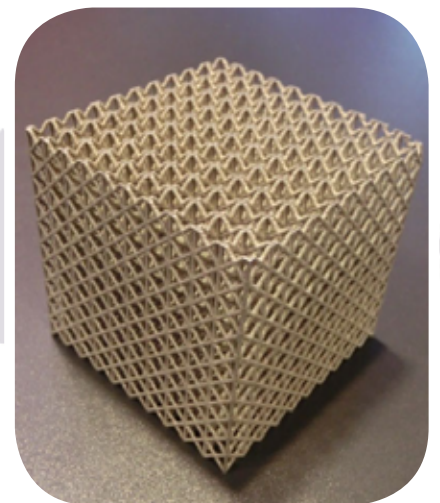


# INTRODUCTION TO **ADDITIVE** **MANUFACTURING** TECHNOLOGY

A guide for Designers and Engineers



# European Additive Manufacturing Group

## What is the European Additive Manufacturing Group?

The European Additive Manufacturing Group (EAMG) launched in May 2013 is open to companies and organisation across the entire powder metallurgy supply chain who are, or become, EPMA Members.

Its objectives are fourfold:

- To increase the awareness of the Additive Manufacturing (AM) technology, with a special focus on metal powder based products
- To enable the benefits of joint action, for example through research programmes, workshops, benchmarking and exchange of knowledge
- To improve the understanding of the benefits of metal based AM technology by end users, designers, mechanical engineers, metallurgists and students
- To assist in the development of International standards for the AM Sector



*EAMG Chairs: Ralf Carlström, Höganäs AB - Digital Metal®, Claus Aumund-Kopp, Fraunhofer IFAM, Adeline Riou, Erasteel, Olivier Coube, EPMA and Keith Murray, Sandvik Osprey*

**Join the EAMG at [www.epma.com/membership](http://www.epma.com/membership)**

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## Additive Manufacturing

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Citim GmbH	MTC	Thales Alenia Space
Concept Laser GmbH	MTU Aeroengines	The Mercury Center
Cookson Gold	Nanoval	University of Coimbra
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Jonathan Wroe, EPMA Executive Director  
Shrewsbury, UK

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## I. INTRODUCTION

Additive manufacturing, also known as 3D printing, rapid prototyping or freeform fabrication, is 'the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies' such as machining.

The use of Additive Manufacturing (AM) with metal powders is a new and growing industry sector with many of its leading companies based in Europe. It became a suitable process to produce complex metal net shape parts, and not only prototypes, as before.

Additive manufacturing now enables both a design and industrial revolution, in various industrial sectors such as aerospace, energy, automotive, medical, tooling and consumer goods.



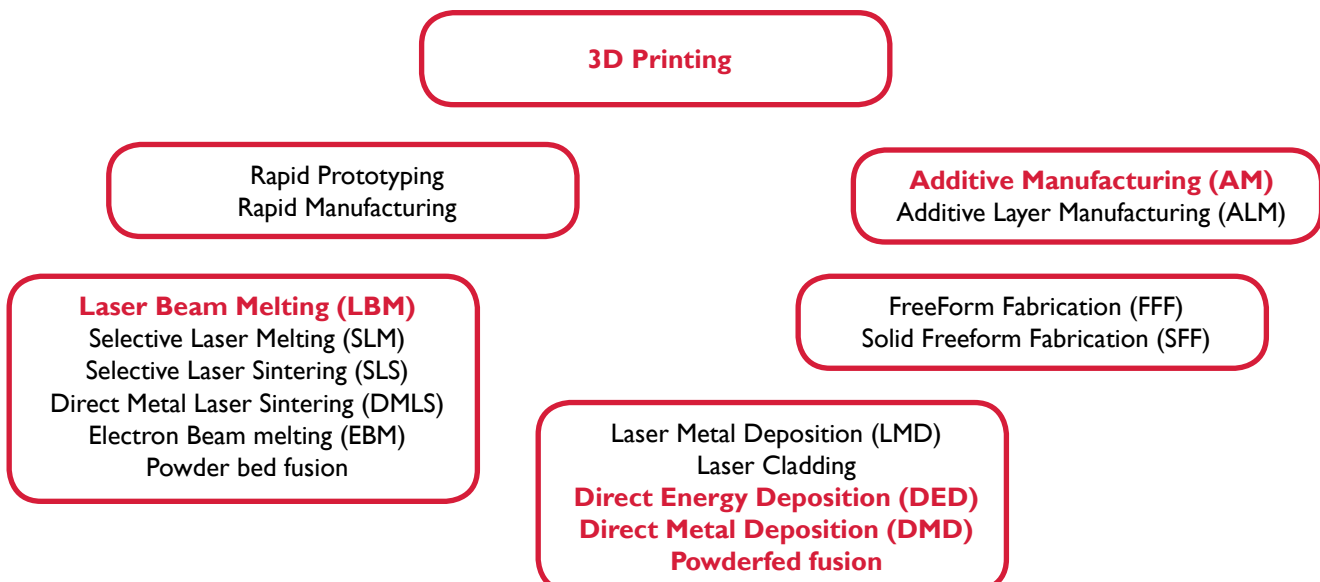
Fine metal part designed by Bathsheba Grossman (Courtesy of Höganäs AB - Digital Metal®)



Gas turbine demonstrator (diameter 250 mm and length 600 mm), by assembling parts made by Selective Laser Melting with Al-, Ti- and Ni-base powders for integration of functions, reduced number of parts, weight saving and increase of performance (Courtesy of FusiA)

### I.1 Vocabulary

According to the ASTM standard F2792-10, additive manufacturing is the « process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining.” Additive manufacturing technologies for metals are numerous, hence the development of a wide variety of terms and acronyms, as can be seen in the graph below. But today additive manufacturing is the most common term in industry markets while 3D printing is more used in the consumer market.



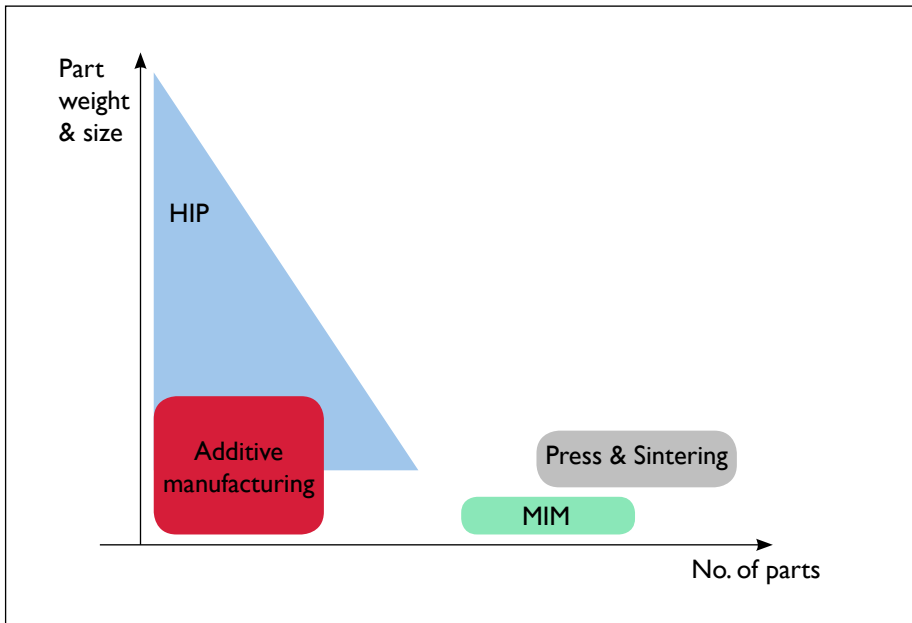
The vocabulary of Additive Manufacturing. In red, most common of standardised vocabulary

## I.2 Positioning of AM vs. other PM technologies

Additive manufacturing is complementing other powder metallurgy (PM) technologies.

Like Hot Isostatic Pressing (HIP), AM is more suitable for the production of small or medium series of parts. While HIP process is generally used for the manufacturing of massive near net shape parts of several hundred kilograms, the AM process is more suitable for smaller parts of a few kilos and it offers an improved capacity to produce complex metal parts thanks to a greater design freedom.

Metal Injection Moulding (MIM) and press & sintering technologies also offer the possibility to produce net shape parts but they are recommended for large series of small parts.



Positioning of various PM technologies according to part weight or size and production series

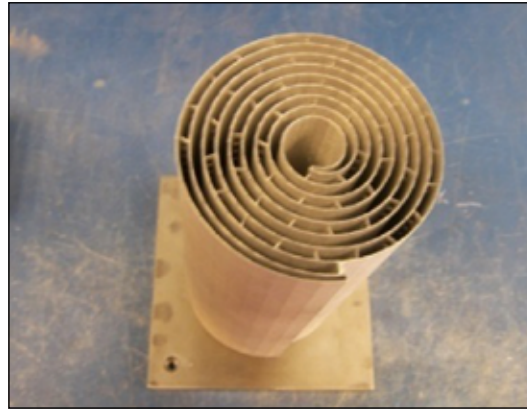
## I.3 The benefits of AM technology

Metal additive manufacturing technologies offer many key benefits.

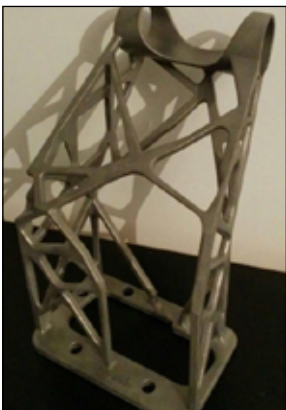
- Increased design freedom versus conventional casting and machining
- Light weight structures, made possible either by the use of lattice design or by designing parts where material is only where it needs to be, without other constraints
- New functions such as complex internal channels or several parts built in one
- Net shape process meaning less raw material consumption, up to 25 times less versus machining, important in the case of expensive or difficult to machine alloys. The net shape capability helps creating complex parts in one step only thus reducing the number of assembly operations such as welding, brazing.
- No tools needed, unlike other conventional metallurgy processes which require molds and metal forming or removal tools
- Short production cycle time: complex parts can be produced layer by layer in a few hours in additive machines. The total cycle time including post processing usually amounts to a few days or weeks and it is usually much shorter than conventional metallurgy processes which often require production cycles of several months. The process is recommended for the production of parts in small series



Hydraulic prototype with complex internal channels, (Source: EU project COMPOLIGHT)



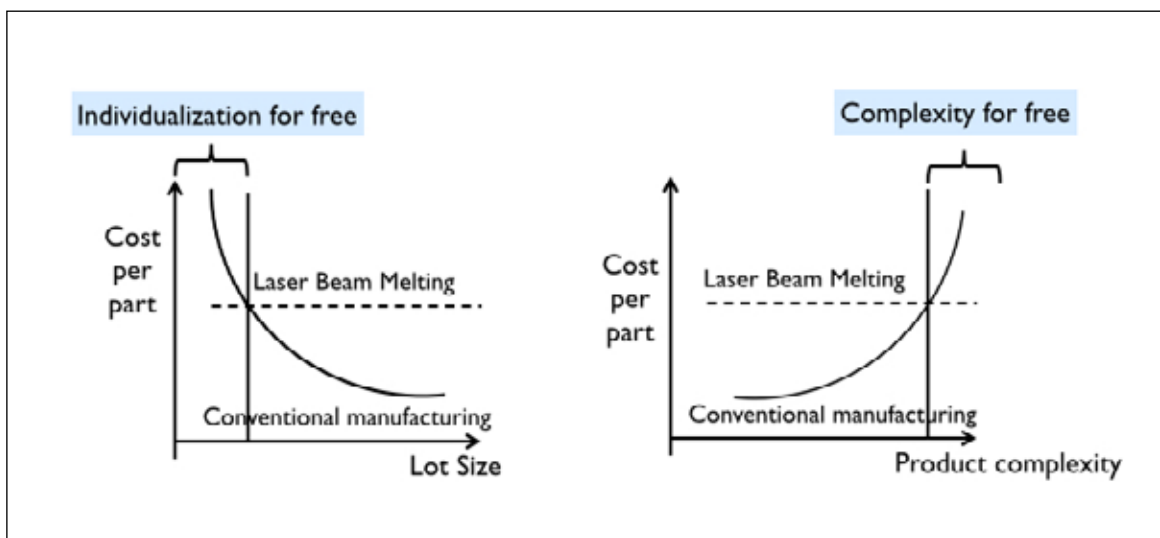
Prototype of 316L vacuum permeator for ITER made by LBM, impossible to produce by conventional processes. (Courtesy of IK4-Lortek)



Ti6Al4V support to satellite antenna made by EBM with a lightweight design made by topology optimization. (Courtesy of Poly-Shape)



Ti6Al4V implant (acetabular cup) with high specific surface design for improved osseointegration. (Courtesy of ARCAM)



Powder bed technologies enables part customization and increased design complexity at no cost, compared with conventional manufacturing (Courtesy of Fraunhofer)

## 1.4 The limits of AM technology

To take full advantage of AM technologies, it is important to be aware of some limitations:

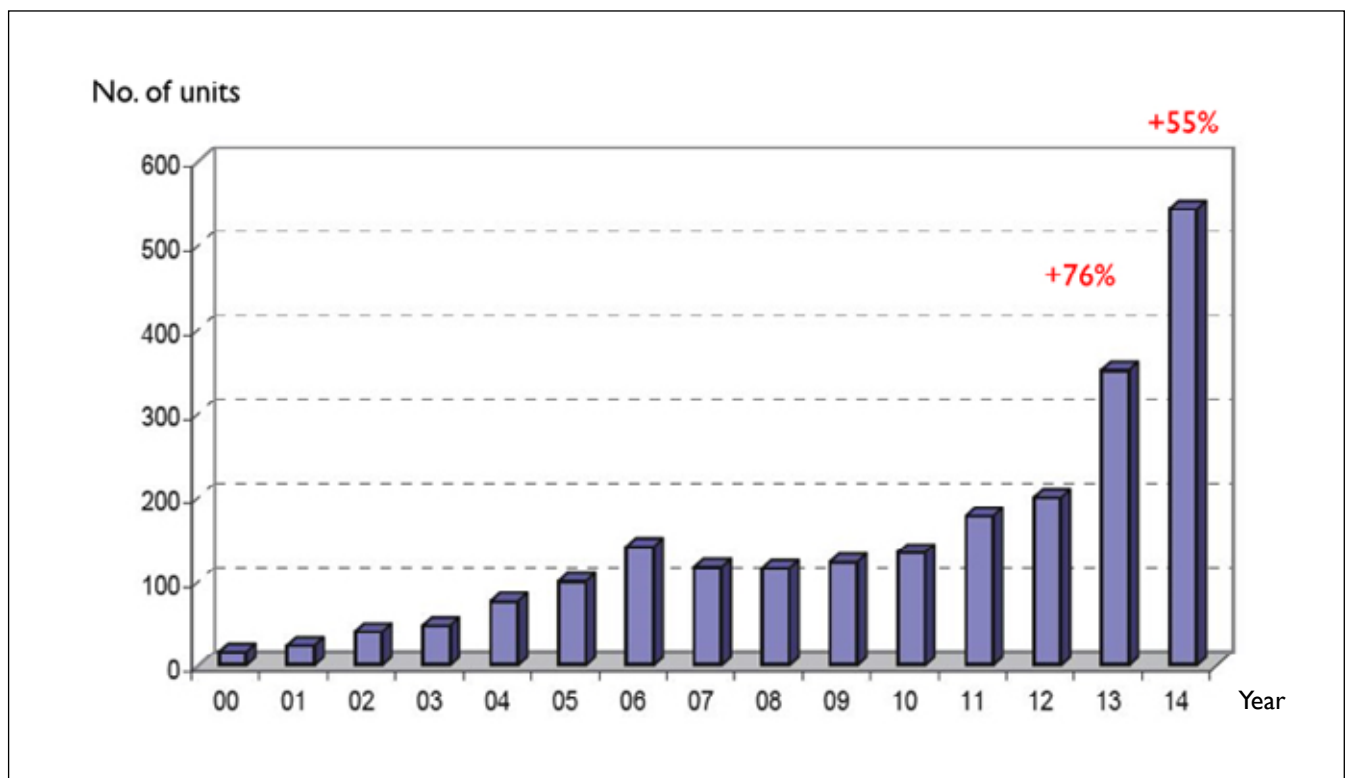
- Part size: In the case of powder bed technology, the part size is limited to powder bed size, such as 250x250x250 mm for standard powder bed systems. However, part sizes can be greater with direct energy deposition (or laser metal deposition) processes. But, due to the low thickness of powder layers, it can be very slow and costly building high parts or massive parts.
- Production series: the AM processes are generally suitable for unitary or small series and is not relevant for mass production. But progresses are made to increase machine productivity and thus the production of larger series. For small sized parts, series up to 25000 parts/year are already possible.
- Part design: in the case of powder bed technology, removable support structures are needed when the overhang angle is below 45°. Other design considerations to be taken into account can be seen in chapter 4 about design guidelines.
- Material choice: though many alloys are available, non weldable metals cannot be processed by additive manufacturing and difficult-to-weld alloys require specific approaches.
- Material properties: parts made by additive manufacturing tend to show anisotropy in the Z axis (construction direction).
- Besides, though densities of 99.9% can be reached, there can be some residual internal porosities. Mechanical properties are usually superior to cast parts but in general inferior to wrought parts.

## 1.5 Market perspectives

The use of additive manufacturing technology is developing in many industries:

- aerospace
- energy
- medical, in particular in surgical implants and dental applications
- tooling in particular for plastics processing
- automotive and transportation
- consumer goods
- etc.

AM technology is no longer used only for prototyping but now also for metal part production, hence the strong growth since 2012 of AM systems sales for the production of metal parts (see graph below).

