Interreg Sudoe

ADDISPACE

DIAGNOSIS AND STUDY OF OPPORTUNITIES OF METALLIC ADDITIVE MANUFACTURING ON SUDOE AEROSPATIAL SECTOR

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STATE OF THE ART OF ADDITIVE MANUFACTURING TECHNOLOGIES: TECHNOLOGIES, TRENDS, OPPORTUNITIES, CHALLENGES AND APPLICATIONS TO THE AEROSPATIAL SECTOR

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1 SCOPE

This report is a contribution to the Work Package 1 of the ADDISPACE project "Diagnosis and study of the opportunities of Additive Manufacturing technologies in the aerospace industry at SUDOE region", and constitutes the deliverables "**E.1.1.1 Study of Diagnosis**","**E.1.2.1 Study of barriers to adoption**", **E.1.3.1 Consolidated study of opportunities**".

This reports describes the state of the art of Additive Manufacturing (AM) Technologies, with special emphasis on the most relevant technologies for Metal Additive Manufacturing (MAM), i.e. *Powder Bed Fusion* (PBF) and *Directed Energy Deposition* (DED) technologies.

This report also describes the technologies and trends in the application of Additive Manufacturing technologies to the aerospace industry, and a study of barriers to adoption of this technology.

Lastly, this report identifies the opportunities for using European Structural Funds for funding MAM R&D activities and its framing in the RIS3 (Research and Innovation Strategy for a Smart Specialization).

2 ADDITIVE MANUFACTURING TECHNOLOGIES: STATE OF THE ART

2.1 Introduction

Additive manufacturing (AM) refers to a group of technologies used for building three-dimensional parts directly from 3D computer-aided-design (CAD) data, by means of an additive strategy based depositing and melting successive layers of base material (powder). AM is herein seen as opposed to conventional subtractive processes using machining operations (such as turning, milling, grinding) or forming methods (such as pressing, casting, injection moulding).

Terms such as 3D printing, rapid prototyping, direct digital manufacturing, rapid manufacturing and solid freeform fabrication are often used to describe AM processes.

Although AM is not going to replace any of the traditional manufacturing processes, it represents a key enabler to create and innovate, also adding potential to complement traditional processes. Therefore, AM is receiving more and more attention and efforts all around the world because there is tremendous interest worldwide in evaluating the potential of AM as a useful and possibly disruptive technology. In fact, the excitement generated by AM includes many fields, from computer science and product design to new materials and lean engineering. This trend is reflected in some indicators, like the expected worldwide 3D printing industry growing forecast, where an exponential increase tendency from 2014 up to 2020 can be observed (2013, 2014 and 2016 forecasts are included in Figure 2-1) [1].

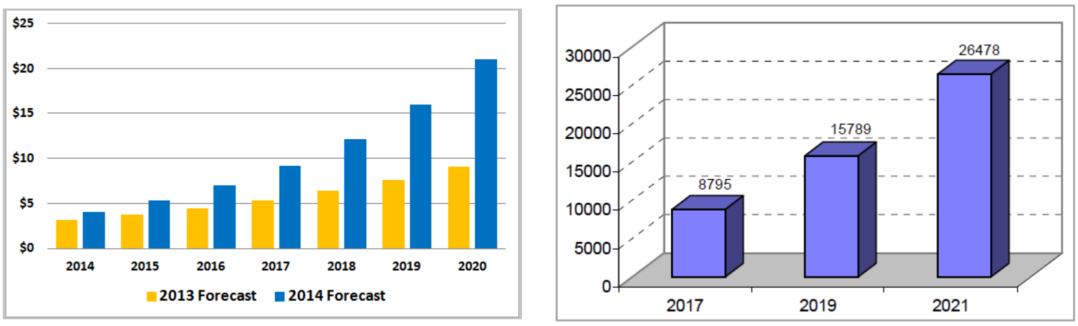

Figure 2-1. Worldwide 3D printing industry forecasts for the sale of AM products and services (expressed in billions and millions of $ respectively): 2013 and 2014 forecast (at left) and 2016 forecast (at right) [1].

In fact, many different countries have been raising their awareness of the technology for already several years. The adoption of AM is rapidly evolving, being now placed at the core of different countries national competencies. In United States of America (USA), 3D Manufacturing is a subject of national priority, so strong investments in the field of AM are expected. In fact, the USA administration launched the National Additive Manufacturing Innovation Institute (NAMII) (2012-13), specifically to coordinate and fund research projects in AM technologies. Asian countries are also playing a relevant role in AM development; around the 30% of the total of AM industrial systems are installed in the region of Asia-Pacific. On the other hand, in Europe, the use of AM with metal powders is a new and growing industry sector [2]. Looking at the recent European projects funded by the European Framework Funding Programme, a high level of research in the field of AM has been achieved in Europe, in particular for specific AM techniques and focused applications within the medical and aerospace sectors. In addition, strong efforts are being done in the development of standardization for the technology and the development for larger AM part production [3].

The Gartner's Hype Cycle is a graphical analysis tool applied mainly to study the maturity and/or the level of adoption and social application of specific technologies. Considering AM technologies, these processes started more than twenty years ago in the market of rapid prototyping of plastic "mock-up" parts for product design [4]. However, public attention has only focused on them in the latest years when opportunities for tooling and direct part production arose in plastics, metals and ceramics. In fact, up to 2009, AM is not even referenced in the Gartner's Hype Cycle. In 2010 AM appears for the first time with an estimation of 5-10 years to mainstream adoption (maturity) of the technology. Between 2013 and 2015, AM technologies appear progressively closer to the level of real production in some sectors (i.e. "slope of enlightenment" phase) (see details in Figure 2-2 [5]).

At this point, it is worth mentioning that the Gartner's Hype Cycle mainly represents trends to the adoption of different technologies, but, in fact, AM technologies have already established themselves in some sectors at the level of real production.

As can be observed in Figure 2-3, a survey performed over 100 key AM system manufacturers and service providers (representing over 100,000 users and customers), asking each company to indicate which industries they serve and the approximate revenues that they receive from, showed that in 2014 the industrial/business machines (including office equipment (printers, computers, routers) and industrial automation equipment (CNC machines and robots)) are the leading sector using AM technologies. Immediately followed by the consumer products/electronics and motor vehicles sectors. Medical/dental and aerospace sectors are also great users of AM technologies [1].

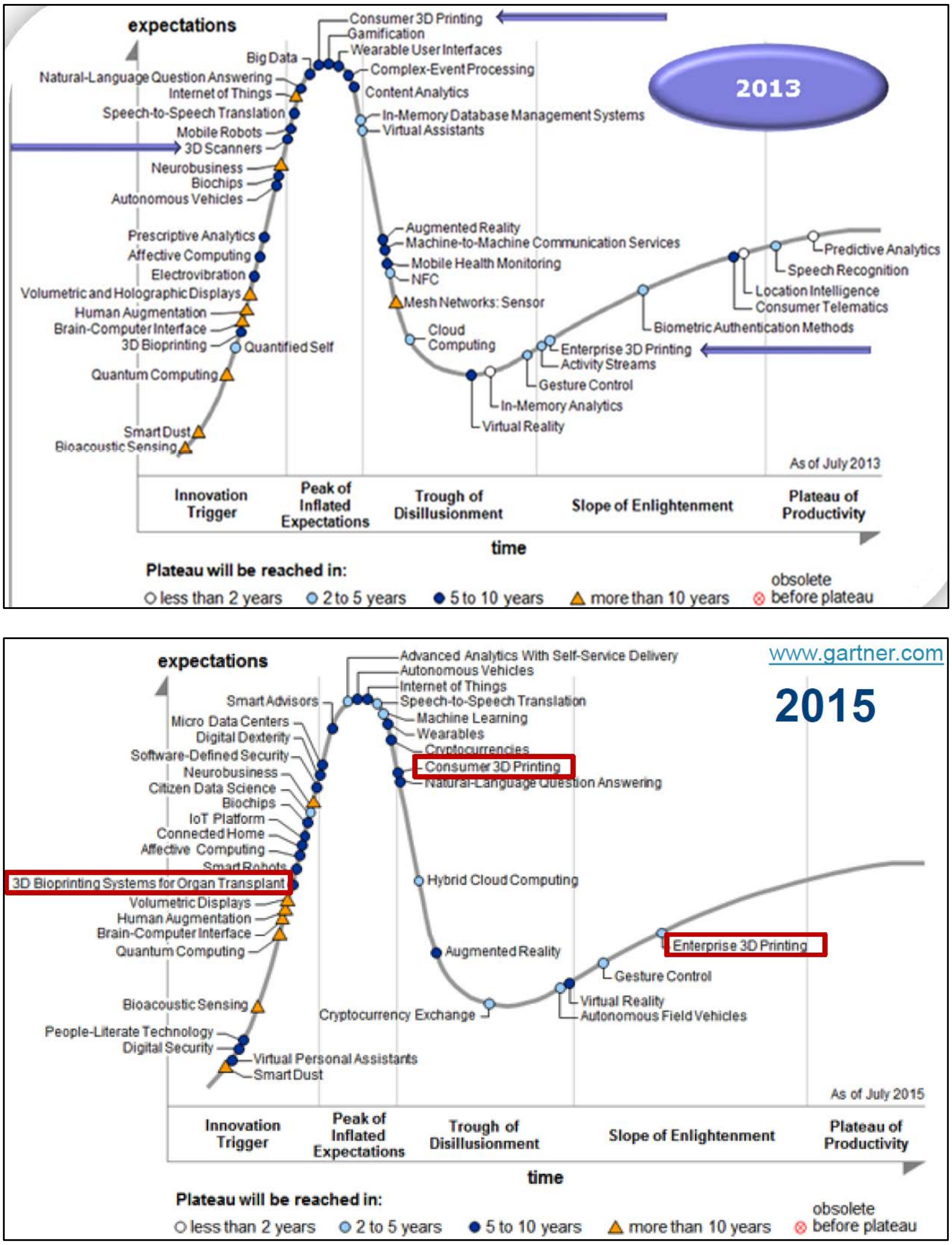

Figure 2-2. Gartner's Hype Cycle. Evolution of Additive Manufacturing from 2013 to 2015. [5].

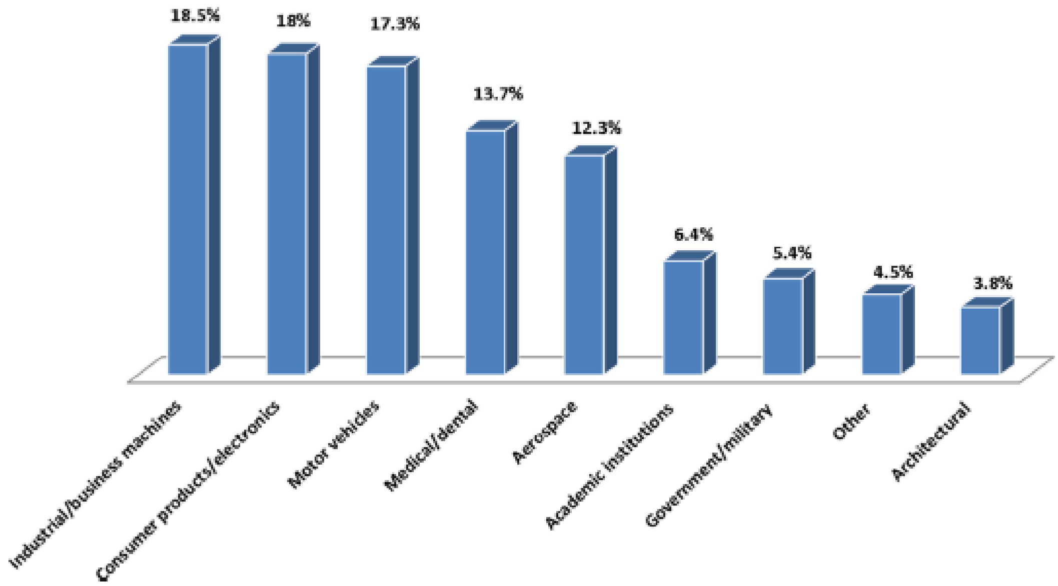

Figure 2-3. Breakdown of the percentage of industrial sectors using AM [1].

Although the described significant usage of AM in particular sectors, there is still a massive potential to further enhance its use and even enter new sectors.

However, one of the present problems for AM is that many of the traditional manufacturing sectors are not aware of, or do not fully understand, how they can utilise AM. AM will replace certain manufacturing methods, but not all of them while it has the added potential to complement many of those it cannot substitute.

Benefits and Constraints

Nowadays AM of metallic parts is well recognized as an interesting alternative to other conventional processes due to its capability to produce complex net-shape parts, with a high versatility on design that makes light-weight structures and new functions, such as complex internal channels, feasible. Furthermore, net-shape processes mean less raw material consumption, up to 25 times less versus machining, important in the case of expensive or difficult to machine alloys and also with significant benefits from the environmental perspective point of view [2], [4], [6].

As mentioned, AM has the ability to offer significant benefits for a wide range of applications, positively impacting on the societal, economic and environmental elements of sustainable development. The main advantages of AM technologies in Table 2-1.

Table 2-1. Advantages of Additive Manufacturing technologies.

Benefits of AM technologies
➢ Reduced time-to-market and quick adaptation to the constantly changing market demands. ➢ Product customization with complete flexibility in design & construction. ➢ Maximum material savings since material is added and not subtracted. Near net-shape production leads to a minimal amount of waste material and post-processing steps. ➢ Minimal need of additional processes (e.g. machining). Reduction of lead times and costs. ➢ The part is obtained directly from its 3D CAD model; therefore punches, moulds or tools are not required. ➢ Unlocked design potential (free from conventional manufacturing design constraints). Design for customization, Design for function, Design for light-weighting. ➢ Full-density of final parts (without residual porosity). ➢ Possibility to manufacture free-form channels, internal cavities, thin walls, as well as, different forms of latticed (lightweight) structures. ➢ Environmental friendly, more streamlined and versatile manufacturing technology.

Considering general characteristics of AM technologies, these are currently recommended for the production of customized parts in small series.

More in detail, the impact on production costs of two different aspects: serial size and parts customization is analysed in Figure 2-4. On one hand, serial size has a low cost impact when AM is applied. On the other hand, AM allows functionalization, customization and complexity of parts with a lower impact on costs than traditional manufacturing. Therefore, **the more complex the final shape, the more likely that AM will be of benefit.**

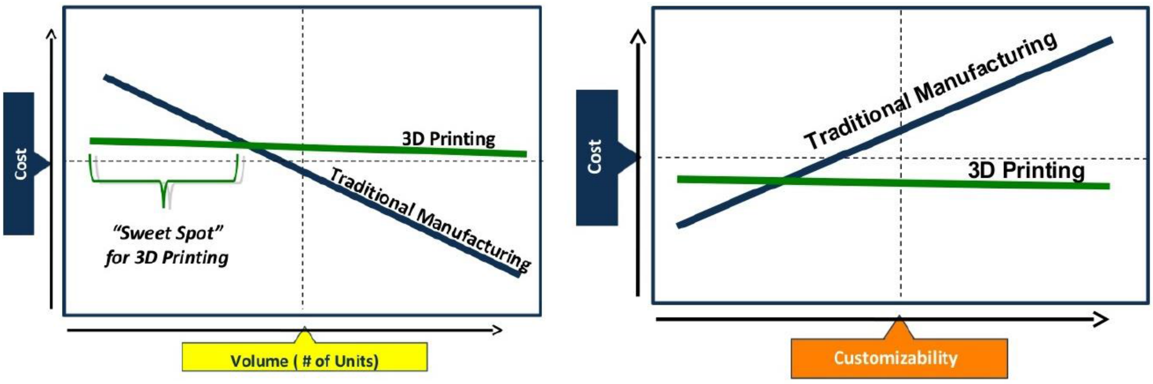

Figure 2-4. Serial size impact on production costs (expressed in number of units or production volume) (on the left), and customizability impact on production costs (on the right).

Apart from the benefits, to take full advantage of AM technologies, it is important to be aware of some **limitations** of these technologies (Table 2-2).

Table 2-2. Limitations of Additive Manufacturing technologies.

➢ Limitations of AM technologies
➢ Part size: In powder bed technologies: part size limited to powder bed size (standard powder bed systems: 250x250x250 mm). In direct energy deposition (or laser metal deposition): part size limited by excessive production time and costs due to the low thickness of powder layers. ➢ Short production series. Moulding and casting are still preferred for high volume production. ➢ Design considerations. In the case of powder bed technologies, removable support structures are needed when the overhang angle is below 45°. Part orientation impacts on surface quality, build time and part cost. ➢ Processability of different materials. 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). Also, there is a process variability: the final part properties depend on a large number of parameters such as build speed or part orientation. ➢ Post processing: it's usually needed to remove material supports after manufacturing. In some cases machining is needed in order to obtain better surface finishing or dimensional accuracy. ➢ Lack of specific standardization.

Classification of Additive Manufacturing Technologies

Within the frame of AM technologies different processes can be identified, where a variety of materials (including plastics, metals, ceramics or composites), different deposition techniques and different ways of fusing/solidifying the materials are applied. AM technologies are typically based on one of the seven **primary manufacturing processes** (which offer more than 30 variations on the basic themes). American Society of Testing Materials (ASTM) Committee F42 has categorized AM processes as follows [7]:

1. Vat polymerization: a liquid photopolymer is selectively cured by light activated polymerization.

2. Material jetting: droplets of a base material (photopolymer) and secondary materials (for example, wax) are deposited on the build area. UV light solidifies the photopolymer to form cured parts. Support material is removed during post-build processing.

3. Material extrusion: thermoplastic material is fed through a heated nozzle and deposited on a build platform. The nozzle melts the material and extrudes it to form each object layer.

4. Sheet lamination: thin sheets of materials (plastic or metal) are bonded together using a variety of methods (e.g. glue, ultrasonic welding) in order to form an object. A laser or knife is used to cut a border around the desired part and unneeded material is removed.

5. Powder bed fusion: particles of material are selectively fused together using a thermal energy source such as a laser. Once a layer is fused, a new one is created by spreading powder over the top of the object. Unfused material is used to support the object being produced.

6. Binder jetting: particles of material are selectively joined together using a liquid binding agent. Once a layer is formed, a new one is created by spreading powder over the top of the object and repeating the process. Unbound material is used to support the object being produced.

7. Direct energy deposition: focused thermal energy is used to fuse material as it is being deposited. Directed energy deposition systems may employ either wire-based or powder-based approaches.

Some other relevant data, including type of materials, main market and some examples of companies for each of the seven processes are included in Figure 2-5. *Powder Bed Fusion* (PBF) and *Directed Energy Deposition* (DED) technologies are the most relevant ones for AM of metals. Polymers are usually processed by material jetting, material extrusion and VAT photo-polymerization. High performance ceramics are generally processed by photo-polymerization technologies.

Process	Example Companies	Materials	Market
Vat Photopolymerization	3D Systems (US), Envisiontec (Germany)	Photopolymers	Prototyping
Material Jetting	Objet (Israel), 3D Systems (US), Solidscape (US)	Polymers, Waxes	Prototyping, Casting Patterns
Binder Jetting	3D Systems (US), ExOne (US), Voxeljet (Germany)	Polymers, Metals, Foundry Sand	Prototyping, Casting Molds, Direct Part
Material Extrusion	Stratasys (US), Bits from Bytes, RepRap	Polymers	Prototyping
Powder Bed Fusion	EOS (Germany), 3D Systems (US), Arcam (Sweden)	Polymers, Metals	Prototyping, Direct Part
Sheet Lamination	Fabrisonic (US), Mcor (Ireland)	Paper, Metals	Prototyping, Direct Part
Directed Energy Deposition	Optomec (US), POM (US)	Metals	Repair, Direct Part

Figure 2-5. Classification of AM processes, related vendors and fabricators, type of materials applied and market sectors [4].

Additionally, in Figure 2-6, AM processes are classified as a function of the base material used (i.e. liquid, solid or powder) and according to previously described primary processes [8]. Concerning PBF and DED technologies, a subdivision is usually made depending on the filler metal format (wire or powder) and on the applied heat source (laser, electron-beam, arc).

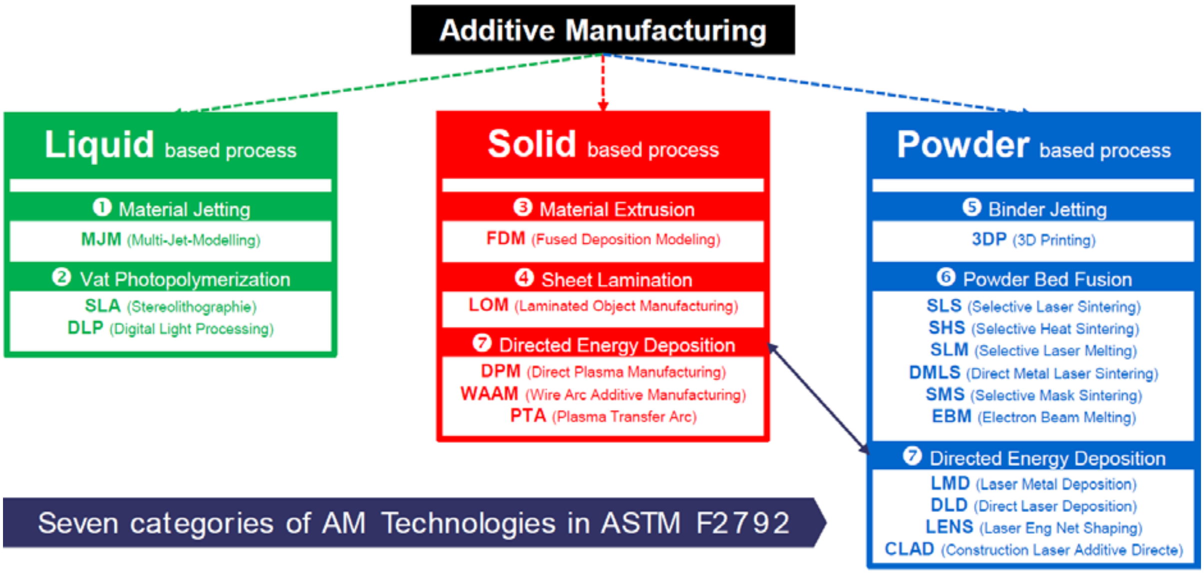

Figure 2-6. Additive manufacturing processes, ASTM F2792/ ISO17296-2 [8].

In the specific case of AM technologies for metallic parts, Figure 2-7 shows a classification, including the process names that each machine manufactured has adopted [9].

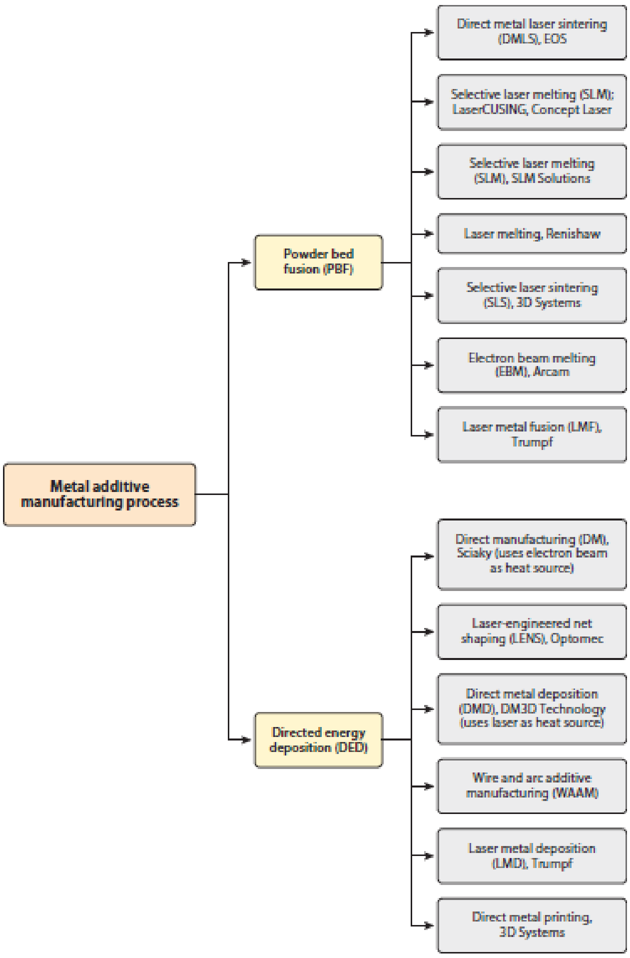

Figure 2-7. Classification of metal additive manufacturing processes.

