Integration of new rapid manufacturing technologies for purpose of prototyping and preseries at Valeo thermal systems

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Integration of new rapid manufacturing technologies for purpose of prototyping and preseries at Valeo thermal systems

Master Thesis made towards obtaining the Master's degree in Mechanical Civil Engineer

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Abstract

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by

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Master Thesis in Mechanical Engineering

2015 – 2016

The last three decades have seen the emergence and evolution of new manufacturing technologies that offer the benefits of complexity, cost and especially speed. The most notable process is additive manufacturing, which involves the construction of an object layer by layer from its numerical model, the revenue it generates has exploded, from €1 billion in 2009 to over €4 billion in 2014 according to the Wohler report 2015. For a company like Valeo which invests heavily in research and development, it is essential to take advantage of these new technologies for their prototyping needs. Heat exchanger is one of the leading products of Valeo THS, for a new design of its plates, it takes up to 44 €k and 8 weeks to have the first functional parts using conventional technologies. While, with a judicious combination of new electromagnetic or hydraulic forming technologies, with tooling produced by additive manufacturing, costs can be reduced by half. However, the new design rules, still unclear do not allow to improve production lead times.

Résumé

Aide au projet d'intégration chez Valeo systèmes thermiques de nouvelles technologies de production rapide pour les prototypes et préseries

par

Armel WANE

Mémoire de Master Ingénieur Civil en Mécanique

2015 – 2016

Ces trois dernières décennies ont vu l'avènement et l'évolution de nouvelles techniques de fabrication, qui offrent des avantages de complexité, de coût mais surtout de rapidité. Le procédé le plus notable c'est la fabrication additive, qui consiste à la construction d'un objet strate par strate à partir de son modèle numérique, il a vu les revenus qu'il génère exploser, de €1 milliard en 2009 à plus de €4 milliards en 2014 selon le rapport wohler 2015. Pour une entreprise comme Valeo qui investit énormément dans la recherche et le développement, il est essentiel de tirer partie de ces nouvelles technologies pour ses besoins de prototypage. Pour une nouvelle conception de plaques d'échangeurs thermiques, l'un des produits phares de Valeo THS, il faut jusqu'à 44 €k et 8 semaines pour obtenir les premières pièces fonctionnelles par les procédés conventionnels. En combinant judicieusement les nouvelles techniques de formage électromagnétique ou hydraulique avec un outillage réalisé par fabrication additive, ce coût peut être réduit de moitié. Toutefois les nouvelles règles de conception encore mal connues ne permettent pas d'améliorer les temps de production.

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List of Acronyms

AM	**A**dditive **M**anufacturing
ASTM	**A**merican **S**ociety for **T**esting and **M**aterials
CJP	**C**olor **J**et **P**rinting
CLAD	**C**onstruction **L**aser **A**dditive **D**irect
CLIP	**C**ontinous **L**iquid **I**nterface **P**roduction
CNC	**C**omputer **N**umerical **C**ontrol
DLP	**D**igital **L**ight **P**rocessing
DMD	**D**irect **M**etal **D**eposition
DMT	**D**irect **M**etal **T**ooling
DED	**D**irect **E**nergy **D**eposition
DMLS	**D**irect **M**etal **L**aser **S**intering
DWT	**D**irect **W**rite **T**echnology
EBAM	**E**lectron **B**eam **A**dditive **M**anufacturing
EBM	**E**lectron **B**eam **M**elting
EHF	**E**lectro **H**ydraulic **F**orming
EMF	**E**lectro **M**agnectic **F**orming
FDM	**F**used **D**eposition **M**odeling
FFF	**F**used **F**ilament **F**abrication
FTI	**F**ilm **T**ransfert **I**maging
HVAC	**H**eating **V**entilating and **A**ir **C**onditioning
ISO	**I**nternational **O**rganization for **S**tandardization
LDW	**L**aser **D**eposition **W**elding
LENS	**L**aser **E**ngineering **N**et **S**haping
LMD	**L**aser **M**elting **D**eposition
LOM	**L**aminated **O**bjet **M**anufacturing

LS	**L**aser **S**intering
ME	**M**aterial **E**xtrusion
MJP	**M**aterial **J**etting **P**rocessing
PAEK	**P**oly**A**ryl**e**ther**k**etone
PEEK	**P**oly**e**ther**e**ther**k**etone
POC	**P**roof **O**f **C**oncept
PSL	**P**aper **S**heet **L**amination
RP	**R**apid **P**rototyping
RT	**R**apid **T**ooling
RM	**R**apid **M**anufacturing
SGC	**S**olid **G**round **C**uring
SHS	**S**elective **H**eat **S**intering
SLA	**S**tereo**l**ithography **A**pparatus
SLM	**S**elective **L**aser **M**elting
SLS	**S**elective **L**aser **S**intering
SSB	**S**olid **S**tate **B**ond
SWOT	**S**trengths **W**eaknesses **O**pportunities **T**hreats
THS	**TH**ermal **S**ystems
TTM	**T**ime **T**o **M**arekt
UAM	**U**ltrasonic **A**dditive **Manufacturing**
3SP	**S**can **S**pin and **S**electively **P**hotocuring

Thanks to C. Chevallier and G. De Pelsemaeker for allowing me to be part of your warmful team,

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Chapter 1

Introduction

The group VALEO is one of the worldwide leader in automotive equipments. It develops and offers innovative, intelligent systems and services to almost all automotive constructors.
Products offered by Valeo are in constant improvement and are a response to current and future problems in the automotive world. As shown in the following figure 1.1, the Valeo main mission is to make driving greener and more intuitive. To achieve its objectives, Valeo invested hugely in creativity and innovative technologies . Thus in 2014 more than 10% of total original equipment sales amounted were reinvested in its research and development teams across the world [5].

FIGURE 1.1: VALEO Missions

1.1 Innovation

Joseph Schumpeter defined Innovation as [6] "*the development or adoption of new concepts or ideas, and/or the new or adopted ideas themselves as well as the successful exploitation of new ideas*". Creativity is limited to having the ideas, while innovation is its implementation. Creativity emerges when an innovator develops an idea that meets a need. Successful exploitation and development of new ideas can lead to many improvements, launch of new products, improvement of actual products and production methods, carrying out a better organization of the industry, and many others.

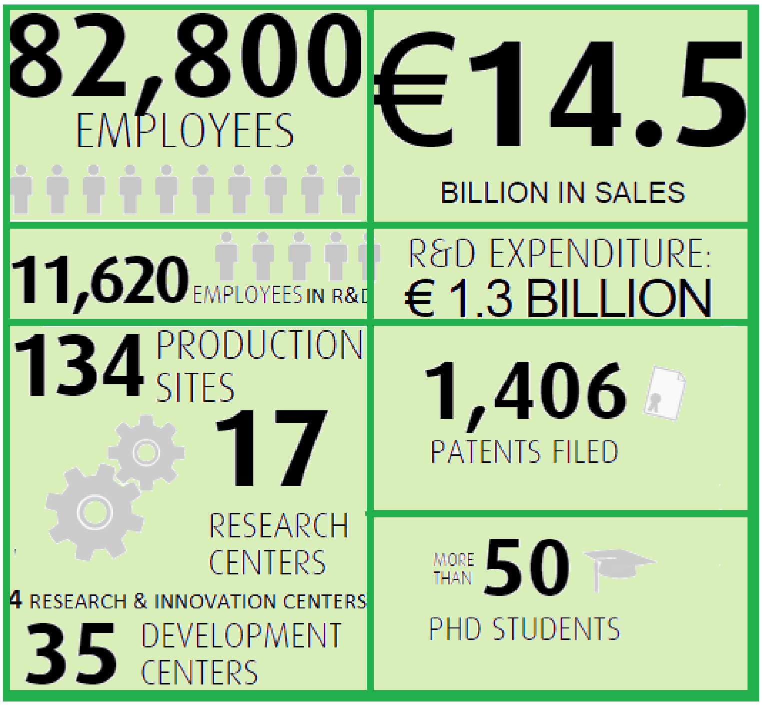


Figure 1.2: Valeo's key figures, December 2015

1.2 Innovation in product development process

The last three decades have seen the emergence and development of many new rapid production processes, including additive manufacturing. This has been made possible thanks to advances in computer tools but also with growing market demand for customized products, complex shapes and with different materials. Apart from the possibility of more complex parts, these processes also allow a significant reduction in costs and production lead time. The figure 1.3[1] rises a brief comparison between a traditional process (subtractive manufacturing) and a new process (additive manufacturing), it appears clear that we can not yet do without conventional methods, however, the benefits and regular upgrades brought by these new processes require some attention. According to the Wohlers report 2015, an estimated 526 industrial AM systems were sold in 1995 to reach nearly 12,850 in

[1]http://chronicle.kennametal.com/, Accessed 2016 May 02

2014 [7]. Some references even speak of a probable industrial revolution, and think that if the AM continues to grow at this rate until its apogee, current production methods will quickly become obsolete.
From Figure 1.3, it also appears a certain compatibility between these processes. If one benefits from each of their advantages, we could totally improve the complete production chain. By the way, in our days one sees more and more hybrid systems that combine these two technologies. They are not yet open to everyone because of their high prices, but promise virtually endless capabilities.

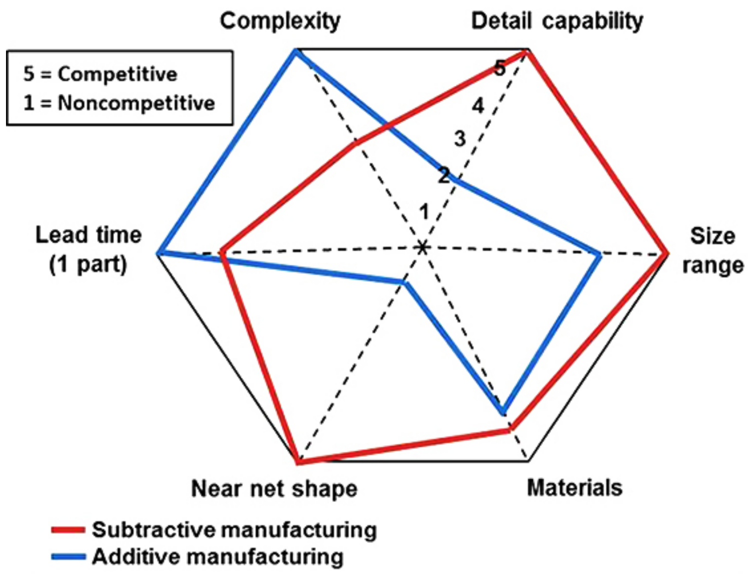


FIGURE 1.3: Additive vs subtractive manufacturing [*chronicle.kennametal.com*]

For any manufacturer, even more in the automotive world where competition is fierce, the timing of the placing on the market of its product is very important. In general it is more interesting to launch them as soon as possible in order to reduce development costs and generate the most profit. This is materialized in the figure 1.4 above, the same product with a quick marketing (blue curve), generates more profit than the product placed a bit later (red curve).

Product development process until its place on the market, include many steps (see *figure*1.5) and each of these steps has numerous iterations. For VALEO, almost all iterations of the development and test steps usually required the conception of prototypes, for visual communication between engineers and for functional testing. The realization of some of these prototypes can take up to eight weeks, because of the complexity of the parts which often requires the realization of special tools for their production. This generates significant costs and is a hindrance to innovation. For these purposes, the AM takes all its interest in being able to

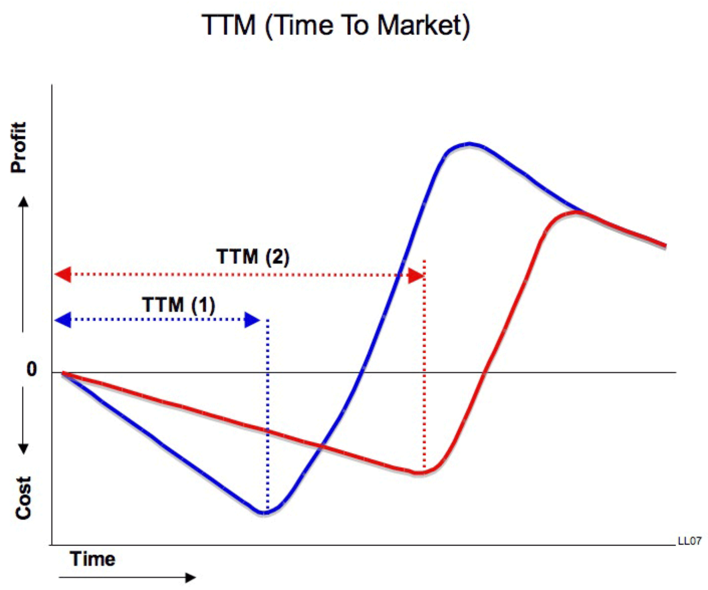


FIGURE 1.4: TTM: interest of reducing development time [*www.andreoletti.com*]

potentially reduce to a few days these lead times, and has the ability to reduce these costs.

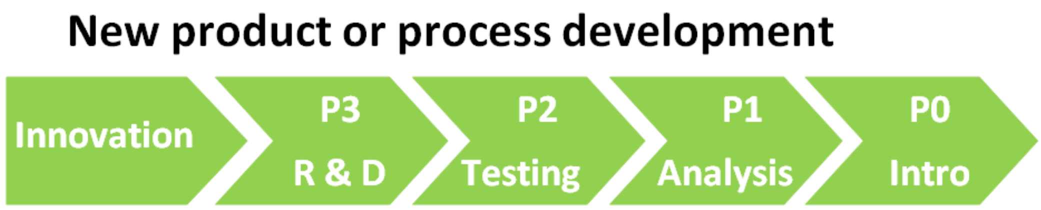


FIGURE 1.5: VALEO product development process

1.3 Working plan

At VALEO, the integration of new processes is done by using POC method. The goal is to take a product in its advanced development phase, which usually is manufactured in a conventional way, and evaluating the possibility of realization through new processes (a combination of several of them thereof may be necessary). If the conclusions are interesting, we move to the implementation, otherwise we retain them for future needs.

1.3.1 Case study: innovative process to form an evaporator plate

We worked on the part called "TC" (see *figure* 1.6), which is a battery cooling plate of 0.27 *mm* wall thickness and in aluminium 3003. It is typically made by stamping and ask up to six successive posts to bring the sheet progressively to its final form. The manufacturing of dies by conventional machining and tools required takes some time, which depends on its complexity. In our case it takes at least eight weeks to get the first functional prototypes. Production costs are also huge. For each of these six tools, VALEO spends as much as €4.7 K, making a total of €28 K for the whole and this represents only 80% of the overall cost of the complete stamping tools. Therefore any improvement or design flaws can have important consequences, we will come back with more precise details on this topic in the *Chapter* 3.

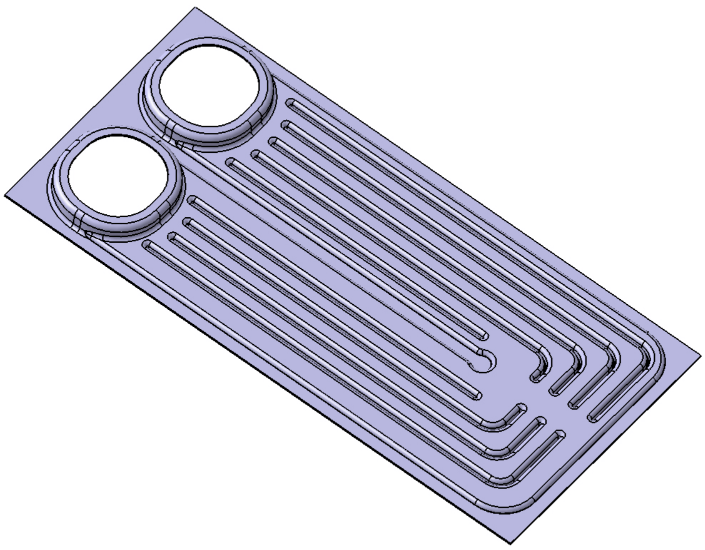


FIGURE 1.6: TC evaporator plate for POC

1.3.2 Work specifications

To provide an innovative response to this problem, and to establish a basis on which to rely in future challenges, we undertook a thorough study of new processes and those in development.
In the following *Chapter* 2, a global presentation of the new rapid prototyping technology will be given. Particular attention will be paid to the additive manufacturing, given its wide range of action and the extent of its processes.

To reach a comparable solution in terms of time and cost regarding the conventional solution, which is currently still problematic, we took as a constraint to keep a relatively close design and the final part must be in VALEO standard materials. These two assumptions will have a broad reach on our research, because as we shall see in dedicated chapters (*Chapter* 4: additive manufacturing, *Chapter* 5: magneto and hydro-forming), the advantage of such processes is essentially in the use of a design and material which are theirs.

1.3.3 Innovative response

The direct additive manufacturing of the "TC" plate being no longer possible, mainly because of the material, we then decided to study the following ways:

- Making a single die by machining and then use it to Hydroforming the "TC" plate (see section 6.4),
- Making a single die by machining and then use it to magneto-forming the "TC" plate (see section 6.3),
- Manufacture of a single die by additive manufacturing (see section 6.2.3) and then use it to magneto-forming the "TC" plate,
- Topological optimization of the matrix and followed by additive manufacturing (see section 6.2).

Their common interest lies in the fact that one can use a single die rather than 12 and therefore already have certainty on the reduction of costs and lead time associated with their obtention, generating simultaneously a greater flexibility. In *Chapter* 6, the taken actions are clearly highlighted and one can fine the different results obtained.

1.3.4 New processes guide lines

This work aims as well to be a platform for informations and advices on the new processes. It thus can be found in *Chapter* 4 an analysis of the various additive manufacturing standard processes and their available materials. *Chapter*5 is meanwhile reserved to magneto and hydroforming which could be the future alternatives to stamping.

Chapter 2

State-of-the-art of rapid manufacturing processes

The innovation process can be described as the researcher, the creation and the implementation of new ideas or processes in a part or the entire development and production chain of a product. with the goal of optimize parameters such as lead time, cost and quality.

Our work is oriented mainly to the latest technologies which can create physical prototypes or real parts rapidly and directly from digital model data (see *figure* 2.1). Theses technologies are often called *Rapid Prototyping* (RP)[1], because at the start, in the early 1980's the output were not strong enough to be end-use product.

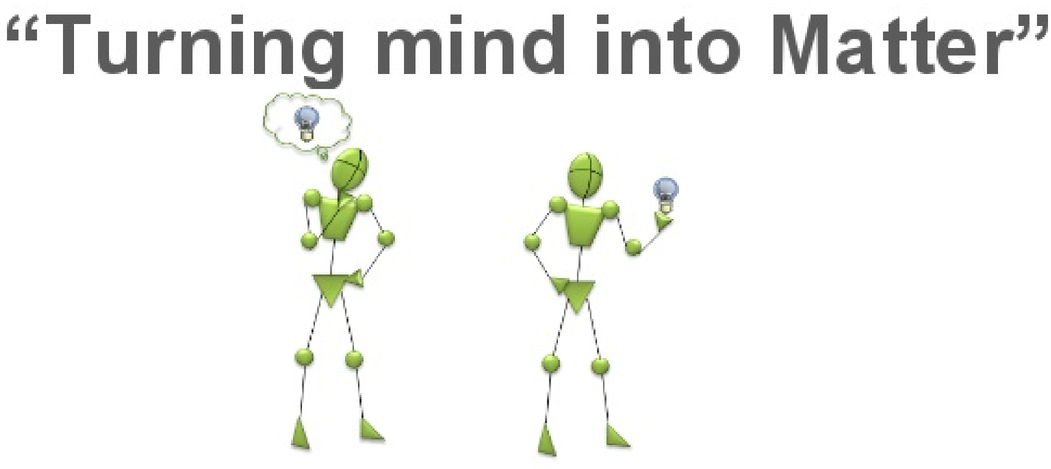


FIGURE 2.1: VALEO innovation process

The level of development of new processes, materials and software have made it largely possible to manufacture functional parts in good material, at almost all levels of the production chain of a product. For example, a survey (see *figure* 2.2) by *Wohlers & Associte* [7], conducted among 127 companies representing over 100,000 users and Costumers, noted that in 2015 over 30% of the products manufactured by AM were the functional parts.

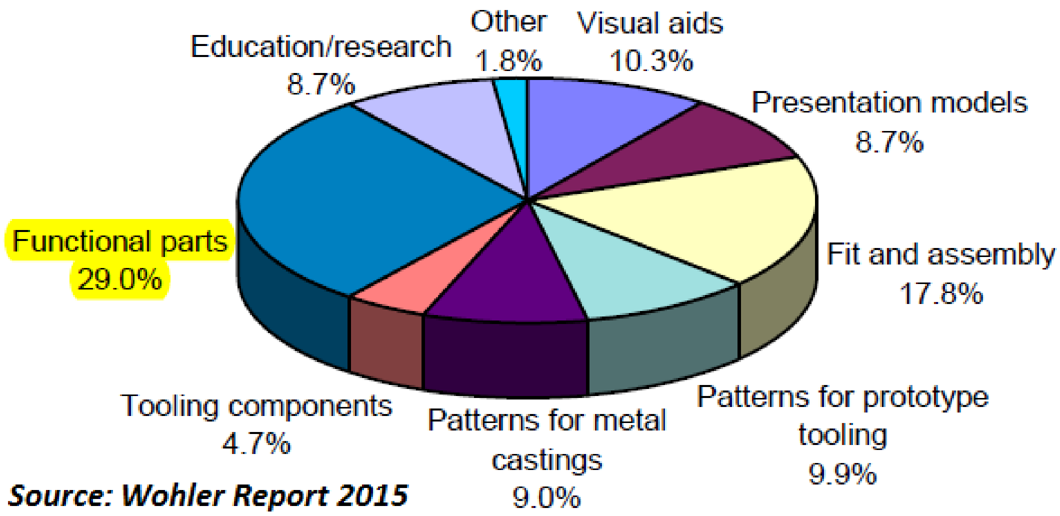


FIGURE 2.2: Use of additive manufacturing parts (courtesy: *Wohler report 2015*)

This is very interesting but one will see later in this report that these new methods can bring constraints that can lead to a complete re-design of the product, or the development of a new material. Prior to integrate them into any production process, it is important to understand the benefits and limitations. At this stage, it is important to clarify that the new RP processes do not include only AM technologies but also CNC machining, and many others.

2.1 CNC machining

The RP technologies contain the subtractive technologies (CNC machining) and additive technologies (SLA, SLS, ...). Apart from the fact that for the subtractive technology, one starts with a block from which the material is removed to obtain the final object, whereas for the additive, the material is added layer after layer as for a sandwich, the main difference between the two being the necessity of a process planning for CNC machining while for the other everything can be done automatically, once the CAD file is transmitted to the machine. Despite today's software that generate automatically and accurately this process planning, the problems of complex part for the fact that is a machining based process (special tools, lots of waste) makes that they are not too interesting for single or small series manufacturing.

For relatively simple geometry parts, this method has several advantages in terms of richness of materials, almost all good materials, steels, polymers and ceramics currently used in production are machinable, apart flexible and elastic polymers. The quality of finish and accuracy are also its strengths, especially when the cut is made at high speed or by laser. This process ofers especially a good repeatability.

The American company *Proto Labs* is a pioneer in this domain, it offers an online service that allows the quotation and adjustment of parts before machining. They manufacture only single parts and small series, the machining code is generated automatically and the lead time range from some hours to several days.

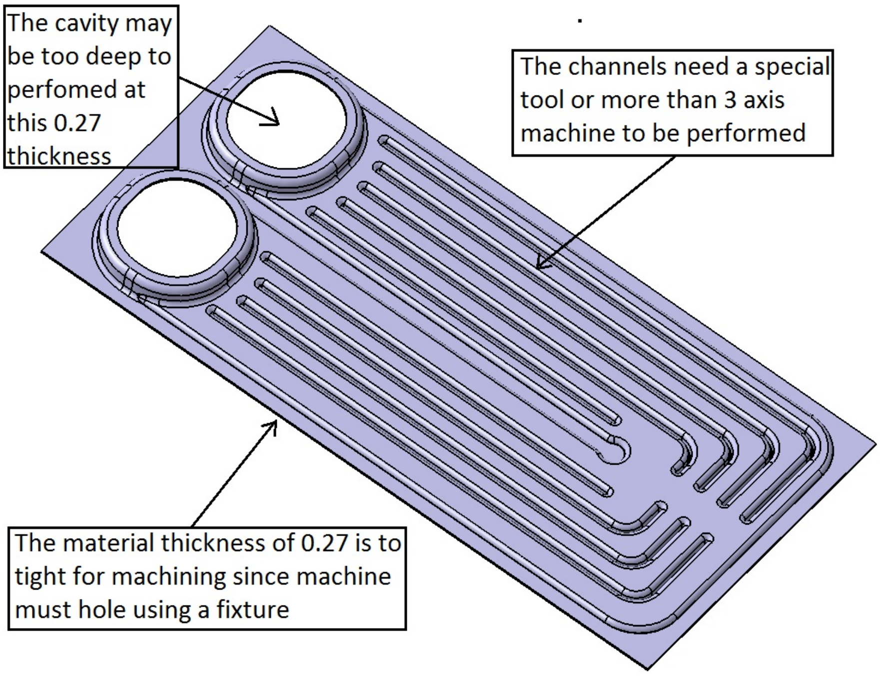


FIGURE 2.3: Features that represent problems using CNC machining

Regarding our "TC" plate (see *figure* 2.3), being given its thickness of 0.27 and complexity of channels, it is not possible to consider its direct production through this method. The question may arise, however, for the realization of the forming die (see *section* 6.3.2).

2.2 Electromagnetic forming and hydroforming

The electromagnetic forming commonly known as "*Magnetoforming*", uses as its name suggests, the Lorentz force generated by a magnetic field. At the other side, hydroforming involves the use of water pressure or shock wave generated by an electric arc between two electrodes (electrohydraulic forming). The resulting efforts of these phenomena are intended to shape or assemble metal sheets. They place the material in a transient state, semi-solid semi-liquid, for a short time (a few milliseconds). This allows a deformation of the material without tearing, but also without residual stresses, and therefore without elastic return. Especially as this forming processes does not involve a significant change in temperature.

The interest of these processes for VALEO lies in their abilities to form metal sheets in good materials with fine details, increasing depths and sharp edges, all that at lower cost and shorter lead time, when compared to conventional stamping. A more details analysis of these processes is given in the *Chapter* 5.

2.3 Additive manufacturing

Additive manufacturing more commonly known as 3D printing, encompasses all production processes by adding material. From a digital model of an object, the physical model is built layer by layer, cordon by cordon or point by point automatically without process planning.
These processes, which are thriving today are in process development for over 50 years, the science fiction author *C. Clarke was* already talking about "*Replicator*" in 1954[1] for naming these 3D object reproduction processes. The first patent was filed however on solid imaging process known as stereolythography (SLA) in 1983 by the American *Chuck Hull*[2]. This process consists of locally polymerize (using an ultraviolet (UV)) a thermoset liquid resin into a vat, layer by layer to obtain a solid object. Be noted that thereafter the first SLA systems have been commercialized in the late 1980s by the company *3D System* for which he works and whom he was one of the founders. It was followed by several important steps, which saw the birth of new processes, materials, until today, *figure* 2.4.