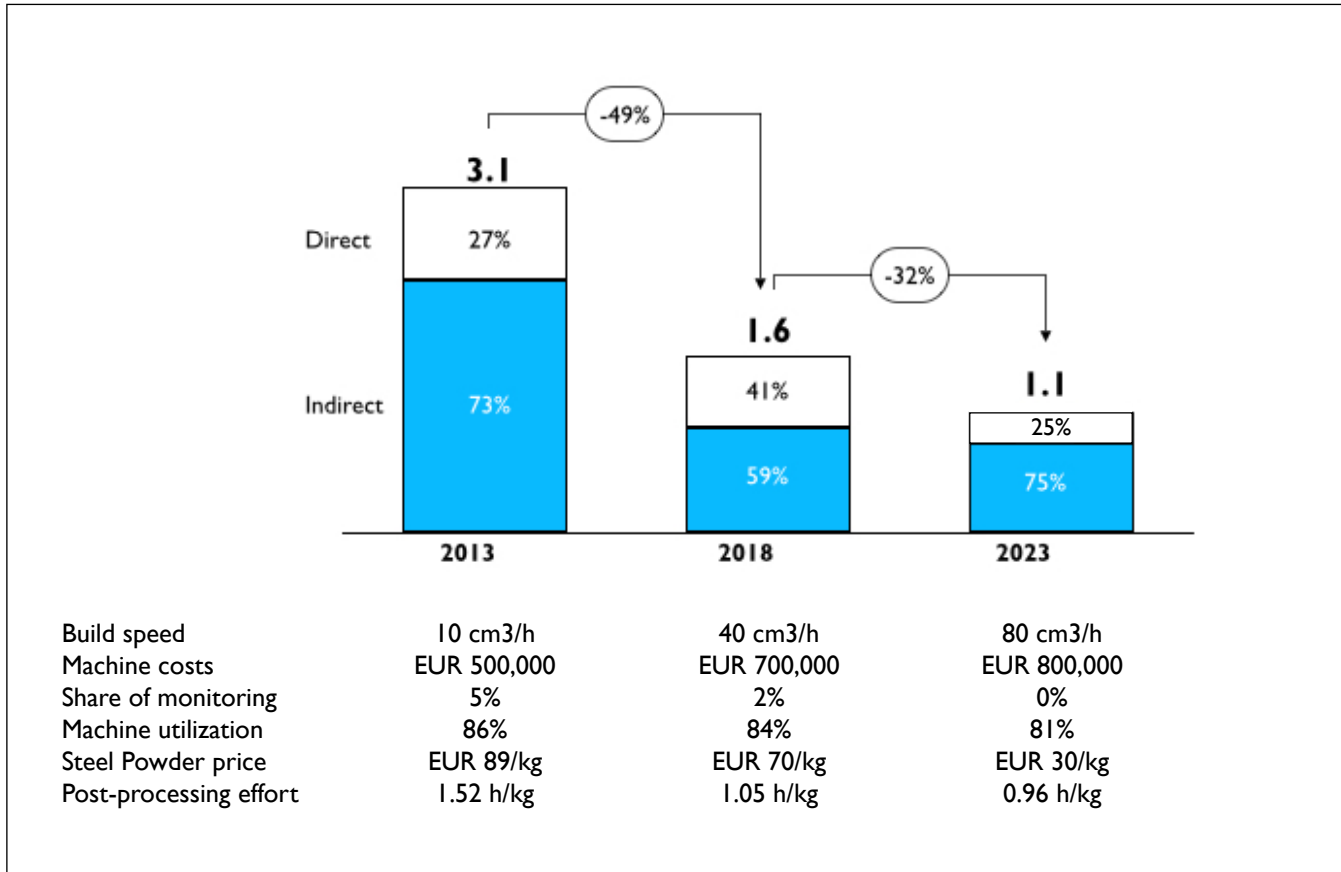


Sales of AM systems for metal parts Source: Wohlers Report 2015. (Courtesy of Wohlers Associates)



In addition, the current market growth should have a positive impact on the cost competitiveness of AM technology. Indeed, according to a DMRC survey in 2013 with interviews of 75 AM experts, it is expected that machine build speed should at least quadruple by 2018.

Besides, increasing metal powder production capacity for additive manufacturing might reduce powder costs too. However, machine utilization is expected to drop slightly due to multiple laser scanners and rising complexity. And the increase in build rate can be limited by the part's geometry (e.g. wall thickness).

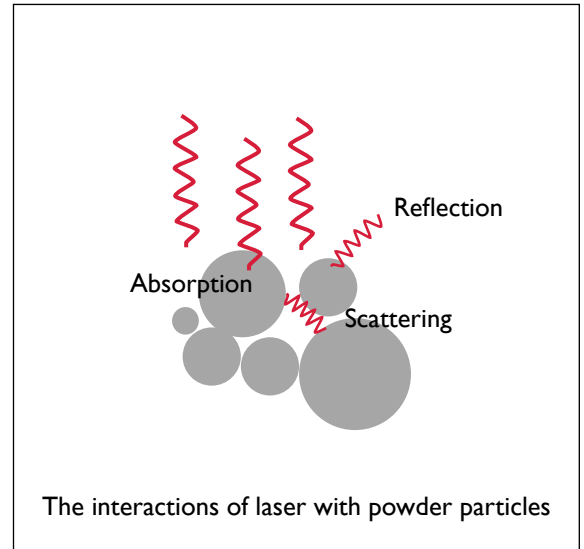
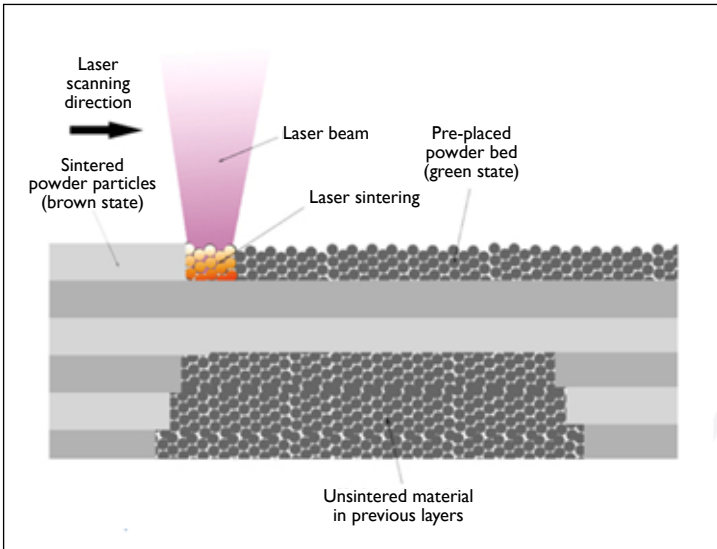


Graph: Forecast of metal AM costs in euros/cm<sup>3</sup> (Courtesy of Roland Berger)

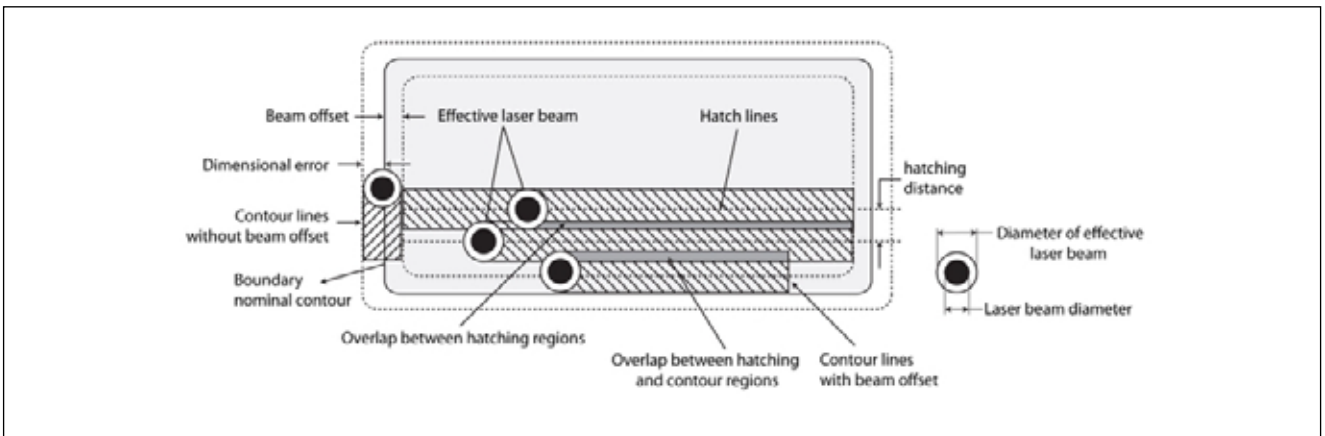
## 2.ADDITIVE MANUFACTURING TECHNOLOGIES

### 2.1 The basics of laser melting with metal powders

During laser beam melting, the laser beam, with diameter such as 100  $\mu\text{m}$ , will locally melt the upper powder layer on the powder bed. The laser will be partially absorbed by metal powder particles, creating a melt pool which solidifies rapidly. Laser power typically varies from 200 W up to 1000 W.

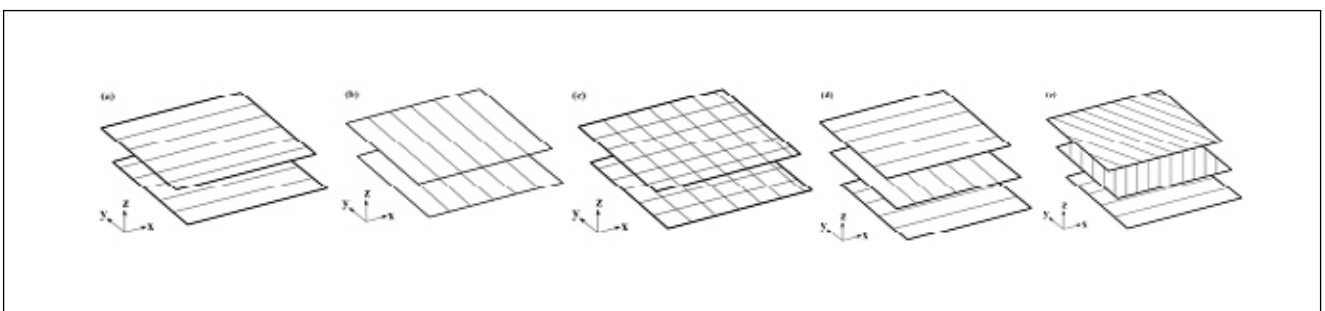


In selective laser melting, different scanning strategies are possible. The laser scanning patterns will influence porosity level, microstructure, surface roughness and heat build-up in the finished the metal components. The stripe pattern is a band defined by the scan vector width (ie stripe width), the hatching space between adjacent tracks and the scan direction as well as the overlap with the neighbouring stripes.



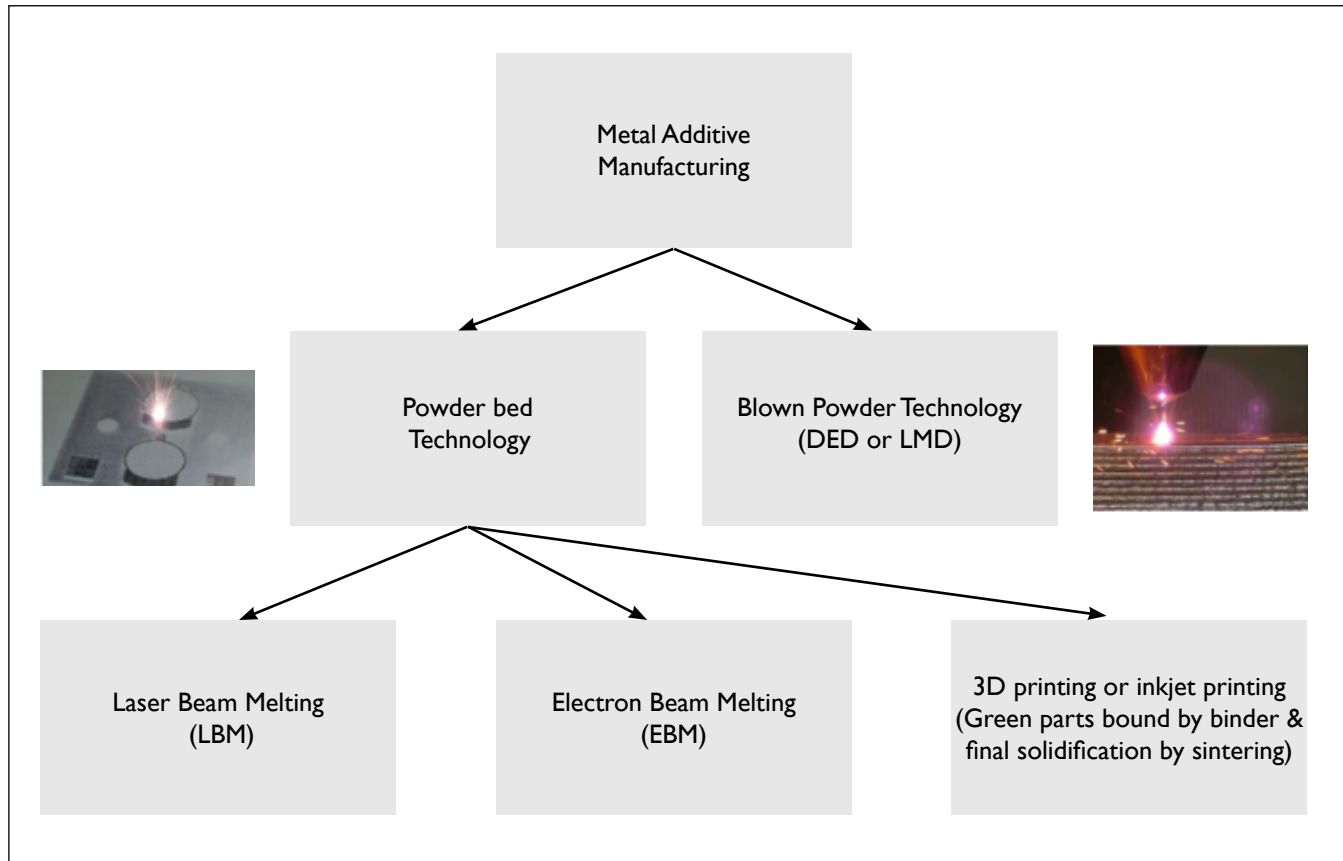
Stripe pattern (Courtesy of Istituto Italiano di Tecnologia and Politecnico di Torino)

On each layer, several laser scanning configurations (or hatch patterns) are possible, as can be seen in the sketch below.



Scanning strategies (Courtesy of Istituto Italiano di Tecnologia and Politecnico di Torino)

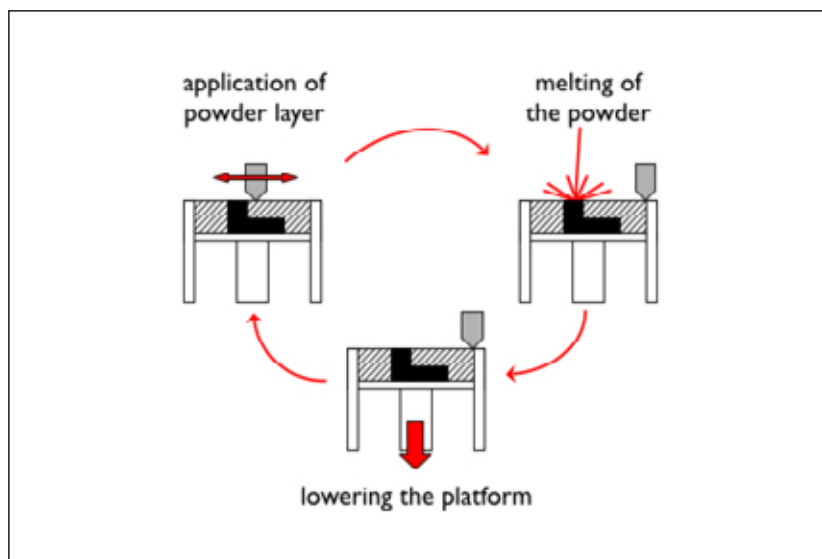
## 2.2 Overview of metal additive manufacturing processes



Mapping of main metal powder additive manufacturing technologies

In beam-based powder bed systems (LBM or EBM), a powder layer is first applied on a building platform. Then a laser or electron beam selectively melts the upper layer of powder.

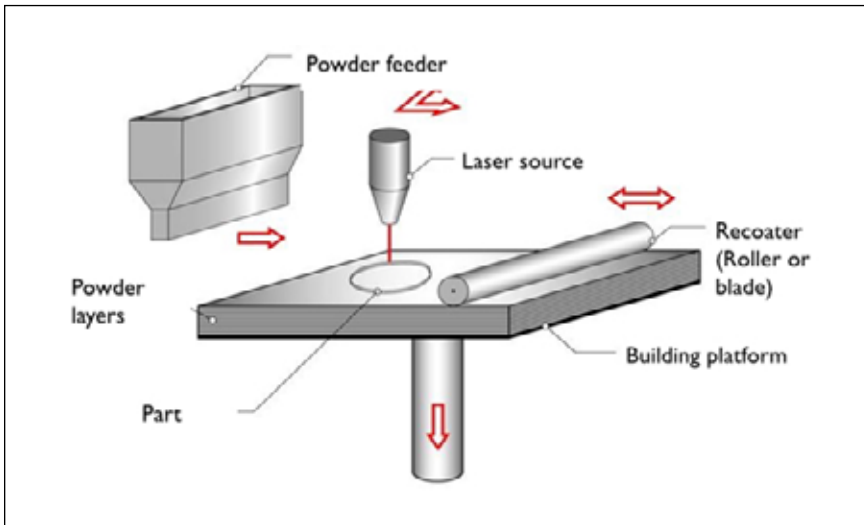
After melting, the platform is lowered and the cycle is repeated until the part is fully built, embedded in the powder bed.



