Promoting Powder Metallurgy Technology

european powder metallurgy association

EPMA european powder metallurgy association

INTRODUCTION TO

ADDITIVE MANUFACTURING TECHNOLOGY

A guide for Designers and Engineers

Additive Manufacturing Technologies
Metal Powders for Additive Manufacturing
Design Guidelines
Case Studies

3rd Edition

www.epma.com/am

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EUROAM AN EPMA SECTORAL GROUP

Representing the European PM industry

european powder metallurgy association

EPMA european powder metallurgy association

European Additive Manufacturing Group

What is the European Additive Manufacturing Group?

The European Additive Manufacturing Group (EuroAM) launched in May 2013 is open to companies and organisations across the entire powder metallurgy supply chain. It's 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.

You will need to be an EPMA member to gain full access to all of the groups benefits including invitation only meetings. More information about **EuroAM** can be found at **www.epma.com/am**

(Courtesy of EOS)

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10 Reasons to join the EPMA

1. Enhance your market knowledge through access to unique industry information using our range of powder metal PM statistics, presentations and papers.
2. Improve your product development through access to EU and EPMA Member initiated R&D programmes.
3. Save money by receiving substantial discounts on attending and exhibiting at the leading annual Euro PM Congress and Exhibition and our series of training courses.
4. Obtain unique international access to government via our lobbying of the EU on key issues such as REACH, ISO standards and health and safety legislation.
5. Promote your sales through free advertising via an entry in the EPMA Members Directory on one of the world's most visited PM websites.
6. Keep updated on PM industry news and developments through the Email News service and the EPMA Newsletter – free to EPMA Members.
7. Develop your high-level networking opportunities through EPMA Sectoral Groups, training seminars and the general assembly.
8. Keep compliant with ISO 9001:2000 and ISO/TS 16949:2002 by participating in the EPMA Europe-Wide Benchmarking programme.
9. Access Member only content from a range of sources via the EPMA website Members Area.
10. Develop the market for your products by supporting promotion of PM technology via exhibitions and web-based information.

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Additive Manufacturing

Promoting Powder Metallurgy Technology

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EPMA would also like to thank the following organisations and companies for supplying images and content that have been used throughout this brochure:

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Atos
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GF Precicast Additive
Hirschvogel Tech Solutions
Höganäs AB – Digital Metal
IFW Leibniz University
IIT – Istituto Italiano di Tecnologia
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Thales Avionics Electrical Systems
The Mercury Center
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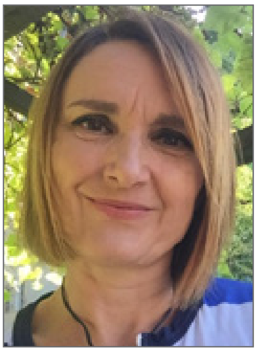


Adeline Riou

for their editorial input and to the EuroAM group members for their support.

Cover photos: Courtesy of Cell Core Gmbh, SLM Solutions and Cookson Gold.

1. INTRODUCTION

Additive manufacturing, also known as 3D printing, rapid prototyping or free-form 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.

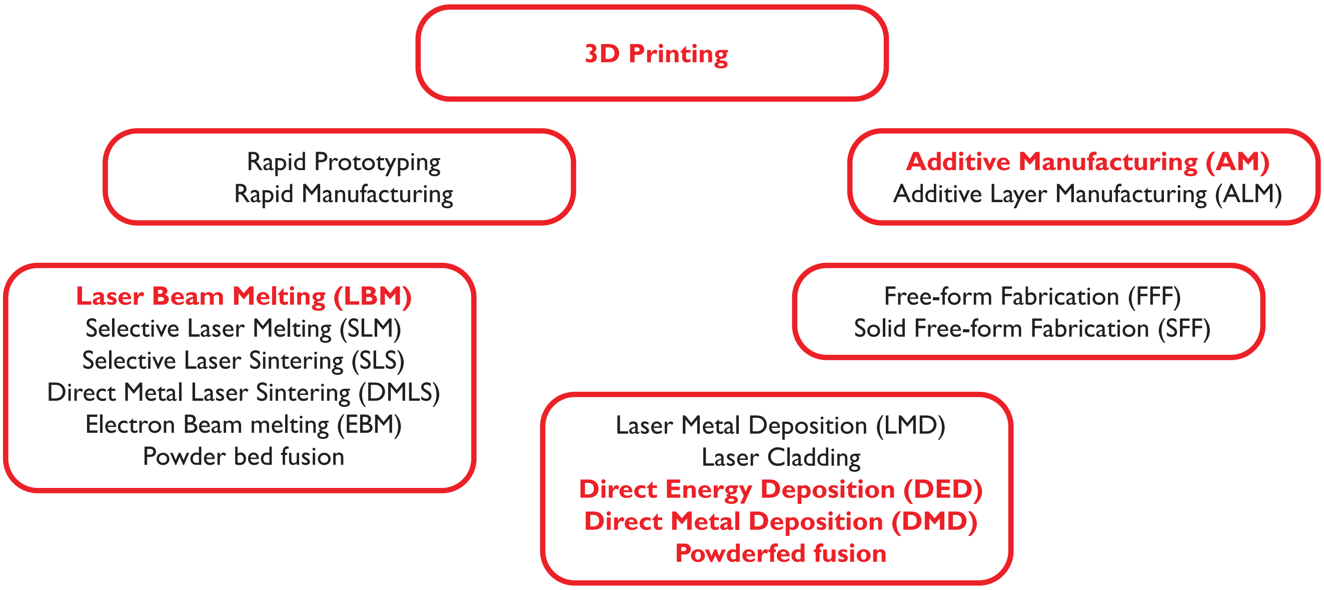
Additive manufacturing now enables both a design and industrial revolution, in various industrial sectors such as aerospace, energy, automotive, medical, tooling and consumer goods.

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)

1.1 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

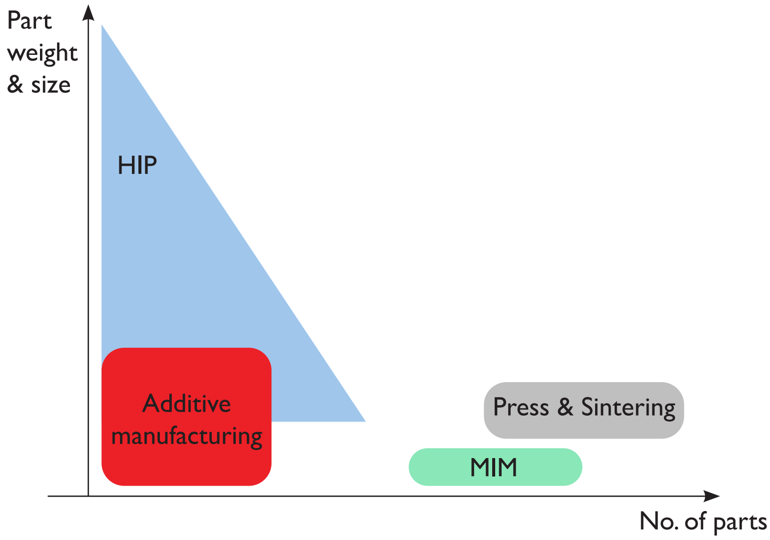
1.2 Positioning of AM vs. other PM technologies

Additive manufacturing works in conjunction with 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 the 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.



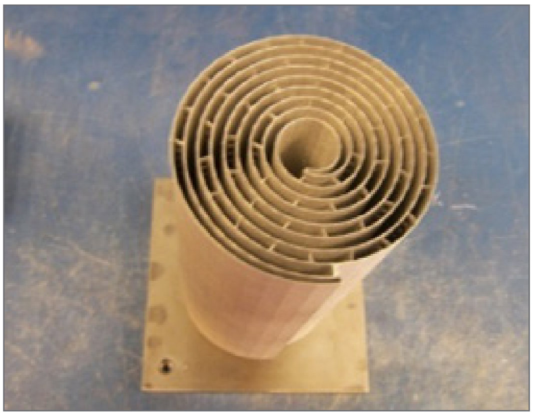
Positioning of various PM technologies according to part weight or size and production series

1.3 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.

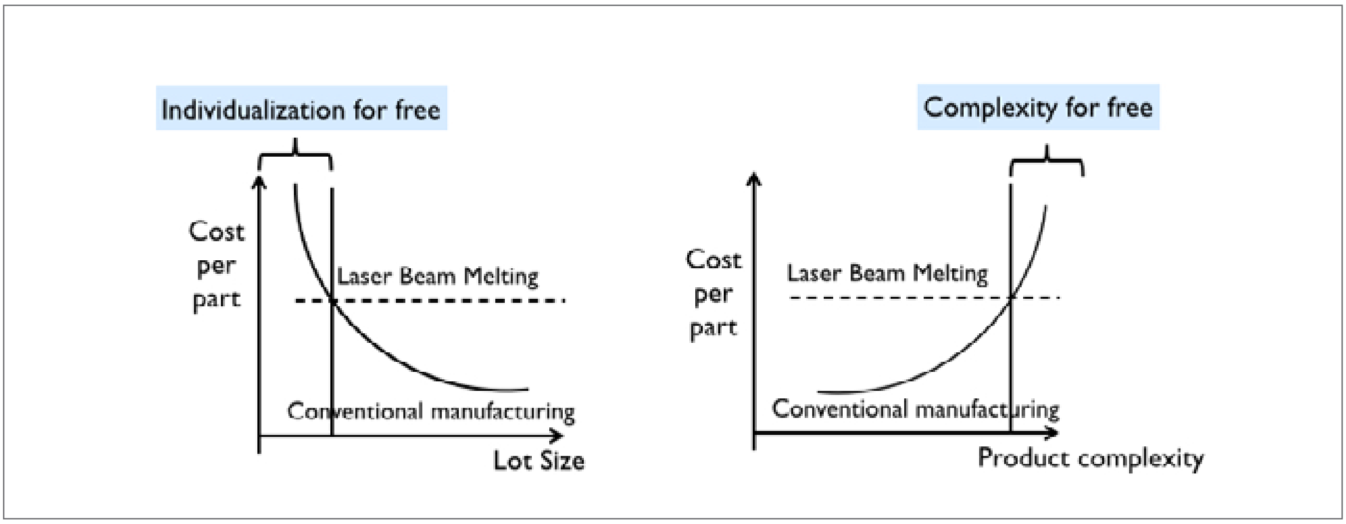
Hydraulic prototype with complex internal channels, (Source: EU project COMPOLIGHT)



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 optimisation. (Courtesy of Poly-Shape)

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



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

1.4 The limits of AM technology

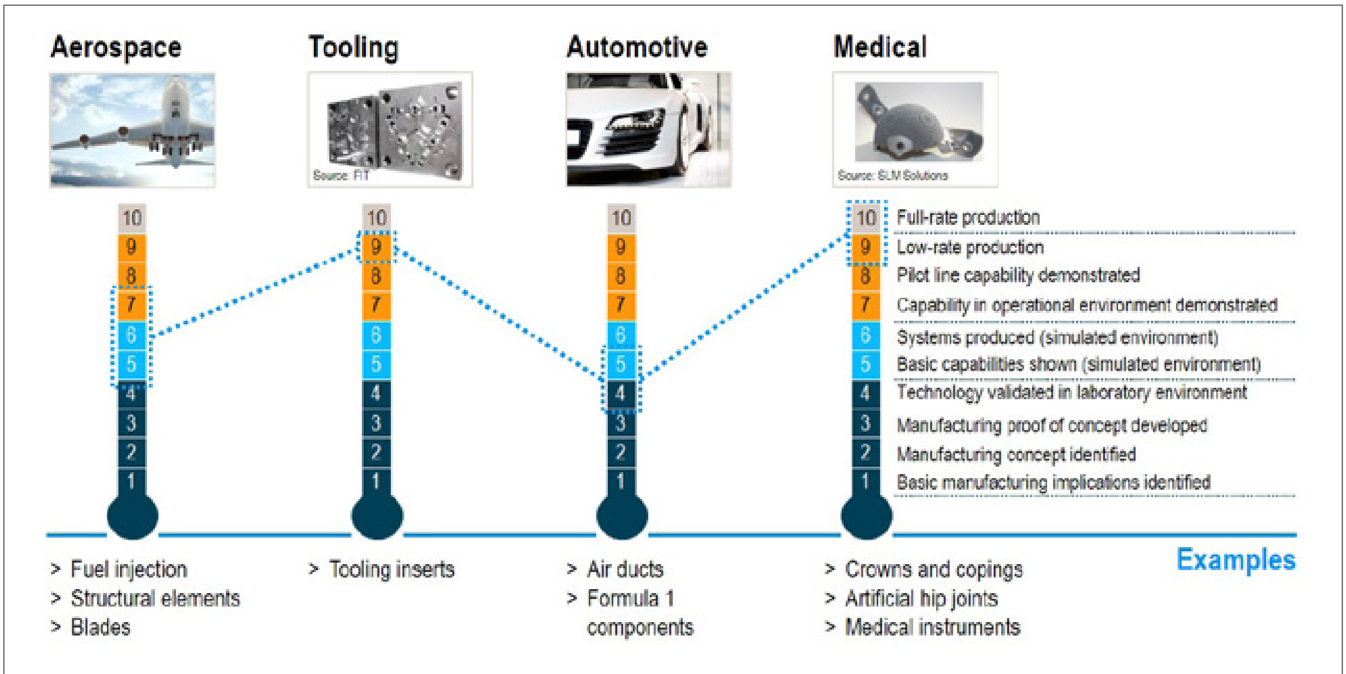
To take full advantage of AM technologies, it is important to be aware of some limitations:

- Part size: In the case of powder bed technology, the part size is limited to powder bed size, such as 250 x 250 x 250mm 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 tall or very large parts.
- Production series: the AM processes are generally suitable for unitary or small series and is not relevant for mass production. Progress is being 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

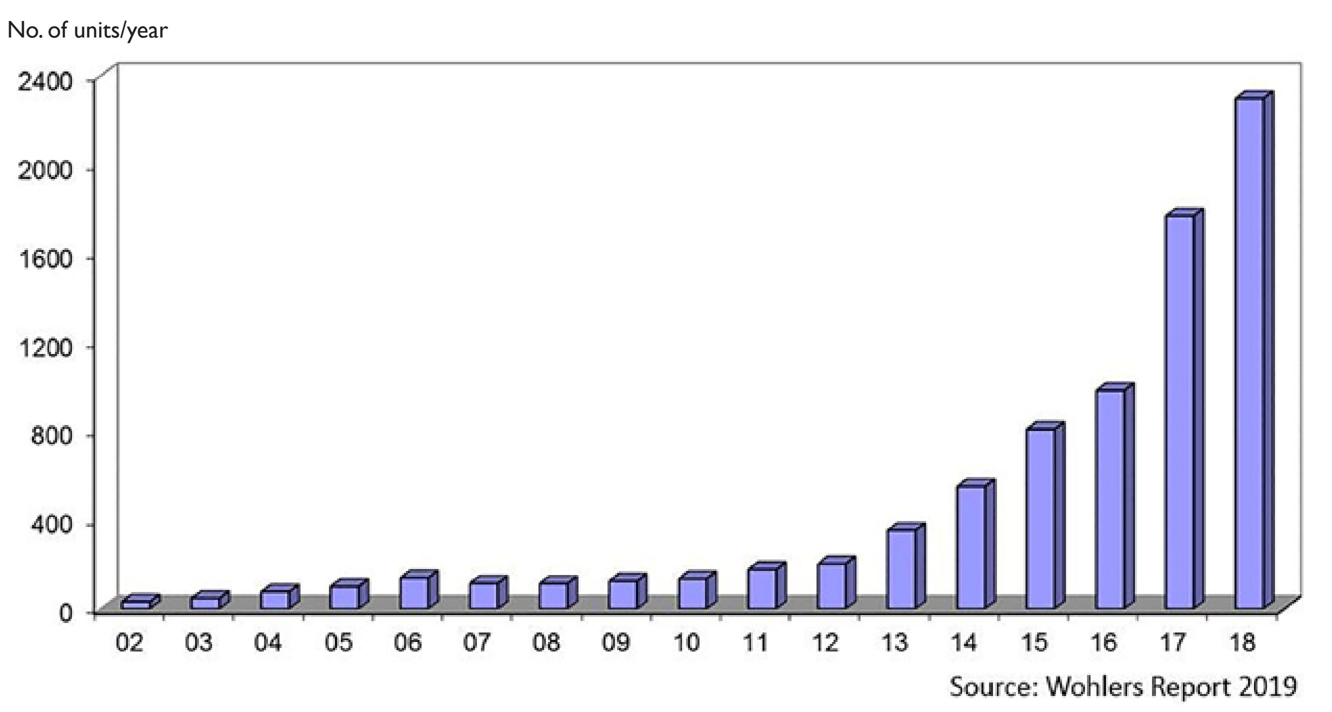
The use of additive manufacturing technology is developing in many industries:

- Aerospace
- Energy
- Medical, in particular in surgical implants and dental applications
- Tooling in particular for plastics processing
- Automotive and transportation
- Consumer goods
- Etc



Manufacturing readiness level in various industry sectors (Courtesy of Roland Berger)

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).

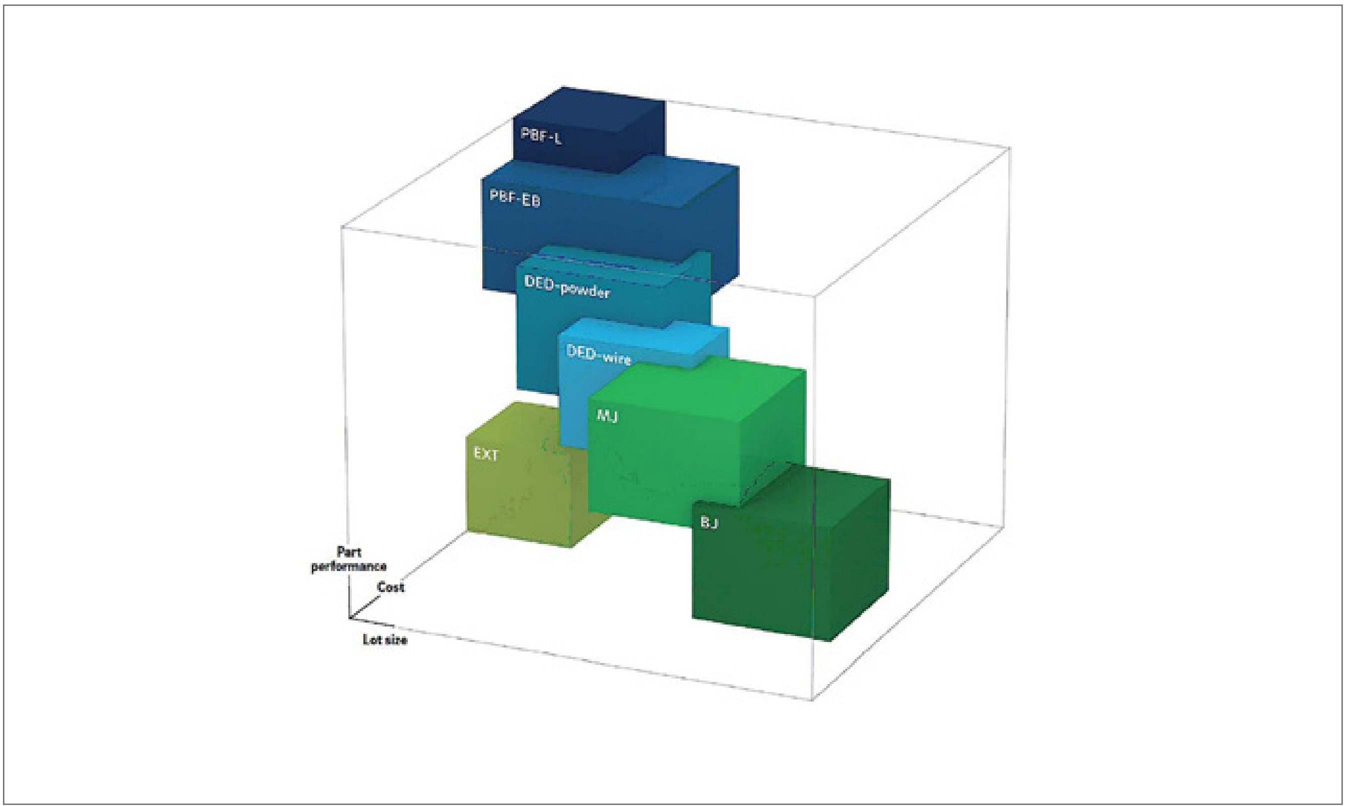


Sales of AM systems for metal parts (Source Wohlers Report 2019)

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 was 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 utilisation 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/cm³ (Courtesy of Roland Berger)

1.6 Overview of standardisation activities in the field of additive manufacturing

The development and publication of internationally recognised, credible standards is widely recognised as a key enabler to support the adoption of Additive Manufacturing technology across the widest possible range of industry sectors. The objective of this chapter is to provide a brief overview of the ongoing international standardisation activities, the organisations involved, the process of standards development and the themes/topics being worked on. Standards development is a dynamic process, particularly for such a new technology as AM, so it is impractical to provide an exhaustive and accurate list of published standards in this handbook. Instead references are provided to allow the reader to access 'live' information on the latest developments.

Short History of AM Standard Development and key players

ASTM International, formerly known as the American Society for Testing and Materials, first established their F42 Technical Committee in 2009 to investigate the requirements for the emerging technology referred to at the time as rapid prototyping, free-form fabrication to name but a few terms. Indeed, it was the F42 committee that first coined the description "Additive Manufacturing". The scope of the committee has been "the promotion of knowledge, stimulation of research and implementation of technology through the development of standards for additive manufacturing technologies". Individuals as well as organisations are free to join ASTM and participate in the technical committees; today the F42 group has more than 500 members representing 25 countries that span industry, academia and research organisations. Each organisation is assigned one vote in the balloting process for approving standards.