[1]https://www.theguardian.com/, Accessed 2016 May 08
[2]http://www.3dsystems.com/30-years-innovation, Accessed 2016 May 08

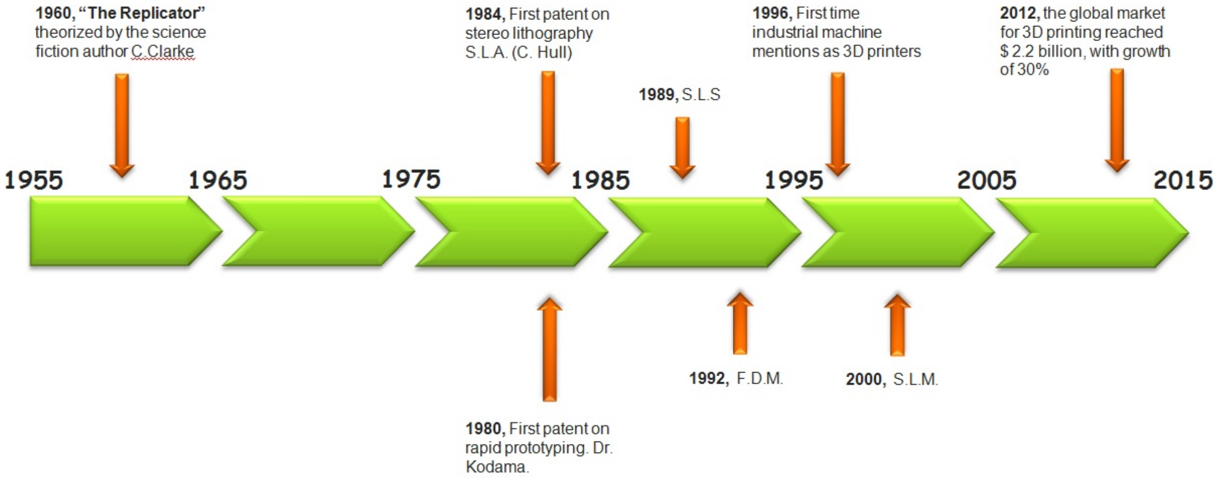


Figure 2.4: History of AM

Permanent changes in these processes and lack of awareness of users has led to many confusions in terms of denominations and the characterization of the elements in the additive world. Fortunately since 2009, collaboration between *ASTM* (ASTM F42 Committee) and *ISO* (ISO Technical Committee 261) gave birth to a standard [8] to facilitate dialogue and communication. Thus in this standardized way, **additive manufacturing** technology is defined as "*process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methods. Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication*".

The term **3D printing**, is for its part defined in standardized way as " *the fabrication of objects through the deposition of a material using a print head, nozzle, or other printer technology* ". A difference is then to be made between these two terms, with a more restrictive scope for the term 3D printing. However, we note that it remains the most known and is generally used instead of additive manufacturing; in particular associated with machines that are low end, cheaper and/or with restricted overall capability. A Google search this May 27, 2016 on the AM-term, and others words frequently and synonymously used, had produced the following results on figure 2.5.

2.4 AM execution process

As we will see in *Chapter* 5, there are 7 different standards of additive manufacturing technologies. These technologies are distinguished for the most by the

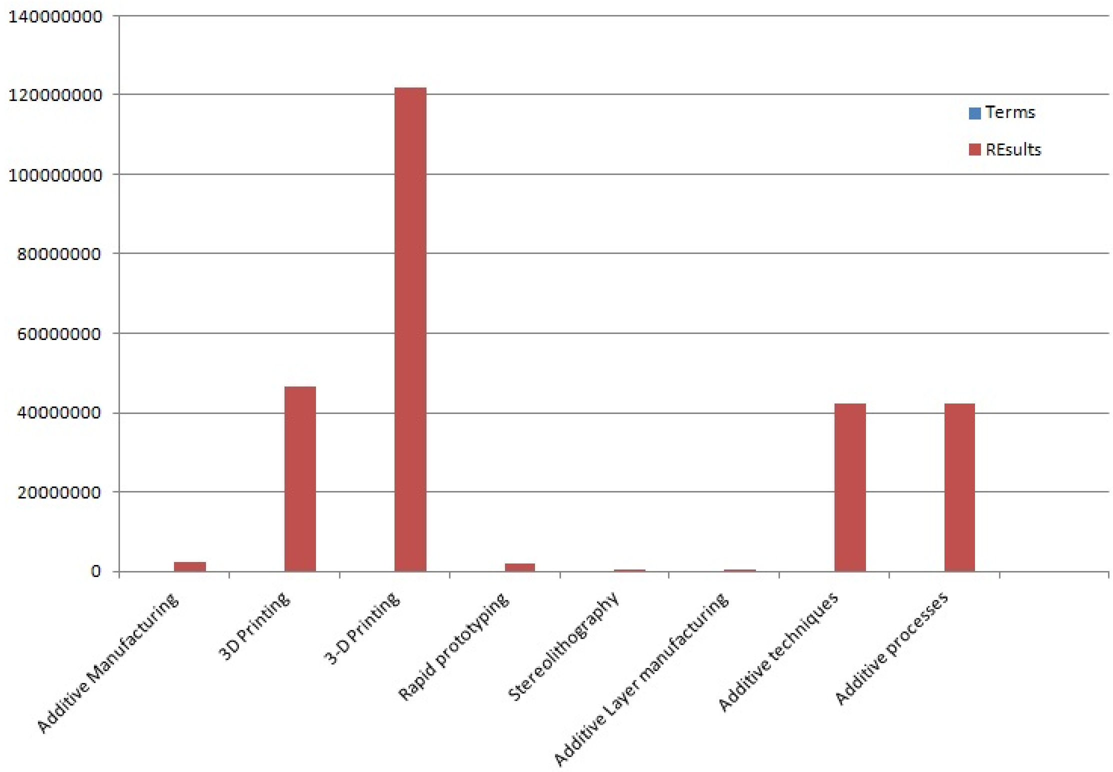


FIGURE 2.5: Google results of AM synonyms [May 27, 2016]

method of making and bonding layers. The main stages of executions from the digital model to the physical one, however, remain the same.

2.4.1 From numerical model to STL file

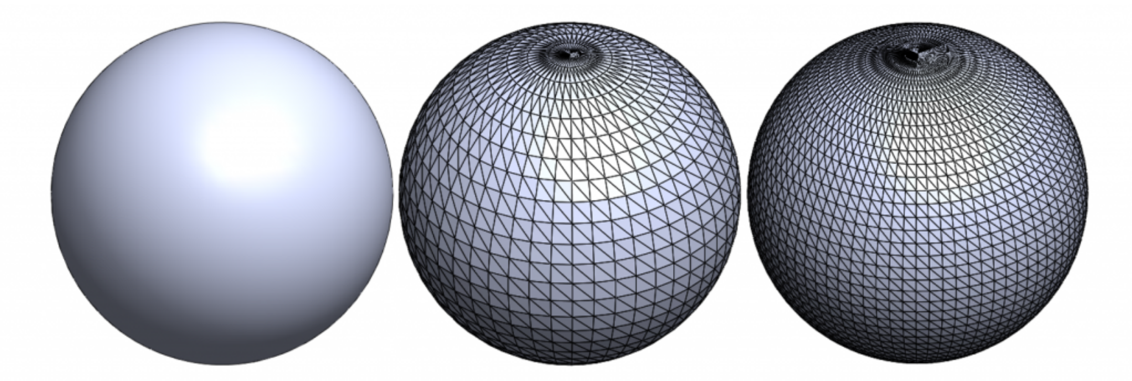


FIGURE 2.6: STL file: different facet size [*blog.gxsc.com*]

A numerical model representing the object to realize is necessary, at least its external surface representation. This can be achieved through a CAD program or be scanned directly from a real model (reverse engineering). This CAD file must then be converted into STL format (broken down logically into a range of small triangles called facets) in other to be readable by most production machines. An "STL" file, which is becoming de facto standard format in AM industry, consists of a set of facet data. Each facet is uniquely characterized by three vertices (corners) and by an orthonormal vector (a line perpendicular to the triangle with a unit length). This file is used to calculate the volume of the model and the broken down into a series of layers. More the facets will be numerous, most the model will be accurate (see *figure* 2.6) but bigger will be its file size.

2.4.2 Machine setting

When the "STL" file is transferred to the machine, there are some manipulations to set up the type of printing, the speed, the materials, the resolution we want for the physical model, the building orientations, and many others. These parameters are usually set according to the use of the final product. For example, if it is a visual object, one will only pay attention to the layer thickness for a better final appearance. While for a functional parts, it should also take into account the building orientation on which relate directly the mechanical properties.

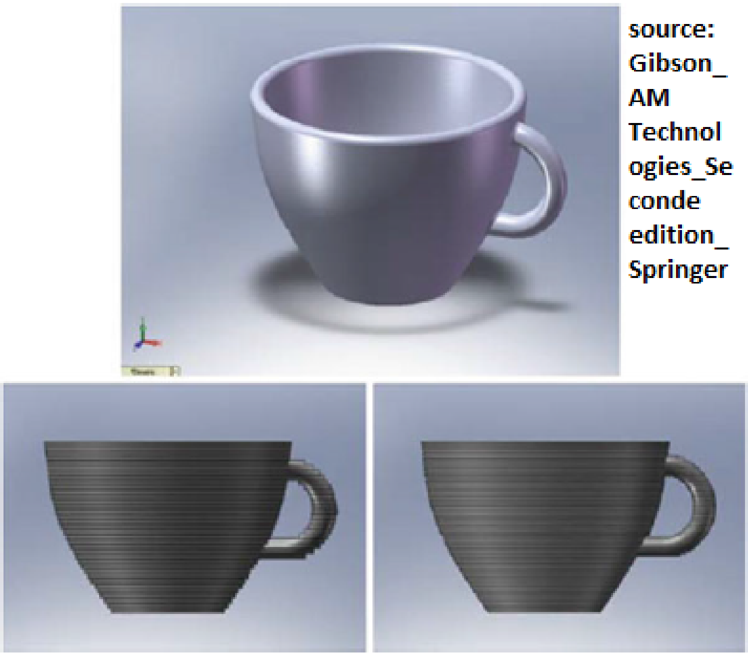


FIGURE 2.7: Effect of layer thickness [1]

2.4.3 Build

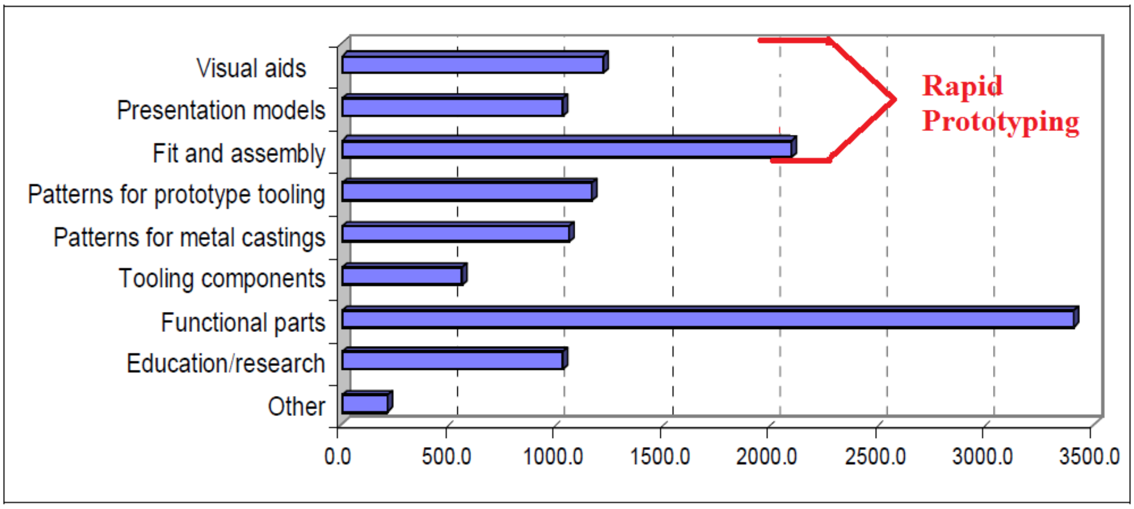
The construction process is done automatically and without planning process. It just requires to ensure that the necessary amount of raw material is present.

2.4.4 From removal to post processing

Once construction is completed, the part should be cleared if necessary of its support structures and of the uncured resin or powder. Such residues can in some cases be recycled for the next printing. The manufactured parts at the exit of the machine can typically require manual post processing or other: UV heating and baking for liquid polymers, sanding for better surface finish, impregnation to improve the density, painting to put the right colour or others.

2.5 Rapid Prototyping (RP)

Additive manufacturing processes can be used today in different stage of the production chain. There are three major classes of processes, which is distinguished from each other by the final function of the part made.



Source: Wohlers Associates, Inc.

FIGURE 2.8: Final function of AM parts (*Wohler report 2015*)

So for products intended for an intermediate physical representation during the design of a product, one speak of rapid prototyping. In a standard manner, ASTM [8] defined this term as the " *additive manufacturing of a design, often iterative, for form, fit, or functional testing, or combination thereof* ".

If we take another look at the analysis on the use of additive manufacturing parts from Wohler detailed above, and in the *figure* 2.8, we realize that rapid prototyping overall remains the first need for AM adherents, with more than 36, 8 %

cumulative. Three applications are concerned here: visual aids, presentation models and fit for assembly.

Prototyping is a very important step in the development of a new product. It lets you communicate designs intentions and clarify engineer drawings ambiguities. With rapid prototyping one can drastically reduce iterations and optimization lead time. Today some 3D printer manufacturers announce photo-polymer printing at speeds up to 2 cm/min[3].

These savings in time but also costs are certainly the main reasons for the success of RP compared to other applications. The limitations at the level of the mechanical properties and the diversity of materials also form a barrier to the development of the other applications. However the most important restraint is the deficiency of experts and lack of knowledge of this processes and its materials available, which creates an absence of overall vision and integration of AM at all levels of the production chain within companies.

2.6 Rapid Tooling (RT)

Although this is slow, people are in the process of awareness of AM and its benefits, but above, that there could have applications other than prototyping. So the one called RT (rapid tooling) is defined by ASTM, as " *the use of additive manufacturing to make tools or tooling quickly, either directly, by making parts that serve as the actual tools or tooling components, such as mold inserts, or indirectly, by producing patterns that are, in turn, used in a secondary process to produce the actual tools* ". RT is more and more widely use because it allows to reconcile the advantages of AM in terms of complex shape and lead time reduction, with a greater choice of final part materials and for larger series. We can now directly make complex and lightweight molds or matrices (Direct tooling) equipped with conformal-cooling channels,(see *figure* 2.9[4]). We can also print master pattern for silicone rubber tooling or investment casting (Indirect tooling). All this with a very short iterations time.

[3]www.prodways.com, Accessed 2016 May 28

[4]www.hrsflow.com, Accessed 2016 May 28

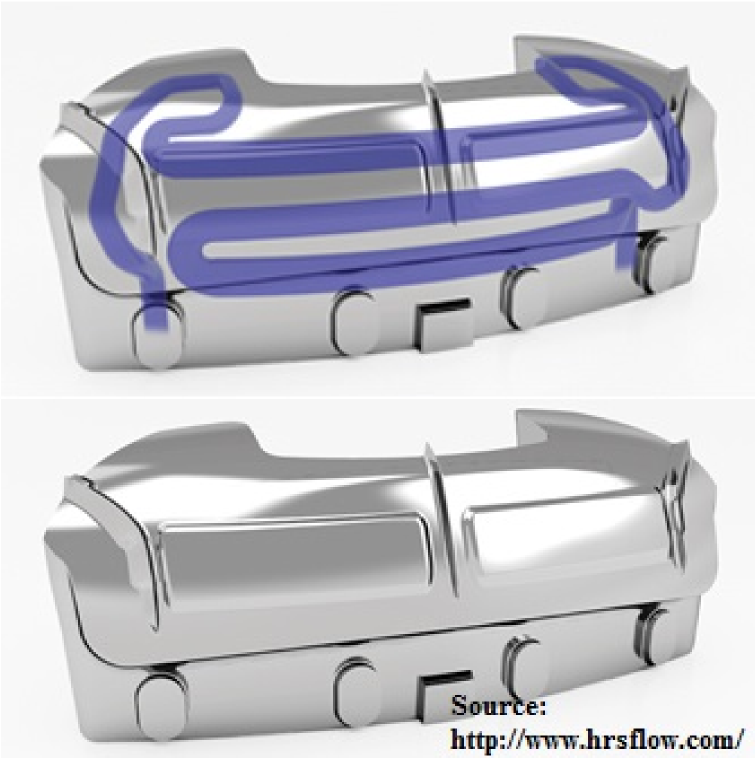


FIGURE 2.9: Tool with conformal cooling channels [*www.hrsflow.com*]

2.7 Rapid Manufacturing (RM)

The additive manufacturing application with the greatest development is certainly the direct manufacturing of end-use parts, usually called "Rapid Manufacturing". AM processes used are exactly the same as those of the previous applications, with the only difference that here we will produce functional parts and usually in series. These series are relatively small (up to 30000 parts) compared to series which may be expected with conventional subtractive, molding or forming processes. For reasons of cost and lead time, we shall see later that RM is not profitable for parts with conventional designs. However it is still worth for certain business sectors such as Aerospace, dentistry,..., because they involve small and medium-size production and parts are usually personalized with structure lightened with complex shapes.

2.7.1 Aviation

For example in aviation, the big group *GE Aviation* is developing a fuel injector (see *figure* 2.10) for their LEAP engine that is 25 percent lighter and more complex than its counterparts and combines into one part what was assemblies in multiple

FIGURE 2.10: Leap fuel nozzle from GE Aviation [*www.geaviation.com*]

parts in the past[5]. They, therefore, come with a gain of time and money. However what is worth noting is that the part has been designed taking into account the manufacturing process, in order to integrate its features. To be effective, additive manufacturing must be thought from the basic design of a product.

2.7.2 Automobile

In automobile, it's racing cars that integrate the most AM. Several parts of structure and even transmission are already done by printing. In 2012 the Belgian team "Formula group T" built the first 3D printed car (see *figure* 2.11[6]). The chassis of more than 2m long was printed in a single block on the machine Mammoth Stereolithography from Materialise (see *figure* 2.12), in just 3 weeks. they have been able to integrated clips, connection points and intelligent air cooling system to lead cold air from the inlet sidepods directly to the heat source[7].

2.7.3 Personalization

Mass personalization is another great universe that opens additive manufacturing. The manufacture of single part, which was still a big dream, not so far from today, gradually beginning to become reality, especially affordable for every type of consumer.

[5] www.geaviation.com, Accessed 2016 June 08
[6] www.formulaelectric.be, Accessed 2016 June 02
[7] www.materialise.com, Accessed 2016 June 08

FIGURE 2.11: First 3d printed race car: Areion, by Group T team [*www.materialise.com*]

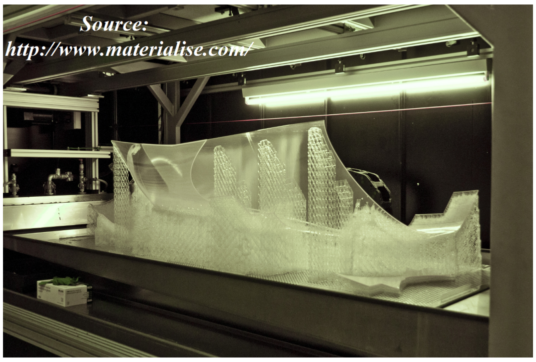


FIGURE 2.12: building of Areion body by Materialize Mammoth [*www.materialise.com*]

In the **medical industry**, research on printing human organs, based on stem cells is very advanced and could reduce the number of rejection in patients. The field of dental (see *figure* 2.14) and other prosthesis 3D printed, in our days, allow to offer fast, lighters and customiser model and even with biocompatible materials[8].

FIGURE 2.13: First 3D printed football cleat by Nike [*news.nike.com*]

FIGURE 2.14: 3D printed dental prosthesis by Stratasys [*www.stratasys.com*]

The **fashion and clothing industry** is not leftovers, finding its main engine in the thirst of consumers to gain unique and differentiable models. In 2015 the NIKE company has produced in SLS, its first printed shoe (see *figure* 2.13) having the cleat with the shaped and structure optimize and based on lightweight polymer to improve the ability of athletes[9].

The **food industry** also knows an interest in additive manufacturing, 3D system has developed a machine dedicated to multicolour printing of complex shapes made of sugar powder, (see *figure* 2.15). NASA is working on printing complete

[8] www.stratasys.com/, Accessed 2016 June 08
[9] http://news.nike.com, Accessed 2016 June 08

meals for its long-term space travel[10].

FIGURE 2.15: Sugar 3D printed palace of Versailles [*3dprint.com*]

FIGURE 2.16: 3D printed jewelry gold, by EOS [*www.eos.info*]

The **luxury and jewelery industry**, that knows a big demand in terms of customized parts in and always innovative form (see *figure* 2.16), also benefits from the contribution of AM. The German manufacturer EOS has there so put on the market a machine dedicated to printing by laser sintering, precious materials such as gold. The main advantage include direct manufacturing without mold and very little waste discharged[11].

2.8 Advantages of additive manufacturing

Additive manufacturing technologies can therefore be found both at the household level and for large-scale users, following any one of the three applications above. Their success lies in the advantage that everyone can draw with respect to said conventional processes.

2.8.1 Cost and lead time improvement

This is definitely the biggest advantage that designers will find to this technology, as it allows to shorten the iterations during the development process of a product. Thus in the three applications of AM seen above, we always find the word "rapid", which characterizes the fact that the forming process is express, independently of the complexity of shape. It is clear that the material removal rate of machining is superior to the one of adding material on additive machine.

[10]www.nasa.gov/, Accessed 2016 June 08
[11]www.eos.info/,Accessed 2016 June 09

However the subtractive process up to the final product may require several operations, assembly/disassembly, change of tools and even machines, planning process and construction of special tools. Which ultimately makes them generally slower.

Another aspect of this advantage is reflected in the improvement of communication for engineers in the design teams, for marketing needs and for decision-making. It reduces or avoids the mistakes of designs that can lead to rework or redesign which require a lot of time and resources.

For most of the AM processes, the building platform can accommodate and build several parts simultaneously, when they are of relatively small sizes. A concrete example is that of the American company KMC (*Kelly Manufacturing Company*), which for one of its products, made a gain of 93% in lead time and 5% in cost, through additive. This company is one of the world's leaders in general aircraft instruments, it has opted for AM on one of its headlight products, the M3500 instrument, a plane turn rate indicator. 500 units of the main part (the toroid housing, see *figure* 2.17) of this M3500 can now be produced simultaneously in 3 days, thanks to the ULTEM 9085 system from Stratasys[12]. While the same 500 units was produced by urethane casting in three to fourth weeks in the past.

Figure 2.17: 500 parts built simultaneously in AM [*www.stratasys.com*]

2.8.2 Quality and performance improvements

It is difficult to broach the subject of additive manufacturing without touching the one of topological optimization, which consists for a part to an ideal distribution

[12]www.stratasys.com/resources/, Accessed 2016 June 13

of materials in a given volume and under a number of constraints and boundary conditions. The topological optimization leads to an overall lightening of parts, the resulting forms are often too complex to be carried out with conventional methods but possible with additive manufacturing.

2.8.2.1 Complexity

Several studies are done in this direction and it is mainly the aerospace industry that benefits, given the impact that can have a mass reduction on energy consumption and CO2 emissions in flying systems. On the next figure 2.18, we see a Airbus nacelle hinge bracket, before and after optimization by EADS, a global leader in aerospace, defence and related services. This work was done in order to highlight the benefits that could be brought in aerospace. The comparison between investment casting and DMLS from EOSINT M 280 system, was made for the manufacture of a single titanium bracket[13].

- By using an optimized design, energy consumption throughout the life cycle, including manufacturing and use was reduced by almost 40%, despite manufacturing with the EOS SLS technology requires significantly energy.

- Bu using the minimum amount of material required for the manufacture of the part, the raw material consumption can be reduced up to 75%.

- The optimized design of the hinge reduces the weight of the aircraft for about 10 kg, which is significant on a plane.

2.8.2.2 Waste and stock management

In terms of production management also, additive manufacturing has several advantages, which properly used can make the most fluid and efficient system. Stock management by example, can be simplified thanks to AM. Parts can be digitally stored and product just-in-time. The problems of customs and transport between production sites, between producers and purchasers, can be reduced by relocating

[13]www.eos.info/press/, Accessed 2016 June 16

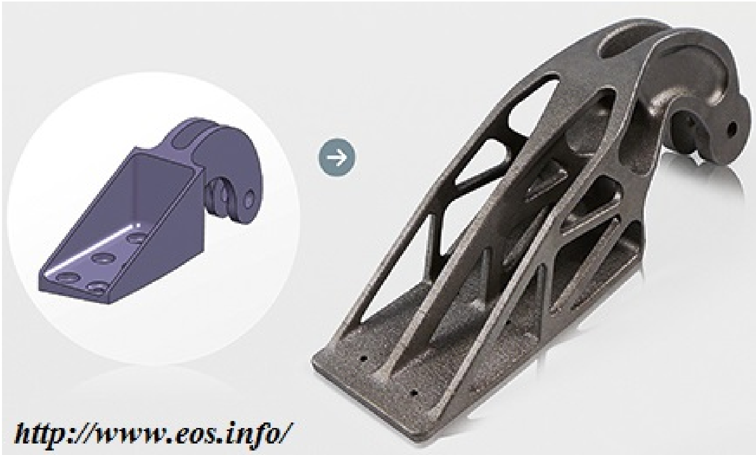


FIGURE 2.18: Part before and after topological optimization [*www.eos.info*]

production on the desired sites. Waste management is another aspect that can be improved, because most of the additive processes use only the amount of raw material required for the part, and the rest can be recycled for future productions.

2.8.2.3 Manufacture of assembled parts

Every designer has already faced assembling/disassembling issues of full or partial system in development phase, because parts are generally manufactured one after the other and then assembled. With additive manufacturing, this constraint can be abolished and we can reach more subtle and more compact mechanisms by directly manufacturing the parts together.

2.8.2.4 Multi-materials structures

The last big benefit of additive processes is in multi material structures. Most of parts are made of single materials and properties are generally homogeneous and isotropic. Yet watching closely, the necessary properties may vary at each point of the entire structure of a part. so far to respond to this problem, an adjustment as much as possible of the shape (shrinking or enlarging) in the desired areas is done. With some additive processes, one can now play on these two parameters (isotropy and homogeneity) and more, combine different materials in a same structure without much difficulty, providing that they are bondable.

2.9 Challenges of AM

After listing all the benefits of new additive manufacturing processes, we will now see what their limits are and why, despite the global interest, people are struggling to integrate them into their production systems.

2.9.1 Cost of machines and raw materials

Additive manufacturing machines are relatively expensive to purchase and use, compared to conventional machines. The purchase of an industrial machine, as discussed later for each process is dependent on the volume of production, precision and formatting speed. An "EOSINT M280" machine for metal sintering of the German manufacturer EOS, with a production volume of $250 * 250 * 325\ mm$ costs €480,000 while a universal milling machine "DMU 50" from the German manufacturer DMG costs only €148,110. A machine like this will be difficult to amortize before many years, when brings it back to the number of manufactured parts. Especially when considering the expensive maintenance costs it demands.