The powder bed manufacturing cycle (Courtesy of Fraunhofer)

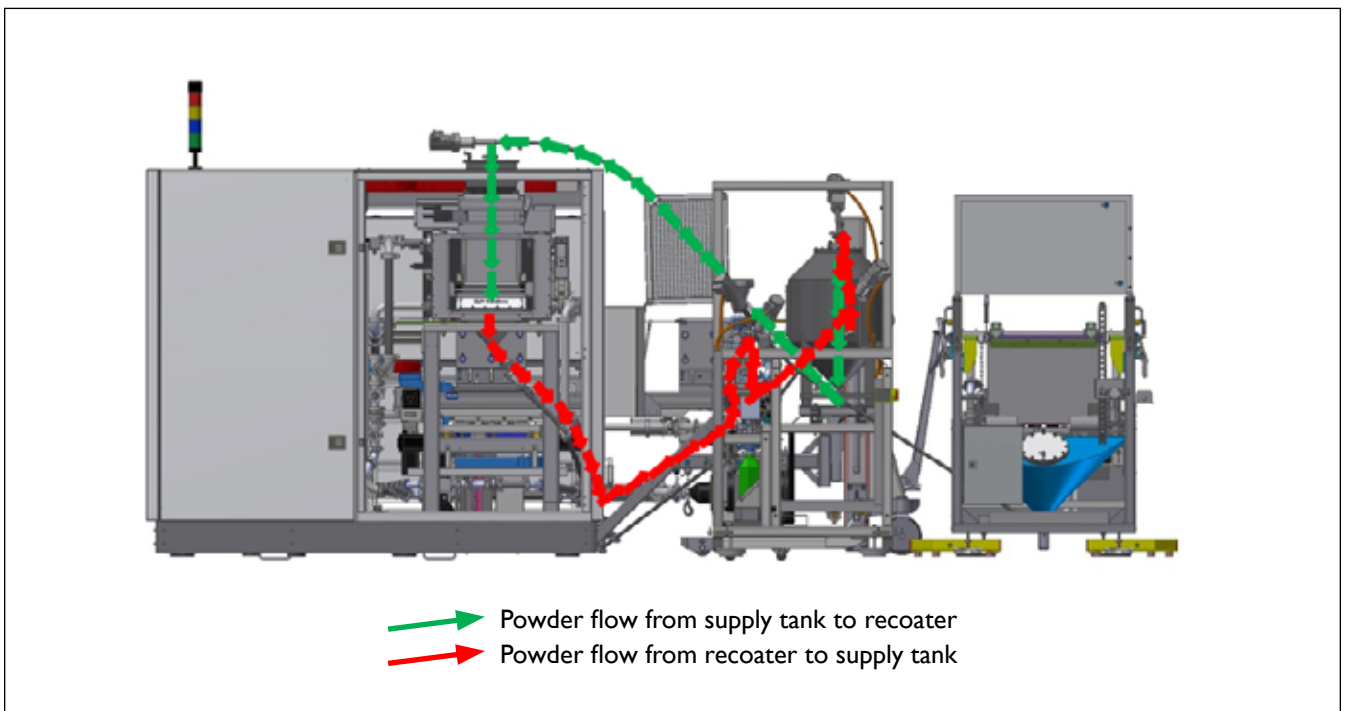
### 2.2.1 Laser Beam Melting (or Selective Laser Melting)

In the laser beam melting process, a powder layer is first applied on a building platform with a recoater (blade or roller) and a laser beam selectively melts the layer of powder. Then the platform is lowered by 20 up to 100  $\mu\text{m}$  and a new powder layer is applied. The laser beam melting operation is repeated. After a few thousand cycles (depending on height of the part), the built part is removed from the powder bed.



#### Manufacturers

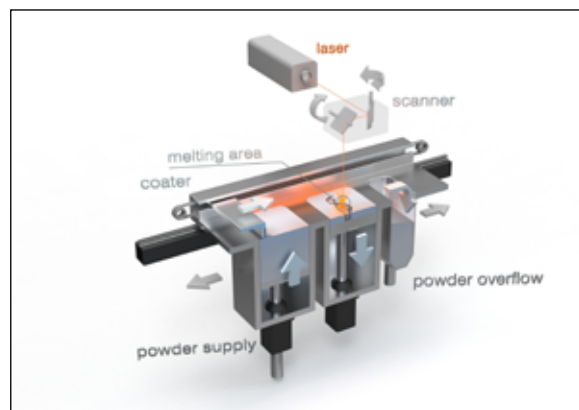
- 3D Systems (US)
- Concept Laser (DE)
- EOS (DE)
- Matsuura (JP)
- Realizer (DE)
- Renishaw (UK)
- SLM Solutions (DE)



The powder flow in a SLM 500HL powder bed machine (Courtesy SLM Solutions)



Complex CoCr Fuel Injection Swirler made by Laser Beam Melting (Courtesy of EOS GmbH)



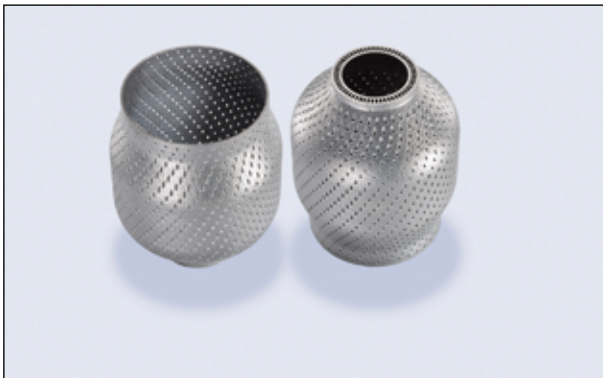
Inside a Laser Beam Melting Machine (Courtesy of Concept Laser GmbH)



Hollow Ni 718 turbine blade made by Laser Beam Melting  
(Courtesy of SLM Solutions)



Tooling insert by Laser Beam Melting  
(Courtesy of BMW)



Ni 718 Combustion chamber made by Laser Beam Melting  
(Courtesy of Concept Laser GmbH)



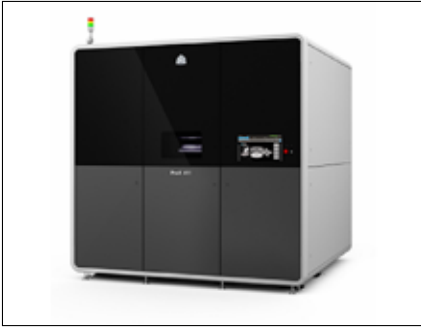
316L Surgical guide made by Laser Beam Melting  
(Courtesy of IK4-Lortek)

A new trend is to develop new systems with larger powder beds, as can be seen in the table below

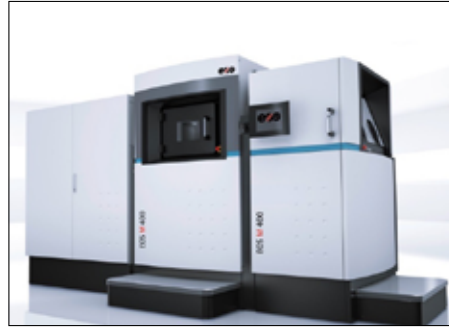
MANUFACTURER		Powder bed size Small (Usually with a diameter of 100 mm)	Powder bed size Standard (Usually 250x250x20 mm)	Powder bed size Large (with 1 or 2 dimen- sions >500 mm)
3D Systems	US& F	X	X	X
Concept Laser GmbH	DE	X	X	X
EOS GmbH	DE	X	X	X
Realizer GmbH	DE	X	X	
Renishaw	UK		X	
SLM Solutions GmbH	DE	X	X	X

Manufacturers of laser beam melting powder bed systems

Examples of large powder bed systems



ProX400 by 3D Systems  
Platform size: 500x500x500 mm



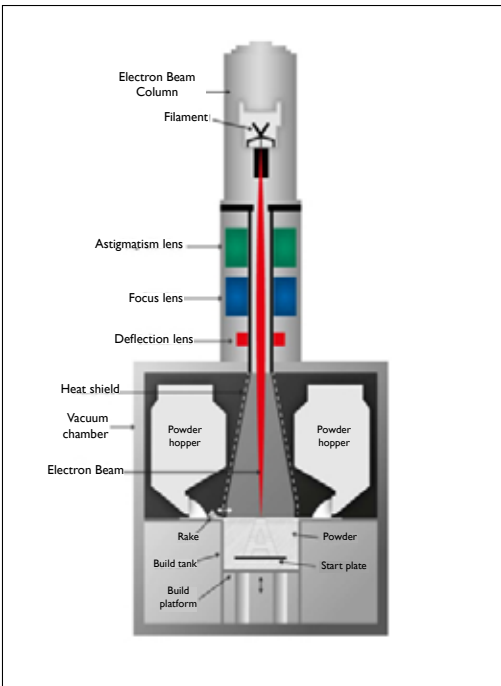
EOS M 400 by EOS GmbH  
Platform size: 400x400x400 mm



SLM500HL By SLM Solutions GmbH  
Platform size: 280x500x320 mm



X Line 2000R by Concept Laser GmbH  
Platform size: 800x400x500mm



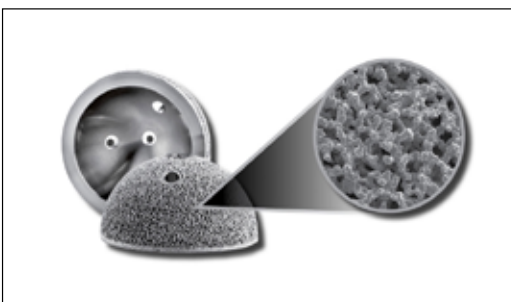
The EBM process (Courtesy of Arcam)

2.2.2 Electron Beam Melting

The EBM process is based on a high power electron beam that generates the energy needed for high melting capacity and high productivity. The electron beam is managed by electromagnetic coils providing extremely fast and accurate beam control. The EBM process takes place in vacuum (with a base pressure of  $1 \times 10^{-5}$  mbar or better) and at high temperature, resulting in stress relieved components. For each layer in the build the electron beam heats the entire powder bed to an optimal ambient temperature, specific for the material used. As a result, the parts produced with the EBM process are almost free from residual stresses and have a microstructure free from martensitic structures.

Manufacturers

- Arcam (SE)



Ti6Al4V acetabular cups with integrated Trabecular Structures™ for improved osseointegration (Courtesy of Arcam)



Low Pressure Turbine blade in  $\gamma$ -titanium aluminide (Courtesy of AvioAero)

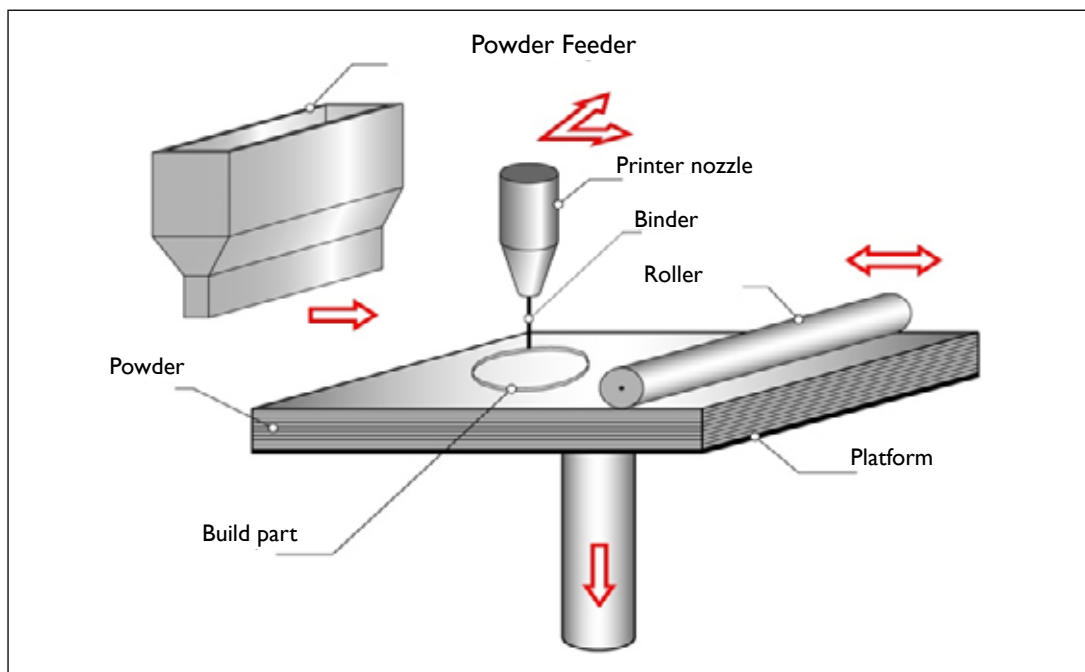
### 2.2.3 3D printing

The 3D printing process is an indirect process in two steps.

After applying a powder layer on the build platform, the powder is agglomerated thanks to a binder fed through the printer nozzle.

The operation is repeated until parts are produced, which shall be then removed carefully from the powder bed, as they are in a « green » stage.

The metal part solidication takes place in a second step, during a debinding and sintering operation, sometimes followed by an infiltration step.



#### Manufacturers

- Digital Metal
- ExOne

The 3D printing technology is more productive than laser beam melting and requires no support structure. Besides it provides a good surface quality by using one of several post processing techniques:

- Peening/Blasting/Tumbling for average of Ra 3.0  $\mu\text{m}$
- Superfinishing for an average of Ra 1.0  $\mu\text{m}$  down to < 1.0 $\mu\text{m}$

But the range of available materials is limited and mechanical properties achieved can be lower than with laser and electron beam melting.



Parts in the powder bed after 3D printing  
(Courtesy of Höganäs AB - Digital Metal®)

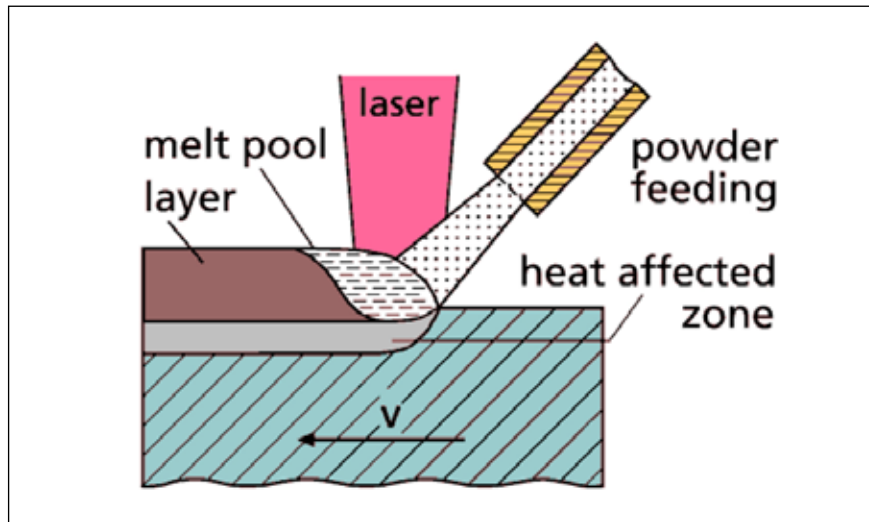


Lightweight stainless screws made by 3D printing  
(Courtesy of Höganäs AB - Digital Metal®)

### 2.2.4 Direct Energy Deposition (or Laser metal deposition)

With the direct energy deposition process, a nozzle mounted on a multi axis arm deposits melted material onto the specified surface, where it solidifies.

This technology offers a higher productivity than selective laser melting and also the ability to produce larger parts, but the freedom in design is much more limited: for instance, lattice structures and internal channels are not possible.

