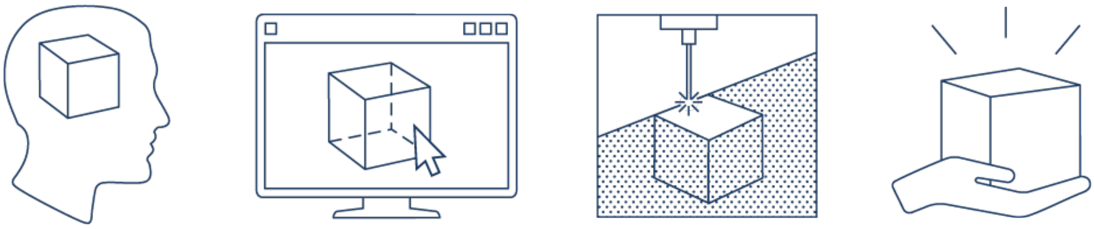

Product development process for additive manufacturing

Considerations on the design of final products for 3D printing

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A mis padres y amigos, que me apoyaron durante este camino.

Abstract

The goal of this thesis is the study of the product development process for Additive Manufacturing. Three Dimensional Printing as a rapid prototyping technique is a reality, but the real challenge that the industry is facing nowadays is the use of this technology for a large-scale production of final parts.

With this whole new scene emerged with additive manufacturing and 3D printing, and because of the demonstrated growth trend during the past years and the worldwide projected value of this market in the near future, it exist an increasing interest in the study of the most adequate product development process for the specifications of this technologies.

This thesis will go over the potential benefits of additive manufacturing, seeking the improved performance of it, and the main advantages in its use for complex and advanced products, but not leaving apart the still substantial limitations, and being mindful of the multiple inherent constraints of the technology.

Keywords

Product development, additive manufacturing, 3D printing mass production, manufacturing, emerging technology, product specifications, constraints in additive manufacturing.

Resumo

O objetivo desta dissertação será o estudo do processo de projeto que mais se adeque à concepção de peças funcionais produzidas por fabricação aditiva.

A utilização de impressão 3D para a execução de protótipos é, há muito tempo, uma realidade nas mais variadas industrias. O verdadeiro desafio é a utilização desta tecnologia na fabricação de peças finais em grande escala, e está no entanto a começar.

Devido ao fato de que esta tecnologia vão experimentar uma demostrada tendência de crescimento nos próximos anos e devido aos altos valores projetados do mercado da fabricação aditiva no futuro próximo, existe um interesse acrescido em estudar o processo de projeto que seja mais adequado às especificidades desta tecnologia de fabrico.

A dissertação percorrerá sobre as potenciais prestaçoes dela fabricação aditiva, e sobre as principais vantagens de sua utilizaçao para a producção de pezas complexas y produtos avançados, mais sem deixar de lado as limitações e tendo consciência das restricçoes desta tecnologia.

Palavras Chave

Desenvolvimento do produto, impressão 3D, prototipagem rápida, indústria de manufatura, tecnologia emergente, especificações de produto,restrições na manufactura en impressão 3D.

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Abbreviations/Acronyms

AM Additive Manufacturing

ABS Acrylonitrile Butadiene Styrene

ASTM American Society for Testing Materials

CAD Computer-Aided Design

CNC Computer Numerical Control

DMLM Direct Metal Laser Melting

DMLS Direct Metal Laser Sintering

EBM Electron Beam Melting

FDM Fused Deposition Modeling

FFF Fused Filament Fabrication

LOM Laminated Object Manufacturing

NPD New Product Development

PC Policarbonate

PDP Product Development Process

PEI Polyetherimide

PPSF Polyphenylsulfone

RP Rapid Prototyping

SL StereoLithography

SLS Selective Laser Sintering

SLM Selective Laser Melting

UV Ultraviolet

1

Introduction

Contents

1.1 Motivation

Additive manufacturing is said to be the next Industrial Revolution. Before 3D printing came to life, the subtractive manufacturing was mainly the way to cut simple designs, then combining multiple of those components by welding or brazing them together into a single complex unit.

Designers had to have in mind the limitations of all manufacturing techniques involved on the product, from the first phases (by casting, stamping,...) to the end up details (by milling, drilling, Computer Numerical Control (CNC) machining centres or any surface finishing technique).

As design tools improved over the years, especially when talking about Computer-Aided Design (CAD) tools, the limitations of the 20th century manufacturing methods were exposed. Computers allow us to design highly complex parts and components limited only by our imagination, but they can not be easily produced with the traditional scheme.

Additive Manufacturing (AM) allows parts, once thought impossible, to be produced. By constructing objects layer by layer, we have the opportunity of designing and building things in a completely new way, which is a benefit that really should be used to attempt to get the full potential offered by this manufacturing technology. As obvious as this sounds, there is somehow a tendency not to follow this advice, as in many cases we keep thinking and designing in the 'old way' because of years of experience and tradition, so not taking all the advantages of the technique.

The additive method allows to produce complex parts with unique geometries that would be difficult or even impossible to create using traditional machining methods. Paired with CAD software, this technique affords the creation of new types of object with unique material properties.[1] Furthermore, it creates them leaving behind little waste, compared with traditional methods like machining and welding.

