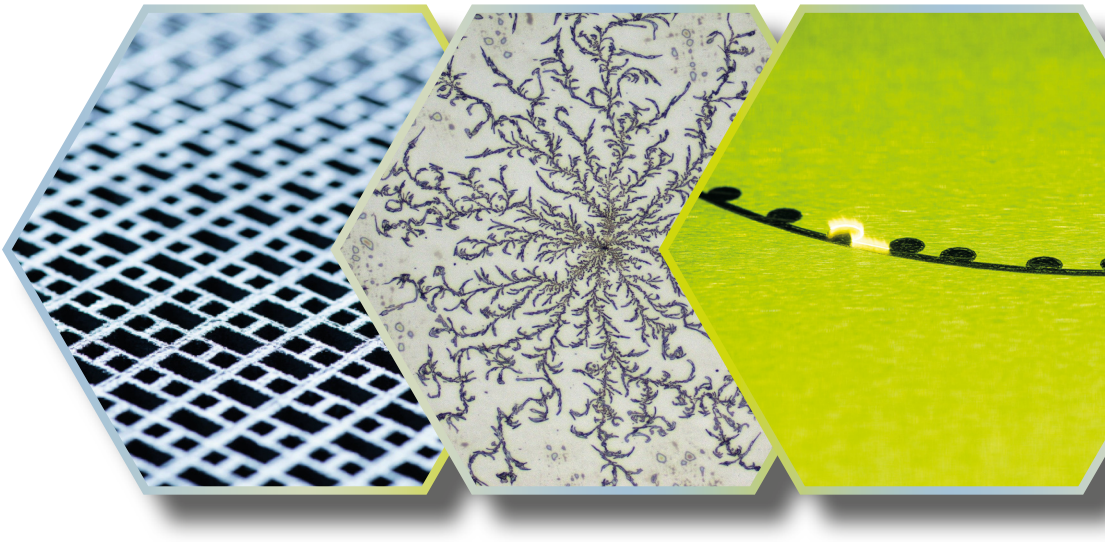
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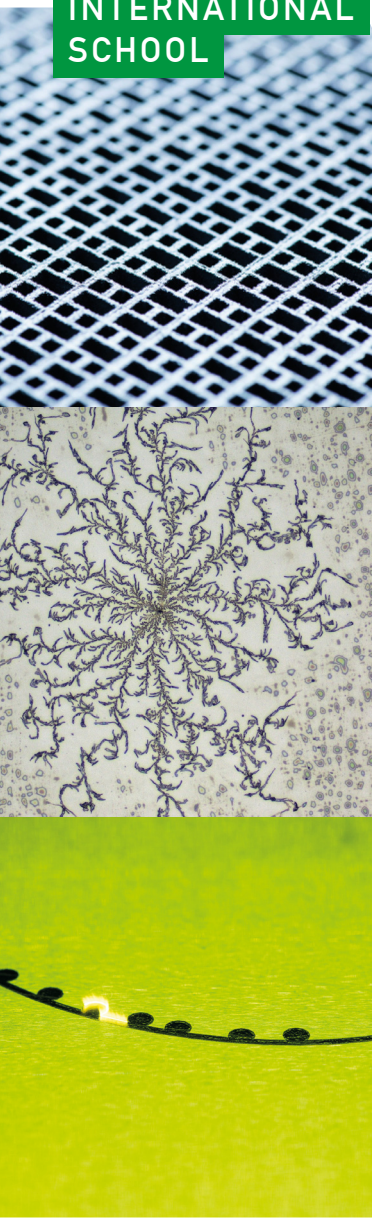
AMETIS

Advanced Manufacturing for Energy and Transportation International School



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AMETIS

Advanced Manufacturing for Energy and Transportation International School

Nihed CHAÂBANE and Frédéric SCHUSTER

The impact of Materials Science and Engineering on innovation in the field of components for low-carbon energy and transportation is considerable. Problems related to the durability of solutions, economic sustainability, are often strongly related to the choice of materials and their production process, which has a very important impact on performance during use all along the lifetime of the components. Therefore, the advanced manufacturing concept integrates the entire value chain, from eco-design to recycling, and even recycling at times, taking into account a number of environmental, social and resource management factors or energy sobriety. That is the systemic presentation that is the core of the AMETIS international school.

AMETIS school will focuses on three emerging processes, and on their possible synergies that can initiate innovations or incremental advances. After presenting an integrated vision of additive manufacturing, the latest advancements in surface engineering and nanomanufacturing technologies, the school will focus on the convergence of these technologies as a source of innovation for advanced energy manufacturing and transport.

ISBN : 978-2-7598-2446-5



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Nihed CHAÂBANE
and Frédéric SCHUSTER

AMETIS

Advanced Manufacturing for Energy and Transportation
International School

Science Press
edp sciences

Printed in France

EDP Sciences – ISBN(print): 978-2-7598-2446-5 – ISBN(ebook): 978-2-7598-2588-2
DOI: 10.1051/978-2-7598-2446-5

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Introduction

Advanced Manufacturing for Energy and Transportation International School

Nihed CHAÂBANE[1] and Frédéric SCHUSTER[2]

[1]*Université Paris Saclay, CEA, Institut National des Sciences et Techniques Nucléaires, 91191 Gif-sur-Yvette, France*
[2]*Université Paris Saclay, CEA, Cross-cutting Program on Materials Science and Engineering, 91191 Gif-sur-Yvette, France*

Abstract

The objective of Advanced Manufacturing for Energy and Transportation International School (AMETIS) is to present an integrated vision of advanced manufacturing dedicated to materials and components for low-carbon energy and transportation. The proposed approach essentially focuses on three main families of emerging processes, as well as their possible synergies to generate an often disruptive innovation framework. The option is also to present new methodologies that allow faster discovery or design of new materials of interest or faster optimization of complex emerging processes. These methodologies are often based on the significant progress made by digital technologies that have a considerable impact on the acceleration of Materials Science and Engineering. In particular, they make it possible to considerably shorten development time and minimize costs. Finally, this approach cannot be global without taking into account the drivers of sustainability in terms of resources, environment, safety and society. Therefore, AMETIS proposes a holistic approach.

1.1 Introduction

The impact of Materials Science and Engineering on innovation in the field of components for low-carbon energy and transportation is considerable. Issues related to the durability of solutions, such as economic sustainability, are often strongly linked to the choice of materials and their production process, which have a very important impact on performance during use all along the lifetime of the

DOI: 10.1051/978-2-7598-2446-5.c901
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components. Therefore, the advanced manufacturing concept integrates the entire value chain, from eco-design to recycling, and even upcycling, taking into account a number of environmental, social and resource management factors including energy sobriety. This systemic presentation is the core of the AMETIS (figure 1).

Among the large families of emerging processes, AMETIS focuses on three of them due to the high potential of each one, and it is also their possible synergies that can initiate breakthrough innovations or incremental advances, as shown in figure 2.

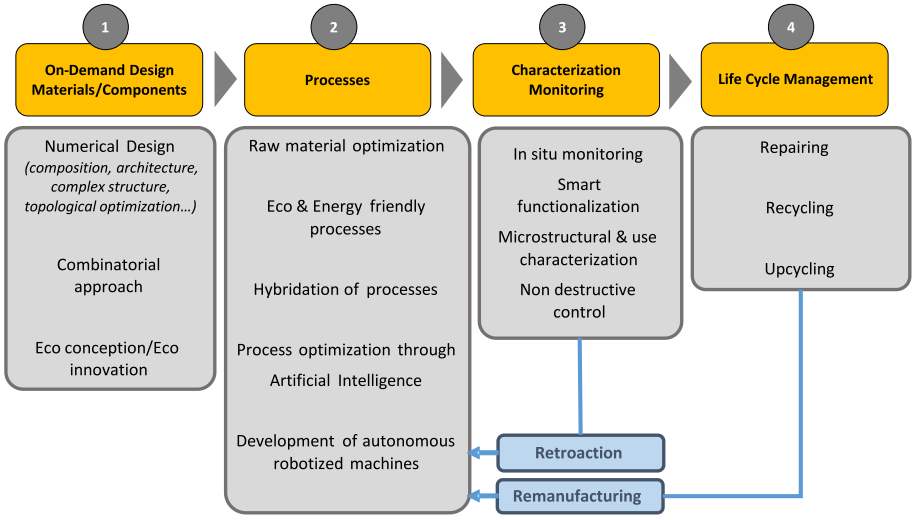


Fig. 1 – Systemic approach of advanced manufacturing.

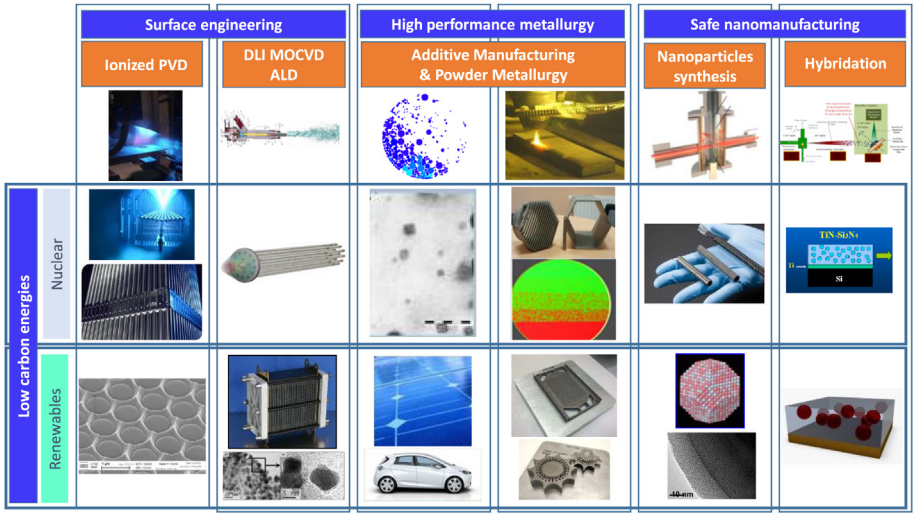


Fig. 2 – Examples of emerging processes for low carbon energies.