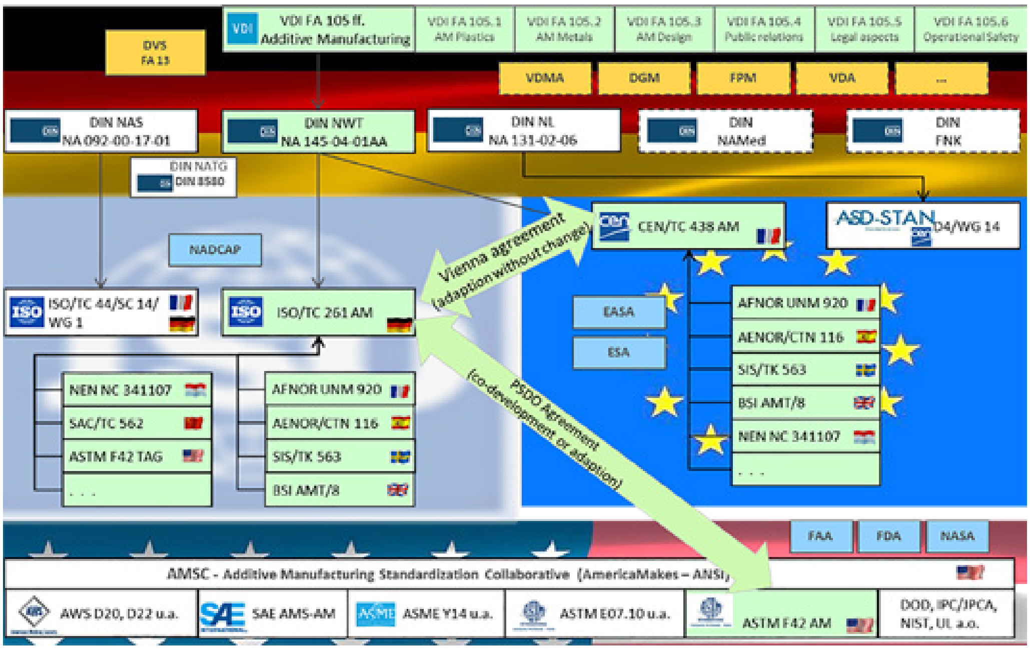
In 2011 ISO, the International Organisation for Standardisation, established Technical Committee (TC) 261, prompted by an initiative from the German National Standards Body (DIN) based on the VDI's (Association of German Engineers) guidelines for "Rapid Technologies". Membership of ISO is comprised from National Standards Bodies; today there are some 22 participating countries and 6 observers represented on TC261. Each member organisation can nominate experts to participate in the different subject working groups and each member subsequently has one vote in the balloting process to approve standards. The remit for the committee is defined as "Standardisation in the field of Additive Manufacturing (AM) concerning their processes, terms and definitions, process chains (Hard- and Software), test procedures, quality parameters, supply agreements and all kinds of fundamentals"

Shortly after the formation of TC261 a Partner Standards Developing Organisation (PDSO) agreement was establish between ASTM and ISO with the ambition of streamlining the development process and creating a common set of global AM standards. In 2016 the combined group published the jointly crafted Additive Manufacturing Standards Development Structure to:

- Guide the work of global experts and standards development organsations involved in AM standardisation
- Identify standards-related gaps and needs in the AM industry
- Prevent overlap and duplicative efforts in AM standards development
- Ensure cohesion among AM standards
- Prioritise AM Standards areas
- Improve usability and acceptance among the AM community, including manufacturers, entrepreneurs, consumers and others

Finally, in the context of European Standards development, CEN-CENELEC (the European Committee for Standardisation and the European Committee for Electrotechnical Standardisation) established CEN/TC 438 AM in July 2015 "To provide a complete set of European standards on processes, test procedures, quality parameters, supply agreements, fundamentals and vocabulary based as far as possible on international standardisation work". It is worth pointing out that CEN standards automatically supersede national standards in all EU member states.

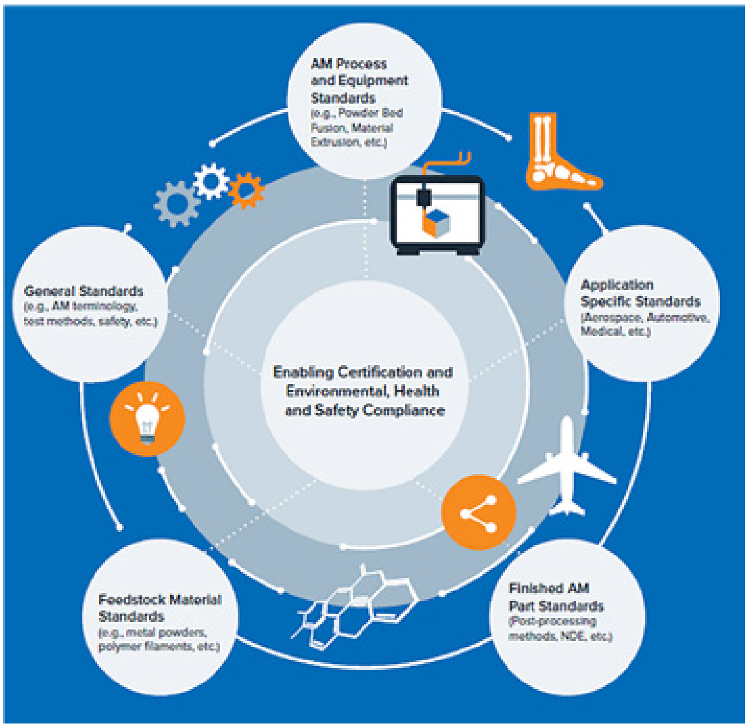
In spite of the cooperation and coordination between ASTM, ISO and CEN-CENELEC there has been a proliferation over recent years of parallel AM standards developments by various organisations. For example, in 2016 the American National Standards Institute (ANSI) and America Makes launched AMSC, the Additive Manufacturing Standards Collaborative. AMSC is a cross-sector coordinating body whose objective is to accelerate the development of industry-wide additive manufacturing standards. More recently the German Institute of Standardisation (DIN) established an AM Steering Committee as part of the DIN standards committee technology of materials (NWT) to coordinate activities across a national, European and international level. The figure below provides an overview of some of the ongoing activities and respective interdependencies, please be aware this is by no means exhaustive.



Courtesy of Klas Bovie

Scope, Structure and Methodology

The diagram below, published by ASTM International, outlines the high-level scope of the AM standards that are currently under development.

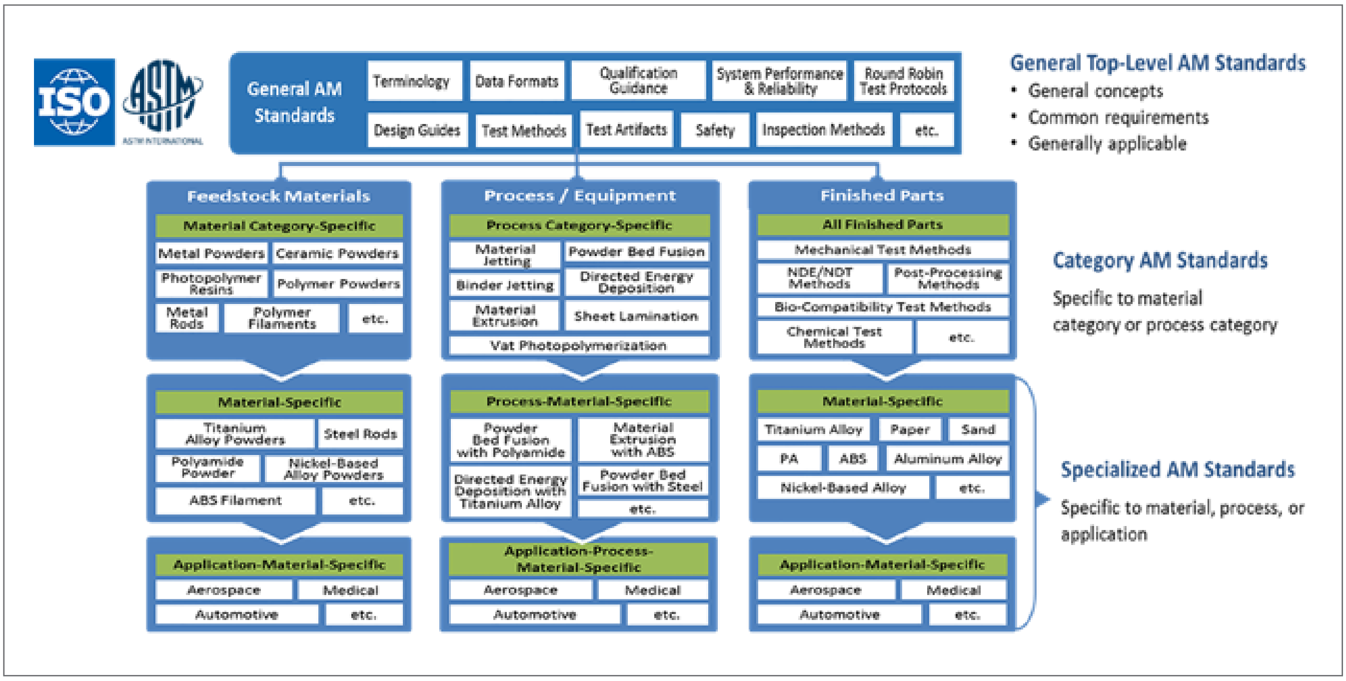


Courtesy of ASTM

Looking at the structure in more detail, the standards being developed can be split into three broad categories:

- General, high level standards covering general concepts and common requirements
- Category specific standards covering Feedstock Materials, Process/Equipment and Finished Parts
- Specialised standards that are material, process or application specific.

The following figure provides some more detailed insight into the details and topics covered under each of the three categories



Courtesy of ISO and ASTM

Current Status

At the time of writing the ASTM F42 group has published some 20 AM standards and has a further 28 standards under development. These standards cover topics including Test Methods, Design, Materials and Processes and Applications. The corresponding ISO/TC 261 group has published 9 standards with a further 25 under development. Details on the specifics standards can be found using the website links highlighted below.

The latest version of the ISO/ASTM 52900 standard on AM Terminology can be viewed on-line at: www.iso.org

Useful references / information sources

ASTM F42 website: www.astm.org

ISO TC261 website: www.iso.org

CEN/TC 438 website: www.cencenelec.eu

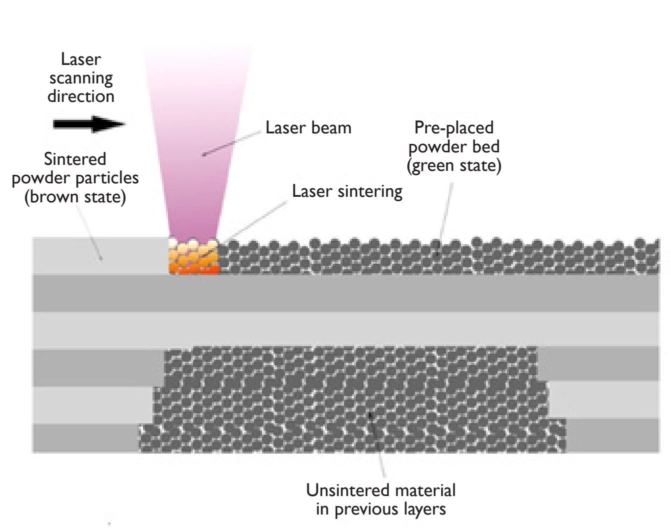
AMSC website: www.ansi.org

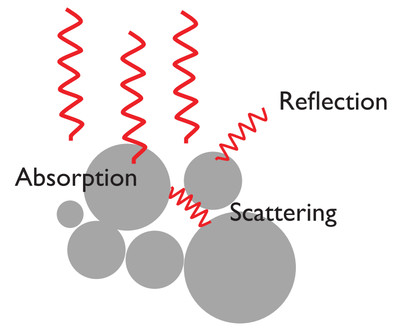
NWT (DIN) website: www.din.de

2. ADDITIVE MANUFACTURING TECHNOLOGIES

2.1 The basics of laser melting with metal powders

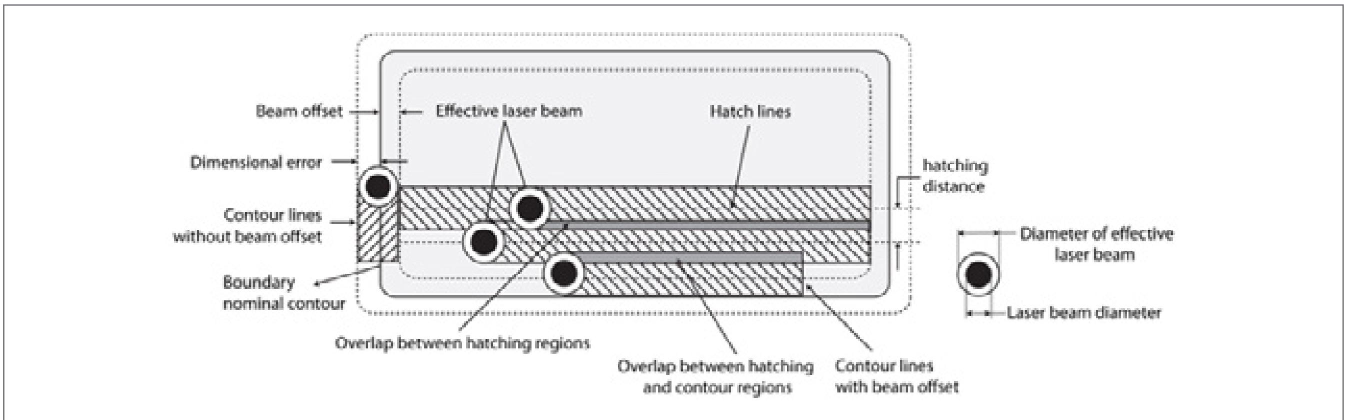
During laser beam melting, the laser beam, with diameter such as 100 µm, will locally melt the upper powder layer on the powder bed. The laser will be partially absorbed by metal powder particles, creating a melt pool which solidifies rapidly. Laser power typically varies from 200 W up to 1000 W.





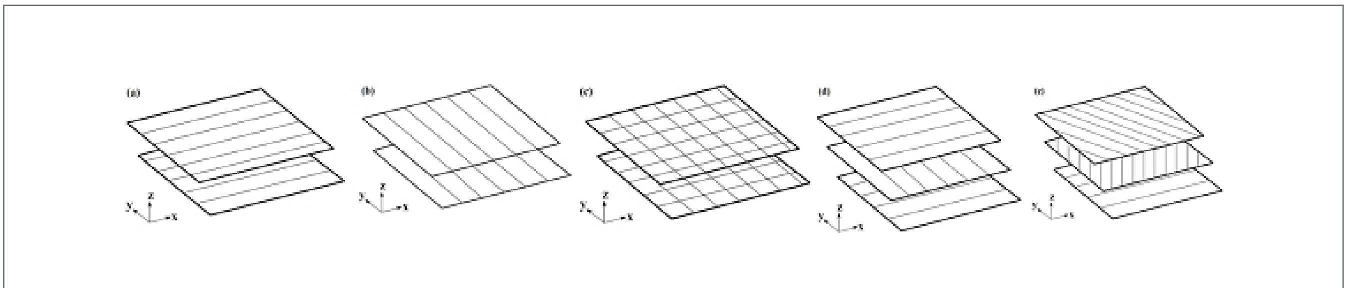
The interactions of laser with powder particles

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.



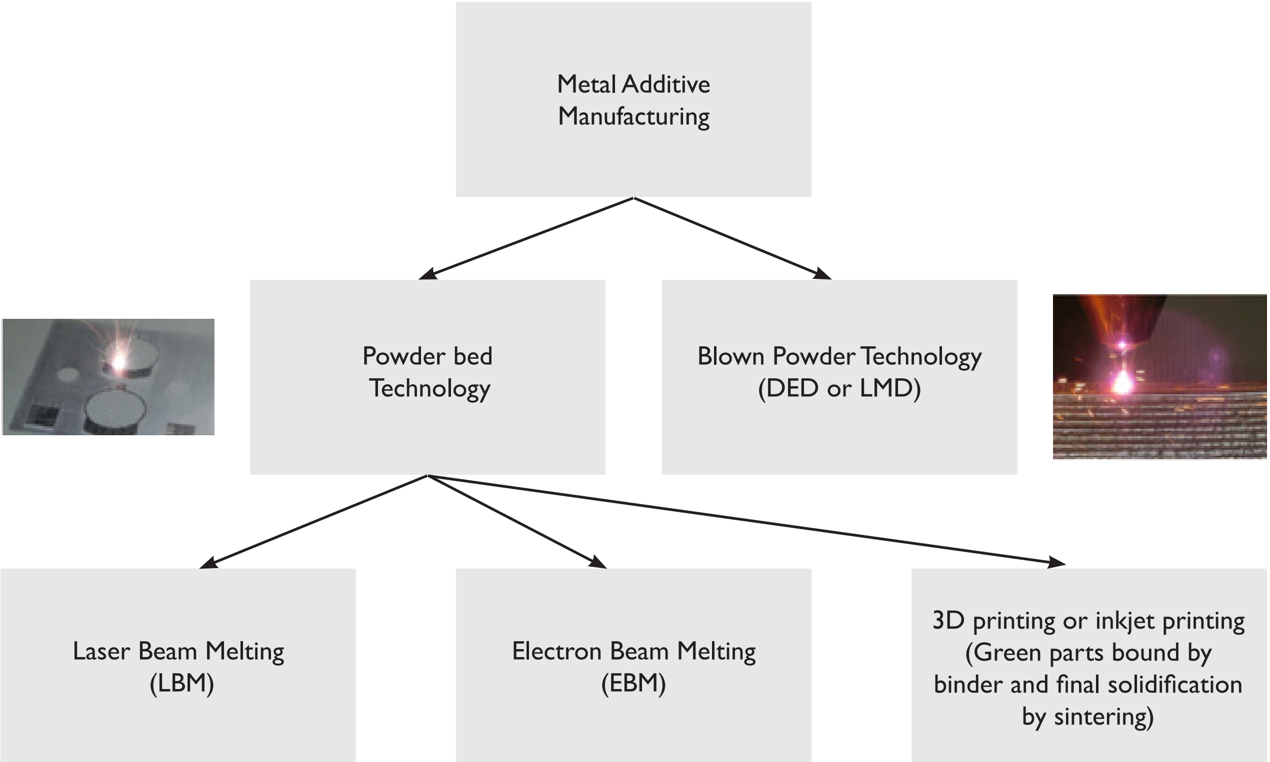
Stripe pattern (Courtesy of Istituto Italiano di Tecnologia and Politecnico di Torino)

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

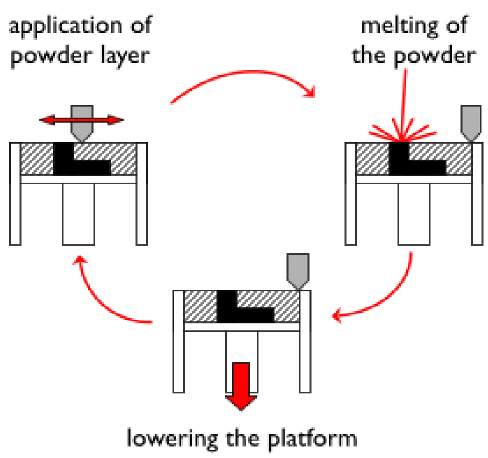


Mapping of main metal powder additive manufacturing technologies

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.

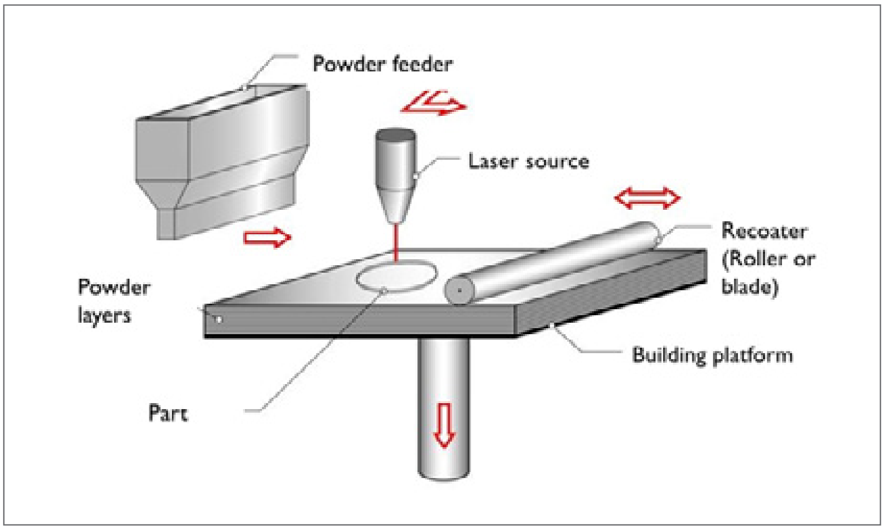
After melting, the platform is lowered and the cycle is repeated until the part is fully built, embedded in the powder bed.



The powder bed manufacturing cycle (Courtesy of Fraunhofer)

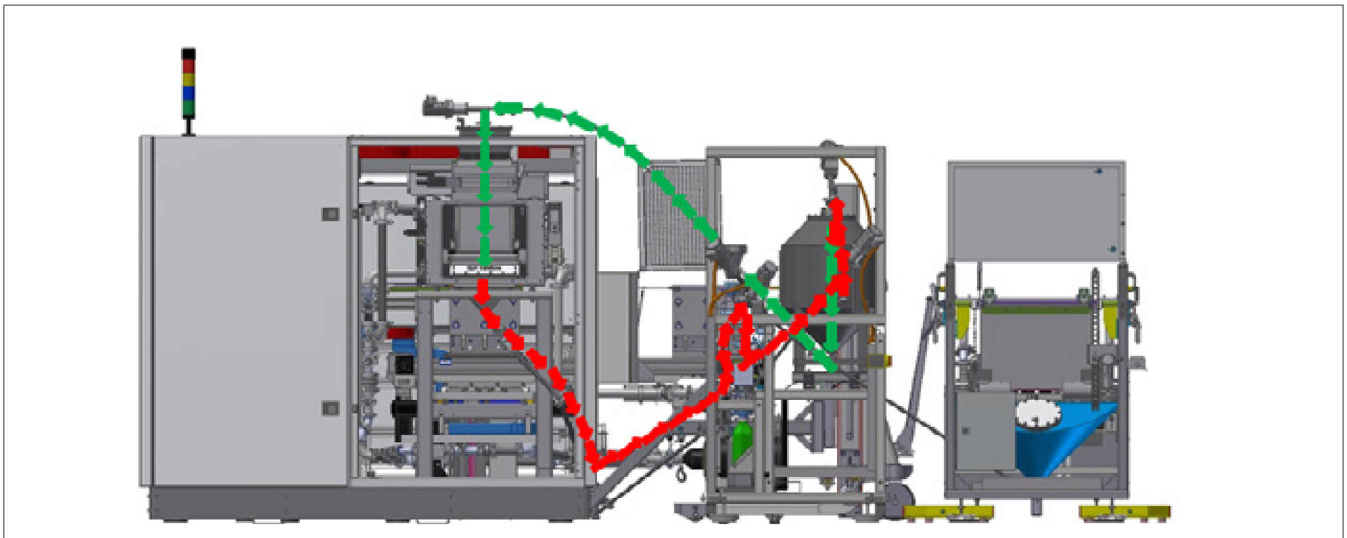
2.2.1 Laser Beam Melting (or Selective Laser Melting)

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 µm 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.