Therefore AM could be in the near future the main procedure to undertake many product enhancements in parts or designs that have been unchanged for years. In many cases it has been known for a long time how to modify those products to become better in aspect, efficiency or safety, but it was not done because it was either not profitable due to manufacturing costs or it was impossible to fabricate or mass-produce with such difficult modifications. With AM all these products may have a second look and a completely new approach.

Additive manufactured components also allow engineers to reduce part count, as it is a great way to replace complex assemblies with single parts that are lighter than previous designs, saving weight and increasing efficiency.[2]

However it is important to bear in mind all the constraints that AM also has, take them into account and learn how to work around or deal with them. Part of the content of this thesis will cover, precisely, several of these issues. For example manufacturing constraints in terms of quality of the surfaces, maximum temperatures reached, availability of materials or thin sections, as well as economic and time limitations for line and high production, among many other.

All constraints will explain the evolution of the market of this industry and solving or mitigating them is the ultimate objective in research for future development.

3D printing is changing, and will revolutionize even more, the way in which many parts are produced, growing them from the ground up. AM is here to bridge the gap between the non-limited design software and the actual limited manufacturing and machining technology.

We can think in how we want the final product to be, and design all the characteristics, not having to think about how we are going to manufacture it any more, or even wondering if it can be made.

In words of David Joyce, President and CEO of GE Aviation, -what additive manufacturing give us is a whole different degree of freedom on how we think about component design. We no longer have to understand what limitations on machining are, and what the cost of those limitations are. So now we have taken many of those processes and enable to blown out with additive manufacturing, giving the designers a whole different palette of colors to play with and truly on a whole new canvas.- [3]

As media interest in AM grows, those involved in the sector are making efforts to integrate the technology into the manufacturing mix.

The market for systems, service and materials for AM currently totals more than EUR 1.7 bn (2012) and is expected to quadruple over the next 10 years. In spite of that the share of AM is still relatively small, with about 1% of the machine tools market. By the moment the investments of this technology are significantly higher than for conventional production, so it can be only justified by special benefits in the life-cycle or tooling costs. A detailed analysis of the current manufacturing cost and evaluation of expected improvements reveals a cost reduction potential of about 60% in the next 5 years and another 30% within the next 10 years. These reductions will significantly boost the market for AM. [4]

It is probably true that we just began to touch the surface of all the potential applications for AM in the near future, but while AM is widely billed as the next industrial revolution, in reality there are still significant hurdles for successful commercialisation of the technologies.[1]

1.2 State of The Art

1.2.1 Origins

In 1972 the idea of using photo-hardened materials, like photopolymers, to produce parts was first proposed. After some research, earlier AM equipment and materials were developed in the 1980s.

In 1981 was invented, by Hideo Kodama in the Nagoya Municipal Industrial Research Institute, an AM fabricating method of a plastic photopolymer Rapid Prototyping (RP) system in three dimensions where the Ultraviolet (UV) exposure area was controlled by a mask pattern. The photopolymer, when exposed to UV light, hardens each layer until the part was completed, and the liquid photopolymer was drained.[5]

In 1986 the StereoLithography (SL) was patented as a technology to create 3d solids by solidification of thin layers of UV light sensitive liquid polymer using a laser.[6] Some years later was first introduced the first Fused Deposition Modeling (FDM) machine, a technology that extrudes plastic to deposit it forming layers on a print bed or over the previous layer.[7]

Then, in 1992, the first SL 3D printer machines were first produce over the patent and simultaneously also the first Selective Laser Sintering (SLS) machine. SLS is similar to SL technology but uses a powder (and laser) instead of a liquid.

First wax printer was released in 1994, and after that, during the year 2000, the first 3D inkjet printer and first multicolour 3D printer were produced.[8]

In the last years many variations, subtypes and different technologies have emerged with different degree of success in the manufacturing industry or between the followers of the DoItYourself or maker movement. Remarkable between this big amount of AM printers is probably, because of its implications in medicine science, the first biocompatible material FDM machine, which was produced in 2008. [7]

It should not be forgotten that concept modeling is the origin of 3D printing. As a way to filter out failures before the production starts and they become costly, it has been for years the main business of the companies of this AM market.

In the world we are living, much more complex products appear each day in the market. Take, for example, an orange squeezer. An orange squeezer is not only a squeezer any more but an automatic and internet-connected juice squeezer with a beautiful and ergonomic design that knows exactly at what hour you want your fresh juice, with sensors to detect the vitamins concentration, the amount of oranges remaining, and able to store you statistics of juice drinking in the last years. Even if the product in this example can be seen as absurd or extravagant, it is not so nowadays.

The products are getting complex in the sense of multi-objective products, which require cross-disciplinary teams in the product development process. Merging the ideas of those designers, engineers, biologist, computer scientists, anthropologists,... in not an easy task. The combination of members in a team with really different backgrounds usually conceive extraordinary ideas and disruptive products, but at the same time requires much more testing and verification than any traditional product with an old and proved scheme.

So concept modeling and RP have their future guaranteed, and will still be an important slice of the cake of AM.

Anyway, even if this last purpose will coexist, the general opinion is that these technologies in the long term will be used more for manufacturing final products than for prototyping.

1.2.2 Different technologies

Today's leading companies and research centres in the market of additive manufacturing are simultaneously developing a multitude of different technologies, with greater or lesser similarities, to try to minimize the main drawbacks found in the production of different parts, and their different specifications, with 3d printing.