Therefore, after presenting an integrated vision of additive manufacturing, the latest advancements in surface engineering and nanomanufacturing technologies, AMETIS will focus on the convergence of these technologies as a source of innovation for advanced energy manufacturing and transport.

1.2 Holistic Overview of Additive Manufacturing

Regarding additive manufacturing, AMETIS will first give a presentation of an integrated vision of this family of technologies, presenting in particular the different processes, the entire value chain, the different types of materials processed, as well as examples in particular in the field of transport and low carbon energies. Then, AMETIS will focus on several trends that are generally not presented in technology-only instruction. AMETIS will first illustrate the relationships between process, microstructure and properties and also the importance of mastering raw materials from the start to the end result in terms of product performance. Next, AMETIS will present the design of on-demand architectures according to the required properties. This approach is based on digital design in a first step and the synthesis of these architectures through additive manufacturing in a second step, to compare reality with prediction, thus illustrating the link that can be established between numerical design and manufacturing of on-demand high-performance materials and components. Finally, AMETIS will focus on the possible smart integration of the electronic functions "Package Electronics Additive Manufacturing" that allows the technology to enter the era of the Internet of Things, with, for example, the possibility of monitoring the performance of the components remotely and their durability during the life time.

1.3 Integrated Approach of Nanomanufacturing: From Nanoobject Synthesis to Applications

The second "pillar process", also with a very generic character, consists of nanofabrication. In fact, the synthesis and safe integration of nanoobjects (nanopowders, nanowires, and nanotubes) into components for energy and transport is a fairly unique way to develop innovation in these sectors. AMETIS will present the main technologies for the development and implementation of nanoobjects, as well as the resulting applications. In addition to these purely scientific and technological aspects, the contribution of nanotechnologies to the development of sustainable solutions will also be presented. In fact, in some cases, nanotechnologies can lead to a reduction in the use of critical metals or strategic materials, and sometimes even allow their replacement. The last, but not least, consideration will be devoted to managing risks using nanomaterials as part of an integrated approach from production to consumer.

1.4 Emerging Surface Engineering Processes

Surface engineering has made remarkable progress in the past decade and new applications, particularly in the energy field, have become possible and are currently under industrial development in part due to this progress. Following a presentation based on the principles of thin films and thermal spray technologies, AMETIS will focus on a more detailed presentation of the progress made in recent years. In the Physical Vapor Deposition (PVD) sector, the development of highly ionized technologies and, in particular, HIPIMS (High Power Impulse Magnetron Sputtering) technology has enabled significant progress to be made, for example, in nuclear applications (EATF: Enhanced Accident Tolerant Fuel and also in the reprocessing sector). In terms of Chemical Vapor Deposition (CVD), the penetration of technologies such as DLI-MOCVD (Direct Liquid Injection MOCVD) and ALD (Atomic Layer Deposition) in the low carbon energy sector exploits all the richness and diversity of the chemistry of organometallic precursors, both for applications in extreme environments and for functional components for batteries, supercapacitors and high-temperature electrolyzers or fuel cell components. Regarding thermal spraying technologies, two very important advances are observed, firstly, the significant development of cold spraying technology, which can also be considered in some aspects as a repair or additive manufacturing technology. Another important innovation refers to the thermal plasma spraying of nanoparticle precursor solutions or suspensions that offers very interesting perspectives for the new generations of thermal and environmental barriers, in particular for the aeronautical and space sector.

1.5 Possible Synergies Between Technologies

After the presentation of the three main families of emerging processes, AMETIS will also present their possible synergies and the resulting innovations (figure 3), in particular:

- At the interfaces between 2D and 3D processes

This is usually the case when, for example, 3D manufacturing processes are combined with surface functionalization processes that give these architectures new functionalities (catalytic, anti-corrosion, electrical, etc.).

- At the border between 3D printing and nanofabrication

This is, for example, the case of the use of nanoparticles as raw material for 3D printing technologies, or for the *in situ* generation of nanocomposite materials in additive manufacturing machines (*in situ* generation of ODS (Oxide dispersion strengthened) steels, for example).

- With a combination of nanotechnologies and surface engineering

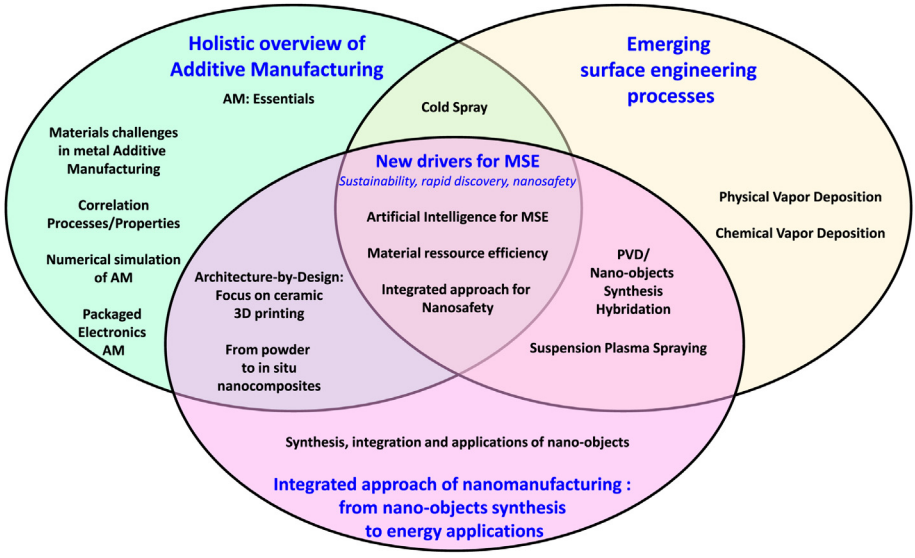


FIG. 3 – The three families of emerging processes, their possible synergies, the new generic methodologies for rapid discovery and optimization and the new drivers for MSE.

It is a completely new generation of innovative processes that combine thin film science and engineering with nanoparticle synthesis technologies. This new approach enables the production of innovative nanocomposite materials, in which the choice of the nature of the matrix is completely independent of the nature of the incorporated nanoobjects, which greatly opens the spectrum of applications for this type of new materials (solar thermal energy, photovoltaic energy, batteries…).

1.6 New Methodologies for Rapid Discovery of Materials and New Drivers for MSE

These three major families of processes also contribute to an accelerated discovery of new materials, components and solutions, either because they often intrinsically allow rapid screening of compositions, microstructures and architectures, or because they give access to new concepts of materials and components hitherto not accessible through more conventional production routes.

This accelerated discovery of solutions also benefits from considerable progress in digital technologies, both for data mining, numerical design of materials, components and architectures, numerical simulation of processes, as well as their optimization using Artificial Intelligence approaches. These new approaches are also intended to be introduced during this first AMETIS.

The final viewpoint to address in this systemic overview of advanced manufacturing is about the new drivers for the development of a sustainable Materials Science and Engineering. These drivers consist in environmental and energy sobriety of the processes, minimization of the use of resources, in particular of strategic metals and, in general, in the impact of emerging processes on the circular economy of materials and recyclability of components. Therefore, the objective of this first summer school on advanced manufacturing is to offer a systemic approach taking into account the drivers of sustainability of the implemented solutions and eco-innovation. In more general terms, this systemic approach and these new convergences are the core business of the scientific project of the IMPACT International Chair of INSTN (National Institute of Nuclear Science and Technology) at the University of Paris-Saclay (https://www.materials-impact-chair.org/).



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Chapter 1

Additive Manufacturing: Development of Sustainable Industrial Processes for Circular Economy Improvement

Abstract

Additive manufacturing is undergoing strong development for various applications in different industrial fields. This global material efficiency addresses various manufacturing fields, taking into account new processes which make it possible to minimize the use of resources thanks to digital ecodesign. This fact allows these technologies to be framed within the circular economy, since it allows the efficient use of resources and introduces the concept of post-manufacturing recycling of raw materials, for instance, of non-melted powders in powder bed processes. This fact permits to reduce the impact of these technologies thus promoting the industrial ecology, since it contributes for example to the better management of critical metals. In this chapter, a holistic approach regarding the sustainable additive manufacturing in the frame of the circular economy is presented. The latter is based on the description of the existing whole value chain. On the one hand, the main technologies, the materials challenges, the innovative powder metallurgy production, the correlation of the process parameters/corrosion resistance, the process simulation and final microstructure prediction are described. On the other hand, the intelligent digital design of architectures associated with the desired final properties, as well as, the full monitoring of final parts by embedded electronic sensors integrated during processing are presented as the most promising developing routes.

DOI: 10.1051/978-2-7598-2446-5.c001

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1.1 Additive Manufacturing: Essentials

Fernando LOMELLO

Université Paris-Saclay, CEA, Service d'Etudes Analytiques et de Réactivité des Surfaces (SEARS), 91191 Gif-sur-Yvette, France

Abstract

Additive manufacturing (AM) or commonly called 3D printing is a set of processes that allow the manufacture of a physical component from a virtual object. The progress made in recent years has taken them from rapid prototyping processes to real technological routes for the production of components with high added value. These technologies allow a significant reduction in the material and energy used, while minimizing the so-called subtractive manufacturing steps, notably related to machining. This is a fundamental point for the development of environmentally efficient manufacturing processes for the French industry of the future.

The reduction in the stock thanks to the possibility of manufacturing parts of great complexity, as well as, with the reduction in the supply chain, allows expecting a diffusion in several fields of high added value. This is the specific case of the aeronautical industry, which fostered the evolution of these rapid prototyping technologies towards true production routes.

Nowadays, technological maturity allows us to have a global vision ranging from the supply of primary materials to recycling aspects. Thanks to these 3D printing technologies, many existing primary materials manufacturing and recycling technologies were revisited. The main idea is to present an overview of the associated technologies and materials, as well as the evolution in the various fields of application in the following pages.

1.1.1 Overview of Additive Manufacturing: AM Common Terms

The term Additive Manufacturing as described by the "Union de Normalization de la Mécanique" (NF E 67-001) includes "all of the processes used to manufacture, layer by layer, by adding material, a physical object from 'a digital object' – see figure 1.1.1.