Figure 2-8 shows a description of some of these technologies including representative applications [10].

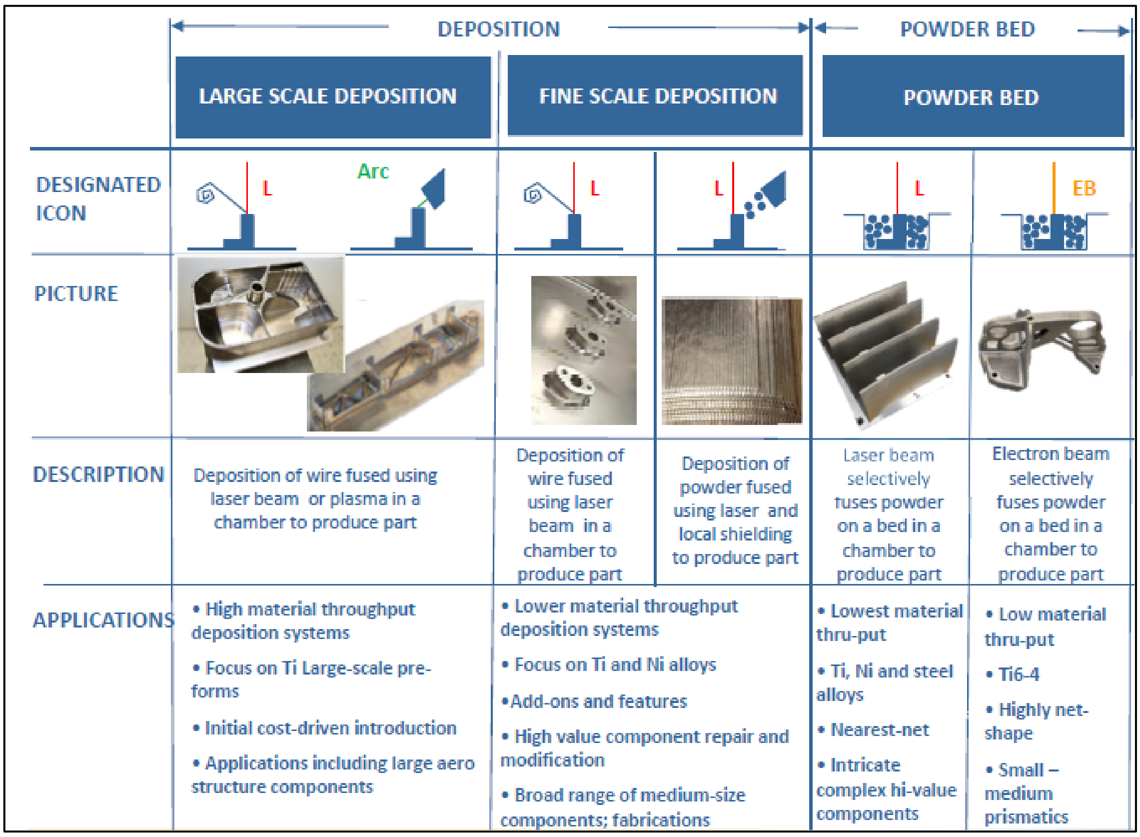

Figure 2-8. Description of metallic AM technologies [10].

Additive Manufacturing Supply Chain

AM shall be considered as part of an integrated process. A schematic representation of the whole manufacturing process it can be observed in Figure 2-9. The manufacturing of a metal part with additive manufacturing technologies starts with 3D modelling: 3D-CAD modelling, 3D scan (reverse engineering) and creation of STL-data (triangulation). Then data preparation shall be organized for and includes the definition of part orientation, the positioning of support structures and the slicing of the model. Once control data are generated, the production of the parts takes place. After part manufacturing, post-processing operations are needed: removal of powder and support structures, heat treatments, post-machining and surface finishing, non-destructive testing, etc.[11].

Different steps can be considered in the AM value chain:

- Raw material. Production step of metallic powders should be taken into account because a high purity level and a very narrow distribution of the granular size is required for the AM processes. Powder quality is key for the final properties on the part, so, robust powder specifications are mandatory to ensure good reproducibility. These prerequisites are difficult to comply, especially for small orders (not very attractive for large providers). Currently raw materials are sold by AM system providers.

- System. It should be noticed that system providers offer low levels of vertical integration. And standard components are usually made by contract manufacturers.
- Software. It is important to differentiate between process control and enhancement software. Process control is normally provided by system providers. Add-on software such as automatic support generation or design optimization is normally provided by specialized companies.
- Application design. Regarding application design to support end customers, it should be noted here that application design can be complex and demanding. It is a complex issue, generally done by system providers, software developers and/or service providers. But not every service provider is able to design applications.
- Production. Different production scenarios can be distinguished in the market: large OEM, contract manufacturers/service provider or specialized part manufacturer.

In general, it can be emphasized that the AM market is fragmented with several small players in all areas. Players' sizes limit investment in R&D (no player can be active in all fields). As a consequence, AM system providers have the greatest range of activities.

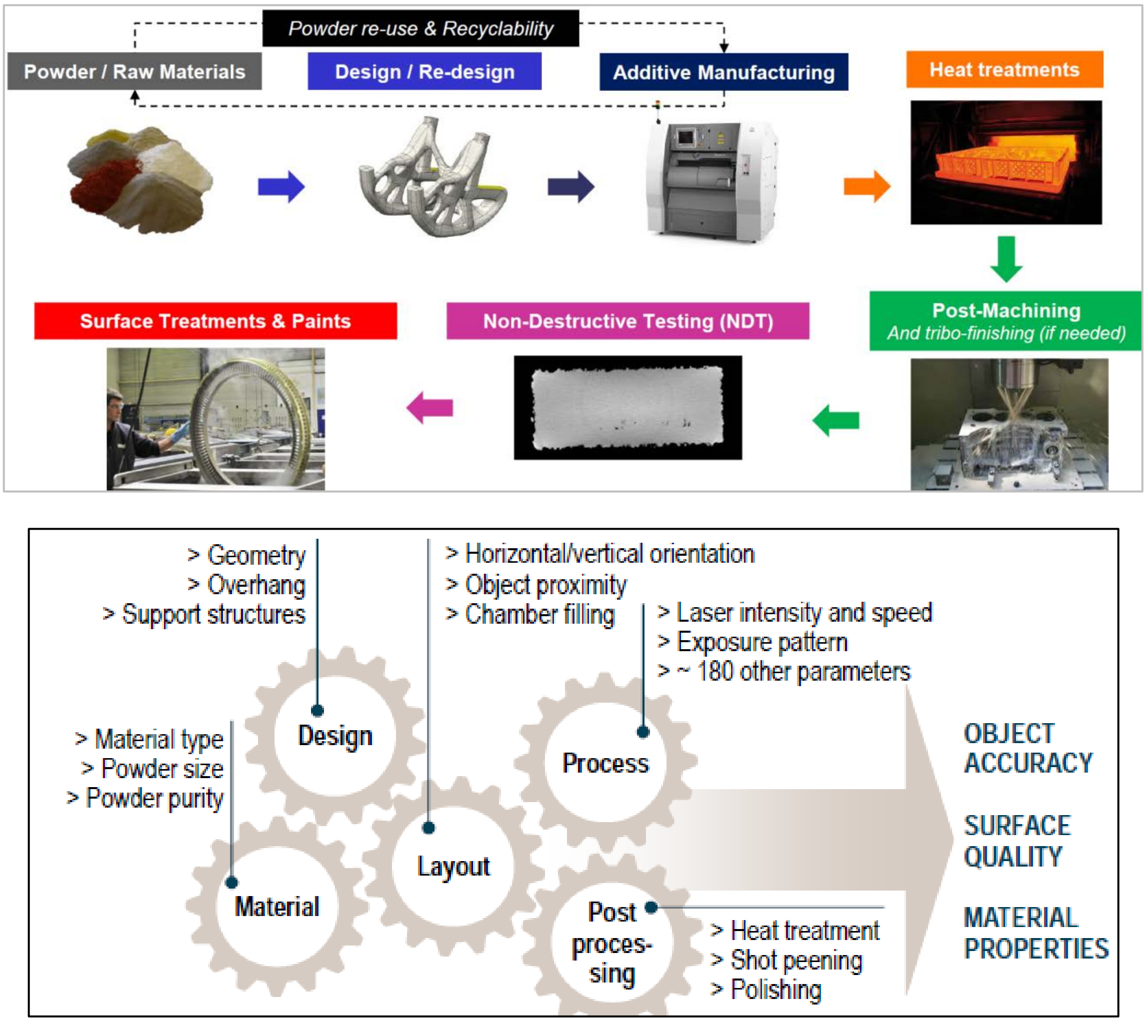

Figure 2-9. The whole process of Additive Manufacturing of a metallic part including different steps [8] [11].

2.2 Powder Bed Fusion Technologies

Powder Bed Fusion (PBF) is the accepted ASTM term for an additive manufacturing process where a point heat source selectively fuses or melts a region of a powder bed.

Powder bed fusion is the most frequently used technique for printing metal objects. PBF systems use either a laser beam (very often) or an electron beam (rarely) to melt regions of a powder bed. Electron beam PBF enables higher build rates, but surface quality and choice of materials are more limited.

Selective Laser Melting (SLM)

Selective Laser Melting (SLM) is a powder bed based Additive Manufacturing technology in which a product is built up in a layer-by-layer fashion, by melting a thin layer of metallic powder particles using a high power laser as the thermal energy source. It enables the production of complex 3D parts, according to the information provided by a CAD file, with high accuracy (± 0.1 mm in 25 mm) and high quality of surface finish (5-15 µm). This layer-wise manufacturing optimizes structure design of the SLM part [12], [13].

From the SLM manufacturing point of view, a powder layer is first applied on the building platform with a re-coater (blade or roller) and a laser beam selectively melts the layer of powder. Then the platform is lowered by 20 up to 100 µm (depending of the manufacturing requirements of the part and desired finishing aspect) and a new powder layer is applied. The laser beam melting operation is repeated. After a few thousand cycles, depending on the height of the part, the build part is removed from the powder bed. A schematic representation of the process is included in Figure 2-10.

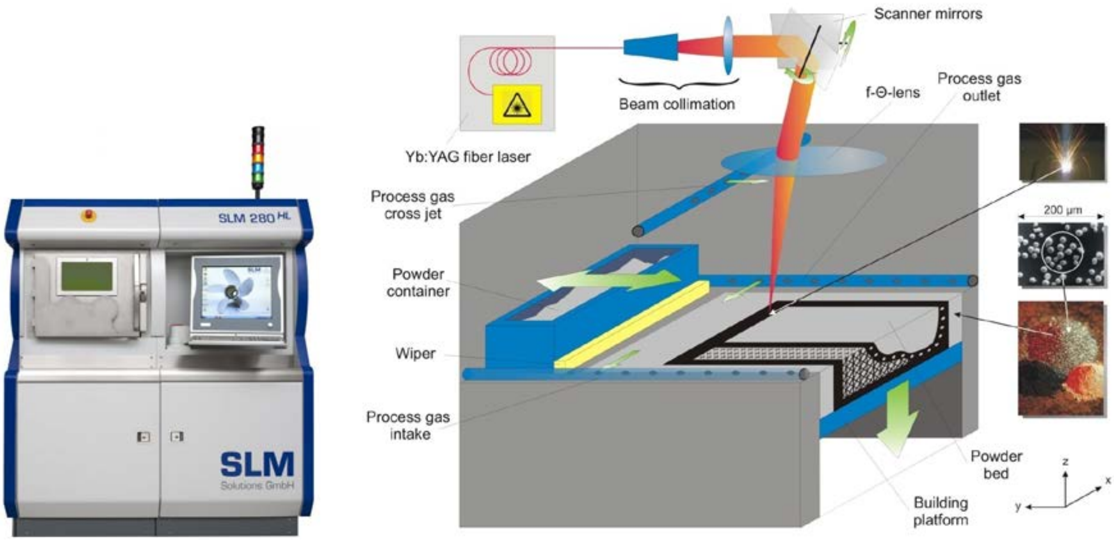

Figure 2-10. Schematic representation of selective laser melting (SLM) process [14].

In SLM different scanning strategies are possible. The laser scanning patterns will influence porosity level, microstructure and surface roughness. The stripe pattern is a band defined by the scan vector width, i.e. stripe width, the hatching space between adjacent tracks and the scan direction as well as the overlap with the neighbouring stripes.

On each layer, several laser scanning configurations (or hatch patterns) are possible. Scanning parameters are schematically represented in Figure 2-11.

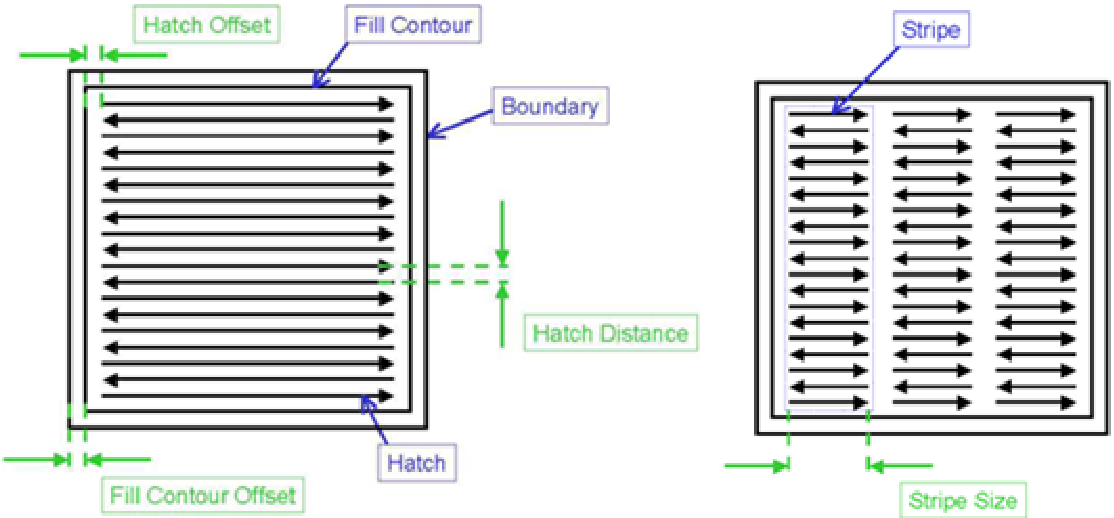

Figure 2-11. Scanning parameters schematically represented

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In Figure 2-12 is included an example of an industrial part manufactured by PBF - SLM technology at the IK4-LORTEK research centre.

Figure 2-12. Industrial part manufactured by SLM technology by IK4-LORTEK research centre.

With respect to advantages and constraints, the most relevant characteristics of SLM process are included in Table 2-3.

Table 2-3. Advantages and disadvantages of SLM technology.

Advantages of SLM technology	Disadvantages of SLM technology
➢ Functional parts and tools with complex, unique shape from metal or ceramic powders. ➢ Functional surface properties. ➢ Surface structuring including micro- and Nano-structuring. ➢ Light weight structures and graded composition (potentially). ➢ Multi-material parts (under development). ➢ High recyclability of the powder raw material.	➢ High surface roughness. ➢ Anisotropic properties. ➢ Highly localized heat input: high residual stresses. ➢ Manufacturing accuracy versus duration. ➢ Absence of quality on-line control. ➢ Difficulties of powder evacuation from small size channels. ➢ High cost of SLM machines.

Regarding materials' availability, currently a variety of materials are processed by SLM manufacturing. A summary is included in Table 4.

Table 2-4. Description of materials processed by SLM.

Material	Properties	Industrial Sectors	Alloys
Stainless Steel	Corrosion resistance Good mechanical properties	Automotive Construction Chemical industry Medicine Consumer goods	1.4404 1.4410
Tool Steel	High hardness High wear resistance Hot hardness Good machinability	Production of injection moulds Biomedical implants For cutting, pressing, extruding and coining of metals and other materials	1.2344 1.4542 1.7228 1.4541 1.4313
Co-Cr alloys	High hardness High wear resistance Good corrosion resistance Adequate mechanical properties Biocompatible	Biomedical implants Dentistry High temperature applications	CoCr (ASTM F75:Co212f)
Ni based superalloys (Inconel)	High corrosion resistance High mechanical resistance at high temperature Good weldability	Aerospace (turbine engines) Power generation Petrochemical and chemical processing	Inconel 625 Inconel 718 Inconel HX

Ti alloys	Corrosion resistance Good mechanical properties Biocompatible Adequate machinability	Biomedicine Aerospace Off-shore Design and jewellery	Ti6Al4V TiAl6Nb7 Ti (Grade 1)
Al alloys	Attractive mechanical properties Light weight alloys	Automotive Aerospace Consumer goods	AlSi12 AlSi10Mg AlSi7Mg AlSi9Cu3 AlMg4 5Mn0.4

Considering manufacturers of SLM machines, there is a wide offer of manufacturers of powder-bed-based laser melting with metals, such as: 3D Systems (USA), Concept Laser (Ge), EOS (Ge), Matsuura (Jp), Realizer (Ge), Renishaw (UK) or SLM Solutions (Ge).

Electron Beam Melting (EBM)

Electron Beam Melting (EBM) process, schematically represented in Figure 2-13, is analogous to the Selective Laser Melting (SLM) process. In this case, the energy source is an electron beam instead of a laser.

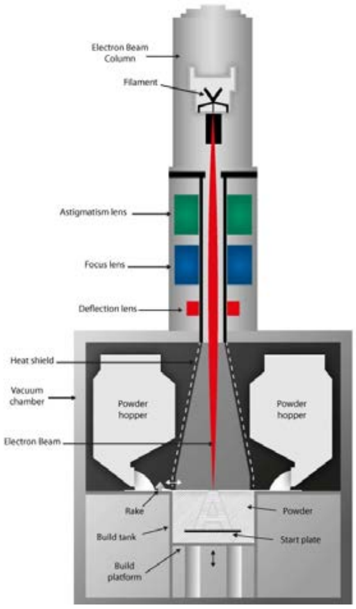


Figure 2-13. Schematic view of the Electron Beam Melting equipment [15].

During the Electron Beam Melting process (EBM), electrons are emitted from a tungsten filament inside the column and are precisely focused and deflected using electromagnetic coils. When the high-speed electrons strike the metal powder, the kinetic energy is instantly converted into thermal energy raising the temperature of the powder particles above their melting point. The EBM parts are built in vacuum to prevent a loss of energy that would be caused by the fast moving electrons colliding with air or gas molecules. The vacuum has two advantages: the process is 95% energy-efficient, which is five to ten times greater than laser technology, and the vacuum supports processing of reactive metal alloys, such as Ti or Al, that is, maintains the chemical composition of the material and provides an excellent environment to building parts. One of the interesting features of this manufacturing method lies in the conditions through the process. For instance, when manufacturing titanium parts, which usually exhibit high residual stresses, the powder bed is preheated up to 600 700°C to obtain a smaller thermal gradient during solidification, avoiding such high stresses [13], [16], [17].

When Electron Beam Melting (EBM) is compared with other Powder Bed processes, such as SLM (see Table 2-5), EBM shows faster building rates (up to 60 cm^3/h) as result of the high power electron beam efficiency. Also fewer supports structures are required when building the part. Another limitation of powder bed systems is the fabricated component size, limited to the bed size, which restricts its application to relatively small components, typically less than 400x400x400 mm in length, width and height. On the other hand, EBM parts are characterized by a very poor surface finishing (mainly related with a thicker layer thickness employed during the manufacturing process) with higher geometrical deviations, with a limited number of materials available comparing to laser based PBF processes (just Titanium Ti6Al4V, Titanium Ti6Al4V ELI, Titanium Grade 2 and Cobalt-Chrome ASTM F75 can be found accessible for EBM).

Table 2-5. Comparison between EBM and SLM processes.

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

It is also worth mentioning that EBM has been particularly effective in the medical industry for creating implants.

In Table 2-6 is included a description of properties of different metallic materials available for SLM and EBM processing. There is a wide range of raw materials which can be potentially interesting for the aerospace industry.

Table 2-6. Physical and mechanical properties description of metallic materials available for different AM processes: PBF-laser based and PB-electron beam based and different companies.

Commercial Name	AM tech	Company	Density [g/cm³]	Tensile Strength [MPa]		HV	Thermal Exp. [K⁻¹] x 10-6		Thermal Conduct. [W/m·K]
				Min	Max		Min	Max	
Pure Titanium	SLM	SLM Solutions	4.5	290	n/a	200 HV	n/a	n/a	22.6

Commercial Name	AM tech	Company	Density [g/cm^3]	Tensile Strength [MPa]		HV	Thermal Exp. [K^{-1}] x 10-6		Thermal Conduct. [W/m·K]
				Min	Max		Min	Max	
		RENISHAW	4.5	290	-	n/a	n/a	n/a	22.6
Titanium Ti6Al4V	SLM	SLM Solutions	4.43	972	n/a	366 HV	n/a	n/a	7.1
		EOS	4.41	1180	1280	320 HV	n/a	n/a	n/a
		RENISHAW	4.43	1061	1121	366 HV	n/a	n/a	7.1
		ARCAM	4.43	1020	1020	327 HV	n/a	n/a	n/a
Titanium Ti6Al7Nb	SLM	SLM Solutions	4.52	1020	n/a	386 HV	n/a	n/a	7
		RENISHAW	4.52	1155	1215	386 HV	n/a	n/a	7
Titanium Ti6Al4V ELI (Extra Low Interstitials)	EBM	ARCAM	4.43	970	970	318 HV	n/a	n/a	n/a
Titanium Grade 2	EBM	ARCAM	4.5	570	570	n/a	n/a	n/a	n/a
Steel 1.4404(316L)	SLM	SLM Solutions	8	595	655	237 HV	n/a	n/a	15
		RENISHAW	8	595	655	237 HV	n/a	n/a	15
Steel 1.2344 (H13)	SLM	SLM Solutions	7.8	1700	1760	578 HV	n/a	n/a	25.6
		RENISHAW	7.8	1700	1760	578 HV	n/a	n/a	25.6
Steel 1.2709	SLM	SLM Solutions	8	1080	1140	528 HV	n/a	n/a	15
Steel 1.4410	SLM	RENISHAW	8	730	770	237 HV	n/a	n/a	15
Stainless Steel GP1	SLM	EOS	7.8	800	900	230 HV	14	14	13
Aluminium AlSi12	SLM	SLM Solutions	2.7	389	429	n/a	n/a	n/a	n/a
		RENISHAW	2.7	310	350	110 HV	n/a	n/a	n/a
Aluminium AlSi10Mg	SLM	EOS	2.67	410	465	126 HV	n/a	n/a	103
Cobalt-Chrome CoCr ASTM F75	SLM	SLM Solutions	8.25	1030	1070	346 HV	n/a	n/a	12.5
		RENISHAW	8.25	1030	1070	346 HV	n/a	n/a	12.5
	EBM	ARCAM	8.25	960	960	471 HV	n/a	n/a	n/a
Cobalt-Chrome MP1	SLM	EOS	8.3	1250	1450	392 HV	13.6	15.1	13
Inconel HX(2.4665)	SLM	SLM Solutions	8.22	910	910	95 HV	n/a	n/a	11.6
Inconel 625	SLM	SLM Solutions	8.44	680	680	n/a	n/a	n/a	11.4
		RENISHAW	8.44	680	680	n/a	n/a	n/a	11.4

Commercial Name	AM tech	Company	Density [g/cm^3]	Tensile Strength [MPa]		HV	Thermal Exp. [K^{-1}] x 10-6		Thermal Conduct. [W/m·K]
				Min	Max		Min	Max	
		EOS	8.4	940	1040	302 HV	n/a	n/a	n/a
Inconel 718	SLM	SLM Solutions	8.19	1200	1200	n/a	n/a	n/a	11.5
		RENISHAW	8.19	1200	1200	n/a	n/a	n/a	11.5
		EOS	8.15	1010	1110	310 HV	12.5	17.2	n/a

2.3 Directed Energy Deposition for Metal AM

Directed energy deposition (DED) for metal AM is less widespread than other AM technologies, primarily due to lower accuracy and required post-processing.