To meet those diverse requirements, the industry nowadays relies on professional AM machines based on one of the seven primary manufacturing processes listed and described below:

Vat photopolymerization

In vat photopolymerization, a liquid photopolymer (i.e., plastic) in a vat is selectively cured by light-activated polymerization. The process is also referred to as light polymerization.

Material jetting

In material jetting, a print head selectively deposits material on the build area. These droplets are most often comprised of photopolymers with secondary materials (e.g., wax) used to create support structures during the build process. A UV light solidifies the photopolymer material to form cured parts. Support material is removed during post-build processing.

Material extrusion

In material extrusion, thermoplastic material is fed through a heated nozzle and deposited on a build platform. The nozzle melts the material and extrudes it to form each object layer. This process continues until the part is completed.

Powder bed fusion

In powder bed fusion, particles of material (e.g., plastic, metal) are selectively fused together using a thermal energy source such as a laser. Once a layer is fused, a new one is created by spreading powder over the top of the object and repeating the process. Unfused material is used to support the object being produced, thus reducing the need for support systems.

Binder jetting

In binder jetting, particles of material are selectively joined together using a liquid binding agent (e.g., glue). Inks may also be deposited in order to impart color. Once a layer is formed, a new one in created by spreading powder over the top of the object being produced, thus reducing the need for support systems.

Sheet lamination

In sheet lamination, thin sheets of material (e.g., plastic or metal) are bonded together using a variety of methods (e.g., glue, ultrasonic welding) in order to form an object. Each new sheet of material is placed over previous layers. A laser or knife is used to cut a border around the desired part and unneeded material is removed. THis process is repeated until the part is completed.

Directed energy deposition

In directed energy deposition, focused thermal energy is used to fuse (typically metal) material as it is being deposited. Directed energy deposition systems may employ either wire-based or powder-based approaches. [9]

Using these primary manufacturing processes as the basis of the operations we can find all the different AM technologies. Classifying them by the materials they are able to use or by the main advantages they present is a typical scheme in the specialized bibliography.

- Direct Metal Laser Melting (DMLM):Solid metal parts are grown from the ground up by a precision 200W laser that melt ultra thing layers of powder metal. Ultra powerfull laser beams are used.

- Fused Deposition Modeling(FDM): Based on material extrusion, the typical materials used are thermoplastics, like Acrylonitrile Butadiene Styrene (ABS), Policarbonate (PC) or Polyphenylsulfone (PPSF). Able to produce complex geometries and strong parts as main advantages, it is also important to bear in mind the poor surface finish as well as the longer build times compared with other techniques.

  In the AM background this process is also known as Fused Filament Fabrication (FFF), as the term Fused Deposition Modeling and its abbreviation to FDM are still trademarked by Stratasys Inc, even if their patents related to FDM have already expired.

- StereoLithography(SL): As it has been said, was born as the first AM technique based on Vat polymerization of liquid photopolymers. Even if a curing process after printing is necessary and using a support structure is needed, the details of the parts and the smooth finish that can be achieve legitimate its use.

- Selective Laser Sintering(SLS): With the fusion of a powder bed as main AM process, SLS can be used for the production of plastic, metal, ceramic, composites or even glass parts. The flexibility in the selection of materials together with the high speed are the main advantages of this technique. On the other hand, the surface finish is rough and the accuracy is limited by the powder particle size, which make the price of the materials higher.

- Direct Metal Laser Sintering (DMLS):Also based on powder bed fusion, DMLS is able to perform with stainless steel, as well as cobalt, chrome and nickel alloys to generate intricate and dense parts. The required finishing make the process not very good for large objects.

- Selective Laser Melting (SLM): Is considered by ASTM International F42 standards committee (the American Society for Testing Materials technical committee on Additive Manufacturing Technologies) as another subtype of laser sintering. This can be seen by many as a mistake because there is not a real sintering process involved but a process in which metal end up as a solid homogeneous mass after being fully melted with a high-power laser beam. A variety of fine metal powders can be used, from stainless steel or tool steel to cobalt chrome, titanium or aluminium.

- Laminated Object Manufacturing (LOM): Mainly with paper or cardboard, but also with plastics, metal sheets, ceramics or composites (even if none of these materials are usually available on a commercial scale), LOM pile up thin laminae cut with cutter or laser from the original material. Only used for RP, is one of the less accurate methods and it give birth to non-homogeneous parts, but even though of the disadvantages mentioned, it is relatively less expensive than other processes and a quick way to make big parts.

- Electron Beam Melting (EBM): An AM technique based on powder bed fusion. As in SLM, the material also end up fully melted after the energy supply. The main difference between both is that while SLM uses a laser, in EBM the energy source is an electron beam. The process is perfect for reactive materials with a high affinity for oxygen, like titanium or cobalt chrome powders.

Even if all technologies are really different and based in distant physical principles, they all share the same philosophy of sequential-layer material addition. This layer by layer manufacturing process is managed under automated control.

The main considerations in choosing a machine are speed while printing, cost of the 3D printer, cost of each printed part, cost and choice of materials, color capabilities, multi-material capabilities, configuration possibilities, resolution and the strength and toughness of the finished part. Some of their implications will be explained throughout this text.

2

From prototypes to final products

Contents

2.1 New audience

2.1.1 Prototyping as the origin of Additive Manufacturing

Prototyping is as a vital part of the product development designing process. The Oxford Advanced Learner's Dictionary of Current English define prototype as the first or original example of something that *has been or will be developed*, like a model or preliminary version.[10].