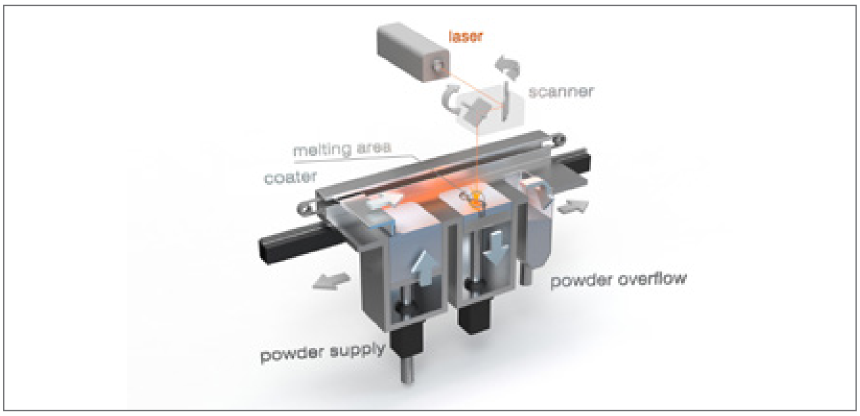
Manufacturers

- 3D Systems (US)
- Additive Industries (NL)
- Addup (F)
- Concept Laser (DE)
- EOS (DE)
- Farsoon (CN)
- Matsuura (JP)
- Realizer (DE)
- Renishaw (UK)
- Sisma (I)
- SLM Solutions (DE)
- Sodick (J)
- Trumpf (D)



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)

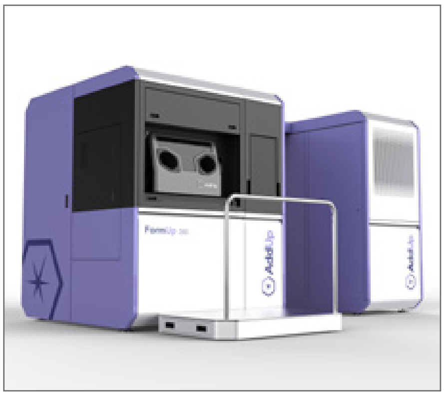


Inside a Laser Beam Melting Machine (Courtesy of Concept Laser GmbH)

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

Tooling insert by Laser Beam Melting (Courtesy of BMW)

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



FormUp350 by Addup

TruPrint3000 by Trumpf

RenAM 500M by Renishaw

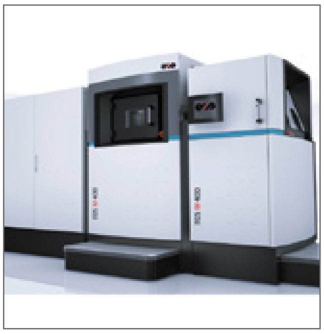
A new trend is to develop new systems with larger powder beds, as can be seen in the table below

MANUFACTURER		Powder bed size: Small (Usually with a diameter of 100 mm)	Powder bed size: Standard (Usually 250 x 250 x 250mm)	Powder bed size: Large (with 1 or 2 dimensions >400 mm)
3D Systems	US& F	X	X	X
Additive Industries	NL			X
Addup	F		X	
Concept Laser GmbH	DE	X	X	X
EOS GmbH	DE	X	X	X
Realizer GmbH	DE	X	X	
Renishaw	UK		X	
Sisma	I		X	
SLM Solutions GmbH	DE	X	X	X
Trumpf	D	X	X	

Manufacturers of laser beam melting powder bed systems

Examples of large powder bed systems

ProX400 by 3D Systems Platform size: 500mm x 500mm x 500mm

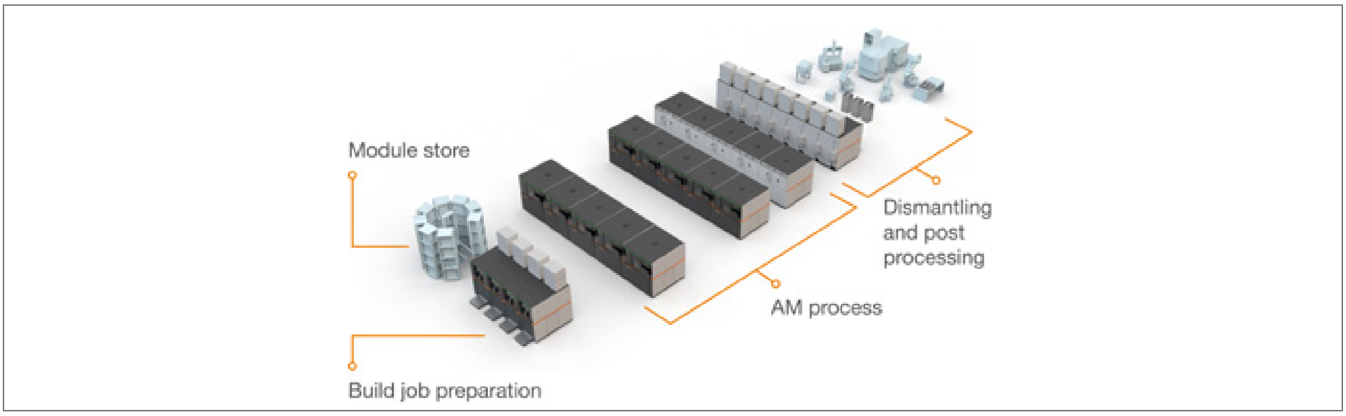


EOS M 400 by EOS GmbH Platform size: 400mm x 400mm x 400mm

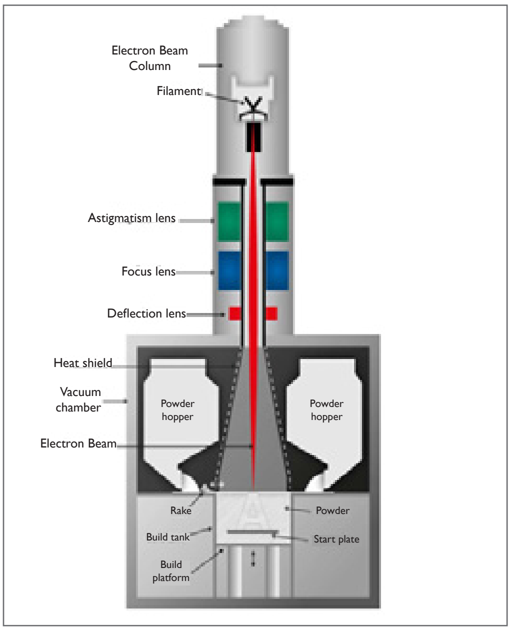
MetalFAB1 (Courtesy of Additive Industries) Platform size: 420 x 400mm

SLM800 by SLM Solutions GmbH Platform size: 500mm x 280mm x 850mm

Another trend is the development of integrated manufacturing lines for production of parts in series.



AM factory of tomorrow (Courtesy of Concept Laser)



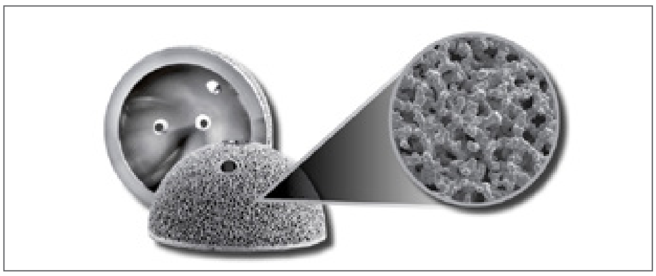
The EBM process (Courtesy of Arcam)

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 1×10-5 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)
- Freemelt (SE)



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

Low Pressure Turbine blade in γ-titanium aluminide (Courtesy of AvioAero)

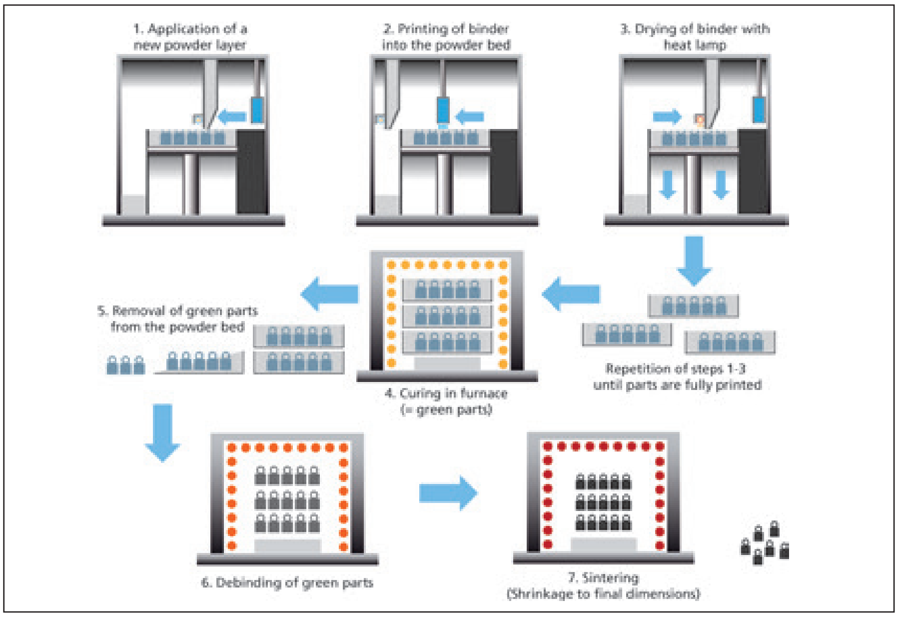
2.2.3 Metal Binder Jetting and Sintering

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.

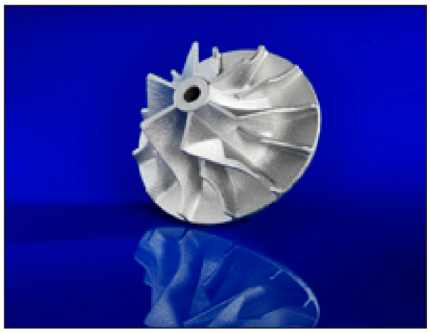
The metal part solidification takes place in a second step, during a debinding and sintering operation, sometimes followed by an infiltration step.



Metal Binder Jetting process (Courtesy of Fraunhofer IFAM)

Manufacturers

- DeskTop Metal (US) – announced
- Digital Metal (S)
- ExOne (US)
- GE Additive (US) – announced
- HP (US) - announced

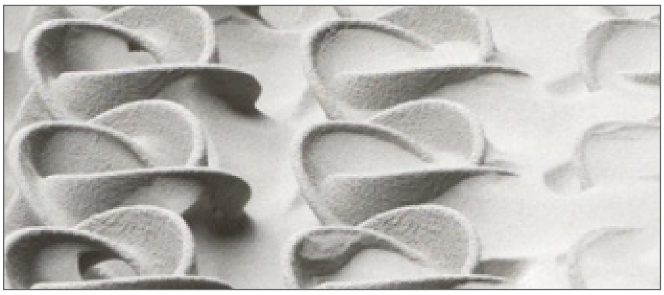


Turbine wheel by Metal Binder Jetting process (Courtesy of Fraunhofer IFAM)

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 µm
- Superfinishing for an average of Ra 1.0 µm down to < 1.0µm

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

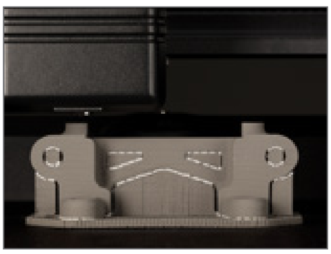


Parts in the powder bed after 3D printing (Courtesy of Höganäs AB - Digital Metal®)

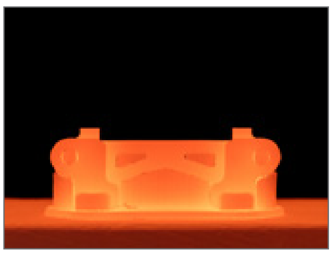
Lightweight stainless screws made by 3D printing (Courtesy of Höganäs AB - Digital Metal®)

In addition, several other companies announced or promote other concepts of sinter-based processes : 3DEO (US), AIM3D (DE), Evo-Tech (AT), Markforged (US), Stratasys (US) and Xjet (Israel).

Fused Filament Fabrication process (Courtesy DeskTop Metal)



Green part after heating & extruding bound metal rod



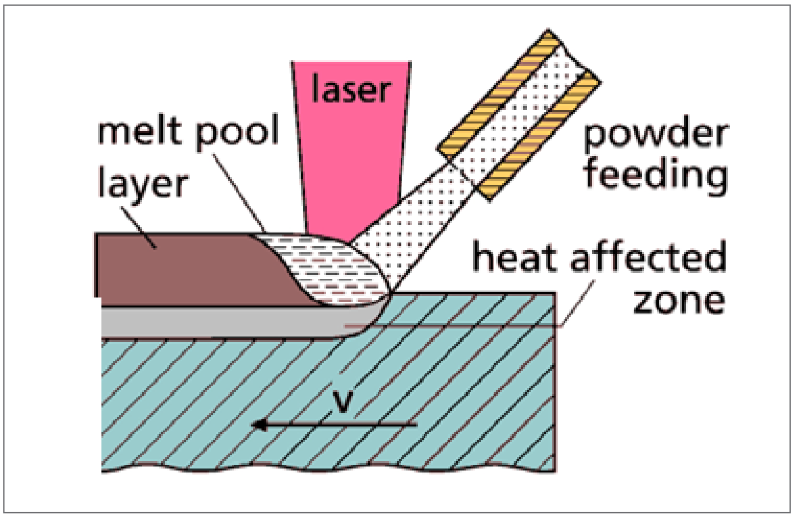
Part sintering

Support removal

2.2.4 Direct energy deposition (or laser metal deposition)

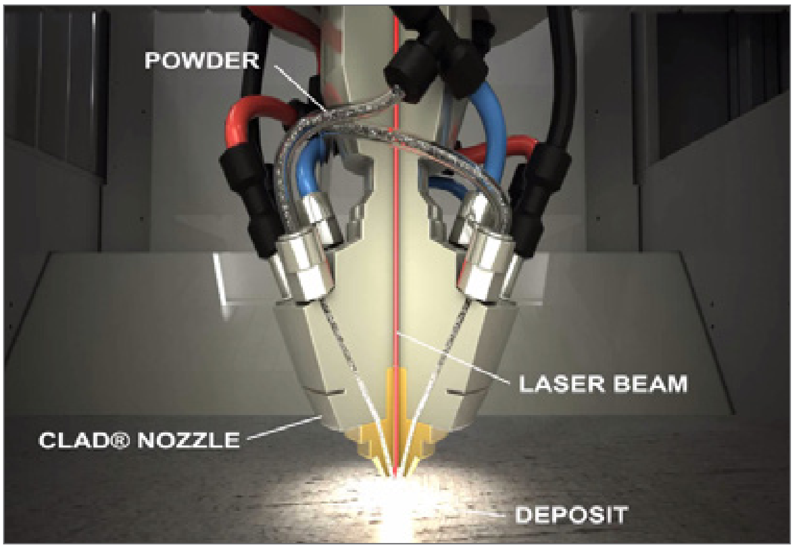
With the direct energy deposition process, a nozzle mounted on a multi axis arm deposits melted material onto the specified surface, where it solidifies.

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.



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	≥ 0.1m	≥ 0.1 mm
Deposition rate	3 – 10 mm³/s	1– 3 mm³/s
Build-up on	• 3D-surface • On existing parts	• Flat surface • Flat preforms
Roughness R_z	60 – 100µm	30 – 50µm
Layer thickness	≥ 0.03 - 1mm	≥ 0.03 - 0.1mm

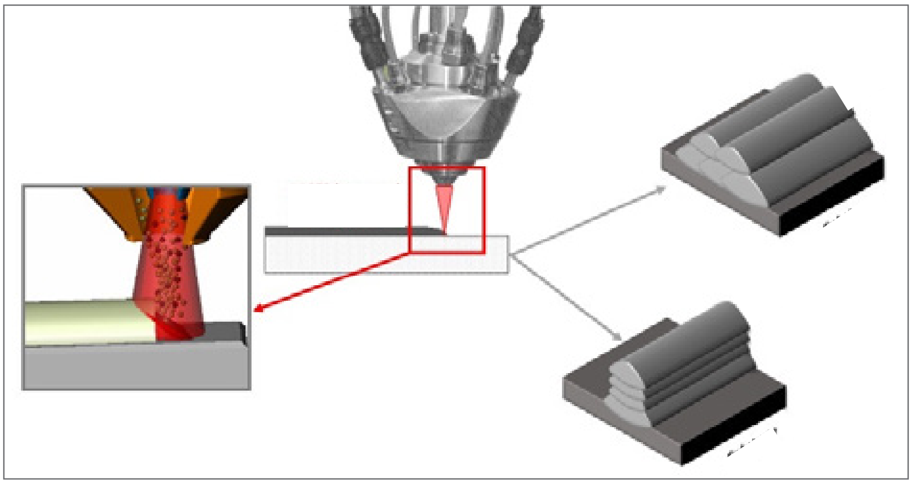
Comparison of LMD vs SLM (Courtesy of Fraunhofer)



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

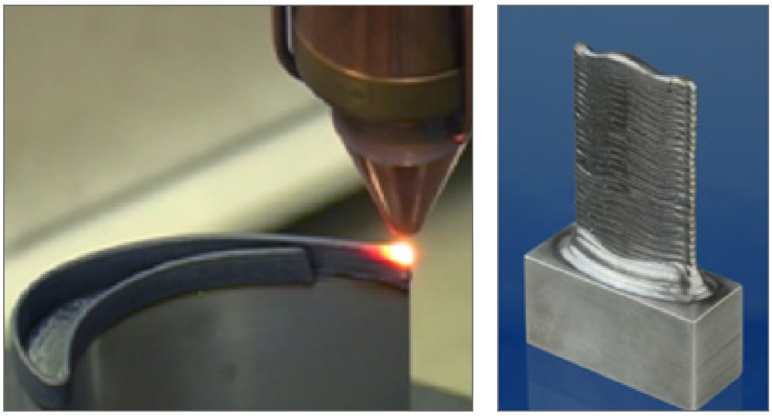
Manufacturers

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



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...

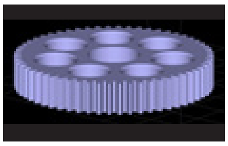
2.3 Main process steps

The manufacturing of a metal part with additive manufacturing technologies starts with 3D modeling. Then data preparation shall be organised 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.

3D-Modeling →

- 3D-CAD Modeling
- 3D Scan (Reverse Engineering)
- Creation of STL-Data (Triangulation)

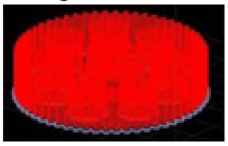
CAD-model



Data preparation →

- Reparation of files, close holes or open surfaces
- Part orientation and support structures
- Create slices from the model, Slicing

Slicing



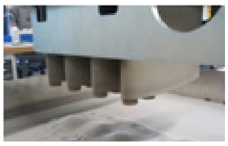
Manufacturing on AM machine →

- Generation of control data
- Production of the parts

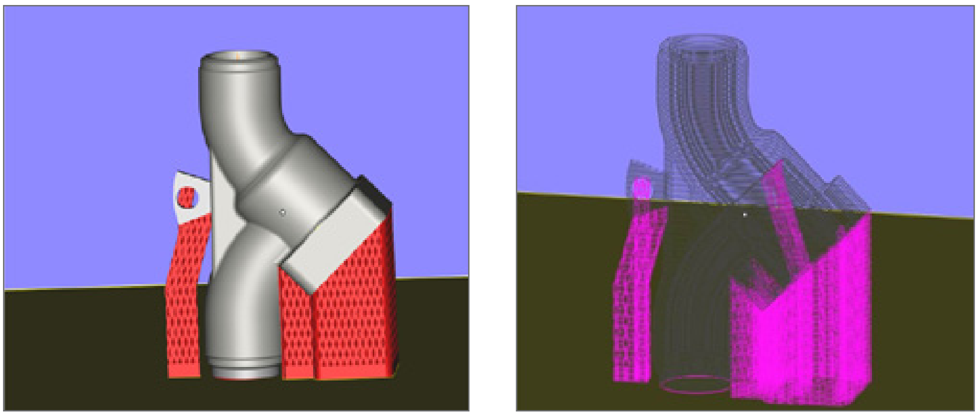
AM Machine

Post process →

- Removal of powder, support structures and platform
- Heat treatment
- Surface finish, polishing, etc.

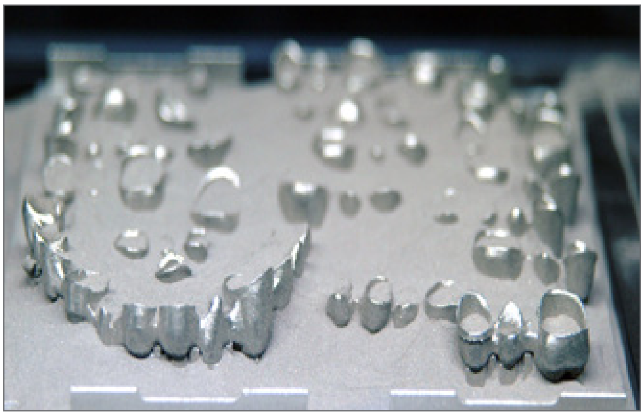


Summary of process steps (Courtesy of Fraunhofer)



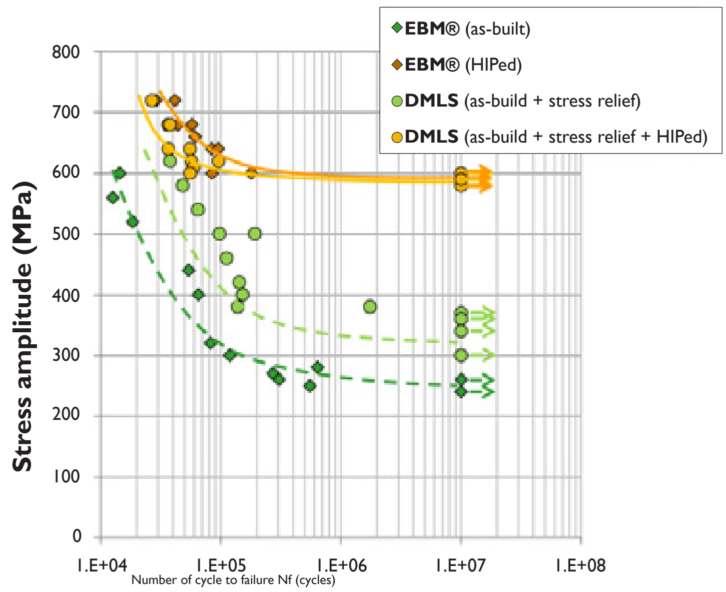
Creation of supports and file slicing with Magics software (Courtesy of Materialise)


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

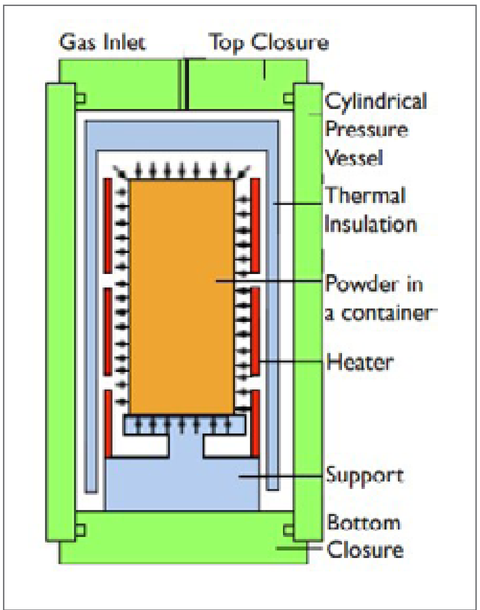


The effect of HIP post processing on fatigue resistance of parts made by SLM and EBM (Courtesy of MTC)

2.4 HIP post processing

Hot Isostatic Pressing (HIPing) for densification of metal castings and additive manufactured parts occurs by application of elevated temperatures up to 2000°C and high gas pressures up to 200MPa whereby internal shrinkage porosity and defects can be eliminated. Pore closure occurs initially by the collapse of the void due to plastic deformation which allows the pore surfaces to come into close contact, the extended hold time at temperature and pressure then allows creep and diffusion mechanisms to diffusion bond the pore surfaces resulting in closure of the void or defect and an increase in density. Pressure is applied by a high purity inert gas so the surface of the AM component is not affected.

HIP can be customised to specific temperature, pressure and hold times depending on the material being processed to achieve 100% densification. Heat treatment post HIP is required for the majority of components to achieve full material properties.