The basic materials used on these machines are another problem, both for diversity and cost. In the chapter on materials, we will come back more precisely on the ranges of available materials and limitations related to layers bonding methods. Overall, those available are expensive for several reasons, the main one being the manufacturing process, particularly for powder which requires expensive facilities and a lot of energy to obtain an accurate and homogeneous particle size (the dimension of each particle is between 1 and 100 pm and preferably between 1 and 50 pm or even between 1 and 20 pm).

The cost of production of these base materials is not the only reason for their high costs on the market. The exclusivity that has the machine manufacturers on materials and the fact to restrict their machines on their own commodity, limits the concurrency, therefore the falling prices. A concrete example is the PEEK filament for FDM, one can easily find online for a 700 €per kg, while pellets of the same material for injection molding just cost around 100 €per kg.

2.9.2 Machine speeds and physical properties of the parts

Another challenge, which could improve the impairment of costly additive manufacturing machines, could be to increase their efficiency. This can go through:

- The reduction of printing time: print speed is a parameter that has evolved greatly in recent years, and has increased the throughput of the machines. In SLA for example the new DLP technology allows to print out the entire surface of a layer at one time, which significantly increased the process speed.
- The expansion of building platforms, so one could produce several items at a time. The larger machines have an average volume of 700 * 700 * 800 mm, which is more than enough for most of the parts, but for simultaneous production of several parts it remains limited.
- Optimize inputs and outputs in the building compartment. In our days, most of the systems fail to produce continuously multiple series of parts automatically. They usually need the help of someone to remove the parts and to level up de raw material.

Physical properties are also an important issue. In terms of structure density, one approaches more and more forged parts for processes by sintering (98%) or melting (99%) of metal powders. But the anisotropy problems its still very present, mainly in the Z direction (normal to the layering). The orientation of the part during printing must therefore be well chosen, depending on its final use. The repeatability of the mechanical properties obtained on a whole series must also be able to be improved because at the moment there is a lot of dispersions.
In optical properties as well, more developments are expected. As can be seen in *figure* 2.19 for the printing of polymers, transparency levels are not great and vary depending on the processes. In the same figure we see the result of the process *"Printoptical Technology® " by LUXeXceL*, which is a first step in the right direction and promises a better future.

As well, one noted that work on the printing optically transparent glass are ongoing. It will shortly be possible to manufacture all types of complex objects in glasses (see figure 2.20) [2].

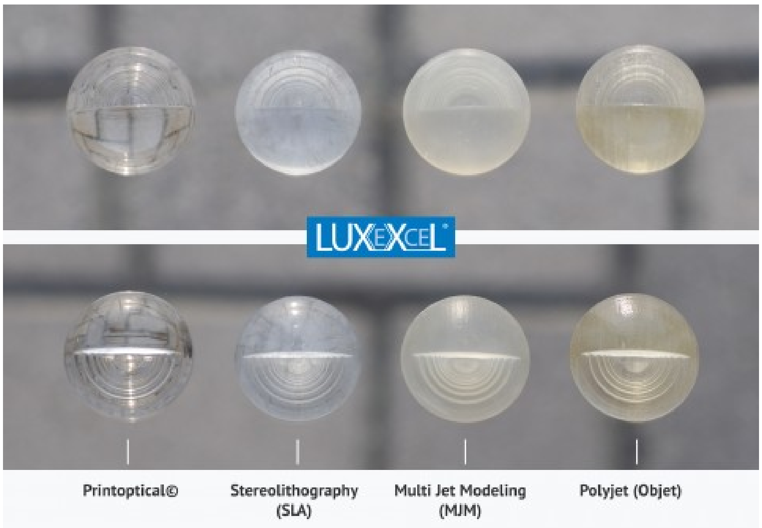


FIGURE 2.19: Transparencies by different technologies [*additivemanufacturing.com*]

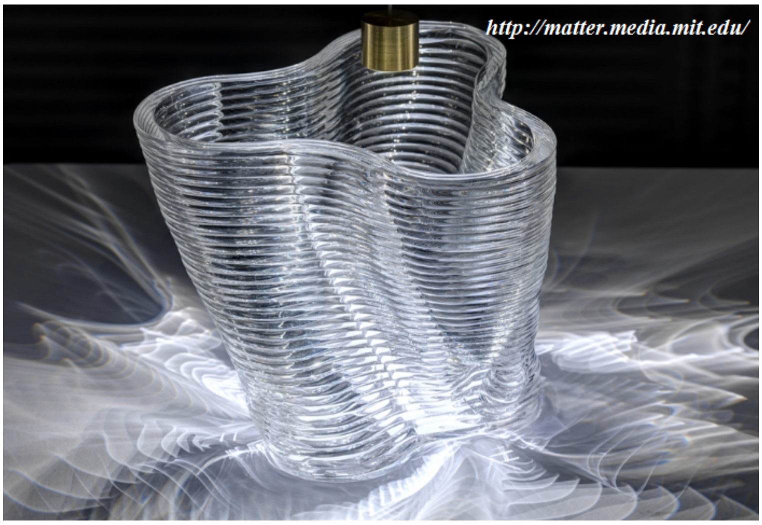


FIGURE 2.20: Optically transparent glass [2]

2.9.3 Information and user training

A big challenge for additive manufacturing is and shall be also to find its place and to integrate an industrial world that has strong habits and huge investments on traditional methods. There is therefore a need for sensibilisation and training of all the players around the industry, so they can get out of their mind set and justify the large investments required by additive manufacturing.

For the cost justification for example, is not that easy to build a business case. When starting with a classic design for series production, additive manufacturing is almost always less profitable than machining, molding or other conventional method. But if from the design and for some suitable phases of the production chain, we include AM, there is a good chance to end up winning. Taking the case of an aerospace part that, manufactured by AM would cost 5 times more expensive than in CNC machining. However, if the design for AM allows to reduce the weight by 25% in the end over a period of 10 years, the AM part could be 10 times lower in running cost.

Scenario	**Description**
Expensive to manufacture	Do you have parts that are expensive because they are complex, have high fixed costs (e.g., tooling), or are produced in low volumes? AM may be more cost effective.
Long lead times	Does it take too long to obtain certain parts? Are your downtime costs extremely high? Do you want to increase speed to market? Using AM, you can often get parts more quickly.
High inventory costs	Do you overstock or understock? Do you struggle with long-tail or obsolete parts? AM can allow for on-demand production, thus reducing inventory.
Sole-sourced from suppliers	Are any of your critical parts sole-sourced? This poses a supply chain risk. By qualifying a part for AM, you will no longer be completely reliant on one supplier.
Remote locations	Do you operate in remote locations where it is difficult, time consuming, or expensive to ship parts? AM may allow you to manufacture certain parts onsite.
High import/export costs	Do you pay substantial import/export costs on parts simply because of the location of your business unit and/or your supplier? Onsite production by AM can eliminate these costs.
Improved functionality	With AM, it is possible to redesign a part to improve performance beyond what was previously possible.

FIGURE 2.21: AM use cases —— Source: Senvol LLC [3]

In the *figure* 2.21 from Senvol LLC [3], were resumed some few cases where it might be interesting to switch to AM. Of course keep in mind that this is general and a study case by case need to be done. We will do this very precisely in this thesis for our study case.

When asked whether one day the AM will replace current methods, *Andrzej Grzesiak*, from of Production and Automation Technologies Institute (IPA) in Stuttgart, answers: *"No, this is not the objective of the current developments. The best approach is to correctly identify the suitable applications and replace conventional approaches only when there is technical and commercial gains is the key. The best is to learn to do that both technologies can coexist and maximize their complementarity*" [9].

Chapter 3

Valeo current process for forming plates

The main activities of business group *Valeo THS* are building HVAC systems for automotive manufacturers. HVAC systems operating principle is simple (see *figure* 3.1), the air from the passenger or from outside is cooled and dehumidified in the evaporator where the refrigerant changes from liquid to a gas state and then is blown into the cockpit.

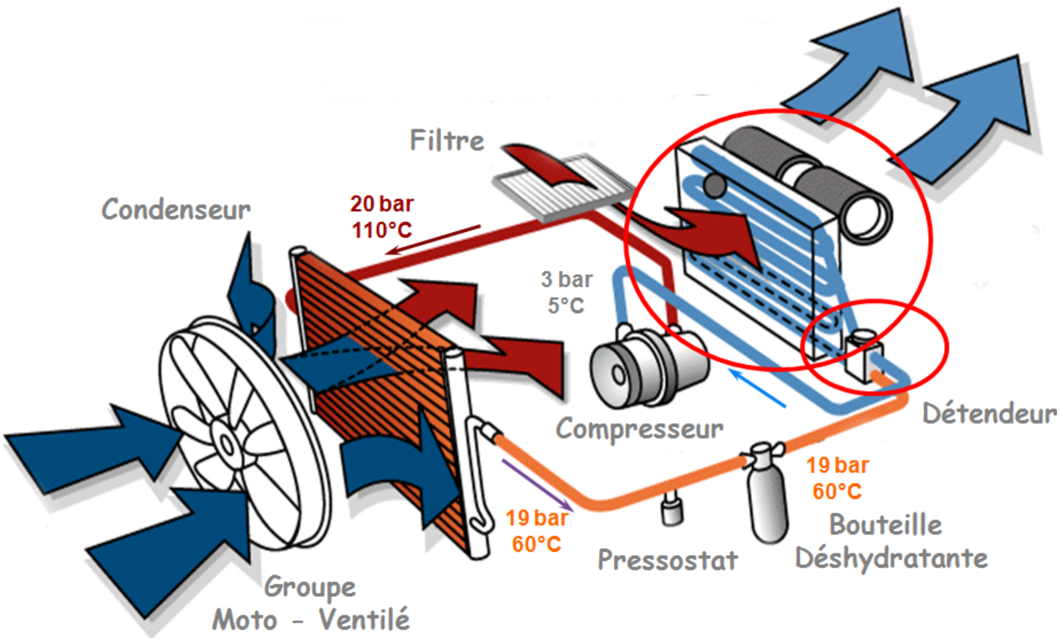


FIGURE 3.1: Principle of operation of HVAC system

Designs, materials and technologies of these systems have much changed thanks to the investment in R&D that were consented by *Valeo* group (see *figure* 3.2). These evolutions are driven by a constant search for improved performances but also by growing constraints, such as lightening. Since 1995, Valeo is moving towards a continually thinner sheet metal and assembly by NOCOLOK flux brazing technology, rather than the mechanical assembly used in the past. The forming of these metal sheets before brazing is done by stamping and requires perfect mastery of this technique.

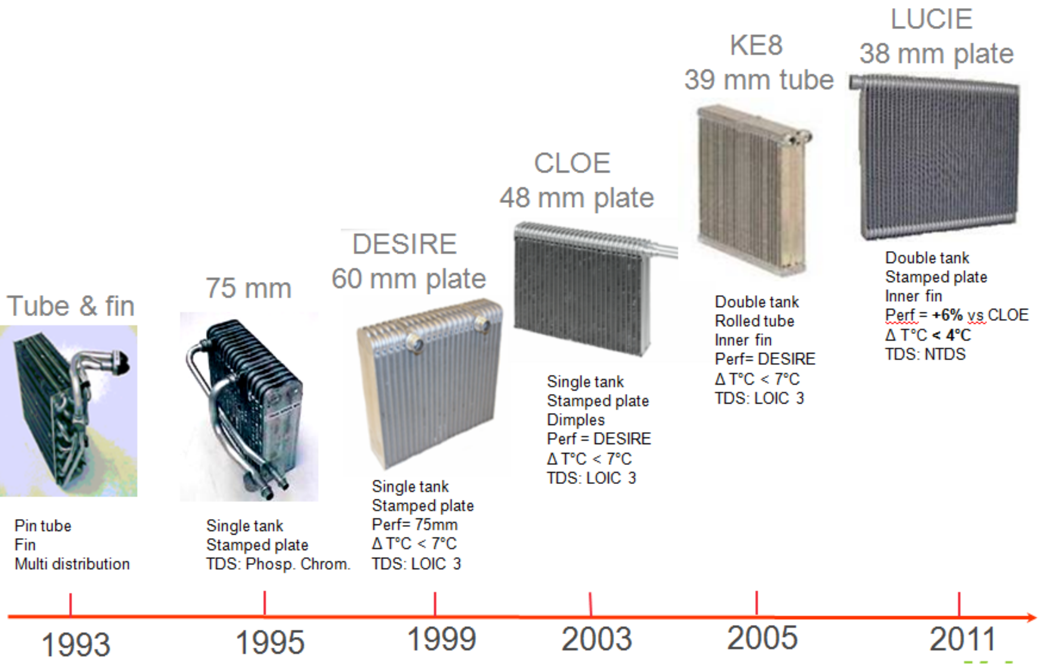


FIGURE 3.2: Evolution of Valeo evaporators

Brazing and stamping therefore constitute the two main processes used by Valeo teams. In this chapter we will try to understand the stamping process, in the particular case of the need for prototyping of a new heat exchanger. The goal is to provide innovative solutions in objective to improve the cost and production time.

3.1 HVAC evaporators

The evaporator LUCIE is one of the great and recent success of VAELO, it allows a progressive cooling of air in 6 steps, up and down (see *figure* 3). Depending on the market need, the number of circulating platelets to be welded can be defined, for a total length of between 149 *mm* and 302 *mm*. For the thickness, one can choose between 48 mm or 38 mm. The assembly is held by welding, which gives it this compactness.

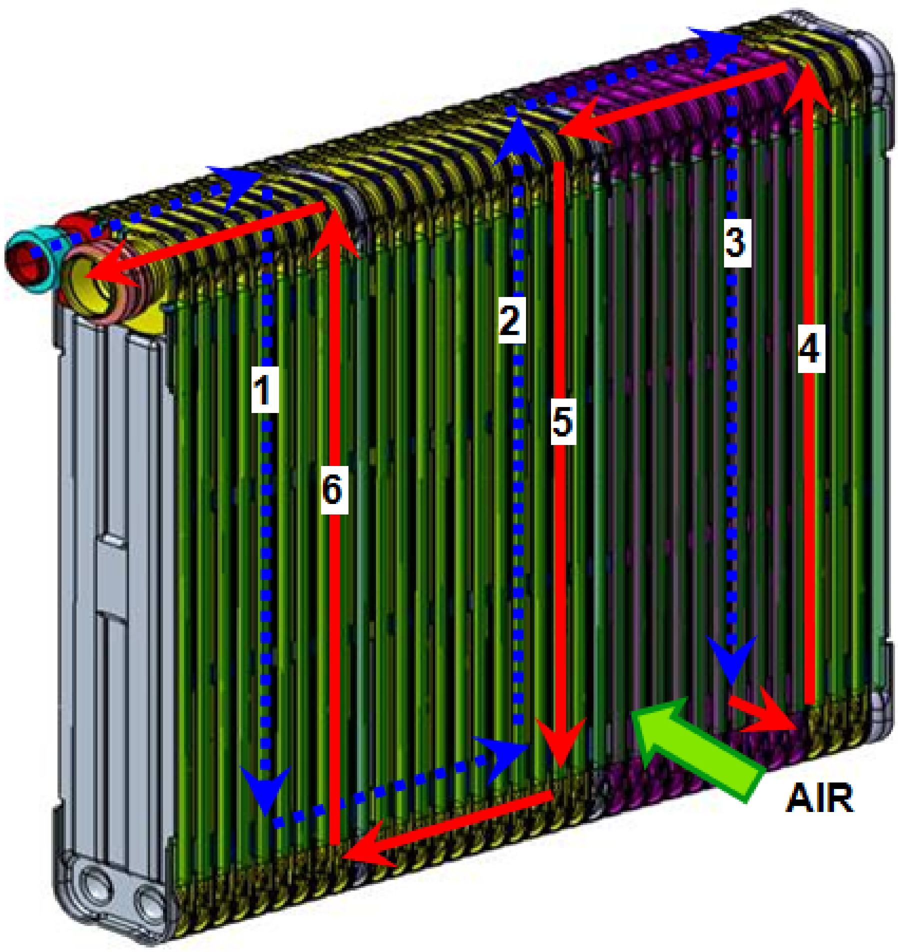


FIGURE 3.3: Lucie evaporator

The evaporator "TC" which will serve as sample in this work is confidential as still being in development, it can not therefore be shown here. However it has characteristics similar to LUCIE, for all of our concerns (material and forming process). Any significant differences which could help the better understanding of the subject will be clarified.

3.1.1 Material

The material used on this "TC" exchanger is a multilayer aluminium (see *figure* 3.4). The main layer is made of 3003 aluminium (melting temperature $643 - 654°C$), and the superficial layers (of a thickness equal to 10% of that of the main layer) are made of aluminium 4045, 4047 or 4343 (melting temperature $577 - 613°C$). These surface layers of a lower melting temperature are used as filler material for the NOCOLOK brazing (temperature $562 - 577°C$). It may possibly be some added layers to improve the corrosion resistance. This material is a Valeo standard and can not be changed during the study.

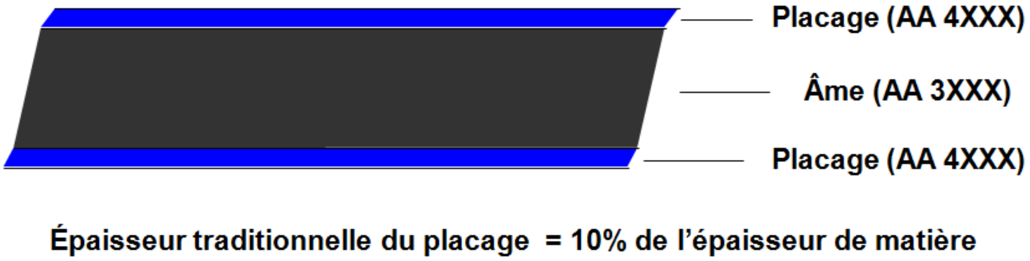


FIGURE 3.4: Multilayer aluminium material

3.1.2 Components

All Valeo evaporators like Lucie is composed of a wide set of components (see *figure* 3.5) and each of them has a very distinct function. The assembly of two plates creates the circulation channel for coolant. The internal fin (inner-fin) creates turbulence in the coolant fluid flowing between the plates, while the square-fin between two traffic channels serves to increase the air/fluid exchange surface. We will focus on the manufacturing of the plates, because they are the main change from an evaporator to other, and may become very complex.

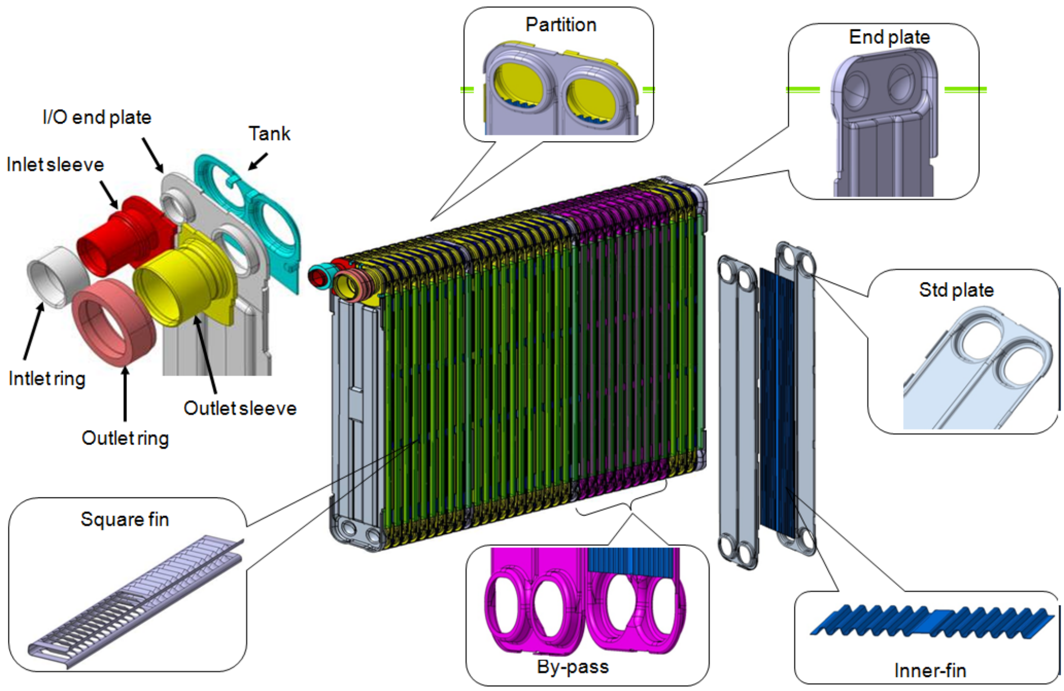


FIGURE 3.5: Evaporator's components

3.1.3 Sheet plate

The plate of "TC" (see *figure* 3.7) that we are willing to produce, has a different technology from that of Lucie (see *figure* 3.6). The channels directly integrated to the plate in the fluid circulation area, is playing the role of the inner-fin we saw above. The input/output of the coolant on the plate is done at the same side. Both main changes have the advantage of making the system more compact, even if the overall thermal efficiency is reduced.

Regarding the innovation processes, work on a complex plate will help reach the limits of what can be done. Arriving to establish a new process for this plate, guaranteed the ability to do the rest.

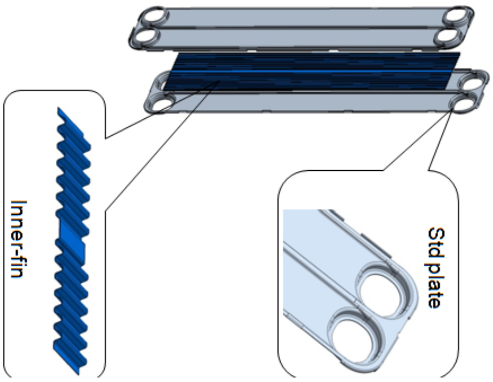


FIGURE 3.6: Lucie standard plate

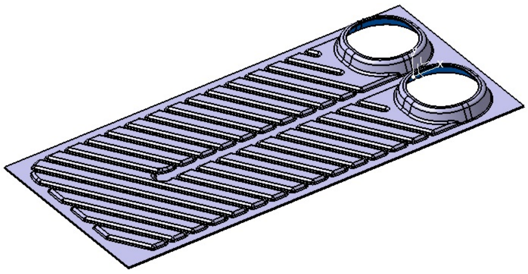


FIGURE 3.7: TC standard plate

3.2 Stamping process

The stamping is defined as a manufacturing technique for obtaining, from a flat and thin sheet of metal and a tool including a die, an object whose shape is directly given by this die (see *figure* 3.8). This process greatly used at Valeo, is based on the principle of plastic deformation consisting of a local elongation or shrinkage of the sheet to form the shape. A rise in temperature to around 200°C, ie one third of the aluminium melting temperature is necessary to facilitate the forming of the plate. Conversely it can also deteriorate the mechanical properties of the part. Lubrication is also used for the same reasons as for the heat supply, and this require a particular attention because the part must be clean for proper brazing.

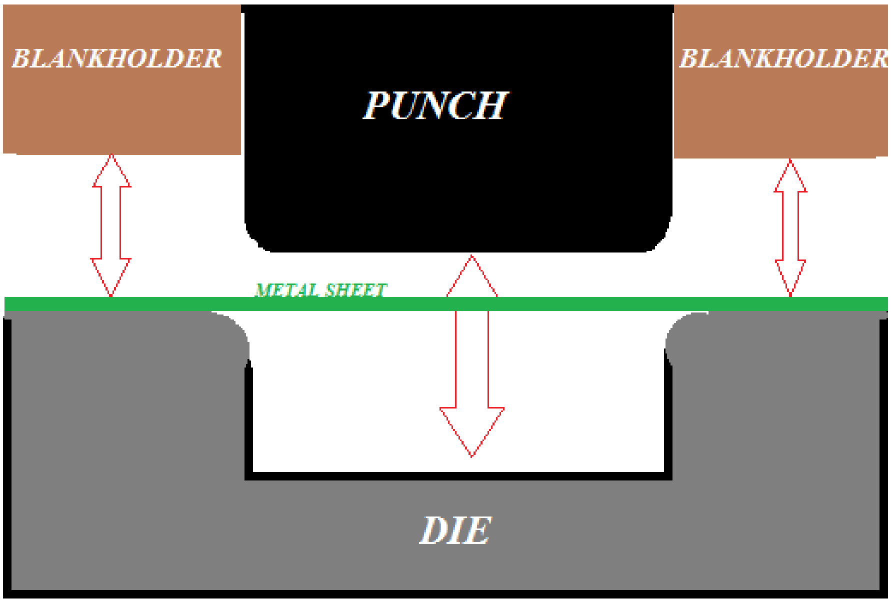


FIGURE 3.8: Stamping system

3.2.0.1 Six steps are necessary for the stamping

For cavities as deep as that of the central pocket (2.96 mm, see *figure* 3.9), it is necessary to proceed by multi-stage, in particular 6 in our case. This is for bring the material progressively thus avoid that this crack. With stamping it is theoretically possible to achieve all angles by adjusting the number of operations, however, the maximum elongation limit should not be greater than 50% for aluminium plates.

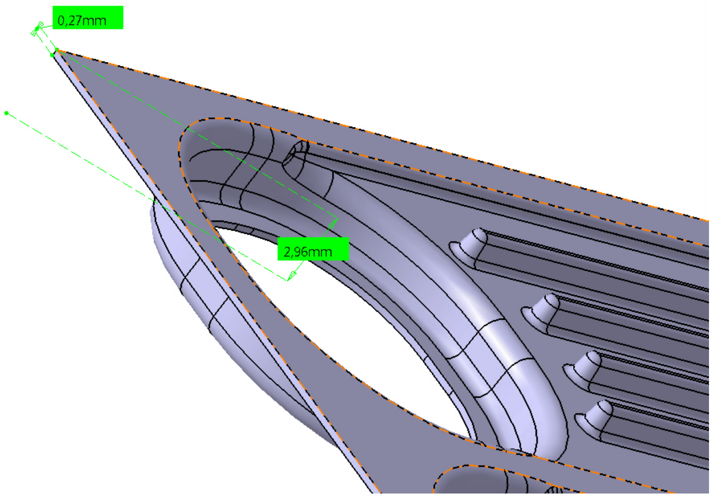


FIGURE 3.9: Initial TC plate

The deformation not being completely plastic, a study of material springback must be completed to ensure a good flatness which is very important for the quality of brazing that will follow.

3.2.0.2 Stamping tool

The forming tool that is fixed on the press, includes apart from the die (see *figure* 3.10, forming die of the last step), other elements essential for proper operation. Including a punch, in relief that adapts its internal shape reserving the thickness of the sheet; a blank holder surrounding the punch lies against the periphery of the die and serves to pinch the sheet during application of the punch; the reeds are used to slow the sliding of the sheet; There is also drageoirs, ejectors, screws, and some others. For each of the six steps, one must develop a similar tool.