The necessity of reaching the market as soon as possible, before competitors or just before a trend is over, is key in the manufactured world market. By detecting the deficiencies in the early stages of the product design, and not less important using the prototype for feedback from potential customers, the product can reach the market with a greater guarantee to success. [11]

Prototyping is a cost in the product development process, and in many cases a big cost, but in the long-term is an smart investment that may save an appreciable amount of money to a company.

The StereoLithography, as the first AM technology, was born as a necessity for this market demand of prototyping in a more accurate and fast way. Production companies and design teams were looking for a machine that let them see and feel a model, as much similar as possible, of the product they were developing. This is usually called a demand-pull technology. The technology was demanded by the industry, so as soon as it was invented it quickly gained a share in the world market. Rapid Prototyping was deep seated.

With this prototyping fever happening in the eighties and nineties, specially the producers of that RP technology quickly noticed the possibility of using it for creating end-use products. By pushing in that direction they will be able to expand their selling market, so they start introducing technological advances to convince the audience about the real capability of these machines to produce final products, which have total different requirements than prototypes.

This is a shinning example of a technology-push case. Even so, big companies like General Electric, Nike, Ford or Boeing are adopting it. [12]

Manufacturing industry nowadays is expert in producing products by traditional methods. The optimization of their processes are based on a completely different scheme from AM so deciding when to take advantage of this technology, or what products are more suitable for changing their production method is not an easy task.

As cited in the last publication of the National Institute of Standards and Technology from the U.S. Department of Commerce, "For manufacturers, understanding the impact of adopting AM is complex and difficult as it impacts factors that are difficult to measure." [13]

"There is a high market uncertainty once the economic barriers have been overcome. The appropriate response to this uncertainty includes investing heavily in background and exploratory research, engaging the future technology users in the innovation process, and to explore novel business models." [14]

2.1.2 Implementation in medium/large consumer goods manufacturers and manufacturing companies

The expansion from pure prototyping to final production has been a real intention across the additive manufacturing industry over the last few years.

With machines that work at higher speeds, with more stable and known processes and, most important, as materials and technology get cheaper, the idea of an industrial additive technology that replace some of the manufacturing techniques is nowadays nearly a reality.

Large consumer goods manufacturers and manufacturing companies sustain their business plan in economies of scale. Namely, by increasing the total production volume, they are able to decrease the final unit cost of the product they are manufacturing. This is because in these industries the cost structure is governed by tooling expenses, that need to be amortized.

Tooling, like stamping moulds or cutting tools or injection dies, are not only expensive because they have to produce, but because they also have to be designed for them to be able to manufacture products as they were projected. So manufacturing companies really need a big output to be able, over time, to pay for that dedicated tooling, tooling that will be obsolete as soon as a modification or new version of that part comes out.

As an example, figure 2.1 shows a 5 tons stamping mold, for a stroke press with installed transfer system. With a price near 150000 €, the mold produces very specific parts of around 150 gramme each, sold at 0,5 €. The company must be able to sell thousands of them before any further change in the design hits the market to have a return on the investment.

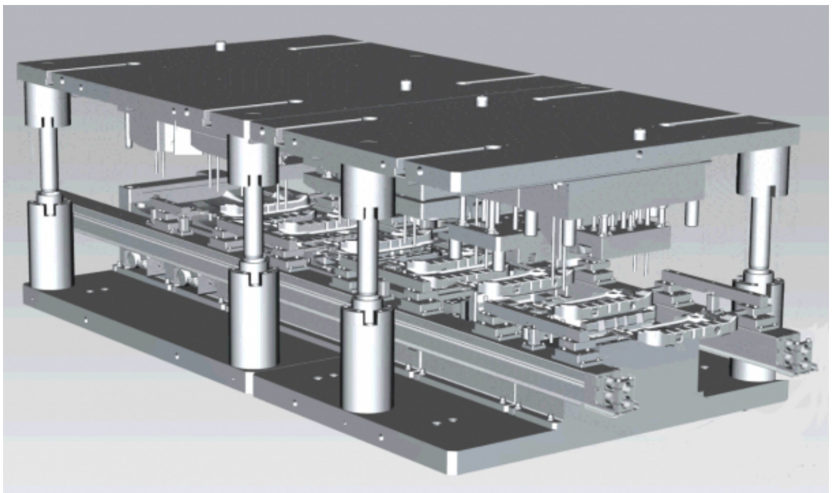

Figure 2.1: 5 tons transfer stamping mold for producing a 150 gramme part. Source: Gestamp Toledo

This is just the opposite of what AM is, as it does not need tooling in any of the steps of the manufacturing process. There is no need of a process born in a scale massive production model. Low quantities of products can be manufactured in an affordable way, precisely because of the absence of these tooling costs.

Even if the per-unit production cost is higher, it will be more than offset by the elimination of shipping. [15]

This gives the industries the capacity of introducing a higher level of flexibility in their production planning and, really important, the possibility of modifying each design hundreds of times even during the mass production stage.

AM removes significant front end fixed costs associated with the introduction of new products, thereby promoting product innovation. [14]. Much faster evolution of components, quick respond to costumer wishes and necessities,... are only some of the benefits of AM for final production.