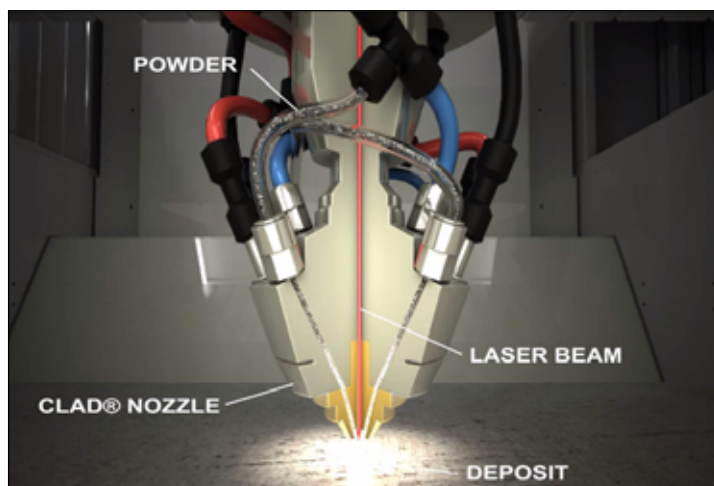


#### Manufacturers

- BeAM (FR)
- DMG Mori (DE)
- Hybrid Manufacturing Technologies (UK)
- INSSTEK (KR)
- MAZAK (J)
- Optomec (US)
- Trumpf (DE)

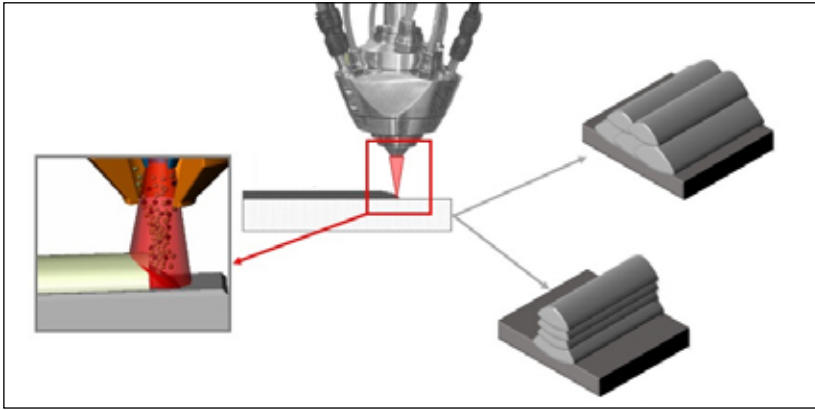
characteristics	LMD	SLM
materials	large materials diversity	• limited and lower experience in comparison to LMD
part dimensions	limited by the handling system	limited by the process chamber (Ø: 250mm, height: 160mm)
part complexity	limited	nearly unlimited
dimensional accuracy	≥ 0.1 mm	≥ 0.1 mm
deposition rate	3 – 10 mm <sup>3</sup> /s	1 – 3 mm <sup>3</sup> /s
build-up on	• 3D-surface • on existing parts	• flat surface • flat preforms
roughness R <sub>z</sub>	60 – 100µm	30 – 50µm
layer thickness	≥ 0.03 - 1 mm	≥ 0.03 - 0.1 mm

Comparison of LMD vs SLM (Courtesy of Fraunhofer)

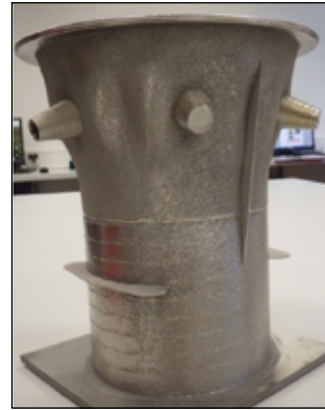


Sketch of the Direct Energy Deposition CLAD process (Courtesy of BeAM)





Laser Metal Deposition process (Courtesy of BeAM)



Ti6Al4V complex demonstrator made by Laser Metal Deposition (Courtesy of BeAM)



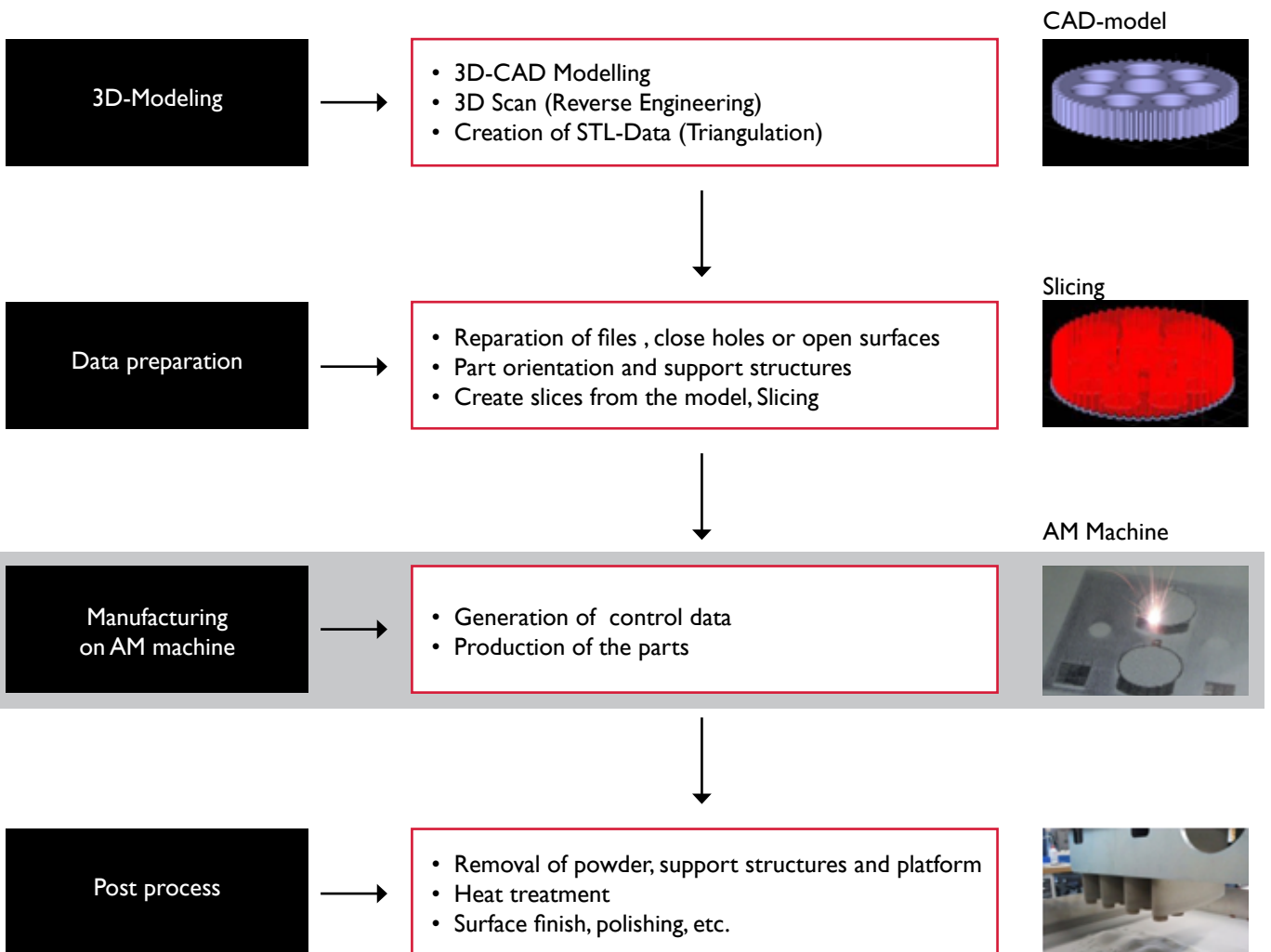
Direct Energy Deposition process for blade repair or building (Courtesy of Fraunhofer ILT)

### Benefits of Direct Energy Deposition process

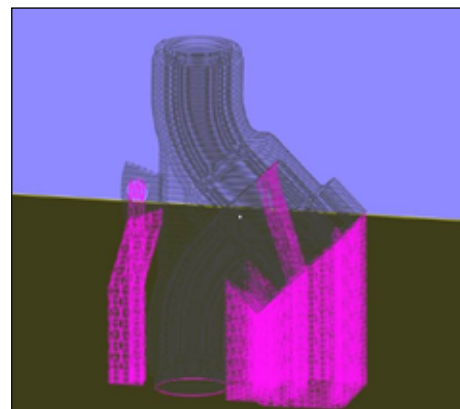
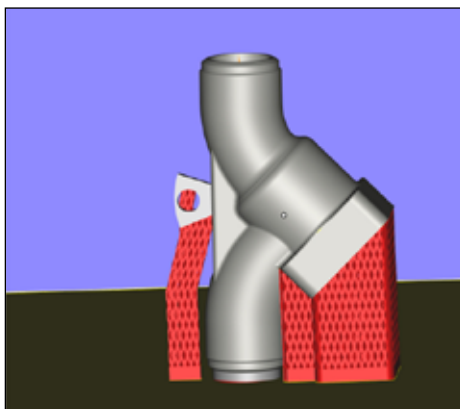
- New topological features possibilities
- Repair of parts that up to now were impossible
- Addition of functionalities on existing parts with either the same or a different material
- No dimensional limits (apart from the machine size)
- Excellent metallurgic quality at least as good as foundry
- Control of the material deposited (gradients, multimaterials, monolithic ...)
- Eco innovative process: less material loss, no tool process...

### 2.3 Main process steps

The manufacturing of a metal part with additive manufacturing technologies starts with 3D modeling. Then data preparation shall be organized for and includes the definition of part orientation, the positioning of support structures and the slicing of the model. After part manufacturing, post processing operations are needed.



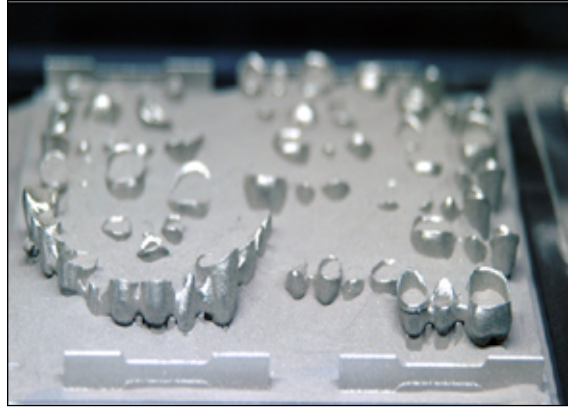
Summary of process steps (Courtesy of Fraunhofer)



Creation of supports and file slicing with Magics software (Courtesy of Materialise)



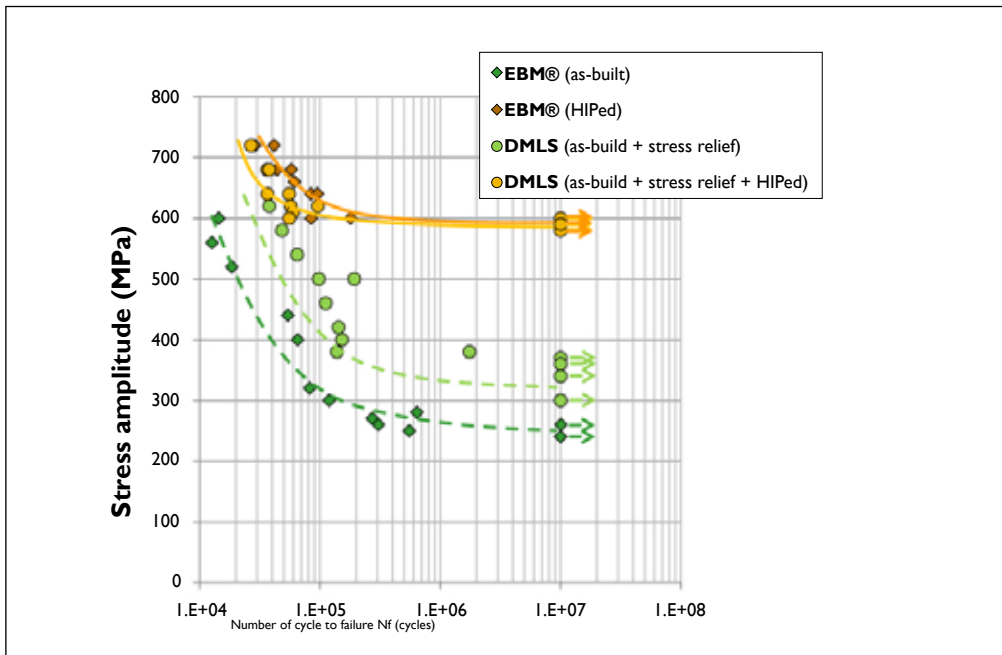
Laser beam melting operation (Courtesy of EOS)



Dental parts on the platform after powder removal (Courtesy of BEGO medical)

### Post processing operations can include:

- Machining
- EDM
- Peening, Grinding,
- Polishing, surface treatment
- Heat treatment
- Hot isostatic pressing (HIP) to eliminate residual porosities
- Control



The effect of HIP post processing on fatigue resistance of parts made by SLM and EBM (Courtesy of MTC)

### 3. METAL POWDERS FOR ADDITIVE MANUFACTURING

#### 3.1 Introduction

Metal powder plays a very important role in the additive manufacturing processes. Indeed the quality of metal powder used will have a major influence on mechanical properties but it can also influence:

- the build-to-build consistency,
- the reproducibility between AM machines,
- the production of defect-free components,
- the manufacturing defects on surfaces.

A very wide range of alloys are used on additive manufacturing machines thanks to the availability of metal powders:

- Steels such : 316L, 17-4PH etc.
- Nickel and cobalt base superalloys : 625, 718, CoCr F75 etc.
- Titanium alloys : Ti6Al4V, CP Ti etc.
- Aluminium alloys: AlSi10Mg etc.

But many other metals are also evaluated and developing:

- copper alloys,
- magnesium alloys,
- precious metals such as gold, silver, platinum,
- refractory metals such as Mo alloys, W and WC ,
- Metal Matrix Composites, etc.

#### 3.2 Powder manufacturing processes

Metal powders for additive manufacturing are usually produced using the gas atomization process, where a molten metal stream is atomized thanks to a high pressure neutral gas jet into small metal droplets thus forming metal powder particles after rapid solidification.

Gas atomization is a physical method (as opposed to chemical or mechanical methods) to obtain metal powders, like water atomization. But powders produced by gas atomization have a spherical shape, which is very beneficial for powder flowability while powders produced by water atomization will have an irregular shape.

Gas atomization is the most common process for additive manufacturing because it ensures:

- A spherical powder shape
- A good powder density, thanks to the spherical shape and particle size distribution
- A good reproducibility of particle size distribution

Besides a very wide range of alloys can be produced using the gas atomization process.



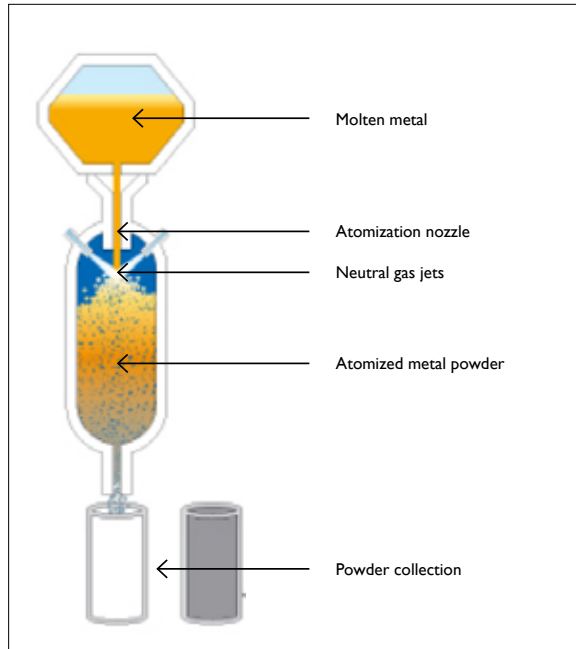
*Metal powders for additive manufacturing (Courtesy of SLM Solutions)*

### 3.2.1 The gas atomization process

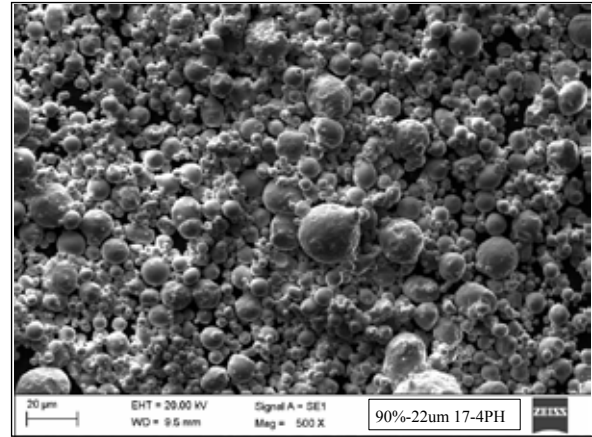
The gas atomization process starts with molten metal pouring from a tundish through a nozzle.

The stream of molten metal is then hit by jets of neutral gas such as nitrogen or argon and atomized into very small droplets which cool down and solidify when falling inside the atomization tower. Powders are then collected in a can.

The gas atomization process is the most common process to produce spherical metal powders for additive manufacturing. It is used in particular for steels, aluminium alloys, precious metals, etc.



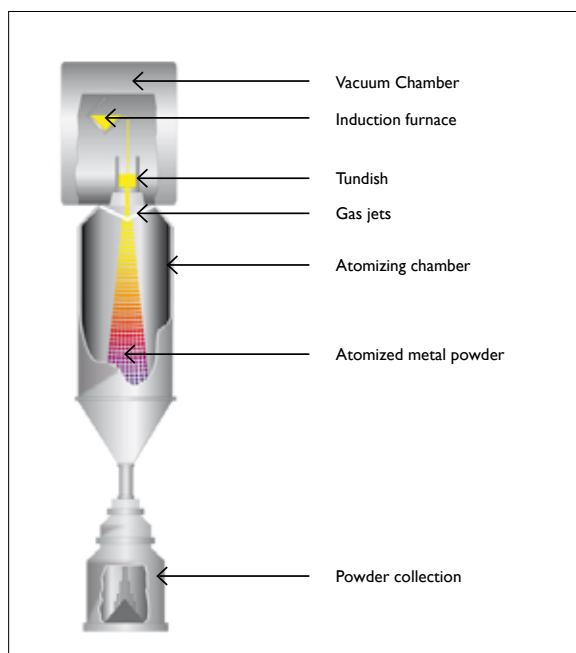
Sketch of the gas atomization process



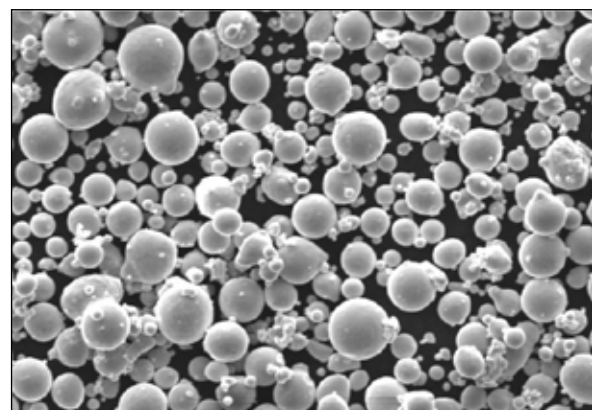
SEM picture of gas atomised 17-4PH powder <math><20\ \mu\text{m}</math> (Courtesy of Sandvik Osprey Ltd)

### 3.2.2 The VIM gas atomization process

In the VIM gas atomization process, the melting takes place in a vacuum chamber. This process is recommended for superalloys so as to avoid in particular oxygen pick-up when working with alloys with reactive elements such as Ti and Al.