A typical DED machine consists of a nozzle mounted on a multi-axis arm, which deposits melted material onto specified surface, where it solidifies. So, DED uses focused energy to fuse materials by melting as the material is being deposited. The principle is similar to material extrusion, but the nozzle can move in multiple directions and is not fixed to a specific axis. The DED processes use material in wire or powder form. Wire is less accurate due to the nature of a pre-formed shape but is more material efficient when compared to powder, as only required material is used. The method of material melting varies between a laser, an electron beam or an electric arc (plasma arc, tungsten-inert gas or metal-inert gas arc processes).

Most systems use a 4- or 5- axis motor system or a robotic arm to position the deposition head, so the process is not limited to successive horizontal layers. Whilst in most cases, it is the arm that moves and the object remains in a fixed position, this can be reversed and a platform could be moved instead and the arm remain in a fixed position. The choice will depend on the exact application and object being printed. However, less freedom of design is obtained compared to PBF processes. Also, post-deposition heat treatments and final machining are normally required to achieve the right mechanical properties and geometric tolerance.

Typical applications include repairing and maintaining structural parts. DED processes are used primarily to add features to an existing structure or to repair damaged or worn parts.

Direct manufacturing (EBAM™ or Electron Beam Freeform Fabrication (EBF^3)

SCIAKY, placed in Chicago, Illinois, is an important supplier for manufacturing systems based on Electron Beam Welding technology [18]. SCIAKY's Electron Beam Additive Manufacturing (EBAM™) is a 3D printing technology that is based on the key benefits already mentioned of AM processes, i.e. parts made faster, with less material waste, reduced machining time and shorter time-to-market. In addition, EBAM™ process excels at producing high quality, large-scale metal structures made of high added value metallic elements; titanium, tantalum, and nickel-based alloys are applied to produce parts in a matter of days, with very little material waste. EBAM™ process can also be used in any phase of the product life cycle: from rapid prototypes and production parts to repair and remanufacturing applications.

Starting with a 3D model from a CAD program, electron beam gun deposits metal (via wire feedstock), layer by layer, until the part reaches near-net shape and is ready for finishing (heat treatment and machining). Gross deposition rates range from 3 to 9 kg of metal per hour, depending upon the selected material and part features. A schematic representation of EBAM™ process is included in Figure 2-14.

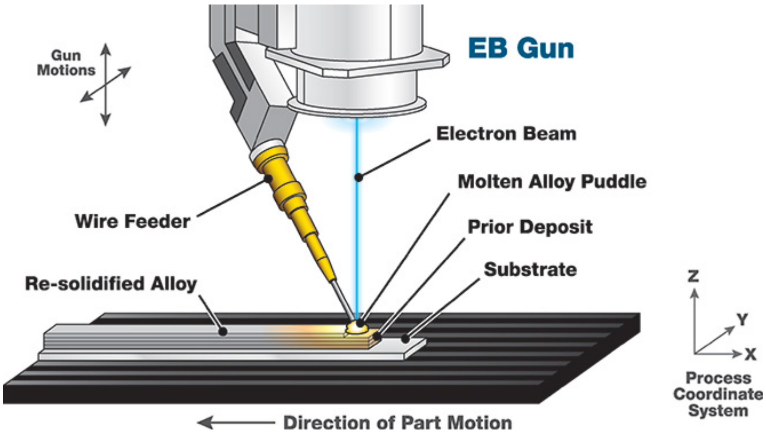


Figure 2-14. Schematic view of EBAM™ process [18].

Laser Metal Deposition (LMD)

During Laser Metal Deposition process (LMD) a nozzle mounted on a multi-axis arm deposits melted material onto the specified surface where it solidifies. Powder-fed systems blow powder through a nozzle, which is melted by a laser beam on the surface of the part. This process is based on an automated deposition of a layer of material with a thickness varying between 0.1 mm and a few millimetres. The metallurgical bonding of the cladding material with the base material and the absence of undercutting are some features of this process. A schematic view of LMD process is included in Figure 2-15.

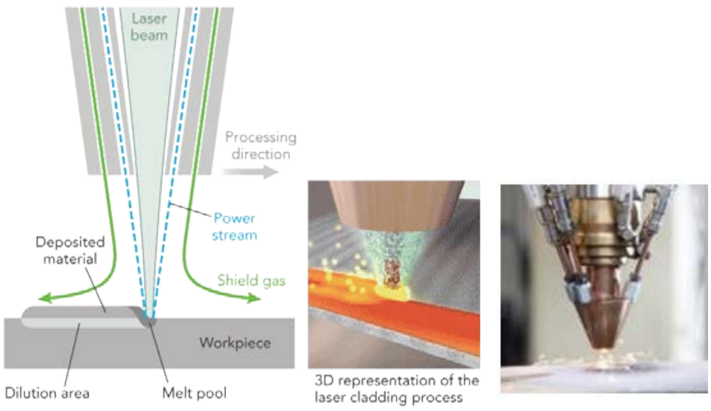


Figure 2-15. Schematic view of the Laser Metal Deposition process.

On the other hand, laser based wire-feed systems, such as Laser Metal Deposition-wire (LMD-w), feed wire through a nozzle that is melted by a laser, which incorporates inert gas shielding in either an open environment (gas surrounding the laser), or in a sealed gas enclosure or chamber. This process provides higher deposition rates as compared with powder bed and blown powder DED.

In general, LMD technology offers a higher productivity than SLM 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 to manufacture. A summary of advantages and constraints of LMD processes are included in Table 2-7.

Table 2-7. Advantages and disadvantages of Laser Metal Deposition technology.

Advantages of LMD technology	Disadvantages of LMD technology
➢ Good adhesion between substrate and deposited material: metallurgical bonding. ➢ High variety of alloys. ➢ A low level of dilution. ➢ Relatively high deposition rates. ➢ High reproducibility of the process. ➢ Low impact on substrate properties. ➢ High flexibility on part size (nearly *unlimited* height). ➢ Can be used as laser cladding to improve surface properties.	➢ High equipment cost. ➢ High raw powder material cost. ➢ Limited design freedom compared to powder-bed processes. ➢ Post-processing steps needed to obtain good surface straightness.

Wire and Arc Additive Manufacturing (WAAM)

Wire & Arc Additive Manufacturing (WAAM) technologies combine an electric arc as heat source and raw material in wire form as feedstock and have been investigated for AM purposes since the 1990s, although the first patent was filed in 1925. WAAM uses welding equipment: welding power source, torches and wire feeding systems. Motion can be provided either by robotic systems or computer numerical controlled gantries. Whenever possible, metal inert gas (MIG) is the process of choice: the wire is the consumable electrode and its co-axiality with the welding torch results in easier tool path. Besides, cold metal transfer (CMT), a modified GMAW variant based on controlled dip transfer mode mechanism, has also been widely implemented for AM processes due to its high deposition rate with a low heat input. In other cases, tungsten inert gas (TIG) or plasma arc welding are other processes applied. A schematic diagram of the GMAW, GTAW and PAW process is shown in Figure 2-16 [57].

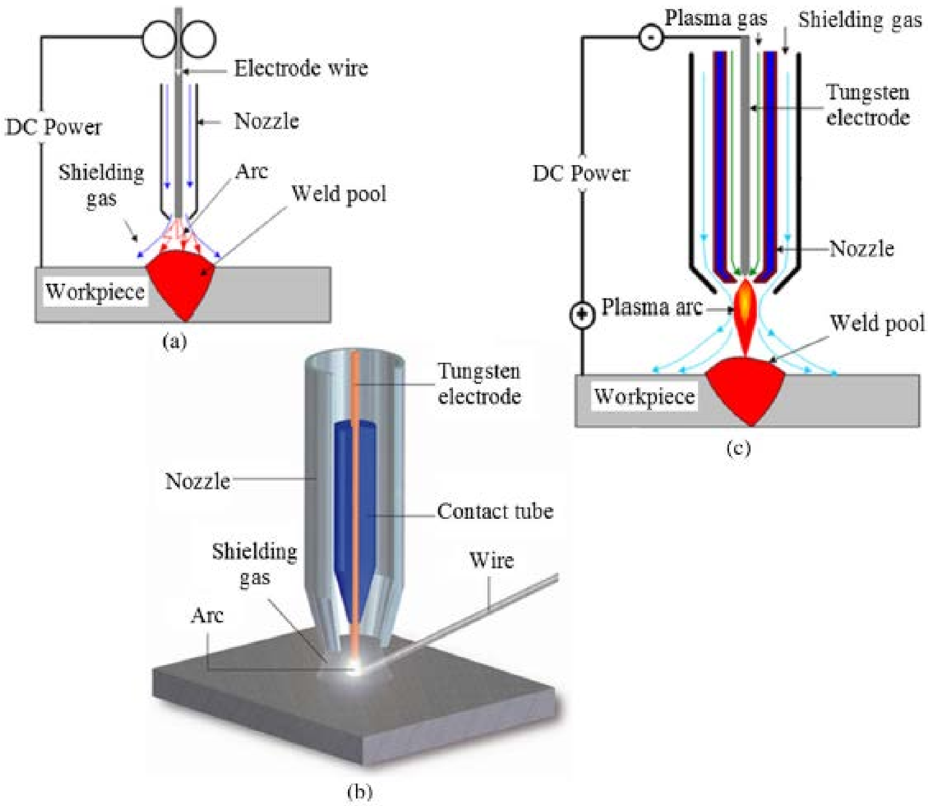


Figure 2-16. Schematic diagram of the a) GMAW, b) GTAW and c) PAW processes [57].

High deposition rates, low material and equipment costs, and good structural integrity make Wire & Arc Additive Manufacturing a suitable candidate for replacing the current method of manufacturing from solid billets or large forgings, especially with regards to low and medium complexity parts. A wide bunch of materials is available for this AM method including steel, nickel alloys and titanium alloys. WAAM technology is particularly promising for the manufacturing of large parts (see Figure 2-17), with a low capital cost compared with other AM processes [58].

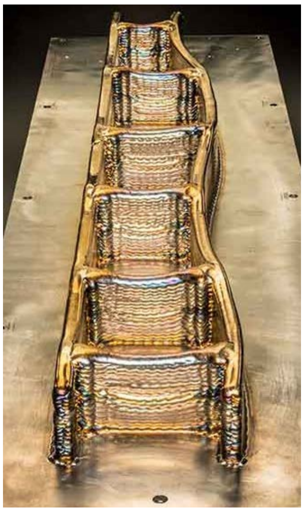


Figure 2-17. Titanium part (BAE systems spar) manufactured by WAAM process [58], [59].

The main advantages and drawbacks of the WAAM technology are listed in Table 2-8.

Table 2-8. Advantages and drawbacks of WAAM processes.

Advantages of WAAM technology	Disadvantages of WAAM technology
➢ Lower capital costs than other AM technologies. ➢ Material cost and utilisation. Welding wire is a cheaper form of feedstock than powder. ➢ Open architecture. The end-user can combine any brand of power source and manipulator. Total control over the hardware. Software can be adapted to the specific equipment available. ➢ Part size. The maximum part size is determined uniquely by reach capability of the manipulator or the size of the inner envelope of the chamber in the case of reactive materials. ➢ High deposition rates, ranging from 1 kg/h to 4kg/h for Al and Steel. Values of 10 kg/h can be achieved.	➢ Residual stresses and distortions is a major concern for the large-scale WAAM. Part tolerances could be affected. Premature failure has also be an issue. ➢ Accuracy. The slicing manner affects accuracy. *Un-match* and *stair-case* effects have been reported. The accuracy is 10 times lower than with powder bead technology. ➢ Surface finish. Surface roughness is related to the weld bead geometry.

Nevertheless, the drawbacks are associated to the production of smaller components with complex geometry since the impulses of high temperature cause considerable distortions, also residual stresses. Distortions lead to poor tolerances while residual stresses affect to the mechanical behaviour of the component. Additionally, post-processing operations are needed due to the deficient surface finish obtained with WAAM.

2.4 Comparison of Powder Bed Fusion and Directed Energy Deposition Technologies

Laser powder bed fusion is the dominant technology for metal AM due to higher accuracy, surface quality and freedom of design. The typical layer thickness in PBF technology is 20–100 µm, and the completed components can achieve a dimensional accuracy of ±0.05 mm and surface roughness of 9–16 µm. In addition, it is possible to produce parts with functionally graded materials (FGM). However, the deposition rate of the PBF technology is extremely low, typically around 10 g/min, which limits its application in fabricating median to large-sized components.

In wire-feed AM, a metal wire is used as supply material instead of metal powder. There are three different energy sources used for metal deposition: laser-based, arc welding-based and electron beam-based wire-feed AM. Wire-feed AM has higher material usage efficiency with up to 100 % of the wire material deposited into the component. Therefore, it is a more environmentally friendly process. In addition, metal wires are lower in cost and more readily available than metal powders having suitable properties for AM. DED processes based on wire as feedstock, compared with the powder-feed processes, have a much higher deposition rate. But it is worth mentioning that there is a trade-off between high deposition rate and high resolution while selecting which type of AM process to use for a certain component.

A comparison of powder bed fusion and directed energy deposition processes is included in Table 2-9.

Table 2-9. Comparison of AM processes: laser powder bed fusion vs. directed energy deposition [2], [22], [23]

	PBF - SLM	DED - LMD	DED – WAAM	DED – EBF3
MATERIALS	Limited and lower experience in comparison with DED	Large materials diversity		High added value metallic elements
PART SIZE	Limited by the process chamber, 500x280x325 mm	Limited by the handling system, 2000x1500x750 mm		
PART COMPLEXITY	Nearly unlimited	Limited		
DIMENSIONAL ACCURACY	±0.04 mm	≥0.1 mm	±0.2 mm	Low
BUILD SPEED	1-3 mm^3/s	3-10 mm^3/s	1-4 kg/h	3-9 kg/h
SURFACE QUALITY (ROUGHNESS, R_Z)	5 – 15 µm	30 - 200 µm	200 µm	High
FOCUS AREA	-Rapid prototyping -Direct manufacturing of parts	-Repair of worn components -Modification of tooling for re-use -Direct manufacturing of parts		

2.5 Maturity of AM technologies

Additive manufacturing is now considered as a disrupting manufacturing at different levels of requirements (applications, materials) and for that different technologies have been developed. This section aims to give information about the relevant data according to the maturity of each AM technology.

Powder Bed Fusion technologies

The technologies analysed in terms of maturity of powder bed fusion are: SLM and EBM.

Table 2-10. Maturity of SLM

Selective Laser Melting (SLM)
Age of technology:
18 years old
From the older to the newer
Fockele & Schwarze
Year to market irruption:
1999
Number of suppliers
19
Most extended use
Medical and tooling sector are the sectors where SLM is more extended. In the aerospace sector fuel injectors, structural elements and blades are the most common applications.
More relevant information
First uses were for plastic prototyping. Maturity of SLM manufacturing depends on materials and application. In the case of SLM for aerospace sector the TRL (technology readiness level) is in the range 5-7 as can be observed in Figure 1. This is very dependent on the material and application.

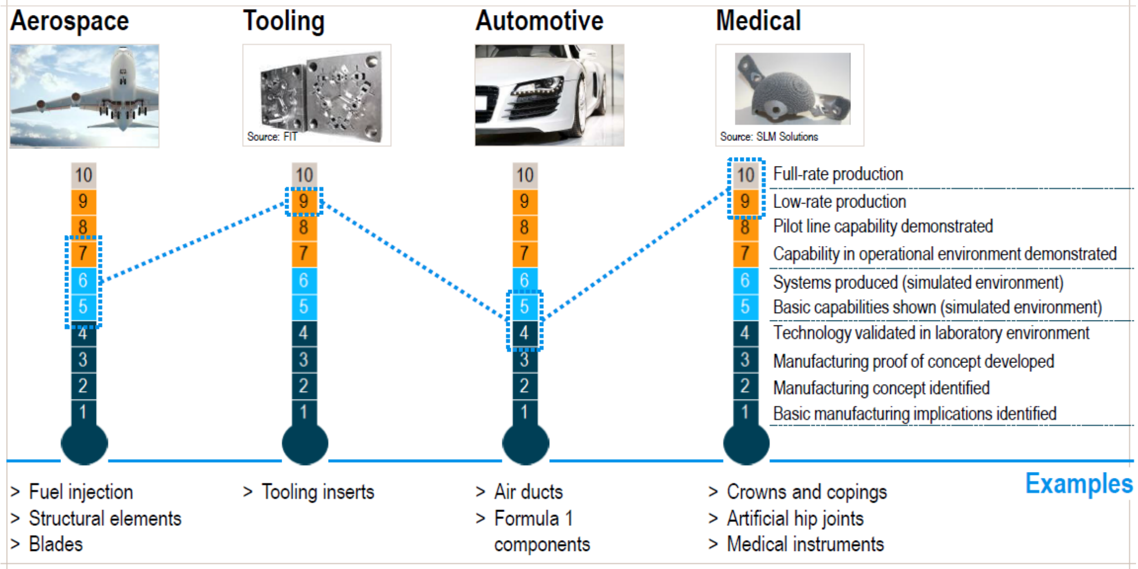


Figure 1. TRL of SLM for different sectors [88].

Table 2-11. Maturity of EBM

Electron Beam Melting (EBM)
Age of technology:
19 years old
From the older to the newer
ARCAM “EBM S12” and newer ones are Arcam Q10 and Q20
Year to market irruption:
1998
Number of suppliers
1
Most extended use
Turbine blades for aircraft engines and implants.
More relevant information
The status for space use of AM is in the case of EBM for titanium is in TRL 9. As in the case of SLM, maturity of EBM depends on material and application.

Directed Energy Deposition technologies

The technologies analysed in terms of maturity of powder bed fusion are: LMD, EBAM® and WAAM.

Table 2-12. Maturity of LMD

Laser Metal Deposition (LMD)
Age of technology:
19 years old
From the older to the newer
Optomec LENS
Year to market irruption:
1998
Number of suppliers
8
Most popular technology
Blown powder and wire
Most extended use
Started for cladding applications and repairing.
More relevant information

Table 2-13. Maturity of EBAM

Electron Beam Additive Manufacturing (EBAM®)
Age of technology:
8 years old
From the older to the newer
Sciaky's EBAM
Year to market irruption:
2009

Number of suppliers
1
Most extended use
Titanium structural components for aircrafts
More relevant information
Excellent choice for refractory alloys and dissimilar materials

Table 2-14. Maturity of WAAM

Wire and Arc Additive Manufacturing (WAAM)
Age of technology:
This manufacturing uses different arc welding technologies: GTAW (gas tungsten arc welding), GMAW (gas metal arc welding) and PAW (Plasma arc welding). These technologies have been broadly developed for joining processes. The use of these technologies for additive manufacturing was patented in 1920s by Baker, producing 3D metallic parts by overlapping weld beads using manual arc welding. More accurate and automated parts could be developed with the insertion of robotic arms. At 1990s WAAM technology was impulse by Welding Engineering Research Centre of Cranfield University.
From the older to the newer
1940 TIG methods, 1950 MIG methods.
Year to market irruption:
This technology is on market from long time ago for welding processes. Innovation in this field came from technologies development in terms of arc stability for different materials and deposition rates. Research and innovation in different places (universities, technological centres in close collaboration with big manufacturers) is being developed but it is not yet industrially implemented.
Number of suppliers
Developing period of industrial machines
Most popular technology
GTAW, GMAW and PAW
Most extended use
The aim of these technologies for additive manufacturing is to build large parts with a

high deposition rate and low buy to fly ratios that allow the use of high cost materials and with low to medium complexity.
More relevant information
Norsk Titanium started to fabricate metal parts by PAW for Boeing to achieve certifications.

2.6 Numerical simulation in additive manufacturing

Introduction

The additive manufacturing (AM) is currently revolutionizing the way to manufacture items thanks to four main advantages [70]:

- AM offers more freedom in the way to design items compared to classical processes (foundry, etc.);
- AM is environment-friendly because only the material needed to build the item is used (partially true because a part of powder is always lost);
- The AM machines are adaptive: the can produce any items (not dedicated to one type of manufacturing/item). Only the item dimensions can be restrictive.
- The item can be personalized, perfectly fitting the needs of the user.

Despite all its advantages, the additive manufacturing faces some problems such as the unknown capability approach of the AM processes. This generates a difference between the expected geometry (in theory) and the real produced one [1]. To solve the problem, it is necessary to carry out some additional finishing operations or to modify successively the theoretical design to produce the expected geometry. Anyway, this implies additional charges for the production cost.

The difference between the 2 designs is mainly due to [71]:

- Lack of knowledge about the physicals phenomena occurring during the manufacturing process. So these phenomena are not fully mastered during the process and it is very difficult to forecast the final quality of the product;
- The implied physical phenomena rely on the manufacturing process and the process plan used. All the parameters should be integrated as soon as possible in the design process.

For the LMD-P, the main parameters linked to the manufacturing process are the material, the laser power, le powder flow, the gas jet and the weld speed [72].

The item orientation during the manufacturing and the selected scan strategy influence also the final characteristics of the product. Considering the "powder bed" process and using the same manufacturing parameters, Bo [73] compares two types of scan strategies, "sweep" and "spiral" scans, to manufacture a part of a turbine. The comparison of the two scans is unquestionable: the part cannot be manufactured using a "sweep" scan! Because of too high thermal constraints, the part collapsed during the manufacturing. The difference of intensity and localization of the thermal constraints induced by each scan strategy depends also on the manufacturing process. Foroozmehr [74] got the same conclusion on the influence of the scan strategy studying the powder projection process.

Finally, additive manufacturing has also an impact on some parameters of the produced item: its surface finish (roughness, curve unsmooth but with a “stair” shape, etc.), its resistance to thermos-mechanical constraints, the inherent strains (Bikas [75]) to model the manufacturing process is necessary for this type of manufacture. But the numerical results are exploitable only if the numerical model is close enough to the real behaviour.