Some authors go as far as saying that the implementation of this new technology by the large manufacturers will contribute to compromise their own situation and to them being put out of business.

"More goods will be manufactured at or close to their point of purchase or consumption." "Dealerships, repair shops and assembly plants could eliminate the need for supply chain management by making components as needed. These first-order implications will cause businesses all along the supply, manufacturing, and retailing chains to rethink their strategies and operations." "China won't be a loser in the new era, but it will have to give up on being the world's manufacturing powerhouse, even if not all products lend themselves to 3-D printing."[15], [16]

2.2 Projected growth

Additive manufacturing technologies are, with a growth of 34,9% in 2013, the most increasing manufacturing technology. [17], [18], [4] The global market of AM products and services grew 29% in 2012 to over $2 billion and unit sales of professional grade industrial systems reached nearly 8,000 units in the same year. This is an increase from an estimated 6,500 units in 2011 and demonstrates a growth trend of industrial AM systems sales worldwide.[1] (see table 2.1) The current market volume of machinery and services of additive manufacturing is estimated at 3.7 billion euros, equivalent to an amount of 2% of the total machine tool market [4].

Significantly faster, the global growth of personal 3D printers averaged 345% each year from 2008 to 2011. Most of these machines are being sold to hobbyists, do-it-yourselfers, engineering students, and educational institutions.[1]

The use of AM for the production of parts for final products continues to grow. In ten years it has gone from almost nothing to 28.3% of the total product and services revenue from AM worldwide. Within AM for industry, there has been a greater increase in direct part production, as opposed to prototyping (additive traditional area of dominance). [1]

Conservative estimations expect a market volume of 7 billion euros in 2016. In 2020 the estimated volume will reach $11 billion [18]. Overall, there is a total market potential of about 130 billion euros[4].

2015	$4 billion
2017	$6 billion
2021	$10.8 billion

Table 2.1: AM and 3D printing industry (products and services) worldwide projected value [17]

2.3 Possible uses

Nowadays the use of AM is almost considered as fashionable. Each day millions of articles, post and news are written related with any kind of additive machine printing the most strange products one has ever heard about. A 100% printed car, houses, pedestrian bridges, politician replicas in real size... Maybe is true that anything can be manufactured with additive technology but, as can be seen on figure 2.2, only in certain areas the technology has already achieved manufacturing readiness (e.g. dental).

Within direct part production, AM serves a different and diverse list of products and sectors, not being limited just to RP. For example, AM is used daily in rapid prototyping, architecture, dental and edical use, but also in specialized manufacturing, mass production, bio-printers and bio technology, nanotechnology, food industry, construction or in arts and fashion.

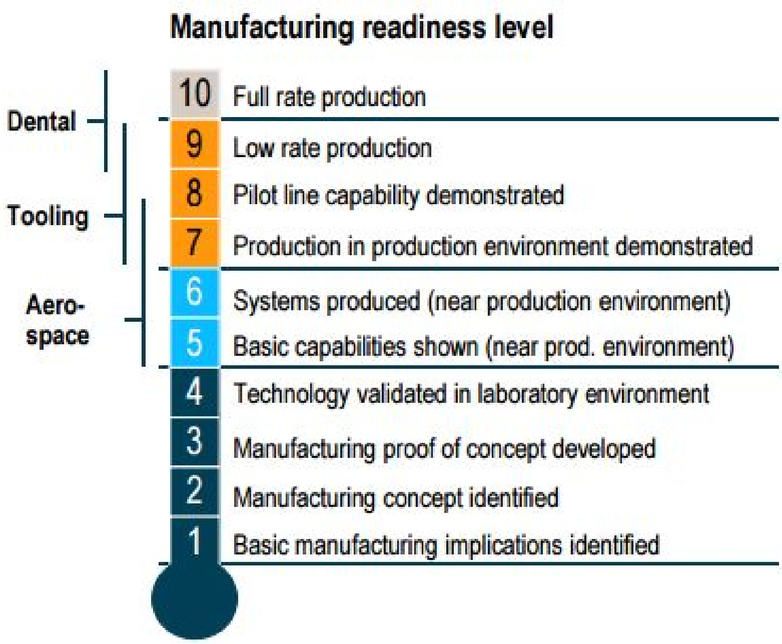

Figure 2.2: Manufacturing readiness level.[4]

But this manufacturing readiness level is progressing at very high rates. In the aerospace and aeronautical industry, for example, a big barrier related to AM has been overcome recently. The U.S. Federal Aviation Administration granted in February 2015 certification for the first additive manufactured part for the GE90-94B engine mounted in the Boeing 777X aircraft. In particular this component is the housing for a sensor (figure 2.3) that has been retrofitted into more than 400 engines in service providing pressure and temperature measurements for the engine's control system. In this case AM has allowed engineers to quickly change the geometry through rapid prototyping and producing production parts, saving months of traditional cycle time for the production of the sensor housing.[2]