Computer-aided design (CAD) allows the creation of a 3D model that is an integral part of the additive manufacturing process. As shown in figure 1.1.1, the volume CAD modeler cuts the virtual object into layers of defined thickness according to a particular orientation. This digital processing requires the use of computer-aided manufacturing (CAM) software in order to save the details of each indexed layer.

The 3D model is stored using different computer formats such as IGES (Initial Graphics Exchange Standard), STEP (STandard for the Exchange of Product) and

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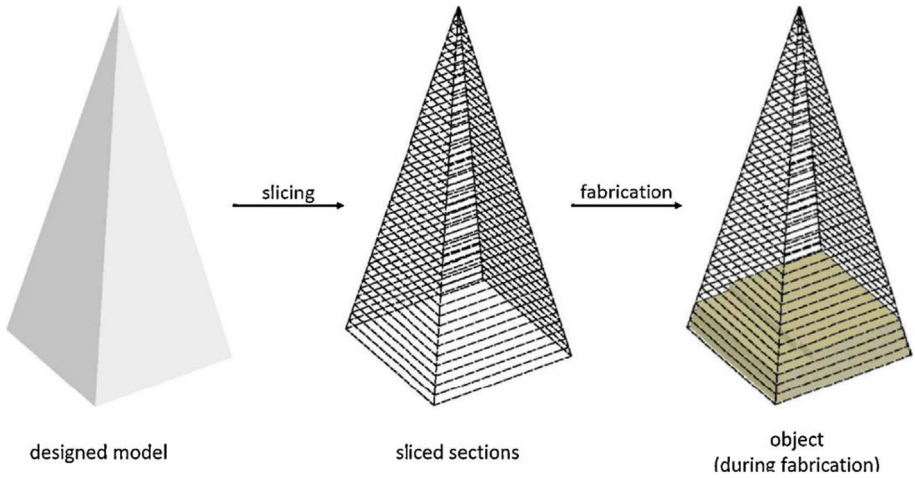


FIG. 1.1.1 – Production method: points common to all processes [1].

STL (Stereolithography Tessellation Language). The latter, the most used in the field of additive manufacturing was created by 3D Systems.

The progress made in recent years has shifted rapid prototyping processes to real technological processes for the production of components with high added value – see figure 1.1.2. Today, three types of materials are most commonly used: metals, polymers and ceramics (very upstream).

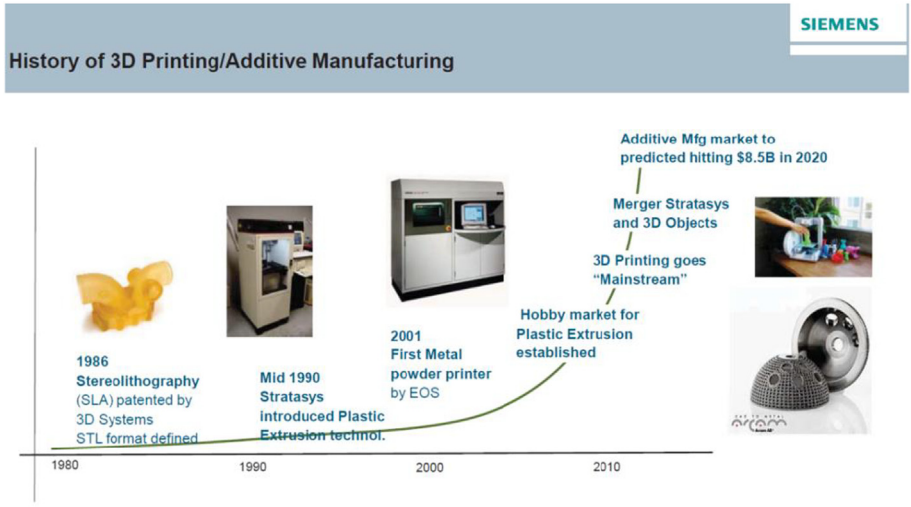


FIG. 1.1.2 – From rapid prototyping to additive manufacturing [2].

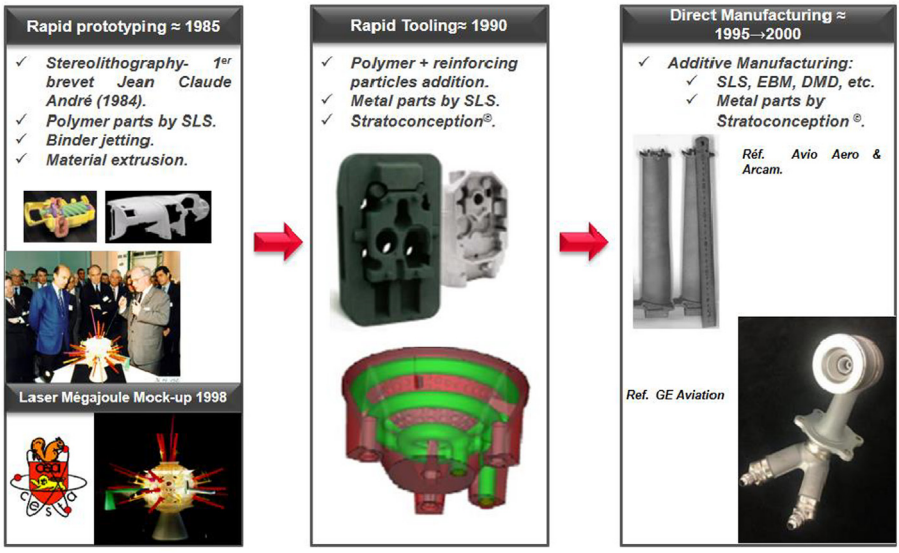


FIG. 1.1.3 – Additive manufacturing evolution.

The progress made by these new manufacturing technologies has enabled rapid prototyping processes to evolve into real new technological routes (figure 1.1.3) for the production of components with high added value. Different industrial sectors are considering new applications (nuclear, aerospace, medical, automotive, hydraulic, pneumatic, tooling, electronics, etc.). Since 1992, rapid prototyping (stereolithography) has been used by CEA CESTA for the production of mock-ups within the framework of the various programs – as shown in figure 1.1.3.

1.1.1.1 Description of Technology Capabilities in AM

In general, the concept of additive manufacturing according to standard ASTM F2792-12A developed by the commission F42 (2013) combines seven technologies (figure 1.1.4) [3]:

- *Stereolithography (SLA, Vat polymerization)*: it uses photopolymerizable resins which it is activated by a UV laser. This technique is used to process polymer-based composites reinforced with ceramics or metals. Stereolithography was born in the mid-1980s under the impetus of French and American researchers. The first patent was deposited by Jean-Claude André with CILAS (Compagnie Industrielle des Lasers) in 1984 followed by the American Charles W. Hull, the creator of the company, 3D Systems a month later. The first machine to be marketed was built in 1988 by 3D Systems. This technique also makes it possible to manufacture ceramic parts using resins loaded with 95% ceramic, followed by a sintering step – as is the case with the process developed by the laboratory "Science of Ceramic Processes and Surface Treatments"



FIG. 1.1.4 – Different additive manufacturing technologies depending on the energy involved.

(SPCTS UMR CNRS 7315) in Limoges. Today, the process is operated by the 3D Ceram. Examples of production: prototypes and dental prostheses. Manufacturer: 3D Systems.

- *Material Jetting*: Direct deposition of materials, layer by layer, which allows for example the manufacture of multi-material components. Two technologies are associated: inkjet printing and aerosol jet printing. This technique makes it possible to manufacture components based on polymer and/or reinforced with metals. Production examples: prototypes. Manufacturers: 3D Systems, Stratasys.
- *Binder Jetting (BJ)*: Deposit of liquid glue to associate grains of powder (metallic, polymer, ceramic) patented by MIT in 1989. The components manufactured by this technique have low mechanical resistance. This type of component requires thermal post-sintering or infiltration treatments in order to obtain an attractive final density. Production examples: prototypes. Manufacturers: Ex-one (digital part materialization), Z-Corp (3D Systems), Voxeljet.
- *Material Extrusion, Fused Deposition Modeling (FDM)*: Process developed in 1988 by Lisa and S. Scott Crump, one of the co-founders of the company Stratasys. In 1991, the technology was introduced to the market. The materials are extruded through a die which is heated. This technique makes it possible to manufacture parts which have low mechanical properties. Production examples: prototypes. Manufacturer: Stratasys.
- *Sheet Lamination – Stratoconception® – Laminated Object Manufacturing (LOM)*: this process was patented by Michael Feygin in 1988. In France, Prof. Claude Barlier in 1991 created the CIRTES R&D center which registered 19 patents on the stratoconception® process. The components are made from previously profiled sheets of preformed materials (polymers, metals, ceramics). The assembled sheets do not allow the production of structural components. Production examples: plastic injection mold. Manufacturers: CIRTES, Mcor Technologies.

- *Powder Bed Fusion (Electron Beam Melting: EBM/Selective Laser Melting: SLM/Selective Laser Sintering: SLS)*: Selective fusion of powders which are distributed as a form of a bed through a laser or electron beam. This technology allows the use of polymeric, metallic and ceramic powders. In particular, electron beam fusion (EBM) technology has several advantages in terms of oxygen content (under vacuum) and residual stresses (initial heating 700 °C). Examples of production: turbine blades, aeronautical engine injectors, stainless steel mesh and tools. Manufacturers: Phenix systems (France – today 3D Systems), 3D Systems, EOS, SLM Solution, MCP Realizer, Arcam.
- *Direct Energy Deposition (Construction Laser Additive Direct: CLAD®/direct metal deposition: DMD/laser metal deposition: LMD/direct energy deposition: DED/Laser Engineered Net Shape: LENS)*: materials as the form of powder or wire are deposited directly by focusing on a target. The geometric complexity is difficult. 5-axis systems need to be developed. Examples of production: composite dies, surface treatment, aeronautical parts and repair. Manufacturers: BeAM (France), POM, Optomec, Trumpf, InssTek, Efesto and Huffman.