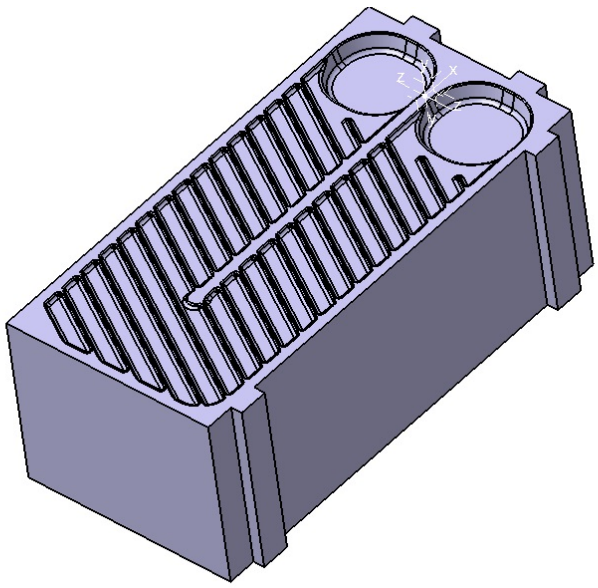


FIGURE 3.10: Stamping die of the last step

3.2.1 Limits of the conventional stamping process

The development of such forming tools is highly specialized and very costly. For the need of prototypes or small series (2000 parts), it takes between one and two weeks for the realization of a complete tool, and eight weeks for the six sets of tools. Their acquisition cost is €35K, 80% of it is dedicated to the dies and punches. When taking into account production costs (100€per hour), its costs €40K for that 200 parts.

That is clearly a major constraint to the development of new models and therefore innovation. On the contrary, for large series (typically 20,000 parts per day at Valeo), this tooling production cost is quickly recovered and this conventional process has a good repeatability, is then well suited to this type of need.

	Stamping
Number of steps (tools)	6
Number of dies and punchs	2 * 6
Total costs of dies and punchs	€28K
Total tools costs	€35K
Lead time for one tool(weeks)	1 to 2
Stamping cost	100 €/h
Number of parts of the serie	2000
Additional operations (cutting)	yes
springback	Yes
Forming temperature	200°C
Total cost	€40K
Total lead time (weeks)	8

Table 3.1: Stamping process specifications

Chapter 4

Additive manufacturing processes

Additive manufacturing is a generic name assigned to a set of processes as large as distinct. Their similarities being the only fact that they all go from the digital model of an object to its building layer by layer. Whereas in reality the mode of construction of this layer, the base material and the energy source may vary from one to the other. This can quickly become confusing to the uninitiated, particularly since that limits are very wide and therefore we see quite often new processes added in the additive manufacturing family.

To navigate in this extended and constantly growing family of processes, a need for classification has become indispensable. Several propositions were made on different bases:

- **The physical form of basic materials**: it may be in liquid, powder, tape, wire or pellet. And can be present from the beginning of the process or be added continuously. An example of this type of classification is given in *figure* 4.1 [4]. The problem of this method is that it generates very odd combinations of processes. Such as for the powder, we have the SLS sintering processes and binder jetting process that is group, While, the results and even the materials involved are very different for each of them.
- **Energy source**: the creation of each material layer (solidification of liquid resins, powder sintering or fusion, beads or pellets fusion) and their assembly together is possible thanks to an energy intake. This is done in most cases by a laser in the field of infra-red, visible or ultraviolet. Are also used electron beams and heating resistors. The input of this energy on the material is

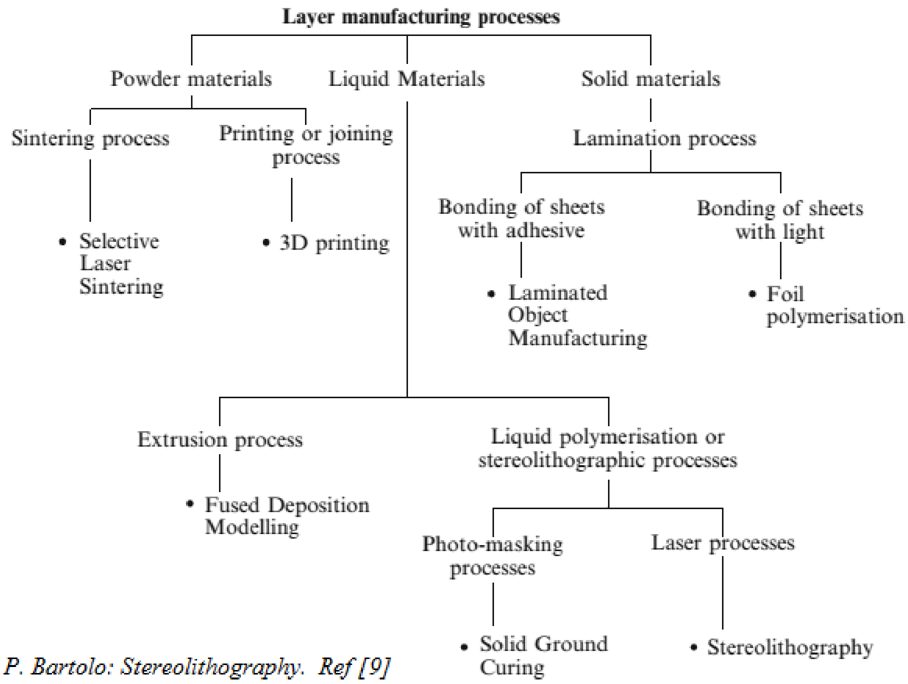


FIGURE 4.1: AM processes, classification by based materials [4]

done of in four different ways: 1D Channels, 2*1D Channels, Array of 1D Channels and 2D Channels. *figure* 4.2 [1] shows a two-axis classification that takes into account the energy source and the physical form of basic materials. This approach is very interesting because it well characterizes the processes, but the 2D approach is not well accepted by everyone.

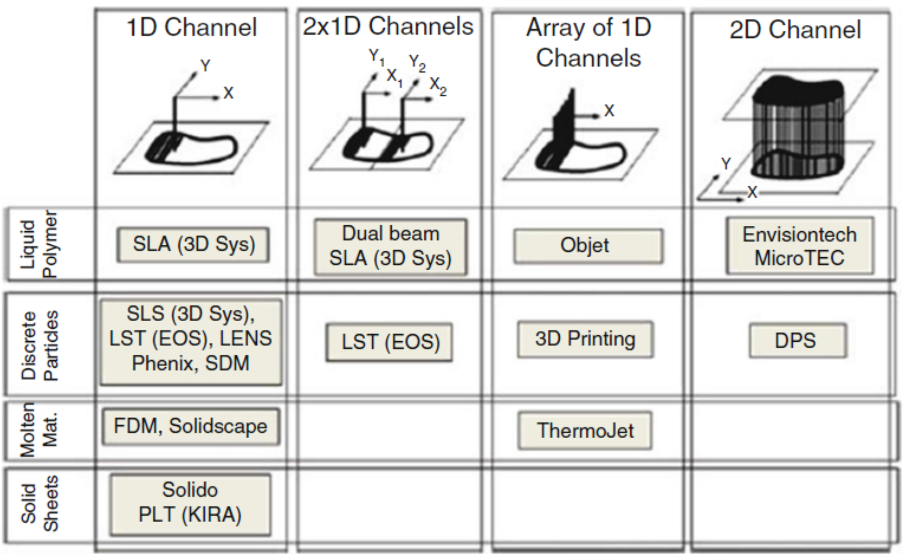


FIGURE 4.2: AM processes, two-axis classification by Pham [1]

- **The forming process**: here we enter a little more in to detail on what happens during the construction of each layer. It takes into account the physical form of basic materials and how is it provided for each layer. It is more subtle and it resulted on a system which groups more or less processes with identical outputs.

In 2012, it is this latter group of classification which has been standardized by ISO (TC 261) and ASTM (F42 Committee) and gradually begins to be a reference in the world of additive manufacturing. It was then naturally adopted in this report. It should be noted that the processes are in constant changing and it is not impossible that new ones do not find their places in this classification in the future. It will therefore be subject to regular updating.

4.1 Vat Photopolymerization

Definition by ASTM [8]: *an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.*

4.1.1 Description of the principle

The stereolithography (or SLA for stereolithography apparatus) was the first additive manufacturing process to be patented, developed and commercialized in 1988 by *3DSystems*. It consists in the use of an ultraviolet laser and two-dimensional galvanometric mirrors, to draw a predefined design on the top surface of a liquid polymer in a vat. This light-activated polymer is then cured (solidified) to form a single layer. Once the first layer is completely draw, it's lowered by a distance equal to the layer thickness (typically $0.08 - 0.025\ mm$) into the vat, and the next layer is done right on top. The superposition of consecutive layers and the self-adhesive property of the material allows the construction of the complete three-dimensional object (see *figure* 4.3)[1].

This process is the most widely used, particularly for is printing speed and accuracy it can provide. It is mainly used for need of creating models, prototypes or patterns. The materials used (photo sensitive resins) being only equivalent to

[1] www.custompartnet.com/, accessed 2016 June 27

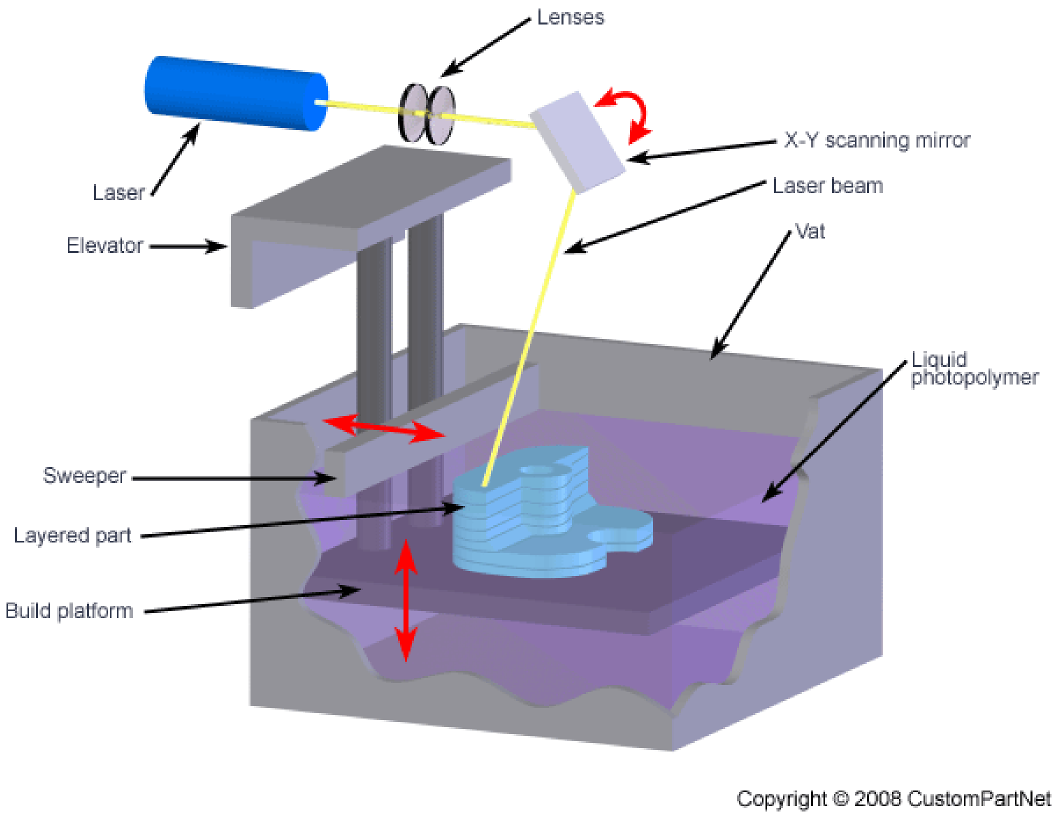


FIGURE 4.3: Typical SLA machine setup [*www.custompartnet.com*]

conventional materials, this process is struggling to evolve towards making functional parts.

However, for having parts with acceptable physical properties, additional steps should be required. The post-curing in an UV oven enables to fully crosslink the polymer and thus improve the hardness of parts, the impregnation allows to reduce the porosity and get parts with better density. The use of resins filled with ceramics is also increasingly for improving the thermal and mechanical properties.

The construction of some complex parts can request the construction of a support structure of the same material as the work-piece, or another more easy to remove. This structure is often generated automatically by the processing software before printing. Its withdrawal must be done after printing but before the post-curing. A finishing process such as sanding or painting is used to erase all signs. This structure must be treated with high importance to avoid weakening the part after its removal.

4.1.2 Associated technologies

SLA photopolymerization technology has changed significantly since its creation, hence the term more comprehensive "*VAT PHOTOPOLYMERIZATION*" to group all processes based on curing a photo sensitive resin into a vat has been adopted. One will see below that there are processes whom, for each layer, the resin is projected and cured simultaneously. Also, the used of the photosensitive term starts to be questioned with the development of similar processes, but that use a heat-activated resin and infrared laser (CO2 laser) [4].

4.1.2.1 Direct Light Processing (DLP)

DLP is a light emitter system based on a technology that uses a digital micro-mirror device[2]. In additive manufacturing, this technology is used similarly to the SLA technology, the only difference being that it is a inactinic bulb (red) which is used to treat the resin instead of a UV laser. And the array of micro-mirrors help to project the entire image of the layer at once, which is faster than scanning it point by point.

Another characteriscs of DLP systems, is the building of the part by the top of the vat, while the excitation light is projected at the bottom through its transparent basis. This constitutes a dual advantage over the conventional SLA, the first being the small amount of resin used, as the layers are built and added to the bottom, the presence of the resin is only necessary in that vat bottom, while for SLA this vat must be full at least until the height of the part. The second benefit is the removal of the uncured resin by gravity effect, hence no resin trapped within the model.

A drawback of these systems is the limited size of parts that can be manufactured. indeed, projecting a large image with good resolution can quickly become costly and difficult technology. For now, the machines using this system have a maximum volume of 10.

[2] https://en.wikipedia.org/wiki/DLP, Accessed 2016 June 28

4.1.2.2 Continuous Liquid Interface Production (CLIP)

Unlike SLA Stereolithography requires the construction of several distinct and successive layers, here the process is completely chemical and continues, it uses a combination of UV light and oxygen.
Light is projected through an oxygen permeable window on a light-activated resin. The support platform rises up continuously and simultaneously with the building of the part. CLIP systems are based on the special window permeable to oxygen and transparent to UV rays. By controlling the flow of oxygen, a dead zone is created (resin film) between the window and the object where the resin can not be cured (see *figure* 4.4). A sophisticated software controls the entire process variables[3].

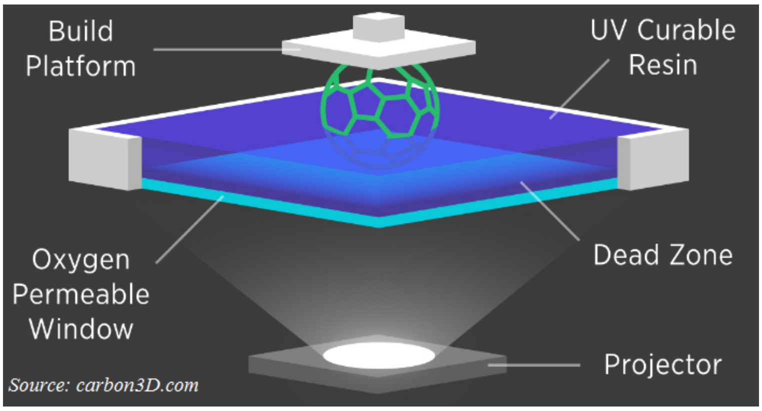


FIGURE 4.4: CLIP principle [*3dprint.com*]

This technique has the great advantage of being free layer and thus ensure extremely high resolution (see *figure* 4.5) and virtually completely isotropic properties of the manufactured part. On top of that, the continuity of the printing process makes the 25 to 100 times faster than a conventional SLA process. However the process is quite new and as for the DLP, the size of parts is limited. *Carbon 3D* is the company that developed this process and its only machine "M1", has a working area of $144 * 81 * 330$ mm.

4.1.2.3 Film Transfer Imaging (FTI)

A transparent film coated with a layer of photopolymer resin is placed in front of the projector integrated in the machine (see *figure* 4.6), the 2D cross-section light projected above will cure the resin selectively. The construction plate is raised up at the layer thickness, while the transparent film made a return trip to the

[3]http://carbon3d.com/, Acessed 2016 June 27

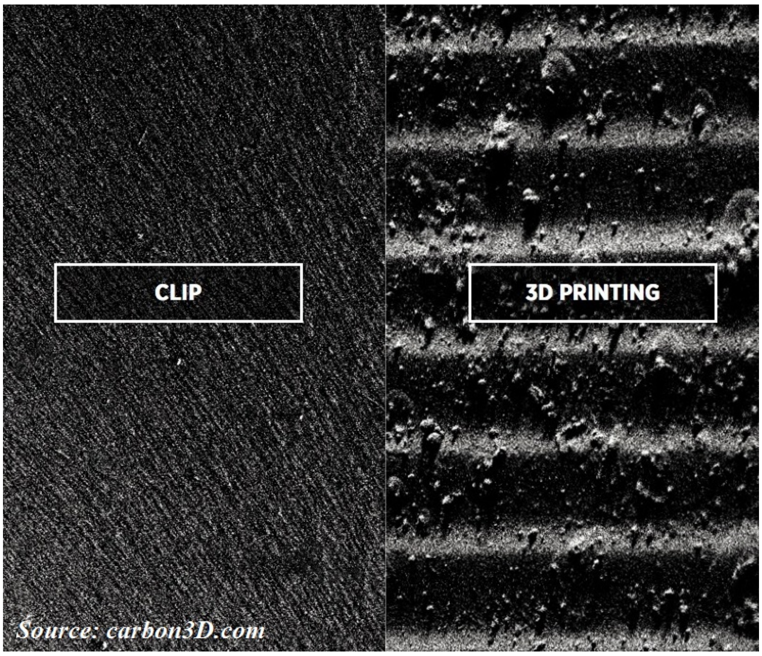


FIGURE 4.5: CLIP high resolution surface finish [*3dprint.com*]

cartridge to receive a new layer of liquid resin, the image of the next 2D cut is projected above and so on. The 3D part is thus reconstituted layer by layer[4].

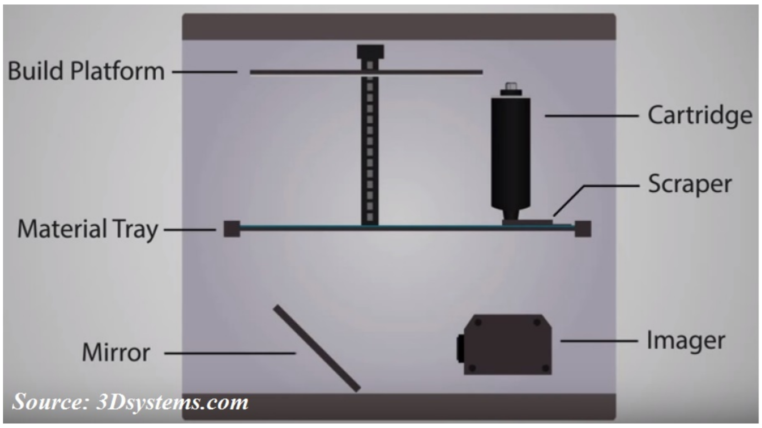


FIGURE 4.6: FTI principle [*3dsystems.com*]

This system is attractive for its simplicity and high resolution, which virtually offers the best value for money on the market of SLA. It also has the unique advantage of making multi-material and multi colour part just by using different resin cartridges.

[4]http://fr.3dsystems.com/, Accessed 2016 June 28

4.1.2.4 Solid Ground Curing (SGC)

The SGC process is based on the exposure of each layer of the model to the UV rays through a mask. The use of a mask makes that the realization time of each layer is independent of its complexity. This process is then fast and offers good precision, but its overall complexity (see *figure* 4.7) makes it expensive to acquire and use. And it has been forsaken by machine manufacturers to more profitable systems and same qualities.

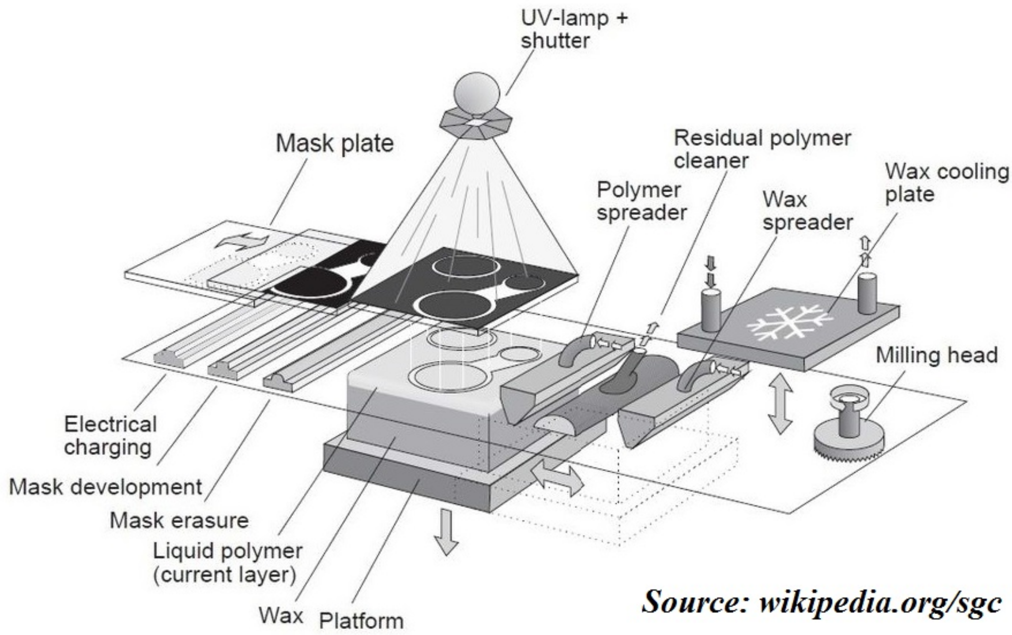


FIGURE 4.7: SGC principle [*en.wikipedia.org*]

However, it has the advantage (in contrast to other SLA processes) of not requiring the construction of a support structure during printing[5].

[5]https ://en.wikipedia.org/wiki/Solid Ground Curing, Accessed 2016 June 28

4.1.3 Specifications and materials

(mm if needed)	SLA	DLP	CLIP	FIT	SGC
Max part size	$1500 * 750 * 550$	330*200*800	$144 * 81 * 330$	$71 * 228 * 203$	$4.1 * 1.7 * 1.5$ m
Min layer thick	$0,025$	0.005	0.0	0.102	na
Max speed	50 mm/h	600 mm/h	500 mm/h	$20,32$ mm/h	na
Resolution(DPI)	4000	$>$ SLA	$>$ SLA	$<$ SLA	na
Price	990 $k$$	450 $k$$	120 $k$$	15 $k$$	na
Multi colors	no	no	no	yes	na
Multi materials	no	no	no	yes	na
Materials	ABS, PEAK, PP, PA, wax		Polyurethane	Colors materials	na

Table 4.1: Benchmark of vat photopolymerization processes

The data presented here in the table 4.1 are guidelines and are subject to changes. For each process, it rarely exists machines that combine at the same time all the best features. A compromise is generally made according to the application to which the machine is intended to be used.

In terms of the process selection, a precise understanding of the need is required:

- For industrial applications, where one wishes to have a wide choice of materials, excellent mechanical characteristics and if the price is not a constraint.

One must clearly turn to conventional **SLA** processes, which offer guarantees of quality.

- If on top of that one works on relatively small parts sizes, choosing the **DLP** would be more appropriate since offers a better resolution combine with a greater rate of printing.

- For reduced models of representation and even testing the **CLIP** is perfect, but the cost is not to its advantage, compared to DLP.

- Finally for scholar, exhibition or representation needs, **FTI** appears as the perfect solution to agree perfectly because it offers up to four different colours that can be mixed on the same model, and all at very affordable cost.

4.1.4 SWOT analysis

In this section is given a **SWOT** analysis of the overall "VAT Photopolymerization" processes with respect to needs that may face the teams of production or/and development of Valeo THS.

strengths	weaknesses
1. Quickest AM process	1. Expensive machines
2. The most widespread technology	2. Only similar materials
3. Prototype with smooth surface finish	3. Expensive raw materials
4. Wide range of materials	4. Low mechanical properties
5. Machines of all sizes	5. Need a support structure

opportunities	threats
1. Wax patterns for casting	1. Technological obsolescence in the machines due to new developments
2. Quick iteration times	2. Not suitable for mass production
3. Small series parts	3. Long period of depreciation
4. Form and fit prototypes	4. New design rules
5. Low cost prototyping	5. Different materials for prototyping and production
6. Reduction of tooling cost	6. Difficulties to develop new materials

TABLE 4.2: Vat Photopolymerization SWOT

4.2 Material extrusion

Definition by ASTM [8]:*an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.*

4.2.1 Description of the principle

Extrusion is a (thermo) mechanical manufacturing process by which a liquefied and compressed material is forced through a selected section of nozzle. This is the method most used by the additive manufacturing machine manufacturers as it is easy to implement and relatively fast at an affordable price.

It is therefore, the entry level of AM processes, because is primarily for individuals rather than for industrials. It is probably the most popular printing process due to the large number of printers of this type available on the market. This method works by adding molten and extruded material through a nozzle of a diameter of the order of one tenth of a millimeter, in order to print by cross-section a 3D object layer by layer. The building platform shifted down for each layer and the process is repeated until the entire 3D object is built (see *figure* 4.8). The layer height then determines the print accuracy.

Again, as for the process of Vat polymerization, a support structure is needed when printing, and it brings the same problems of fragility that may result at its removal. The materials used here are mainly plastics, more precisely thermoplastics, as they can pass from a solid state to molten one and be easy to paste by applying heat without damaging. The materials used here can be good materials, opposed to photopolymerization where materials was just plastic like. But the process does not allow to have a good impermeable structure and smooth surface finish.

4.2.2 Associated technologies

They are two main different technologies that are based on this material extrusion principle.

4.2.3 Fused Deposition Modeling (FDM)

FDM developed by the American company Stratasys in 1991, is the main method using extrusion material. FDM is proving to be very affordable when compared to other 3D printing technologies. Stratasys remains the world leader for this type of systems, although it is highly democratized and there are lots of small suppliers, which offer equivalent systems. Most of the FDM machines have two (or more) print-heads capable of printing different colours, materials and overhang areas of a complex three dimensional printing[6].

The systems are simple, clean, not dangerous at all and materials are inexpensive. Allowing the development of desktop machines and the average acquisition prices are lower than 5 *k*€.

In terms of materials, it has predominantly plastics, aluminas and composites. Some food and civil construction materials are used on experimental machinery similar to FDM.

[6]www.stratasys.com/, Accessed 2016 June 27

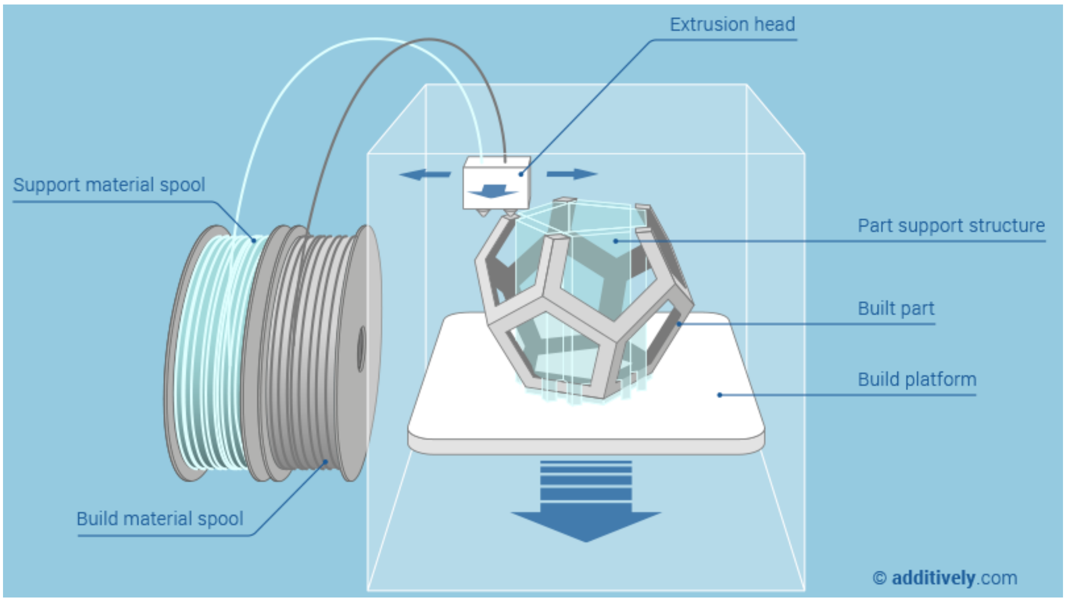


FIGURE 4.8: Material extrusion: FDM system [*www.additively.com*]

4.2.3.1 Arburg Plastic Freeforming (APF)

An other way of using material extrusion technology was developed in 2013 by the German company Arburg. Instead of extruding a continuous bead of plastic, here it is a droplet of material which is deposited at the frequency of 60 to 200 hertz. The raw material is also changed from thermoplastic filament (FDM) to thermoplastic pellets, which is more affordable[7].