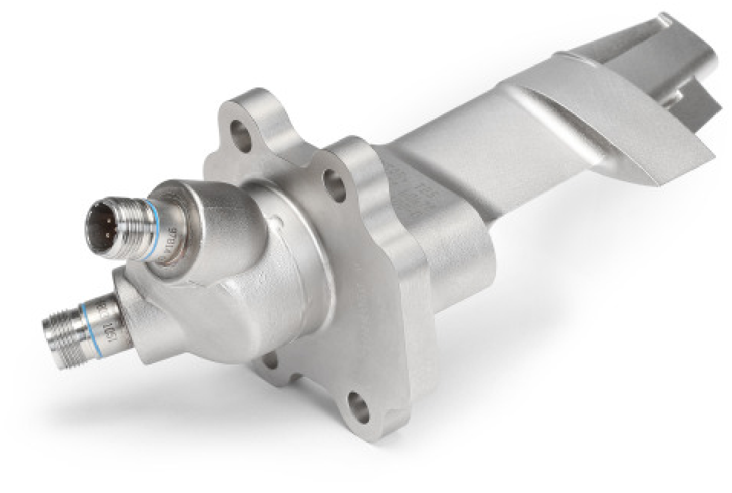

Figure 2.3: 3D-printed housing for the T25 sensor located in the inlet to the high-pressure compressor.[2]

But what we are now seeing in the sector is just the emergence of a future trend. General Electric (GE) Aviation has already started flight tests with several next-generation jet engines currently in development, that will incorporate up to 19 3D-printed fuel nozzles (figure 2.4). The engines will power new planes like the Boeing 737MAX and the Airbus A320neo. [2]

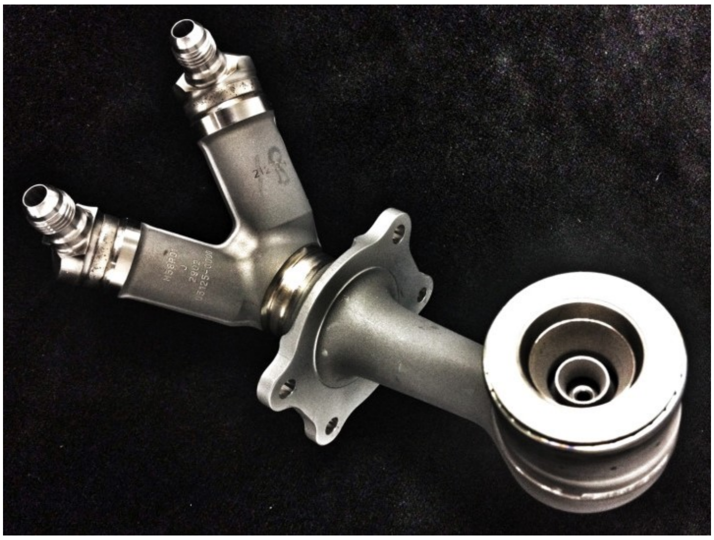

Figure 2.4: 3D-printed fuel nozzle for the GE9X engine.Image credit:"CFM International".[2]

3

Impact of 3D printing in Product Development Process

Contents

3.1 Pains and gains

Additive manufacturing has a lot of advantages, but is also true that there are plenty of disadvantages and constrains.

Freedom of design is always mentioned as one of the main advantages of AM.

A product can be produced of one or many parts in any shape. This increases the level of complexity that a product can have, but there is something even better because that complexity is free. This free complexity mean that a part that is very difficult to produce by conventional manufacturing techniques, something that always translate into increased expenses, will be produced in AM as any other. If two parts are the same size and weight, the complex one may have only a marginal increase in production costs.

To produce that part there is also no requirement of tooling. This is based in the possibility of producing directly the part from the AM machine, without the necessity of expensive tooling This is what is usually called the AM Potential Elimination of Tooling [4]

Creating single components with mobile parts is a reality with additive technologies. This reduce the assembly requirements and specially the assembly costs, but also also reduce weight as there is no need of joining parts. Lightweight can also be achieved with AM in an easier way as, printing layer by layer, it is possible to create not massif but internal structured parts and still retain enough strength and stiffness.

As has been said, there are also drawbacks that limit the expansion of AM. Designers and production managers must be aware of them, because only knowing and understanding this drawback they will be aware of the limitations they will have to avoid.

AM processes are characterized almost always by slow build rates, that can penalize production volume, time to market, or many other crucial factors when designing and manufacturing a product. Processes are not completely efficient.

There is a limitation in the size of the parts that can be produced with most of the additive techniques, and not just because the size of the chambers (See 4.1.1). As a way to prevent this drawback, some companies are working in Big Area Additive Manufacturing (BAAM) systems. [19]

Also potentially anisotropic mechanical behaviour can be expected from this AM parts.

The price of the specially designed raw material for almost any additive technology is very high compared with many of the basic materials daily used in the industry to manufacture similar products.

The processes in which different AM machines are based are difficult to understand in many cases by engineers and designers, as they are out of what industry is used to. This make difficult to properly set up the machines for each specific product or part or material. There are complex configurations and set-ups that must be learned, something that require a big effort for companies and employees.

3.2 Costs

In the AM market, prices, even if very high, seem to be accepted by customers and industry. Despite of the fact that the current generation of machines will be more affordable each day, increasing addition of process and quality control electronics as well as number of lasers/printing heads/ink jets will raise even more the machine prices for new generation equipments. [4]

These costs are supposed to be partly offset by economies of scale as technology evolves enough to become a final parts production method. So the trend of this key parameter in the near future will be a slightly upward trend. Some of these concepts and ideas will be explained in more detail hereafter.