As mentioned above, it is their implementation and their use for a layer-by-layer construction of objects which thus classify the 7 technologies. The base material can be in the form of liquid, powder, tape or wire. This material can be present at the start of the manufacturing process or deposited as you go. The material is shaped using a heat source: electron beam, laser, visible light, UV or IR. The manufacturing process is done *via* three different routes depending on the technique used: solidification, fusion and bonding of sheet materials (stratoconception®).

1.1.1.2 Categorization of Material Types Used in AM

The available printable materials for each AM technologies described in the previous lines is shown below in figure 1.1.5.

1.1.1.3 Additive Manufacturing Advantages for Decision Making: Discussion of the Impact of Both Process and Material Selection

As claimed in the Roland Berger report in 2017, the materials are extremely dependent on the decision making (figure 1.1.6).

The metal additive manufacturing processes could be classified into three main groups (figure 1.1.7): powder bed, powder projection and wire deposition.

First Group: Powder Bed Fusion

The first group, powder bed fusion technologies, allows the fabrication of a part by stacking successive layers. The scraper brings a layer of powder which is fused on the lower layer by a focused energy beam (laser, electron beam). These technologies have the advantage of making it possible to produce components having complex shapes with a good surface finish. On the other hand, they have technological limits in terms of working chamber size, volume of powder used and manufacturing speeds.

Materials	Example materials	Process categories						
		Vat photo-polymer-ization	Material jetting	Binder jetting	Powder bed fusion	Material extrusion	Directed energy deposition	Sheet lamination
Thermoset Polymers	Epoxies and acrylates	X	X					
Thermo-plastic polymers	Polyamide, ABS, PPSF		X	X	X	X		X
Wood	paper							X
Metals	Steel, Titanium alloys, Cobalt chromium			X	X		X	X
Industrial ceramic materials	Alumina, Zirconia, Silicone nitride	X		X	X			X
Structural ceramic materials	Cement, Foundry sand			X	X	X		
Note: Combinations of the above material classes, e.g. a composite, are possible								

FIG. 1.1.5 – Additive manufacturing process families & processes [4].

We can distinguish a first sub-group according to the ability to merge and/or sinter the materials:

- A first process, SLS (Selective Laser Sintering) was invented by R.F. Housholder who patented the concept in 1979, but without commercial exploitation – see figure 1.1.8. In addition, Dr. Carl Deckard at the University of Texas (Austin) invented and patented in 1987 a first SLS system for sintering PA 6.6 nylon powders. This patent contributed to the creation of the start-up DTM Corporation in Austin, Texas, which filed the main patent in 1992. In 1997, 3D Systems bought the patent filed which fell into the public domain in 2014. 3D Systems has signed an agreement with EOS in 1994 for the exploitation of the patent in exchange for the design of EOS stereolithography machines. This process is called by EOS "DMLS" (direct melting laser sintering). Historically, these systems allowed the selective sintering of powders with a certain porosity rate without achieving fusion due to the low powers of lasers (100 kW<). This is not the case today, the latest machines like ProX™ from 3D Systems which have two fiber lasers of 500 kW or one of 1 kW allowing the realization of dense parts. In France, the company Phenix Systems has developed its own machines since the year 2000. Today, the company belongs to the 3D Systems group.
- SLM (Selective Laser Melting) was developed and patented in 1995 at the Fraunhofer ILT Institute in Aachen, Germany by Dr. Dieter Schwarze and Dr. Matthias Fockele. Due to intellectual property issues, the patent will be used

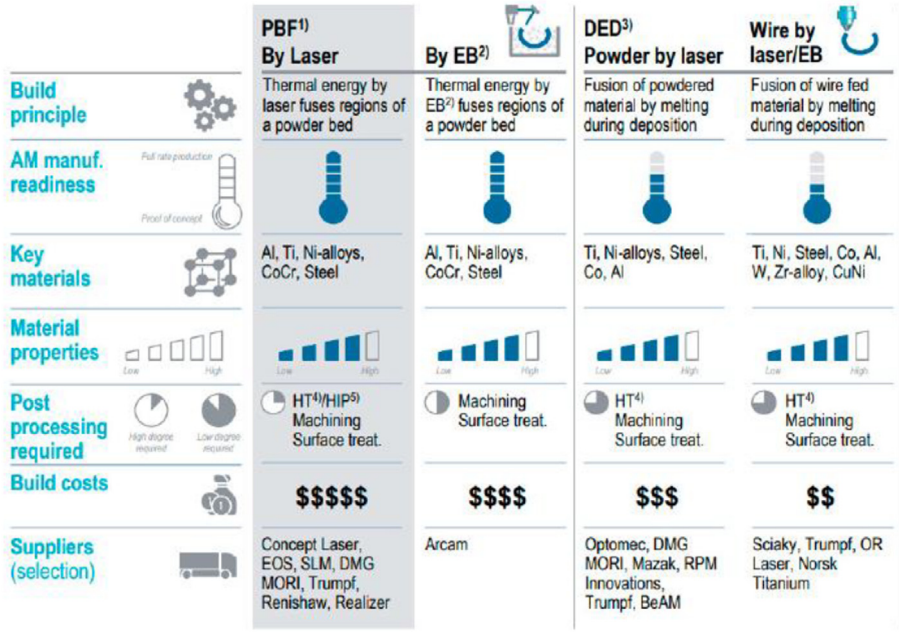


FIG. 1.1.6 – Additive manufacturing methods in the process decision [5].

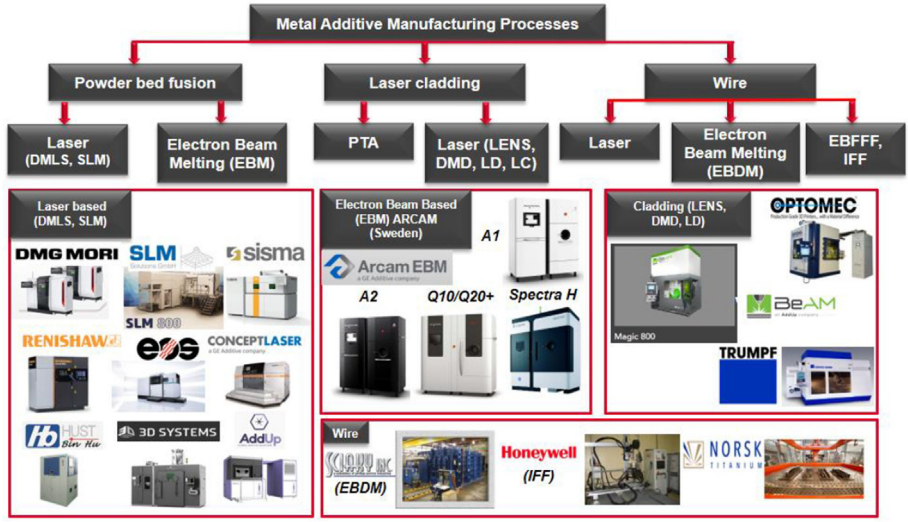


FIG. 1.1.7 – Different metal additive manufacturing processes.

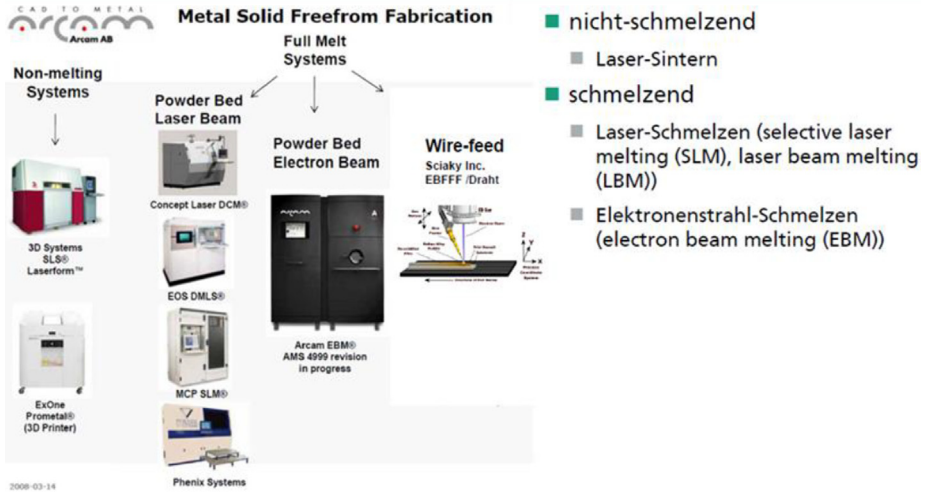


FIG. 1.1.8 – Powder bed fusion technologies [6].

by the Trumpf group and EOS. These allowed the patent to be used by MCP Realizer which, after its commercial separation, led to the birth of two new companies, MTT Technologies group (Germany) and MTT Technologies LTD (England). Today, the companies have been renamed SLM Solutions and Renishaw, respectively – see figure 1.1.9.

- LaserCUSING® is a technology very close to SLM patented in 2000 by Concept Laser GmbH. The first machine was sold in 2002. Today it is the manufacturer of the largest laser machine in the market, the X line 2000R.
- The electron beam melting (EBM) technology was patented in 1993 in Gothenburg by researchers from the Chalmers University of Technology – see figure 1.1.10. The same researchers with the help of the Swedish government created the company Arcam in 1997. The main advantage of an electron beam is the power (3.5 kW) used which melts different materials at high melting points (2700 ° C<), preheating the powder bed (reduction in stresses) and working under secondary vacuum (low oxygen content).

Second Group: Direct Metal Deposition

The second group, powder projection technologies are based on selective powder injection then laser fusion at the exit of a coaxial nozzle allowing the production of a part layer by layer or the reconstruction in service of worn areas of an existing room. One of the main obstacles to overcome is the development of new materials such as aluminum alloys, Inconel and materials with a functional gradient. Also, it is necessary to demonstrate technological maturity in terms of geometric resolution. Regarding this process, the first patent was filed in the United States by D.S. Gnanamuth in 1976 – see figure 1.1.11.