Sketch of the VIM gas atomization process (Courtesy Erasteel)

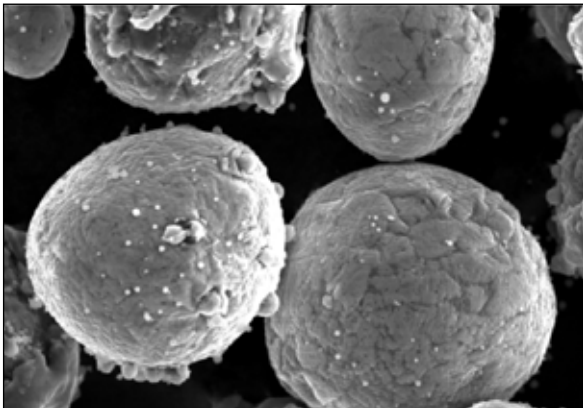


SEM picture of VIM gas atomised Pearl® Micro Ni718 powder (Courtesy of Erasteel)

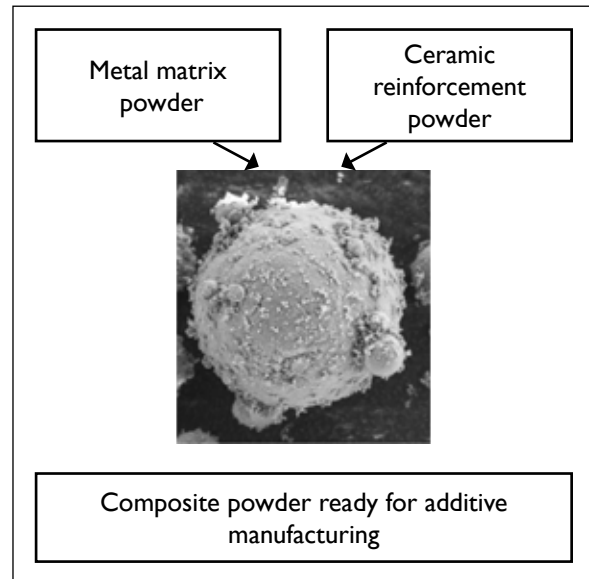
### 3.2.3 Other powder manufacturing processes

Some other powder manufacturing processes are used for specific alloys such as :

- Plasma atomization and spheroidization consists of in-flight heating and melting thanks to a plasma torch of feed material followed by cooling and solidification under controlled conditions. Depending on processes, the raw material can be particles as well as bar or wire feedstock. Plasma atomization can be used in particular to spheroidise refractory metals such as Mo alloys, W and WC.
- Centrifugal atomization, also known as plasma rotating electrode process, consists in melting with a plasma torch the end of a bar feedstock rotating at high speed and thus ejecting centrifugally the molten droplets of metal
- Powder blending and mechanical alloying, to produce Metal Matrix Composites (MMCs)



SEM picture of gas atomized Elektron® MAP+ magnesium powders (Courtesy of Magnesium Elektron)



Innovative Metal Matrix Composite AlSiMg powder for additive manufacturing , reinforced with micronized SiC or nanosized  $MgAl_2O_4$ . (Courtesy of IIT Istituto Italiano di Tecnologia Politecnico di Torino - DISAT)

### 3.3 Metal powder characteristics for additive manufacturing

Key metal powder characteristics for additive manufacturing can be sorted in four main categories:

- Chemical composition
- Powder size distribution (PSD)
- Morphology
- Physical properties

In all cases, there are several useful existing standards to determine methods for characterizing metal powders.

- Additional points are important to consider when selecting metal powders for additive manufacturing processes:
- Storage and aging of powders
- Reusability of powder after additive manufacturing cycles
- Health, safety and environmental issues

### 3.3.1 Chemical composition

Regarding chemical composition, alloy elements and chosen measurement techniques (ICP, Spectrometry, etc.) are very important but it is also important to take into account:

- interstitials, such as Oxygen, Nitrogen, Carbon and Sulfur, to measure by combustion and fusion techniques
- as well as trace elements and impurities, as they may affect significantly material properties depending on alloys.

With the gas atomization process, all powder particles have the same chemical composition but finer particles tend to have a higher oxygen content due to the higher specific surface.

The chemical composition will influence in particular:

- Melting temperature
- Mechanical properties
- Weldability
- Thermal properties (thermal conductivity, Heat capacity etc.)
- Etc.

Last, the chemical composition can also evolve slightly after multiple uses in additive manufacturing machines.

### 3.3.2 Particle size distribution

Depending on additive manufacturing technology and equipment, two main types of particle size distributions are considered:

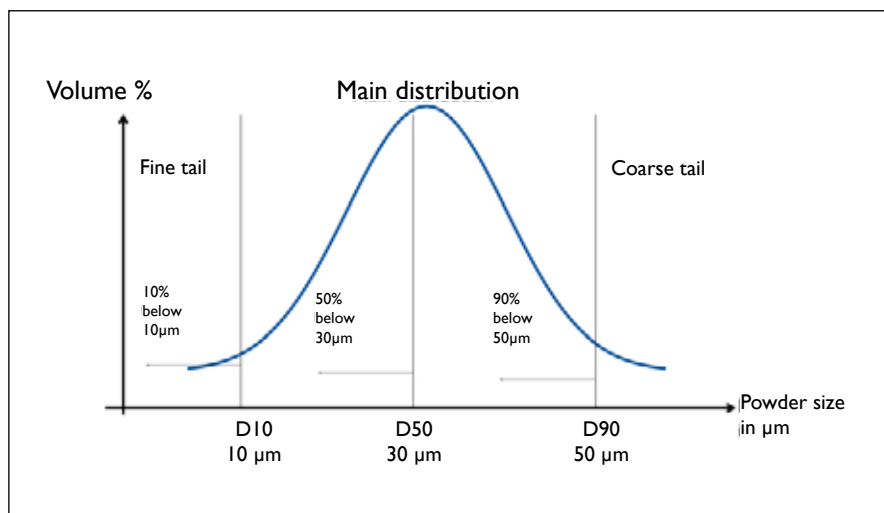
- powders usually below 50 microns for most powder bed systems. In this case, finer powder particles below 10 or 20 microns shall be avoided, as they are detrimental to the powder flowability.
- powder between 50 and 100 to 150  $\mu\text{m}$  for EBM and LMD technologies.

The Particle Size Distribution (PSD) is an index indicating what sizes of particles are present in what proportions i.e. the relative particle amount as a percentage of volume where the total amount of particles is 100 %) in the sample particle group to be measured.

The frequency distribution indicates in percentage the amounts of particles existing in respective particle size intervals whereas cumulative distribution expresses the percentage of the amounts of particles of a specific particle size or below. Alternatively, cumulative distribution expresses the percentage of the amounts of particles below a certain size.

A common approach to define the distribution width is to refer to three values on the x-axis (volume %):

- the D10 i.e. the size where 10 percent of the population lies below D10
- the D50, or median, ie the size where 50 percent of the population lies below D50
- the D90, ie the size where 90 percent of the population lies below D90



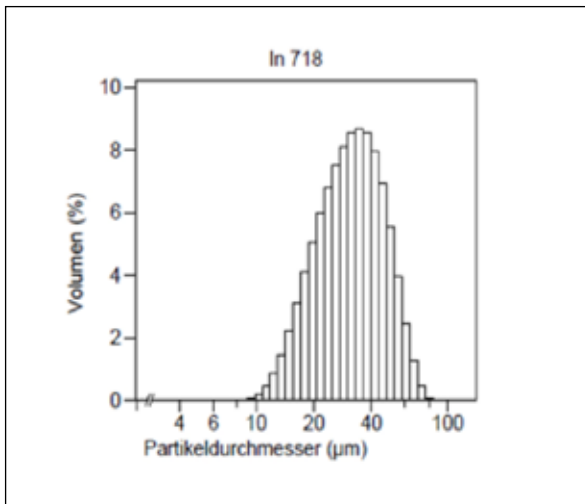
Example of D10, D50 and D90 on a PSD curve for a 10-50 microns powder

Powder sampling is also an important point due to the powder segregation (applicable standard ASTM B215)

Usual methods and standards for particle size distribution measurement are:

- ISO 4497 Metallic Powders, Determination of Particle Size by Dry Sieving (or ASTM B214 Test Method for Sieve Analysis of Metal Powders)
- ISO 13320 Particle Size Analysis – Laser Diffraction Methods (or ASTM B822 Test Method for Particle Size Distribution of Metal Powders and Related Compounds by Light Scattering).

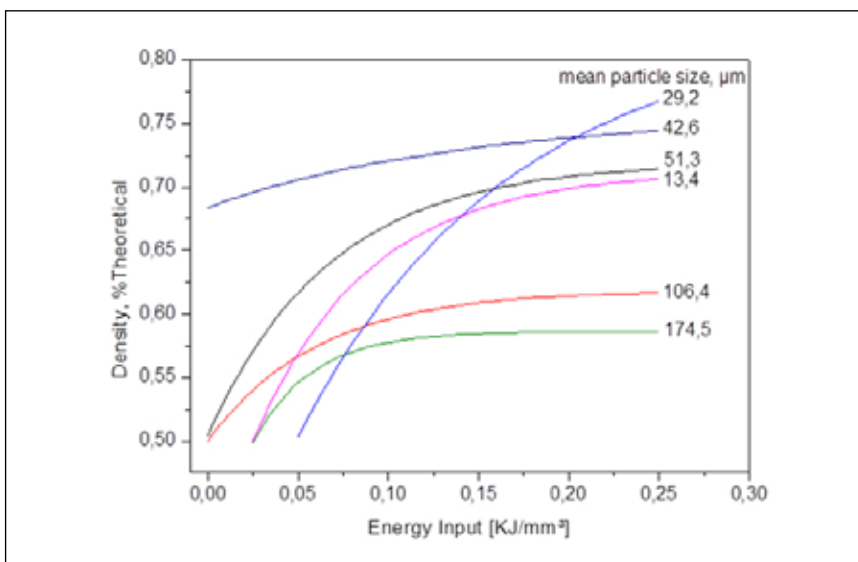
It is important to note that the PSD results will be dependent of the chosen test methods, which can provide different results in particular depending on powder morphologies.



Example of PSD curve by laser diffraction for In718 powders (Courtesy of Fraunhofer IFAM)

The particle size distribution is a major point in additive manufacturing as it can influence many aspects such as:

- Powder flowability and ability to spread evenly
- Powder bed density
- Energy input needed to melt the powder grains
- Surface roughness
- Etc.



Energy input and powder density as a function of mean particle size (Courtesy of Fraunhofer IFAM)



### 3.3.3 Powder morphology

The recommended particle morphology for additive manufacturing is spherical shape because it is beneficial for powder flowability and also to help forming uniform powder layers in powder bed systems.

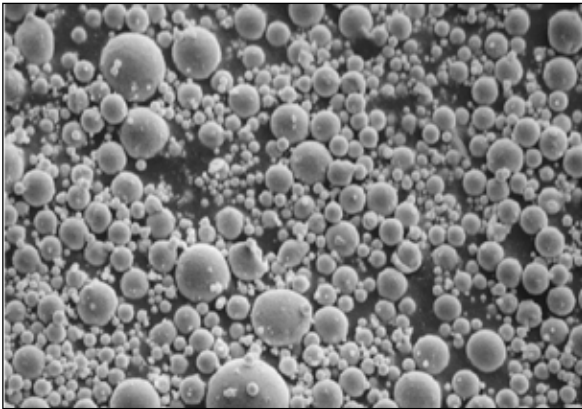
The powder morphology can be observed by SEM (Scanning Electron Microscope).

Typical defects to be controlled and minimized are:

- irregular powder shapes such as elongated particles
- satellites which are small powder grains stuck on the surface of bigger grains
- hollow powder particles, with open or closed porosity.

Porosity content can be evaluated either by SEM observation or by Helium Pycnometry. The presence of excessive amounts of large pores or pores with entrapped gas can affect material properties.

Applicable standard: ASTM B923 Test Method for Metal Powder Skeletal Density by Helium or Nitrogen Pycnometry.



SEM picture of gas atomized stainless powder <20 microns  
(Courtesy of Nanoval)

### 3.3.4 Other powder physical properties

Rheological properties are very important for metal powders used in additive manufacturing equipment, both for powder handling from powder container to working area and in the case of powder bed systems to form uniform layers of powders.

Rheology is a complex matter but some standard test methods are available, though not always fully appropriate for the particle sizes typical of additive manufacturing systems:

- Density (apparent or tap)
- Flow rate
- Angle of repose
- Etc.

Applicable standards:

- ISO 3923, Metallic powders — Determination of apparent density or ASTM B212 Test Method for Apparent Density of Free-Flowing Metal Powders Using the Hall Flowmeter Funnel
- ISO 3953, Metallic powders — Determination of tap density or ASTM B527 Test Method for Determination of Tap Density of Metallic Powders and Compounds
- ASTM B213 Test Methods for Flow Rate of Metal Powders Using the Hall Flowmeter Funnel
- ISO 4324, Powders and granules — Measurement of the angle of repose

### 3.3.5 Other powder characteristics

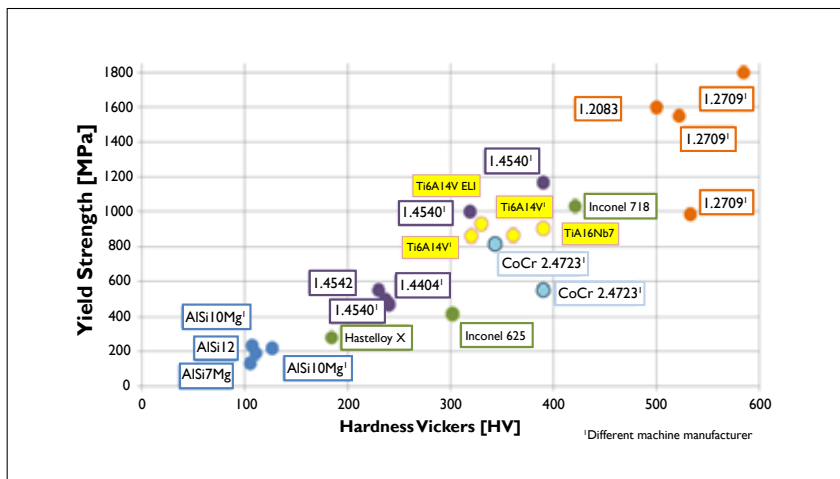
- Powder storage, handling and aging . For almost all alloys, shielding gas, the control of hygrometry and temperature is important and strongly recommended.
- Powder reusability, i.e. the definition of conditions of re-use of unused powders after additive manufacturing cycles (sieving of agglomerates, control, number of re-use etc.)
- Health, safety and environmental issues

### 3.4.1 Introduction

The material properties obtained with additive manufacturing processes are unique and specific of these technologies, due to the small melting pool and rapid solidification.

Mechanical properties of parts produced by additive manufacturing are usually:

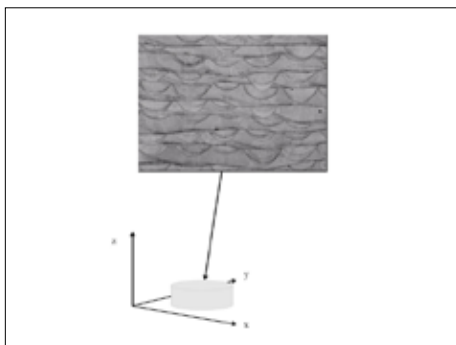
- superior to the properties obtained with investment casting process
- inferior or sometimes close to the conventional wrought part.



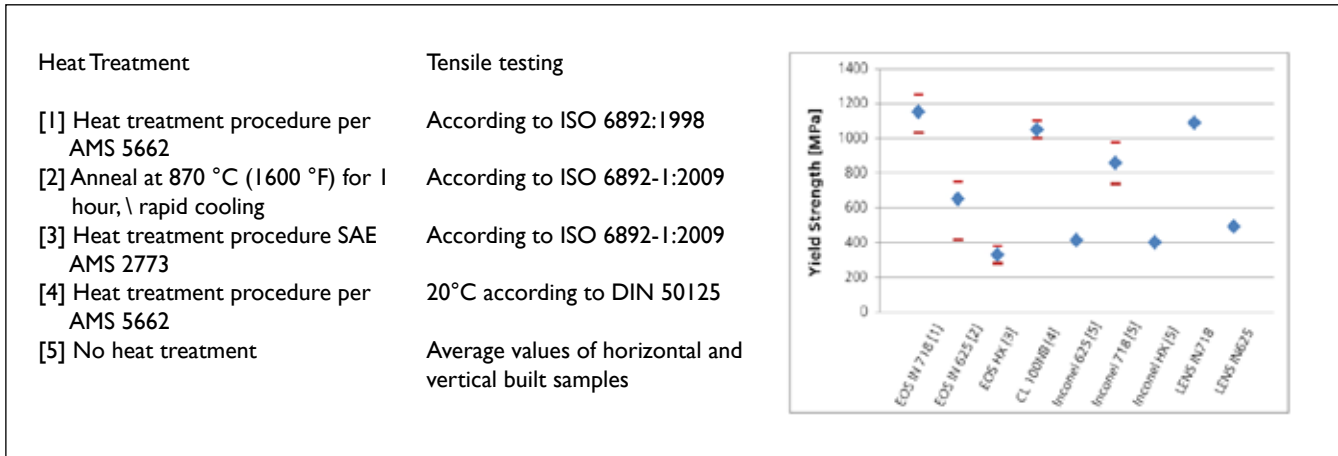
Hardness and Yield strength for various materials produced by powder bed additive manufacturing technologies (Courtesy of Fraunhofer IFAM)

**Key features of materials produced by additive manufacturing are:**

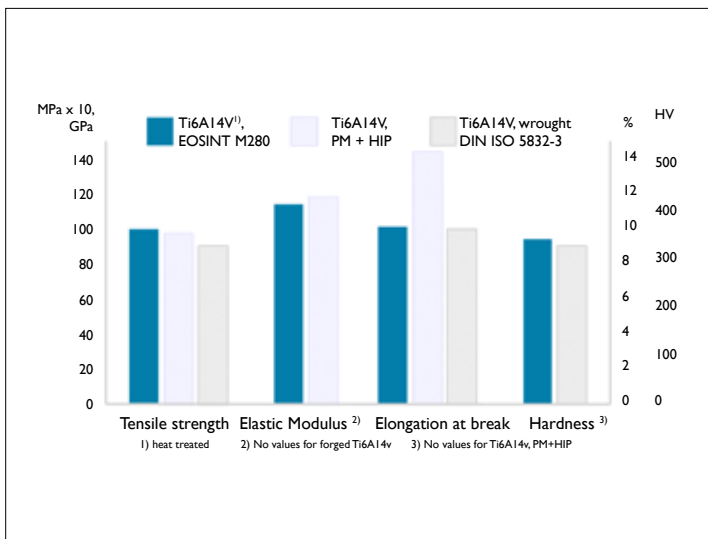
- The fine microstructure, due to the very rapid solidification process
- A slight anisotropy in Z direction, which induces slightly lower mechanical properties due to the superposition of layers. Anisotropy can be avoided in X and Y directions by using an adapted laser strategy.
- A few small residual porosities, in particular below the surface. However, densities of 99.9% are commonly reached with additive manufacturing processes. To achieve full density, post processing by HIP can be done, like for parts made by investment casting.