It is true that there is no need for any extra machine (except for possible finishing operations) or the fabrication of specific dies or moulds or any other kind of tool when manufacturing with layer-by-layer processes of AM, but this fact should not lead so directly to the idea that additive processes are cost-effective or a profitable investment. One of the main challenges now is to evaluate the processes of AM technology for calculating the exact product cost, as well as knowing which are the important parameters or cost drivers that have an influence on it.

Some companies are generating software to estimate or calculate with more or less accuracy the cost model of each generative manufacturing process, based on research work and literature as the Hopkins and Dickens model, the model by Ruffo, Tuck and Hague, models by Gibson, Rosen and Stucker or by Lindemann or Ingole. In general all these models take into account the integration of recycling and waste of material as well as support structures, the calculation of the printing time, the maximum possible number of products that can be printed simultaneously in the workspace and the variations with different disposals of products, the level of complexity of the product, the duration of the post-processing and the integration of modern quality management methods for the monitoring of product and process quality. [20]

The general approach is a time-driven costing, in which the costs of the processes are determined by the time they require to be accomplished. Each activity is described with a cost function, parametrized through technical information provided by the manufacturer of the AM machine and some other technical data sources.

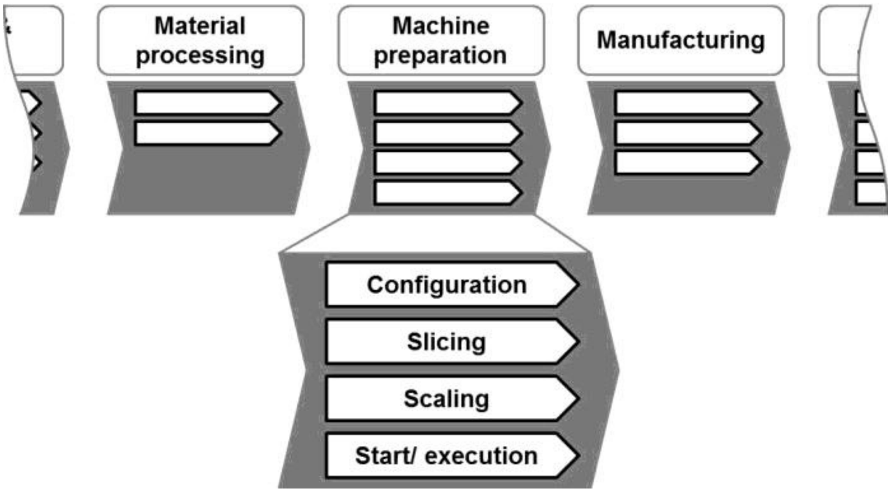

Figure 3.1: Main process steps and subprocesses chart for AM.[20]

The time required for printing one part is one of the most important factors for the final price of it, so machine type, thickness of layers, distance between points in the part or speed are some of the most sensitive technology factors and strongly influence the manufacturing costs.[20]

Managing the machine hour rate, the load factor or utilization rate and the number of components printed simultaneously can also have an important weight into the final cost of production per unit, but these aspects are more closely related to engineering performance of processes, as they are key metrics for improvements in planification and profitability but they are highly dependent on workloads and machines availability, and they are not only inherent to AM, but to all manufacturing processes.

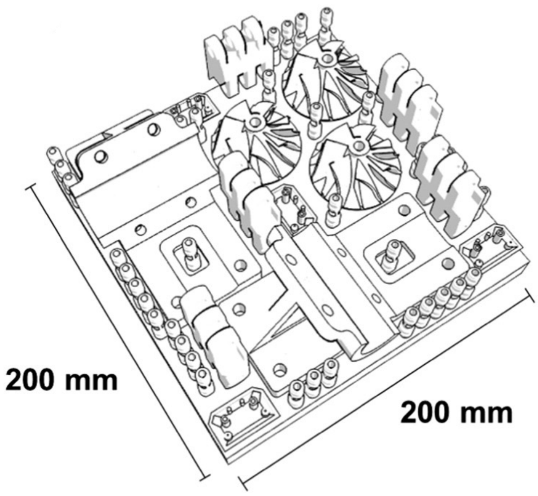

Figure 3.2: High load factor scheme in a 200x200mm chamber.[14]

One of the most simple cost models that can be used draws on direct costs. Considering energy consumption and raw materials as the main direct costs, and combining them with other indirect costs that appear during the building time, which are time dependant, the following equation can be written:

$$C_{Part} = (m \cdot P_{RawMaterial}) + (E_{Build} \cdot P_{Energy}) + (\dot{C}_{Indirect} \cdot T_{Build}) \tag{3.1}$$

where C_{Part} is the cost estimation for each single object produced with AM, m is the mass in kg of all parts including sacrificial support structures, $P_{RawMaterial}$ is the price of the material measured in x/kg, E_{Build} and T_{Build} are the estimates of energy consumption in kWh, and build time respectively, P_{Energy} is the electricity cost, measured in eur/kWh, and $\dot{C}_{Indirect}$ is the total indirect cost rate, measured in eur/h (or any other currency). [14]

It is important to note that this type of cost models exclusively reflect what can be defined as a well-structured costs [21]. Other costs relating to quality or failures, which in fact may be very relevant within AM [22], are not included in the analysis.

The use of that cost equation led to realize, for instance, that the utilization of low density materials tend to moderate raw material costs, despite the high specific costs of the material. This is not always true as that particular material can be paired with a high indirect cost rate, related, for example, with a post production cleaning process. Is because of this that another metric for the comparison of manufacturing cost, the total cost per cm^3 of material deposited, is more useful [14], calculated simply by dividing the total cost C_{Part} by the total volume V of the manufactured part.