In additive manufacturing, the influencing parameters of the process are numerous: they characterized the manufacturing process (such as laser speed, powder flow, laser power…), the final produced item (residual strains …), the position of the part during the welding… If the numerical simulation seems necessary, it is currently impossible to model a complete part in additive manufacturing taking into account all the implied parameters [70]. Even if it has been investigated over the past years, there is not any method or any tool allowing the simulation of the manufacturing of a complex part in a reasonable time. By “complex”, it is implied that the part is not a straight weld bead (with one or multiple straight layers). This lack of numerical tools is due to the relative youth of these manufacturing processes but also to the partial knowledge of the multi-physical phenomena involved. In addition, the complexity of these phenomena makes the establishment and the solution of the numerical models more complicated, rising the time needed to solve the equations (Kumar [76]).

Modelling with finite elements

Over the ten past years, lots of studies have been published dealing with the direct modelling of physical phenomena implied in additive manufacturing. These phenomena are coupled and interacted together. For powder projection, the final geometry of the parts mainly depends on two factors:

- The evolution of the welding local geometry during the manufacturing;
- The displacements and the inherent strains induced by the manufacturing.

The evolution of the welding local geometry directly relies on the dimensions of the molten pool created by the laser on the substrate. It is also influenced by the powder flow in terms of powder quantity and repartition. Concerning the residual strains and the displacements, they depend on the temperature gradient and the thermos-mechanical properties of the materials used.

Thus, Toyserkani [77] has developed a 3D model to study the impact of the main parameters of the process on the melted zone characteristics. Cho [78] has completed the model adding the impact of the latent temperature on a semi-infinite domain. The comparison of the numerical and experimental results shows a very match between them for one layer weld bead.

Concerning the displacements and inherent strains due to temperature fields, some studies have already been carried out. Ghosh [79] has developed a model including the material change of phase in order to determine the inherent strains manufacturing one layer weld bead. Foroozmehr [74] has considered the continuous supply of material activating little by little the mesh elements of the part. All the residual strains are modelling this way for one complete layer of a weld bead.

In most additive manufacturing studies, the deformation of the part is calculated with the following equation:

$$\epsilon i,=\epsilon_{i,j}{}^{M}+\epsilon_{i,j}{}^{P}+\epsilon_{i,j}{}^{T} \qquad (1)$$

With $\epsilon i,,$ $\epsilon i,jP$ et $\epsilon i,jT$ the deformations respectively due to the mechanical stress, the plasticity of the material, and the temperature gradient. The relation stress/deformation is generally considered linear:

$$\sigma_{p,}=D_{p,q,i,j}.\epsilon_{i,j} \qquad (2)$$

Whit σp, the elastic stress and $Dp,,i,j$ the stiffness tensor of the material used.

The studies focused on the link between stresses and part deformations usually integrate experimental results validating the thermal model. But most of them are conducted on simple geometries such as straight weld beads with one or multiple layers.

In order to define the local geometry of the welding, multiple approaches already exist. In Morville's study [80], a 2D model determines the local geometry of the welding deforming the initial mesh in accordance with the capillary and thermos-capillary forces induced by the temperature field (the "Marangoni" effect). Others like Toyserkani [77] also model the welding but in 3D. To do so, they define the melting pool boundary for each time step and model the material supply in this zone with the following equation:

$$\delta h(x,y) = \delta t.\dot{m}_p \,/\, \rho.Spowder \qquad (3)$$

With δt the time step of the simulation, $\dot{m}_p$ the mass flow rate, ρ the density of the powder and $Spowder$ the surface of the powder jet projection on the part.

This model has been reused in some studies underlying its validity for one layer weld bead but also for multiple layers weld beads (Alimardani [81], Fallah [82]). However, the simulation of complex parts is occasional because a lot of time is needed to solve the models. Currently, to simulate one straight weld bead with a length of few tens of millimetres, the time needed varies from few hours to several days depending on the computer and models used.

Common software used

There are different ways to model the additive manufacturing of a part using different simulation software. In the literature some are found such as:

- Toyserkani [77] who has determined the analytical equations of the different phenomena involved. Then, he used MATLAB and FEMLAB to solve them. A tetrahedron mesh was used with an adjustment step by step.
- Cho [78] used the ABAQUS software. He focused on the latent heat and its effect on the additive manufacturing. He developed a complete model of additive manufacturing.
- Like Foroozmehr [74], Fallah [83] used Ansys APDL to solve his numerical model. The "additive" principle of the manufacturing is represented thanks to the addition/remove of mesh elements. The thermo-mechanical behaviours are also taken into account.
- Alimardani [81] used COMSOL Multiphysics 3.2a to develop his own numerical models thanks to the possible coupling with MATLAB codes.

The usual software of mechanical simulations have not been developed for additive manufacturing simulations (Ansys, Abaqus, Matlab, CodeAser) which makes them less interesting. Some new software has been developed to meet the specifications of the additive manufacturing simulations:

- Virfac by GeonX. Based on weld bead simulations, this software is adapted to bed powder process and a new module for powder projection process will be integrated soon;
- Simufact Additive Manufacturing seems very complete simulating the whole additive process to determine the inherent strains in the final product;
- SolidThinking Inspire,
- 3DSIM: with ExaSIM, it is dedicated to laser sintering.
- Project Pan: it is focused on processes of powder bed, Wire-Fed and Power-Fed. But it offers a module providing the manufacturing parameters in order to limit the inherent strains of the final product.

2.7 Topological Optimisation

Introduction

Topological optimization is a technique defining the best repartition of material in order to get the optimal design. To do so, the use of the item and the different stresses applied are taken into account. The design characteristics are modelled such as the number, location and form of holes, etc. (Driessen [83]).

The topological optimization is used to redefine the topology of the part keeping only the material needed (boundaries, number of holes, etc.) and increase the potential of optimization. For Takezawa [84], among all the different kind of mechanical optimizations, the topological optimization is the one offering the best way to find the optimal functional design of a part. Two ways are usually considered: continuous and discrete approaches.

The continuous approach or homogenization method (studies of Bendsoe and Sigmund [85]) is a common method based on a density method. The part is divided into an infinite number of infinitesimal variables. The design space (in blue on Figure 2-18) is divided into infinitesimal volumes. A variable is associated to the density of each volume. The variables can have two values: 1 if the density is positive (the volume is kept, in red on Figure 18) or 0 of the density is null (the volume is removed, in white on Figure 2-18). So the geometry of the part after the optimization process is the one formed by the infinitesimal volumes with a positive density. The main advantage of this method is that the optimal design does not depend on the initial geometry. The approach is not influenced by any negative or positive bias. The method leads to geometries very different from the usual designs we first think about.

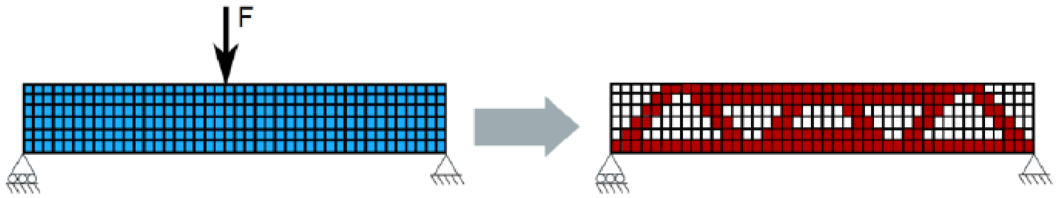


Figure 2-18. Illustration of the continuous topological optimization process.

The second approach is with discrete elements. It is based on basic elements of structural mechanics (beam, shell,…). This method is a combination of multiple kinds of optimization (scale, form and topology) more than one technique of topological optimization by itself. The structure modification is done by the addition or the removal of some elements. This way, the designer deals with elements he uses to work with and it is easier for him to forecast the impact of the changes on the global structure behaviour. On the other hand, the final result clearly depends on the initial geometry. To illustrate the method, the same example as Figure 2.19 is used. The initial beam is modelled by the assembly of several small beams. The designer can choose to keep or not the small beams. The final result on Figure 19 is closed to the continuous process but it is more depended on the initial geometry and the initial position of the small beams.

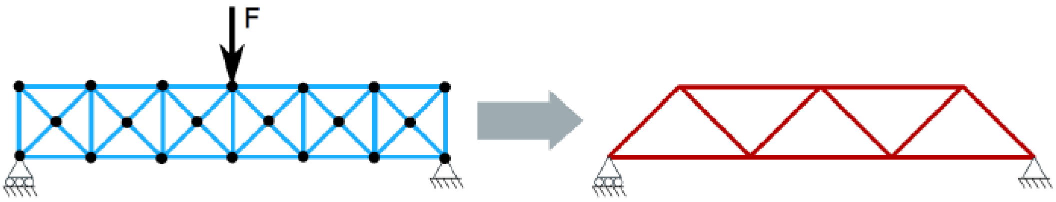


Figure 2-19. Illustration of the discrete topological optimization process.

Among the different type of optimization problems, the continuous topological optimization seems the best way to take the advantage of the additive manufacturing opportunities (Ponche [70]). Indeed, this method is the best one considering that the initial design space does not impact the final result. That is why we focus on this kind of optimization.

Techniques of continuous optimization

One of the most commonly used method is the penalization (SIMP - Solid Isotropic Material with Penalization) presented by Bendsoe [85]. This method uses a penalized rigidity model to interpolate the elastic modulus of the material:

$$(x)=x_e^p\, E_0 \qquad (4)$$

With (x) the elastic modulus of the element e, x_e^i the design or density variables of the elements, E_0 the elastic modulus of a solid element and p the penalization parameter.

In the SIMP approach, the penalization parameter is generally chosen greater than 1 (often p=3). This interpolation method leads to intermediate densities which are not suitable because of their low rigidity compared to their density (Driessen [83]). Some authors like Zegard [86] use a different version of the model to avoid some difficulties.

The technique "void-solid" is also commonly used with the BESO algorithm for additive manufacturing optimization because it provides very interesting results. Other methods exist such as genetic algorithms or level set method but their capacity to solve in a relevant way the problems has not been proved yet (Brackett [87]).

The topological optimization software are currently developed in order to take into account the main constraints induced by the common manufacturing processes. One of the most important interests of the additive manufacturing is precisely that most of manufacturing constraints are not applicable to this additive process. Indeed, the "Layer-by-Layer" manufacturing allows all geometries, in particular the ones impossible to produce with common manufacturing techniques: the part designs are almost unconstraint by the manufacturing process but only by the user's needs (strength of materials, forms, etc.). Thanks to the printing process, the rise of part complexity does not mean a more expensive product: the manufacturing cost is almost the same than common processes or it can be cheaper if supports are not used.

Main difficulties with topological optimization for additive manufacturing

Mesh size

The first restriction of the topological optimization for the additive manufacturing process is the maximum size of the mesh elements in order to get a topological optimization which means something. Indeed, the additive manufacturing allows very thin wall thickness. But, topological optimization requires minimum 2 or 3 elements for each thickness. This lead to very small elements and a very large number of elements to mesh the whole part; so the time needed to optimize the part topology would rise drastically.

Manufacturing constraints

Some designs need supports because of theirs slope angles (with the horizontal plane) and the manufacturing method used (temperature gradient more or less important). Depending on the slope angle, there is a maximum distance value on which the additive manufacturing can be done. For example, the study of Brackett [87] shows that, with an angle of 25°, the maximum distance is 15 mm, with an angle of 30°, the maximum distance is 20 mm and there is no limit if the angle is greater than 45°. In the other cases, the use of supports is necessary.

The surface finish of the produced parts is generally unsatisfactory. A finishing step should be done in order to get a functional product. This means that an access to all these surfaces is needed which is not always feasible.

The topological optimization is based on a discrete form of the part from which some elements are removed. It is generally needed to smooth the surfaces after the topological optimization. Some software such as Materialise Magics, Netfabb Studio and Marcam Autofab do the exportation of the smoothed geometry, otherwise, the designer has to do it by himself with CAD software. The OSSmooth module of Optistruct does it. This module allows the direct modification of the geometry or the mixing between optimized designs and local CAD designs (imported in ".stl").

Finally it is important to underline that each new design should be simulated two times: a first one to simulate the manufacturing and define the inherent strains, the second one to check the material strength.

Single or multi-materials to manufacture?

Some manufacturing processes are more adapted to multi-materials manufacturing than others. The manufacturing processes by jet (3D printing) or by extrusion are particularly suitable to multi-materials production whereas powder bed, SLM/SLS and stereolithography techniques are single material process (Brackett [87]).

Software

Among the possible software, TOSCA (FE Design) has been tested by Brackett [78]. This commercial software is not wall adapted to topological optimization for additive manufacturing parts because there is only 2 layers refinement possible for each thickness. In addition, the level of remeshing needed for additive manufacturing parts is not enough.

Currently, the weld bead thickness is the only constraint which should be taken into account in a topological optimization. This constraint can be found in Optistruct (and 3-MaticSTL for the post-treatment of the geometry before manufacturing) of Altair and Nastran (MSC).

Among the commercial software, the more commonly used are:

- Materialise Magics,
- Netfabb Studio,
- Marcam Autofab,
- NX Hybrid Additive Manufacturing (allowing the prototyping, the manufacturing and the fixing of products),
- MI:Additive Manufacturing,
- GENESIS Topology (Ansys),
- 3DSIM (including a module of manufacturing simulation).

2.8 Scan strategies

As already explained in this document, some studies have already underlined that the scan strategy chosen in additive manufacturing impacts the final geometry of the product (Bo [73]). So several software have been developed to get the optimal trajectories such as:

- PowerCLAD,

- ➢ The Grasshopper module from Rhino (Duballet [19]); which can also be used for topological optimization (Ren [20]).

PowerCLAD is based on PowerSHAPE and PowerMILL modules developed by Autodesk (previously named Delcam) and IREPA LASER. From the PowerMILL module, the machining trajectories have been reversed and the collision between the tool and the raw part in order to define the scan strategies. This way to reverse the strategy compared with classical manufacturing processes can also be applied to other CAM software such as CATIA. But Dassault Systems has chosen to develop his own module, «Delmia», to determine the trajectories. In a similar way, Siemens has added a new module to its CAD NX software (dedicated to the additive manufacturing) named «Nx Hybrid Additive Manufacturing».

Finally, each machine builder dedicated to additive manufacturing has to supply a solution (a home-made software generally) to generate the scan strategies. The most known are Cura 3D and MakerBot Print.

3 ADDITIVE MANUFACTURING – TECHNOLOGICAL OFFER

3.1 Motivation and Potential

Additive Manufacturing (AM), popularly known as 3D printing, promises to transform fundamentally the development from concept to production-of new products. Since this technology became popular with the rapid prototyping of polymer components, is the technological capability to produce metal components by AM has the potential to be a real “game changer". Am no longer a simple shortcut that allowed designers and engineers quickly materialize its concepts from digital models on physical prototypes, Instead, the process of AM offers the possibility to create completely new products that could not be manufactured using conventional methods of production.

AM technologies can revolutionize many manufacturing sectors worldwide, reducing time-to-market, cost, material waste, energy consumption and carbon emissions. In addition to these facts, the AM comes bring new methodologies and new production capacities that so far were limited by using conventional subtractive production processes, come open new frontiers to the life cycle of equipment and components allowing you to extend the life of the parts in service through innovative repair methodologies or through the production of replacement parts without the need for tools in many cases already slaughtered. As an example we can cite the case of aerospace industry where the use of these capabilities of targeting AM could lead to a reduction in the amount of new raw material required to manufacture a component already in service, known as the "buy-to-fly".

The capacity to explore the potential use of AM can also lead to the emergence of innovations for light structures, which could see use in unmanned aerial vehicles, in the first instance and later come even to be applied across the aviation industry in General, as a first phase in the production of non-structural components and then in primary components. Below (Figure 3-1) presents what will be a typical cycle of the process of AM.

Figure 3-1. AM Process flow. [39]

The technology for the production of metal components for AM and is currently in an active phase of development where the production of components, reliable and reproducible technical components perfectly functional is already possible.

However, it is clear that only through the combination of virtual product design, including CFD, FEM and other numerical analysis tools, and the application of optimized design principles for AM, one can explore the true potential of the additive production. The sub-processes of the development of components for production by AM most common are presented in Figure 3-2.

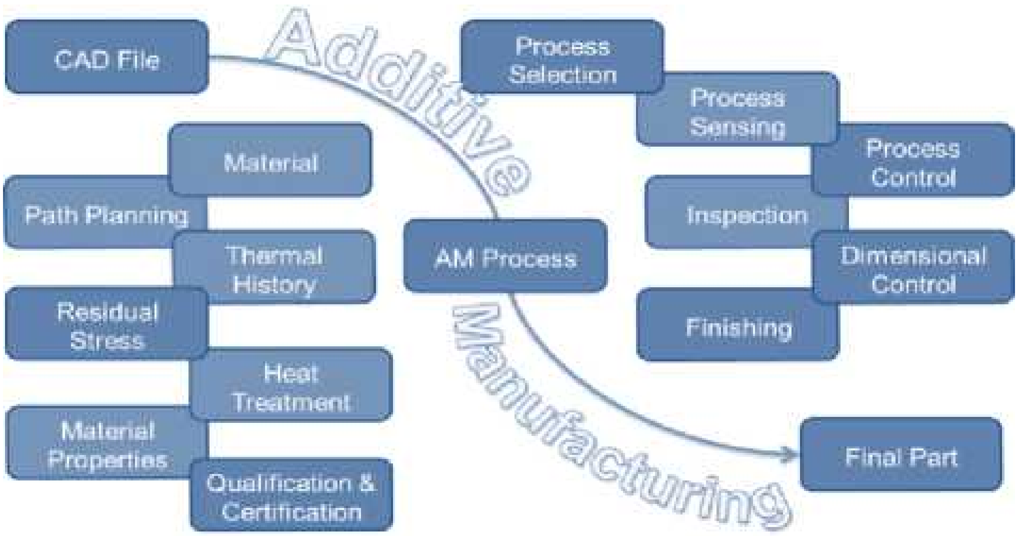


Figure 3-2. AM Workflow. [40]

Recently, Caffrey and Wohlers have come to demonstrate the increasing popularity of the use of AM-in the production of metallic industrial components, through the tracking equipment sales of metal per year-AM Figure 3-3.

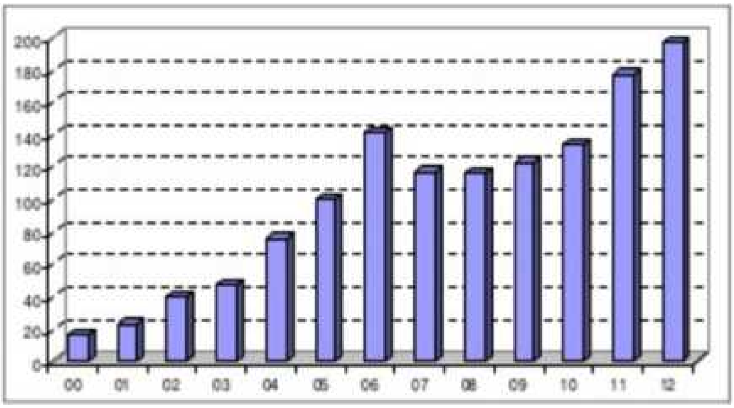


Figure 3-3. AM equipment's sales. Source: Wohlers report 2013 [41, 42]

In 2010, Holmstrom *et al*. [41] suggested that the main benefits of additive manufacturing, regarding to subtractive manufacturing would be the following:

- There is no need for production tools, fade-out time to "ramp up" production;
- Small "batches" of production are feasible and economically viable;
- Design changes made easy and quick to implement;
- Product optimization focused on function (e.g. cooling channels optimized);
- The ability to produce complex geometries;
- Potential to simplify the supply chain industry, smaller delivery times, lower inventory dimension.

In 2014, *Ford* [42] suggested that, as the technology of AM continue its evolution, is likely to result in the following changes:

- Shorter "time to market" due to rapid prototyping and design cycles, as well as the possible elimination of many traditional manufacturing steps, such as transport, manufacture of moulds and Assembly;
- Greater competition resulting in greater diversity of solutions/products due to the Elimination of barriers to entry;
- Smaller supply chains more efficient and cheaper, especially for the production of complex components with reduced production volume.

3.2 Foresight

It is expected that manufacturing in 2050 will look completely different as it is moving from cheap mass production to personalised production, adapting to changeable global markets [65][66]. These technologies enable clean production, by energy and material efficiency. In these years AM industry moved from prototyping to production, where quality requirements and complexity are much greater. Wohlers Report 2016 indicates that the "tipping point" of AM reached in 2012 [67]. After then huge investment was done in research and commercialisation. Many equipment manufacturers appeared in 2015 and it will continue advancing impressively into the next 5-15 years [67].

Aerospace sector is giving an impulse to the AM. In this sense GE opened a 32 million AM research centre in Pennsylvania in 2016. The US Federal Aviation Administration authorised one of their AM components which will be added to 400 reaction engines of commercial aircrafts. GE is working to achieve the authorisation for nozzles built by AM for a new generation of reaction engines. These nozzles are 25 % lighter than conventional ones [67]. They expect to build 100,000 parts by AM for aircraft engines by 2020. Also Airbus includes AM plans in their future. They worked hard in topology optimisation advanced methods, achieving sometimes a reduction of weight of 50 % or more. Their aircrafts contain numerous polymer and metallic parts. They plan to build 30 tons of metallic parts monthly by 2018 using a network of AM systems. They also trained nearly 300 additional employees in AM in 2016 [67].

The scarcity of raw materials, big data [66] bases availability and product customisation trend make AM a perfect alternative to conventional manufacturing. The foresight of AM pays attention to different points to improve this technology in terms of making viable in an industrial scale.

- Productivity and flexibility
- Data collection
- Quality standardisation
- Material availability
- Multidisciplinary teams and training programs

A cost reduction of AM equipment of 25-45 % by 2020 is expected. The high costs of AM equipment can be justified by higher manufacturing speed, bigger chambers and easiness for load or unload of parts among others. To increase the deposition rate and productivity, main research is focused in different key points. As example lasers with higher power are being studied [68]. Also multi-laser equipment using more than one laser is being taken into account to work in parallel or to follow different strategies like skin-core strategies which use a high power laser to build the core and another one with lower power to build the skin which needs better precision. Multi-spot array systems mounted in a printer-like processing head with fume removal and local shielding gas are being investigated due to the advantages like high manufacturing speed and no chamber size limitations. Also the concept of full powder bed illumination or multi-jet fusion is in development stage. This system uses chemical agents to reduce or amplify the melting process achieving high surface accuracy, and masks to control the laser radiation. Another option to reduce process time is the use of novel systems that make possible a faster powder deposition or to make simultaneously deposition and melting processes.

Surface roughness and accuracy can be optimised by a post treatment like milling, polishing and/or machining. For this purpose hybrid machines integrate additive manufacturing and machining which increase the productivity and reduce timeouts. Also modularisation and integration concepts provide flexibility combining and integrating peripherals, bigger fabrication chambers, post processing and an automated handling or unloading station which can reduce considerably costs of production.

Good quality complex components are difficult to achieve. For that it is important to create and follow methodologies to select the appropriate parameters and strategies for different materials. The integration and communication between machines, for data collection and analytical programs for their management, are of high importance. Besides, simulation is a useful tool to predict and control the distortions, residual stresses and microstructures, limiting the number of experiments.

In the field of control monitoring systems different methodologies have been developed to assure a robust fabrication process without differences in terms of quality and dimensions between batches. Chamber process control provides monitoring of any irregularity during the layer deposition but also the physical parameters of the laser and the oxygen level and pressure of the atmosphere. Melt pool process control provides monitoring of the temperature and shape of the melt pool in real time with the aid of high resolution sensors. This improves traceability, quality, reliability, repeatability and efficiency. There are also simulation software programs that predict the melt pool and the behaviour of metal powder.