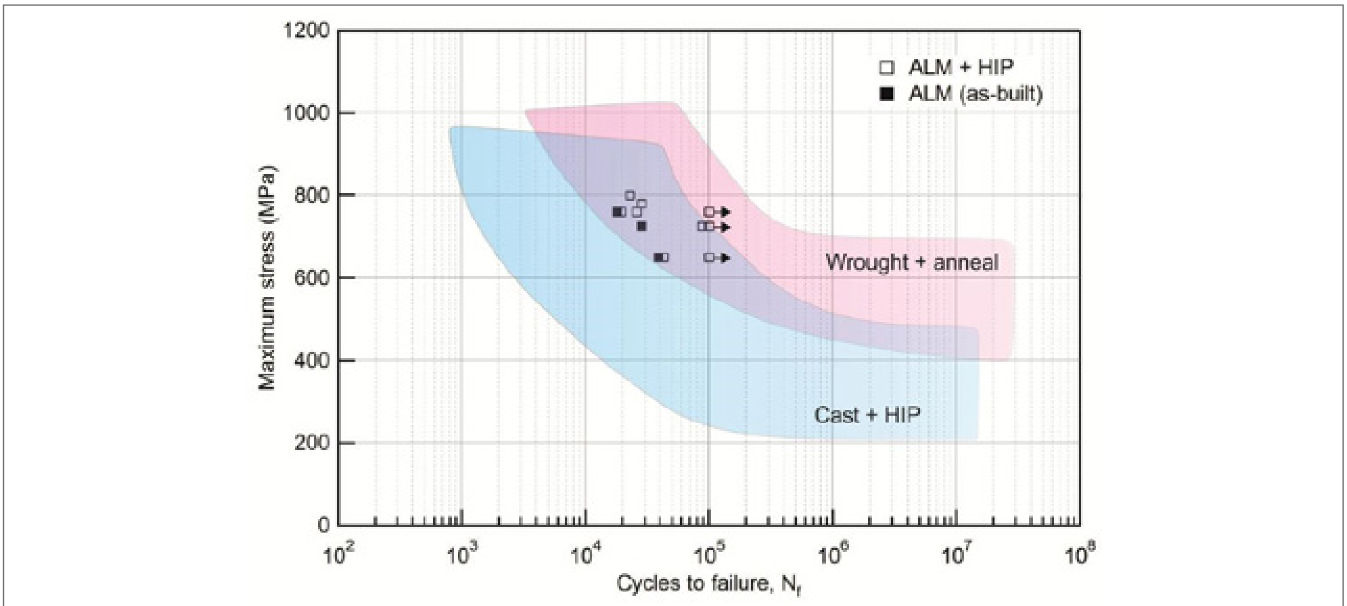


Schematic picture of a HIP vessel

The density of parts produced by metal powder based additive manufactured (AM) is often very high, but there is always the risk of defects in the material such as microporosity or cracks, depending on the machine used as well as the type of powder. AM parts can contain a small amount of porosity for instance due to:

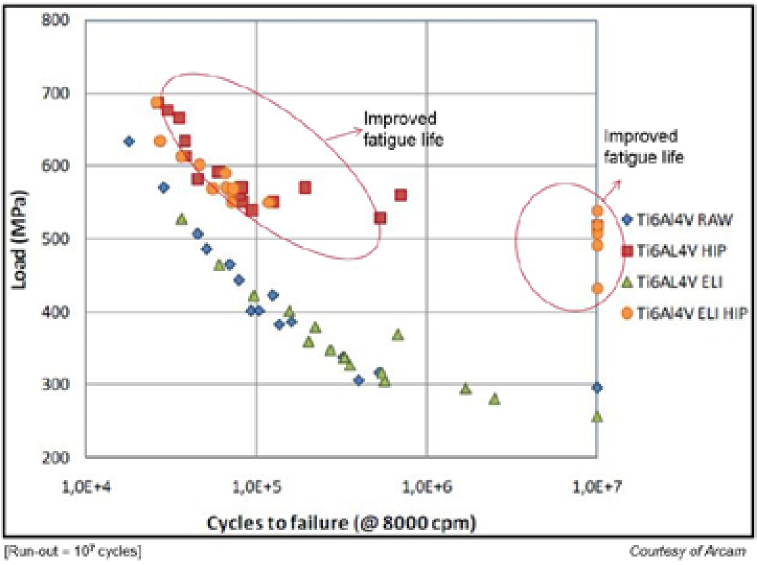
- Scanning calibration mismatch
- Key-hole beam-weld interaction
- Gas (can be internal to individual powder particles)
- Shrinkage as previous layers solidify
- Micro-cracks.

Eliminating the microporosity that forms during building can significantly improve fatigue life, impact toughness, creep strength and ductility. Besides, HIP provides stress relief to remove as built residual stresses and HIP reduces the extent of as built segregation due to recrystalisation and homogenisation of the micro structure.

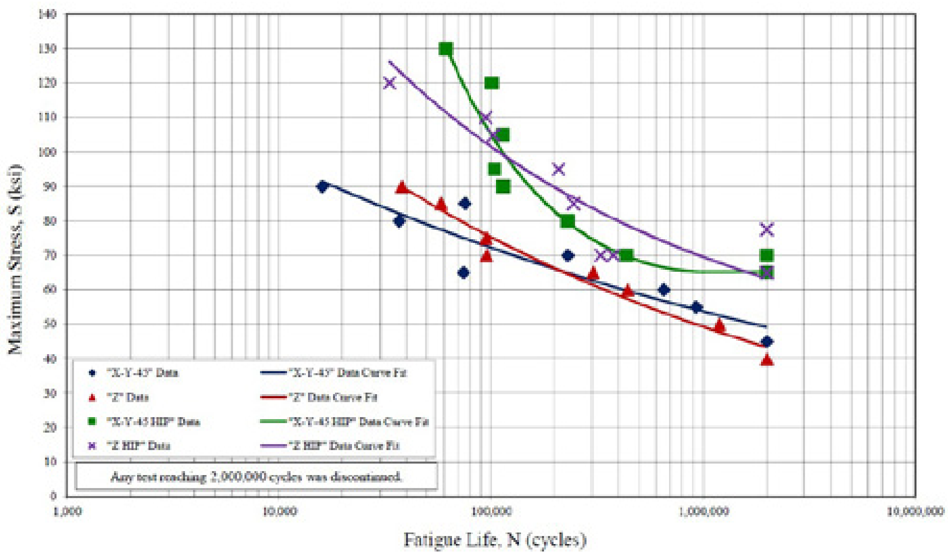


Comparison of Fatigue Performance for Cast + HIP, Wrought and AM as Built and AM+ HIP (Courtesy of Mercury Centre, University of Sheffield)

Promoting Powder Metallurgy Technology



Comparison of rotating beam fatigue performance of EBM Ti-6Al-4V (Courtesy of Arcam)



Comparison of fatigue performance of Alloy 718 (Courtesy of Bodycote)

Benefits of HIPing AM Components:

- HIP enhances AM components in a similar way to that experienced by castings or MIM components
- The majority of AM components will require heat treatment post HIP to realise full material properties
- Elimination of the microporosity that forms during building can significantly improve fatigue life, impact toughness, creep strength and ductility
- HIP can decrease the scatter band in mechanical property values, i.e. increase consistency and minimum design strength
- Improve Z-direction properties to be more consistent with X-Y
- Fatigue properties on par with wrought material
- Reduction in rejection rates and inspection costs
- 100% reduction in porosity possible
- Improved machined surfaces and consistency in properties
- Improved microstructure

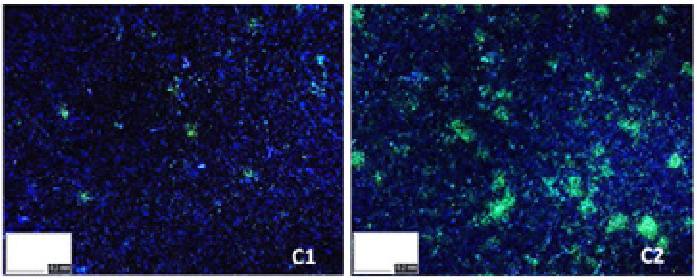
2.5 Non-destructive testing of AM parts

Surface Soundness

To check the presence of surface discontinuities in non-magnetic parts produced by additive manufacturing, the recommended method is penetrant inspection. This inspection is carried out into six steps:

- Surface preparation by a mechanical and/or a chemical treatment then by degreasing
- Application by capillarity of a penetrant inside the discontinuities
- Removing the penetrant in excess, most often by means of an air/water spay gun
- Drying, often in an oven
- Detecting by applying a product designed to reveal the penetrant by wicking effect
- Inspection under UV-A light in the case of a fluorescent penetrant

A good surface preparation is essential for a good detection of discontinuities, as shown in the example below.



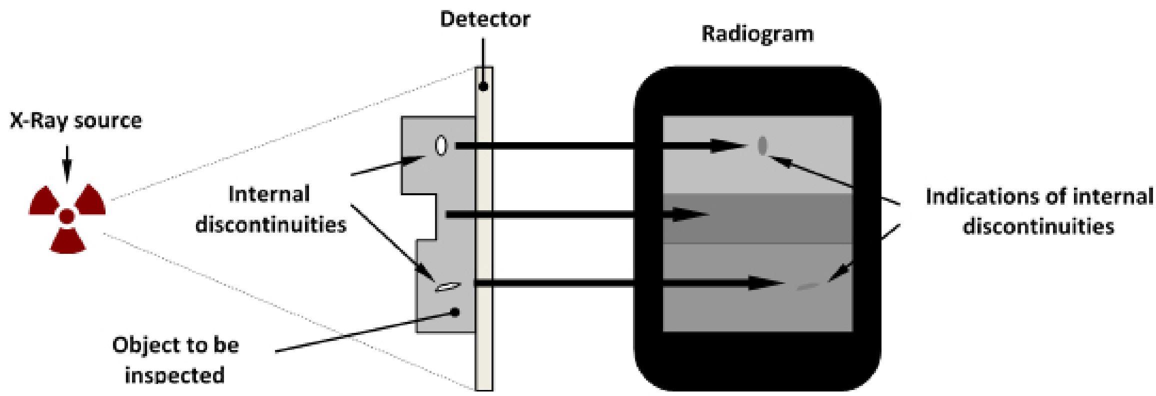
Porosities visualisation with (C2) and without (C1) sand blasting (Courtesy of CTIF)

Internal Soundness

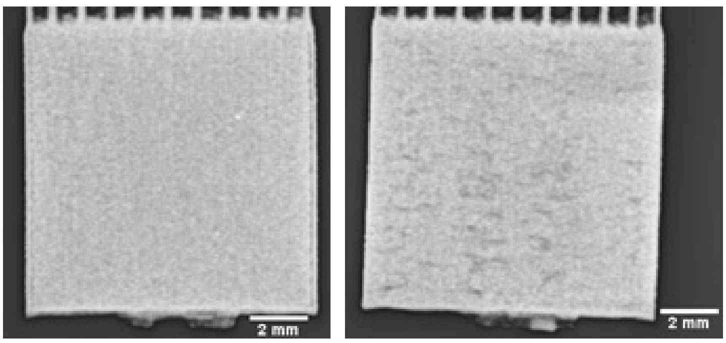
To detect internal discontinuities, both radiography and tomography by X-Ray inspection can be carried out. But radiography can only be used for parts like thin plates.

Radiography (in two dimensions) is based on the differential absorption of X-rays by the material.

Any lack of material will lead to a weaker absorption and therefore, locally, to a higher level of grey level on the digital picture or on the silver film according to the detector used.

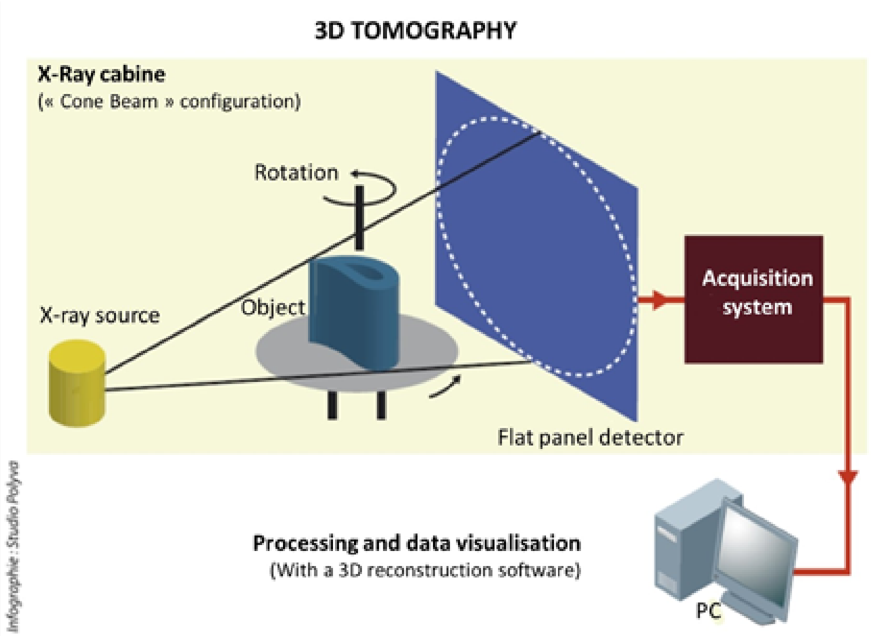


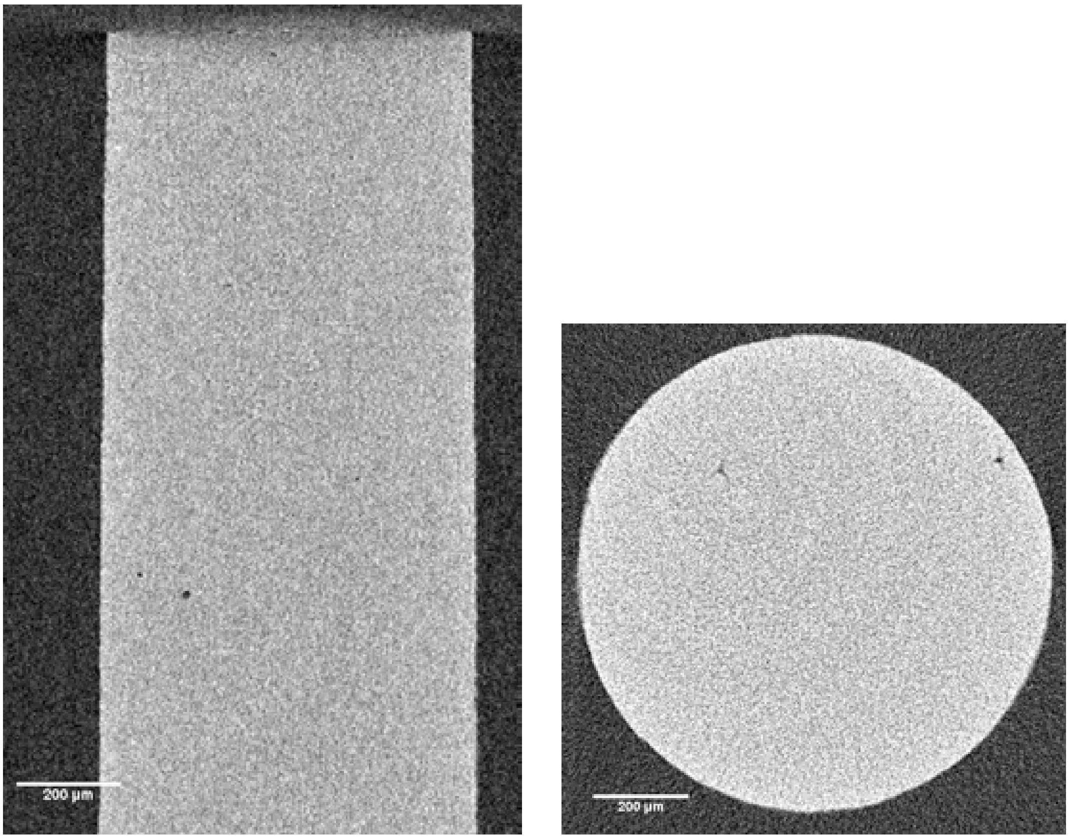
X-ray Radiography (Courtesy of CTIF)



Radiography of small AlSi10Mg parts produced by the Additive Manufacturing with different laser parameters (Courtesy of Zodiac Aerospace)

Tomography makes use of a large quantity of views obtained by rotating the object following different angles and height positions. The different views allow to determine the absorption of each volume element called "voxel" to rebuild the object in 3 dimensions. It is then possible to obtain several representations of the volume of the object, including visualisation in the form of virtual slices that define the word "tomography". This representation is the most conventional one and the most used to determine the porosity level or to measure discontinuities. To examine all the volume, one only needs to scroll the 2D slices on the screen.





Example of traditional tomography inspection of AlSi10Mg parts (Courtesy of CTIF)

Traditional tomography systems 'Cone-Beam' sometimes have a too high spatial resolution for small porosities. In this case, synchrotron radiation can be used, as a parallel beam allows to reach a resolution close to the one achieved with a micrograph.

Ultrasonic Testing

Another method that comes to light in the non-destructive testing (NDT) world for additively manufactured (AM) parts is ultrasonic testing (UT). UT consists in transmitting ultrasonic waves inside the sample under test. These waves are reflected by the sample geometry and possibly flaws. The reflections are then interpreted by the operator in order to assess the integrity of the sample. Over the past few years, impressive improvements have been made in the understanding and implementation of UT.

Depending on the sample characteristics (type of material, type of the defect, geometry, environment…), Phased Array Ultrasonic Testing (PAUT) techniques can be used for complex and accurate inspection needs. Phased Array techniques work with probes with multiple ultrasonic transmitters-receivers (called elements) that can be pulsed individually with a time delay controlled by the software. It results in an emission of beams that covers the defect, and the data collected is processed, providing high resolution imaging (Figure 1).

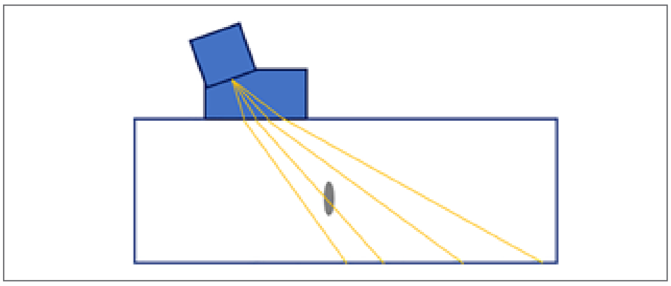


Fig. 1: Simplified depiction of a Phased Array probe in use. The probe (in blue) is placed on the top of the sample. Each yellow line corresponds to a specific ultrasonic path.

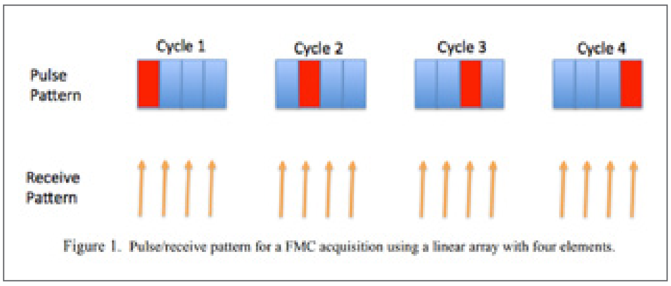


Fig. 2: Pulse/receive pattern for a TFM acquisition using a linear array with four elements.

Total Focusing Method (TFM) is a recent technique derived from Phased Array [1]. It describes a pulse/receive method implemented during data acquisition. Each element of an array is pulsed individually, and the reflected signal from this emission is received on all elements in parallel. Figure 2 shows an example of a four elements array [2]. This acquisition process results in a much larger amount of data on which the TFM algorithm is applied. As a consequence, a postprocessing image reconstruction of a very high resolution and contrast is obtained [1]. The TFM method can also be adapted to complex sample geometries using an adaptive technique [3].

The TFM method is very attractive for the inspection of additively manufactured parts and replies perfectly to two specific requirements that are the need to detect small defects (deserving high resolution) and the need to adapt complex geometries. These two points are particularly demanding in AM part inspection. A review of NDT methods for AM parts has been proposed by Obaton et al. [4]. In this paper, UT and PAUT have been described and compared to standard methods. It results that TFM offers good advantages compared to X-Ray computed tomography, that is the state-of-the-art method for controlling such pieces. As an example, illustrated in Figure 3, the TFM method has been applied to additively manufactured lattices. The goal here is to detect missing struts that are supposed to be connected together. The inspection is conducted in water in order to facilitate the ultrasonic wave propagation. A mechanical scan is then performed to control the whole sample. In the images, the right side lattice shows a missing strut whereas the left side lattice does not (which serves as a reference). This example shows that TFM can detect geometry defects in addition to internal defects [4], because of its high resolution. Moreover, scanning can be achieved very fast. For instance, it takes a few seconds for these samples.

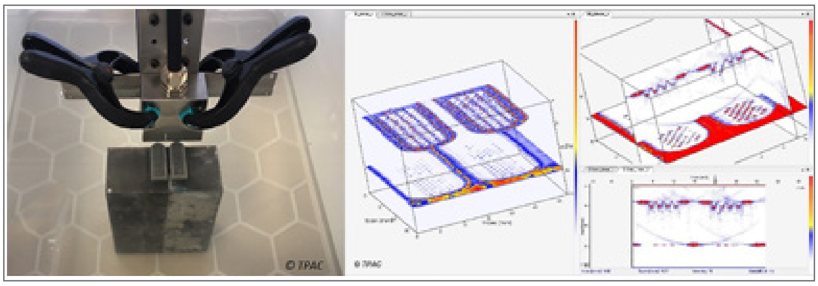


Fig. 3: TFM images obtained with TPAC instrument and software from AM lattice designed and manufactured by LNE/NIST.

- [1] C. Holmes, B. W. Drinkwater, and P. D. Wilcox. "Postprocessing of the full matrix of ultrasonic transmit receive array data for non-destructive evaluation". NDT&E International, Vol. 38, No. 8, pp 701–711 (2005).

- [2] Gavin Dao, Dominique Braconnier, Matt Gruber, 'Full-Matrix Capture with a Customisable Phased Array Instrument', AIP Conference Proceedings, vol. 1650, No. 1, p 1001-1006, 2015.

- [3] https://www.thephasedarraycompany.com/tfm-definitions/

- [4] A.-F. Obaton, B. Butsch, S. McDonough, E. Carcreff, N. Laroche, Y. Gaillard, J. B. Tarr, P. Bouvet, R. Cruz, A. Donmez. "Evaluation of non-destructive volumetric testing methods for additively manufactured parts", ASTM Symposium on structural integrity of additive manufactured parts, November 6-8, Washington, USA, 2018.

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 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: 316L, 17-4PH etc.
- Nickel and cobalt base superalloys: 625, 718, CoCr F75 etc.
- Titanium alloys: Ti6Al4V, CPTi 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 atomisation process, where a molten metal stream is atomised thanks to a high pressure neutral gas jet into small metal droplets thus forming metal powder particles after rapid solidification.

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

Gas atomisation 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 atomisation process.

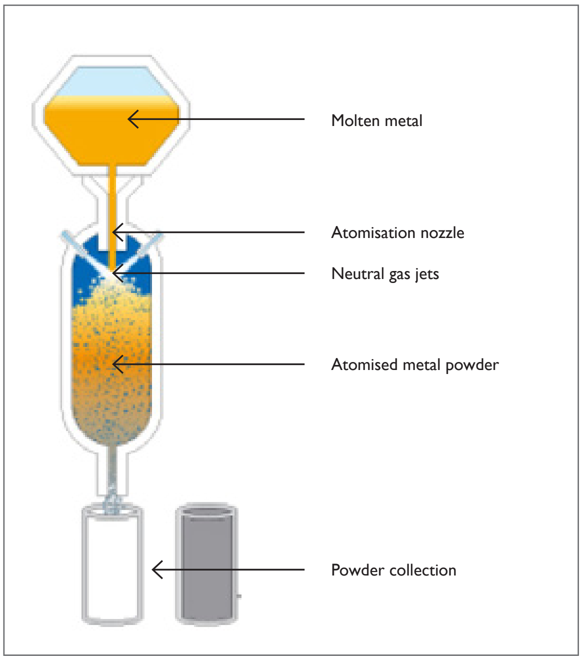
Metal powders for additive manufacturing (Courtesy of SLM Solutions)

3.2.1 The gas atomisation process

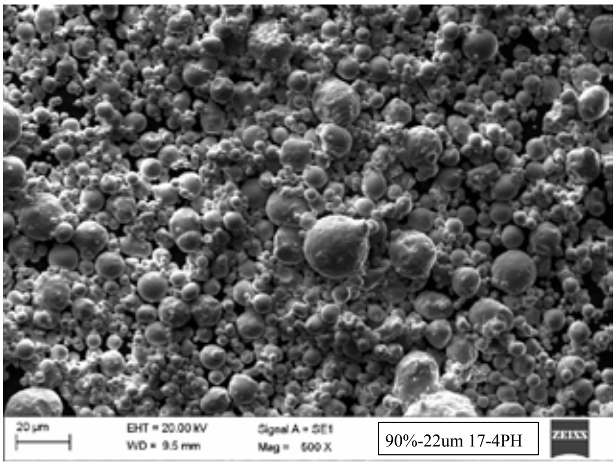
The gas atomisation process starts with molten metal pouring from a tundish through a nozzle.