Microstructure of material produced by laser beam melting



Yield strength for various Ni base materials by SLM and LMD (Courtesy of Fraunhofer IFAM)

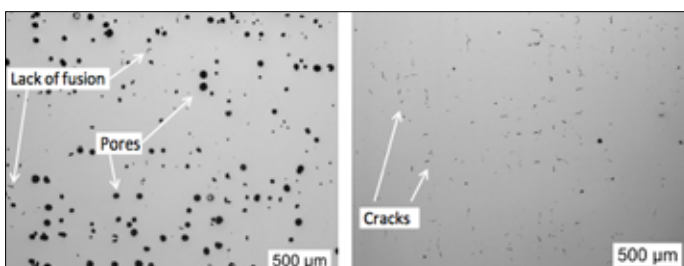


Mechanical properties for Ti6Al4V materials by SLM, SLM+HIP and wrought (Courtesy of Fraunhofer IFAM)

### 3.4.2 Specific defects in materials obtained with additive manufacturing process

In case of incorrect process parameters, build strategy, part orientation or insufficient powder quality, some typical defects can be observed:

- Unmolten powder particles
- Lacks of fusion
- Pores
- Cracks
- Inclusions
- Residual stresses
- Poor surface roughness.



Defects that can be found and shall be avoided in parts manufactured by SLM technology (Courtesy of IK4 Lortek)

### 3.4.3 How to optimize process parameters to improve material properties?

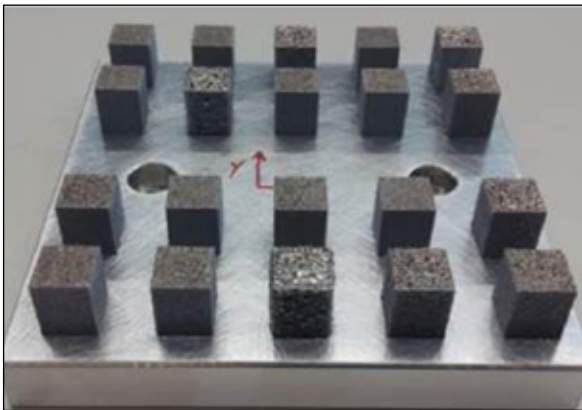
To achieve high mechanical strength and adequate fatigue behaviour, it is important to produce high density parts with optimal surface quality and to minimize defects, through the optimization of process parameters. In this way, a working window is obtained with a define set of laser parameters where parts with high densities and low roughness are guaranteed.

In laser processes, the Energy density (E) is a key factor:

- sufficient energy density is needed to melt powder particles of the layer being processed and of the previous layer to assure a correct joining between successive layers and avoid lacks of fusion and porosity.
- excessive energy can cause vaporization of the material creating defects and reducing material density.

The optimization of parameters shall be done both for the interior of the part and for the borders, where a good balance of minimized defects in the sub-surface and low roughness is pursued.

To optimize parameters, it is a common practice to manufacture simple geometries like cubes maintaining constant the power and varying the scanning speed in each cube, for a given layer thickness and hatch spacing. Thus, each cube is manufactured with different energy density. Afterwards, the cubes are characterized where interior density, sub-surface density and roughness are determined, so as to identify the right energy density window and corresponding parameters



Test cubes (Courtesy of IK4 Lortek)

$$E = \frac{P}{v \cdot h \cdot t}$$

E = energy density

P = power (W)

v = scanning speed (mm/s)

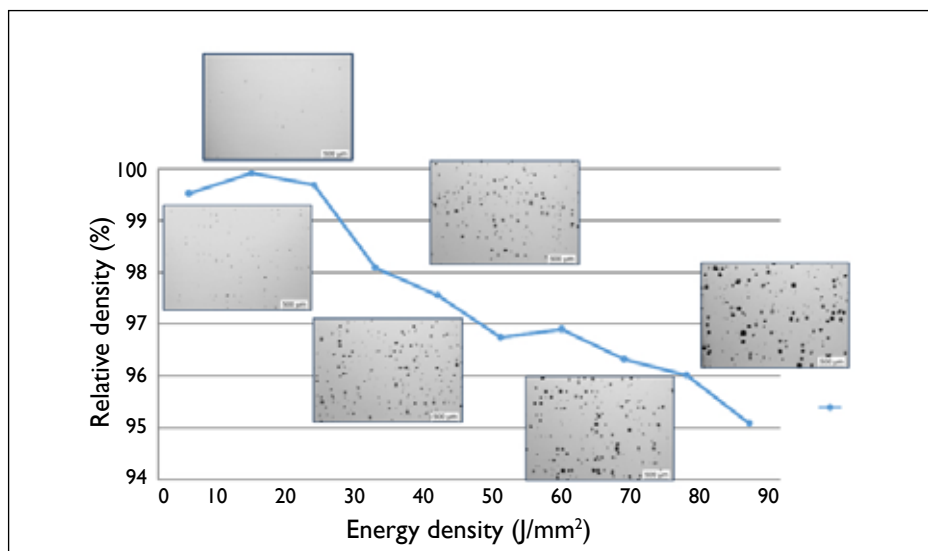
h = hatch spacing (mm)

t = layer thickness (mm)

The example below with different laser parameters for H13 steel, shows that at lowest energy densities lacks of fusion and pores are generated.

When increasing the energy density the amount of porosity is increased considerably.

The optimum energy density to achieve highest density is around 78 J/mm<sup>3</sup>.



Evolution of relative density of H13 with energy density and the obtained micrographs (Courtesy of IK4 Lortek)

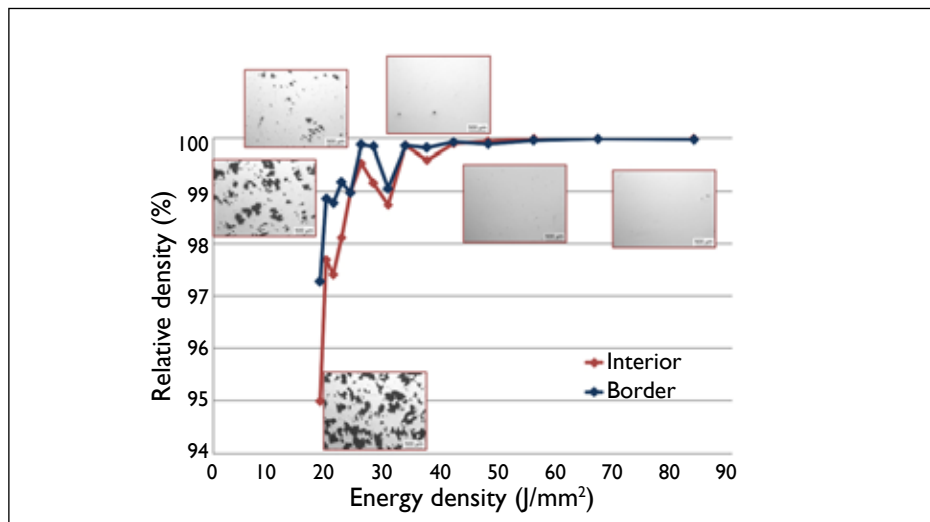
The second example below with different laser parameters on a SLM machine for Ti6Al4V was achieved to optimize them both for interior and borders.

Here, both interior and borders are practically free of defects when  $40 \text{ J/mm}^3$  energy density is surpassed.

In addition, not only the number of pores varies with energy density, but also the morphology of defects is different.

At low energy densities where the scanning speed is high, huge ( $> 100 \text{ }\mu\text{m}$ ) and irregular defects are found in the samples due to partial melting of the particles which induces a defective powder deposition.

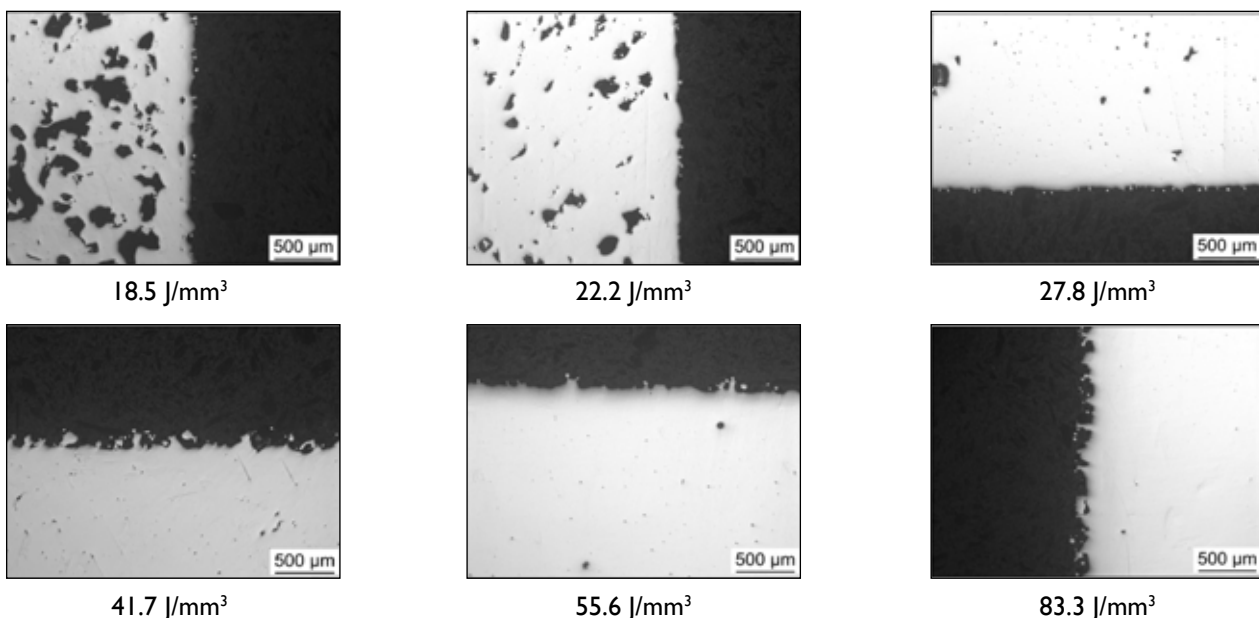
At high energy densities with low scanning speeds, the pores are spherical and small ( $< 100 \text{ }\mu\text{m}$ ) due to gases trapped in the melt pool.



Relative density vs energy density applied in the optimization process for Ti6Al4V and the obtained micrographs for the interior of the cubes on a SLM machine (Courtesy of IK4 Lortek)

The defect and material density analyses were completed with roughness measurements. The lowest roughness values ( $\sim 10\text{-}12 \text{ }\mu\text{m}$ ) ensuring improved surface quality, are obtained at low energy densities ( $< 30 \text{ J/mm}^3$ ). However, in these conditions the sub-surface porosity is too high. Increasing slightly the energy density up to  $30 \text{ J/mm}^3$  the roughness is still low and pores in the subsurface are reduced significantly.

At higher energy densities, although the number of pores is minimal near the surface, the roughness gets worse. It can be concluded in this example that energy densities superior to  $40 \text{ J/mm}^3$  are necessary to obtain parts with 99.7-99.9% relative density, whereas an energy density of  $30 \text{ J/mm}^3$  is enough to have both improved surface quality and minimized defects in borders.



Appearance of borders of the Ti6Al4V cubes for different energy densities (Courtesy of IK4 Lortek)

## 4. DESIGN GUIDELINES FOR LASER BEAM MELTING

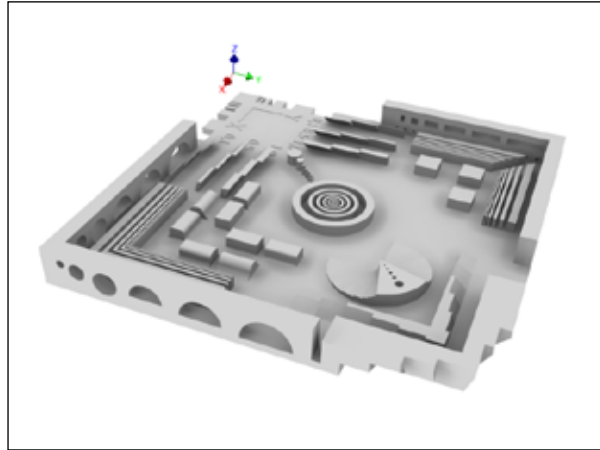
### 4.1 Basic design rules

These design guidelines are relevant only for laser beam melting (i.e selective laser melting) and not for EBM nor for LMD.

AM technologies offer unique possibilities regarding part design and possible geometries.

The example of platform below is useful to help evaluating the machine capability for many geometrical features such as:

- Min. wall thickness
- Min. hole diameter
- Max. arch radius
- Max. channel diameter/ channel length
- Min. strut diameter
- Min. gap distance
- Reproducibility
- Geometrical accuracy
- Surface roughness vs. overhang angle

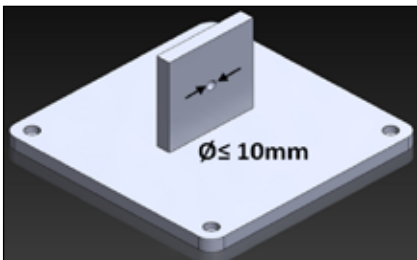


Platform of various standard geometrical elements to evaluate machine capability and parameters (Courtesy of Fraunhofer)

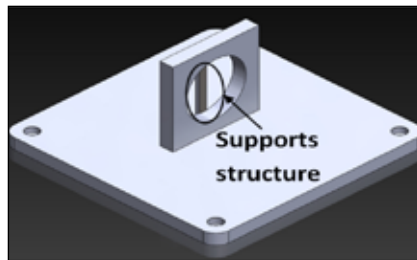
#### 4.1.1 Holes and internal channels

Recommended minimum standard hole size is currently 0.4mm. Holes and channels with a diameter below 10 mm usually do not require support structures. But for diameters above 10 mm, support structures are needed, which can be difficult to remove in the case of non linear channels. To avoid support structures in this case, a possible option is to modify the channel profile, as can be seen below with the example below of an ellipse profile minimising overhang area.

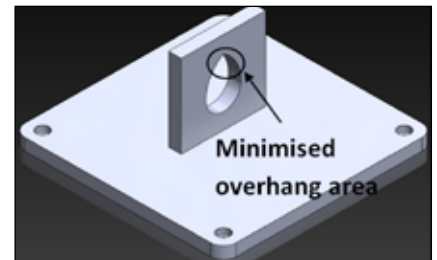
Another approach can be to integrate functionally the supports so as to avoid removing them.



Round hole without support structure (Courtesy of Renishaw)



Round hole above 10 mm with support structure (Courtesy of Renishaw)

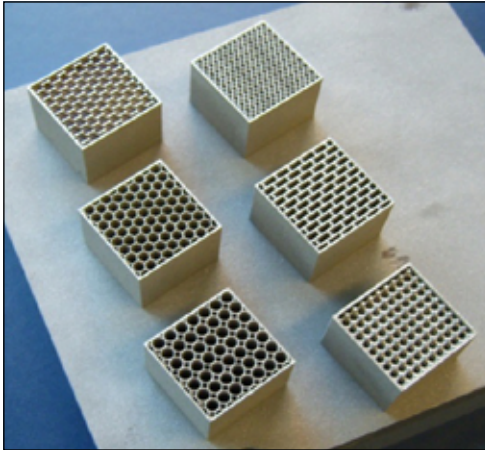


Ellipse profile to avoid support structures (Courtesy of Renishaw)

### 4.1.2 Minimum wall thicknesses

Recommended minimum wall thickness is usually 0.2 mm. But it can vary depending on machine, powder used and material. If wall sections are too thin or not supported, then there is a chance of buckling in the surface as can be seen on the example of a Ni718 manifold below.

The part is fully dense but due to the large part diameter of what the 200 micron thick wall section cannot support itself. In this case, the wall section needs to be thickened to avoid buckling effect.



Cubes with thin wall thicknesses  
(Courtesy of Fraunhofer IFAM)



Ni718 manifold showing buckling effect  
due to too thin walls (Courtesy of Renishaw)

### 4.1.3 Maximum length-to-height ratio

The length-to-height ratio shall usually not exceed 8:1.

In the example of bike frame component below, the length-to-height ratio was too great. In a second iteration, a lattice support structure was installed to avoid part distortion.

But if the part has a reasonable section or supporting geometry, then it is possible to build at a higher width-to-height as can be seen in the example below.