In the other hand, non-destructive tests (NDT) assure the quality of the fabricated components. In this field, computering tomography is a useful tool to detect porosity in complex geometries. Due to the youth of AM for final metallic parts, specifications for inspection are still being developed and many manufacturers of inspection methods are exploring new methodologies for AM [67].

Optimisation of topology design has to be improved by specialised software. Designers will change their designing way to a more functional way and less manufacturing way giving them more freedom to design. Topology optimisation software enables optimised and efficient designs with reticular and bionic-like structures applying mathematical algorithms. In reticular structures, materials are only added to the useful zones achieving rigid structures with the optimisation of the weight, which reduces the metallic powder consumption and manufacturing time.

The lack of standardisation, makes it difficult certification and normalisation of additive manufacturing for fields where the certification is very important like the aerospace sector. Standardisation is necessary to achieve a robust process. Process standardisation can be achieved by the generation of a data base with the properties for different applications in function of the material and parameters, and by the optimisation of the mechanical properties in function of the heat treatments and process parameters. Design standardisation needs the definition of design rules and fabrication criteria. It is expected that in the future these rules will be shared and unified [69].

The number of available materials continues growing. However, an increment of the materials choice is necessary. Developments are being done in the processability of new metallic materials like Ni super alloys, Al alloys, refractory metals and martensitic steels among others. Generation of data bases of the properties of specific materials built by AM and different processes may provide information for the design of proper new alloys for AM.

EXMET developed a process to build glassy metal parts by AM. Glass metals combines in a unique way properties like high strength, elasticity, hardness, corrosion resistance, conductivity and biocompatibility, all of them very useful for future high value application in electronics, aerospace and mechanical engineering [68].

A new manufacturing process to build multi-material components for specific functions is emerging. They are based on the material transition in a body during the manufacturing process. They have to exhibit compatibility between both materials. They can be made in two different chambers or by changing the feed by combination of 3 different materials in different proportions.

In the field of powder manufacturing, the tendency is to reduce the price of powders and to increase powder volume production. METALYSIS is a new powder manufacturing process using electrolysis. Its advantages are the cleanness, low energy consumption and cost reduction of 75 % [68]. However, a methodology to validate powder manufactured by new technologies is required. Also a deep study on the influence of recycling or reusing powder maintaining good properties of built parts is necessary.

Future requirements include educational and training programs, as a key point to provide skilled workers, as well as the creation of multidisciplinary teams to develop complex products by AM [65]. To achieve this, educational training design, focused on metal AM techniques and technology, from junior to middle school, university and job training are of high importance to include different roles and great number of qualified professionals in this field [67].

3.3 The market opportunity

This chapter describes the current investment in AM technologies on a global level.

Europe

The overall global market for AM surpassed $ 1 billion in 2009, with direct revenues for systems and sales of more than $ 500 million.

90% AM equipment sold are the 3D printers that allow the production of polymer-based components and equipment, it should be noted that the visibility of this kind of equipment is contributing definitively to the market growth of AM technology. At the beginning of 2010, a group of companies led by Materialise formed a group to make collective marketing for AM. The cover story of a recent issue of the British magazine The Economist addressed the potential of AM as a revolutionary manufacturing technology.

Although currently most of the overall activity on AM use polymer-based systems, there has been a good deal of activity and interest, with regard also to metal fabrication. Metal fabrication has sparked interest mainly due to the possibility that features direct manufacturing of components "near-net-Shape", and in some cases even final components, without the need for tools or machining. There has been particular interest in aerospace, automobile industry, especially of low grade, and biomedical industries, due to the possibility of production of high-performance components with reduced total cost of production. Researchers and industry leaders in the European Union (EU) have identified the AM as an emerging technology key.

Different countries outside the EU have increased their awareness of AM technology since for years and, at this point, North America is at the forefront when it comes to the adoption of AM. However, the importance given to these systems and technologies tends to spread quickly to other countries, putting the AM in the centre of the development of their national jurisdiction. Yet, the situation of different countries in Europe is not homogeneous as pictured below:

Country	Market Opportunity
Belgium	The Belgian Flanders regional government invested in a program in AM for materials called STREAM (Structural Engineering Materials through AM). The program involves universities, research centres and industry gave rise to three projects funded starting in 2014. The projects aim to develop the selective laser sintering of polymer and the selective laser melting of metals. A series of educational initiatives have been developed towards the dissemination of AM technology [43].
France	The French Association of rapid prototyping has contributed to an increase in levels of standardization of AM technologies, both nationally and international [43].
Germany	Germany has a strategy for AM that develops through the establishment of transport links between the scientific community and industry. Direct Manufacturing Research Centre (DMRC), based at the University of Paderborn in Germany is a joint between industry and universities in order to develop the technologies of AM. The DMRC and the German State of North-Rhine-Westphalia made a joint investment of more than € 2 million. Was made an additional investment of € 3,400,000 by German State in order to supplement the equivalent investment made by industry, which gave rise to an overall budget of about € 11 million to a development AM plan of five years [43].
Holland	In Netherlands, the product development process has become an essential part of AM. For example, the Dutch research institute TNO initiated a shared development initiative-Penrose-with a number of industrial partners with the goal of developing the next generation of tools and AM devices with a view to industrial production of components through AM process [43].
Portugal	The Portuguese strategy for Additive Manufacturing has early aligned with the European initiatives on rapid prototyping, namely for moulds. RTD projects were also funded and a national network for rapid prototyping (RNPR) created. Industry was pushed by curiosity but with limited results.

Portugal	Year 2000 was crucial for leverage of rapid prototyping, systems development, business models, initiatives and events. After 2010 the “industry 4.0” initiatives by Ministries of Economy and Science and Technology raised the interest of various sectors of activity, such as metalwork, ceramics, glass, construction, health and aeronautics. Today Portugal is skilful in applications but provision of systems is still awakening. Presently a Portuguese Additive Manufacturing Initiative (PAMI) is underway, which will network several research Centres in the field of additive manufacturing. In 2016 the CDRSP was given the role to coordinate a national platform of additive manufacturing, by the Minister of Science.
Spain	In Spain, private research centres took the lead for industrial applications in AM and, in recent years, many start up companies have been directly involved in these new technologies. Some regions are very active and pushing in European initiatives, such as Andalucía, Asturias, Catalonia and the Basque Country, covering various sectors of applications, such as aerospace, construction and transports. The Spanish government, beyond channelling H2020 funding, directly finances specific projects on AM technologies and applications. Furthermore, ADDIMAT, the Additive & 3D Manufacturing Technologies Association of Spain operated by AFM, was founded at the very end of 2014 with a main goal: to bring together all the forces of the sector and accelerate the adoption of additive manufacturing by the Spanish industry. Today, it represents over 60 organizations with different profiles: equipment manufacturers, raw material and parts manufacturers, end users, service providers, dealers and marketing subsidiaries, research centres, universities and education centres. www.addimat.es
United Kingdom	The United Kingdom has seen a significant investment in AM in a number of sectors of industry as we see by the following numbers: consumer industry contributed about £ 2,500,000 to leverage about £ 7,500,000 of State support, the automotive industry contributed about £ 3,500,000 to leverage a State funding of £ 6.5 million on activities and research AM and the medical sector secured an investment of £ 3 million to supplement funding of £ 11.5 million in this area. At the same time, the United Kingdom's Aerospace industry invested £ 13 million in development in the area of AM. More recently, the British Government has invested £ 30 million in equal parts with the industry for a period of seven years for the development of a new aerospace technology. The EPSRC-Engineering and Physical Sciences Research Council released also a Fund of £ 4 million for the development of AM. The bet on additive manufacturing worldwide, and with special emphasis in Europe as you can see above in various aspects and sectors should be leveraged because in this area the technologies, despite his 27 years of history and evolution are still in a phase of germination and there is much room for the development and affirmation of the Portuguese companies in the fields already identified since the applications to the development and manufacture of systems (equipment + materials) [43].

United States of America

In 2012, the National Additive Manufacturing Innovation Institute (NAMII), 22 research projects funded with $ 13,500,000 public investment and $ 15 million of investment in the industry. He was also responsible for launching a series of research projects run by public agencies who received more than $ 7 million of funding. In March 2014, it was announced that the federal Government will increase the funding commitment of $ 50 million euros [43].

Asia

Asian countries are also investing. In fact, 26.4% of all AM industrial systems installed around the world are in the region of Asia/Pacific. Anhui Province (China), Hefei and Bozhou and Xery3D are investing together about $ 245 million for a period of six years to develop the 3D printing. In April 2014, the Ministry of economy, trade and industry (METI) of Japan has invested more $ 36,500,000 to launch a new research association to develop the technology of AM metallic. In March 2013, the Singapore Government announced that it would invest about $ 400 million over a period of five years in advanced manufacturing technologies. At the same time, the Nanyang Technological University will build a research centre in AM associated with a planned investment of $ 30 million.

The Ministry of science and technology in Taiwan has initiated a program to develop 3D printing with annual funding of $ 2.33 million.

South Africa

During 2013, were invested in South Africa more than $ 10 million in AM with about 80% of this investment to focus on AM systems belonging to the category personal 3D printer. The South Africa seems to be available to increase investment in the area of AM and explore specific areas, such as medical, dental and aerospace industry [43].

Australia

Advanced Manufacturing Cooperative Research Centre (AMCRC), a major development initiative in Australia has funded a number of projects based on AM and leads a consortium to establish a National Centre for development of AM should have access to an investment of AU $ 50 million over seven anos5. European countries have also developed their national competences in AM, being sensitive advances in expansion and commercialization of technologies [43].

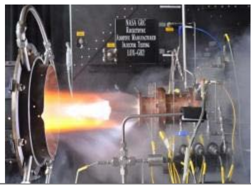
3.4 Industry Framework

With regard to the aeronautical industry, which requires light, resistant, parts geometrically complex and normally produced in small quantities, the application of technologies AM dating back to 1988, when some companies began to experiment with the technology. With the passage of time, the adoption of different technologies of AM has increased in all sectors. Currently, according to the report from 2013 of Wohler, the aerospace industry contributes about Defence of & 10.2% of global revenues of AM of 2012. In the USA exclusively, the aerospace manufacturing industry (traditional and addictive) features a yield estimated at 2011 $ 157.7 billion. The aerospace industry is responsible for about 12.1% additive production, with estimated values of about $ 29,800,000, which accounts for less than 0.05% of the total value of the U.S. aerospace industry.

The aerospace industry is increasingly attentive to AM facing it as the answer to try to reduce the cost of developing prototypes and even as an alternative to create functional components. In an attempt to reduce the weight of the aircraft, the industry is developing a growing proportion of aircraft parts in lightweight materials, which are generally expensive, having AM technology the ability to reduce the raw material to a minimum, thus optimizing the weight, cost, and delivery time appears as a viable solution. Although AM technologies and their applications are in constant evolution, the following table aims to present some current and future applications in the aerospace industry:

Table 3-1. General Applications of AM technology in the automotive industry, aeronautics, space and molds [44]

Current applications	Future applications
Prototyping and conceptual development	Embedment electronics produced by Additive manufacturing directly on the parts
Spare parts Production	Additive manufacturing of aircraft wings
Production of parts with minimal wastage of raw materials	Production of components directly on site repair
Production of components with complex internal structures	Production of motor complex parts

Challenge	Resulting Product	
Fuel Nozzles GE LEAP engine (General Electric and Morris)		Fuel nozzle that is 25% lighter and five times more wear resistant than conventional play [45].
Jet engine GEnx (General Electric)		Fully functioning Jet engine capable of reaching 33,000 RPM [46]
Bigger, faster and more complex UAV produced by AM (Stratasys and Aurora Flight Sciences)		Engineering development time and reduced 50% production [47]
Rocket engine nozzle (NASA Aerojet and Rocketdyne)		Development of engineering, production and testing of a critical component such as a nozzle of a rocket engine with 70% cost reduction [48]
Cabin support for the Airbus A350 XWB (Airbus and Concept Laser GmbH)		Printed part using titanium (Ti) with a weight reduction of more than 30% [49].
Demonstrator a wing model (Concept Laser GmbH)		Prototype of the additive production capacity lightweight structures (produced at once) [50].
Gas pipeline (RSC Engineering GmbH)		Optimized design of a emission conduct. [51]

Challenge	Resulting Product	
Engine model (Concept Laser GmbH		Full engine model produced in stainless steel ncluding the gears and the 3D wing covers [51].
Combustors (Concept Laser GmbH)		Prototype of Capabilites of additive production process, prove our capability to produce and an internal expiral walls.
Universal connection (Concept Laser GmbH)		Prototype a functional gear
Hollow gear tool (VBN Sweden)		Shorter delivery time, less waste of and reduced tool weight reduction in 40%. [51]
Multi component support (Airbus and 3T)		Single piece with 35% less weight. Support produced by AM is 40% more rigid than the original component, and also reduces the waste produced by conventional methods. [52]
AbramsM1AGT1500 tank engine (Optomec)		AbramsM1AGT1500 tank engine using the AM system LENS. [53]
Fuel injectors in a spiral (Morris Technologies)		Production of extremely complex design, produced as a single piece, dramatic reduction of production time (2 weeks vs 6 weeks), 50% of cost reduction and increase of rubostes. [54]

Challenge	Resulting Product	
Unsure of thermoplastic injection moulding (Renishaw)		Production of extremely complex design, durability and better performance.
Cooling ducts to Motosport (Green Team and Renishaw)		Wheel support and cooling ducts made as to improve cooling capacity, complex design
Unsure of thermoplastic injection moulding (Linear Moulds)		Cycle time optimized, greater durability of tools insert.
Exhaust tips Koenigsegg One: 1 (Koenigsegg)		Koenigsegg supercar exhaust Tip One: 1 produced in titanium, permitium a weight gain of 400 grams in a production time of 3 days. [55]
Variable geometry turbo Koenigsegg One: 1 (Koenigsegg)		Variable geometry turbo produced at once with internal moving parts of high performance [55]
Roll up ARC titanium protection for F1 (T RPD ® LTD, Within Technologies)		Production of extremely complex design of arc protection approved in titanium to F1.

Despite previously submitted projects, which represent major advances in the application of technologies of AM in the sectors of activity contracted industries selected for this project, there are factors such as the size limitations of the components to be produced by AM that has limited a broader adoption of these technologies by the industry. Problems with materials, precision, surface finish and certification standards are further challenges that seek to ensure a solution widespread adoption of these technologies by industry. Thus, the increased size and the increased complexity of future applications are driving research towards improved control of production processes, materials and inspection to ensure the safety and traceability of produced components aiming at its use as end components.

Frazier [56] presented some of the specific technical challenges in AM that need to be overcome for the operational use of the technology industry, and AM especially in the air force, becomes a reality:

- Must be understood and controlled the effect of variability of machine-to-machine;
- Should be developed specifications and industry standards for the processing of components. To achieve this goal, Frazier suggests that priority be given to the development of integrated processes, through the development of technologies for monitoring and control of production processes;
- Must be alternatives to conventional qualification methods based on validated models, probabilistic methods and standard parts, among others. There is a need for new standards and advanced non-destructive (NDT) capable of sensing critical defects with a high degree of certainty;
- New guidelines of design with innovative structural features are required in order to produce optimized components in structural terms and weight. Is required for validation of virtual models based on physical models in order to predict the characteristics of microstructure, mechanical and electrochemical properties;
- New materials should be developed in order to optimize the production process and the final properties of the components;
- Must be developed the understanding of how to achieve better will fatigue properties and surface finish.

The real potential of the AM can only be achieved if the engineering development process is optimized and the advantages of this new manufacturing technology are fully embraced. However, this also means that the existing components projects currently have to be totally reviewed.

Metallic materials currently available for additive production

The selection and use of certain material is fundamentally defined by the end use requirements, however is also influenced by additive technology used.

The different additive production technologies present on most of the possibilities of using similar materials. In this way the titanium and nickel-based super alloys (for example Inconel) high-strength and stainless steels are the materials most commonly using additive production-this way seeks to take advantage of additive production to process expensive materials, which are hard to machine, seeking to benefit from the additive production by removing economic benefits from the reduction of material used and the reduction in production time of the components.

The technologies based on laser, beam of electrons and plasma arc probably can process the majority of metals, but still require some research to ensure full understanding and mastery of each of these processes for each of the available materials, leading to the industry to focus on processing the materials you want to economically more attractive by conventional processing difficulty. The processes of deposition of powder material present enormous potential since they can use multiple nozzles of deposition of materials allowing to change the chemical composition of the deposited material, within the same piece, in addition to deposition ratios and different precision depending on the size and use of the piece [64].

3.5 Aerospace Industry Trends

Introduction

Nowadays, AM enables both a design and industrial revolution in various industrial sectors such as aerospace, automotive, energy, medical, tooling and consumer-goods. In Figure 3-44, current distribution of AM technologies as a function of the industrial sector has been included. In particular, in the case of aerospace sector, a growing tendency of AM technologies has been observed, from 9.9% up to 16.6% in the period from 2011 to 2016 [1].

The aerospace industry was an early adopter of AM and began to explore applications soon after the technology was commercialized. Boeing and Bell Helicopter began to use polymer AM parts for non-structural production applications in the mid-1990s. Boeing has installed tens of thousands of flying production parts, representing more than 200 unique parts on 16 different commercial and military aircraft. NASA, the European Space Agency, SpaceX, and other organizations are exploring the use of AM for igniters, infectors and combustion chambers on rocket engines.

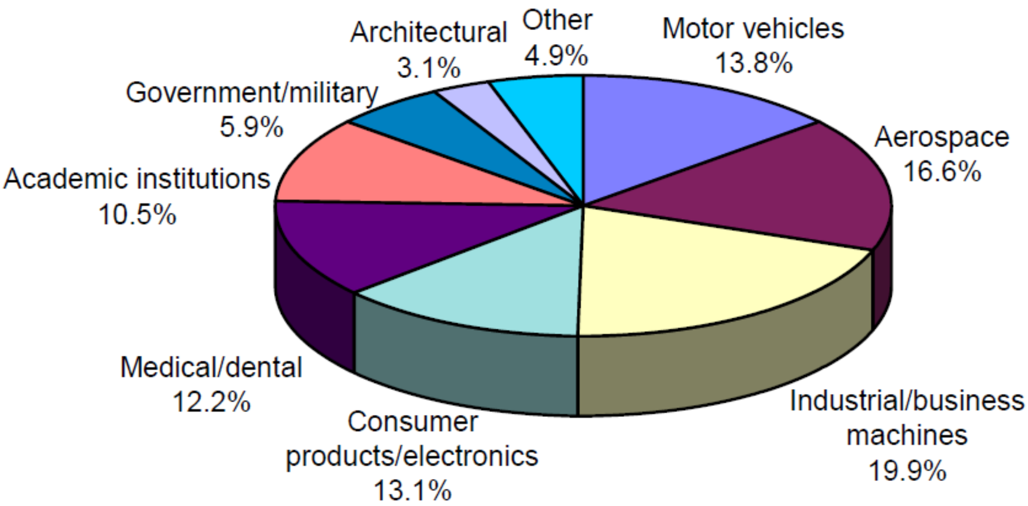


Figure 3-4. AM applied to major industrial sectors [1] .

In general, aerospace industry is challenged by stringent requirements in terms of: constant pressure to improve the efficiency of aircraft, reduce air and noise pollution and sustainability and emission controls. These aspects require the aerospace industry to operate extremely efficiently, pushing technologies and manufacturing capabilities to their limits.

In this sense, AM is an attractive alternative manufacturing route for this sector due primarily to its high material use efficiency and ability to process aerospace grade materials, like titanium and nickel alloys. In addition, AM is seen as an enabling technology for light-weighting or topology optimization, because of its freedom of design and capability to create complex structures; this can have the additional benefits of improving performance and reducing waste. Another area of interest for the AM application on aerospace industry is the area of testing of complex of difficult to implement designs, including extensive tests in "full engine" rigs.

Additive Manufacturing (AM) areas of application are closely related to the selection of material as well as the technology. Some of the major applications for AM technology are classified by field of expertise, such as aerospace and automotive industry, biomedical, architectural, retail and jewellery industries.

Weight reduction and the increase of the strength-to-weight ratio are transversal to many industrial sectors. Aerospace is one of the sectors where weight reduction is key. The production of Aerospace parts become very expensive using conventional processes due to highly wasteful operations. By using AM processes in the aerospace industry, parts can be redesigned to lose weight, which means lower costs of fabrication. Also, a lower weight of aerospace structural parts has repercussions on reducing fuel consumption.

The advantages offered by AM can be summarised as follows: reducing the use of raw material; reducing buy-to-fly ratios; freedom from geometrical constraints and reducing the use of energy.

Undoubtedly, the most interesting AM applications are lightweight parts manufacturing and engineering solutions. The main objective of aerospace industry is the achievement of low weight structures to ensure system safety testing. Moreover, high-performance components can be produce by AM technology and in a wide range of alloys: stainless steels, tool steels, nickel alloys, titanium Ti64, cooper alloys, aluminium, etc. Different parts such as turbine blades or inlet pipes can be obtained by both the SLM and the EBM method.

Furthermore, of all the potential areas of application for AM, the automotive industry probably offers the most significant opportunities for changes in the way manufacturing is carried out. The design constraints currently imposed on the automotive designer owing to tooling design limitations will be removed. Sport automotive industry and manufacturers of general production car uses AM technology for many end user products.

In short, **<u>AM offers the following advantages for the aerospace industry</u>** [24]–[26]:

(1) **Reduction of lead times: shorter development process and time to market**. AM allows the rapid prototyping and conceptual design review and validation. Tooling manufacture can be skipped and one can go straight to finished parts. For low-volume production, such as for demonstrators fabrication, AM reduces or eliminates the cost for expensive and poorly amortized tooling. Also suits well for collaborative engineering and R&D aspects.

(2) **Flexibility on design.** The high level of complexity of the parts, reduction of component weight and improvement of parts' performance and reliability. AM offers topological optimized design and superior flexibility in terms of feasible geometries. Complex components can be built up. AM also offers designers to better serve maximum performance without need to accommodate manufacturing limitations. In addition, aerospace industry already succeeded to additively manufacture some aerospace

components with complex geometries made of exotic materials such as Titanium Ti6Al4V and Inconel 718, which are traditionally difficult to shape without compromising their excellent (and desired) properties.

(3) **Reduction of both production and operational costs**. The higher design freedom allows decreasing the number of sub-components that compose system assemblies, so, the number of components, assembly time and costs are reduced (AM helps reduce tooling, welding, inventory and, in some cases, entire assembly lines). Weight reduction gives also a competitive advantage of reduced costs. On the other hand, considering space components, space vehicles require intricately designed parts too, in order to minimize packaging space and weight. Produced in very small volumes they are expensive and time-consuming when traditionally manufactured.

(4) **Reduction of the negative environmental impacts of production**. As a consequence of the weight reduction of aerospace components lower fuel consumption and CO_2 emissions are expected.

It is also worth mentioning that one of the key drivers in manufacturing of high value aerospace components is **improving the buy-to-fly ratio of metallic components** (with BTF ratio values typically ranged between 5 and 20). Figure 3-5 highlights why AM is such an attractive potential alternative manufacturing route due primarily to its high material use efficiency and ability to process aerospace grade titanium and nickel alloys.

