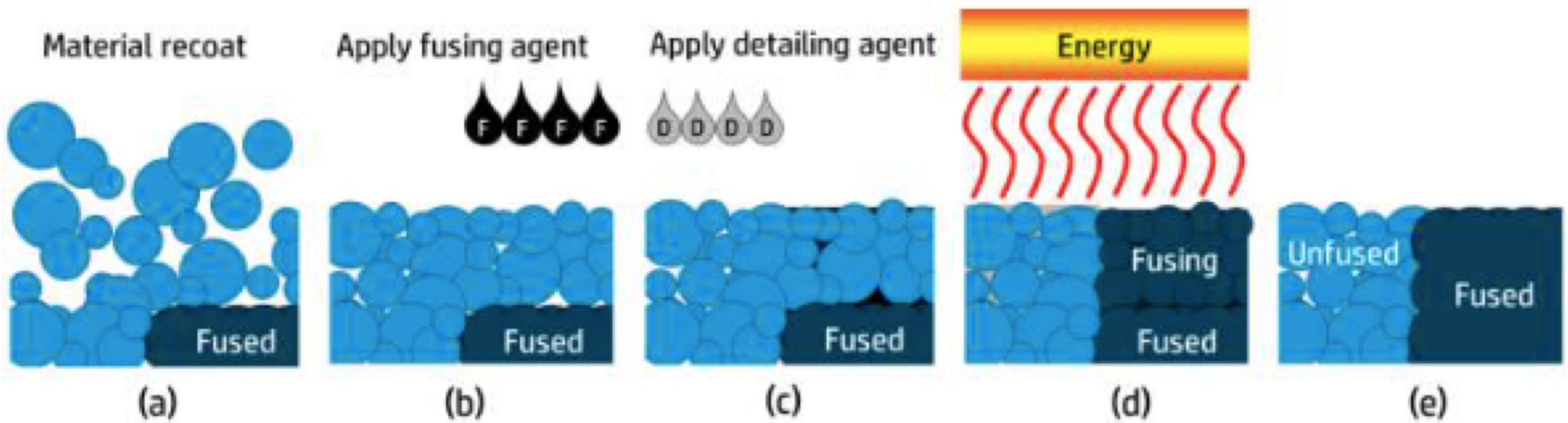
binder jetting + thermal energy

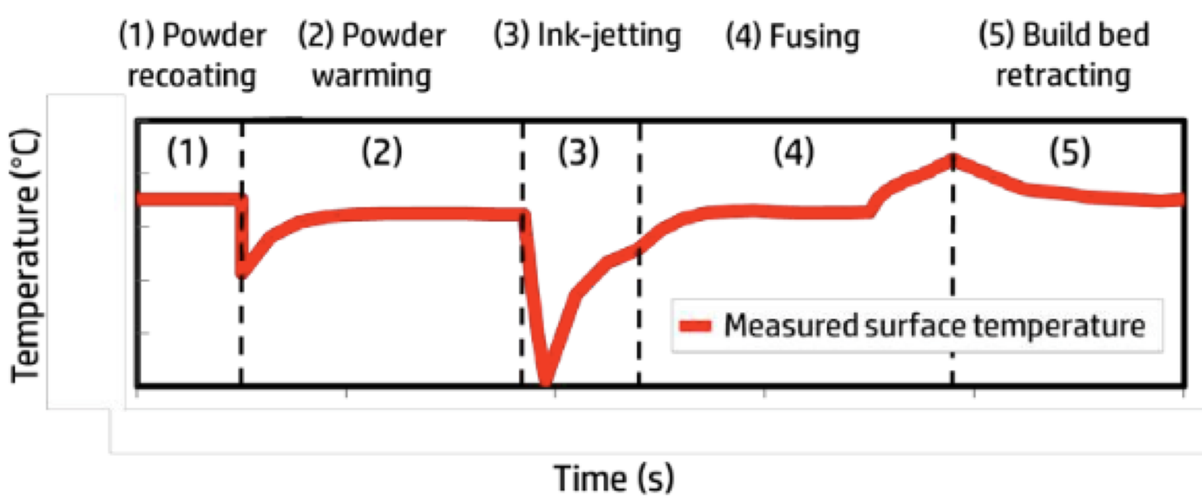
Multijet Fusion





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[10] and, in many cases, industry-leading reusability[8] at the lowest cost per part.[2]

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.[11] This robust thermoplastic is ideally suited for complex assemblies, housings, enclosures, and watertight applications. It provides the best balance between mechanical properties and reusability,[12] and provides biocompatibility certifications.[13] It also delivers consistent performance—while achieving 80% surplus powder reusability[8]—at the lowest cost per part.[2]

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.[10] It provides dimensional stability along with repeatability.[14] Customers experience quality results at a low cost per part and get consistent performance while achieving 70% surplus powder reusability.[15]