Bike frame component showing buckling effect  
due to too high length to height ratio.  
(Courtesy of Renishaw)

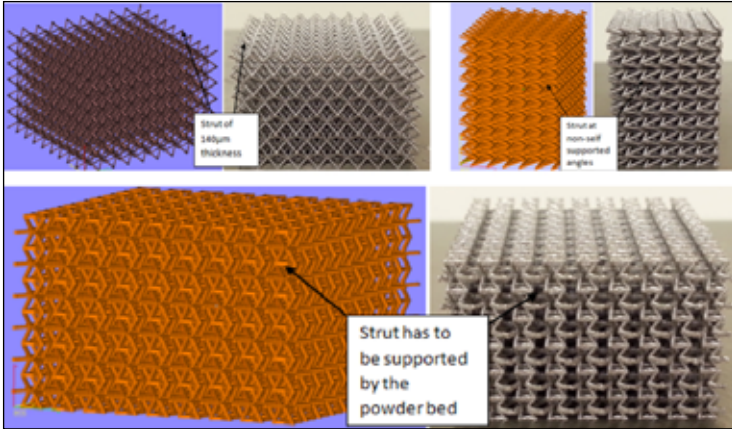


Parts with high length-to-height ratio  
(Courtesy of Renishaw)

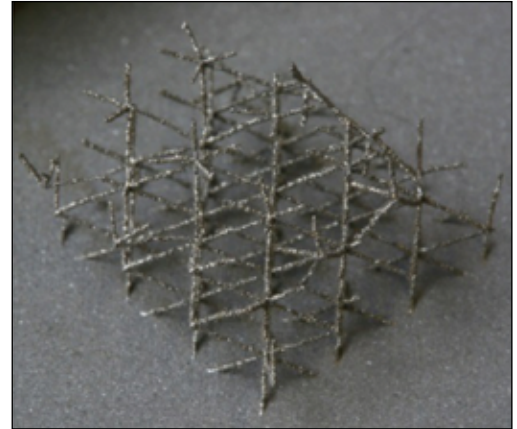
#### 4.1.4 Minimum strut diameter and lattice structures

Minimum strut diameter is usually 0.15 mm. Thanks to this unique design possibility offered by powder bed AM technologies, complex lattice structures can be achieved, impossible to produce by any other technologies.

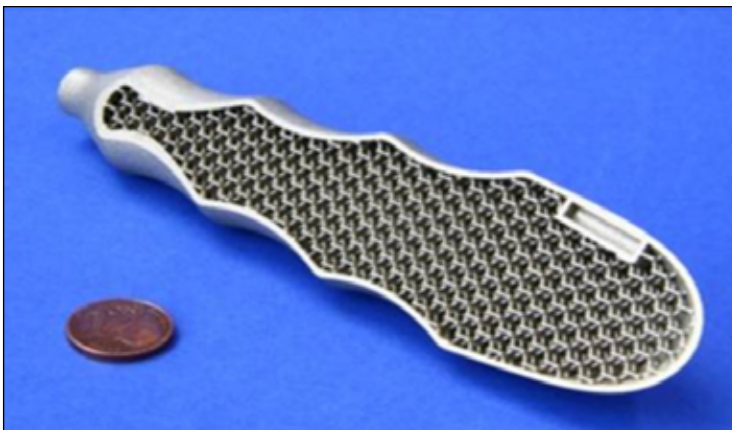
Lattice structures offer the major advantage of reducing part weight without reducing part strength, which is very important in industries such as aerospace and transportation.



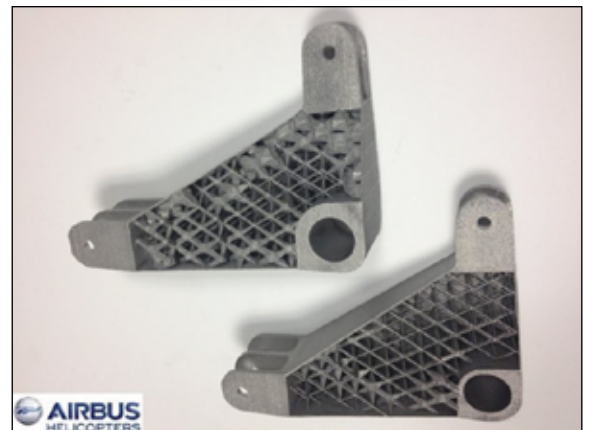
Examples of lattice structures (Courtesy of Renishaw)



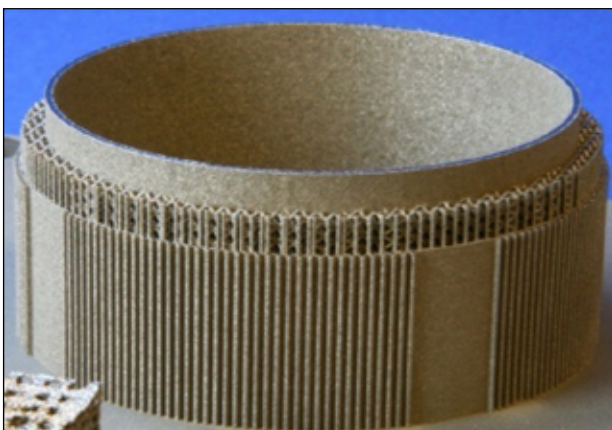
Structure with 0.15 mm strut diameter (Courtesy of Fraunhofer IFAM)



Lightweight handle with internal lattice structure (Courtesy of Fraunhofer IFAM)



Lattice structure for mass reduction (Courtesy of Airbus Helicopter and Poly-Shape)



Prototype of heat exchanger for electrical motor with struts of 0.4 mm diameter for COMPOLIGHT project (Courtesy of Fraunhofer IFAM)



## 4.2 Part orientation

The orientation of parts in the powder bed is a key point of attention both for quality and cost. Indeed, part orientation influences the build time, the quantity of supports, the surface roughness and residual stresses.

Finding the best suitable part orientation helps achieving:

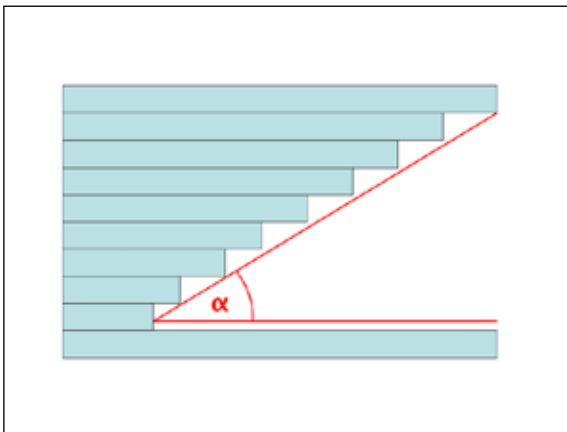
- the shortest build time ie minimizing the number of layers and part height
- the minimal amount of supports
- an easy access to supports so that they can be easily removed
- the best possible surface roughness and minimal staircase effect
- the minimum level of residual stresses which can lead to part distortion

### 4.2.1 Overhangs

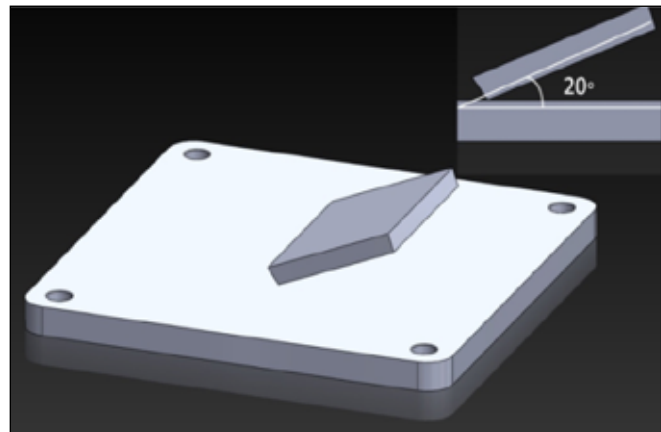
An important rule when building part layer by layer is to avoid having a too low overhang angle because each new welding seam must be supported at least partly by the previous welding seam in the previous layer. When the angle between the part and the build platform is below  $45^\circ$ , support structures are needed to avoid poor surface roughness as well as distortion and warping leading to build failure as can be seen on the photo below.

The poor surface roughness is the result of building directly onto the loose powder instead of using the support structure as a building scaffold. In this case the area melted at the focal point cools very quickly and the stress generated curls the material upwards. Supports would act as an anchor to the build plate tying parts down to the plate in order to avoid upward curl. Besides, the very poor surface consists of melted and partially melted/sintered powder because the laser penetrates the powder bed and starts to agglomerate loose powder particles surrounding the focal point instead of dissipating the excessive heat through the support structure.

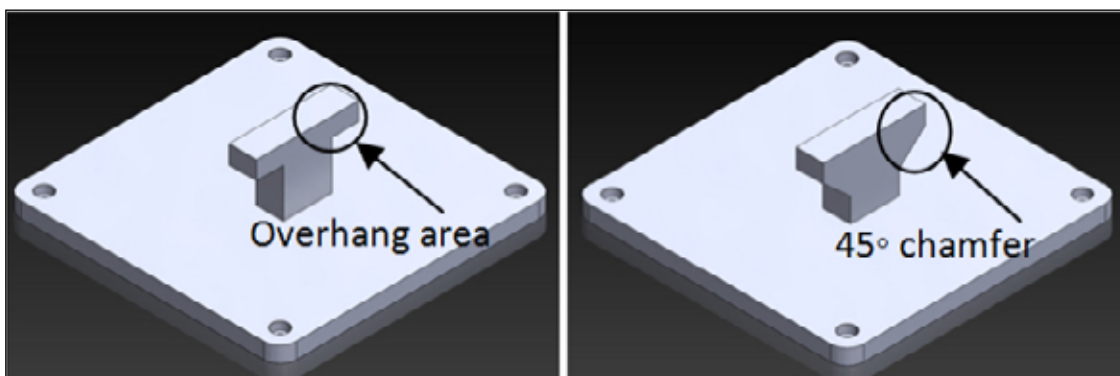
The warping and curled area can also cause build failure if higher than the desired profile because it prevents spreading a new layer of powder.



Overhang angle between build platform and part



With overhang angle below  $45^\circ$ , poor surface roughness and part distortion can cause build failure (Courtesy of Renishaw)



In case of angles of  $90^\circ$ , a solution to avoid supports is to create a  $45^\circ$  chamfer (Courtesy of Renishaw)

### 4.2.2 Supports

Support structures have several functions:

- support the part in case of overhangs,
- strengthen and fix the part to the building platform,
- conduct excess heat away,
- prevent warping or complete build failure.

Besides, optimised supports shall be easy to remove mechanically and have a minimal weight. The position and the orientation of the part on the build platform have a significant impact on the need and nature of support structures, hence on the quality of the built and the post-processing operations.

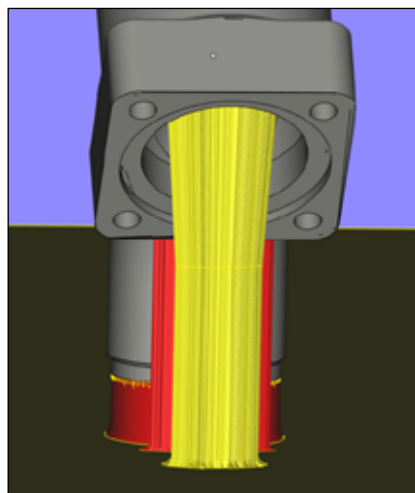
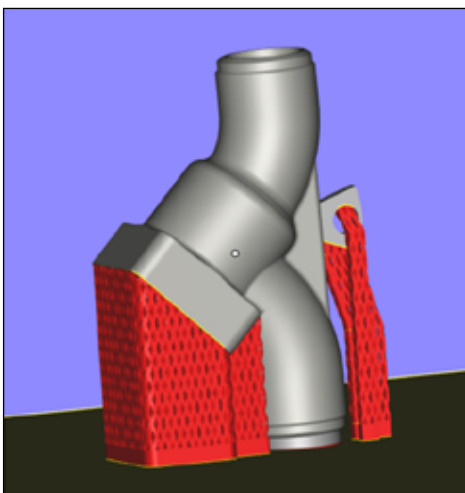
Below are some examples of different support structures on a simple part, based on different part positions and orientations. In some cases, removing the supports can be impossible, even though it is the best option in terms of processing. Besides, many designs of support structures are possible.



*Different part positions and orientations and their influence on the location and importance of support structures (Courtesy of Spartacus 3D)*



*Supports for dental parts (Courtesy of Bego Medical)*



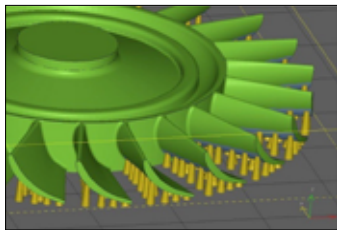
*Design of supports with Magics software (Courtesy of Materialise)*

The design of supports shall be optimized to achieve above functions and shall also to be easy to remove mechanically after the laser beam melting operation.

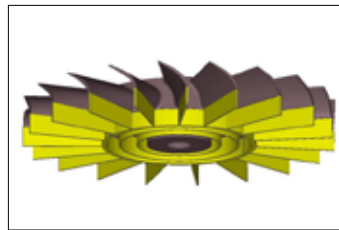
In the impeller example below by Fraunhofer IFAM, two support designs have been evaluated:

- tree supports with many struts
- wall supports with one wall for each blade

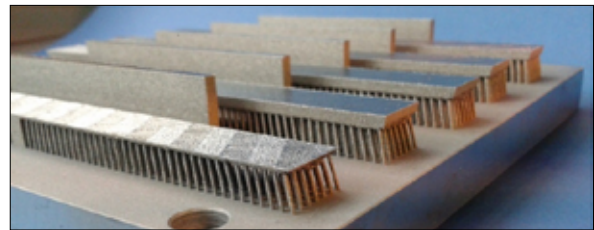
In this example, the wall support proved better both for post processing and for improved stability during manufacture.



Tree support design  
(Courtesy of Fraunhofer IFAM)



Wall support design  
(Courtesy of Fraunhofer IFAM)



Distortion of tree supports  
(Courtesy of Fraunhofer IFAM)

### 4.2.3 Surface roughness

With laser beam melting, achievable surface roughness (Rz) are usually between 25 and 40  $\mu\text{m}$  in as built state. Polishing helps reaching much lower values as can be seen on the table below. But important to remember is that part design complexity may affect its ability to be polished efficiently.



Polished aerospace fuel swirler  
(Courtesy of EOS)

Achievable roughness average Rz in $\mu\text{m}$																					
	0.04	0.06	0.10	0.16	0.25	0.40	0.63	1.0	1.6	2.5	4.0	6.3	10	16	25	40	63	100	160	250	
Turning																					
Milling																					
Polishing																					
SLM - as built																					
SLM - after shot - peening																					
SLM - after polishing																					

Average Range  
Less Frequent Range

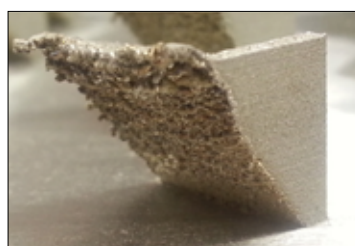
Standard roughness of parts made by SLM versus machining  
(Courtesy of Hoischen "Technisches Zeichnen" and EOS)

### Typical surface defects to be avoided are:

- The staircase effect, which can be observed on curved surface and is more pronounced when the surface angle increases vs. vertical axis.
- Poor down-skin surface roughness and decreased dimension accuracy, which is linked primarily to the fact that the heat generated by the laser beam does not evacuate quickly on down-facing surfaces



Staircase effect (Courtesy of Fraunhofer IFAM)

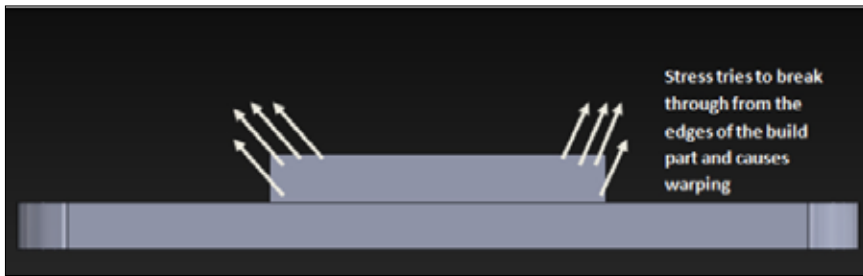


Poor down-skin surface roughness (Courtesy of Renishaw)

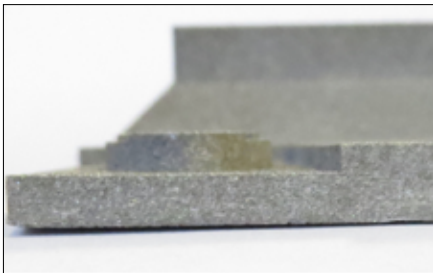
## 4.2.4 Thermal stress and warping

Warping is due to thermal stresses caused by the rapid solidification.

Warping can lead to part distortion, bad junctions between supports and components or recoating problems.



Effect of stress on build part (Courtesy of Renishaw)



Part distortion due to residual stresses (Courtesy of Renishaw)



Part distortion due to residual stresses leading to the separation of part from supports (Courtesy of Renishaw)

## 4.3 Design optimization for AM technology

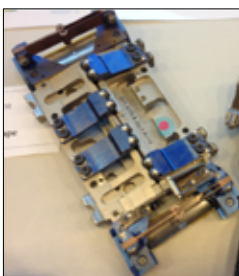
### 4.3.1 Introduction

To take full advantage of AM design possibilities, it is important to redesign conventional parts. Design optimisation can be done in several directions:

- Reduce the total number of parts
- Design for functionality
- Design parts to be multifunctional
- Lightweight
- Topological optimisation
- Design for ease of fabrication.

The example below shows a redesign case study of a solar panel deployer for satellites aiming at reducing drastically the number of parts and total weight.

The initial design manufactured by conventional technology is a mechanical assembly of 25 separate parts. The systemic approach of DFAM led to a patented 3 parts solution which provides not only a reduction of part number but also of the weight (5 times lighter) and size of the assembly.