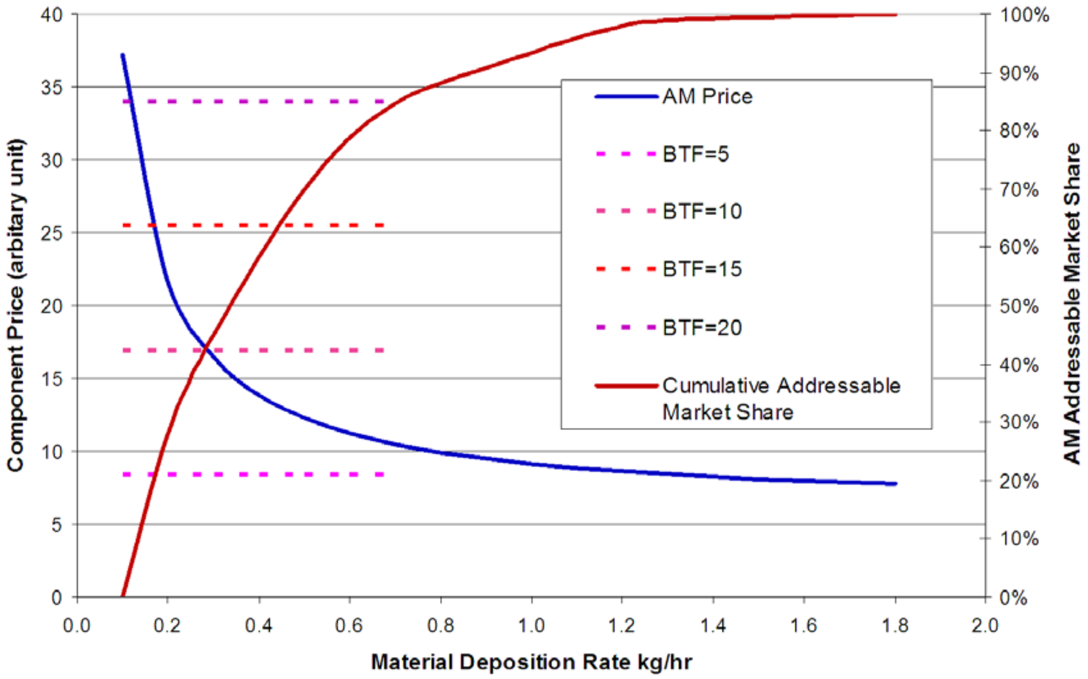


Figure 3-5. Analysis of component Price vs. material (metal) deposition rate in AM, with "break even" point compared to traditional machining manufacture at typical aerospace buy to fly ratios [27].

Challenges for using Additive Manufacturing in aerospace

Regarding main challenges to achieve a*erospace quality*, following points should be taking into account:

- **Design**: current design tools do not allow taking full advantage from AM because AM specific features are missing, compatibility with AM machines is not checked and design rules for AM are not fully established. Moreover, designers are constrained by design rules of conventional manufacturing processes.
- **Raw material**: physical (morphology, flowability, particle size distribution, humidity,…) and chemical properties (impurities level, interstitials content,…) of AM powders are not fully defined for getting *aerospace quality*. Moreover, there are not handling or recycling specifications to ensure traceability and avoid contamination of feedstock.
- **Processing**: today AM process robustness, repeatability and reliability is not fully guaranteed because two machines from the same manufacturer can yield different part quality, AM machines lack of process monitoring and impact of process parameter on final product quality is not fully understood.
- **Post processing**: different post processing treatments are currently applied to AM parts including thermal treatments (vacuum furnaces, high isostatic pressing (HIP),…), surface treatments (electrochemical polishing, abrasive flow polishing,…) and cleaning procedures (jet blasting, sand blasting…). However, it is not clear how these treatments affect final properties.
- **Qualification**: a change on classical *Product level qualification* method must be applied to AM parts because adjoining testing samples are not fully representative of the part, there are not defined and qualified process and part verification methodologies and the Product Assurance of AM parts must be established.
- **Failure analysis**: previous aerospace projects have addressed the development of AM parts which have not been tested in real flight conditions or even at representative conditions. Usually, technological readiness level (TRL) of investigated applications is lower than 4. Therefore, it is not clear how AM parts will behave in real flight conditions and potential source of failure. This will be realized after inspection of faulty AM parts and replacement of damaged ones.
- **Design for demise**: in the case of space components, this concept involves the intentional design of space system hardware so that it will completely burn up – or 'ablate' – during uncontrolled atmospheric re-entry as a means of post-mission disposal. This is especially required for uncontrolled re-entries. This concept is leading to the change from high-melting point materials like titanium or stainless steel to high strength aluminium alloys (7XXX series, Al-Li alloys).

Within this framework, European research activities are currently focused on studying the effect of feedstock, AM process parameters and post-treatments on resulting properties of the Aerospatiale parts. Moreover, another important goal is defining process and supplier qualification procedures and standards for manufacturing of AM aerospace parts.

Aerospace Trends for AM

Current trends in aerospace sector are focused on new design strategies for weight reduction of the Aerospatiale components, including: topological design and bionic and cellular lattice structures [23].

Design concepts for bionic and cellular lattice structures are motivated by the desire to put material only where it is needed for a specific application. From a mechanical engineering viewpoint, a key advantage offered by this kind of materials is high strength accompanied by a relatively low mass. These materials can provide good energy absorption characteristics and good thermal and acoustic insulation properties as well. Designed cellular structures typically exhibit strong structure strength per unit weight than typical foam structures. However, due to their complexity, these structures are often difficult to generate using existing CAD packages. Furthermore, metallic additive manufacturing techniques, such as PBF-selective laser melting process which shows the great capability to fabricate strong and lightweight metallic lattice structures, are still facing certain process limitations in terms of the geometrical capability and support structure requirement for the fabrication of cellular lattice structures [27]–[29].

As an example of development of optimized design, in Figure 3-6 is included the optimization of the connector support for the ACU part of the space launcher VEGA (belonging to the ESA) carried out by CATEC (Spain). The evolution process includes the substitution of the original 4-part component for an integrated geometry, followed by conventional optimization and bionic design of the geometry of the component.

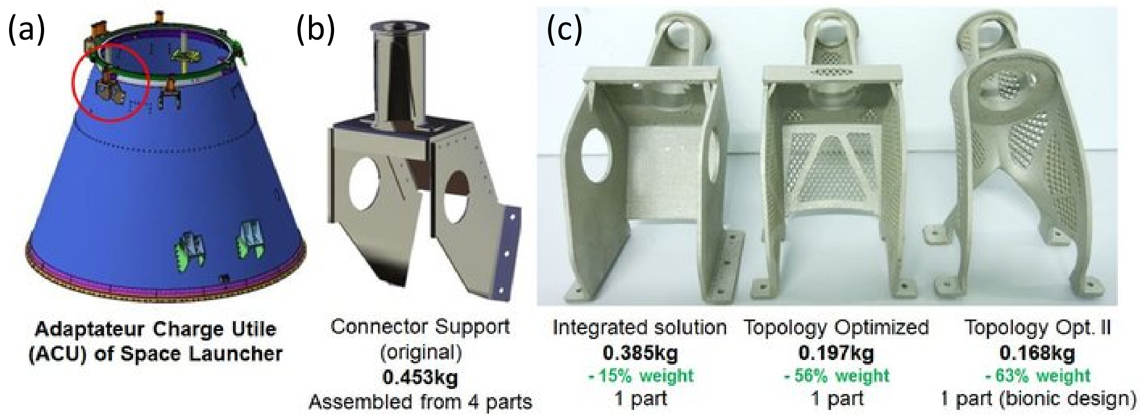


Figure 3-6. Application for Space, developed by CATEC and AIRBUS D&S: (a) ACU assembly for VEGA launcher, (b) original connector support, (c) optimized supports: i. one-shot manufacturing (integrated assembly), ii. conventional optimization; and iii. bionic design

In Figure 3-7, it is included also another space component that includes topology optimization. In particular is a fitting from the satellite Hipparcos (belonging to the). The fitting of bracket is part of the supporting structure of the telescope baffles as part of the payload which protects against light diffusion.

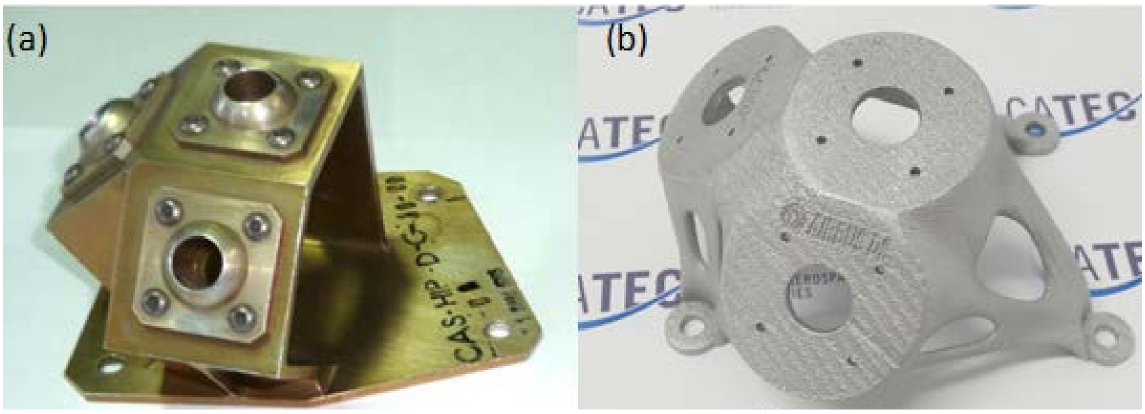


Figure 3-7. Space application developed by CATEC and AIRBUS D&S (a) Original bracket of Hipparcos, (b) Topology optimized bracket, produced by SLM.

On the other hand, an example of a bionic spoiler it can be observed in Figure 3-88. For bionic structures, design strategy is based on learn out of nature, looking for obtaining enough rigidity with the lowest weight of the component [30] [31].

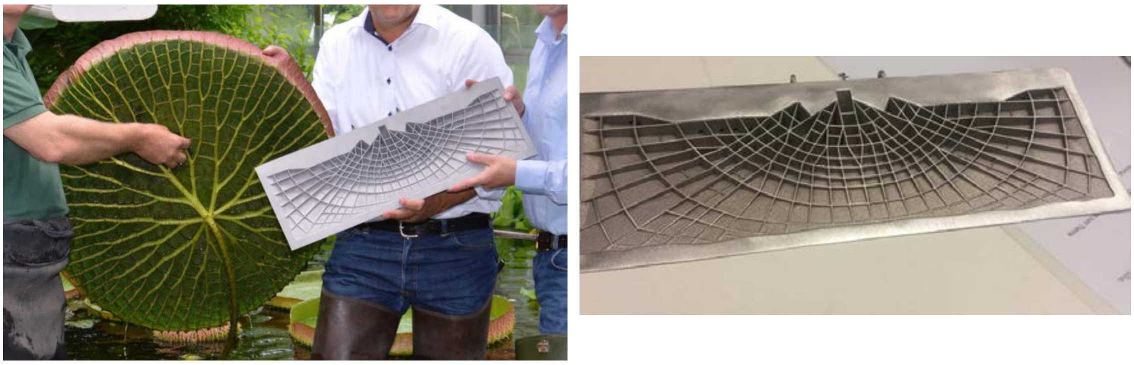


Figure 3-8. Bionic aircraft spoiler developed by Airbus. Design is inspired form the water lily [30].

It is also remarkable the world's largest 3D printed airplane cabin component developed by Autodesk and Airbus: a "bionic partition" to separate the passenger cabin from the galley. The innovative design mimics the organic cellular structure and bone growth found in living organisms (see Figure 3-9). The result of the project creates sounded expectations: a partition that is structurally very strong but also lightweight, weighing 45% (30 kg) less than current designs. This makes the bionic partition a ground breaking development for a sector in which less weight equals less fuel consumption. When applied to the entire cabin and to the current backlog of A320 planes, Airbus estimates that the new design approach could save up to 465,000 metric tonnes of CO_2 emissions per year.

Figure 3-9. Airbus' bionic partition was showcased at the Autodesk University [30].

Another noteworthy trend of mass customization of lightweight construction in industry is based on combine AM technology with conventional, subtractive technology, enabling each process to work together on the same machine and even on the same part [23], [32], [33]. Hybrid Manufacturing reduces the risks and costs associated with adopting metal AM technology, providing a more pragmatic and evolutionary pathway for industrial manufacturers. Although this is a general trend for different sectors, it is relevant for the aerospace sector from the reduction of weight point of view.

Finally, regarding space industry, it is remarkable the line of research followed by the Net Shaping Centre in the School of Metallurgy and Materials at University of Birmingham (PhotAM project funded by the ESA) [34]. Currently, if a component breaks whilst in space, such as a bracket or hinge, rectifying the issue can be problematic, costly and potentially dangerous. With the International Space Station (ISS), replacement parts can be launched from earth. However, as human space exploration looks further afield, it becomes less and less feasible to send 'spares' from home. The development of 3D printing in space will allow astronauts to solve this problem by efficiently manufacturing replacement, while current research could potentially mean that some equipment could be produced entirely in space.

Examples of AM aerospace components

Currently, the aerospace market is quite varied in the use of AM, with many examples of niche components being made and supplied using various forms of AM (in both polymers and metals). AM for aerospace application is applied in: prototyping, moulding and tooling, spare parts manufacturing, repairing of existing components and also to manufactured the entire part [35].

AM has been widely used in the first stages of development of structures, that is, in **prototyping** and producing physical 3D "mock-ups" (some examples are included in Figure 3-10 and Figure 3-11). Prototyping serves to provide specifications for a real working system rather than a theoretical one. CAD model verification, visual aids, presentation models, scaling, etc. are common uses for AM prototyping. Physical 3D "mock-ups", a term first introduced in the aircraft industry, are used for final testing different aspects of the parts.

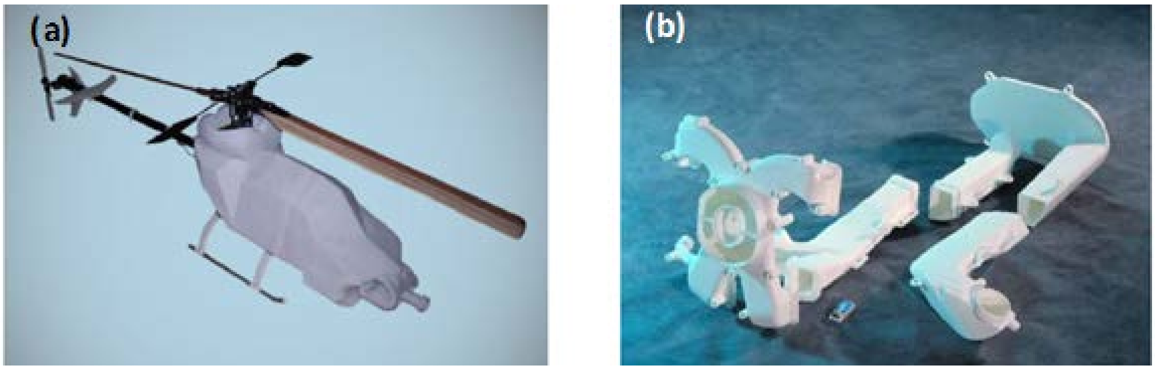


Figure 3-10. (a) Helicopter concept model; (b) Outlet gas "mock-up" part [36].

Figure 3-11. Prototype manufactured by SICNOVA.

With respect to **moulding and/or tooling** for aerospace industry, there is a wide variety of components. Some examples are included in Figure 3-12.

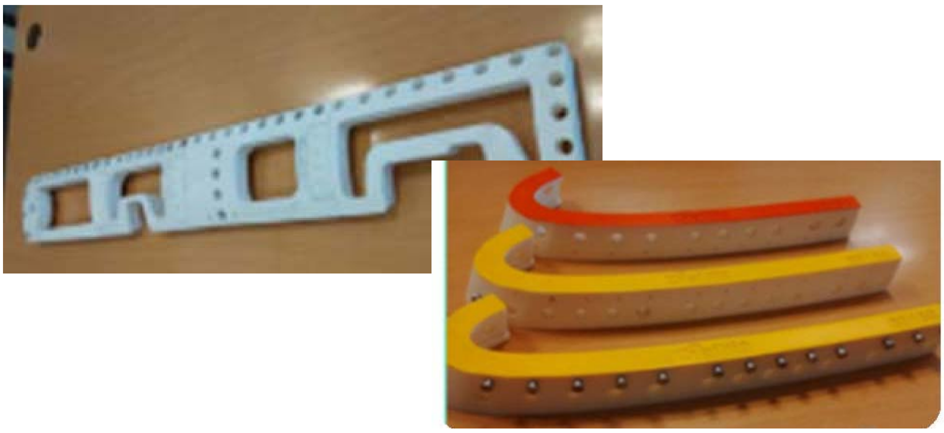


Figure 3-12. Some examples of industrial parts for moulding and tooling in aeronautics provided by AERNNOVA.

In the area of **repairing and spare parts manufacturing**, Additive Manufacturing technologies have shown a great flexibility. Spare parts can be manufactured *on order*, so their storage is avoided. Also, AM allows to manufacture the spare part exactly in the needed location. On the other hand, considering repairing, AM can be applied to repair damaged parts, adding material only where is required. It is also remarkable the capability of AM to functionalize an existing part, adding new functionalities. AM-repairing gives rise to a remarkable reduction in production costs and time.

With respect to **final parts**, AM is applied for: turbine blades, structured parts for unmanned aircrafts, customized interiors for business jets, private helicopters, swirlers or fuel injectors by Morris Technologies, windshield defrosters by AdvaTech, etc. Some examples are included in Figure 3-13. Nowadays, AM technologies can be applied to manufacture aerospace components with a high level of geometrical complexity and with precise aerodynamic properties.

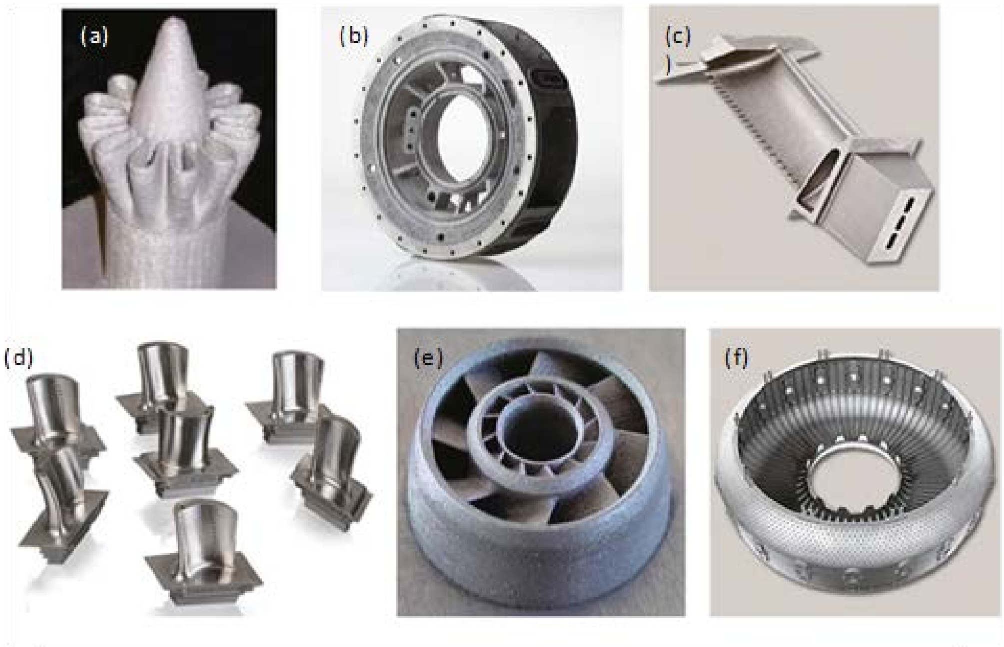


Figure 3-13. (a) Mixing nozzle for gas turbine exhaust produced by DED-LENS by Optomec, (b) compressor support case produced by PBF-EBM by Arcam, (c) turbine blade produced by PBF-SLM by Concept Laser, (d) turbine blades fabricated by PBF-SLM by Morris Technologies

Regarding **space application**, several flight hardware demonstrators have been redesigned and manufactured by AM technologies including injectors, monolithic thrusters, chambers, nozzles, etc. In this sense, AIRBUS Group has recently developed an FLPP ISCAR bracket made of Ti-6Al-4V for *Ariane5ME* and 6 launchers with more than 30% weight saving. RUAG Group has also developed a 42% lighter bracket for *Sentinel1* satellite. A consortium led by DMRC has developed a reaction wheel bracket made of AlSi10Mg with 56% mass saving and topology optimized disruptive design for *Artes5.1* project. ESA, TESAT and ILT have collaborated to apply AM to radiofrequency hardware such as waveguide harness, filters and antennas. All these projects have demonstrated the possibilities of AM technologies in secondary structures and non-critical parts. As an example regarding secondary structures development, in Figure 3-14 is included a development of Airbus D&S for the satellite EUROSTAR3000. An aluminium telemetry bracket has been topologically optimized to obtain a mass reduction of the 35%.

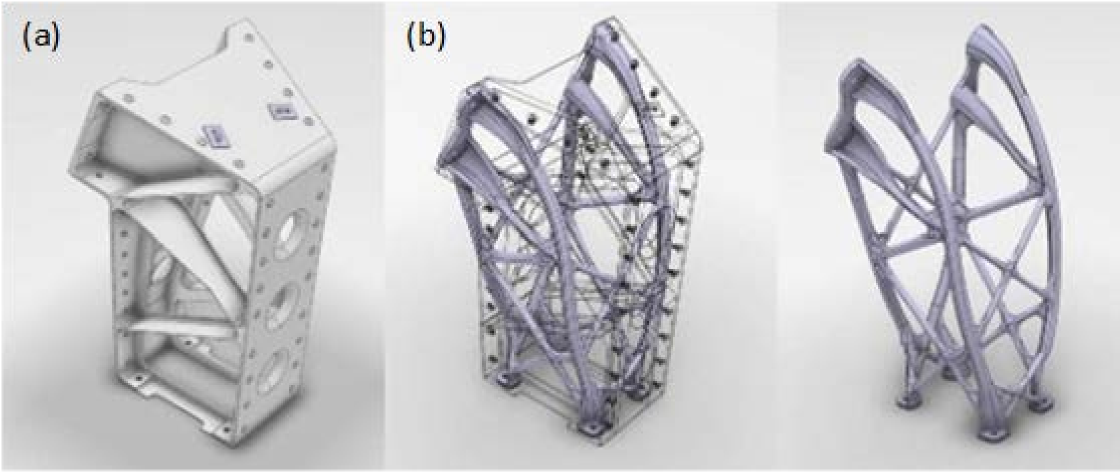


Figure 3-14. Telemetry bracket produced in Aluminium, space application developed by AIRBUS D&S: (a) original version; (b) view of the optimized component.

With respect to the development of primary structures in both space launcher and probe applications, it has to be highlighted the work of CATEC (Spain) in association with AIRBUS D&S (Space Systems, Madrid). Some of the developments of CATEC-Airbus D&S currently on going are included in Figure 3-15.