Thermoplastics +
glass beads

HP 3D High Reusability PA 11

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

+ MultiJet Fusion

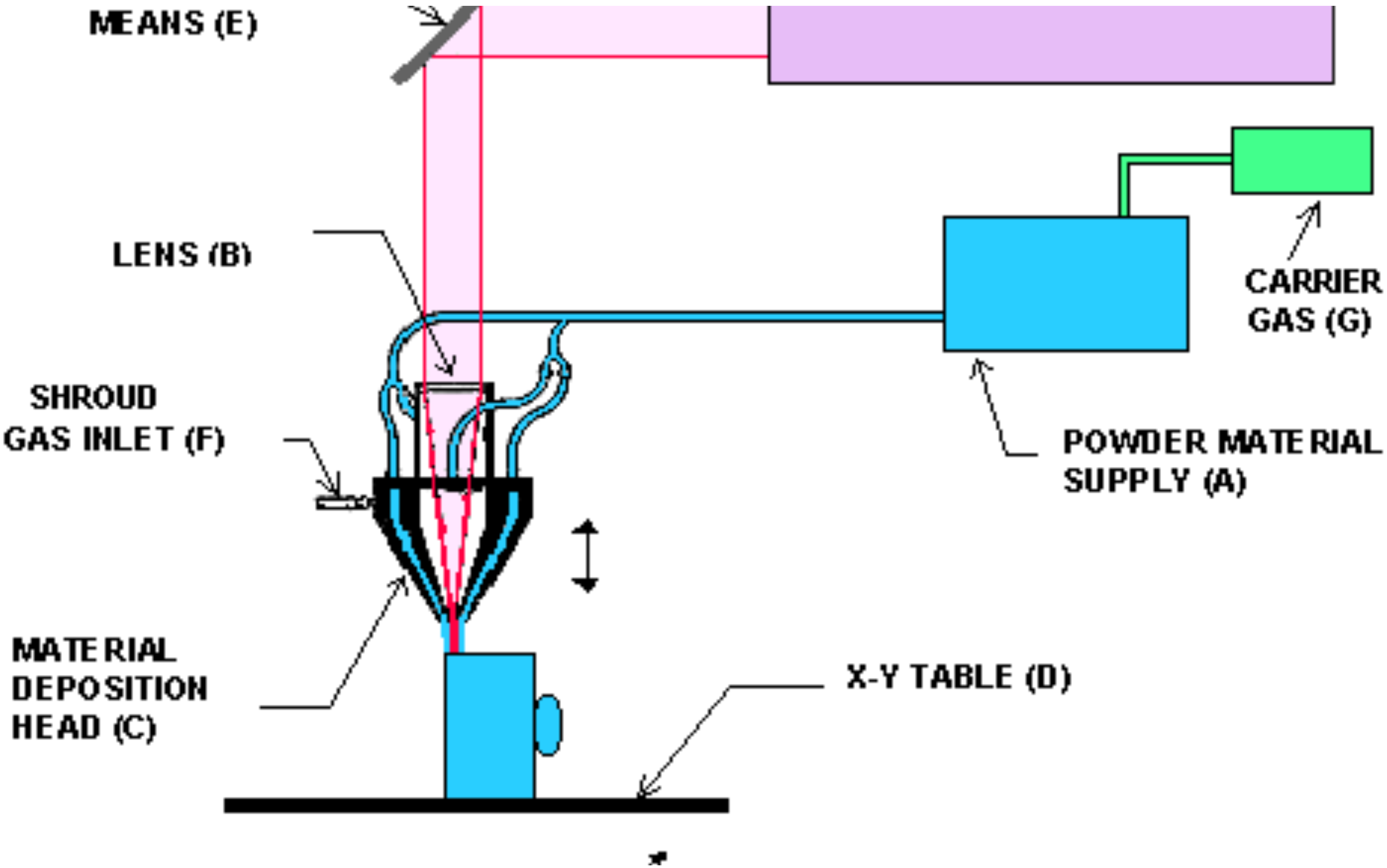
HP Jet Fusion 3D 4210/4200/3200 Printer

Printer performance	Technology	HP Multi Jet Fusion technology
	Effective building volume	380 x 284 x 380 mm (15 x 11.2 x 15 in)
	Building speed	**3200 Printer:** 2800 cm^3/hr (170 in^3/hr)[21] **4210/4200:** 4500 cm^3/hr (274 in^3/hr)[22]
	Layer thickness	**3200 Printer:** 0.08 mm (0.003 in) **4210/4200:** 0.07 to 0.08 mm (0.0027 to 0.0031 in)
	Print resolution (x, y)	1200 dpi
Dimensions (w x d x h)	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)
Weight	Printer	750 kg (1653 lb)
	Shipping	945 kg (2083 lb)