FIG. 1.1.9 – Powder bed fusion by laser: characteristics of the current machines.

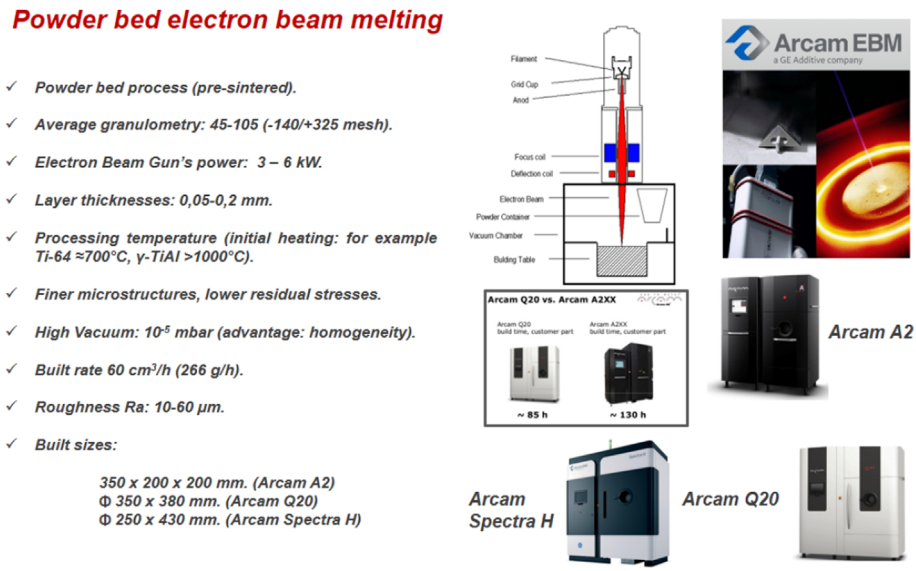


FIG. 1.1.10 – Powder bed fusion by electron beam: Arcam technology.

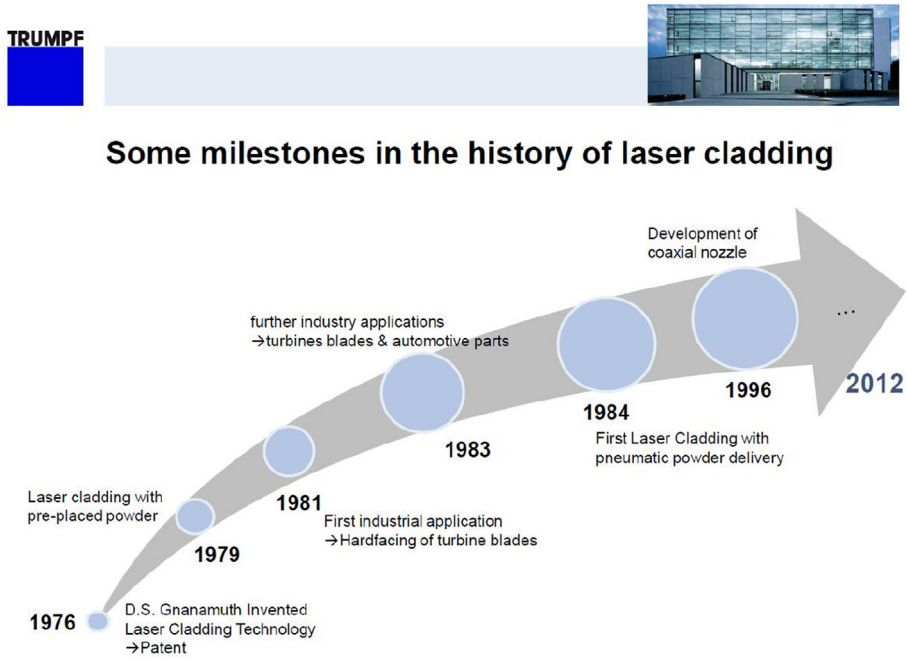


Fig. 1.1.11 – Direct metal deposition evolution [7].

Similar processes with certain technical variations were patented in the 1990s such as:

- Direct Metal Deposition (DMD – University of Illinois Urbana-Champaign, 1993): POM.
- Laser Engineered Net Shaping (LENS – Sandia National Laboratory, 1996): Optomec.
- Direct Light Fabrication (Los Alamos National Laboratory, 1996).
- Controlled Metal Build up (Fraunhofer ILT, 1996).

Third Group: Wire-Based Additive Manufacturing

The third group, wire fusion technologies uses an energy source to melt a metal wire on a metal support. The energy beams can be of different nature: electron beam, electric arc, etc. These technologies allow the local addition of material as well as the repair of components.

Technology Comparison

The table in figure 1.1.12 shows that the most suitable processes also for short-term industrialization are those based on manufacturing from metal powder – powder bed (figure 1.1.8).

++++ => best	Powder bed (laser)	Powder bed (EB)	Powder feed	Wire feed
Beam thickness	++++	+++	++	+
Layer thickness	++++	+++	++	+
Construction speed	+	++	+++	++++
Roughness	++++	+++	++	+
Internal stress level (less deformation)	+++	++++	++	++
Shape complexity	++++	+++	++	+
Repair capability	0	0	+++	+++
Multi material capability	0	0	++	0
Size of the part	++	+	+++	++++
Hollow and lattice structure capability	++++	++	0	0
Wall Thickness and precision	++++	+++	+	++

FIG. 1.1.12 – Metal additive manufacturing technologies comparison (Frost & Sullivan 2012).

Hybrid Technologies

We can add to this classification a fourth group, that of hybrid machines for additive manufacturing and by subtractive alternation based on powder bed fusion (Matsuura) and laser projection processes (Hamuel, DMG Mori, Mazak, WFL Millturn Technologies) – see figure 1.1.13. The Matsuura, Hamuel, DMG Mori and WFL M80 machines were introduced to the machine tool market the first two in 2013, the third in 2014 and the last in 2015, respectively. This group of processes is of interest for certain applications such as the production of tanks having improved interior surface roughness.

1.1.1.4 Additive Manufacturing Using Cases: List of Examples of Real-World Application on AM

1.1.1.4.1 Aeronautics

Since the installation of the Arcam A2 machine in the MATPERF joint laboratory (Mecachrome-CEA) in 2009, various prototypes for the aerospace industry have been produced. In particular, supports for the communication satellite Atlantic Bird 7 (figure 1.1.14) were manufactured in 2010 for the company Astrium – today Airbus Defense & Space. This satellite was transported to the geostationary transfer orbit by the Zenit-3SL rocket. This manufacturing route has allowed a significant reduction in weight (30%). Given the results, the European Space Agency (ESA) considers that additive manufacturing has a level of technological maturity equal to 9 (small-scale production).



FIG. 1.1.13 – Hybrid manufacturing processes: additive and subtractive.

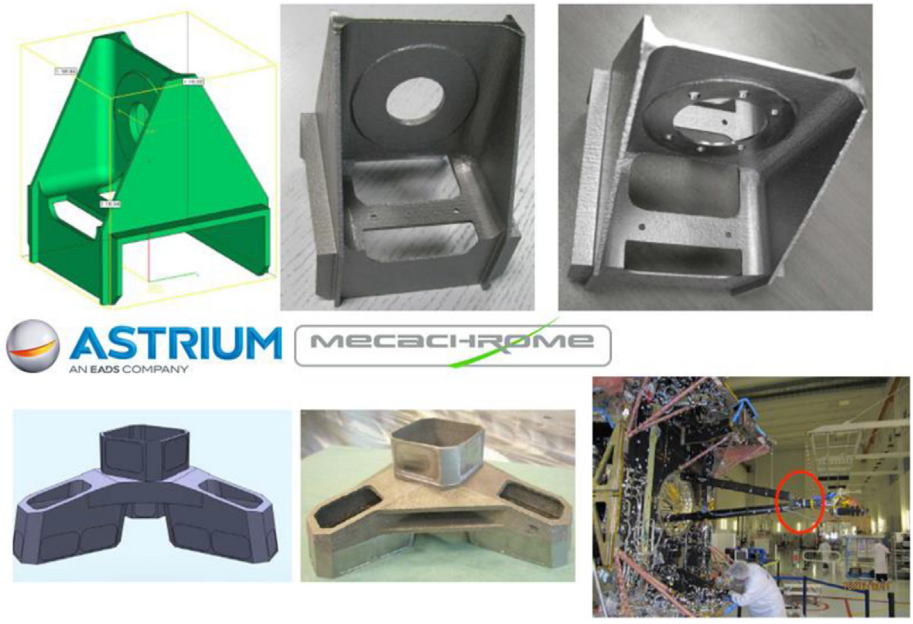


FIG. 1.1.14 – Atlantic Bird 7 satellite antenna supports [8, 9].