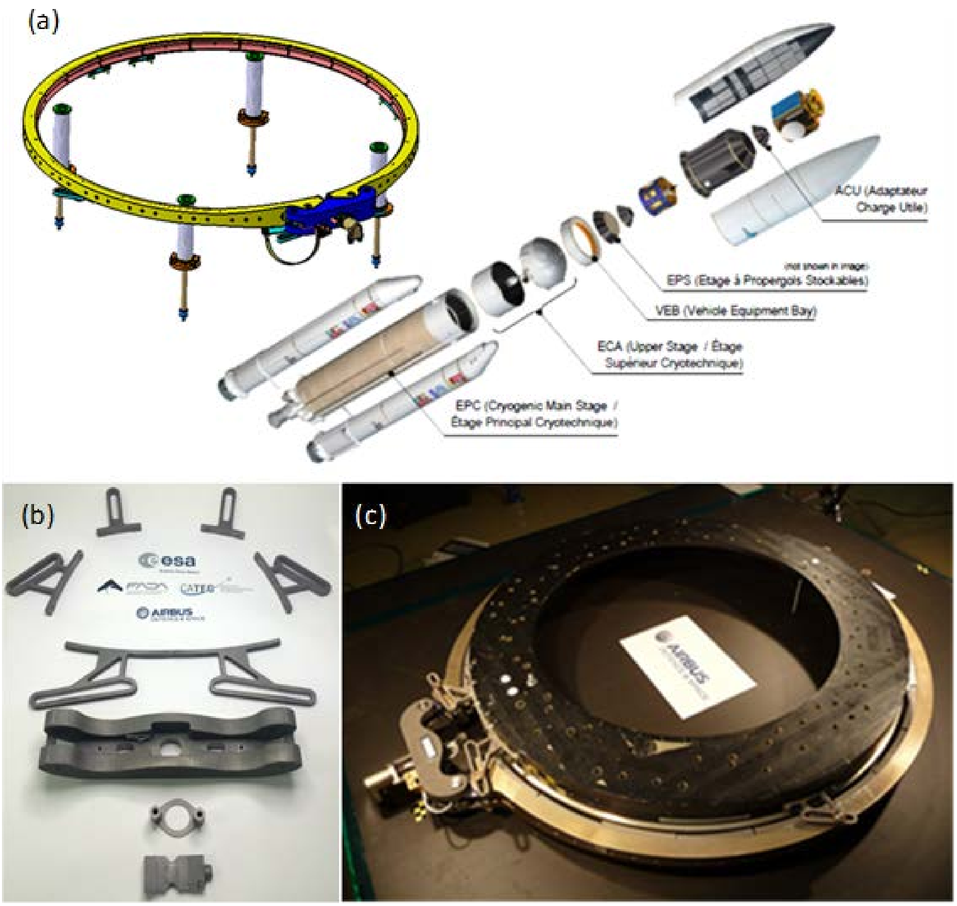


Figure 3-15. Development of primary structure of ARIANE5, by CATEC and AIRBUS D&S: (a) View of LPSS and launcher ARIANE5 (the band is assembled with the Adapter of Useful Charge (ACU)), (b) AM components manufactured by SLM, (c) System assembly, functional test (up

In this sense, Airbus and GE efforts on AM developments should be highlighted. In the case of Airbus, in Wohlers Report 2016, this work is emphasized: "Perhaps more than any other major OEM, Airbus is planning a future that integrates AM into production processes. An astounding variety of exploratory projects have been conducted using AM for metal and polymer parts, for repairing and tooling. It has done considerable work with the design and production of parts for its aircraft. The company has also worked to develop advanced methods of topology optimization that reduce material and weight in designs, sometimes by more than 50%". On the other hand, GE Aviation is producing metal AM final parts for its LEAP engine. By 2020, the company expects to manufacture more than 100.000 parts by AM for the LEAP and other aircraft engines [1].

3.6 Main MAM Industry players in SUDOE

The table 3.3 below compiles most of the SUDOE capacity in Metal Addictive Manufacturing technologies, from research centres, manufacturers, customers and added value resellers.

Table 3-2. List of main industry players in Metal Additive Manufacturing

Name	Type	Activity / description	Country	website
ACITURRI	Aerospace company / Aerospace Tier 1 supplier	Tier 1 Provider for aircraft structural assemblies and a Tier 2 for engine components	SPAIN	www.aciturri.com
AD Industrie	Aerospace company / Aerospace Tier 1 supplier	AD INDUSTRIE is an industrial group specialized in mechanical and hydraulic engineering. Study, assembly and testing of equipment. Industrialization and production of complex parts, metallic and composite materials, gears and transmissions, EDM, heat treatments, welding, bonding, plasma deposition, magnetic analysis, bleeding, radio, ultrasound).	FRANCE	http://www.adgroupe.com/
AIRBUS	Aerospace company / Aerospace Tier 1 supplier	European aeronautic manufacturer	FRANCE	http://www.airbus.com/fr/

Name	Type	Activity / description	Country	website
AIRBUS SAFRAN Launchers	Aerospace company / Aerospace Tier 1 supplier	Development and production of Ariane 5 and Ariane 6 launch vehicles. R&D for future European launcher programs. Responsible for the ballistic missile system of the French oceanic deterrent force: development, production and maintenance services for the various components.	FRANCE	https://www.airbusafran-launchers.com/fr
AKKA Technologies	Aerospace company / Aerospace Tier 1 supplier	Technology Engineering and Consulting Group	FRANCE	https://www.akka-technologies.com/fr
ALESTIS	Aerospace company / Aerospace Tier 1 supplier	ALESTIS Aerospace, leader in the carbon fibre and composites technologies. Responsibility for the design, development, certification, manufacturing and support of complex carbon fibre aero structures. Involved in different MAM programmes	SPAIN	www.alestis.aero
ASSYSTEM France	Aerospace company / Aerospace Tier 1 supplier	Innovation engineering and consulting	FRANCE	http://www.assystem.com/
ATR	Aerospace company / Aerospace Tier 1 supplier	Manufacturing Advanced Turboprops	FRANCE	http://www.atraircraft.com/
DASSAULT Aviation	Aerospace company / Aerospace Tier 1 supplier	Design, produce, manufacture and support civil and military aircraft.	FRANCE	http://www.dassault-aviation.com/fr/
FIGEAC AERO	Aerospace company / Aerospace Tier 1 supplier	A first-tier partner of major aerospace manufacturers, Aeronautical sub-assemblies (machining and assembly), Structural parts, Engine parts, Precise parts.	FRANCE	http://www.figeac-aero.com/

Name	Type	Activity / description	Country	website
Fusia	Aerospace company/ Aerospace Tier 1 supplier	Manufacture of precision parts for aeronautics, space, defence	FRANCE	https://www.fusia.fr/
ITP	Aerospace company / Aerospace Tier 1 supplier	ITP is currently the ninth largest aircraft engine and components company in the world by revenue	SPAIN	http://www.itp.es
LATECOERE	Aerospace company / Aerospace Tier 1 supplier	A major player in the aerospace industry, the Latécoère Group is active in the fields of aerostructures and interconnection systems through the phases of definition, industrialization, manufacturing and installation. The group also performs product support activities (repair, spare parts, etc.).	FRANCE	http://www.latecoere-group.com/
Prismadd	Aerospace company / Aerospace Tier 1 supplier	Founded in October 2014 in Montauban, PRISMADD proposes a global offer for very technical industrial sectors, such as armaments, aeronautics and nuclear.	FRANCE	http://prismadd.com/
Rochette Industrie	Aerospace company / Aerospace Tier 1 supplier	Metals - Finishing, heat treatments, surface treatments. Coatings by physical processes. Metals Machining, Manufacture of mechanical subassemblies. Milling, turning. Plastics Processing and Secondary Processing Machining	FRANCE	http://www.mecanicsud.fr/
SAFRAN Group	Aerospace company / Aerospace Tier 1 supplier	SAFRAN is an international high-tech group, a leading supplier of aerospace, defence, and security equipment	FRANCE	https://www.safran-group.com/fr/groupe

Name	Type	Activity / description	Country	website
SAFRAN Helicopter ENGINES	Aerospace company / Aerospace Tier 1 supplier	Design, manufacturing, sales and support of helicopter turbines.	FRANCE	https://www.safran-group.com/fr/societe/safran-helicopter-engines
AEROSOFT France	Aerospace company / Aerospace Tier 1 supplier	Specialized in systems and structures engineering and cabin layout	FRANCE	http://www.aerosoft.it/
CAETANO Aeronautic	Aerospace company / Aerospace Tier 1 supplier	Design, produce and manufacture parts for civil and military aircraft.	PORTUGAL	http://www.caetanoaeronautic.pt
ELEMCA	Aerospace company / Aerospace Tier 1 supplier	Laboratory of tests, analyses and independent expertise CND + Metallurgy	FRANCE	https://elemca.com/
LAUAK Portuguesa	Aerospace company / Aerospace Tier 1 supplier	Design, produce and manufacture parts for civil and military aircraft.	PORTUGAL	http://www.groupe-lauak.com/
SOGECLAIR Aerospace	Aerospace company / Aerospace Tier 1 supplier	SOGECLAIR is responsible for large-scale projects of studies, co-development for large industrial accounts and develops innovative simulation and virtual reality solutions.	FRANCE	http://sogeclair.com/fr/
AIRGRUP	Aerospace company / integrator	AIRGRUP is an industrial firm engaged in the manufacturing of aeronautical pipeline systems. Involved in different MAM programmes	SPAIN	www.airgrup.com

Name	Type	Activity / description	Country	website
Egile Corporation	Aerospace Company/ Aerospace Tier1 Supplier	It is a Technology-Based Entrepreneurial Corporation which, with High Precision Mechanics as its core material competence, develops High Value Products, Services and Solutions for its Customers. In the Aeronautical sector, Egile is developing production processes in new specific work cells adapted to additive manufacturing as a future strategic commitment.	SPAIN	www.egile.es
EMBRAER	Aerospace integrator	Design, produce, and manufacture parts for civil and military aircraft.	PORTUGAL	www.embraer.com
STELIA (Airbus Group)	Aerospace integrator	STELIA Aerospace offers global solutions for aeronautical manufacturers and airlines.	FRANCE	http://www.stelia-aerospace.com/
ADDIMAT	Cluster/association	The Spanish Association of Additive Manufacturing Technologies and 3D, groups together all the players with interests in developing and promoting additive manufacturing and 3D.	SPAIN	www.addimat.es
2MA Tech	Consulting	2MAtech is an engineering and expertise company in the fields of advanced mechanics and materials.	FRANCE	http://www.2matech.fr/
3R	MAM equipment and solution provider	Designer and manufacturer of testing machines to characterize materials and structures	FRANCE	http://www.3r-labo.com/fr/
ADDILAN	MAM equipment and solution provider	ADDILAN is a new additive machine manufacturing company founded at the end of 2016, which engages in the manufacture of medium-large parts generated by WAAM technology	SPAIN	www.addilan.com

Name	Type	Activity / description	Country	website
ADIRA – Metal Forming Solutions	MAM equipment and solution provider	Equipment and Solution provider Manufacturer of metal cutting equipment, based on laser technology. Manufacturer of large-scale metal 3D printer, combining Powder Bed Fusion and Direct Metal Deposition in a single machine. ADITA features the largest metal powder processing area and a system that enables manufacturing beyond the chamber volume.	PORTUGAL	http://www.adira.pt
CODI	MAM equipment and solution provider	Equipment and Solution provider. Engineering and product development. Additive manufacturing of polymer parts.	PORTUGAL	http://codi.pt/
IBARMIA	MAM equipment and solution provider	With more than 60 years of experience in the machine tool business, has developed its new ZVH ADD+PROCESS machining centre model which combines additive manufacturing with machining	SPAIN	www.ibarmia.com
KALLISTO	MAM equipment and solution provider	A company specializing in the commercialization, integration, implementation of design, analysis and rapid manufacturing systems and services related to these technologies. Wide range of 3D prototyping and rapid manufacturing machines.	FRANCE	http://www.kallisto.net/
METALLIED Powder Solutions	MAM equipment and solution provider	Metal Powder producer for Additive Manufacturing markets	SPAIN	www.erasteel.com
Micronorma	MAM equipment and solution provider	Tailored metalworking machinery. Product design. They are currently part of a project to develop processes based on laser additive manufacturing.	PORTUGAL	http://www.micronorma.pt/

Name	Type	Activity / description	Country	website
PROCUT	MAM equipment and solution provider	Manufacturer and supplier of carbide cutting tools, known for its Tailor made Precision Cutting Tools.	PORTUGAL	www.procut.pt
Zayer	MAM equipment and solution provider	with over 60 year experience in the manufacture of milling machines and machining centres, it keeps research lines about different hybrid machines configurations that combine additive and subtractive technology.	SPAIN	www.zayer.es
ADDIMEN	MAM operator or component manufacturer	Focuses its activity in the design and manufacture of functional metal component	SPAIN	www.addimen.com
BBE	MAM operator or component manufacturer	Product Development, analysis and design, Computer Aided Engineering (CAE), Design and Redesign of products, prototype manufacturing moulds, metal and plastic sintering.	PORTUGAL	http://www.bbe.pt/pt/
DIMLASER	MAM operator or component manufacturer	Additive manufacturing of metal parts. Solution provider	PORTUGAL	http://www.dimlaser.com
DURIT	MAM operator or component manufacturer	Produce hard metal components based on powder metallurgy	PORTUGAL	http://www.durit.com/pt/
EDAETECH	MAM operator or component manufacturer	Development, trial and manufacture of prototypes and the production of small series of metallic components, especially for the automotive industry.	PORTUGAL	http://www.edaetech.pt/
GNC LASER	MAM operator or component manufacturer	GNC Laser offers hardening, welding and additive manufacturing services based on laser technology.	SPAIN	www.gnclaser.es

Name	Type	Activity / description	Country	website
I3D CONCEPT	MAM operator or component manufacturer	Management of MAM projects: Processing digital files, Manufacture parts (prototypes and series), Post treatment and Characterization	FRANCE	http://www.i3dconcept.fr/
IBEROMOLDES Group	MAM operator or component manufacturer	Engineering and Solution provider. Support conception and product development phases, including cutting-edge rapid prototyping technologies and rapid manufacturing solutions for a wide range of applications in a broad array of materials.	PORTUGAL	http://www.iberomoldes.pt/
INDRAERO / Ebas Group	MAM operator or component manufacturer	Design, manufacture and assemble accessories for the aerospace industry. With vast experience in plastics, metals, textiles, foams and rubber materials. Capabilities in MAM technologies based on cladding (DED Directed Energy Deposition	SPAIN	http://ebasgroup.com/
MIZAR	MAM operator or component manufacturer	Mizar offers a service specialised on the design and production of all types of personalised components.	SPAIN	www.mizaradditive.com
GNC LASER	MAM operator or component manufacturer	GNC Laser offers hardening, welding and additive manufacturing services based on laser technology.	SPAIN	www.gnclaser.es
I3D CONCEPT	MAM operator or component manufacturer	Management of MAM projects: Processing digital files, Manufacture parts (prototypes and series), Post treatment and Characterization	FRANCE	http://www.i3dconcept.fr/
IBEROMOLDES Group	MAM operator or component manufacturer	Engineering and Solution provider. Support conception and product development phases, including cutting-edge rapid prototyping technologies and rapid manufacturing solutions for a wide range of applications in a broad array of materials.	PORTUGAL	http://www.iberomoldes.pt/

Name	Type	Activity / description	Country	website
INDRAERO / Ebas Group	MAM operator or component manufacturer	Design, manufacture and assemble accessories for the aerospace industry. With vast experience in plastics, metals, textiles, foams and rubber materials. Capabilities in MAM technologies based on cladding (DED Directed Energy Deposition	SPAIN	http://ebasgroup.com/
MIZAR	MAM operator or component manufacturer	Mizar offers a service specialised on the design and production of all types of personalised components.	SPAIN	www.mizaradditive.com
MIZAR Additive Manufacturing	MAM operator or component manufacturer	Company specializing in the design and production of any kind of custom components. Aerospace, medical or industrial sectors in general	FRANCE	http://mizaradditive.com/fr/
VEROT	MAM operator or component manufacturer	VEROT, S.A. offers metal transformation services, metal transformation service and 3D printing by metal additive manufacturing.	SPAIN	www.verot.com
LISI Aerospace Additive Manufacturing	MAM operator or component manufacturer	Components and fasteners for assembly in the aeronautical industries	FRANCE	https://www.lisi-group.com/
PAMI	Public bodies, programmes and initiatives related to MAM & Aerospace	Portuguese Additive Manufacturing Initiative	PORTUGAL	www.pami.pt
TOYAL Europe	Raw material powder	leader in the manufacturing of advanced aluminium pigments and atomized powder	FRANCE	http://toyal-europe.com
AIMEN	Research & Development	AIMEN is specialized in Laser technologies (cutting, surface treatment, cladding and additive manufacturing)	SPAIN	www.aimen.es

Name	Type	Activity / description	Country	website
CATEC	Research & Development	A technology centre which has been working on the development of additive manufacturing technologies since 2004, with highlight outcome in aeronautics and space sector, providing solution for the industries bases on MAM technologies capabilities.	SPAIN	www.catec.aero
CATIM	Research & Development	Research Centre for metalworking industry, which performs provision of testing, quality control and metrology services. CATIM is creating a project to educate their members in the opportunities offered by metal additive manufacturing.	PORTUGAL	http://www.catim.eu/en/
CDRSP - IPL	Research & Development	Research Centre of the School of Engineering of the Polytechnic Institute of Leiria, focused on the applications of rapid prototyping and Additive technologies	PORTUGAL	http://cdrsp.ipleiria.pt/
CEA CESTA	Research & Development	The Centre for Scientific and Technical Studies of Aquitaine (CESTA) has as its primary mission to ensure the industrial architecture of the weapons of the deterrent force.	FRANCE	http://www.cea.fr/
CEIIA	Research & Development	Engineering centre focused on cutting-edge mobility solutions. Production of components and products for automotive and aeronautics industries, including Additive manufacturing of polymer parts cutting-edge mobility solutions.	PORTUGAL	https://www.ceiia.com/
CENTIMFE	Research & Development	CENTIMFE is a Non-profit public institute for developing pre-competitive activities for industrial uptake. Develops projects with Additive Manufacturing technologies.	PORTUGAL	http://www.centimfe.com

Name	Type	Activity / description	Country	website
CIRIMAT INP	Research & Development	Interuniversity Centre of Research & Engineering of materials	FRANCE	http://www.cirimat.cnrs.fr/
CNES	Research & Development	CNES, a public institution with an industrial and commercial character (EPIC), proposes to the public authorities France's space policy and implements it in 5 main strategic areas: Ariane, Science, Observation, Telecommunications and Defence.	France	https://cnes.fr/fr
ESTIA	Research & Development	Development of a new Platform for MAM: ADDIMADOUR. LMD/P machine, CMT, Robotic, composite, etc.	FRANCE	http://www.estia.fr
IK4-CEIT	Research & Development	CEIT is a private technologic centre with expertise in powder atomisation and heat treatments (HIP).	SPAIN	www.ceit.es
IK4-CIDETEC	Research & Development	CIDETEC is a private research centre with expertise in mechanical treatments.	SPAIN	www.cidetec.es
IK4-IDEKO	Research & Development	IDEKO is a private research centre with expertise in LMD.	SPAIN	www.ideko.es
IK4-LORTEK	Research & Development	LORTEK is a private technologic centre with broad expertise in different technologies of Metal Additive Manufacturing (SLM, LMD, WAAM) and different NDTs.	SPAIN	www.lortek.es
IK4-TEKNIKER	Research & Development	TEKNIKER is a private research centre with expertise in LMD, NDT and monitoring.	SPAIN	www.tekniker.es

Name	Type	Activity / description	Country	website
IK4-VICOMTECH	Research & Development	VICOMTECH is a private technologic centre with expertise in design software and artificial intelligence solutions.	SPAIN	www.vicomtech.org
INEGI	Research & Development	Institute of Science and Innovation In Mechanical And Industrial Engineering bridging the University and industry,	PORTUGAL	http://www.inegi.up.pt/
PRODINTEC	Research & Development	PRODINTEC is a technology centre which has been working on the development of additive manufacturing technologies since 2004.	SPAIN	www.prodintec.es
TECNALIA	Research & Development	TECNALIA is a private funded applied research and technological development centre with expertise on Metal Additive Manufacturing.	SPAIN	www.tecnalia.com
THALES	Research & Development	Equipment and systems for: Aeronautics, Space, Land transportation, Security and Defence	FRANCE	https://www.thalesgroup.com/fr
THALES Alenia Space	Research & Development	Thales Alenia Space designs, integrates, tests, operates and delivers innovative space systems.	FRANCE	https://www.thalesgroup.com/fr/global/
TKNIKA	Research & Development	TKNIKA is the Basque Centre of Research and Applied Innovation in Vocational Education and Training	SPAIN	www.tknika.eus
UPV	Research & Development	The University of the Basque Country (UPV/EHU), particularly the High Performance Manufacturing Group of the Dept. of Mechanical Engineering, has been investigating in additive manufacturing processes with metallic materials since 2004.	SPAIN	www.ehu.eus/manufacturing

Name	Type	Activity / description	Country	website
VLM Robotics	Research & Development	Robotic study office + Development of MAM	FRANCE	http://vlm-robotics.fr/
Ecole des Mines D'Albi Carmaux	Research & Development	Higher School (Engineer) + Research Laboratory with MIMOSA platform : Machine SLM	FRANCE	http://www.mines-albi.fr/
IST	Research & Development	School of Engineering + Research laboratory + Research centre	PORTUGAL	www.tecnico.ulisboa.pt
REDIT	Research & Development	The Network of Technology Institutes of the Region of Valencia is a private, non-profit association that was established in 2001 by the Technology Centres of the region with the collaboration and the support of the Regional Government.	SPAIN	www.redit.es
IMH	Research & Development + Education	The IMH is both a Singular Training Centre and an Centre for Innovation Service in Advanced Manufacturing with equipment and training offer on MAM	SPAIN	www.imh.eus
Polyshape	Research and Development	Poly-Shape is an innovative company specializing in the design and rapid manufacture of functional prototype parts and in the production of small series.	France	Research and Development
Pôle formation des industries technologiques	Training	Formation	France	https://formation.les-industries-technologiques.fr/
GetReady43D	Training	Training and knowledge transfer on additive manufacturing	PORTUGAL	http://www.getready43d.com

3.7 OUTCOME OF THE SURVEY - MAM FOR AEROSPACE

Introduction

The ADDISPACE consortium has conducted a survey among SUDOE players. This was answered by 78 aerospace entities form France, Spain and Portugal, namely, Aerospace integrators and Tier 1 suppliers, MAM providers and operators, public bodies, clusters and associations, training centres and research and innovation agents.

The objective of the survey was to qualify and identify the needs of players in the Metallic Additive Manufacturing (MAM) domain and within the aerospace sector.

Results

According to the answers, three important sectors are impacted by this manufacturing technology: AEROSPACE, SPACE AND DEFENCE, the first of which is in the majority with more than 47% of responses versus 37% and 14% respectively for the other two.

The respondents stated that in their educated opinion the world market will be 68% dominated by EUROPEAN BASED COMPANIES. However, even if a few large companies take the lead on the MAM market (like General Electric, Airbus, Thales Alenia Space, Boeing or Thales), MAJOR CHALLENGES are still to be confronted. Indeed, the certification (50% of respondents), the manufacture (20% of respondents) and the change in design rules (19%) are the most recurrent challenges this technology is facing.