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

The gas atomisation 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.



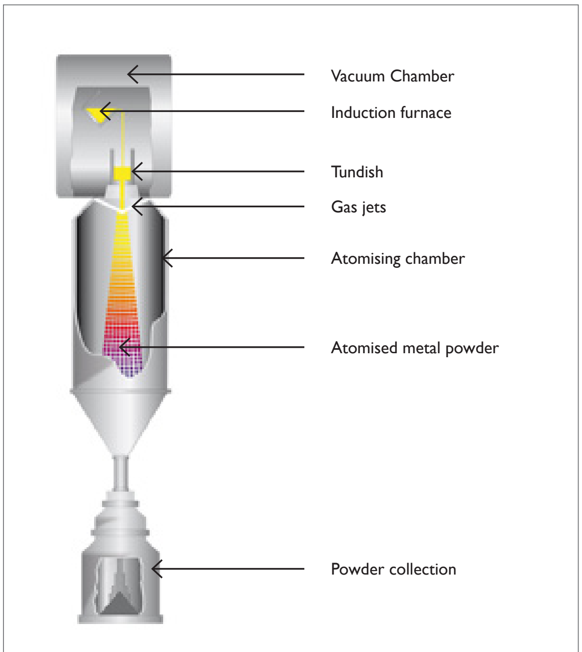
Sketch of the gas atomisation process



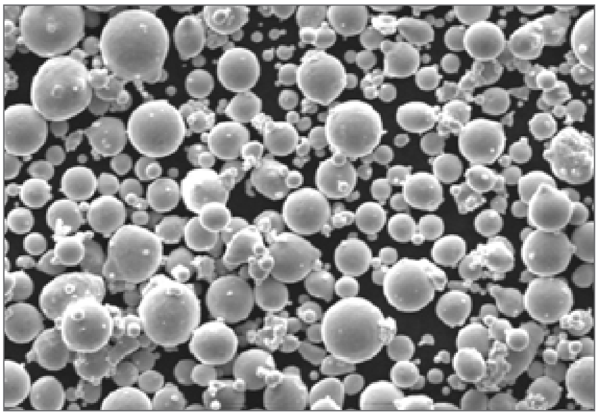
SEM picture of gas atomised 17-4PH powder <20 µm (Courtesy of Sandvik Osprey Ltd)

3.2.2 The VIM gas atomisation process

In the VIM gas atomisation 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 atomisation process (Courtesy Aubert & Duval)

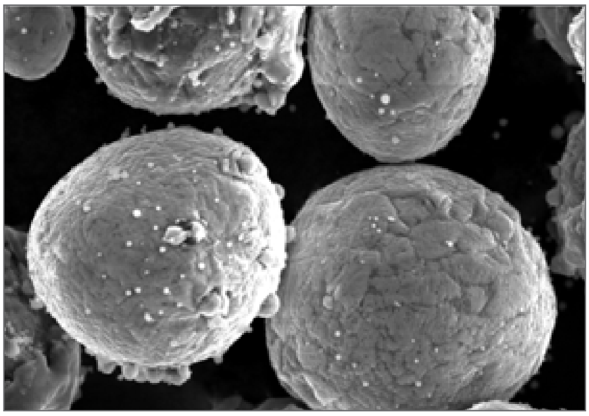


SEM picture of VIM gas atomised Pearl ® Micro Ni718 powder (Courtesy of Aubert & Duval)

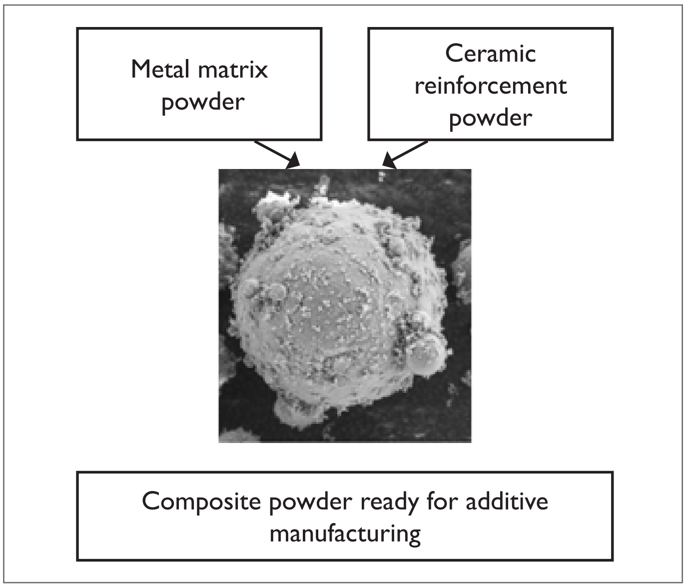
3.2.3 Other powder manufacturing processes

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

- Plasma atomisation and spheroidisation 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 atomisation can be used in particular to spheroidise refractory metals such as Mo alloys, W and WC.
- Centrifugal atomisation, 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 atomised Elektron® MAP+ magnesium powders (Courtesy of Magnesium Elektron)



Innovative Metal Matrix Composite AlSiMg powder for additive manufacturing , reinforced with micronsised 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 characterising 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 atomisation 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 µm for EBM and LMD technologies

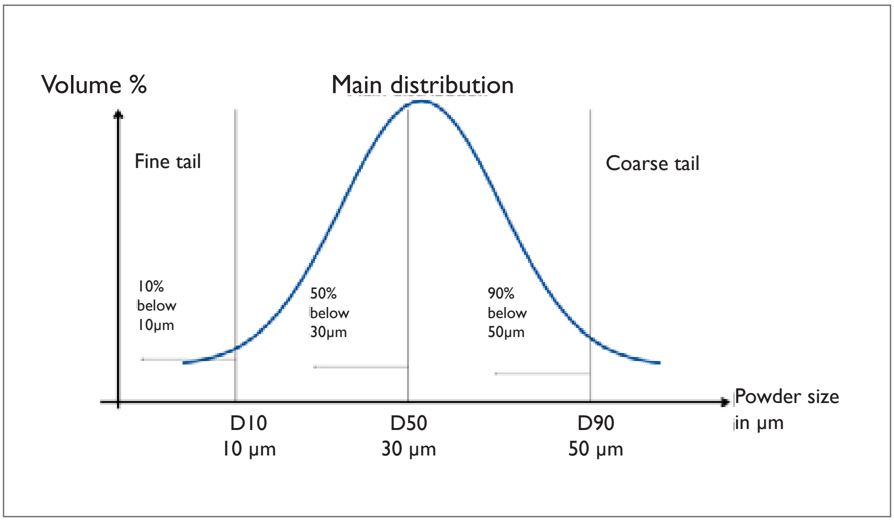
The Particle Size Distribution (PSD) is an index indicating what sizes of particles are present in what proportions (i.e. the relative particle amount as a percentage of volume where the total amount of particles is 100 %) in the sample particle group to be measured.

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% of the population lies below D10
- The D50, or median, ie the size where 50% of the population lies below D50
- The D90, ie the size where 90% of the population lies below D90



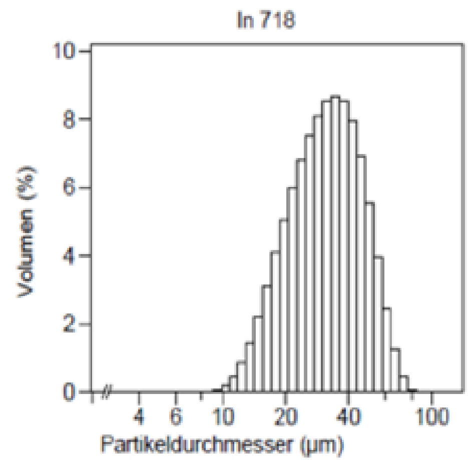
Example of D10, D50 and D90 on a PSD curve for a 10-50 microns powder

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)

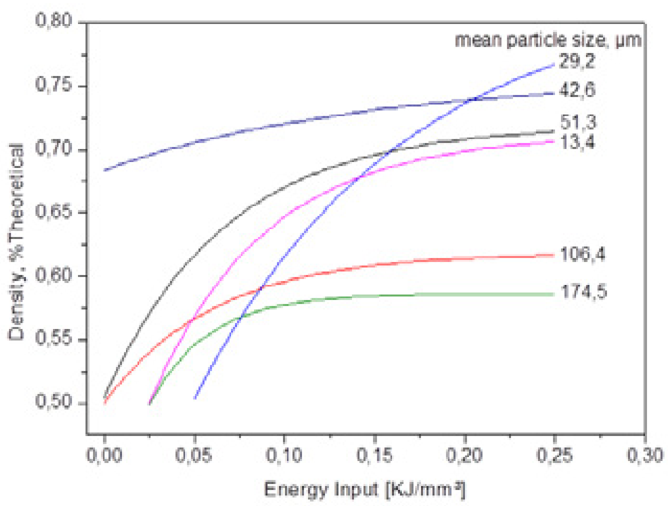
It is important to note that the PSD results will be dependent of the chosen test methods, which can provide different results in particular depending on powder morphologies.



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 a spherical shape because it is beneficial for powder flowability and also to help forming uniform powder layers in powder bed systems.

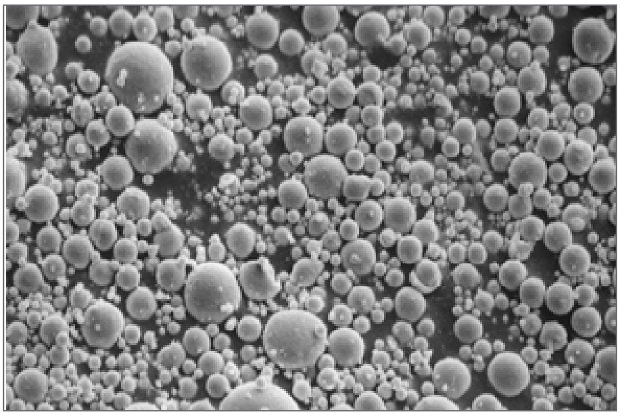
The powder morphology can be observed by SEM (Scanning Electron Microscope).

Typical defects to be controlled and minimised 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 atomised 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

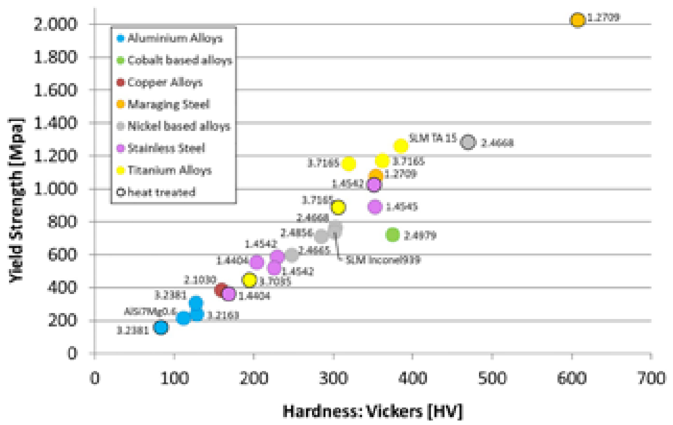
3.4 Alloys and material properties

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:

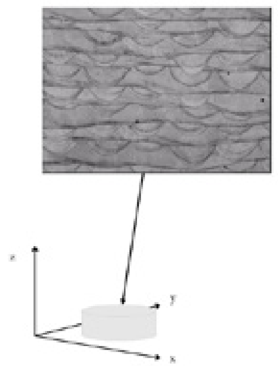
- Superior to the properties obtained with investment casting process
- Inferior or sometimes close to the conventional wrought part



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

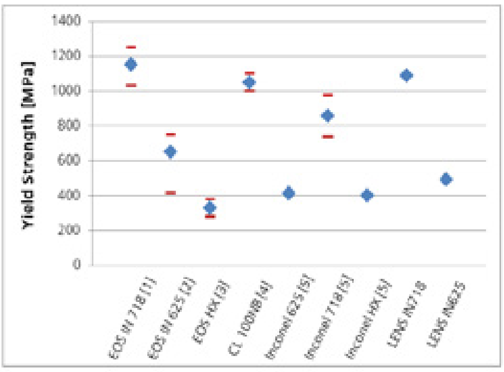
Key features of materials produced by additive manufacturing are:

- 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

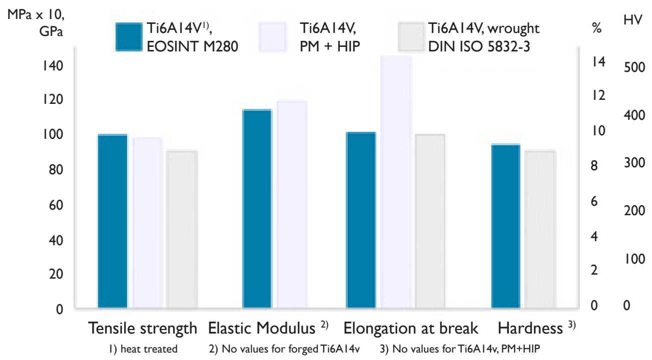


Microstructure of material produced by laser beam melting

Heat Treatment	Tensile testing
[1] Heat treatment procedure per AMS 5662	According to ISO 6892:1998
[2] Anneal at 870 °C (1600 °F) for 1 hour, \ rapid cooling	According to ISO 6892-1:2009
[3] Heat treatment procedure SAE AMS 2773	According to ISO 6892-1:2009
[4] Heat treatment procedure per AMS 5662	20°C according to DIN 50125
[5] No heat treatment	Average values of horizontal and vertical built samples



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

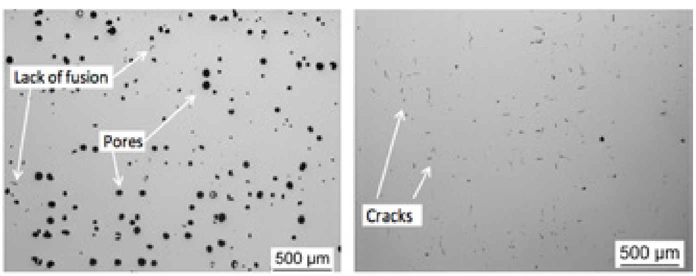


Mechanical properties for Ti6Al4V materials by SLM, SLM+HIP and wrought (Courtesy of Fraunhofer IFAM)

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 Optimising process parameters to improve material properties

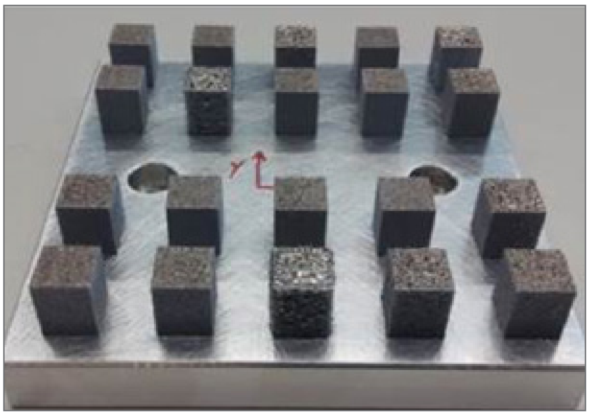
To achieve high mechanical strength and adequate fatigue behaviour, it is important to produce high density parts with optimal surface quality and to minimise defects, through the optimisation of process parameters. In this way, a working window is obtained with a define set of laser parameters where 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 vaporisation of the material creating defects and reducing material density.

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

To optimise 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 characterised 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)

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

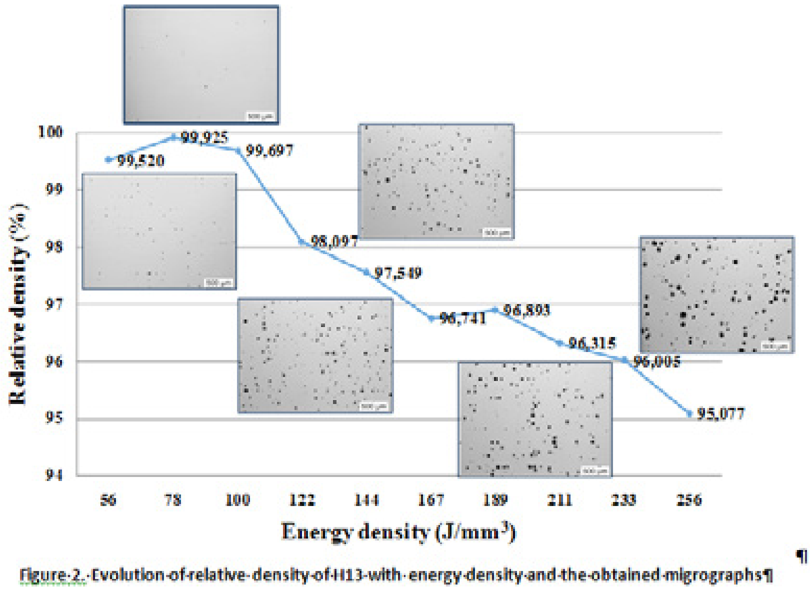
E = energy density

P = power (W)

v = scanning speed (mm/s)

h = hatch spacing (mm)

t = layer thickness (mm)



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

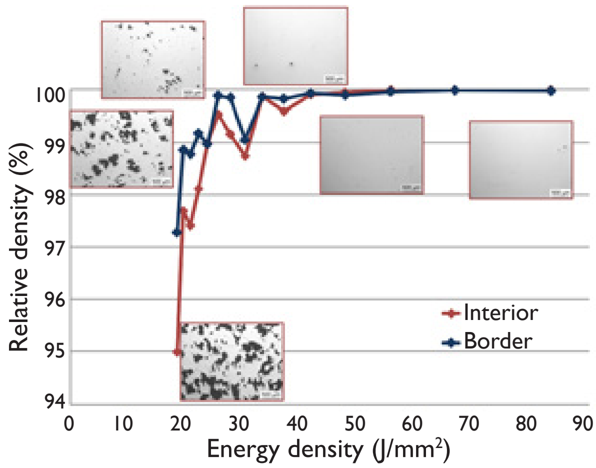
The second example below with different laser parameters on a SLM machine for Ti6Al4V was achieved to optimise them both for interior and borders.

Here, both interior and borders are practically free of defects when 40 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 μm) and irregular defects are found in the samples due to partial melting of the particles which induces a defective powder deposition.

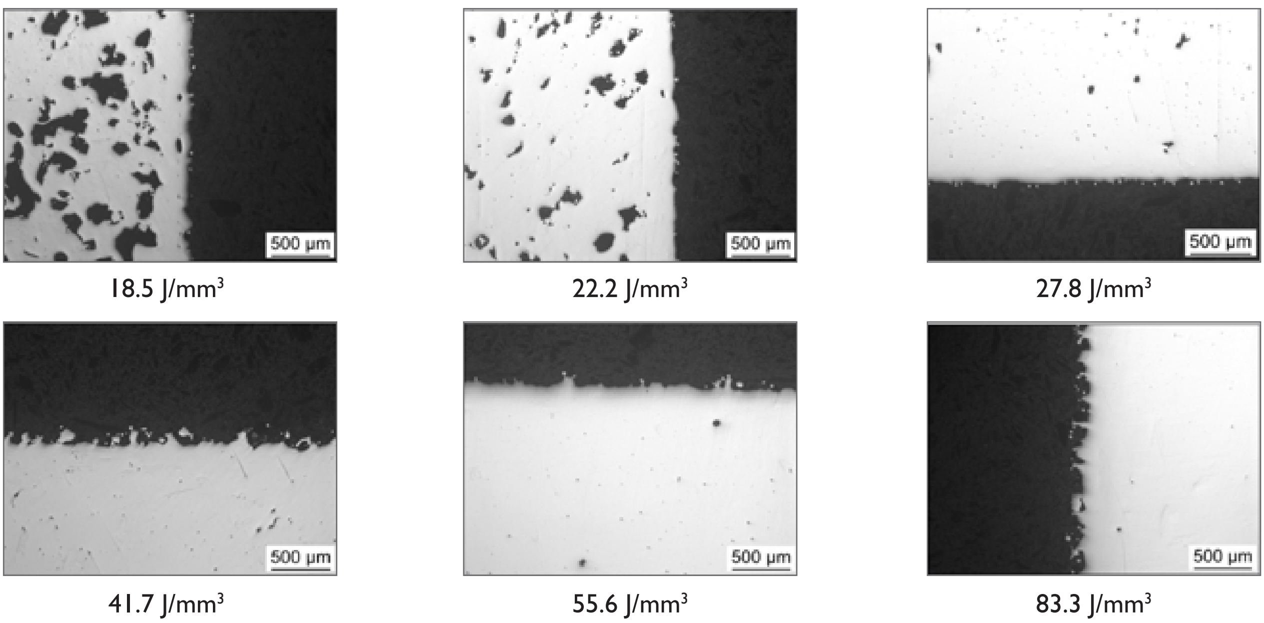
At high energy densities with low scanning speeds, the pores are spherical and small (<100 μm) due to gases trapped in the melt pool.



Relative density vs energy density applied in the optimisation 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 (~10-12 μm) ensuring improved surface quality, are obtained at low energy densities (< 30 J/mm^3). However, in these conditions the sub-surface porosity is too high. Increasing slightly the energy density up to 30 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 J/mm^3 are necessary to obtain parts with 99.7%-99.9% relative density, whereas an energy density of 30 J/mm^3 is enough to have both improved surface quality and minimised defects in borders.