In the international context, a first study was carried out by the English subsidiary of EADS Innovation Works (today Airbus Group) in collaboration with the company EOS. The study was focused on the topological optimization of an A320 hinge (see figure 1.1.15) in TA6V in an M270 (DMLS) machine using Altair Hyperworks software. Topological optimization consists in defining the ideal

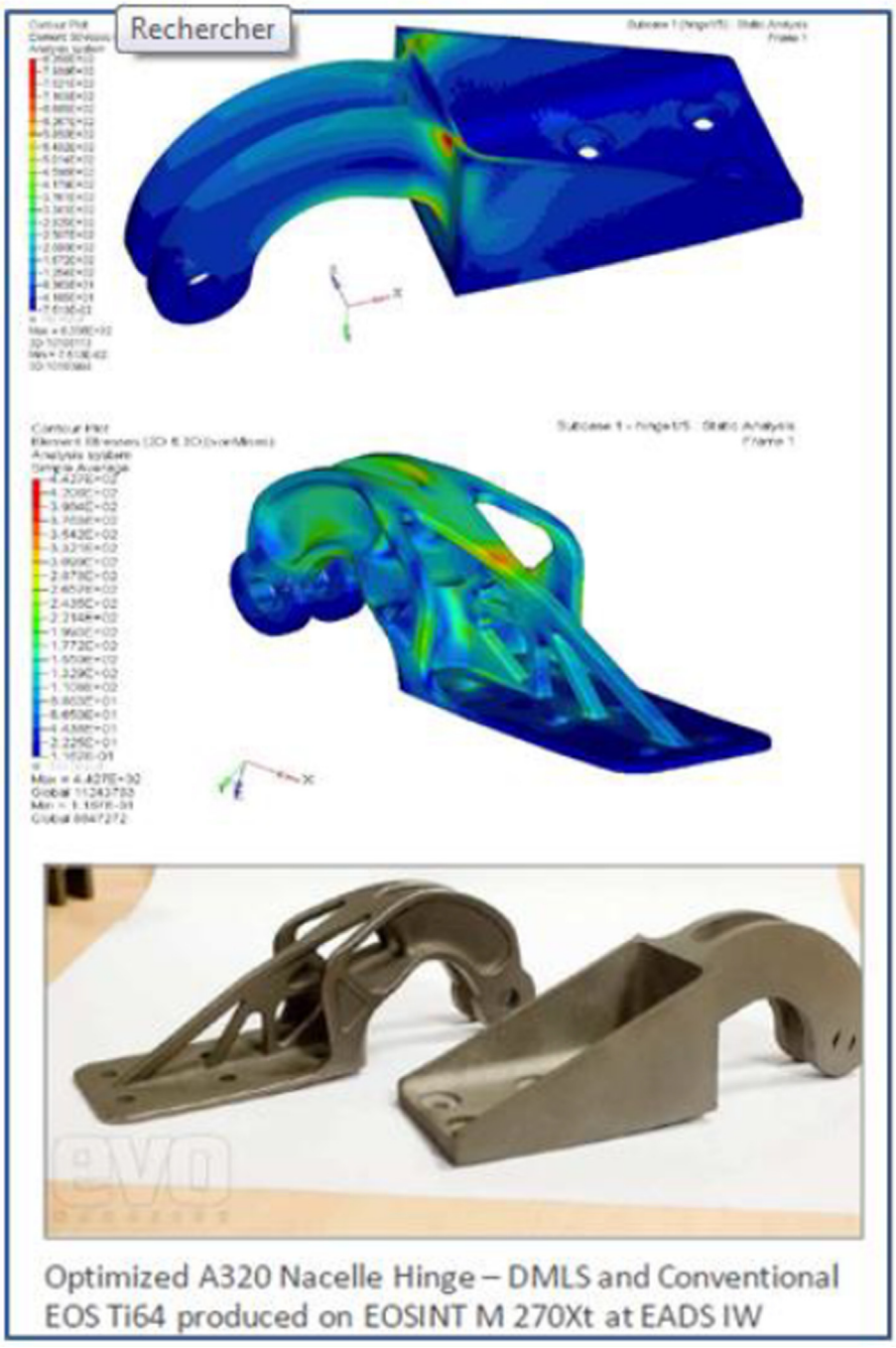


FIG. 1.1.15 – Topologically optimized hinge demonstrator for the A320 aircraft [10, 11].

material distribution in a room in the form of finite elements in a given volume taking into account the mechanical constraints. This approach allowed the creation of an optimized part 60% lighter.

A recent, a relevant example is that of the fuel injectors for the new LEAP-X engine from SAFRAN-GE (see figure 1.1.16) by laser fusion using a powder bed (EOS technology). This technology replaces the manufacturing and assembly of 20 parts by the production of a single part by additive manufacturing (19 injectors per engine). This induces a reduction of 25% and an increase in service life by a factor of 5). The GE (Morris Technologies) ALM research center is currently working on qualification, process optimization and non-destructive testing. GE announced an investment of 50 million euros in the Auburn and Alabama facilities to prepare the production lines (≈35–40 k injectors/year). Entry into service is scheduled for 2020.

Below is detailed the historical evolution of applications in the aeronautics/space industry according to the consulting company "Deloitte" – see figure 1.1.17.

In the same process, Avio Aero, an Italian subsidiary of the GE group in Cameri, has adapted electron beam technology (EBM) for the production of low pressure turbine blades made of titanium aluminide (γ-TiAl) for different LEAP-X, Genx and GE90 engines – in qualification stage. It has 11 Arcam machines, 2 EOS (DMLS) and an atomization tower (50 tonnes/year) to ensure the production of powders. Avio Aero forecasts growth in the number of machines installed at 60 – see figure 1.1.18.

The GE90 engine from the same group is the first engine to have composite materials in the blades (section of the Turbofan) and a part called T25 housing manufactured by ALM – see figure 1.1.19. The component is placed in the high

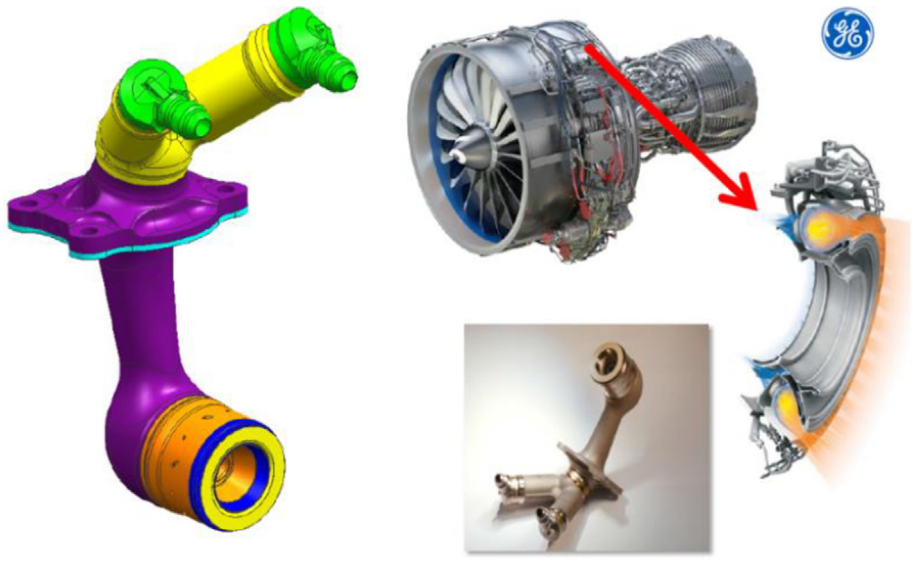


FIG. 1.1.16 – LEAP-X engine fuel injector produced by powder bed laser fusion (EOS) [12].

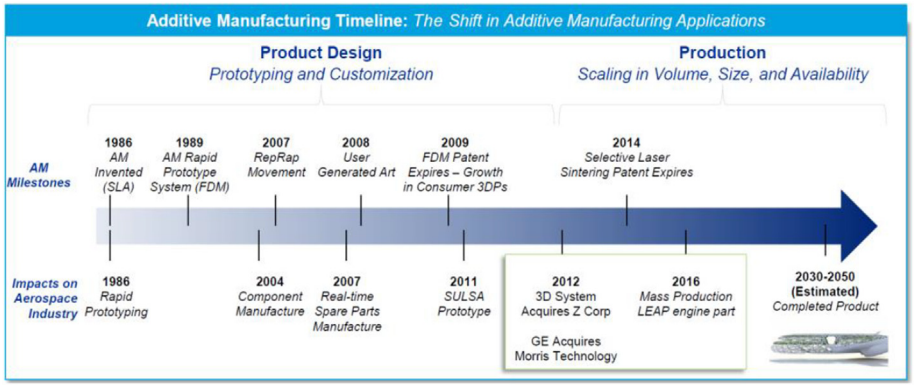


Fig. 1.1.17 – Chronology of the introduction of additive manufacturing technologies in the aeronautical field [13].



Fig. 1.1.18 – Avio Aero strategy [14].

pressure compressor allowing the protection of an electronic sensor – it was qualified in 2014.

Pratt & Whitney delivered Bombardier PurePower® PW15000G engines with components manufactured by ALM. Parts of the compressor stator and synchronization rings were produced by SLM.

Lockheed Martin explores the development of titanium-based components by powder-bed fusion by electron beam (EBM), wire deposition by free-form electron beam (EBF3 – the technology is shown in the following section) and by laser projection technologies.

Moreover, the British Air Force carried out the first flight test of various parts manufactured by ALM on the Tornado GR4 aircraft in 2014. The company BAE (British Aerospace) replaced several parts of the landing gear and cabin. This meant a reduction in manufacturing costs of £ 300 k.

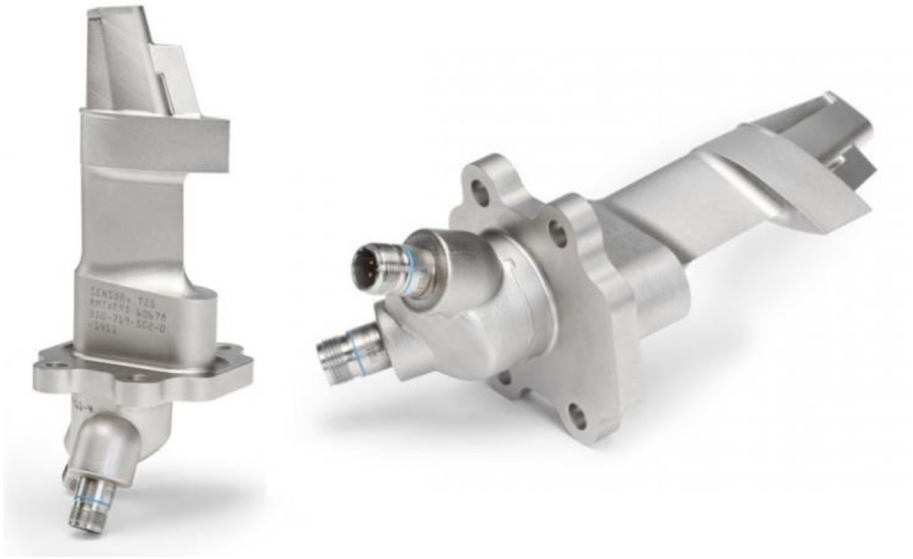


FIG. 1.1.19 – T25 housing component manufactured by SLM (GE Aviation).