Solar panel deployer for satellite made by SLM in 3 parts (right) vs 25 parts (left) with conventional manufacturing (Courtesy Thales Alenia Space and Poly-Shape)

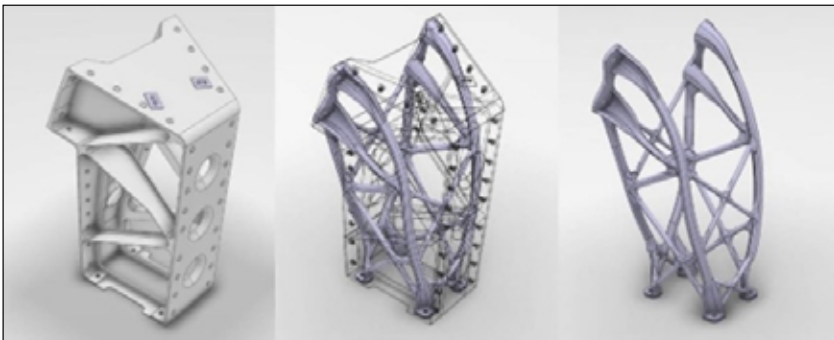
### 4.3.2 Topology optimisation

To take into account all AM design possibilities and limitations, the first step is to reduce the part into its basic functional requirements (such as functional surfaces, load-case, etc.). This step allows the designer to only focus on the requirements and prevents him from limiting his design, hence maximizing the possible improvements. This can be especially interesting when dealing with assemblies (or even entire products).

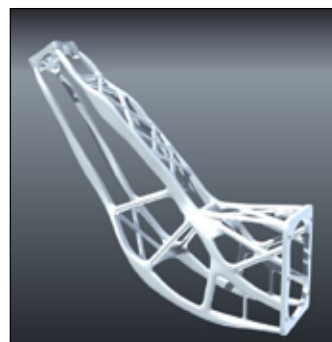
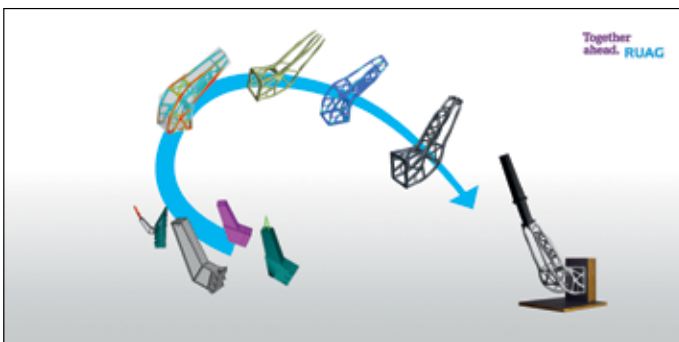
From the functional requirements, the minimal volume of material is then placed in order to link the surfaces and to sustain the load case (be it mechanical, thermal, coupled, etc). This second step is usually achieved by using topology optimisation tools that suggest geometries able to sustain the loads while keeping the volume to a minimum.

The last step is to redesign the optimized volume in order to cope with the manufacturing constraints (such as angular orientation, machine dimensions, machining allowances, etc).

The examples below show case studies of redesign based on topology optimisation.

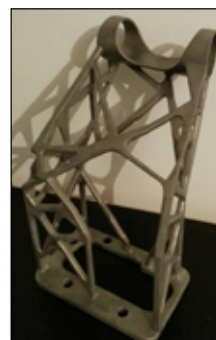
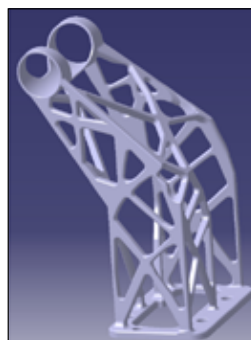
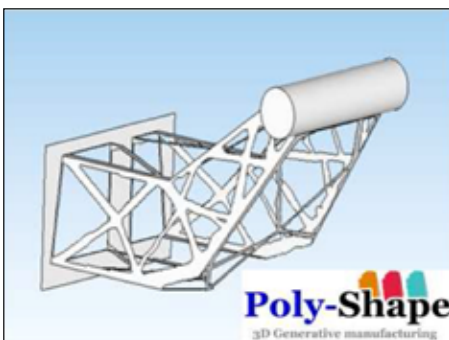


Satellite bracket redesigned for additive manufacturing with topology optimisation (Courtesy of Airbus Defense & Space and Poly-Shape)



Satellite component redesigned by topology optimisation for additive manufacturing (Courtesy of RUAG and Altair)

Since Topology Optimization leads to noisy geometries, caused by tessellation, it is usually necessary to implement model reconstruction and smoothing as can be seen in figures below. This step can be very time-consuming, especially if the load cases that were used during the optimisation are very specific and do not take into account some steps of the product life cycle (such as machining which can require high rigidity).



Satellite bracket redesigned for additive manufacturing with topology optimisation: left after topology optimisation, middle after smoothing and right after manufacturing (Courtesy of Poly-Shape)

## 5. CASE STUDIES



Courtesy: MTU Aero Engines

### 5.1 Aerospace

#### Borescope bosses for A320neo Geared Turbofan™ engine

- Industry user sector: Aerospace Industry
- Material: Nickel alloy 718
- Part dimensions: Volume: 15.600 mm<sup>3</sup>
- LxBxH Boundary Box: 42x72x36 mm
- Additive process used: Laser Beam Melting
- The bosses are made by selective laser melting (SLM) on an EOS machine.
- They form part of MTU's low-pressure turbine case and allow the blading to be inspected at specified intervals for wear and damage using a borescope.

#### Benefits of AM technology

- Series production of up to 2000 parts per year.
- Lower development production leadtimes and lower production costs.
- Suitable for producing parts in materials that are difficult to machine, as, for example, nickel alloys.
- For complex components that are extremely difficult, if not impossible to manufacture using conventional methods.
- Tool-free manufacturing and less material consumption.



Courtesy: Poly-Shape

#### Support to satellite antenna

- Industry user sector: Aerospace
- Material: Ti6Al4V
- Part height and weight: 380 mm, 3.3 kg
- Additive process used: Electron Beam Melting
- Part made by EBM with optimized design thanks to topology optimisation

#### Benefits of AM technology

- Weight reduction: 55%



Courtesy: RSC Engineering GmbH  
www.rsc-engineering.com

#### RSC Emission Rake

- Industry user sector: Aerospace / Experimental research
- Material: Inconel 718
- Part dimensions: 270 mm x 80 mm x 180 mm
- Part weight: 2.0 kg
- Additive process used: Laser Beam Melting
- The water cooled emission rake is placed into the exhaust duct of a high pressure combustion facility. It is used to sample hot exhaust gases using 6 sampling tubes and supplies the gas to an analyzing system. It can sample gas at temperatures of 2100°C and a maximum pressure of 45 bar. The part was produced on a laser cusing M2 machine by Concept Laser.

#### Benefits of AM technology

- Manufacturing of all components and details in one single step (fast manufacturing)
- Additional design freedom (individual cooling geometries, conical and helical sampling tubes,...)
- Cost saving up to 60% compared to a conventional manufactured rake for similar use



Courtesy: BeAM

### Repair of worn lips on a labyrinth seal

- Industry user sector: Aerospace
- Material: Nickel alloy 718, Nickel alloy 713, Waspaloy, Ti6242
- Additive process used: Laser Metal Deposition
- This engine's part is turning at 30 000 RPM. After 10 000 hours of flight, the different lips of the parts are worn and do not guarantee the efficiency of the seal. With the LMD process, it was possible to rebuild the different worn lips.

### Benefits of AM technology

- Repair of parts that were impossible to repair up to now
- Certification for 5 repair cycles : lifetime extended from 10 000 to 60 000 hours
- Material savings

## 5.2 Energy

### Burner repair

- Industry user sector: Energy
- Material: Nickel alloy HX
- Additive process used: Laser Beam Melting
- Customised EOSINT M 280 machine for precise, cost-effective, and faster repair of worn burner tips of gas turbines exposed to extreme temperatures.

### Benefits of AM technology

- Time required for the repair process of burner tips has fallen by more than 90%
- Old burner versions can quickly be brought up to the latest standards of technology
- Potential cost reductions already seen at an early stage



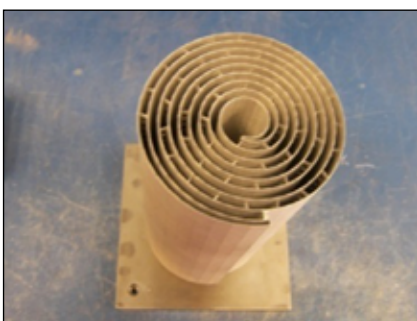
Courtesy: EOS, Siemens Industrial Turbomachinery AB

### Vacuum permeator

- Industry user sector: Energy (fusion), Science Industry
- Material: Stainless steel (AISI 316L)
- Part weight & dimensions: 2 kg, 10x10x20 cm
- Additive process used: Laser Beam Melting
- Part of a bigger system (designed and assembled by SENER) to demonstrate the possibility of tritium recovery in fusion reactors. Its manufacturing entailed various challenges: component dimensions, geometric changes along its section, metallurgical, file handling.

### Benefits of AM technology

- Geometry impossible to produce by conventional manufacturing process



Courtesy: IK4-LORTEK



Courtesy: Mercury Centre and School of Clinical Dentistry, University of Sheffield

## 5.3 Medical

### Removable Partial Denture (RPD) Framework

- Industry user sector: Dental
- Material: Cobalt Chrome (ASTM F75)
- Part dimensions: 60 x 30 x 0.5 mm, 15 g
- Additive process used: Laser Beam Melting
- The part is a metal framework for a removable partial denture (RPD). When fully assembled, the RPD is a denture for a partially edentulous dental patient. 3D data retrieved directly from the patient's mouth.

### Benefits of AM technology

- The conventional manufacturing of cast frameworks involves a lot of work and time
- AM is faster and has a high volume output, more accurate and parts have high strength.



Courtesy: 3D Systems

### Hearing aid

- Industry user sector: Biomedical
- Material: Ti6Al4V ELI (grade 23)
- Part height: 15 mm
- Additive process used: Laser Beam Melting

### Benefits of AM technology

- High accuracy
- High biocompatibility
- High mechanical resistance
- High flexibility of manufacturing



Courtesy: EOS GmbH, Alphaform and Novax DMA

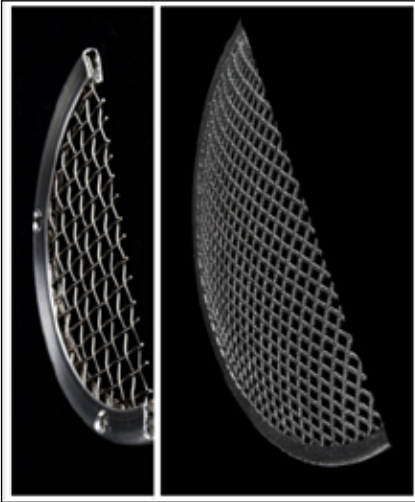
### Cranial implant

- Industry user sector: Medical
- Material: Titanium alloy
- Part dimensions: 12 x 8 cm
- Additive process used: Laser Beam Melting
- Development and manufacture of a customized and precision-fit implant with high permeability for liquids and perfect heat dissipation on an EOSINT M 280 machine

### Benefits of AM technology

- Implant is stable yet permeable for liquids because of its porosity of 95%
- lattice structures protect against heat and support in-growth of bone tissue





Courtesy: Croft Additive Manufacturing

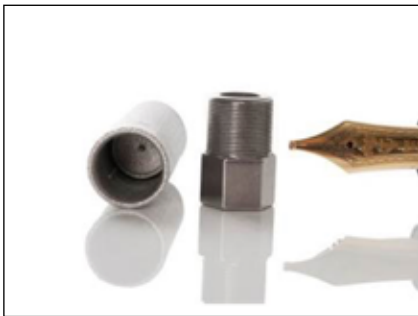
#### Cleanable Filter Disc

- Industry user sector: Medical Instruments
- Material: Stainless Steel 316L
- Part dimensions: Ø55mm
- Additive process used: Laser Beam Melting
- Traditional methods of creating filters often result in gaps between the securing steel ring and the mesh, as well as the weft and warp strands of the woven wire. Known as 'bugtraps', these can quickly gather bacteria and dirt.
- By using additive manufacturing, CAM removed these bugtraps from the design, meaning the filters can be cleaned much more easily, decreasing downtime for the customer, as well as the requirement for replacement parts.

#### Benefits of AM technology

- No recesses in part compared with conventional woven wire mesh equivalent
- Less contamination through particulate build up
- Easier to clean to a high standard, decreasing customer downtime and costs
- Design size can be easily altered to suit customer requirements, including a change in aperture size, without the creation of new tooling

### 5.4 Industry



Courtesy: Höganäs AB - Digital Metal®

#### Pressure sensor house

- Industry user sector: Industry Application
- Material: Stainless steel 316L
- Part dimensions: 50x12x12mm
- Additive process used: Precision inkjet on powder bed
- Pressure sensor house printed with membrane, threads and internal features for the electronics

#### Benefits of AM technology

- All machining operations joining and assembly where eliminated.
- Internal features that is hard to obtain with other technologies
- Design for service



Courtesy: The Mercury Centre

#### Tool insert for die casting

- Industry user sector: Die-casting
- Material: Stainless Steel 316L
- Part weight: 150g
- Additive process used: Laser Beam Melting
- Connector blocks used in the Gripple wire joining system are manufactured using die-casting, the internal cavities being formed by mould tool inserts. To facilitate the rapid evaluation of new design concepts, a series of tool inserts were manufactured using direct metal laser sintering, with up to 12 unique designs produced in a single build. Post build finishing was then performed to produce the surface finish required for the die-casting process. This dramatically reduced the lead times associated with obtaining tool inserts compared to traditional machining.

#### Benefits of AM technology

- The ability to make each insert different allowed many more designs to be evaluated.
- Quick turnaround times dramatically shortened the development programme



Courtesy: EOS GmbH and Innomia

**Tooling insert**

- Industry user sector: Tooling
- Material: Maraging Steel
- Part dimensions: 35 x 20 cm
- Additive process used: Laser Beam Melting
- Inserts with conformal cooling channels to produce arm-rests for cars, built on EOSINT M 270 machine. Optimize the cooling process to reduce the production cycle period, improve component quality and increase maintenance intervals.

**Benefits of AM technology**

- Production plant maintenance extended from every 2 weeks to every 5-6
- Uniform cooling prevents deformation of the plastic end product
- Costs are lowered through a 17% cut in cycle time



Courtesy: Metal Technology Co. Ltd.

**Conformal cooling channel in mold/nozzle etc.**

- Industry user sector: Moldmaking
- Material: Ti-6Al-4V
- Part dimensions: Outline : 80 mm dia. x 100 mm H
- Channel volume/length : approx. 5000 mm<sup>3</sup> / 1 meter L
- Additive process used: Laser Beam Melting
- Complicated cooling channel can be installed inside of parts by AM with 3D design data.

**Benefits of AM technology**

- Higher reproducibility of complicated cooling channel network inside of parts with utilizing of 3D design data
- Freedom in 3D design for cooling channel network in accordance with thermal loading in each location
- Flexible shape/dimension/location of cross section in cooling channel network design

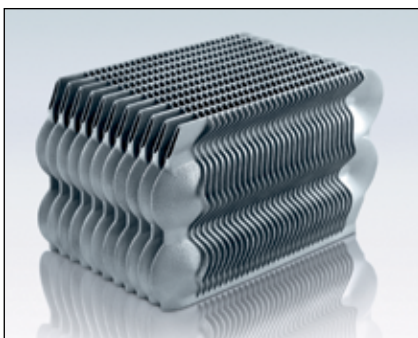
**5.5 Automotive and Car Racing**

**Prototype of heat exchanger**

- Industry user sector: Motor sport
- Material: Al Si 10Mg
- Additive process used: Laser Beam Melting
- New design with self supporting integrated cooling fins on outside surfaces and turbulators inside cooling tubes to disrupt the flow of the cooled fluid. Produced on an EOS M290 machine.

**Benefits of AM technology**

- Maximum heat transfer
- Compact and scalable design



Courtesy EOS and Within



Courtesy: Dash-CAE (design),  
The Mercury Centre (manufacture)

### FI Roll Hoop

- Industry user sector: Motorsport, F1
- Material: Ti6Al4V
- Part weight & dimensions: 2.6kg, 370mm long
- Additive process used: Electron Beam Melting
- The impact structure used to protect the driver in the event of roll over incident is traditionally made by investment casting. In order to meet stringent weight targets, material needs to be removed from low stressed regions. AM has the advantage of being able to produce these complex designs with a very short lead time. This novel design was produced by Dash-CAE and manufactured at the University of Sheffield's Mercury Centre. The part had to be sectioned such that it could fit within the build envelope of the AM process. These sections were then welded together and the completed hoop integrated into a chassis for testing.

### Benefits of AM technology

- The short lead times enabled the F1 team to swiftly take a new design concept through to manufacture and testing.
- Weight saving over castings due to more complex design.

## 5.6 Consumer goods



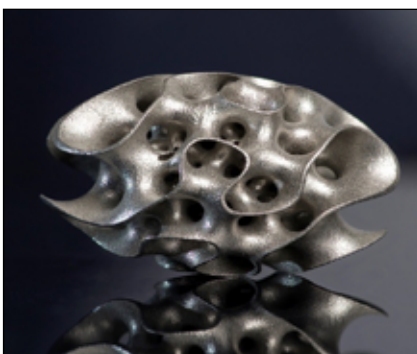
Courtesy: Progold S.p.A.

### Platinum hollow charms

- Industry user sector: Jewellery
- Material: 950 ‰ Platinum powder alloy
- Part dimensions: 31 parts of 2,8g each (2,4 g after polishing)
- Additive process used: Laser Beam Melting
- Platinum has always been difficult to use with casting. With SLM technique it's possible to match its fashion effect with the maximum freedom of shape, also preserving light weights to let it be affordable.

### Benefits of AM technology

- Hollow parts costs less than full parts made by cheaper material
- Maximum customization for exclusive jewellery
- Eco-friendly production process



Courtesy: Höganäs AB - Digital Metal®

### Rygo sculpture

- Industry user sector: Fashion & Design
- Material: Stainless Steel 316L
- Part dimensions: 25x25x30 mm
- Additive process used: Precision inkjet on powder bed
- Bathsheba Grossman is an artist recognized for her 3d printed art and sculptures. Not many of her complex designs can be produced in any other way than additive manufacturing

### Benefits of AM technology

- High level of resolution and surface quality
- Effective mass customization of designs
- Possible to achieve very thin walls and sections

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