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

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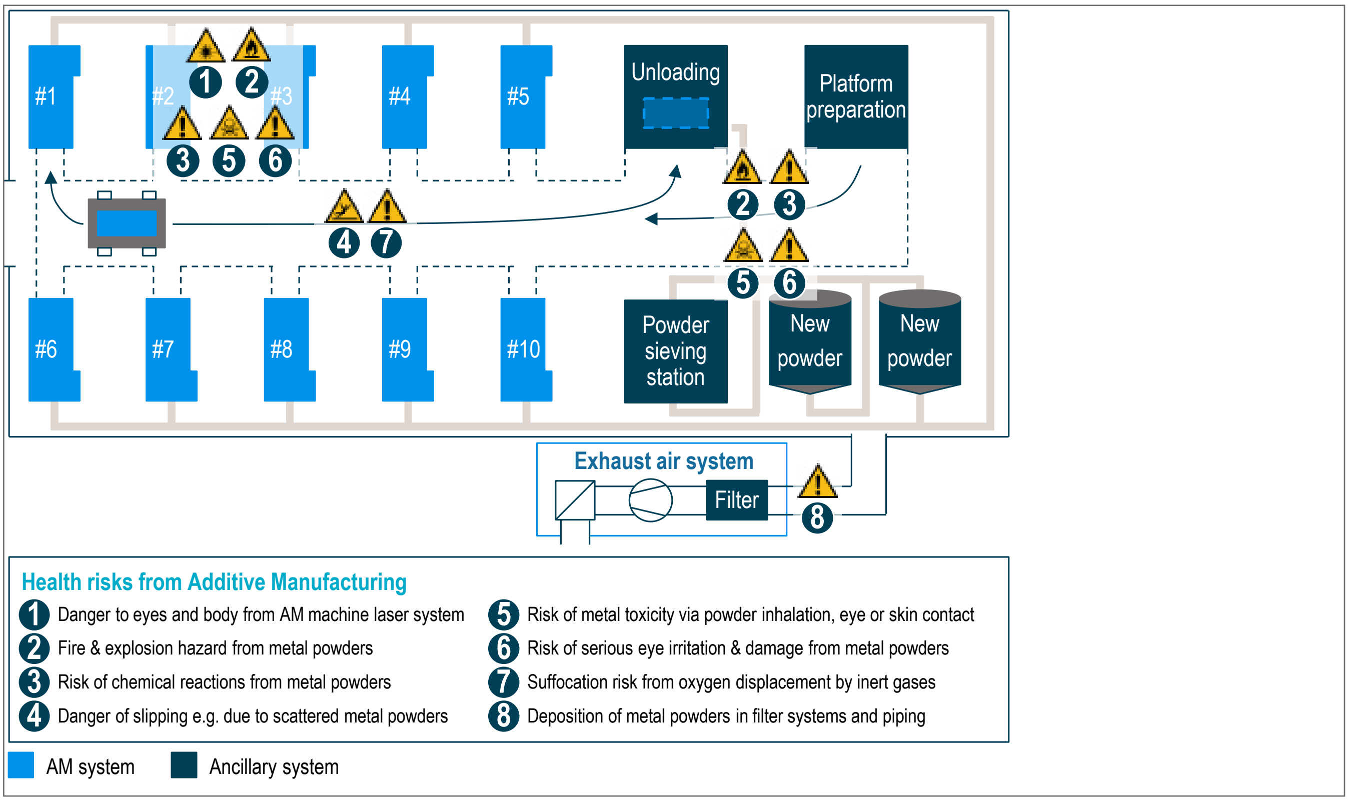
3.5 Powder Handling and Safety

With metal additive manufacturing process, health risks may come from the AM machine (including laser system), inert gases or metal powder.

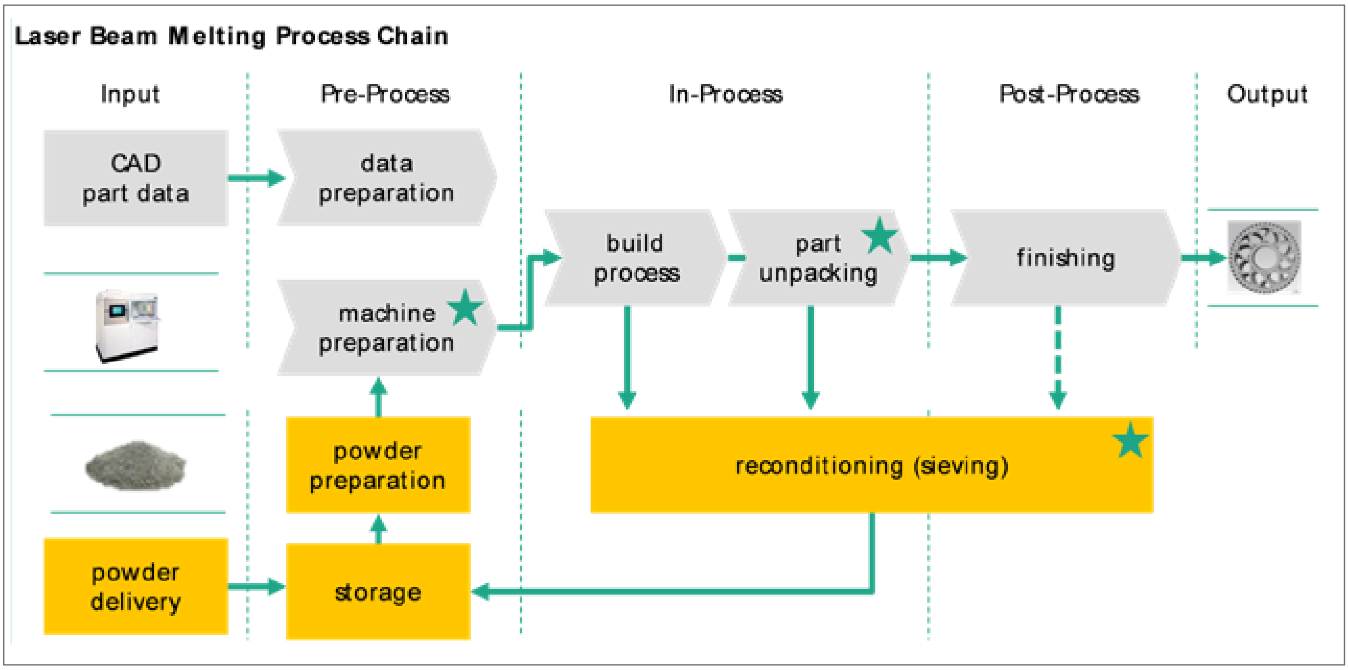


Health risks in AM factories (non-exhaustive) (Courtesy of Roland Berger)

Regarding metal powders , they undergo various operations during the additive manufacturing process such as:

- Logistical operations (filling of powder into the machine, filling of powder from one container into another)
- Preparative steps for processing
- The build-up process itself
- Post process steps such as sieving

The figure below shows an example of process steps for LBM-process including the powder path.



Example of process steps for the LBM-process, according to Lutter-Günther et al. 2016. Process steps with increased risk for airborne powder are marked with a star (*) (Courtesy of Fraunhofer IGCV)

Some of these steps may bring the powder into contact with the operators and ambient atmosphere.

The particle size distribution of the used powders may contain a fraction which is considered respirable dust or even so called alveolar dust. Respirable dust can reach the lung through the respiratory system while the even more noxious alveolar dust particles have an even smaller diameter and can reach the pulmonary alveoli. Several alloys including most steel powders contain alloying elements which are carcinogenic.

Besides, alloys like aluminum or titanium are reactive and could therefore lead to a risk of explosion.

In order to avoid these risks, the formation of airborne dust should be avoided wherever possible.

Therefore personal protective equipment (PPE) is needed during powder handling, and shall include at least:

- Dust mask to avoid the inhalation of airborne powder
- Protective clothing to avoid powder contamination on regular clothing
- Protective gloves to avoid powder contamination on skin
- Safety shoes with protection against electrostatic discharge (ESD) combined with an electrostatically dissipating ground to avoid possible ignition sparks

Machine operator wearing PPE rigged for person specific dust contamination measurements

The photo below shows a machine operator wearing all the above mentioned personal protective equipment. The operator is additionally equipped with a dust exposition measurement probe in order to assess the personal exposure.

As the amount of airborne powder is strongly dependent on the additive manufacturing process applied, the used equipment, and the surrounding facilities, a dust measurement may be advisable in order to assess the amount of airborne powder within the production facility. In some European countries this can be organised in cooperation with the Employer's Liability Insurance Association. In Germany the limits of exposure can be found in TRGS 900. However dust exposure limits are not defined on a European level, thus national exposure limits have to be considered.

Work on health and safety issues of additive manufacturing processes is currently carried out on multiple levels and at an international level within the ISO TC261 and ASTMF42– Joint Adhoc group 'EH&S Considerations for Additive Manufacturing'.

Allowed safety values for general airborne dust and some defined metallic alloying elements according to German regulations can be seen in Table 1.

Table 1

	Safety Value	Source
Alveolar dust	1.25 mg/m³	TRGS 900
Respirable dust	10.00 mg /m³	TRGS 900
Chrome (respirable)	2.00 mg/m³	TRGS 900
Cobalt	5.00 µg/m³	TRGS 561
Nickel (alveolar)	6.00 µg/m³	TRGS 900

Safety values for dust in air according to German regulations

Work on health and safety issues of additive manufacturing processes is currently addressed on multiple levels. In Germany the "VDI 3405 Blatt 6.1" is in the process of being published. In this guideline most regulatory aspects are summed up in order to help reduce insecurities on EHS-aspects in additive manufacturing. At an international level, the ISO TC261 and ASTMF42– Joint Adhoc group "EH&S Considerations for Additive Manufacturing" together with its national supporters is also working on international standards on the matter.

4. DESIGN GUIDELINES FOR LASER BEAM MELTING

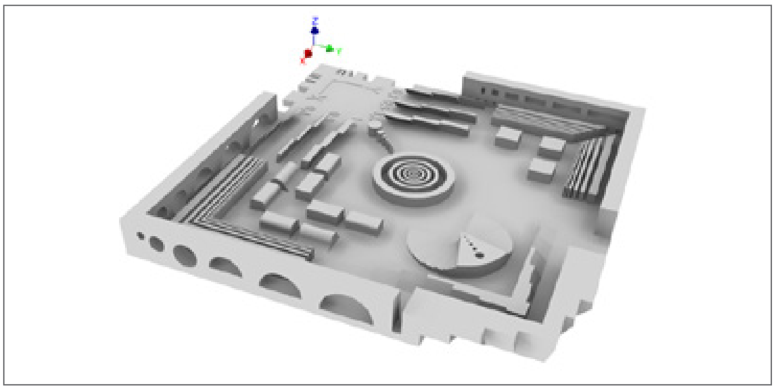
4.1 Basic design rules

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

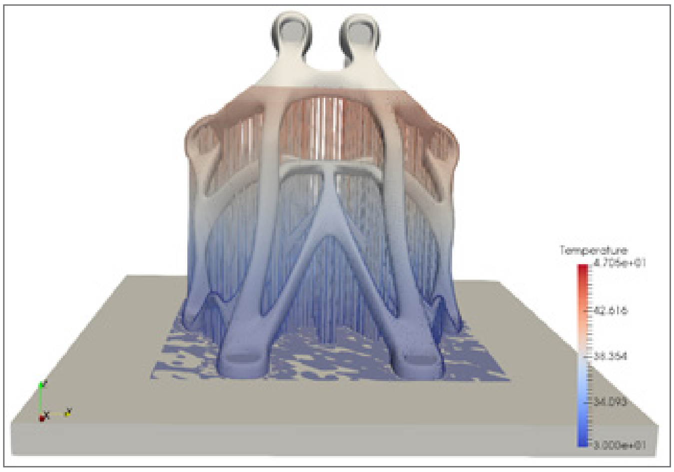
AM technologies offer unique possibilities regarding part design and possible geometries.

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)

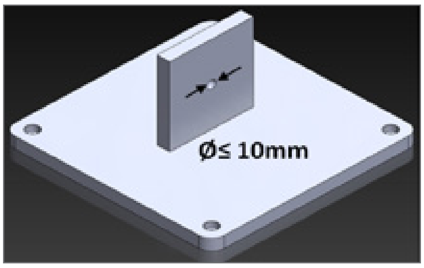


Simulation of Additive Manufacturing on a 3d printed part using Virfac® software (Courtesy of GeonX and Poly-shape)

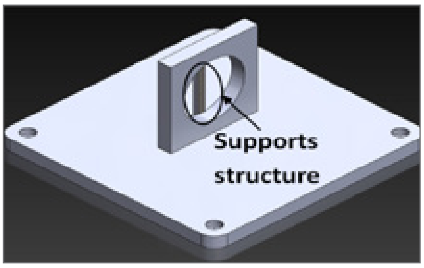
4.1.1 Holes and internal channels

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 elipse profile minimising overhang area.

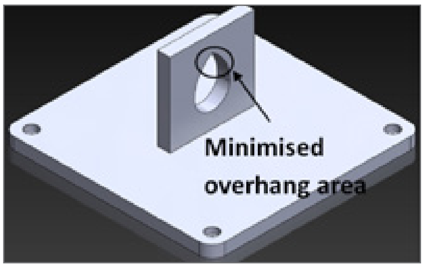
Another approach can be to integrate functionally the supports so as to avoid removing them.



Round hole without support structure (Courtesy of Renishaw)



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



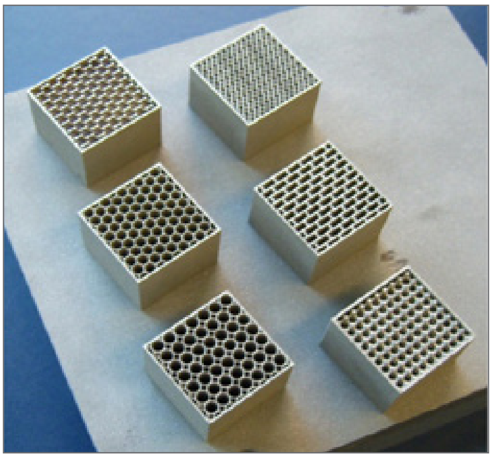
Elipse profile to avoid support structures (Courtesy of Renishaw)

4.1.2 Minimum wall thicknesses

Recommended minimum wall thickness is usually 0.2mm. 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)

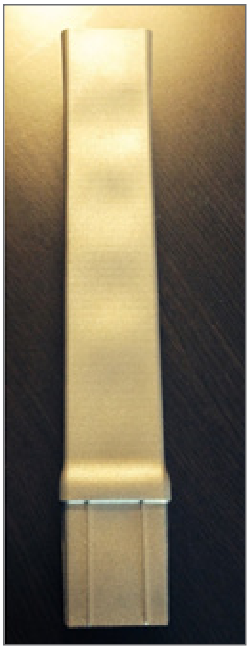
Ni718 manifold showing buckling effect due to too thin walls (Courtesy of Renishaw)

4.1.3 Maximum length-to-height ratio

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

In the example of the 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.



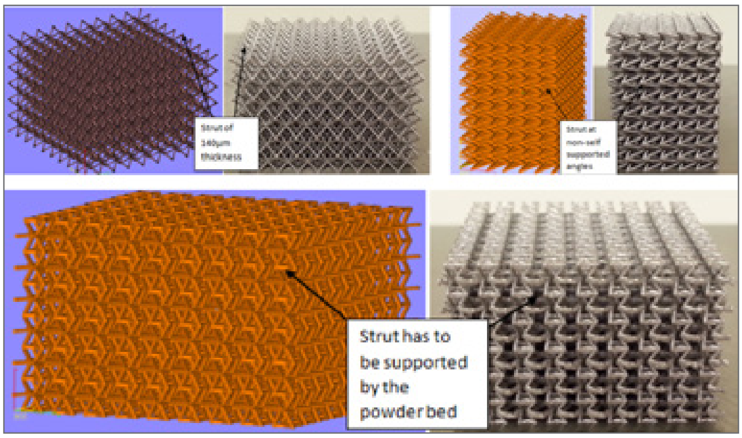
Bike frame component showing buckling effect due to too high length to height ratio. (Courtesy of Renishaw)

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

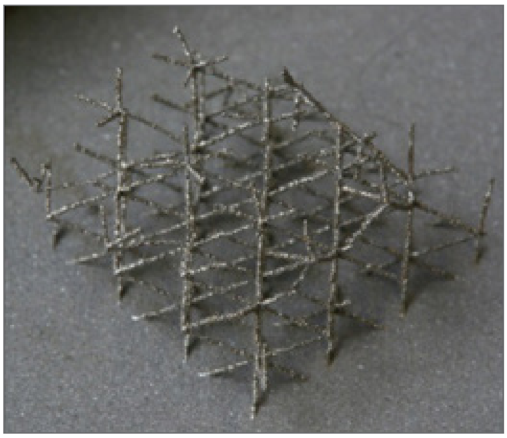
4.1.4 Minimum strut diameter and lattice structures

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.

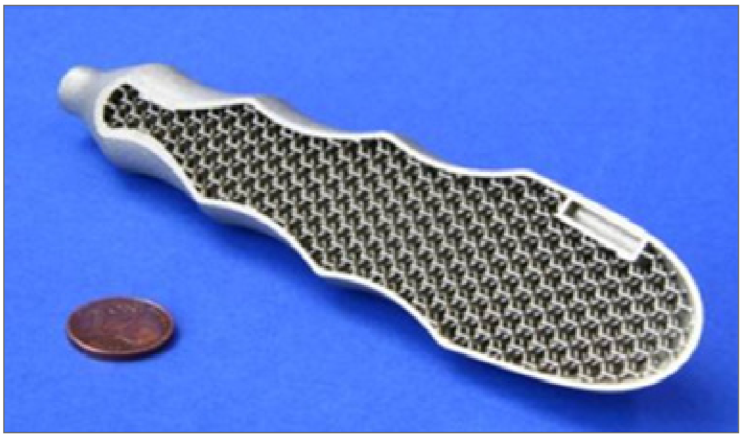
Lattice structures offer the major advantage of reducing part weight without reducing part strength, which is very important in industries such as aerospace and transportation.



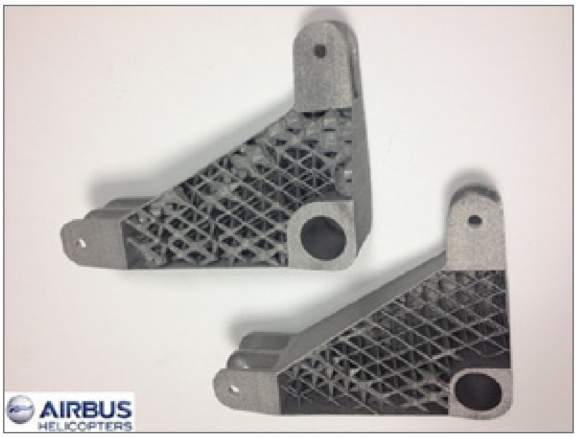
Examples of lattice structures (Courtesy of Renishaw)



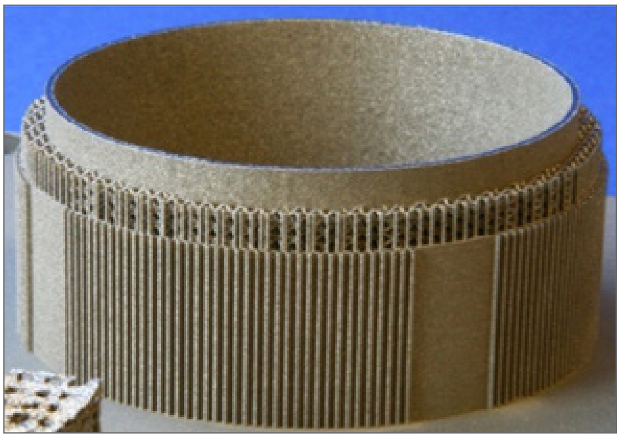
Structure with 0.15 mm strut diameter (Courtesy of Fraunhofer IFAM)



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



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



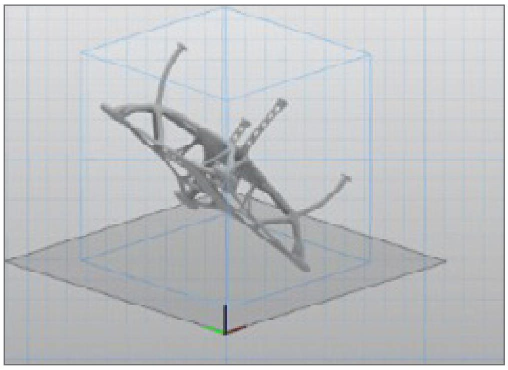
Prototype of heat exchanger for electrical motor with struts of 0.4 mm diameter for COMPOLIGHT project (Courtesy of Fraunhofer IFAM)

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 helping to achieve:

- The shortest build time (i.e. minimising 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



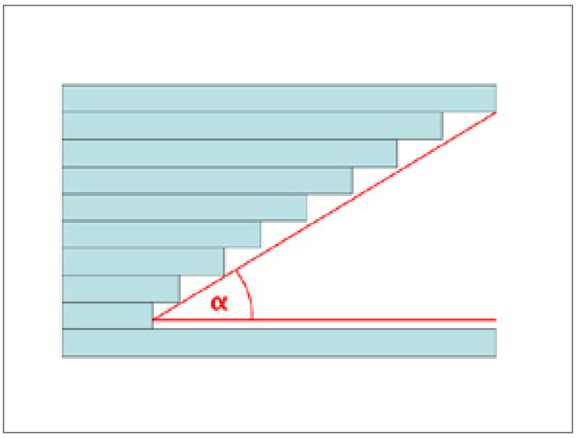
Part orientation with AMT software (Courtesy of Sculpteo)

4.2.1 Overhangs

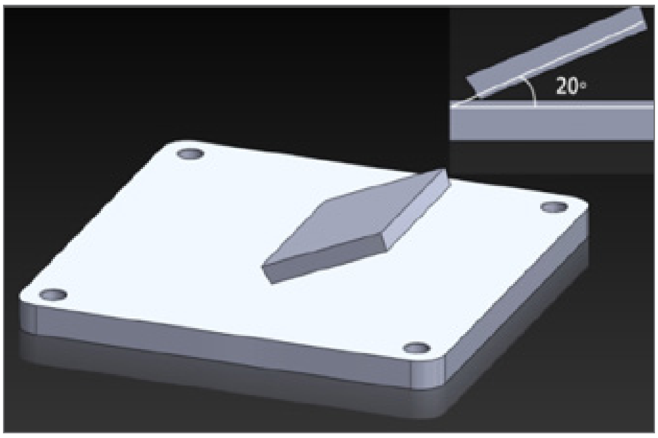
An important rule when building part layer by layer is to avoid having a too low overhang angle because each new welding seam must be supported at least partly by the previous welding seam in the previous layer. When the angle between the part and the build platform is below 45°, support structures are 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.

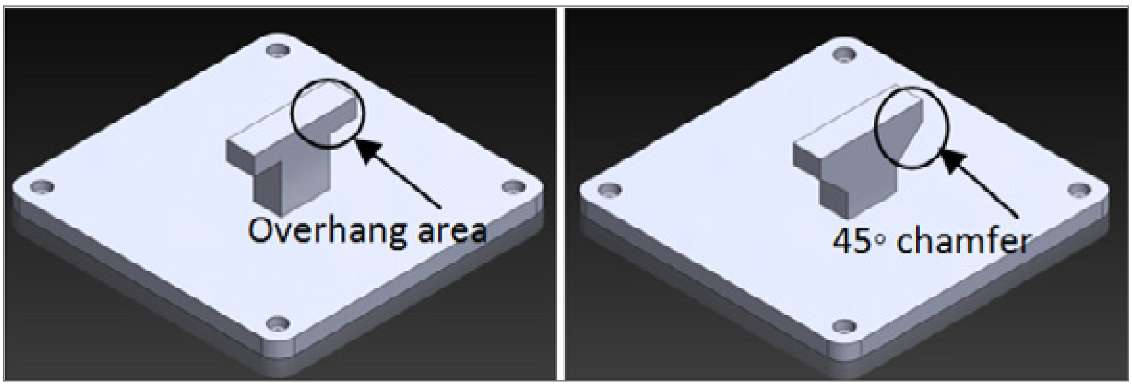
The warping and curled area can also cause build failure if higher than the desired profile because it prevents spreading a new layer of powder.