In 2016, the SAFRAN group presented at the last "Paris International Air and Space Show" an auxiliary power unit of the Dassault Falcon 20 (APU SAPHIR 4.2) entirely manufactured by laser fusion in aluminum alloys and nickel. This project is piloted by the Monash Center for Additive Manufacturing (MCAM-Australia) in partnership with the Commonwealth Scientific and Industrial Research Oraganization (CSIRO), the University of Deakin and Microturbo – see figure 1.1.20.

Turbomeca announced in January 2015 that it will install fuel injectors manufactured by SLM on the Arrano and Ardiden 3 engines – see figure 1.1.21.

SAFRAN (Aircelle) has also planned for the application of Vinci cryogenic engines, the evaluation of ALM for the realization of collectors in Inconel 718. The SLM process is well adapted to the rates because it allows the reduction in the production cycle to 8 weeks between definition and the first part delivered. According to SAFRAN, the part has characteristics "close to those of the forged, much superior to those of the foundry". They are currently planning to build chambers based on copper alloys for the Vulcan and Vinci engines. They are in the development phase of different materials: Cu-Cr-Nb and refractory metals.

In 2014, NASA showed an example of the feasibility of producing injectors for Aerojet Rocketdyne RL-10 (liquid oxygen/hydrogen gas) engines. Indeed, different components have been manufactured by laser fusion (SLM) as well as by electron beam (EBM) – see figure 1.1.22.

1.1.1.4.2 Nuclear

In the nuclear field, there exist many potential applications for PWR (Pressurized Water Reactors) as well as for BWR (Boiled Water Reactors) as described in the



FIG. 1.1.20 – Auxiliary Power group SAPHIR 4.2.

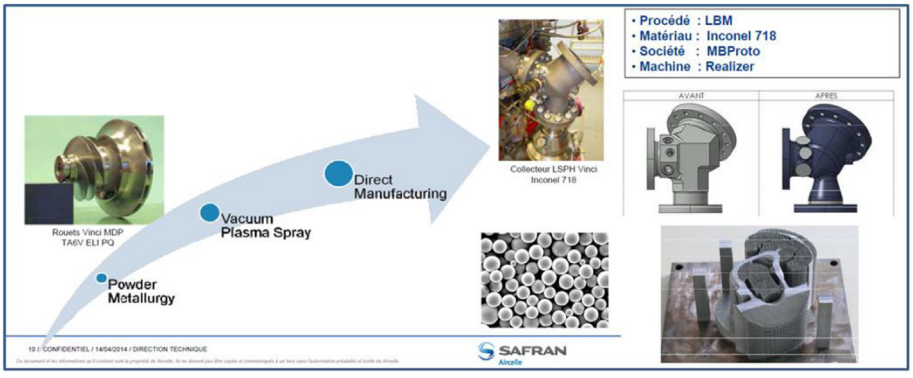


FIG. 1.1.21 – LSPH manifold for the VINCI engine [15].

figure 1.1.23. Majority of them are located in the core structure, which involves the stainless steels, nickel & zirconium based-materials.

In fact, there exist many challenges regarding the qualification that should be addressed in order to prove that additive manufacturing is suitable to the nuclear power operation plants as described in figure 1.1.24.

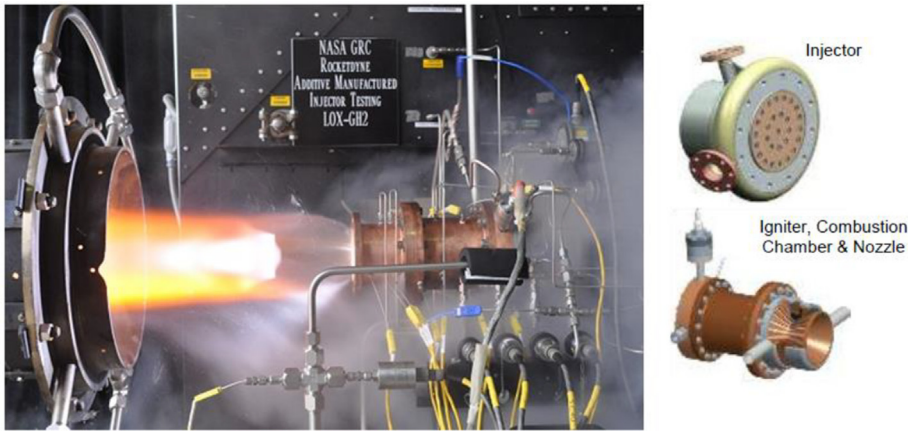


FIG. 1.1.22 – First test of an Aerojet Rocketdyne RL-10 engine injector manufactured by additive manufacturing (NASA Glenn Research Center) [16, 17].

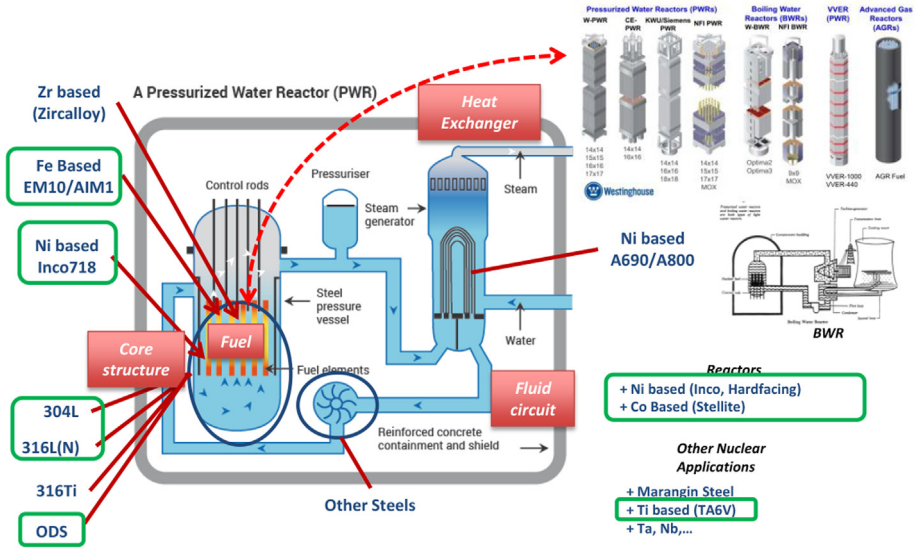


FIG. 1.1.23 – Potential application of additive manufacturing on the actual nuclear reactors.

With regard to the nuclear industry, in England Rolls & Royce and Sellafield launched a program on the application of additive manufacturing for the replacement of current components in the sanitation and dismantling sector. At the same time, the Nuclear National Laboratory in England was carrying out significant activity to assess new technologies such as powder bed fusion and spark plasma sintering for the manufacture of advanced nuclear fuels [18].

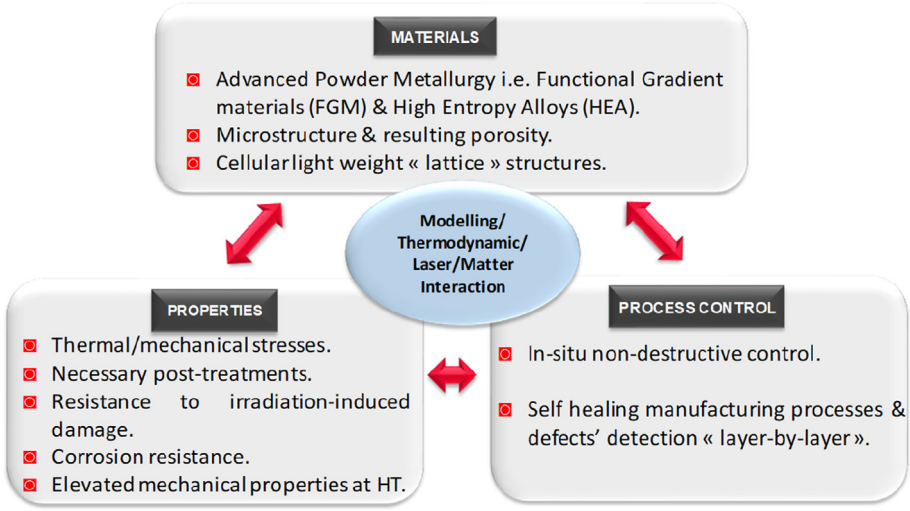


FIG. 1.1.24 – Principal challenges of additive manufacturing in the nuclear field.

Other more up-to-date metallurgical understanding studies are currently being supported by the United States Department of Energy (DOE) as part of a program called "Nuclear Energy Enabling Technologies (NEET): Advanced Manufacturing Methods (AMM)". Nuclear demonstrators, such as fuel assembly grids, have been manufactured by Lockheed Martin Space Systems Company using laser powder fusion technology (see figure 1.1.25). The final technical report of this study was published on December 31, 2015 [19].

DOE is also supporting additive manufacturing development of a new TRISO fuel concept for light water reactors (REL) through the company Free Form Fibers, LCC.

Another example in the nuclear field concerns the manufacture of components with complex shapes in FeCrAl steel reinforced by oxide dispersion (ODS) – see figure 1.1.26. This action is part of an approach led by the Oak Ridge National Laboratory, the Ames Laboratory and the University of Liverpool. Using the powder bed laser sintering (SLM) process, they demonstrated the technological feasibility of producing technological demonstrators.

The United States Department of Energy (DOE) also funded a study at the Lawrence Livermore National Laboratory (LLNL) for the evaluation of the SLM technique for the densification of ODS powders (Incoloy® MA956). The first results were published in 2015 in the "Journal of Nuclear Materials" 41. Weaker mechanical performance compared to forging due to the agglomeration of yttrium oxide particles was measured. A second publication by Chinese researchers on ODS steels produced by electron beam technique (EBM) was published in 2016 [24].