Directed energy deposition methods

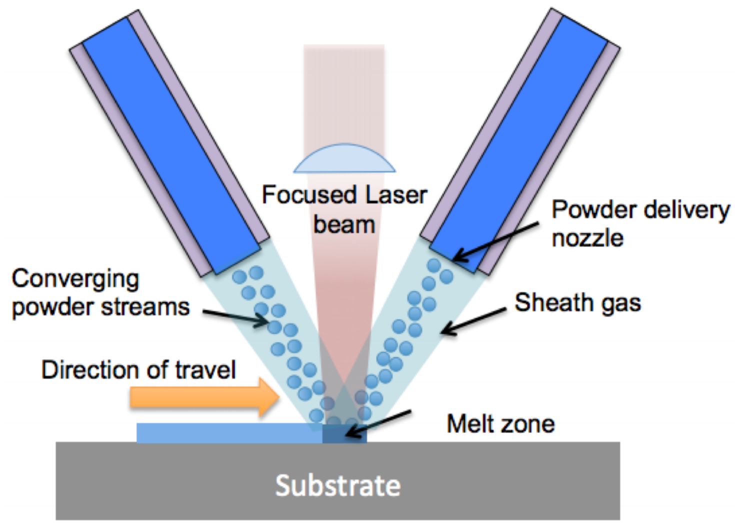
LASER ENGINEERED NET SHAPING

Laser Engineered Net Shaping



Laser Engineering Net Shaping

- Direct energy deposition



Laser Engineered Net Shaping

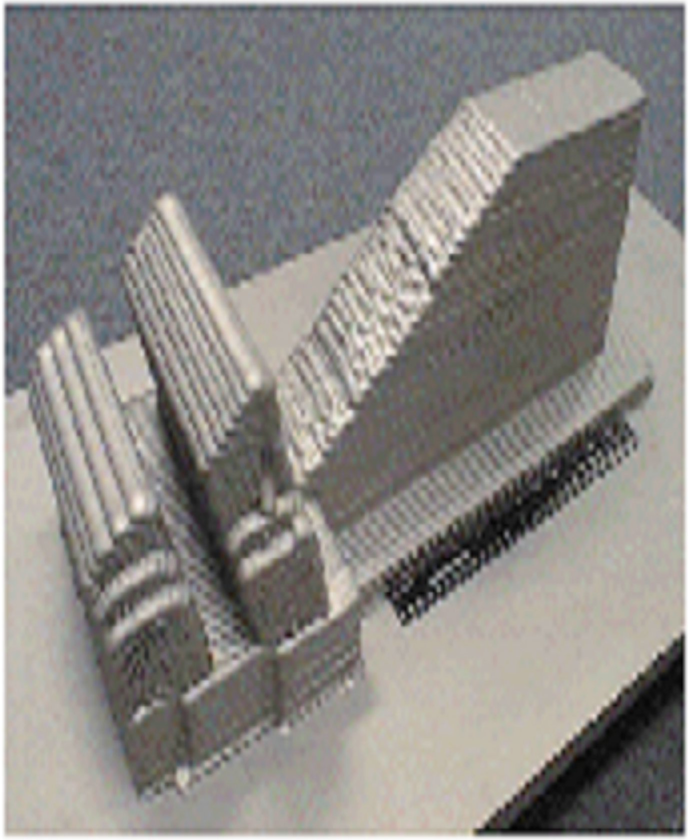
- Fully Dense Metal parts with good metallurgical properties
- Laser melts metal powder
- Powder delivered coaxially with laser
- Inert gas protects weld pool
- Near net shape with some finish machining

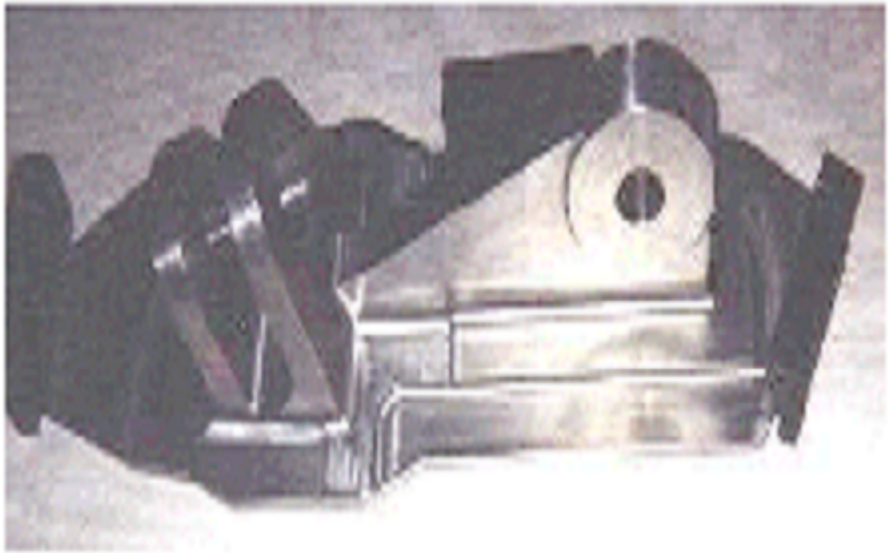
http://home.att.net/~castleisland/sgc.htm

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