The main advantage of this system compared to FDM is that the based materials used herein is typically conventional plastics, and therefore cheaper, more available on the market, and with standard mechanical properties. The material is firstly melted in a plasticising cylinder like for injection moulding. Then for injection, the pressures raised up to 500 bar. This generates droplets which are expelled through a special nozzle (diameter size between 0.08 and 0.3 mm) by a stationary discharge unit. The structure obtained is isotropic and depending on the size of the droplets, it is more or less possible to obtain watertight structure. The surface quality, however, remains rough (see *figure* 4.10).

[7] www.arburg.com/, Accessed 2016 June 28

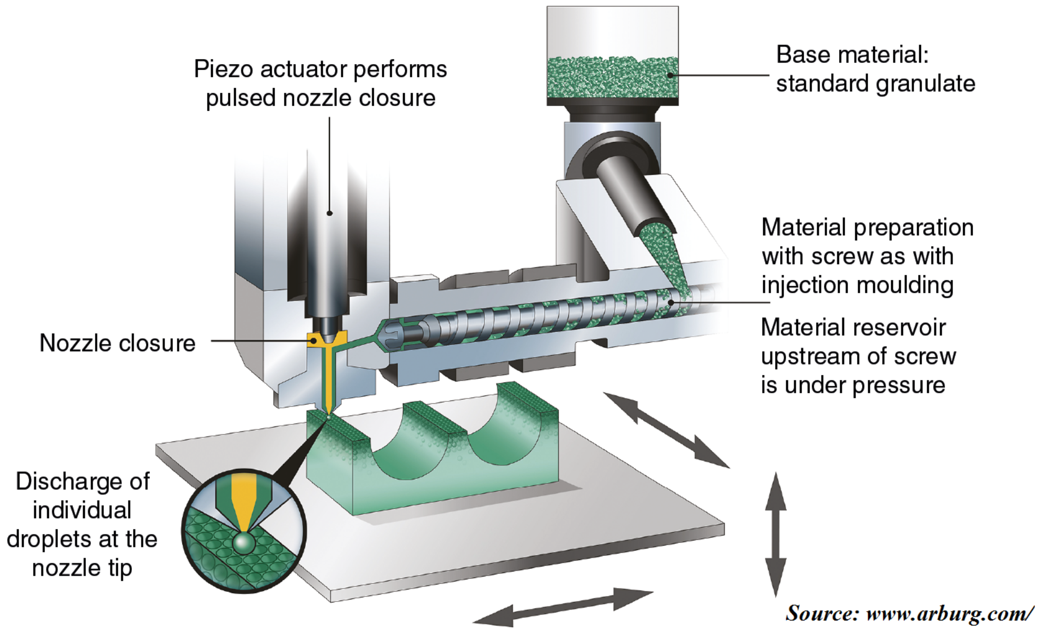


FIGURE 4.9: Material extrusion: APF system [*www.arburg.com*]

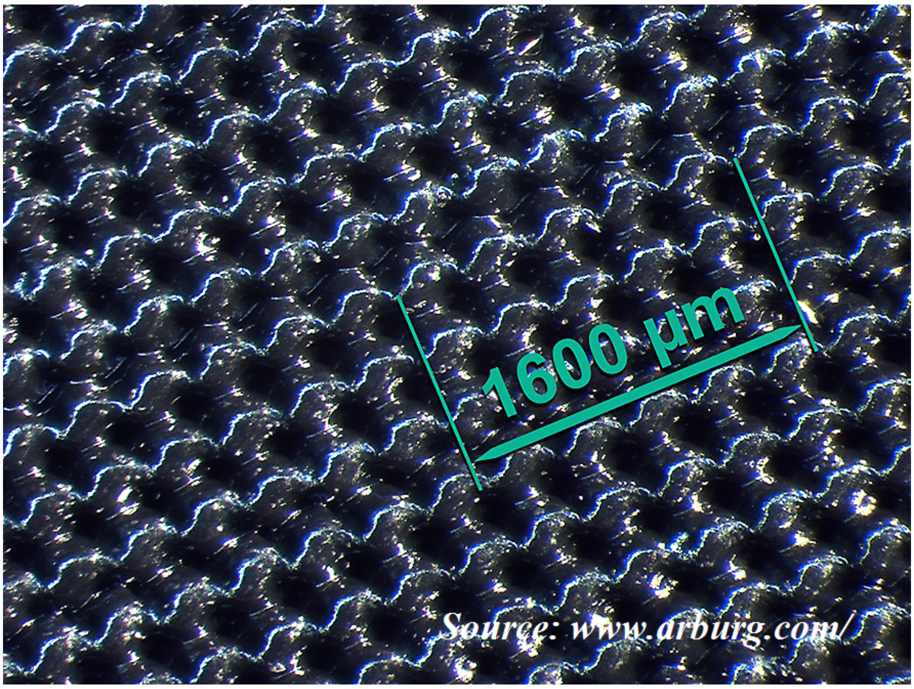


FIGURE 4.10: ME: APF surface finish [*www.arburg.com*]

4.2.4 Specifications and materials

(mm if needed)	FDM	APL
Max part size	$914 * 610 * 914$	$190 * 135 * 250$
Min layer thick	0.178	0.21
Max speed	fast	fast
Resolution	good	$>$ FDM
Price	145 $k\$$	150 $k\$$
Multi colours	yes	yes
Multi materials	yes	yes
Materials	ABS, PC, PA12, PP, PEEK	ABS, PC, PA12, PP

TABLE 4.3: Benchmark of materials extrusion processes

The information given in the table 4.3 are guidelines. Both processes are very close in terms of principle, but it appears clear that, the APF produces mechanical characteristics closest to the molding injection (even better for the crack propagation). However APL systems are fairly recent, limited in size and for the same construction space they are five times dearer than FDM.

4.2.5 SWOT analysis

In this section is given a **SWOT** analysis of the overall "material extrusion" processes with respect to needs that may face the teams of production and development of Valeo THS.

strengths	weaknesses
1. Use standard materials 2. Low cost machines 3. User friendly 4. Wide range of materials 5. Machines of all size 6. Clean and safe machines	1. Fine details can't be realized 2. Rough surface finish 3. Lot of porosities 4. Limited to thermoset plastics
opportunities	**threats**
1. Can be installed in R&D rooms 2. Suitable for production of small parts (jigs, fixtures, helps) 3. Quick prototyping 4. Form / fit and functional testing prototypes 5. Patterns for casting 6. Local production	1. Technological obsolescence in the machines due to new developments 2. Not suitable for mass production 3. New design rules

Table 4.4: Material extrusion SWOT

4.3 Material Jetting

Definition by ASTM [8]: *an additive manufacturing process in which droplets of build material are selectively deposited.*

4.3.1 Description of the principle

Two-dimensional inkjet printing excist since the 1960s[8], it allows from a digital file to reproduce very simply an image, photo or any type of document. The question of whether it was possible to go further and reproduce 3D objects by spraying a material other than ink has quickly arose.

Two different ways to build a 3D model using a printing head has been developed. The first that we will see here, consists in spraying a liquid material which is simultaneously solidified (see *figure* 4.11). The second, which name is binder jetting, that will be seen in the next section 4.4, consists in spraying a binder liquid on a powder bed.

In 1994, the first MJ system was commercialized by *Sander prototype* (now *Solidscape*)[1], its only material was wax used to print models for casting. Subsequently photopolymers have been added to the range of materials thanks to the addition of the laser system, allowing to cured this light-activated materials, just as for vat photopolymerizations process, seen in the section 4.1.

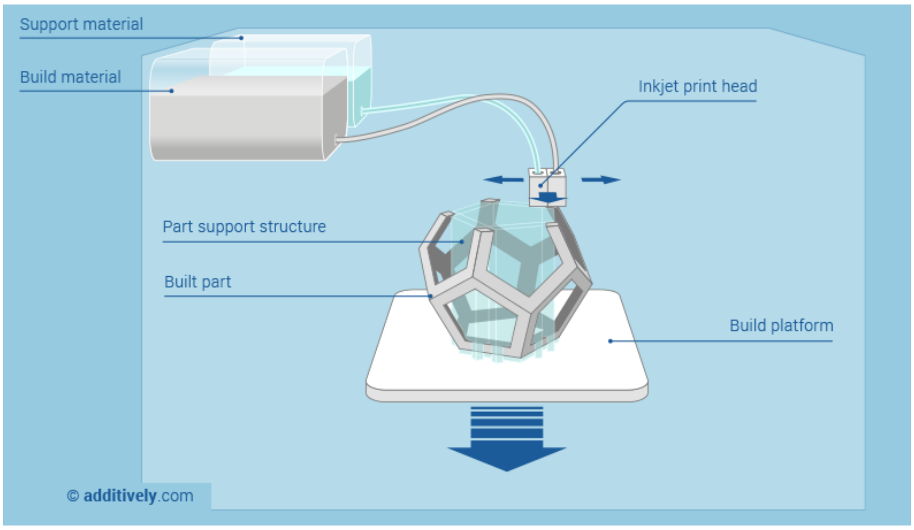


FIGURE 4.11: Material jetting system [*www.additively.com*]

However, this process drags some high technical challenges that can be a barrier to broader expansion. They are mainly related to the formation of droplets as parameters such as viscosity, pressure, temperature and even the size of the holes must be properly took into account. All this does that the researches on the integration of new ceramic materials, metal or plastic are struggling to succeed.

[8] https://en.wikipedia.org/wiki/Inkjet_printing, Accessed 2016 July 01

4.3.2 Associated technologies

The main processes using this technique is distinguished of each other in particular by the number of print heads, more they will be, faster will be the printing rate. In some cases this head multiplication also allows a combination of different materials to achieve specific mechanical properties structures or multicolour structure. It also allows to print the part and the support structure of different materials. This base material of the support structure also plays a major role in how it is removed, because the parts resulting from this process are generally intended to visual representation or to lost wax casting, the outer surface should therefore not be damaged.

4.3.2.1 MultiJet Printing (MJP) of 3D Systems or 3D PolyJet of Stratasys

This process can project up to three different photopolymer materials in variable proportions, with a resolution of 16 micron layers and accuracy up to 0.1 mm, it provides thin walls and complex shapes a wide variety of colours and physical properties[9].

4.3.2.2 Direct Write Technology (DWT)

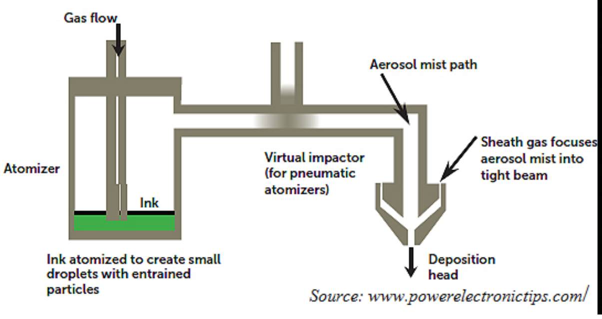


Figure 4.12: Schematic of the aerosol jet process [*powerelectronictips.com*]

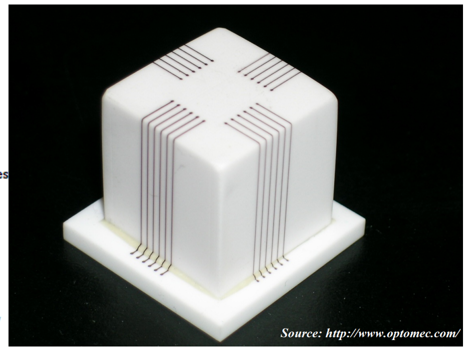


Figure 4.13: 3D silver interconnects (150 μm line width) written over an alumina cube [*www.semitronics.co.uk*]

This other technology also based on material jetting, involving the deposition of functional inks. Aerosol jet printing of "*Optomec*", is one of this. It consists in atomizing the material in nano-particles and mixed them with an inert gas in an aerosol, the aerosol then sprayed on a surface. An annular stream of jetted

[9] www.stratasys.com, Accessed 2016 July 01

gas helps to focus the aerosol spray in a precise way on a specific line (see *figure* 4.12). The materials used can be metal or non-metal and conductors or dielectrics, giving the possibility to print electronics circuits (see *figure* 4.13). However, it is not possible to built a full complex 3D model with this technology, because it is only a 2.5 dimensions. But when properly equipped the deposition of the material on curved surface can be possible[10].

4.3.3 Specifications and materials

(mm if needed)	MJP	DWT
Max part size	$1000 * 800 * 500$	$200 * 300 * 200$
Min layer thick	0.016	0.01
Resolution	high as SLA	very high
Price	150 k€	300 k€
Multi colors	yes	no
Graded material	yes	no
Electronics	no	yes
Materials	Wax, PAEK, Polypropylene, ABS	silver, copper, gold, platinum, polymers, several biomaterials

TABLE 4.5: Benchmark of material Jetting processes

Again, the data in *Table* 4.5 here are indicative for each technology. The "*MJP*" is very interesting because for a resolution equivalent to the proceeds by "*Vat Photopolymerization*" discussed in *Section* 4.1, it has a wide range of colour and for more affordable price because it does not use laser beam, which is considerably expensive. However, its range of materials is limited because of the difficulties of viscosity management for the creation of droplets. The "*DWT*"

[10] www.optomec.com/, Accessed 2016 June 28

for itself, offers the unique feature in additive manufacturing of printing electronic circuits of conductors or semiconductor materials.

4.3.4 SWOT analysis

In this section is given a **SWOT** analysis of the overall "Material Jetting" processes with respect to needs that may face the teams of production and development of Valeo THS.

strengths	WEAKNESSES
1. High resolution 2. Graded material 3. Low price compared to VP 4. Electronic circuits printing 5. Multi color structure 6. Soluble support structure	1. Short range of materials 2. Low mechanical properties 3. No full 3D metal printing 4. Need a support structure
opportunities	**threats**
1. Low cost representation model 2. Streamline time-to-market 3. Easier manufacturing of electronics 4. Master pattern for lost wax molding 5. Reduced environmental impact, less wastes 6.	1. Can't build functional models 2. Difficulties to develop good materials 3. New design rules 4. Not strong enough for stamping tools 5. Technological obsolescence in the machines due to new developments

Table 4.6: Material Jetting SWOT

4.4 Binder Jetting

Definition by ASTM [8]: *an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.*

4.4.1 Description of the principle

Binder-jetting processes also use print head to print the 3D model, but instead of jetting the structure material like in *section* 4.3, here it is "glue" which is used as printed material to hold powder together in the desired shape (see *figure* 4.14). This process starts, by firstly, deposit a thin layer of powder. The print head is then used to selectively jet a glue pattern onto the powder, which then form the first layer. The next layer of powder is deposited and glue is printed again. This action is automatically repeated until the part is completely built.

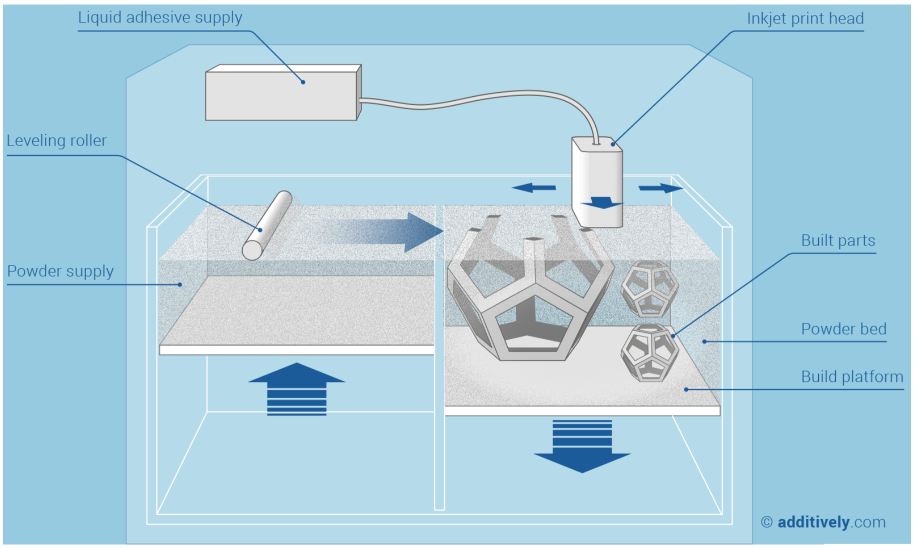


FIGURE 4.14: Binder jetting system [*www.additively.com*]

4.4.2 Associated technologies

Binder jetting technology was developed in the early 1990s by *"MIT"* under the name 3D printing (3DP), it has subsequently been licensed and commercialized under various forms by several companies.
"ZCorp, Inc". (now acquired by *"3DSystems"*) was one of the first of them, its machine was used to build concept models in plaster powder using a low viscosity water-based binder. The new *"3D Systems"* machines based on ColorJet Printing

(CJP), use acrylate powder and can print in the full spectrum of colors[11].

"ExOne" is an other big manufacturer of machines based on binder jetting. They provide machines that use metal or silica sand powder, with a binder in polymer material, it can be used for sand casting applications[12].

The new company *"Voxeljet"*, provides machines also based on BJ. They use foundry sand and acrylic polymer powders for functional or concept models, investment casting patterns, and sand casting applications. They offer the machine with the largest building area which can produce continuously several series of parts[13].

There are also several other variants of BJ. The *"HP Multi jet Fusion technology"* just put on the market, combines the bonding of powder and the selective fusion of bonded areas, thanks to a source of energy. The output part has one of the best Mechanical properties of all AM processes[14].

[11] www.3dsystems.com/, Accesed 2016 June 26
[12] www.exone.com/, Accesed 2016 June 26
[13] www.voxeljet.de/, Accesed 2016 June 26
[14] www8.hp.com/, Accessed 2016 June 26

4.4.3 Specifications and materials

(mm if needed)	Binder jetting
Max part size	$4000 * 2000 * 1000$
Min layer thick	$0,1$
Max speed (mm/h)	20
Resolution(DPI)	$600 * 600$
Price	110 k€
Multi colors	yes
Materials	Steel, bronze, ceramics, PA12, glass, inconel silicasand, PMMA, inorganic sand

TABLE 4.7: Benchmark of binder Jetting processes

The data in *Table* 4.7 are indicative and are subject to changes. This MJ process offers a full selection of colours which is very interesting for the representation models. Despite its wide range of materials, it still struggles to provide functional parts with good Mechanical properties and especially a good surface roughness. Set out the post treatment, it practically do not uses energy and raw materials can be recycled at will. Making it a less expensive process for acquisition and use.

4.4.4 SWOT analysis

In this section is given a **SWOT** analysis of the overall " Binder Jetting" processes with respect to needs that may face the teams of production and development of Valeo THS.

strengths	weaknesses
1. Support structures aren't needed 2. Largest build area 3. High deposition speed 4. No high-powered energy, no risk 5. Low cost machines 6. Full colour printing	1. Poor mechanical properties 2. Poor accuracy 3. Post-curing usually needed 4. Poor density, need for infiltrating 5. Cost of powders 6. Not suitable for thin metal sheets
opportunities	**threats**
1. Assemblies of parts and Kinematic joints can be fabricated 2. Injection mold with conformal cooling channels 3. Visual prototypes 4. Patterns for investment casting 5. Virtually all powder materials 6. Numerous parts can be built at one time	1. Not suitable for functional parts 2. Difficulties to develop good materials 3. New design rules 4. Not strong enough for stamping tools 5. Technological obsolescence of the machines due to new developments

Table 4.8: Binder Jetting SWOT

4.5 Sheet lamination

Definition by ASTM [8]: *an additive manufacturing process in which sheets of material are bonded to form an object.*

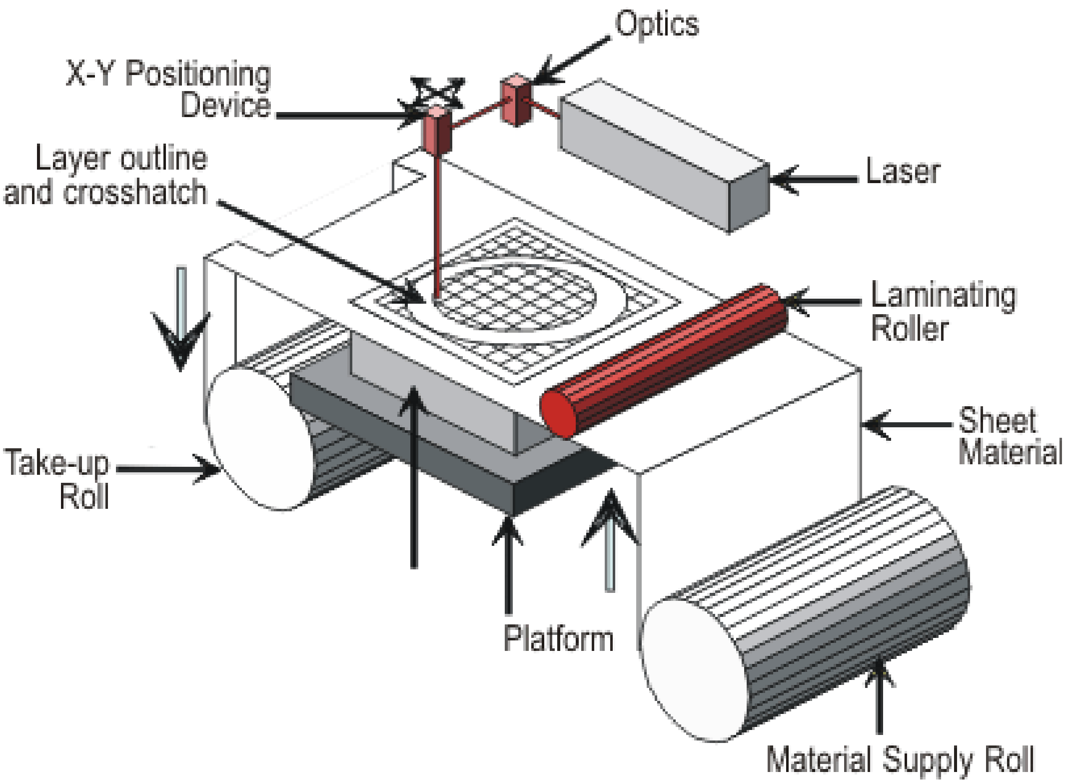


FIGURE 4.15: Sheet lamination system [*www.azom.com*]

4.5.1 Description of the principle

Sheet lamination is a hybrid process that combines the subtractive manufacturing for obtaining layers and additive manufacturing for the bonding and assembly of the final object. It is important to note that the layers can be three-dimensional, unlike other additive processes. It was one of the first AM technologies to be marketed in 1991 by "*Helisys*" (now "*Cubic Technologies*") under the LOM (Laminate object manufacturing)[15] name. The principle is simple, generally a complex 3D object is broken into several pieces to be machined by CO2 laser or micro-milling then bonded to each other by the contribution of energy or binder (see *figure* 4.15).

4.5.2 SL associated technologies

There are further SL technologies other than "LOM", they are mostly differentiated by the way sheets are bonded together and the associated base materials.

[15] www.cubictechnologies.com/, Accessed 2016 June 24

4.5.2.1 Ultrasonic AM: Solid State Bond (SSB)

This sub process of SL is based on ultrasound, it allows to paste the layers together only by vibration without any heat source or adhesive substance (see *figure* 4.16). Ultrasonic welding of metal sheets is obtained from the mechanical vibrations by a Sonotrode[16]. The high frequency vibrations are known as ultrasonic because they are in the range frequencies of 20 and 70 kHz [10]. The sonotrode locally transfers the vibration by hitting one of the metal sheets kept together under pressure. The friction of the two elements causes sufficient heating to create an intermolecular fusion, and ultimately weld the parts together (see *figure* 4.17).At the end of the bonding process a micro milling operation help adjust the tolerances and get good surface finishes.

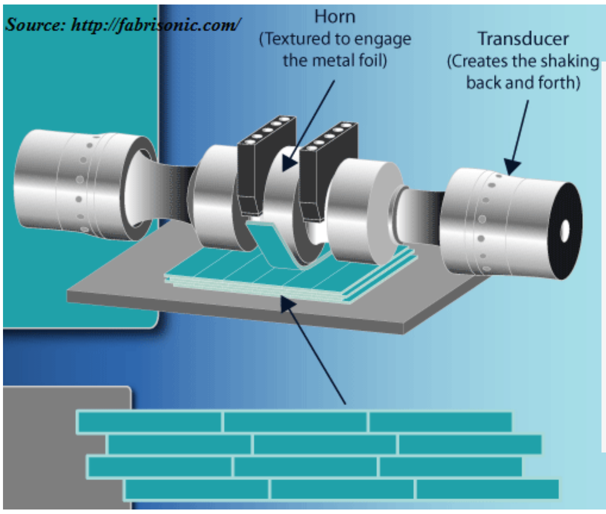


FIGURE 4.16: Ultrasonic AM system [*fabrisonic.com*]

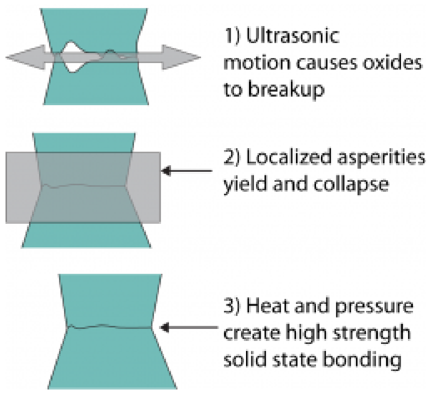


FIGURE 4.17: Ultrasonic AM principle

This process commercialized by Fabisionic[17], presents several advantages, the direct integration into the structure of electronic devices (sensors, actuators, communication circuits, etc.) or even "intelligent materials", without risk of damaging by temperature. This low temperature welding allows also the building of multi-material structure.

[16]The sonotrode is a metal part or tool which creates ultrasound, and restores this vibratory energy in an element (gas, liquid, or solid tissue)

[17]http://fabrisonic.com/, Accessed 2016 June 24

4.5.2.2 Stratoconception

This process commercialized by CIRTES[18], involves an automatic decomposition of the 3D model, in a series of additional layers called "strata", in which positioning inserts are placed. These layers are then produced by micro-milling, laser cutting or hot wire cutting. The assembly can be done through inserts, bridges or nesting, then the whole is laminated to obtain the final object.