As mentioned in particular in the context of FP7, a second project called Oxigen (Oxide Dispersion Strengthened Materials for Additive manufacturing of High

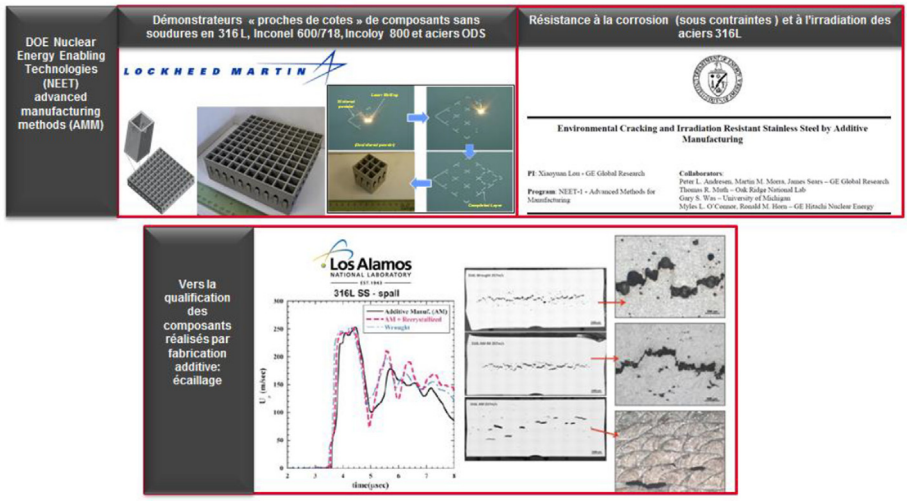


FIG. 1.1.25 – Examples of actions launched in the United States by the Department of Energy (DOE) as part of the Nuclear Energy Enabling Technologies (NEET): Advanced Manufacturing Methods (AMM) program [20, 21].

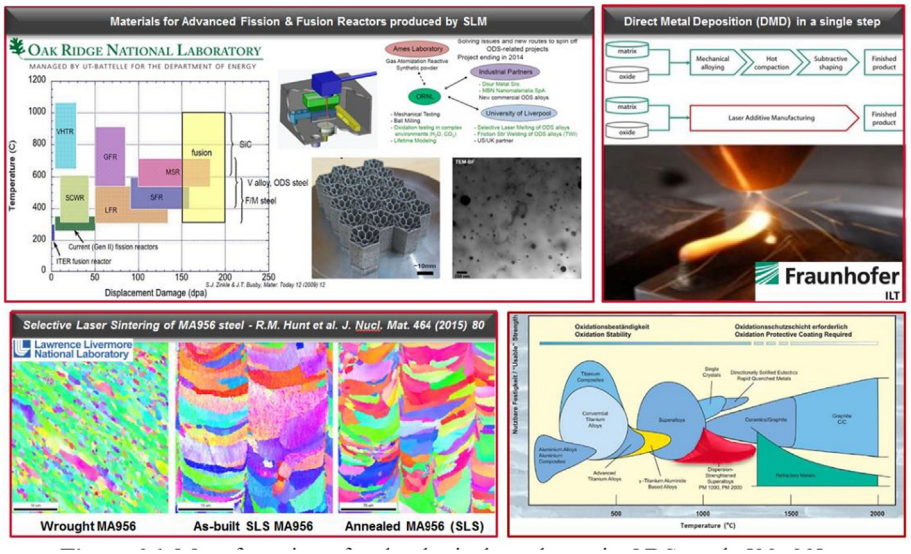


FIG. 1.1.26 – Manufacturing of technological mock-ups in ODS steels [22, 23].

Temperature in Power Generation), started in 2013, aimed to develop components in steels reinforced by dispersion of oxides based on Y_2O_3 (ODS) manufactured by additive laser fusion/projection manufacturing technologies – see figure 1.1.27.

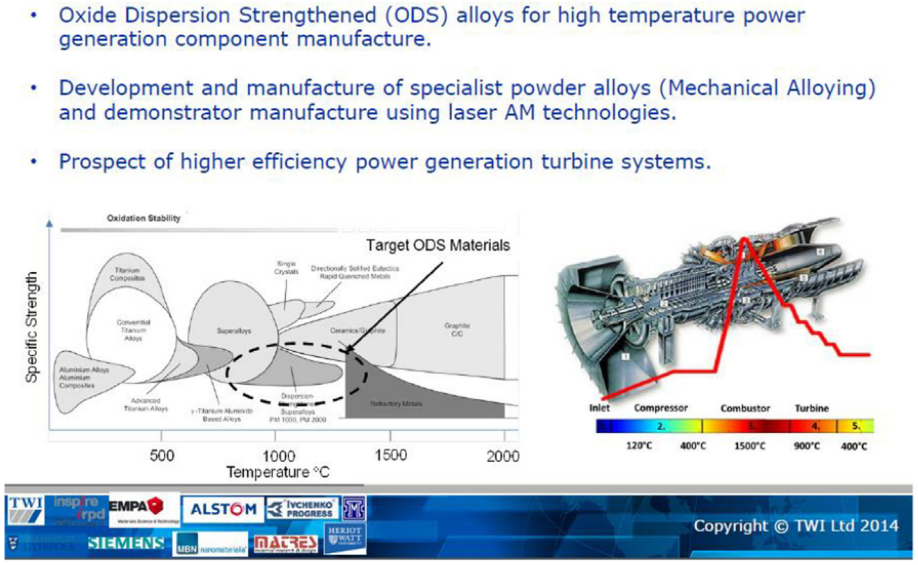


FIG. 1.1.27 – FP7 Project européen Oxigen (Oxide Dispersion Strengthened Materials for Additive Manufacturing of High Temperature in Power Generation) [25].

Research on direct manufacturing by laser projection (co-projection: metals and reinforcements) is also carried out by the Max-Planck and Fraunhofer ILT institutes (Aachen).

In India, "honeycomb" assembly grids for the Prototype Fast Breeder Reactor (Indian RNR-Na prototype) was manufactured by direct metal deposition – see figure 1.1.28a. Demonstrators of REP assembly grids for the CAP1400 reactor (Chinese evolution of the AP1000 "Westinghouse") produced by the laser fusion technique were also presented in January 2016 by the Chinese National Nuclear Company (CNNC) – see figure 1.1.28b.

In France, since 2016 CEA at the SAMANTA platform (Saclay's Advanced MANufacturing & Technological Applications) produced nuclear components in the frame of Sodium-cooled Fast Reactors (SFR) program. In the World Nuclear Event (WNE) 2016, CEA presented the first French additively manufacturing parts – see figure 1.1.29.

Thanks to additive manufacturing, it was possible to improve the manufacturing in one single step, thus avoiding milling and welding of complex nuclear grids.

In fact, the first prototype processed employing traditional techniques does not respect the dimensional tolerances (rails & chamfers manufacturing → difficult tool access). It is also possible to evolve into an internal conical cone.

CEA developed advanced nuclear materials such as ODS steels additively manufactured, such as Fe-14 Cr, traditionally processed by hot isostatic pressing and/or extrusion. As shown in figure 1.1.30, samples processed by selective laser melting exhibited a homogeneous distribution of only Y-Ti-O oxides ranging between few to 200 nm.

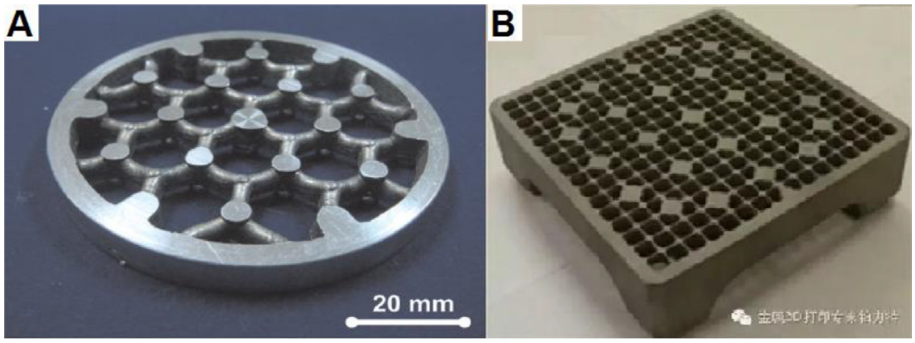


FIG. 1.1.28 – Nuclear component demonstrators produced by different additive manufacturing techniques: (a) "Honeycomb" assembly grid for the Indian concept of the future RNR-Na prototype and (b) Assembly grid belonging to the CAP1400 reactor [26, 27].

1.1.1.4.3 Alternative Energies

In the alternatives energy field, CEA has shown that is possible to produce *near-shape* components as developed at the POUDR'INNOV 2.0 platform, which proves that additive manufacturing is completely suitable with alternative energies (figure 1.1.31).

1.1.1.4.4 Defense

In the defense field, the National Nuclear Security Administration (NNSA) is currently conducting multidisciplinary research in the United States, piloted by the Lawrence Livermore, Sandia and Los Alamos laboratories for the "nuclear warhead" application – see figure 1.1.32. This study is centered on the understanding of metallurgy and on the development of new cellular materials (lattice structures). In particular, component manufacturing was transferred by Westinghouse to the Kansas City Plant (KCP) and Y12 sites. Thanks to the use of this new technology, they estimate a cost reduction of 85%, accompanied by a considerable improvement in mechanical properties. Similar studies are currently being carried out by the Naval Undersea Warfare Center (NUWC) belonging to the United States Navy.

Since the 90s, the American army (US Army) has used the direct metal deposition (laser engineered net shaping: LENS) developed by the Sandia National Laboratory, today marketed by the company Optomec, for repair (reloading) turbines of the Abraham M1 tank – see figure 1.1.33.

The United States Department of Energy (DOE) supported a collaborative study between the Oak Ridge National Laboratory (ORNL) and the company Lockheed Martin Aeronautics in order to evaluate the EBM technology for the realization of a support for the Lockheed Martin F-35 Lightning II aircraft: a reduction in the 33: 1 "buy-to-fly" ratio has been obtained, which means a reduction of 50% in terms of final cost (mainly related to machining) – see figure 1.1.34.

DOE also funds the ORNL for the enhancement of its neutronography skills for the observation of ALM components in its large research instruments, the spallation