Nevertheless, there is a STRONG BELIEF in this new manufacturing process, since more than 96% of respondents recommends the AERONAUTICS INDUSTRY SHOULD INVEST in this technology. Similarly, the curve below clearly shows the industrialists' confidence in the development, maturity and appropriation of the MAM for the years to come:

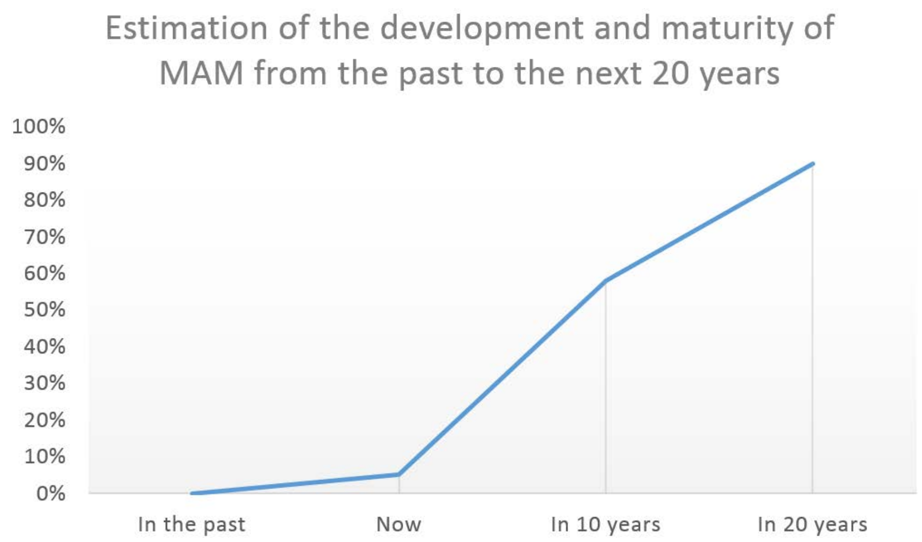


Figure 3-16. Estimation of the evolution in the development and maturity of Metallic Additive Manufacturing

Within the next 20 years, in order to make MAM a standard, reliable and competitive technology, several OBSTACLES need to be tackled, namely, "High Cost of production" (23%) being the main factor, followed by "need for post surface treatment of surfaces" (20%) and the "long printing time" (18%). Last but not least "Lack of skills and training" (14%) and technical concerns with mechanical performance (9%). One interesting outcome is the "supply of source materials" showing low impact (6%), certainly reflecting the increase in the number of suppliers worldwide.

Nonetheless, the survey reveals that respondents are very CLOSE TO ADOPT the technology in the upcoming years. The outcome shows that 31% of the entities will own MAM EQUIPMENT, and from these the large majority (96%) are planning to acquire equipment in less than 5 years. Specifically, the equipment and technologies of choice turn to SLM Power Bed fusion (26% of respondents), LMD Direct Energy Deposition (17%) and EBM Power Bed fusion and WAAM Direct Energy Deposition (15%).

In what concerns INDUSTRIAL MANUFACTURING 47% of respondents will very soon be producing prototypes, and from these 22% will focus on manufacturing aero structures parts, 18% engine parts and 17% fuselage parts.

The survey allowed to identify MAM ADVANTAGES AND WEAKNESSES for the aerospace sector. The top five ADVANTAGES for preferring MAM over conventional manufacturing processes are reduction of mass, freedom of design in conceiving the parts, direct printing from CAD in one operation instead of an assembly of many parts, Buy to Fly ratio clearly favourable to MAM and the production on demand.

On the other hand, the top five MAM WEAKNESSES are current maximum part size (100cm x 50cm), surface roughness of the printed parts requiring finishing, lack of standards and homologation procedures, low manufacturing speed of current machines and the high cost of equipment and raw material.

Respondents were also asked to specify the AREAS OF IMPROVEMENT for MAM. The collected answers address processes, technologies, design, raw materials and integration with other technologies or processes, namely:

- Post processing (surface finishing, support removal and heat treatment), part design and machine setup were mentioned by 68% of the respondents.
- Raw material is nowadays considered well above reasonable both in terms of quality (79%) and availability (57%). Same with quality of parts currently produced with MAM, considered well above reasonable (82%). Yet, production costs, raw material costs and inspection costs are too high, according to most of the respondents (over 56%).
- Currently Metallic Additive Manufacturing requires every part produced to be screened and tested. Yet 83% of the respondents agree that an inspection method based on batch tomography could well be used instead. Moreover, the respondents have privilege non-destructive tests based on tomography, ultrasound, thermography and infrared cameras over X-ray.

The survey has highlighted TRAINING NEEDS should not be ignored, since nearly 59% of respondents believe that the current training offer does not meet the needs of their staff engaged in MAM activities, mainly Industrial Engineers, Electrical / Mechanical Engineers and Technicians /Operators. Respondents report that they might increase the MAM staff in the coming years mainly for Design and Control activities. Main training gaps were identified in the fields of Topological optimization, Process & Regulation, Design rules, non-destructive control and surface finishing.

Methodology

This survey was available online directly from www.addispace.eu and was also distributed in Lisbon on February, 01st 2017 during a workshop on the Additive Manufacturing and in Albi on March, 07th 2017 during an SLM day organized by Aerospace Valley.

The survey got 78 responses distributed as follows:

- France: 68% of responses
- Spain: 22% of responses
- Portugal: 10% of responses

Out of the total number of people interviewed, 32% came from the Research & Development sector, 28% from Aeronautics companies or Aerospace Tier 1 supplier, 15% from MAM operators or Component manufacturers and 25% from other sectors (MAM equipment, Consulting, Aerospace integrator, Training, Laboratory, etc.).

It is also interesting to note that 20% of those who responded felt that they had no experience with MAM, 32% had basic experience, 36% had good experience and 12% considered themselves an expert in FAM.

Full Report on MAM Survey Analysis available in Annex.

4 RIS3 REGIONAL POLICIES IN SUPPORT TO MAM

4.1 Introduction

The European Commission has defined the Key Enabling Technologies (KETs) as the technologies for knowledge intensive activities. KETs are associated with high R&D intensity, as well as rapid innovation cycles, high capital expenditure and highly-skilled employment. Additive Manufacturing Technologies are commonly referred as KETs. In this context, the MAM (Metallic Additive Manufacturing) offer capabilities that could be revolutionary when applied to the transport industry. For instance, such a method which can substantially shorten the processing because it omits the cutting tool, fixture and multi-step forming processes. In addition, MAM has the power to handle complex shapes and to bring gains in manufacturing speed and lead time.

On the other hand, it is extremely relevant the return on investment concerning the KETs, showing that public investments can have a very positive value, generating a return as taxes and social security contributions. Thereby, the benefits can be up to four times the initial investment, as well as it can have a strong leverage effect in upgrading the competitiveness of businesses and providing employment, causing growth and wealth in the economy.

In the following chapters the support from regional policies is visited. The three SUDOE regions involved in ADDISPACE make use of the ***Research and Innovation Strategy for a Smart Specialization*** (RIS3) as integral part of its multilevel support to KET regional development.

4.2 The SUDOE region coverage

The ADDISPACE project addresses MAM technologies in the entire SUDOE region, depicted in the map below (Figure 4.1). The SUDOE region covers the Southwest European geographies including all Spanish Autonomous Communities (except Canary Islands), the six Southwestern regions of France, all continental regions of Portugal, United Kingdom (Gibraltar) and the Principality of Andorra.

Figure 4-1. SUDOE region map 1

4.3 The SUDOE RIS3 axis and priorities on behalf of MAM

This chapter focuses on the adequacy of RIS3 axis and priorities for developing Metallic Additive Manufacturing activities in SUDOE region.

Country	FRANCE	**Region**	NOUVELLE AQUITAINE OCCITANIE
RIS3 AXIS AND PRIORITIES			

Nouvelle Aquitaine :
- Chemistry, industrialization of materials and mobilization of biomass and Bio refineries for industry
- Laser, photonics and imaging systems
- Precision agriculture and eco-efficiency, agri-food
- Wood-based Eco construction and energy efficiency of the building
- Geosciences, metrology / monitoring for sustainable management of natural resources
- Embedded software and connected objects
- Intelligent asset delivery for wellness and health
- Integrated care pathways and patient assistance techniques
- Clean and intelligent mobility
- Competitive factory centred on the human factor

Occitanie (Languedoc Roussillon - Midi Pyrenees): All accommodation
- Embedded systems
- Innovation of the territorialized agri-food chain
- Industrial biotechnologies for the recovery of renewable carbon
- Advanced materials and processes: aeronautics and diversification
- Translational research in oncology and gerontology
- Cellular engineering and regenerative medicine

REGIONAL ADVANTAGES

-Optimize governance and increase stakeholder support
-Develop and implement strategies for economic transformation:
(A) the renewal of traditional sectors through higher value-added activities and new market niches
(B) modernization, through the adoption and diffusion of new technologies;
(C) technological diversification in relation to existing specializations in the related fields;
(D) the development of new economic activities through radical technological change and bold innovations;
(E) the exploitation of new forms of innovation such as open and user-driven innovation, social innovation and innovation in services.
-Answering to economic and societal challenges
-Increase regional visibility for international investors
-Improve internal and external contacts of a region
-Promoting the spread of knowledge and technological diversification

TARGETS

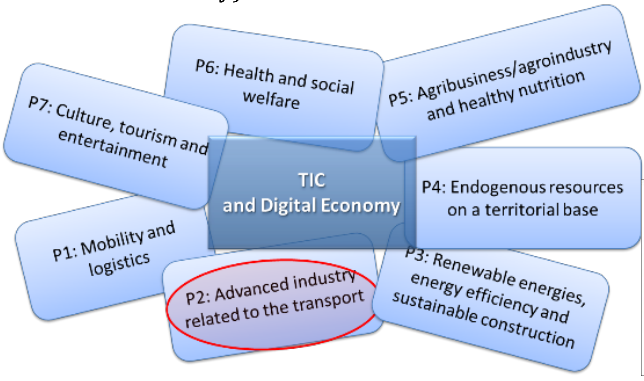
The coupling of advanced materials and processes for aeronautics and diversification aims to interface and synergize skills distributed throughout the region.
The areas of the future are beyond the aeronautics sector alone.
With 25 leading industrial establishments, 150 specialized high-tech SMEs, 7 projects for future investments and an established culture of RDI's collaborative programs, this specialization contributes to the strengthening and diversification of the industrial economy in the regions.
The ADDISPACE Project is part of this approach and aims to develop the dissemination of applied research in relation to key generic technologies. This in order to promote innovation capacities for smart and sustainable growth. Implementation of a regional strategic study on the stakes of the AM (stakes by sector, impact and regional potential). Restitution planned this autumn
Launch of a study on AM training (needs + offer proposal)
The working group has identified new directions for AM, namely:
Agro materials / agro composites: Identification of structuring actions in favour of the sector following the structuring of the CRTCI (Composite Transfer and Resource Centre Innovative) in Tarbes
Recycling / Valorisation: Reflection in progress to clarify the stakes / needs of the sector

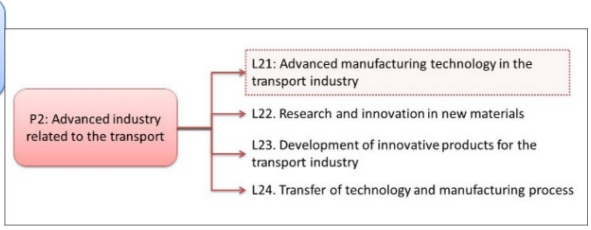
Country	SPAIN	**Region**	ANDALUCIA

RIS3 AXIS AND PRIORITIES

The “Visión Andalucía 2020” orientation document list the major vectors for innovation, including the resources endowments and capabilities of Andalucía in the scope of the current global context and future trends.
Eight specialization priorities have been selected to the implementation of the proposed strategy of innovation in Andalucía (). Axis P2 (“Advanced industry related to the transport”) is among the eight priorities for implementation in four different lines of action (L21-L24), as showed on the figure below.
L2 action line highlights that MAM technologies might contribute to development of new methodologies and to

delivering process improvements (.) and to Andaluzia strategy to achieve significant innovation in production processes of transport industry, given its potential to increase the productivity in components, parts and systems for the aerospace and other industries (aviation industry, naval industry, railway industry and automotive industry).





REGIONAL ADVANTAGES

Most KETs research and development activities in Spain are being carried out in Andalucía, not just in universities but also research centres.
CATEC has extensive experience in research and development of AM technologies, namely in Additive Layer Manufacturing (techniques (also known as Rapid Prototyping (RP), Rapid Manufacturing (RM), solid-free form fabrication, digital manufacturing (DM), etc.).
Two main directions are proposed : 1) To turn Andalucía into a world reference for research and development, technology demonstration and 2) Stimulate spill overs to another sectors of the economy, thus promoting knowledge and transfer of technology

TARGETS

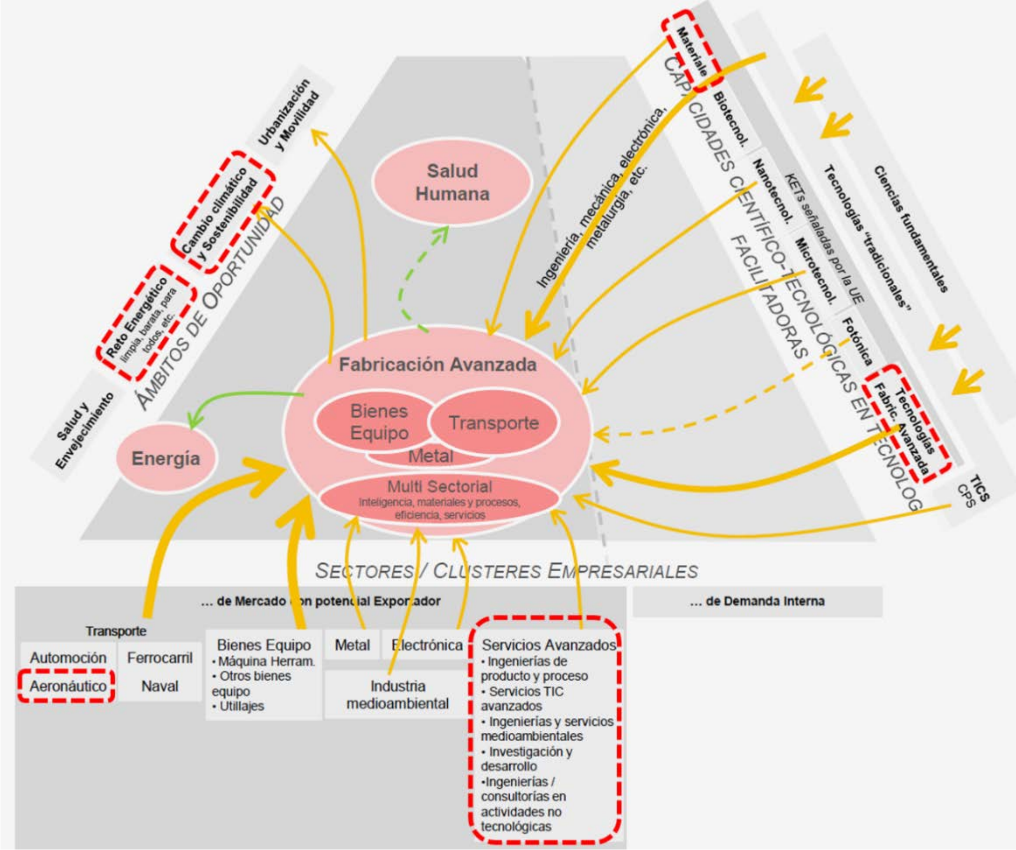
Aerospace and Defence are targets for Andalucía. Assembly lines of world tractor companies, such as ADS new military European transport plane and carbon fibre plants.
In this line work will be pursued in order to improve the current advanced manufacturing technologies and systems. It will be also work on the automation, robotization and digitalization of production processes for the transport industries.

The beneficiaries of the priority P2 (advanced industry related to the transport) and target group are:
Agents of the Andalusian Information System related to the advanced transport industry.
Research groups of the Andalusian Universities related to the transport.
Transport industrial companies.
Companies from other sectors which would present potential linkages with the transport industry.

Country	SPAIN	**Region**	BASQUE COUNTRY

RIS3 AXIS AND PRIORITIES

In the Research and Innovation Strategy for Intelligent Specialisation (RIS3) defined by the Basque Government, Advanced Manufacturing has been defined as one of the THREE META-PRIORITIES, together with Energy and Bioscience. It is a commitment to research focused on the incorporation of intelligence into production means and systems, the use of emerging technologies and capabilities in new products and processes, the integration of advanced materials into solutions with greater added value, or improved processes, the efficiency and sustainability of the resources used and the integration of high added value services.



REGIONAL ADVANTAGES

The choice of “Advanced Manufacturing” as a Meta-priority of the Basque Country is based on its cross-cutting applicability, on the marked Basque industrial tradition, on the relative strength of a diverse business sector, as well as on the existence of important scientific-technological capabilities in facilitating technologies associated with manufacturing activities.

TARGETS

RIS3 specialisation areas related to the ADDISPACE Project with greater development potential in the Autonomous Community of the Basque Country:
Development of advanced materials and processes for MAM aimed at the different transport subsectors, such as the aeronautical sector.
Development of MAM production means, studying scalable technologies at Machine-Tool level (LMD, WAAM technologies) and new machine concepts (process hybridisation) Research groups of the Andalusian Universities related to the transport.
Transport industrial companies.
Companies from other sectors which would present potential linkages with the transport industry.

Country	SPAIN	**Region**	OTHER REGIONS

RIS3 AXIS AND PRIORITIES

Besides the target regions of Basque Country and Andalusia, it should be noted that a relevant number of other

Spanish regions do consider the Aerospace sector and/or Additive Manufacturing as a Key Enabling Technology (KET), among their RIS priorities.

For instance, the regions of Madrid, Castilla-León and Castilla y La Mancha consider the aerospace sector among their target priorities based upon their established technology capabilities. Galicia region also considers this sector as a niche opportunity as a means to diversify the traditional metal-mechanic sector.

The number of Spanish regions embracing the advanced manufacturing technologies as priority KET is numerous; among them the following consider additive manufacturing technologies among their specialization priorities: Aragón, Asturias, Cantabria, Cataluña, Madrid, Navarra, and Valencia.

Country	PORTUGAL	Region	CENTRE OF PORTUGAL

RIS3 AXIS AND PRIORITIES

The main objectives of the RIS3 in Portugal sit on scientific and technological domains where Portugal has comparative advantages or competitiveness.
The Portugal 2020 vision is based on 4 fundamental pillars:
Digital economy;
Science and creativity;
Technological industrial capacity;
Enhance endogenous capabilities and differentiators.
And 5 thematic axis
The promotion of the potential of scientific and technological knowledge base;
The promotion of cooperation between the public and private R&D institutions and between companies,
The focus on goods and added value services
Promoting entrepreneurship, promoting the creation of employment and qualification of human resources;
The transition to a low-carbon economy.
The area of MAM (and therefore ADDISPACE) is strongly aligned with some of the structural axis and priorities, referred above, since it promotes the development and transfer of scientific and technological knowledge. ADDISPACE contributes further to dissemination and cooperation between companies and research and towards the creation of clusters of services for aerospace as a leveraging effect for competitiveness of this sector of high added value.
ADDISPACE fits in the transversal innovation platform "Sustainable Industrial Solutions" within four priority areas: "Automobile, Aeronautics and Space", "Energy", "Materials and Raw Materials" and "Production Technologies and Product Industry

REGIONAL ADVANTAGES

Since the RIS3 for the Centre of Portugal aims at developing processes, materials and sustainable systems of greater added value, applied research and key enabling technologies, there is a strong match for additive manufacturing (AM) and as such to MAM, as well as their integration in traditional manufacturing equipment and systems. The application development of these technologies of AM by the knowledge centres, the transfer and adoption of these new advanced
The regional strategy also includes the aerospace industry, as a market of high added value, which brings another match with ADDISPACE.
The RIS3 for the region also defines as priories for the region the development of advanced technology and/or emerging processes, innovative products and eco systems of higher added value.
The development of MAM technologies fall under the RIS3 line for assessment of sustainability of processes, products and systems and resource efficiency and reducing environmental impact in production processes.
The use of MAM technologies with a high degree of sophistication allows fabrication of high-added-value components with higher quality, in short production time and reduction of manufacturing costs, with clear benefits on efficiency.

TARGETS

Development of MAM technologies by companies of the central Portugal region, in order to develop the local economic activity, creating partnerships, supply of components, products and services. The target of RIS3 is to foster local companies export capacity to supply advanced technologies to the aerospace market, and thus contribute to increase the competitiveness of the region. The adoption of additive manufacturing technologies by companies of the region is a target and a positive contribution to sustainability and efficiency in the use of resources, since the additive process minimizes the use of cutting processes for chipping (Subtractive technologies), with consequent substantial decrease of swarf waste. Thus, ADDISPACE fits into the RIS3 regional targets by sustaining the efficient use of raw materials, waste reduction as well as energy efficiency.
Another target of RIS3 is to improve the human capacity through actions of dissemination and knowledge transfer and via pilot training courses and retraining. Additive manufacturing technologies, and ADDISPACE are again strong contributors to this priority RIS3 action.

5 GLOSSARY

[AM]: Additive Manufacturing

[MAM]: Metallic Additive Manufacturing

[LMD]: Laser Metal Deposition

[LMD-w]: Laser Metal Deposition-wire

[DMLS]: Direct Metal Laser Sintering

[SLM]: Selective Laser Melting

[EBM]; Electron Beam Melting

[EBAM}™: Electron Beam Freeform Fabrication (EBF^3)

[WAAM]: Wire and Arc Additive Manufacturing

[PBF]: Powder Bed Fusion technologies

[DED]: Directed Energy Deposition technologies

[R&D]: Research and Development activities

[RIS3]: Research and Innovation Strategy for a Smart Specialization

[CAD]: Computer-Aided-Design

[3D]: Three Dimensional

[NAMII]: National Additive Manufacturing Innovation Institute of the United States of America

[USA]: United States of America

[ASTM]: American Society for Testing and Materials

[STL]: STL is the standard file type used by most additive manufacturing systems

[MIG]: Metal Inert Gas

[TIG]: Tungsten Inert Gas

[CMT]: Cold Metal Transfer

[GMAW]: Gas Metal Arc Welding

[GTAW]: Gas Tungsten Arc Welding

[PAW]: Plasma Arc Welding

[FGM]: Functionally Graded Materials

[CFD]_: Computational Fluid Dynamics tools

[FEM]: Finite Element Model tools

[METI]: Ministry of Economy, Trade and Industry of Japan

[AMCRC]: Advanced Manufacturing Cooperative Research Center of Australia

[STREAM]: Structural Engineering Materials through AM programme

[DMRC]: Direct Manufacturing Research Centre of Germany

[TNO]: Dutch research institute

[RNPR]: Portuguese National Network of Rapid Prototyping

[FDM]: Fused Deposition Modelling

[FCT]: Foundation for Science and Technology of Portugal

[PAMI]: Portuguese Additive Manufacturing Initiative

[CDRSP]: Centre for Rapid and Sustainable Product Development

[EPSRC]: Engineering and Physical Sciences Research Council of UK

[NDT]: Non Destructive Technologies

[NASA]: National Aeronautics and Space Administration of USA

[HIP]: High Isostatic Pressing

[TRL]: Technology Readiness Level

[CATEC]: Centre for Advanced Aerospace Technologies of Sevilla, Spain

[ESA]: European Space Agency

[FLPP]:Future Launchers Preparatory Programme of ESA

[ISCAR]: Internal Rotation and Attitude Control System Bracket for FLPP

[ACU]: Adapter of Useful Charge for ARIANE

[OEM]: Original Equipment Manufacturer

[LEAP]: Leading Edge Aviation Propulsion. High-bypass turbofan engine produced by CFM International

[KET]: Key Enabling Technologies

[RP]: Rapid Prototyping

[RM]: Rapid Manufacturing

[DM]: Digital Manufacturing

[CRTCI]: Composite Transfer and Resource Centre Innovative in Tarbes, France

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