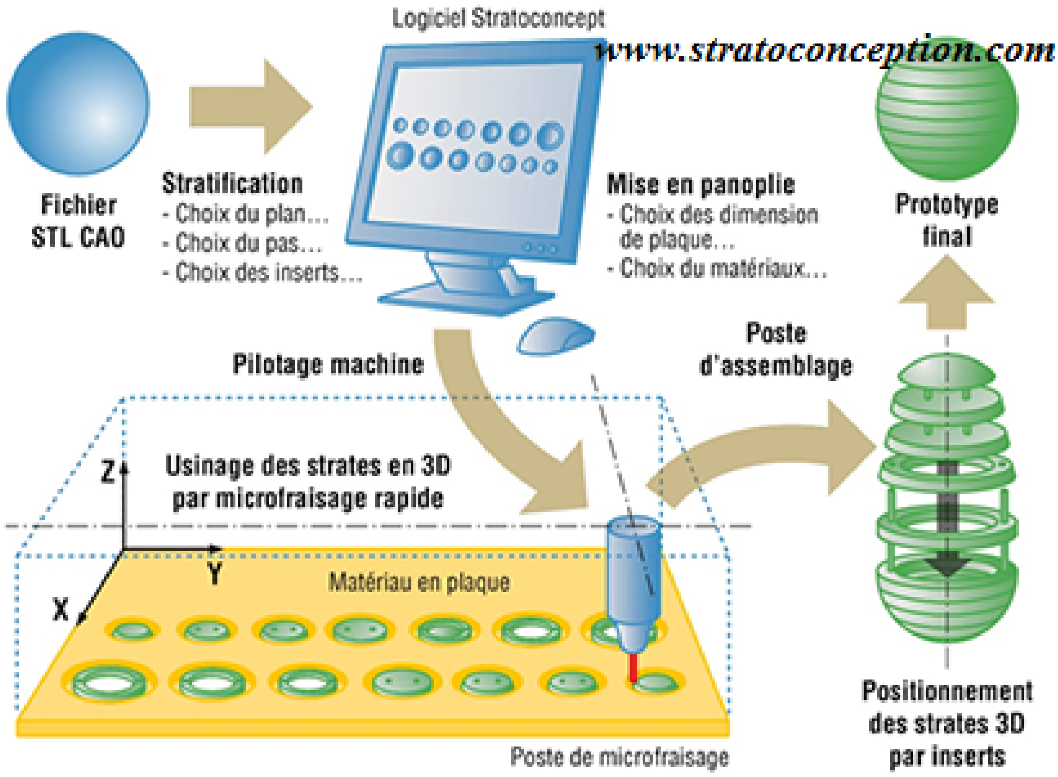


FIGURE 4.18: Stratoconception system [*www.stratoconception.com*]

This process has no limitation in terms of materials, shapes and dimensions. But its biggest defect due to its bonding method, is in the inhomogeneity and anisotropic parts obtained. Which greatly reduces the mechanical characteristics.

4.5.2.3 Paper Sheet Lamination (PSL)

This sub SL process is completely dedicated to the manufacture of representation model. It used A4 or letter paper sheet as the base material, they are cut and then bonded to one another to construct the final object. Each sheet may be covered

[18] www.stratoconception.com/, Accessed 2016 July 04

with a different colour which allows to obtain completely colour model. This easy and light process is suitable for office machine (*MCOR*[19] and *Wuhan Huake 3D*[20]).

4.5.3 Specifications and materials

(mm if needed)	Solid-State Bond	PSL	Stratoconception
Max part size	$1800 * 1800 * 900$	$600 * 400 * 500$	$5000 * 2500 * 500$
Min layer thick	$0,025$	0.1	–
Price	na k€	40 *k*€	na k€
Multi materials	yes	no	yes
Multi colors	no	yes	no
Bonding agen	ultrasonic	glue	glue
Materials	steel, copper, Alu	Papers	Polymers, metals, wood

TABLE 4.9: Benchmark of Sheet lamination processes

The data presented here in the *table* 4.9 are guidelines and are subject to changes. For each process, it rarely exist machines that combine the same time all the best features. A compromise is generally made according to the application to which the machine is intended to be used.

Compare to PBF processes (see *section* 4.6) which also produce metal parts, SSB produces parts without residual warping or thermal stress, because it does not use heat source for building. The internal structure of the material is then not altered. But overall mechanical properties of the parts obtained by SL may be limited in the border areas between layers if there is a bonding default. This

[19]mcortechnologies.com, Accessed 2016 June 22
[20]www.huake3d.com/en, Accessed 2016 June 22

method is, however, ideal for the manufacture of molds and shaping dies. It could be well suitable (subject of a thorough study) for the realization of "*Lucie*" magneto or hydroforming die.

4.5.4 SWOT analysis

In this section is given a **SWOT** analysis of the overall " Sheet Lamination" processes with respect to needs that may face the teams of production and development of Valeo THS.

strengths

1. Do not need support structures
2. Good density and surface finish
3. Wide range of materials
4. Full colour desktop machine
5. Large build area
6. Good surface finish

weaknesses

1. Poor bonds between layers
2. Generation of waste
3. Inhomogeneity and anisotropic parts
4. Not able to form thin metal sheet
5. High acquisition cost

opportunities

1. Ability to weld dissimilar metals
2. High manufacturing speeds
3. Mold of complex internal geometries
4. Ability to embed electronics in part
5. Good materials
6. Cheap stamping die

threats

1. Technological obsolescence in the machines due to new developments
2. Long machine depreciation time
3. New design rules
4. Not suitable for mass production
5. -
6. -

TABLE 4.10: Sheet lamination SWOT

4.6 Powder bed fusion

Definition by ASTM [8]: *an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.*

4.6.1 Description of the principle

Under the effect of a heat source, the powder material into a bed is selectively fuse together, forming the cohesion of the 3D part, layer by layer (see *figure* 4.19). For good results, the particles constituting the powder should be fine (about 50 μm diameter) and uniform. The heat source must be well controlled and usually comes from a laser radiation. Almost all materials (polymers, metals, ceramics, composites) can be used with this principle. Exception for materials whose fusion is irreversible such as thermosetting polymers.

4.6.2 Associated technologies

There are several systems applying laser sintering or melting, with as main differences the range of the basic materials used, the origin and the power of the energy source.

4.6.2.1 Selective Laser Sintering (SLS)

Sintering is a process of heating a powder without melting it. The material remains in the liquid/solid phase and only liquefied superficially at the grain boundaries. The SLS developed by "*3DSystems*" is certainly one of the best known and most widespread of sintering technology[21]. From a numerical model, it is the realization of a real functional part by solidifying powder layer by layer. This solidification takes place thanks to the energy bring by the carbon dioxide (CO2) laser beam. The complete building chamber is also heated and supplied with inert gas to reduce thermal stresses and deformation of the part after building.
There process includes a wide range of polymers and sand. They are now many

[21] www.3dsystems.com/, Accessed 2016 July 04

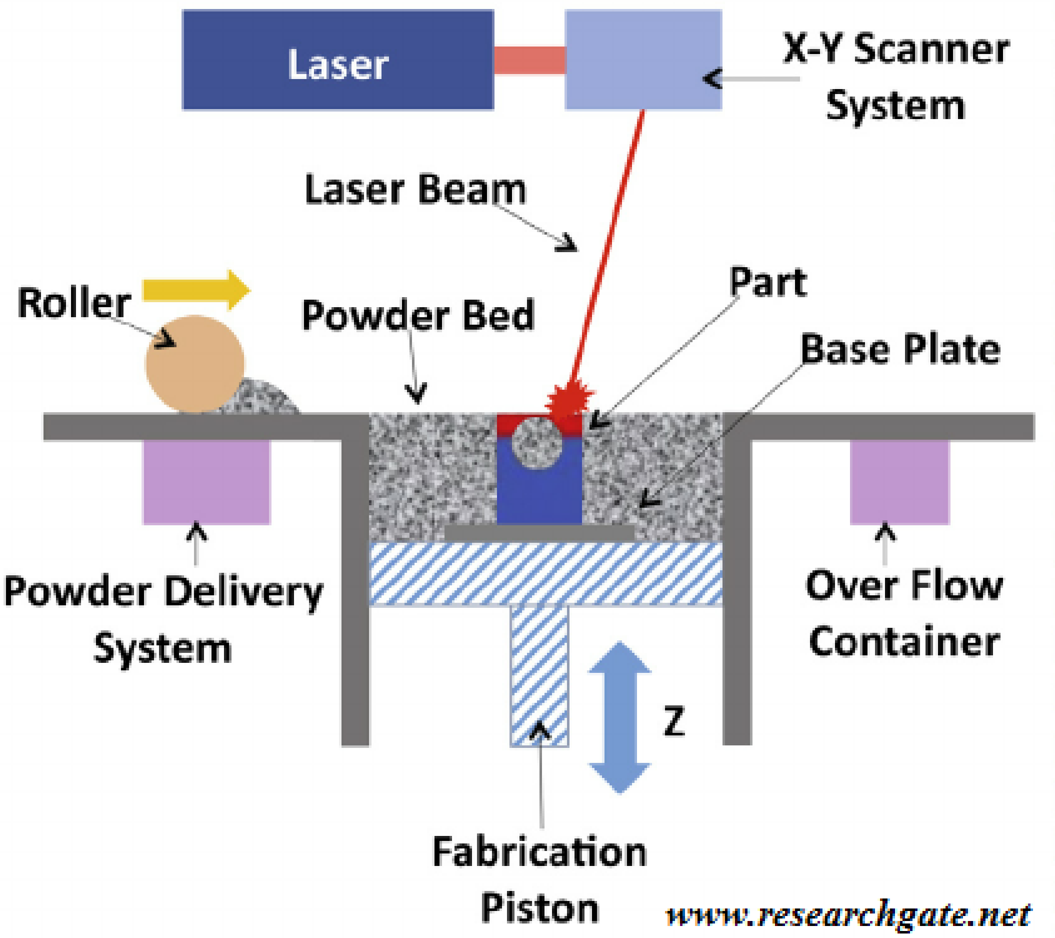


FIGURE 4.19: Schematic of Powder Bed Fusion system [*www.researchgate.net*]

manufacturers that provide SLS on different names, "*EOS*" is the only one to provide PEEK polymer[22], which has best mechanical characteristics. Each manufacturer has its own base material and they are usually dearer than conventional materials.

4.6.2.2 Direct Metal Laser Sintering (DMLS)

The *DMLS* was developed by the German company *EOS*[23] in the late 1990s, it uses exactly the same process as the previous SLS. The main difference is, as its name indicates in the materials used. The metal and some ceramics can be printed thanks to a more powerful source of energy that is here a laser optical fiber doped with ytterbium [1].
DMLS is suitable for making either large or small sizes parts with a high geometric complexity, they can be directly functional or serve as master pattern for

[22]www.eos.info/material, Accessed 2016 June 03
[23]www.eos.info/, Accessed 2016 June 28

molding. Like for polymer SLS a major challenge of sintering remains the control the porosity which can be up 45 % of the total volume and is not distributed uniformly, which may deteriorate significantly the mechanical characteristics of the part. Some manufacturers still claim they can reach a densities of about 99, 5 %. One also note that unlike the polymer SLS, DMLS need to build a support structure for holding complex parts during manufacturing, once more, the removal of this structure can weaken the part.

4.6.2.3 Selective Heat Sintering (SHS)

This technology developed by the Danish company "*Blueprinter*" is also based on the same principle as the SLS. The only difference is that here the energy source is not a laser but a lower power print-head. SHS is limited to thermoplastic polymeric materials and is only suitable for prototyping purposes. The advantage here is that the machines can be smaller in size and installed everywhere without any danger, they are directly operational no need to preheat[24].

4.6.2.4 Selective Laser Melting (SLM)

The melting involves the transition to the liquid state of a solid body thanks to the heat. The processes like "*SLM Solution*"[25] using this principle do heat one or more powder materials beyond their melting points (the liquid phase is reached) and after cooling they form a single solid. What is different from sintering, where the materials do not reach their melting temperatures (it remains in the liquid/solid phase). The main advantages of using the melting methods is that they do not require precise control of the heat source and do not need a support structure (unlike sintering). The parts obtained have a density close to those obtained by molding. As limit, one note that after liquefaction, if the material is wet, it will infiltrate the adjoining powder and alter the surface definition. The SLM is not suitable for thin work-pieces ($<$ 0.15 mm for metals, 0.3 mm and 0.7 mm ceramic for plastics).

[24]blueprinter-powder-3dprinter.co.uk/, Accessed 2016 June 28
[25]slm-solutions.com, Accessed 2016 June 28

4.6.2.5 Electron Beam Melting (EBM)

The PBF process of melting by electron beam (EBM), developed by the Swedish company "*Arcam AB*", is similar to SLM process with one distinct difference: EBM uses as heat source a high power electron beam instead of the laser used by the other. This electron beam is obtained by heating under vacuum a tungsten filament. These free electrons are then accelerated and directed by electromagnets to be thrown at high speed on the surface of the powder. The powders used with this technology must be based on conductive materials without which no interaction with the electron beam is possible.

For the EBM there is a first phase of preheating the powder (between 750 and 850^0C for titanium alloys). Throughout the process, the manufacturing chamber is kept under vacuum and once the part is complete, it is slowly cooled by means of a controlled supply of helium gas. This carefully controlled environment allows to maintain proper internal structure of the material[26].

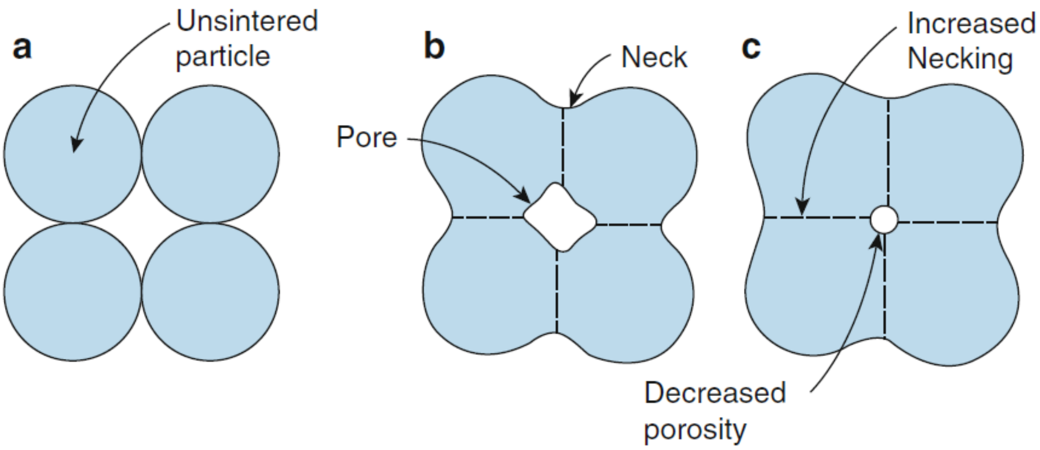


FIGURE 4.20: **(a)** Solid-state sintering, **(b)** at half of the absolute melting temperature, **(c)** As sintering progresses, neck size increases and pore size decreases [1]

[26] www.arcam.com/, Accessed 2016 July 03

4.6.3 Specifications and materials

(mm if needed)	SLS	SHS	DMLS	SLM	EBM
Max build area	$550 * 550 * 750$	$200 * 157 * 150$	$400 * 400 * 400$	$700 * 280 * 320$	$350 * 380 * 380$
Min layer thick	$0,06$	0.1	0.01	0.02	0.05
Min feature size	$0,12$	0.5	0.15	0.2	0.1
Build rate	High	$<$ SLS	$=$ SLS	$=$ DMLS	$<$ SLM
Price	300 k€	26 k€	480 k€	400 k€	700 k€
Porosity	99.5%	$<$ SLS	99.5%	99.8%	100%
Support structure	no	no	no	yes	na
Materials	PA11, PA12, PA6, PS, PP, PEEK, Wax, coated Sand, Carbon filled, Glass filled	Thermoplastic powders optimized to work on SHS	Steel, Ti, Al, CoCr, Inconel, gold, Ni, Metal alloy	Steel, Ti, Al, CoCr, Inconel, Ceramics, Ni, Bronze, Metal alloy	Ti, CoCr, Steel, Alloys

TABLE 4.11: Benchmark of powder bed fusion processes

The data presented in the *table* 4.11 are guidelines and are subject to changes. For each process, it rarely exist machines that combine at the same time all the best features. A compromise is generally made according to the application to which the machine is intended to be used.

All these processes of PBF are based on the principle of minimizing the free energy of the powder particles, as shown in *figure* 2.21. The energy is proportional to the total surface of the particles. By heating, the particles stick together and eventually merge to reduce their outer surfaces. The uniformity of the particle size and a thermally controlled environment help generates better results.

The SLS involves heating just beyond half of fusion energy of the material, it provides more uniform structures and offers better extension characteristics with better surface finish, than the processes by fusion. It also prints the polymeric materials. However, the porosity of the final structure and the difficulty to control the building temperature are their mains drawbacks. They are any how in the same price range as the SLM (for the similar characteristics), which has good density and faster building rate, but poor surface finish. The EBM is a little more expensive, because it is the fastest and it produced best mechanical characteristics.

The last important point of PBF concerns the recycling of non-fused powder. The build chamber being continuously maintained at a high temperature, it affects all the powder contained in the bed. And its becomes unusable with time. Although manufacturers announce the complete recycling of the unused powder, it is only valid a limited number of times.

4.6.4 SWOT analysis

In this section is given a **SWOT** analysis of the overall " PBF" processes with respect to needs that may face the teams of production and development of VALEO THS.

strengths	weaknesses
1. Wide range of materials	1. High acquisition cost
2. Parts of complex geometry	2. Poor surface finishes need a finish process
3. Good mechanical properties	3. Thermal stress and warping
4. Density close to molding	4. High energy demand
5. Less production waste	5. Dear and non standard raw materials
6. Recycling of non-fused powder	6. Limited build area

opportunities	threats
1. Time and cost saving for complex forms and small series	1. Technological obsolescence in the machines due to new developments
2. Achievements of new designs	2. Not suitable for mass production
3. Mold of complex internal geometries	3. Long period of depreciation
4. Prototypes for form / fit and functional testing	4. Random mechanical properties
5. Mass optimization	5. New design rules
6. Local production and stock management	6. -

Table 4.12: Powder bed fusion SWOT

4.7 Direct energy deposition

Definition by ASTM [8]: *additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited..*

4.7.1 Description of the principle

This process consists to come up melt the top surface of a metal part using a laser. Simultaneously, a powder stream is projected onto the molten area (see *figure* 4.21). The powder melts on the molten zone and is thereby form a layer which merges with the substrate. Just like the conventional welding, the nozzle mounted on a 4- or 5-axis machine that moving creates welds.

With this process it is only the melting zone which is continuously fed with inert gas (gas surrounding the laser) to always have a better bonding layers and a good final internal structure. The amount of gas used can therefore be significant compared to the PBF where gas is provided only once in the hermetically sealed build chamber.

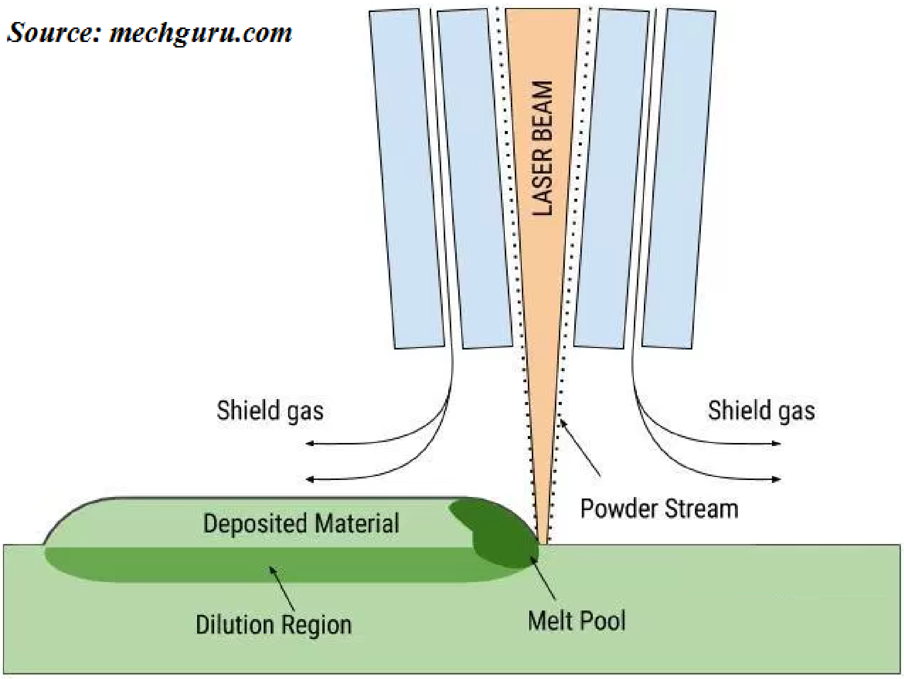


FIGURE 4.21: Direct energy deposition system [*blog.mechguru.com*]

Unlike the powder bed, the powder deposition offers great geometric flexibility. Among others, work on non-planar substrates, which is impossible with the powder bed, because the roller would hit the overflowing areas during the spreading of powder. It is thus possible to completely create a full part, restore worn areas or to provide a surface coating. Besides that, the part not being dipped in the powder bed, it is possible to recover by machining the desired areas during construction. So to combine the additive and subtractive process (hybrid machine) without much trouble.

4.7.2 Associated technologies

This process in theory offers the possibility to work with any type of material, but it is the metals that are commonly used, hence the synonyms DMD (Direct Metal Deposition) and LMD (Laser Metal Deposition) are encountered frequently. The arrival of material in the welding area and the inert gas delivery method constitutes the main differences between the system found on the market. Thus the powder may be supplied laterally or concentric with the laser beam, the material may also be in the form of molten wire rather than powder. Hybrid systems can also be differentiated to all of them.

4.7.2.1 DED : Powders systems

With this system, it is the powder that is blown on the molten are. in the figure 4.22, one can see the two main ways of blowing the powder. They are highly precise and the layer thickness varying between 0.1 mm and a few millimeters. The establishment of the side nozzle is easier but it takes more space while the coaxial nozzle provides a more uniform deposit and better efficiency of fused powder. The best well-known systems are: LENS (Laser Engineering net shaping) from Optomec[27], easyCLAD (*Construction Laser Additive Directe*) from Irepas Laser[28], TLDED (TruLaser DED) from Trumpf[29], POM[30] and RPM[31].

4.7.2.2 DED : Wire feeding systems

For this technology, it is therefore a wire which is added in place of the powder, providing a greater range of materials and a faster process. But the final output is rough and almost always requires re-machining. The residuals stress are also higher compared to the powder deposit. SCIAKY, is one of the manufacturer "*DED-wire*". It offers this technology under the name EBAM (Electron Beam Additive Manufacturing)[32].

[27]www.optomec.com/, Accessed 2016 July 03
[28]www.irepa-laser.com, Accessed 2016 July 03
[29]www.trumpf-laser.com/, Accessed 2016 July 03
[30]www.pomgroup.com/, Accessed 2016 July 03
[31]www.rpm-innovations.com/, Accessed 2016 July 03
[32]www.sciaky.com/, Accessed 2016 July 03

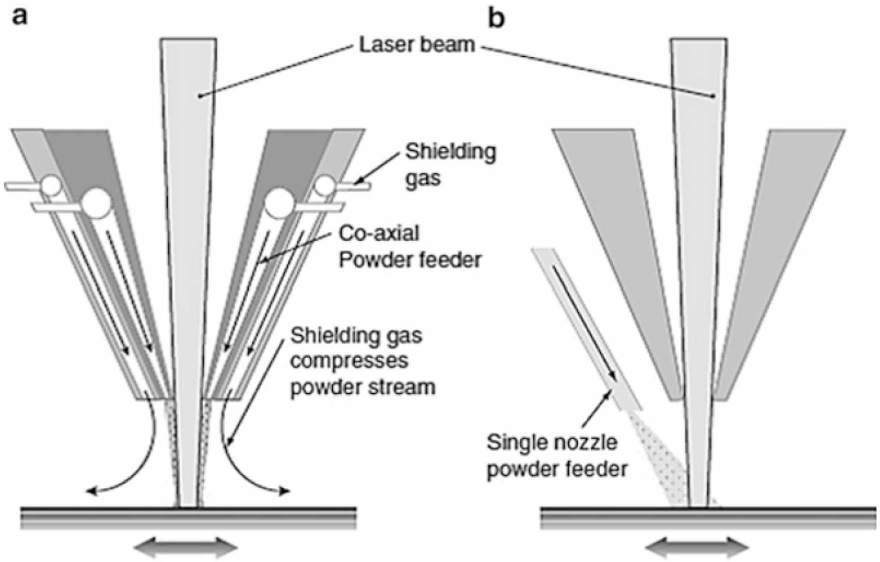


FIGURE 4.22: DED powder supply: (a) coaxial nozzle feeding and (b) single nozzle feeding [1]

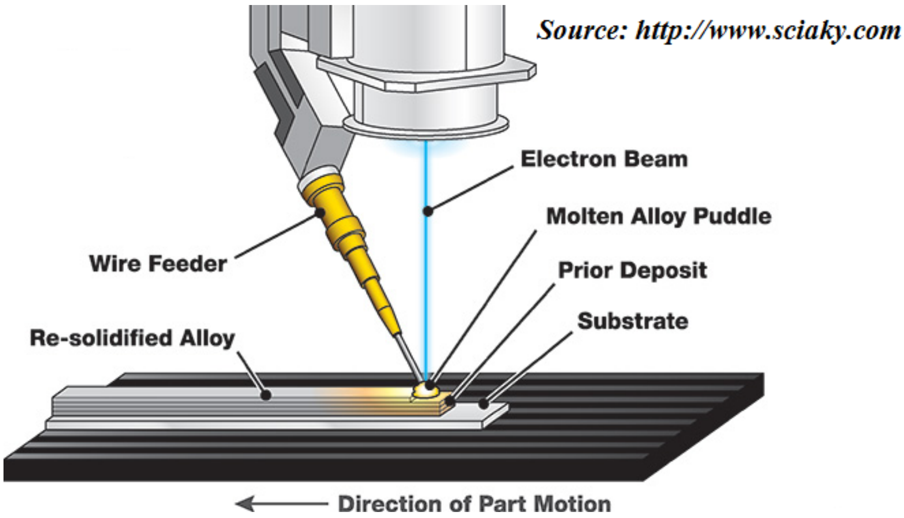


FIGURE 4.23: DED: Wire feeding system [*www.sciaky.com*]

4.7.2.3 Hybrid systems

Hybrid systems are nothing more than a 5-axis conventional milling machine, to what has just been add a tool for powder projection and melting. The establishment and the combination "addition/subtraction" is not obvious and makes it an expensive systems. However, they have the only capacity in additive manufacturing to produce parts with good material, complex and multi-material structure, all this with a finishing similar to machining. "*Trumpf*" offers the possibility to add the additive tool on existing machine, while "*DMG MORI*" offers (*Lasertec 65 3D*), a complete hybrid machine under the name LDW (*Laser Deposition*

Welding)[33].