Overhang angle between build platform and part



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



In case of angles of 90°, a solution to avoid supports is to create a 45° chamfer (Courtesy of Renishaw)

Promoting Powder Metallurgy Technology

4.2.2 Support Structures

Support structures have several functions:

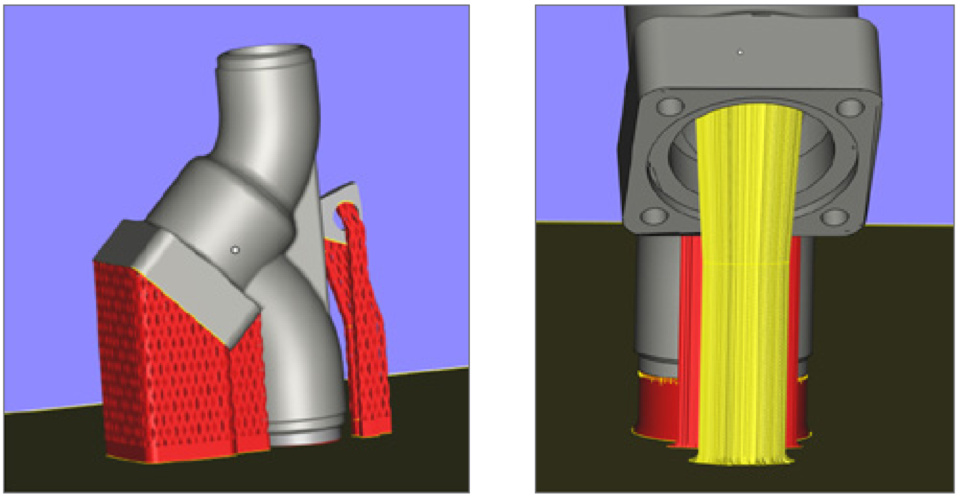
- Support the part in case of overhangs
- Strengthen and fix the part to the building platform
- Conduct excess heat away
- Prevent warping or complete build failure

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)



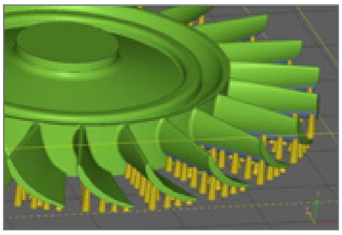
Design of supports with Magics software (Courtesy of Materialise)

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

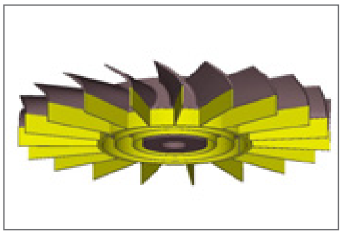
In the impeller example below by Fraunhofer IFAM, two support designs have been evaluated:

- Tree supports with many struts
- Wall supports with one wall for each blade

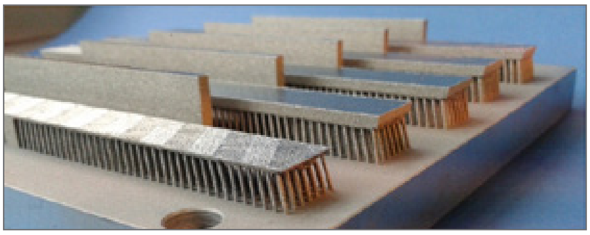
In this example, the wall support proved better both for post processing and for improved stability during manufacture.



Tree support design (Courtesy of Fraunhofer IFAM)



Wall support design (Courtesy of Fraunhofer IFAM)

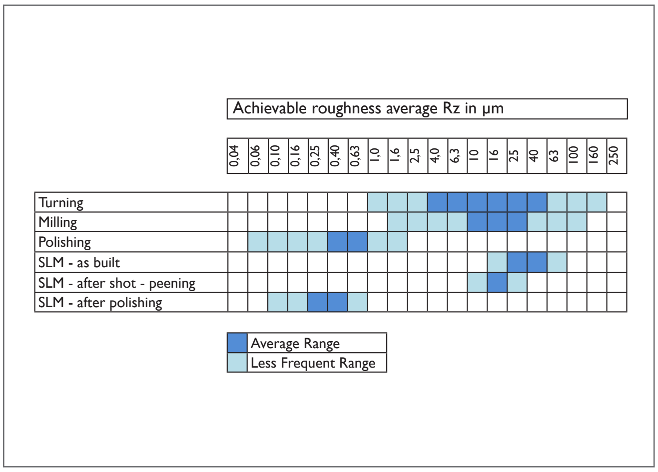


Distortion of tree supports (Courtesy of Fraunhofer IFAM)

4.2.3 Surface roughness

With laser beam melting, achievable surface roughness (Rz) are usually between 25 and 40 µm 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)



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

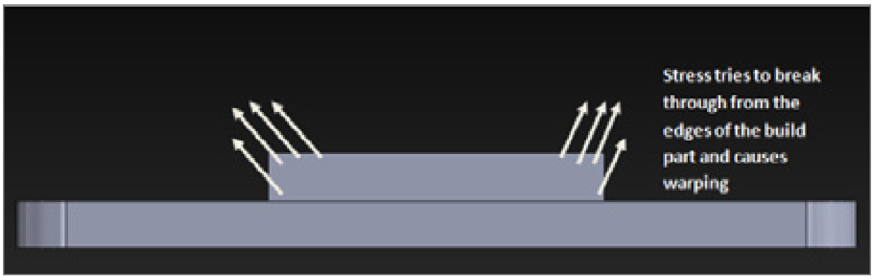
Staircase effect (Courtesy of Fraunhofer IFAM)

Poor down-skin surface roughness (Courtesy of Renishaw)

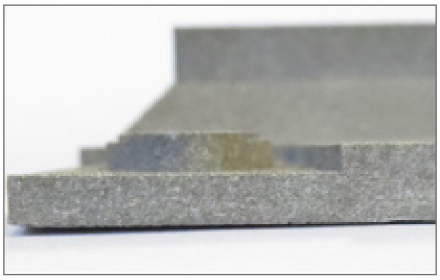
4.2.4 Thermal stress and warping

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

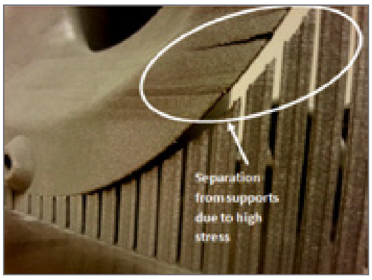
Warping can lead to part distortion, bad junctions between supports and components or recoating problems.



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 optimisation for AM technology

4.3.1 Introduction

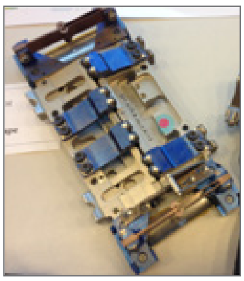
To take full advantage of AM design possibilities, it is important to redesign conventional parts.

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)

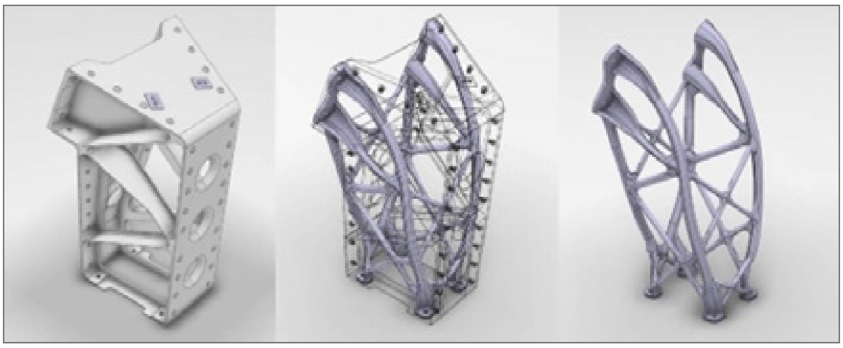
4.3.2 Topology optimisation

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 them from limiting their design, hence maximising the possible improvements. This can be especially interesting when dealing with assemblies (or even entire products).

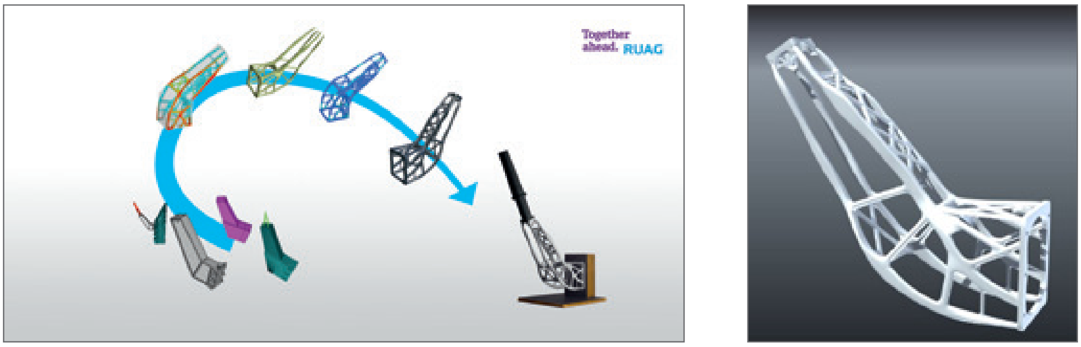
From the functional requirements, the minimal volume of material is then placed in order to link the surfaces and to sustain the load case (be it mechanical, thermal, coupled, etc). This second step is usually achieved by using topology optimisation tools that suggest geometries able to sustain the loads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

The last step is to redesign the optimised 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.

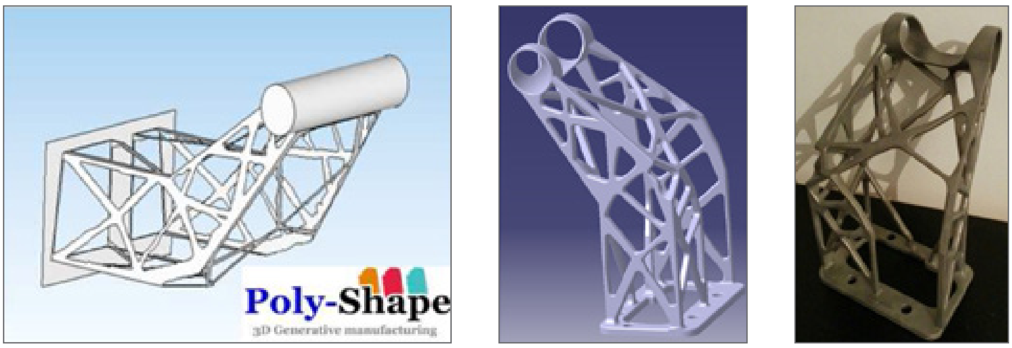


Satellite bracket redesigned for additive manufacturing with topology optimisation (Courtesy of Airbus Defense & Space and Poly-Shape)



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

Since Topology Optimisation leads to noisy geometries, caused by tesselation, 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

The information below is provided by third parties and although EPMA does its best to ensure the case studies are accurate, it is not liable for any mistakes or wrong information.

5.1 Aerospace

Air mixer trump

Material: Nickel alloy C263

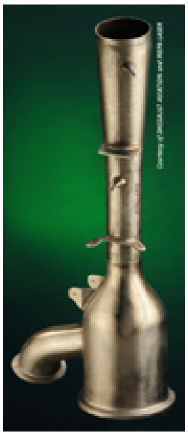
Part size (mm): Length 700

Additive process used: Laser beam melting and laser metal deposition

Part made within the framework of FALAFEL French supported project by combining SLM for the subpart and then building of the upper long pipe of the trump by LMD-CLAD® process, including pressure pads and lugs.

Benefits of AM technology

- Innovative AM process combination giving an optimised and flexible manufacturing process, without tooling fixture.
- Easier modifications of geometry without need for tooling modification or design.
- Shorter delivery time : only 3h46 for the LMD-CLAD® pipe manufacturing



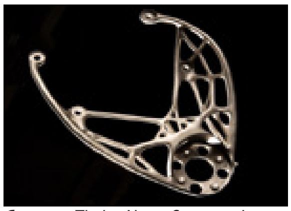
Courtesy: Dassault Aviation and IREPA LASER

Antenna bracket

Material: Titanium

Part diameter (mm): 190 x 230 x 290

Additive process used: Laser Beam Melting



Courtesy: Thales Alenia Space and 3D Systems

Large antenna bracket for a geostationary telecommunications satellite -printed on a 3D Systems' ProXDMP 320 printer-which is 25% lighter, has a better stiffness-to-weight ratio and was completed in half the time vs. traditional manufacturing process.

Benefits of AM technology

- Improved functionality through topological design
- Faster production or reduced manufacturing time

Bionic partition wall

Material: Scalmalloy™ (AlMgSc)

Part size (m): 2,1 x 1,4

Part weight: (kg) 35

Additive process used: Laser Beam Melting

Courtesy: Airbus Operations GmbH, Autodesk, TheLiving, APWorks

Full-height partition wall (line-and retrofit solution) for Airbus A320 aircraft with generative design and additive layer manufacturing with Scalmalloy™ for weight reduction. Besides the Bionic Partition is fully recyclable and follows the design-for-disassembly philosophy. It is easy repairable and thus reduces the consumption of raw materials.

Benefits of AM technology

- Weight reduction: 45% lighter (30kg)
- Reduced fuel costs by approximately $1,500 /year & aircraft
- Reduced CO^2 footprint by ten tonnes/year & aircraft
- Improved operational costing, better recyclability, easy customisation

2016 WINNER

Boroscope bosses for A320neo Geared TurbofanTM engine

Material: Nickel alloy 718

Part dimensions (mm^3): 15.600

Boundary Box (mm): 42 x 72 x 36

Additive process used: Laser Beam Melting

Courtesy: MTU Aero Engines

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 boroscope.

Benefits of AM technology

- Series production of up to 2,000 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

Bracket

Material: TiAl6V4

Part size (mm): 225 x 225 x 120

Additive process used: Laser Beam Melting

Courtesy: Airbus and MBFZ Toolcraft GmbH

Light weight bracket for cabin door

Benefits of AM technology

- 30% weight reduction

Cardan cross for Ariane 5 Vulcain® 2

Material: Nickel base 718

Part size (cm): 23 x 23 x 10

Additive process used: Laser Beam Melting

Courtesy: ArianeGroup and VOLUM-e

Structural part localised in the exhaust lines of cryogenic engine Vulcain®2 of Ariane5 first stage. 1st metallic ALM part by ArianeGroupto fly, on November 2016 on Ariane5 Vulcain®2 engine.

Benefits of AM technology

- Lead time reduction of ~ 20%
- Optimisation of supply chain by replacement of casting

Fitting for the satellite Hipparcos

Material: Aluminium (Scalmalloy®)
Part mass (g): 97
Additive process used: Laser Beam Melting

Courtesy: Airbus Defence & Space and CATEC

New design of satellite fitting by topology optimisation, which only can be fabricated using AM processes to support baffles for the Hipparcos satellite by ESA launched in 1989, as an alternative to the 209 g. original bracket manufactured by a complex milling operations from conventional AL7075-T5 aluminium alloy.

Benefits of AM technology

- Weight reduction
- Same mechanical behavior

Flange

Material: Nickel base HX
Part size (mm): D 75 H 110
Part weight (g): 652
Additive process used: LBM, LMD and WAAM

Courtesy: TECNALIA, VENTANA, University of the Bask Country

Comparison of 3 LBM , LMD and WAAM (Wire Arc Additive Manufacturing) AM processes for the manufacturing of a prototype of flange for aerospace.

HRM cone

Material: AlSi10Mg
Additive process used: Laser Beam Melting

Courtesy: IK4-LORTEK

Redesign by topological optimisation and introduction of variable lattice structures mixed with massive zones (Addispace project).

Benefits of AM technology

- Around 30 % weight reduction compared to original design
- Multifunctionality by weight reduction and surface maximisation

Jet Pump

Material: Stainless Steel 15-5PH
Part height (mm): 259
Part weight (kg): 0.950
Additive process used: Laser Beam Melting

Courtesy: Liebherr Aerospace and Fusia

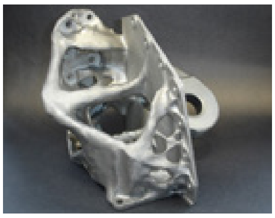
The Jet pump is placed into air conditioning pack of aircraft. It is used to generate air flow inside the pack

Benefits of AM technology

- Design freedom to reach optimised aeraulic air flow
- One step manufacturing (all components in one single part)
- Weight reduction compare to conventional solution
- Shorter development leadtime

Main Gearbox Bracket

Material: Ti6Al4V
Part weight (kg): 1.6
Additive process used: Electron Beam Melting



Courtesy: Airbus Helicopters, Fraunhofer IFAM and Technical University Dresden

Two structural parts of a helicopter merged into one and redesigned by topology optimisation, allowing for 40% weight reduction.

Benefits of AM technology

- Highly complex geometry which can only be produced by additive manufacturing
- Weight reduction

Mini TRV

Material: Nickel base 718
Part size (mm): Height 96, OD 500
Part weight (kg): 7.3
Additive process used: Laser Beam Melting

Courtesy : GF Precicast Additive SA

Aeronautical structural component printed on a 3DS/GF DMP Factory 500 machine.

Benefits of AM technology

- Integration of functions

Prometheus Central Casing

Courtesy: *ArianeGroup and VOLUM-e*

Material: Nickel base 718
Part size (cm): 39 x 39 x 35
Additive process used: Laser Beam Melting

This part is a casing of the turbomachinery of future demonstrator Prometheus (LOX-CH4 reusable rocket engine) developed by ArianeGroup under a CNES initiative. It was produced on an EOS M400 machine.

Benefits of AM technology
- Co-engineering between engineering and themanufacturing team in order to minimise support structures

Repair of worn lips on a labyrinth seal

Courtesy: *BeAM*

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

RSC Emission Rake

Courtesy: *RSC Engineering GmbH*

Material: Inconel 718
Part size (mm): 270 x 80 x 180
Part weight (kg): 2.0
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 analysing 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

Satellite bracket

Courtesy: *RUAG and EOS GmbH*

Material: AlSi10Mg
Additive process used: Laser Beam Melting

Cost effective, lighter and stiffer components for space applications, produced on EOS M 400, two parts in one job, with 1kW laser power in 41hours.

Benefits of AM technology
- About 40% weight reduction compared to traditionally manufactured object
- Advanced part properties (e.g. rigidity, frequency)

Thrust Chamber

Courtesy: *Cell Core GmbH, SLM Solutions*

Material: Nickel base 718
Part size (mm): D 75 H 110
Part weight (kg): 5.48
Additive process used: Laser Beam Melting

Prototype of complex monolithic rocket engine (injector and thrust chamber) produced on a SLM280 machine to combine numerous individual components in to one, together with multifunctional lightweight construction. The engine is designed to avoid support structures, which would have required time-consuming post-processing

Benefits of AM technology
- Integrated design
- Multifunctional lightweight construction
- Time saving

Two-phase cooling system

Courtesy : *NLR, Thales Avionics Electrical Systems SAS*

Material: AlSi10Mg and Scalmalloy
Part size (mm): 148 x 250 x 210
Part weight (kg): 2.6
Additive process used: Laser beam melting

Cooling system for high power electronics with small tubing diameters and compact components produced by LBM process. Clean Sky 2 project No. 738094.

Benefits of AM technology
- Weight reduction
- Complex internal cooling structures

Titanium Insert for Satellite Sandwich Structures

Material: TiAl6V4
Part weight (g): 500
Additive process used: Laser Beam Melting

Courtesy: Atos and Materialise

Each kilogram put into orbit costs around $20,000. Every gram saved helps make space a more attainable frontier. With an optimised design by Materialise & Atos, the new inserts are just one-third of the initial weight of 1454 grams, with some improved properties added in.

Benefits of AM technology
- Weight reduction by using topology optimisation & lattice design
- Reduction of thermo-elastic stress issues during the curing process of carbon fiber-reinforced polymers
- Increased lifetime

5.2 Energy

Burner repair

Material: Nickel alloy HX
Additive process used: Laser Beam Melting

Courtesy: EOS, Siemens Industrial Turbomachinery AB

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

ForgeBrid®

Material: Nickel base 718
Part weight (kg): 13,2
Additive process used: Laser Beam Melting

Courtesy: Rosswag Engineering, a Division of Rosswag Ltd.

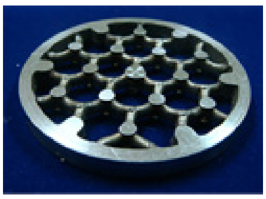
The ForgeBrid® is a hybrid component, consisting of an open die forged ring and an additively manufactured blade geometry on top of the ring. Both body parts are proceeded at Rosswag and combine the advantages of forging and additive manufacturing technologies.

Benefits of AM technology
- Blades with inner channels (impossible to machine)
- Improved cost efficiency thanks to hybrid process approach

2018 WINNER

Honeycomb Orifice grid plate

Material: 316L
Part size (mm): H 7, D 65
Additive process used: Laser Metal Deposition



Courtesy : RRCAT

Complex shape and hanging structure produced on a 2 kW fibre laser based LMD system developed in house.

Benefits of AM technology
- Complex geometry difficult to produce by casting & EDM

Heat Exchanger

Material: Nickel base 718
Part size (mm): 80 x 38 x 19
Additive process used: Laser Beam Melting

Courtesy: Italian Institute of Technology and Politecnico di Torino

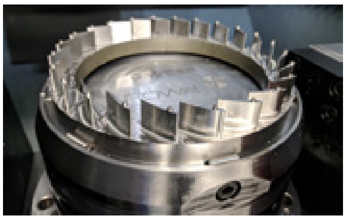
Heat exchanger designed within HELMETH FP7 Project, to operate at high temperature and under high pressure in a severely aggressive ambient (with H_2 and O_2). Each side of the heat exchanger has three channels and inside the channels longitudinal triangular fins have been inserted in order to act as fins for the enhancement of the heat transfer and in order to act as structural support for the plates. Each channel is sandwiched between two cold side channels and vice versa, except for the external ones.

Benefits of AM technology
- Slightly improved performances with a global HTC of 50 [W/m²/°C] than traditional gas-gas counter-flow heat exchanger (10 and 40 [W/m²/°C])

Nozzle ring

Material: Stainless and Nickel-based alloys

Additive process used: Hybrid Laser Metal Deposition



LMD Process development within HYPROCELL project for multi-materials with digital approach, from raw material to final welding of the blades on top ring by laser cladding.

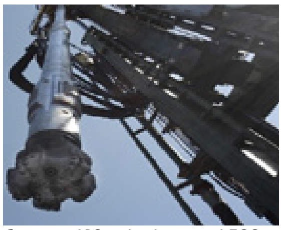
Benefits of AM technology

- Reduction of lead time
- Capability of multi-material deposition
- Reduction of material scrap

Rotary steerable system

Material: 17-4PH

Additive process used: Laser Beam Melting



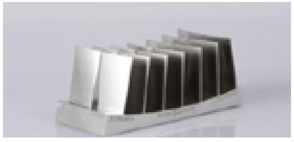
Courtesy: APS technologies and EOS GmbH

More durable and flexible oilfield drilling equipment made on EOSINT M 280 machine.

Benefits of AM technology

- Drilling assembly with part number reduced from four separate components to one
- Optimised design increases drilling accuracy, and reduces post-processing and production costs
- Shorter lead times and time-to-market

Stator segment of axial compressor



Courtesy: EOS GmbH

Material: Nickel base 718

Part size (cm): 10 x 5

Additive process used: Laser Beam Melting

Thin and high stator blades are difficult to manufacture because of vibration issues during milling process and the surface finishing is very challenging and time intensive. Produced on EOS M 290 and one step post processing with MMP Technology®.

Benefits of AM technology

- Reduction of production complexity: only two steps
- Easy post processing with MMP
- New designs with more and closer stator blades possible
- Larger Segments reduce installation time and installation complexity on axial compressor

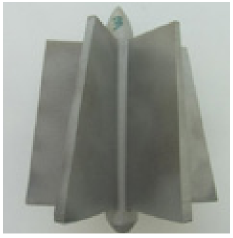
Twister used in an air extraction pump

Material: 316L

Part height (mm): 185

Part diameter (mm): 95

Additive process used: Laser Beam Melting



Courtesy: ENGIE Laborelec

Twister component used in an air extraction pump of a combined cycle gas turbine plant condenser to create a swirl in the water flow. After an internal qualification program, the twister was successfully put into service in October 2016 and removed after 2000 hours in operation. Non-destructive evaluation did not reveal any cracking or critical degradation.