4.7.3 Specifications

(mm if needed)	Powder DED	Wire DED	Hybrid DED
Max build area	$4000 * 2000 * 1000$	$3800 * 3800 * 3000$	$\phi 600 * 400$
min Track width	$0,1$	1	1.6
building rate	$>$ PBF	Very high	High
surface finish	$<<$ PBF	$<$ Powder DED	$=$ machinig
Price	700 $k€$	$-$ $k€$	$1,500$ $k€$
Density	100%	100%	100%
Multi materials	yes	no	yes
Materials	Steel, Ti, Inconel, Ni, CrCo, Tg, Bronze, Stellite, silica, Cu, Zirconia	Same as PowderDED, with added Al and Al alloys, metal alloys, ceramics	Same as Powder DED

TABLE 4.13: Benchmark of direct energy deposition processes

The data presented here in the table 4.13 are guidelines and are subject to changes. For each process, it rarely exists machines that combine the same time all the best features. A compromise is generally made according to the application to which the machine is intended to be used.

At equal volume, DED machines are less expensive than the PBF (see *section* 4.6), because the technology is limited for some high complex forms and provides

[33]http://en.dmgmori.com/, Accessed 2016 July 03

a poor surface finish (out put hybrids). Yet the parts have a better density and less internal stresses, and the ability to print on non-planar substrates.

4.7.4 SWOT analysis

In this section is given a **SWOT** analysis of the overall "DED" processes with respect to needs that may face the teams of production and development of VALEO THS.

strengths	weaknesses
1. Good and wide range of materials 2. Good internal structure 3. Can merge different material 4. Deposition on non planar surface 5. Functional parts 6. High build rate compared to PBF 7. High building area	1. Expensive machines 2. Need high quantity of inert gas 3. Rough surface finish if no machining 4. High inert gas consumption 5. No plastic models 6. Limited for high complex geometry 7. No desktop machine
opportunities	**threats**
1. Improve resistance to corrosion or wear 2. Repair of mould tool surfaces 3. Deposition of novel materials 4. Reduction of component lead times 5. Reduction of tooling costs 6. functionally graded and multi materials 7. Near net shape	1. Technological obsolescence in the machines due to new developments 2. Not suitable for mass production 3. Long period of depreciation 4. New design rules

TABLE 4.14: Direct energy deposition SWOT

4.8 Synthesis

(mm)	SLA	ME	MJP	BJP	SL	PBF	DED
Build area	XXX	XXX	XX	XXX	XXXX	XXXX	XXXXX
Layer thick.	0, 025	0.178	0.01	0.1	0.025	0.01	0.1
Speed	XXXXX	XXXX	XXX	XXX	XXX	XXX	XXXX
surface finish	XXXXX	XX	XXX	XXX	XXXX	XXX	XXXXX
Price	XXX	XXXXX	XXX	XXXX	XXX	XX	XX
Density	XXXX	XXX	XX	XX	XXXX	XXXX	XXXXX
Multi mat.	XX	XX	XX	X	XXXX	X	XXXX
Multi colors	XX	XXX	XXX	XXXXX	X	X	X
Polymers	XXX	XXXXX	XXX	XX	X	XXXX	X
Metals	X	X	XX	XXX	XXXX	XXXX	XXXXX
Ceramics	XXX	X	X	XXXX	X	XXX	X
Desktop print.	XXXX	XXXXX	XXXX	XXXX	X	X	X

TABLE 4.15: Benchmark of additive manufacturing processes
XXXXX = very high or suitable, ..., **X** = very low or not adapted

Although grouped under a single name, additive manufacturing processes, as shown on the table 4.15, have quite different features and therefore clearly distinct applications. The choice of either process should be after a deep analysis of requirements, particularly since that it can require a consequential investment.

As already presented in generalities (see *Chapter* 2), additive manufacturing should not be seen as an alternative to conventional manufacturing, such as molding or machining. Here we could see that there is no mature AM technology to support the Valeo production rates, sharp quotations or good materials. However by integrating them in a complementary way and at strategic levels of the entire production process, from development to manufacturing stages, one can find a certain profit.

In terms of **fit and form prototypes**, either for design validation, for trade-show exhibitions or simply for communications. The AM process based on polymer are quite suitable because they can significantly reduce the cost and production time. The SLA process will be chosen for its high building rate and its smooth surface finish. While ME process will be chosen for the affordable cost and suitability to be installed in every environment, but with a rough surface finish and a porous structure. For full colour models the right process will be the BJP.

For the need of further more **functional prototypes** that can be used for tests and validations, resins filled with ceramic of SLA process or the polymers found in the ME or PBF processes, offer excellent mechanical properties and does not require the construction of molds or special tools.

For end use parts, two ways of doing stand out clearly. The first is through **direct manufacturing**, processes based on metals like PBF or DED, nowadays allow to obtain mechanical characteristics close of the forging. This opens the door to more complex designs (by topological optimisation) or realization of small series, ranging from one to a few hundred parts. The quality concerns particularly in terms of surface finish, are lessened or abolished by an additional machining or the use of hybrid machines, although expensive.

The second is **indirect manufacturing** by molding, stamping or others, they are widely used here at VALEO and can also be improved by additive processes. Masters pattern in wax of excellent quality can henceforth be obtained in minutes with SLA, ME, MJP or BJP. Molds or matrices can be optimized and made with cooling channels close to functional surfaces (conformal cooling) with SL, PBF or DED. These same tools or conventional ones can be repaired and extended life through DED recharge processes.

Chapter 5

Magnetoforming and hydroforming technologies

In the new forming technologies, which are currently revolutionizing the industrial world, there is apart from additive manufacturing processes, the high speed forming techniques primarily based on the principle of high power pulsed.

This principle was set out for the first time in Germany by Erwin Marx in 1923. Its industrial applications are, however, relatively new. The Idea that lies behind helps simply to produce very high powers by temporally compressing a much smaller energy, usually stored in electrostatic or magnetic forms. The power is by definition the energy divided by time, an energy of a joule ($1\ J$) liberated in a billionth of a second ($10^{-6}\ s$), produces one billion watts ($1GW$).

Regarding the forming of flat or tubular thin metal sheets, this high power can be used in different ways to generate strong currents and/or voltages, in a single pulse or a burst of successive pulses. The deformation force that results is so powerful that it moves the sheet in a viscoplastic state, and then accelerated against the forming die. The process is extremely fast (a few milliseconds) and isothermal (slight temperature variation but not significant).

5.1 Magnetoforming

The electromagnetic forming (EMF) is a cold deformation process of metal by the magnetic field. The application of intense pulsed magnetic field on an electrically conductive material, made it suffer enough pressure (up to $5 * 10^7\ Pa$) that easily overcome its yield strength and allows its forming. [11].

This process is addressed only to conductive materials and needs only one forming die because the other one which generate plating force is replaced here by induction created by the variable magnetic field. This gives the possibility of more complex shapes than with conventional stamping. The size and thickness of formed metal sheets (up to 2 mm for steel and 5 mm for aluminium) directly depend on the size and power of the inductors. The cycle time of a few seconds depends primarily to the charging time of the energy source because the discharge time is extremely short.

5.1.1 Description of the principle

The electrodynamic, an Ampere fundamental discovery, shows that two neighbours and parallel conductors cables, travelled by current in same or opposite directions attract or repels. It's exactly the same principle that is used here. By penetrating the coil (see *figure* 5.1) with a sinusoidal high intensity current (approximately 100 kA), it arises in the vicinity thereof, a variable magnetic field. This will generate in the skin depth of the conductive sheet metal an induced current in the opposite direction to the one that excited the coil, so that the two bodies repel. The coil being fixed, the sheet will be pressed against the die placed opposite.

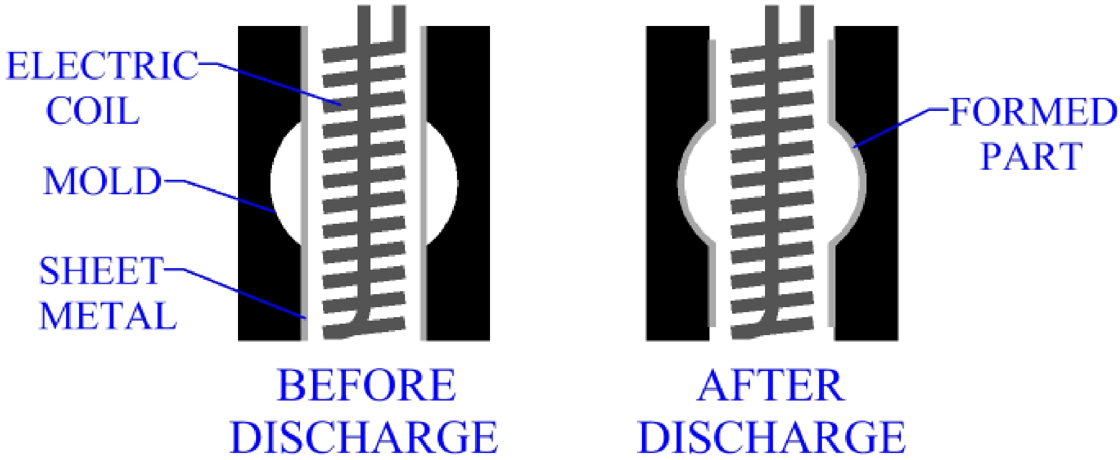


FIGURE 5.1: Magnetoforming [*thelibraryofmanufacturing.com*]

5.1.2 Specifications

	EMF
Max build area	Limited by inductor
Pressure	1500 bar
Steps	1
Max sheet thick.	2 mm for steel and 5 mm for aluminium
Surface finish	smooth
Drilling	yes
welding	yes
Disimilar materials	yes
Materials	conductive materials

TABLE 5.1: Electromagnetic forming general specification

5.1.3 SWOT analysis

strengths	weaknesses
1. Use a single die 2. No warping 3. One step process 4. Clean process, no lubrication 5. Good surface finish 6. Cutting and perforation in same operation 7. Small radii and complex geometries	1. Experimental technology 2. Only conductive materials can be 3. Limited thickness 4. No plastic forming
opportunities	**threats**
1. Reduction of tooling cost 2. Faster realization of tooling 3. Quick prototyping of new designs 4. functionally graded materials 5. Near net shape 6. Designs with fine details and sharp edges	1. High voltages and currents can cause several damages 2. Not yet suitable for mass production 3. New design rules 4. - 5. - 6. -

Table 5.2: Magnetoforming SWOT

5.2 Electrohydraulic forming

Unlike EMF, here the high power discharge is released into a forming tank containing water (liquid transmitter). This discharge created as a shock wave that drives the sheet metal against the submerged forming die. The metal sheet is not necessarily conductive, the strain rates are similar but the efficiency of EHF is almost two times higher than the EMF [12].

5.2.1 Description of the principle

The pulses generator is substantially the same as that of magnetoforming, the magnetic field coils are replaced here by electrodes between which the discharge takes place. We will not go into details in the complex phenomena that occurs during the creation of the shock wave between these electrodes. In short, when the capacities that store energy are short-circuited with electrodes, there is creation of a discharge plasma in the water that converts electrical energy into internal energy (heat movement, ionization, dissociation and agitation of particles), electromagnetic energy (ultraviolet, infra-red and visible) and mechanical energy (shock wave, compression and set in motion the elements of the middle) [12]. It is the latest phenomenon that is most important and that will contribute to the deformation of sheet metal. To initiate the electric arc a thin conductive wire is often used (see *figure* 5.2).

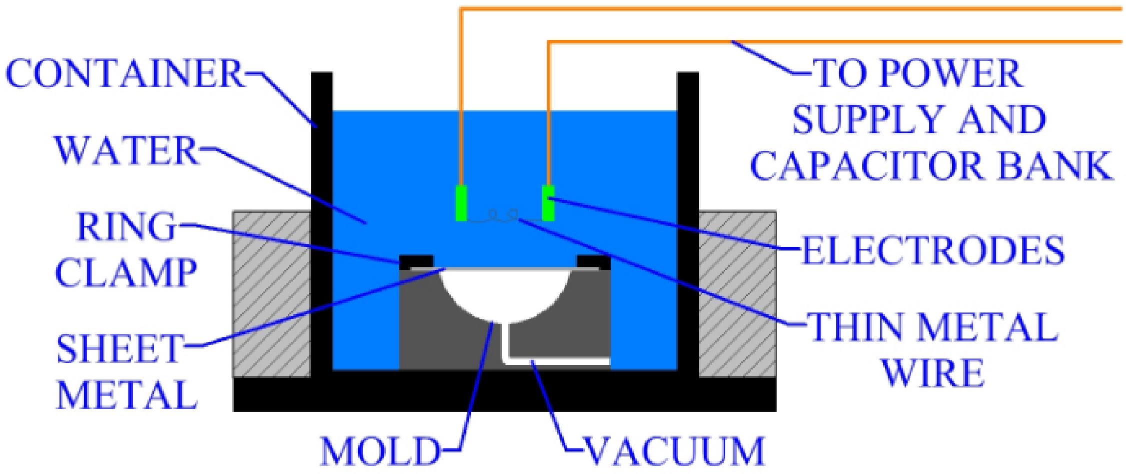


FIGURE 5.2: Electrohydraulic forming [*thelibraryofmanufacturing.com*]

A variant of this technique does not use the shock wave but simply the water pressure (up to 3000 bar) and the fact that it incompressible)(see *figure* 5.2). It is very suitable for the forming of pipes and complex applications, ie difficult demolding, material hard to form.

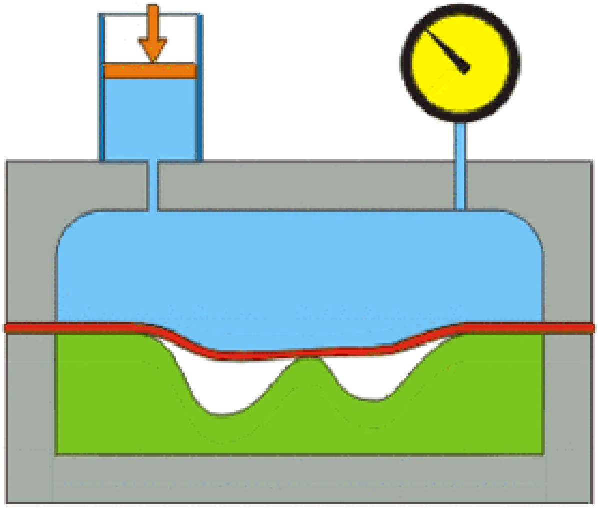


FIGURE 5.3: Hydroforming [*fr.wikipedia.org*]

5.2.2 Specifications

	EHF
Max build area	no limitation
Pressure	3000 bar
Steps	1
Max sheet thick.	4 mm for steel and 10 mm for aluminium
Surface finish	smooth
Drilling	no
welding	yes
Disimilar materials	yes
Materials	all materials

TABLE 5.3: Electrohydraulic forming general specification

5.2.3 SWOT analysis

strengths	weaknesses
1. Use a single die 2. No warping 3. One step process 4. clean process, no lubrication 5. Good surface finish 6. Small radii and complex geometries 7. Equipment has small footprint	1. Experimental technology 2. Limited thickness
opportunities	**threats**
1. Reduction of tooling cost 2. Faster realization of tooling 3. Quick prototyping of new designs 4. Functionally graded materials 5. Near net shape 6. Designs with fine details and sharp edges	1. High voltages and currents can cause several damages 2. Not yet suitable for mass production 3. New design rules

Table 5.4: Hydrofoming SWOT

5.3 What could we learn?

	Magnetoforming	Hydrofoming	Stamping
Max build area	Limited by inductor	same as EMF	> EMF
Pressure (bar)	1500	2000	-
Steps	1	1	many
Stamping die	1	1	2
complexity	High	> EMF	< EMF
Forming rate	high speed	high speed	quasi-static
Surface finish	smooth	smooth	< EMF
Drilling	yes	no	no
welding	yes	yes	no
Disimilar mate.	yes	yes	no
Materials	conductive materials	any materials	any materials

Table 5.5: Magnetoforming, Hydrofoming and Stamping benchmark

The use of a single die for forming, is a big advantage in terms of cost and lead time of tooling production, especially since the process is done in one step. No need for 8, 10 or even 12 successive steps, which is equivalent to 16, 20 or 24 dies in conventional stamping currently used in Valeo production facilities. The switch to a single step is made possible by the move of the material in a viscoplastic state, which makes it more malleable. This situation presents other advantages including low residual stress, no warping and cold processing. The elastic property is then improved.

Using these methods, however, causes some technical challenges, including the establishment of vacuum in the matrix for optimal quality, power electronic, the safety considerations related to the use of high voltages, continuous production capacity , control of internal phenomena and many others. All these issues make the industrials reluctant to adopt these technologies[13].

Things are changing, during this work, we have seen two industrial suppliers offering solutions based on these methods (Bmax[1] and Borit[2]). At Valeo these processes could be used for the realization of piping, electronics and batteries cooling, or platelets for exchanger. Directly in multilayer aluminium sheet, for the purpose of manufacturing prototypes or small series.

[1] www.bmax.com, Accessed 2016, 15 July
[2] www.borit.be, Accessed 2016, 15 July

Chapter 6

New Process and general debate

From the new processes studied, we have devised an innovative approach that combines the best way their advantages in order to meet our need. The tooling (die) will be realized in additive manufacturing, with the investigation of the possibility to optimize its shape in order to reduce its mass and gain in material costs. This tool will then be used firstly in magnetoforming and secondly in hydroforming for forming the "TC" plates. As the goal is to challenge the technology already in place, a comparative study of the results will be given at the end.

6.1 Design iterations

The study started with a initial design (see *figure* 6.1 and 6.2), which has been changed during many iterations to reach the final design (see *figure* 6.3 and 6.4). These changes were done in order to integrate the parameters of the testing results:

- The channels have been expanded so that the local strain rate be less than 50% and so that the material does not crack during the magneto or hydroforming.
- The tabs of the die has been added to improve its positioning in the magnetoforming machine and ensure repeatability of the production.
- The top radius of the central pocket is increased from 0.25 to 0.9 mm for avoiding the cracking of the sheet metal.

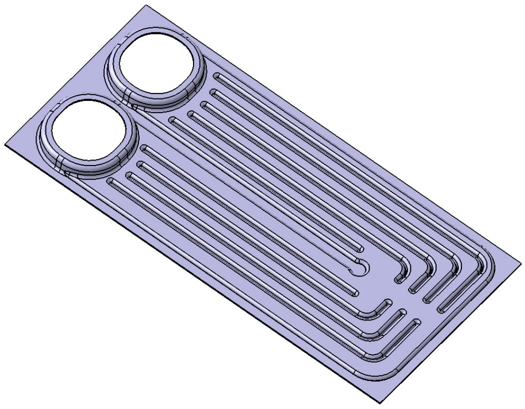


FIGURE 6.1: Initial part design

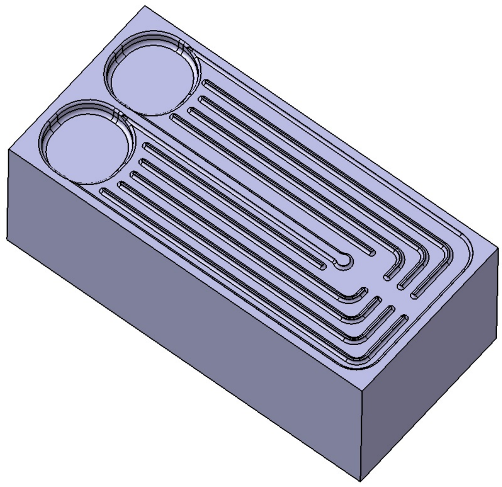


FIGURE 6.2: Initial die design

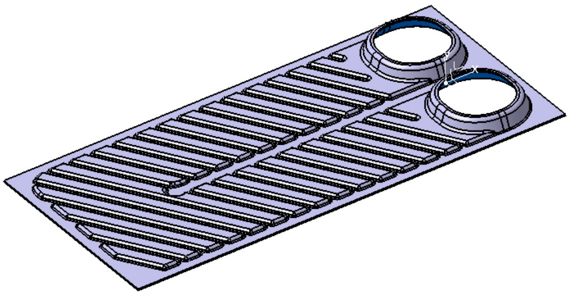


FIGURE 6.3: Final part design

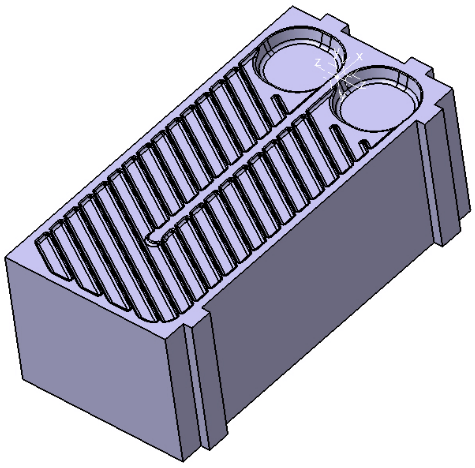


FIGURE 6.4: Final die design

6.2 Die optimization

The topology optimization consists of finding the ideal material distribution in a given volume under specific constraints. The main objective for a stationary part as our die, is the reduction of necessary material for its forming, which would reduce its final cost.

6.2.1 Specifications

The constraints that concern us here are mainly:

- The load applied to press the sheet metal on the active area of the die, here it is 2000 *bar*, evenly spread over the entire surface (see *figure* 6.5).

- The positioning, tart is hold regarding normal direction on the red surfaces (see figure 6.6)
- The flatness of the brazed surfaces (see figure 6.8) has to be below $1/10mm$, it is the difference between the max displacement and the average displacement between two parallel plans (see figure 6.7)
- The design space is the whole volume of the initial design, height of the die = 30
- The die material is stainless steel 316L, it is isotropic, Poisson's Ratio = 0.3, the life of the die is 90 000 cycles, fatigue limit = $Rm/2$ (Rm: tensile strength)

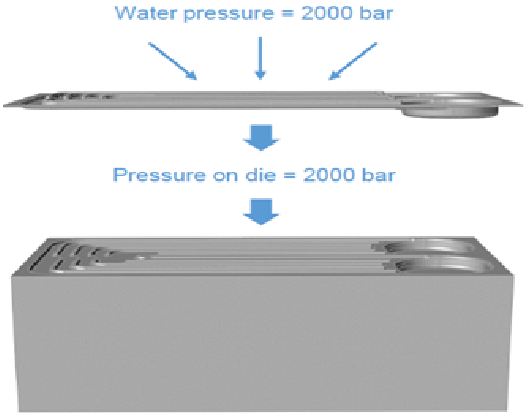


FIGURE 6.5: Loads

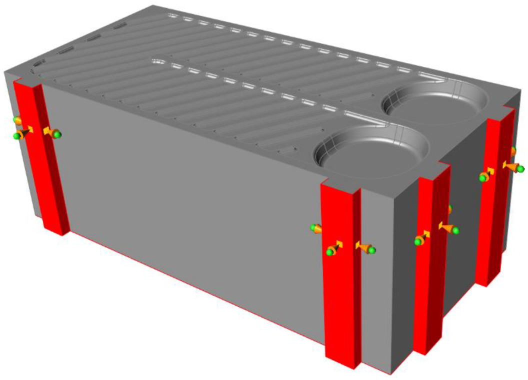


FIGURE 6.6: Boundary conditions

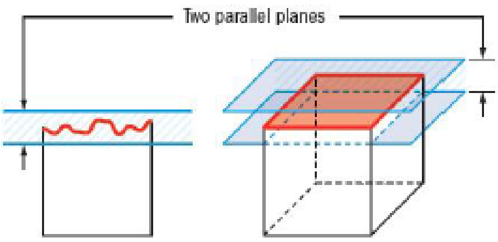


FIGURE 6.7: Flatness = MAX(disp) - AVG(disp)

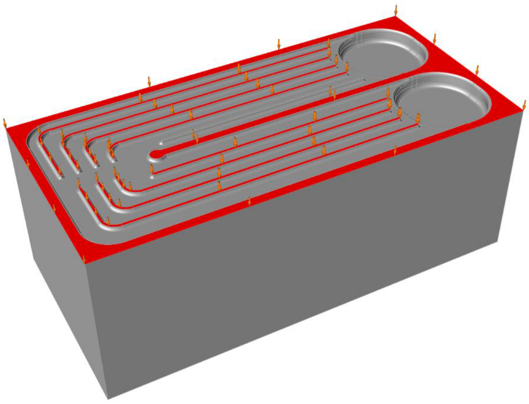


FIGURE 6.8: Flatness is checked on the red surfaces

6.2.2 Optimization results

Different strategies have been followed in order to get a topology optimization result which fulfil the flatness and stress requirements. The primary remark is that the stress level is already close to the limit before optimisation. It becomes very hard to remove material on the design without stress violation. When analysing the optimization results, the mass reduction is less than 20% and the part tends to be weakening, this seems not interesting at all. On another approach whose figures are not listed here, only the die height was reduced and there was no violation of constraints. It is this last approach which has been retained, the height of the die will then be reduce from 30mm to 10mm for future additive manufacturing.

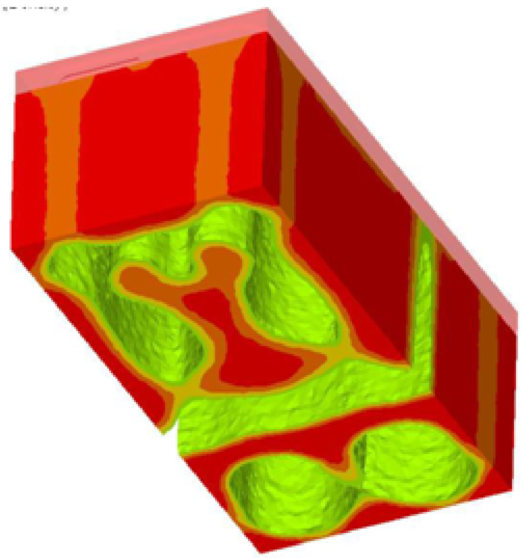


FIGURE 6.9: Die after optimisation 1

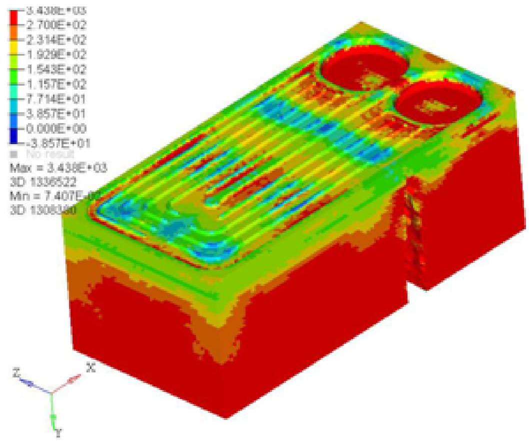


FIGURE 6.10: Die after optimisation 2

6.2.3 Additive manufacturing of the die

No significative results so far. All what can be said here is that, from the two AM processes (PBF and DED) selected for this application, only hybrid DED can fulfil our design specifications. For PBF, the surface finish of the active area can not be directly manufactured.

6.3 Magnetoforming of the metal sheet

As discussed in *Chapter* 5, magneforming uses high intensity magnetic impulsions to accelerate a conductive material on a forming die. The very high speed deformations implemented with this type of process allows to extend the formability limits of certain materials and limit significantly its springback.