Benefits of AM technology

- Shorter leadtime and cheaper than conventional casting
- Suitable for on-demand manufacturing of spare or obsolete parts, with comparable costs vs. 5-axis CNC machining

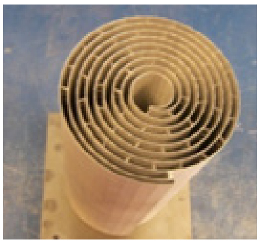
Vacuum permeator

Material: Stainless steel (AISI 316L)

Part weight (kg): 2

Part dimensions (cm): 10 x 10 x 20

Additive process used: Laser Beam Melting



Courtesy: IK4-LORTEK

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

5.3 Medical

Cleanable Filter Disc

Courtesy: Croft Additive Manufacturing

Material: Stainless Steel 316L
Part size (mm): Ø55
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 needs, including a change in aperture size, without the creation of new toolings

Cranial implant

Courtesy: EOS GmbH, Alphaform and Novax DMA

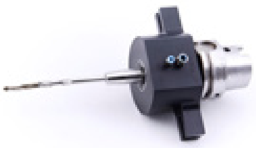
Material: Titanium alloy
Part dimensions (cm): 12 x 8
Additive process used: Laser Beam Melting

Development and manufacture of a customised 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

Internally cooled bone drill



Courtesy: Toolcraft, IFW – Leibnitz University

Material: 316L steel
Part height (mm): 1
Part diameter (mm): 100 x 50
Additive process used: Laser beam melting

Bone drill with integrated cooling ducts allowing the coolant to flow inside the tool along the helix and back to the tool holder without coming into contact with the wound. New design to avoid both tissue damage by tool heating and coolant fluid to enter the wound.

Benefits of AM technology

- Temperature reduction by 70%

Removable Partial Denture (RPD) Framework

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

Material: Cobalt Chrome (ASTM F75)
Part dimensions (mm): 60 x 30 x 0.5
Part weight (g): 15
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

Patient specific mandibula reconstruction plate

Courtesy: Mimedis AG, FHNW

Material: CP Titanium Grade 2
Additive process used: Laser Beam Melting

Project started in 2007 with initial SLM processing of titanium to produce patient specific implants followed by cell and animal studies. First clinical trial achieved end of 2012 with titanium implants for cranio-maxillo-facial applications.

Benefits of AM technology

- Shorter leadtime and lower production cost vs. milling and drilling of plates and bone substitutes
- Improved geometrical complexity for individualised surgical solutions

Hip Implant

Courtesy: Instrumentaria and EOS GmbH

Material: Ti6Al4V
Part size (cm): 21 x 15
Additive process used: Laser Beam Melting

Design and construct a precision-fitting, lightweight, yet stable hip implant in a short period of time, manufactured with the EOSINT M 280.

Benefits of AM technology

- Precise fit
- Short planning and production times for imminent operation
- Minimum weight for high patient comfort

5.4 Industry and Tooling

Bolometer

Material: Nickel base 625
Part size (mm):
H 220, L 115, W 132
Part weight (kg): 2.6
Additive process used: Laser beam melting

Courtesy: Poly-Shape

Benefits of AM technology

- Improved performance
- Increased Component Complexity
- Weight Saving

Core and cavity molds for PVC pressure reduction valve

Material: Stainless steel
Part weight (kg): 7
Additive process used: Laser Beam Melting

Courtesy: GF Machining Solutions and IPC (Centre Technique Industriel de la Plasturgie et des Composites)

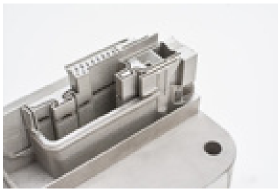
Project to demonstrate the possibilities of AM for improved mold temperature management applied to the core and cavity inserts used in the injection process of a high-quality plastic valve and taking into account injection pressure, cooling cycle and cooling fluid speed. Besides, the previous insert was build out of four individual parts, while employing AM allowed building the core in one part or two parts (conventional manufactured preform + AM).

Benefits of AM technology

- Conformal cooling/heating channels enabling a variotherm mold temperature management (heat&cool) alongside the whole mold surface
- Less sink marks on plastic parts produced
- O-ring flatness with good tolerances and reduced welding line
- Cost efficiency by assembling the AM part on a conventional preform

Cooling & calibration unit for polymer extrusion

Material: 316L steel
Part size (mm): 120 x 60 x 120
Additive process used: Laser beam melting



Courtesy: VIVES University College

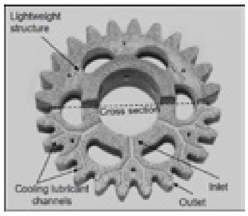
Calibration unit used to cool the plastic extrusion profiles to give them their final and exact shape, withhighly complex cooling channels and vacuum slots that can only be achieved with AM process.

Benefits of AM technology

- Reduced number of parts and less assembly operations
- Increased production speed
- Improved geometrical quality of extruded profile

Gear Wheels

Material: Case hardening steel (AISI / SAE 5115; 1.7131; 16MnCr5)
Part mass (g): 812
Part volume (mm³): 103.000
Part dimensions (mm): (LxBxH): 118 x 118 x 30
Additive process used: Laser Beam Melting



Courtesy: Fraunhofer IGCV

New concept of gear drives designed for and produced by Laser beam Melting with normal module 4,5 mm and 24 teeth. The gear drive includes a biomimetic lightweight design and functional integration such as a conformal cooling and an integrated cooling lubricant supply. Project done with the support of German Research Foundation (DFG).

Benefits of AM technology

- Lightweight design
- Active cooling of the gear allowing entirely new operating points
- Pre-series production of gears for prototyping
- Economical production of gears for special applications with a low production volume

Hydraulic valve

Material: Aluminium
Part weight (g): 600
Additive process used: Laser Beam Melting

Courtesy: Materialise, VTT and Nurmi Cylinders Oy

Strong and light hydraulic valve with minimal risk of leakage. To save time, VTT enhanced the topologically optimised valve in STL in Materialise 3-matic, positioned the part, created support structures in data preparation software Materialise Magics, and sent the file directly to the SLM metal printing machine.

Benefits of AM technology

- Weight reduction by 76% compared with the original part (2.5kg)
- Cost effective for bionic design produced in small series
- Less risk of leakage since auxiliary drillings are no longer needed
- Improved flow thanks to smooth transitions between the internal channels

Injection mold cavity

Material: AlSi10Mg
Part weight (g): 600
Additive process used: Laser Beam Melting

Courtesy: Growthobjects – Leitat

Injection mold cavity with air cooling for Neraflix patented disposal individual ham holder. It utilises a non-solid optimised generative lattice that drops the cooling time in the injection cycle, compared with traditional water cooling systems..

Benefits of AM technology

- Material reduction
- Easier & lower cost cooling system
- Increased production
- Shorter lead time

Injection mould

Material: Tool steel

Part I size (mm): 125 x 120 x 90

Part I size (mm): 125 x 114 x 40

Additive process used: Laser beam melting

Courtesy: Toolcraft

Injection mould with topologically optimised design and thus smaller size, reduced number of components, close contour cooling as well as increased cross-sectional area with optimised flow capacity.

Benefits of AM technology

- Reduced machine forces
- Reduced injection cycle time

Lathe tool

Material: Tool steel 1.2709

Part size (mm): 50 x 30 x 4

Part weight (g): 32

Additive process used: Laser beam melting

Courtesy: Rosswag GmbH, ARNO Werkzeuge

ACS4 Arno Cooling System (ACS4) for lathe tool with four outlet nozzles produced on a SLM280 machine, to improve and optimise coolant supply to the cutting tool for longer service life.

Benefits of AM technology

- Improved cutting performance
- Increased component complexity

Pivot

Material: AlSi7Mg0,6

Part size (mm³): X*Y*Z – 259*219*220

Additive process used: Laser Beam Melting

Courtesy: CETIM

Component of rotating machine to produce cables with a speed of 700rpm.

Benefits of AM technology

- Mass reduction
- Number of components in a welded assembly reduced

Rubber extrusion tool

Material: H13 tool steel

Part size (mm³): 90

Part weight (g): 453

Additive process used: Laser Beam Melting

Courtesy: Swerea IVF AB and Trelleborg Sealing Profiles AB

Traditional manufacturing of rubber extrusion tool involves many operations like electro-discharge machining, high-precision machining, threading, soldering and assembly. However, using additive manufacturing, it was possible to print the tools integrated with the internal air channels and threads. To achieve the required mirror blank surfaces, extrude honing was used with diamond-based suspension. This resulted in significantly shorter manufacturing time and hence time to market.

Benefits of AM technology

- Reduced manufacturing time
- Increased part functionality
- Improved production flexibility

Single-Piece Extrusion Tool

Material: AlSi10Mg

Part weight (kg): 1

Additive process used: Laser beam melting

Courtesy: Monalab GmbH and SLM Solutions

Extrusion tool to produce technical hoses with a diameter of 10 millimeters with fewer components for reduced assembly as well as flow-optimised construction. The high-pressure durability ensures efficient production and long tool life.

Benefits of AM technology

- Integrated functions
- Flow-optimised construction
- High-pressure durability for efficient production and a long tool life

Spider bracket

Material: Titanium

Additive process used: Laser Beam Melting

Courtesy: Altair, Materialise and Renishaw.

Prototype of spider bracket to connect the corners of architectural glass panels, used in atriums and floor-to-ceiling wall glazing. New design with hybrid lattice structures created with Altair's lattice-based optimisation software, Materialise's Magics, 3-matic and Build Processor software, and manufactured with advanced settings of the Renishaw metal AM system.

Benefits of AM technology

- Unique, organic shape that is both light and strong.
- Stability and improved thermal behavior thanks to the lattice structures

Tool insert for die casting

Material: Stainless Steel 316L
Part weight (g): 150
Additive process used: Laser Beam Melting

Courtesy: The Mercury Centre

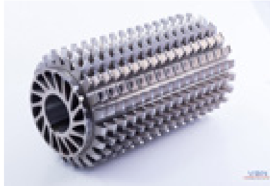
Connector blocks used in the Gripple wire joining system are manufactured using die-casting, the internal cavities being formed by mould tool inserts. To facilitate the rapid evaluation of new design concepts, a series of tool inserts were manufactured using direct metal laser sintering, with up to 12 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

High Performance Lightweight Vibenite® Gear Hob

Material: Vibenite® 280
Part dimensions (mm): 132 x 235
Part weight (kg): 15.3
Additive process used: Metal powder bed melting



Courtesy: VBN Components.

VBN Components has developed the additive manufactured wear resistant material Vibenite® 60 and tested this in a number of gear hobs at Volvo Powertrain, Sweden. In the tests, the hard and heat resistant material performed very well resulting in twice the lifetime and also the possibility for running with double feed in hobbing. The possibility to build lightweight structures resulted in a weight reduction of 40% of these heavy tools, from 15kg to 9kg.

Benefits of AM technology

- Improved material properties (hardness and cleanliness/purity)
- Performance increase (double life time and double feed)

5.5 Automotive and car racing

Ball joint

Material: Nickel base
Part size (mm): D 70 H 45
Additive process used: Laser Beam Melting

Courtesy: Poly-Shape

Patented PSPM ball joint exhaust system link for WRX car racing vehicles which offers a +/-10° rotation on any axis to give freedom of motion for any given exhaust system installation. Besides a male ball joint rotating in a two-layer female joint ensures proper sealing while allowing relative motion between the pipes it joins.

Benefits of AM technology

- Improved Performance
- Increased Component Complexity
- Weight Saving

Car Steering Knuckle

Material: AlSi10Mg
Part weight (kg): 3.5
Additive process used: Laser Beam Melting

Courtesy: Hirschvogel Tech Solutions, SLM Solutions

Car steering knuckle produced on a SLM500 Quad machine with integrated lightweight bionic design. The design allowed fewer support structure so to reduce post processing and 40% material saving vs conventional forging part.

Benefits of AM technology

- Integrated approach
- Lightweight design
- Reduced post-processing

Cooling and Heating prototype combining HIP + AM

Material: Ti6Al4V and copper
Additive process used: Hybrid HIP & Laser beam melting

Courtesy: Metal Technology Co. Ltd.

Part with complex cooling structure where a HIP container was produced on ProX DMP320 machine and then filled in with metal powders for full densification by HIP process.

Benefits of AM technology

- Increased HIP Component Complexity
- Cost Saving
- Improved Performance

Motorsport Upright Suspensions

Additive process used: Electron Beam Melting

Courtesy: National Centre Additive Manufacturing

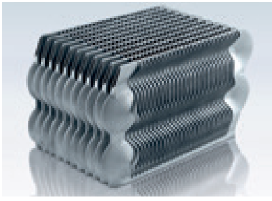
The formula student car, Oxford Brookes racing team in collaboration partnership with The Manufacturing Technology Centre (MTC) demonstrated the capability to manufacture complex automotive parts using Additive Manufacturing (AM), Electron Beam Melting (EBM) process.

Benefits of AM technology

- A demonstration of how AM can be used to manufacture complex geometries
- Weight saving by >30% through topology optimisation
- Reduced lead time from design changes to manufacture of parts in comparison to existing conventional methods

Prototype of heat exchanger

Material: Al Si 10Mg
Additive process used: Laser Beam Melting



Courtesy: EOS and Within

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

Titanium wishbone

Material: Titanium
Part weight: Should check
Additive process used: Laser Beam Melting

Courtesy: InMotion Automotive, Materialise, Gerlach Delissen

This lightweight 3D-printed wishbone was created by Materialise and InMotion, a team of engineering students from the Technical University of Eindhoven. It is part of an electric race car and holds the wheel in place, coping with all the forces. It's created with Materialise 3-matic software and printed by Materialise.

Benefits of AM technology
- Fast creation
- Lighter without compromising strength

Wheel suspension

Material: AlSi10Mg
Part size (cm): 15 x 10
Additive process used: Laser Beam Melting

Courtesy: EOS GmbH, Rennteam Uni Stuttgart

Reliable, lightweight axle-pivot with high rigidity and topology-optimised steering stub axle , manufactured with the EOSINT M 280.

Benefits of AM technology
- Optimised form and contouring for 35% weight reduction and 20% increase in rigidity
- Speed: significant reduction in development and production time
- Safety: reliable on the track

Windscreen coil nozzle

Material: 316L
Part weight (g): 6,25
Additive process used: Digital Metal® binder jetting technology

Courtesy: Koenigsegg Automotive AB and Höganäs AB – Digital Metal

Special design combined with fine surface finish of internal channel allowing the nozzle to be made in one piece. Exposed surface is hand polished to mirror glass finish.

Benefits of AM technology
- Internal channel with fine surface finish
- Made in one step

Inside door handle cover

Material: Ti6Al4V
Part size (cm): 20
Additive process used: Laser Beam Melting

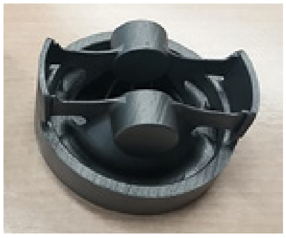
Courtesy: PSA Group, Spartacus3D

Innovative door handle cover designed by PSA Group for its DS3 Dark Side model by DS Automobiles. A few hundreds of vehicles have been delivered with 3D printed titanium door handles and also key holders. The parts have been manufactured by Spartacus3D on an EOS M290 machine with high work on process optimisation so as to reduce costs.

Benefits of AM technology
- Design freedom
- Small series

Steel piston for racing motorbike

Material: 42CrMo4 steel
Part size (mm): D 80 H 40
Part weight (g): 191
Additive process used: Laser beam melting



Courtesy: TECNALIA, AKIRA Technology

Prototype of redesigned piston for motorbike racing with lower weight and higher temperature resistance vs. conventional aluminium piston for improved engine efficiency.

Benefits of AM technology
- Weight reduction
- Freedom of design

5.6 Consumer

3D printed dial for Montfort watches

Material: Stainless 316L

Part diameter (mm): 35

Additive process used: Precision Ink Jet Printing on Powder Bed (Digital Metal)

Courtesy: Höganäs AB - Digital Metal

The Dials are produced with tight tolerance requirements of OD, thickness, pin positioning and flatness. Surface finish: As blasted to average Ra 3 µm

Benefits of AM technology

- Unique topographic design of the watch surface
- Dials with positioning pins are produced in one piece without printing support

Bi colour flexible bracelet

Material: Yellow and white 18Ct gold

Part weight (g): 41

Additive process used: Laser beam melting

Courtesy: Cookson Gold

Fully flexible bracelet made in 8 ½ hours on a Precious M080 machine which enabled the seamlessly switch between 18K White gold powder, and 18K Yellow gold powder to continue the build.

Benefits of AM technology

- Avoid casting process where each link would have been soldered individually, an almost impossible task

Bike saddle clamp

Material: AlSi10Mg

Additive process used: Laser beam melting

Courtesy: Rosswag GmbH, ANSYS Germany GmbH

Saddle clamp with topology optimised geometry printed on a SLM280HL machine.

Benefits of AM technology

- Cost Saving
- Increased Component Complexity
- Weight Saving

Lancôme Perfume packaging

Material: 316L

Part size (mm): 84 x 62 and 82 x 46

Part weight (g): 29 & 37

Additive process used: Laser Beam Melting

Courtesy: Lancôme / AddUp

Exclusive limited edition 3D printed and plated design for perfume bottle developed by AddUp & Decayeux for Jasmins Marzipane perfume by Lancôme.

Benefits of AM technology

- Complex design
- No tools necessary to produce parts
- Customisation of a unique model
- Time to market divided by 2 or 3

Platinum hollow charms

Material: 950 ‰ Platinum powder alloy

Part dimensions (g): 31 parts of 2,8 each (2,4 after polishing)

Additive process used: Laser Beam Melting

Courtesy: Progold S.p.A.

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 it affordable.

Benefits of AM technology

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

Rygo sculpture

Material: Stainless Steel 316L

Part size (mm): 25 x 25 x 30

Additive process used: Precision inkjet on powder bed

Courtesy: Höganäs AB - Digital Metal

Bathsheba Grossman is an artist recognised 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 customisation of designs
- Possible to achieve very thin walls and sections

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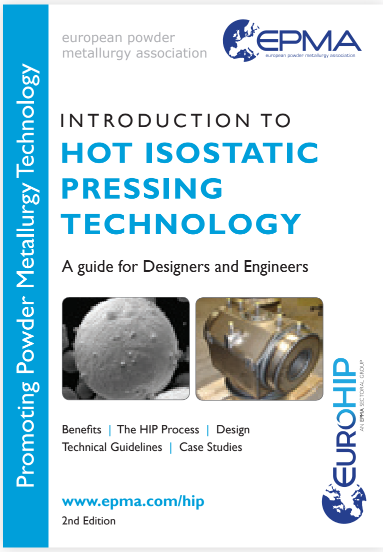

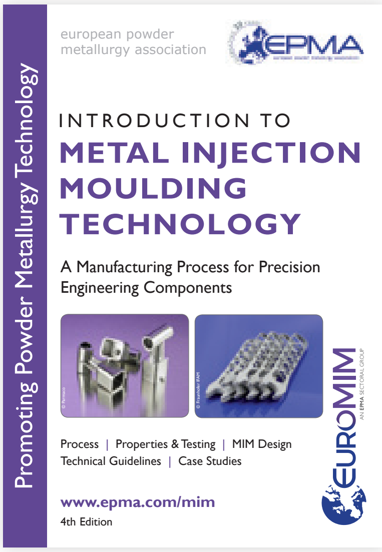

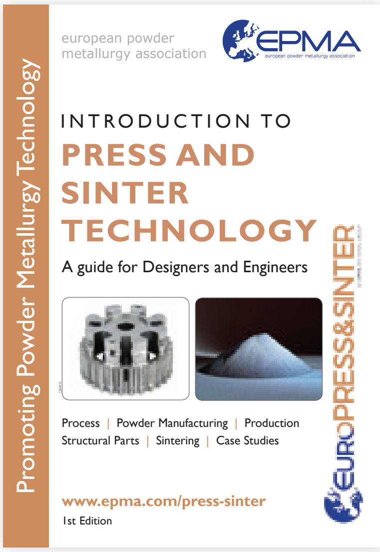

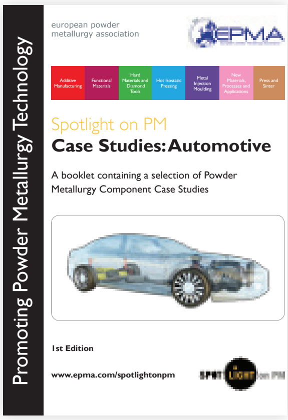

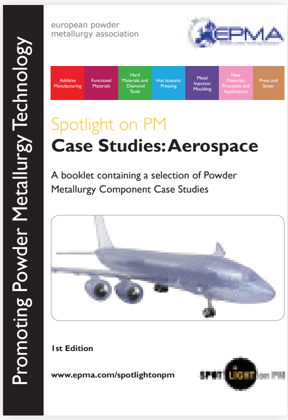

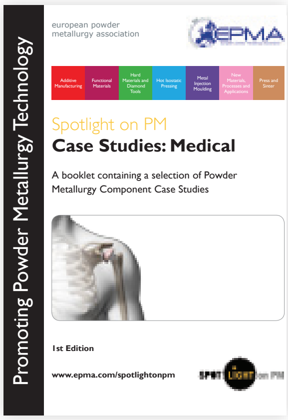

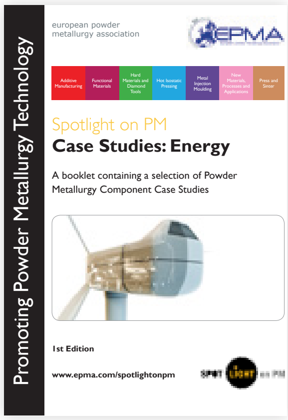

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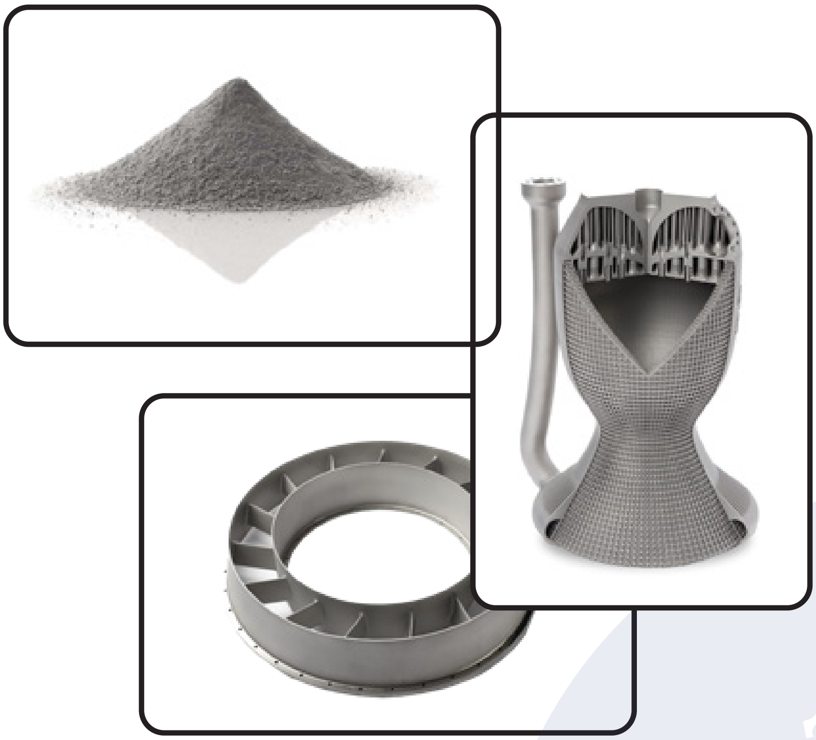

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