6.3.1 Experimental device

The experimental device installed on the frame of a milling machine (see *figure* 6.11) is made up of:

- A modular generator with a maximum capacity of 18 kJ, and whose characteristics are :
$$C = 540\mu F;\ L = 0.227\mu H;\ R = 1.98 * 10^{-3}\,\text{hom}$$
- A double spiral planar inductor comprising with low inductance. The work area is approximately 50 *mm x* 250 *mm*.
- A vacuum system vacuum installed on the table to create the vacuum between the sheet metal and the die;
- A forming tool comprising the die. This die is placed within a thick plate (see *figure* 6.12). The thick plate is placed on the vacuum table and an O-ring located on the periphery of its upper surface allows to ensure the seal with the sheet.

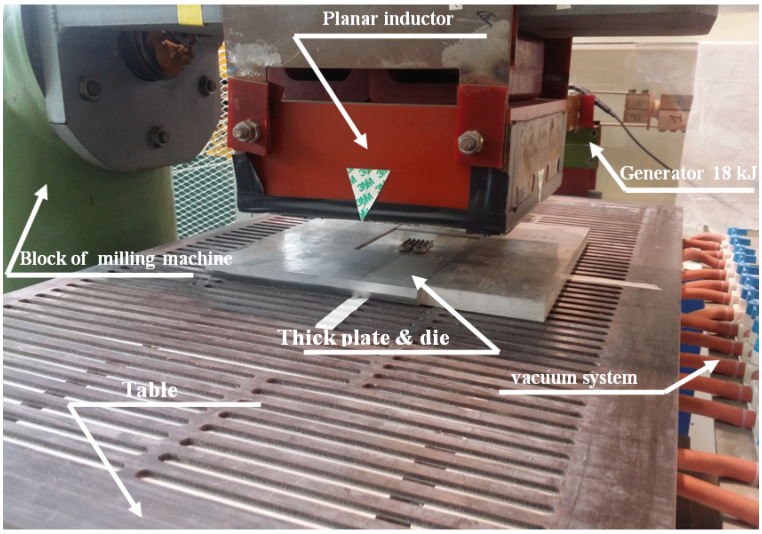


FIGURE 6.11: Magnetoforming machine

6.3.2 Tuning

The implementation took place following several tests divided into three main steps:

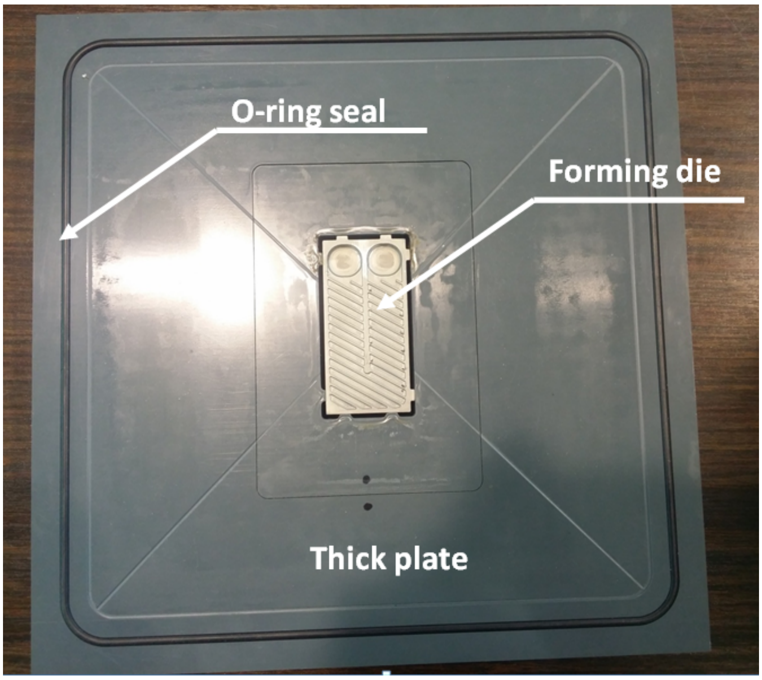


FIGURE 6.12: Tool with vacuum system

Tests	Die	Energy (kJ)	Gap sheet/die (mm)	Vacuum (Y/N)
1	DED-S-P	11.5	1	N
2	DED-R-F	11.5	0	N
3	DED-M-F	4.5	0	N
4	DED-M-F	8.8	0	N
5	DED-M-F	4.5	2	N
6	CNC-M	4	0.3	Y
7	CNC-M	11.5	0.3	Y
8	CNC-M	4	1.3	Y
9	CNC-M	8	1.3	Y

Table 6.1: Test specifications for magnetoforming; DED-S-P: direct energy deposition, sample part; DED-R-F: direct energy deposition, raw finish, DED-RM-F: direct energy deposition, machined finish, CNC-M: computer numerical control machining

Step 1: Surface rougness

The objective of this step is to evaluate (qualitatively) the ability of magnetoforming to reproduce the surface finish of a die. For this a tensile specimen (see *figure* 6.13) is used as die, it is manufactured by direct energy deposition in 316L stainless steels, one side is left in raw finish while the other half is blasted with glass beads.

Figure 6.13: Test 1: Reproduction of surface quality; 1050, 11.5 kJ

The specimen is placed on a rigid plate (40 mm thick aluminium plate), and between the specimen and the metal sheet is placed an insulator (green sheet) having a thickness of 1 *mm*. This insulating plate has the function of providing a gap between the die and the sheet to allow its acceleration. The result of the test (see *figure* 6.13) with a 1050 aluminium sheet shows no significant difference between the blasted surface and the non-blasted surface.

Step 2: DED Die with raw and re-macined finish

The objective of this second phase of tests, is to evaluate to what extent it would be possible to use the magnetoforming on a die obtained by additive manufacturing, in raw finish (see *figure* 6.14) or machined finish (see *figure* 6.16)

- On the raw finish die, manufactured by the DED process, the result obtained (see *figure* 6.15) on an 1050 aluminium sheets with an energy of 11.5 kJ, shows a major tear behaviour, favored by the sharp ends of the surface finish.

Figure 6.14: Die manufactured by DED, raw finish

Figure 6.15: Test 2: result with DED die and raw finish

- On the die manufactured by DED, and then re-machined, three tests were made, them all with the multilayer aluminium sheets of Valeo (aluminium 3003 H14). For the first two tests, the sheet is placed on the assembly in direct contact with the top of the die channels. While for last test, the plate is elevated for 2 mm above the channels so as to been projected onto the die before it reach the channels.

  Between the tests 3 and 4 (see *figure* 6.17 and 6.18), the energy was increased gradually. At 4.5 kJ no tear was observed, by cons for superior energies, the sheet start to tear. For each of these tests the stamping is not deep enough between the channels, because they are actually too deep.

Figure 6.16: Die manufactured by DED, machined finish

Figure 6.17: Test 3: DED die and machined finish; 3003 at 4.5 kJ

- To improve the depth of forming between the channels the die, the sheet was propel ensuring a 2 mm gap. The result (see *figure* 6.19), shows that the stamping has the desired depth but the metal sheet tears.

Figure 6.18: Test 4: DED die and machined finish; Al 3003 at 8.8 kJ

Figure 6.19: Test 5: DED die and machined finish; Al 3003 at 4.5 kJ, gap 2 mm

Step 3: CNC Machined die

Having been unable to get in time the dies manufactured by AM, we switched on CNC machining, which is suitable as well for this type of application. Within a week we were able to order and receive the die (see *figure* 6.20) in 316L steel, at a price of €1.5k. On this die, 4 tests have been done. To qualify the forming precision, the contact area between the sheet and the die at the bottom of the central holes were measured. higher is the surface, better is the forming precision.

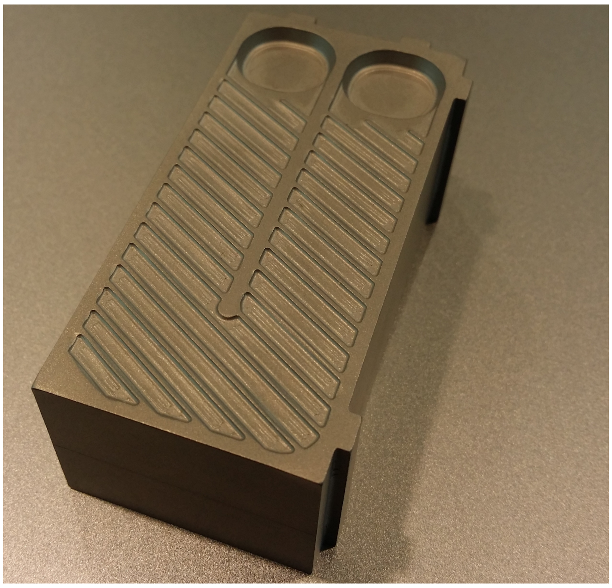


Figure 6.20: CNC Machined die

- For test 6, an energy of 4 kJ is used, a gap (distance between sheet and die) of 0.3 mm, is obtained an area of 33 mm^2. The sheet does not tear, but does not accommodate to the shape of the die (see *figure* 6.21).

- For test 7, an energy of 11.5 kJ is used, a gap of 0.3 mm, is obtained an area of 122 mm^2. One noted that with greater energy, the forming is more accurate but quickly the sheet tears around central pocket. The induced currents become too high and the material is burned (see *figure* 6.22).

FIGURE 6.21: Test 6: Machined die; Al 3003 at 4 kJ, gap 0.3

FIGURE 6.22: Test 7: Machined die; Al 3003 at 11.5 kJ, gap 0.3

As said, the gap is intended to allow the material to be accelerated. If the gap is not big enough, the material do not accelerate as much as it could. If the gap is too high by cons, when the Laplace force disappears, the sheet is not more accelerated, it will therefore slow down due to the plastic dissipation and friction. Order to verify this assertion, the gap is increased for the tests 8 and 9 (from 0.3 to 1.3).

- For test 8, an energy of 4 kJ is used, a gap of 1.3 mm, is obtained an area of 41 mm^2. the forming is more accurate than with a gap of 0.3 mm (see *figure* 6.23);
- For test 9, an energy of 8.8 kJ is used, a gap of 1.3 mm, is obtained an area of 118 mm^2. the more the energy is increased, the better the forming accuracy. But there is still the tearing of the sheet, principally between the two pockets and at their peripheries and finally in their bottoms (see *figure* 6.24).

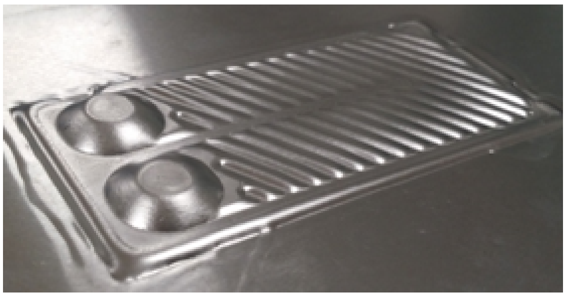


FIGURE 6.23: Test 8: Machined die; Al 3003 at 4 kJ, gap 1.3

FIGURE 6.24: Test 9: Machined die; Al 3003 at 8.8 kJ, gap 1.3

6.3.3 Conclusion

From the results above, it seems difficult to not tear the sheet at the top of the central pockets. To avoid tearing the connection radius of 0.25 mm should be increased up to minimum 0.8 mm, and possibly drill simultaneously the bottom the holes so as not to block the flow of material.

At this stage, the test results are not successful and should be continued. During the next steps coming out of the period of my internship, stable solution that works can be found if one takes into account the latest design specification.

6.4 Hydroforming of the metal sheet

6.4.1 Experimental device

For confidentiality reasons, we could not present the experimental system used by our hydroforming partner. However, the figure 6.25 shows the schematic elements of which it consists. It is noted that here is the 1500 bar water pressure which allows the forming of the sheet metal in the die. The working area is about $300 * 300\ mm^2$ and the process can be continuous unlike magnetoforming. The system must be watertight and it can not cut or make holes in sheet metal, like magnetoforming.

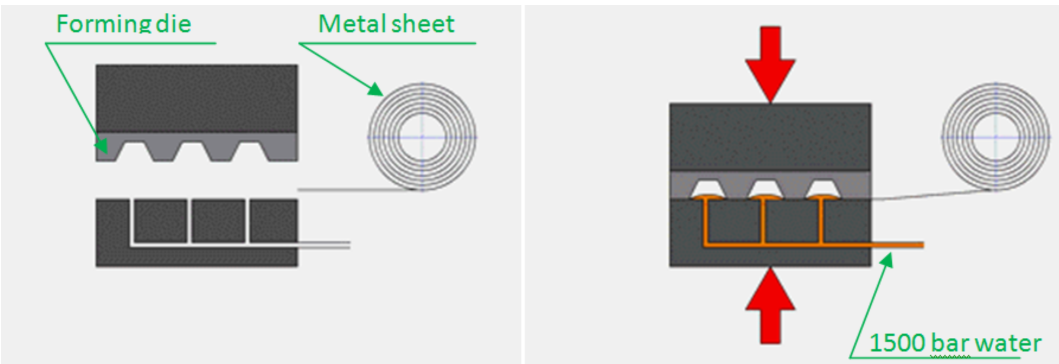


FIGURE 6.25: Hydroforming experimental system

6.4.2 Tuning

The feasibility approach used here is different from that of the previous magnetoforming, being given that we already had a number of design rules. The red area shown in *figure* 6.26 is thus the only one that will have to undergo the forming tests.

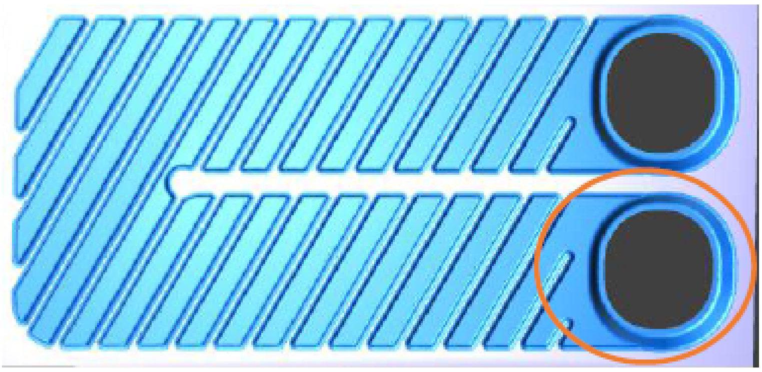


FIGURE 6.26: Area for forming test

Step 1: Forming with the original design

The first test is the forming of the sample exactly as in the original design. From the formed samples as shown above, it is evident that the channels (see figure 6.27) and the pocket (see figure 6.28) crack. This is due to small rays used which result in too high local elongation for aluminium (over 50%).

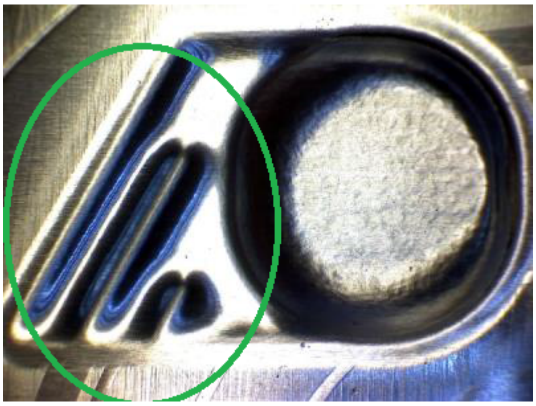


FIGURE 6.27: Test 1: Channels crack

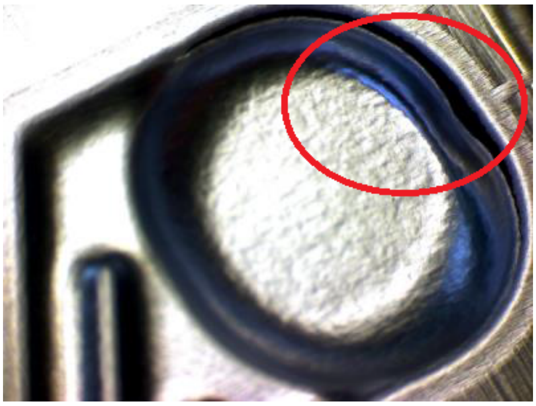


FIGURE 6.28: Test 1: Pocket crack

Step 2: Forming the pocket with radius R0.5

For a second iteration only the pocket is examined. The top radius has been increased from $r0.25\ mm$ to $r0.5\ mm$. The forming resulted in better at the top radius (see figure 6.29), but at the bottom still some cracks appear (see figure 6.30).

Step 3: Forming the pocket with radius R1

For this last iteration the top radius has been increased from $r0.5\ mm$ to $r0.9\ mm$. There is no more crack (see *figure* 6.31), but some granularity is visible at the bottom

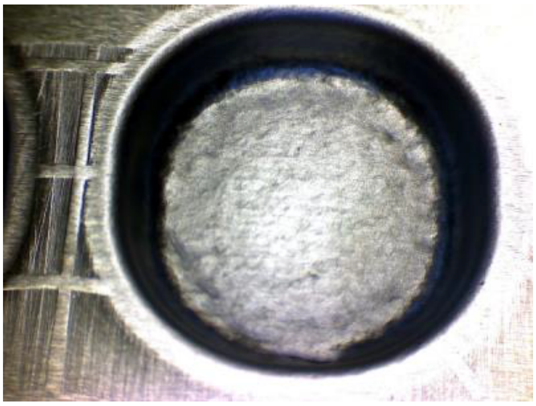


FIGURE 6.29: Test 2: No crack on the top pocket

FIGURE 6.30: Test 2: Crack on the bottom of pocket

of the formed feature (see *figure* 6.32). This does not matter because this bottom will be cut after forming and has no functional property.

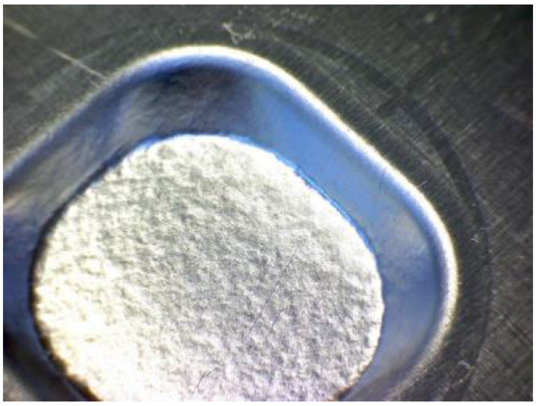


FIGURE 6.31: Test 3: No crack on pocket

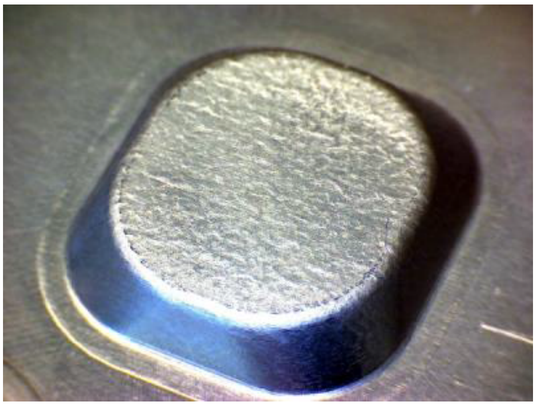


FIGURE 6.32: Test 3: Granularity at the bottom

6.4.3 Conclusion

From these tests, one comes out with clear design rules (see *figure* 6.33 and 6.34) that can be integrated directly into any new design for hydroforming. During the tests, it was also noticed that the milling direction has an important effect of the forming behaviour. This could influence the manufacturing options, as the coil can be fed only in 1 direction relative to the die in the hydroforming system.

In *figure* 6.35 we can see a part of our "TC" plate manufactured by hydroforming. The entire plate will be manufactured in the period not covered by this report.

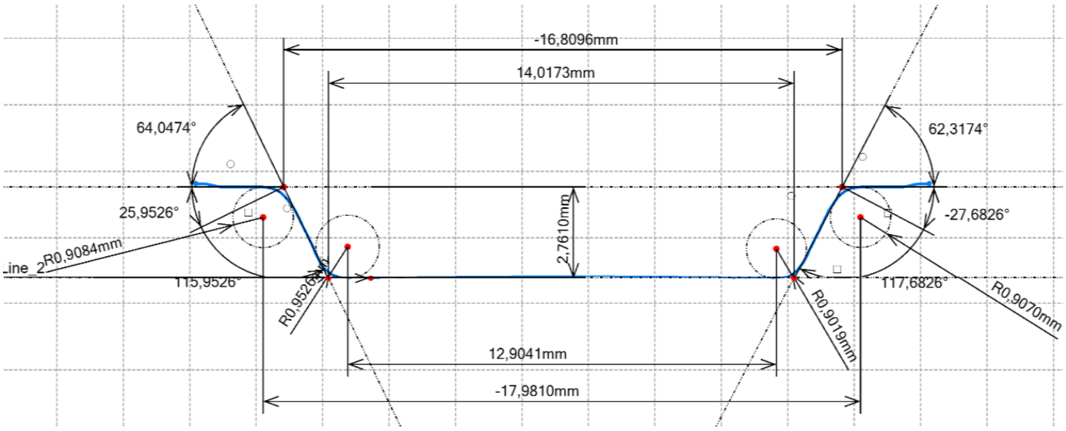


FIGURE 6.33: Design rule for pocket

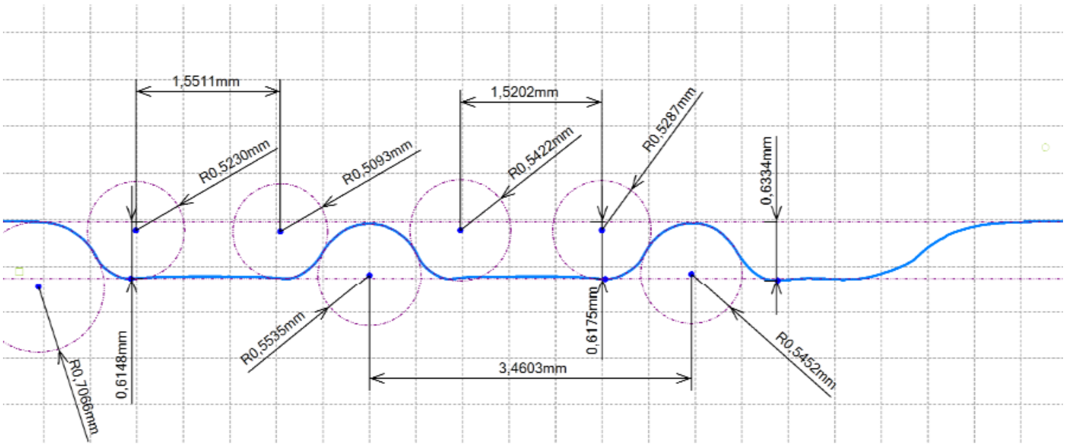


FIGURE 6.34: Design rule for channels

6.5 What is the benefit?

A quantitative analysis of the innovative process put in place in this work is presented in *Table* 6.2. Overall we can be satisfied with the reduction of production cost resulting of these processes (16.5k for magnetoforming and 24k for hydroforming instead of 40k for conventional stamping). The expectations regarding the reduction of lead time are not forthcoming, however, when the new design rules will be well integrated, they could be greatly reduced. As we can see, it is the tuning time that slows down these new processes.

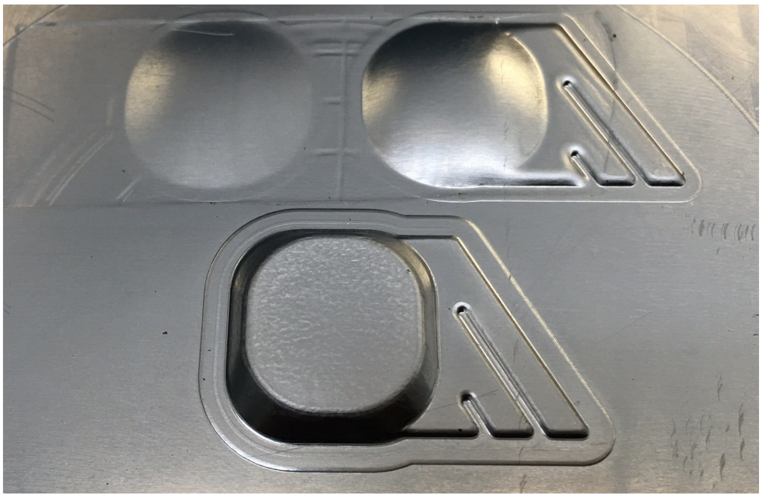


FIGURE 6.35: Hydroforming ”TC” plate

	Stamping	Magneto	Hydro
Number of Tools (stepss)	6	1	1
Tool cost (€)	35k	1.5k	16k
Tool manufacturing time (weeks)	8	1	1
Tool AM cost	-	-	-
Tool AM manufac. time	-	-	-
Add. tool (cutting) (€)	-	0	3k
Tuning (week)	0	12	6
Total manufacturing time (Tools and parts)(week)	8	13	7
Tool cost (€)	40k	16.5k	24k
Number of prototypes	2000	400	400
Quality	ok	ok	bad

TABLE 6.2: Global results

Chapter 7

Conclusion and Perspectives

7.1 Conclusion

For the prototyping purposes of the "TC" heat exchanger plate, one saw in *Chapter* 3 that, the traditional stamping process currently used by Valeo development teams raises problems of time and cost (it takes at least 8 weeks and 44 €k), mainly because of the large number of tools that it requires.

It was necessary to identify a new technology that could respond to these issues. Although the additive manufacturing processes are experiencing significant progresses in terms of metallic materials (see the end of *Chapter* 4), it remains impossible to consider the direct manufacture of our exchanger plates thereon. By cons one also saw that the forming tools could fully benefit from the advantages such as the complexity of form, rapid manufacturing and low cost production. In *Chapter* 5, it has been discussed the ability of magnetoforming and hydroforming processes to form metal sheets, with less tools than conventional stamping.

It therefore followed in *Chapter* 6, the implementation of a combination of new processes, that significantly reduced the prototyping cost. By using a single die on magneforming it only costs 16.5 €k and asks 13 weeks, for hydroforming it costs 24 €k and asks 7 weeks. However the lead times are not up to our expectations, mainly because of the tuning time and the new design rules.

The ability of AM processes to form our die has not been evaluated during this working period as intended. However, this has little impact on the overall results, as the topological optimization of the die has not led to a complex model, because of high forming pressure supported (1500 bar). With a conventional design as the one we finally used, with metallic materials, the processes such as CNC machining remains better than AM, even for single part

7.2 Perspectives

This work also aims to raise awareness on new processes, their advantages and limitations and supports decision-making for future needs.

In the short term, according to Valeo's need, there are things to do at the level of forming tools: firstly for the repairing of existing tools, we saw that with the deposition processes such as DED, their lifetime could be increased; Secondly for the design of new tools, one could incorporates cooling channels near the active surfaces (conformal cooling), this would increase their lifetime and also the quality of the parts made.

Regarding plastics, we have seen that for representative purposes or in any non-functional cases, additive manufacturing processes are already fairly well accepted. However, the issues of density, surface roughness and especially good material prevent to cross the step towards to the end use parts. Three-way partnership between manufacturers of materials, machines and products should be encouraged to solve issues and support the development.

All the new technologies debated here, provide new design constraints. We have seen that the tuning time can become very important, particularly when one did not have enough informations. For future needs, it should be investigated and built a database of the design characteristics for each new processes. All designers and stakeholders must be sufficiently trained to integrate them at at the very early stage of the development process of a new product.

At the Valeo Group level, make THS the Group benchmark in terms of additive technologies knowledge, Set up standardized tools and training modules, Investigate all additional business opportunities that these technologies could bring...

I would be pleased to have the opportunity to deepen the AM topic in the context of a doctoral thesis.

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