In this context, another measure illustrating the technologie's efficacy in turning raw material and energy into products is more interesting.[14] Is the ratio r of all direct costs over total cost, C_{Part}, which can be obtained as follows:

$$r = \frac{(m \cdot P_{RawMaterial}) + (E_{Build} \cdot P_{Energy})}{C_{Part}} \tag{3.2}$$

This r value varies from 0 to 1, meaning that from every euro spent for an AM process, r euros are for raw materials and energy, and the remaining $1 - r$ are indirect costs. So the smaller the r ratio is in a process, the less effective is the conversion of energy+materials into final products.

Roughly and in a very schematic way (see figure 3.3), it can be said that AM is a technology in which the costs are so proportional to product volume and material selection that complexity almost stay out of the equations, making it perfect for producing very complex parts.

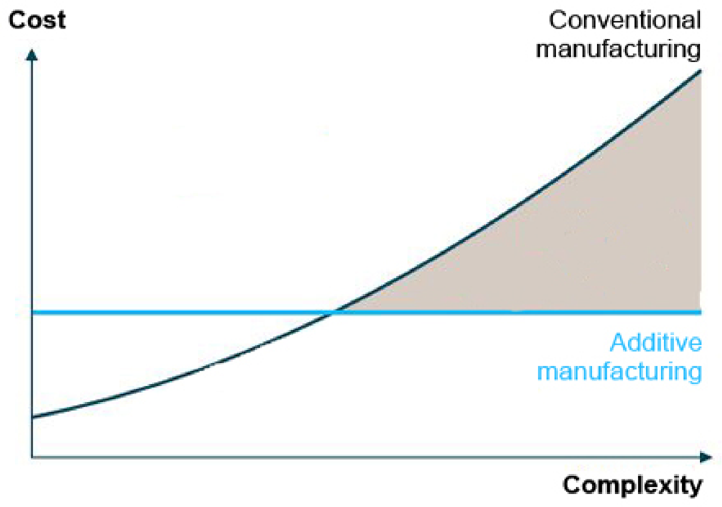

Figure 3.3: Complexity versus cost in conventional and additive manufacturing.

3.2.1 Built rates

First of all, why including a subsection about *built rates* in the *costs* chapter?

As it has been just said, system productivity is a central driver of manufacturing cost on AM technology. It has a very significant effect on the cost performance, and each technology productivity goes hand by hand with its built rate. While additive technologies reach material deposition rates in the order of tens or at most hundreds of grams per hour, conventional manufacturing processes such as machining or injection moulding, report typical process rates of well over 100 kg/h, [23], so one hundred times faster. This fact leads many experts to consider that current AM systems are almost in all cases unable to support high-volume production.[14]

In mostly all AM techniques the built rate is limited by the process itself. Each specific material can absorb a certain amount of energy in a certain amount of time to change its structure, no matter which specific process is taken in consideration. Even for extrusion of plastic in FDM, for sintering steel with a laser or in the process of photopolymerization of reactants with UV, nowadays machines are almost at the limits of that speed rates, so the introduction of a system with two or more printing heads/lasers/light focus points seems the most promising alternative.[4]

Some other solutions play with the concept of running a large number of machines simultaneously. This lay on the idea that future advances in AM technology will bring the equipments prices down, allowing to depress the average part cost and increase the output rate of the whole factory.

Red Eye is an example of an experimental company with this approach. Manufacturing parts on demand, they have an industrial plant in Eden Prairie (Minnesota) housing more than 100 industrial 3D-printers, which is nowadays the world's single largest additive manufacturing facility.

The idea of having a large number of inefficient -or at least not very efficient- machines in operation does not seem like the best way to face the low built rates problem.

The AM-platform, in their Additive Manufacturing Strategic Research Agenda, suggest that deposit rates should increase to gain build-speed by researching new approaches but specially new sources of energy for the material transformation. [24] The main objective would be to bring closer the values for deposit rates in AM to the ones found in the traditional manufacturing industry.

This speed-up would make easier the amortization of the machine cost by bringing up productivity, and the machine price could be only a secondary factor in the strategic decision-making when looking for a manufacturing process. Therefore, in the development of next generation of AM machines, the focus should lie on reducing some of the operating costs rather than on the purchase cost of the equipment itself.[14] Nowadays, machine accounts for more than 50% of the costs due to low build rate.[4]

Having this in mind, manufacturers are working on the build rate parameter and it is supposed to increase fast in the coming years, by improving or introducing one or more simultaneous new solutions.

It has been already cited the idea of the implementation of two or more deposition systems working at the same time in a single chamber, sometimes referred as process parallelization, but also interesting would be another approach based on introducing two or more chambers for continuous production in which some more specific work can be done in each one of it. This is related also with the correct utilization of the workspace, as parts could be automatically transported between chambers if software consider so the optimum.

The layer structure and layer thickness is also key for the built speed as is evident that deposition rates are directly proportional to selected thickness. This is because ”printers” take approximately the same time for printing a thin or a thick layer. With almost all AM systems capable of selecting between various layer thickness, in chapter 4 will be shown how thin layers lead to a fine-detail level and high resolution components with tighter tolerances, but in exchange of a more time-consuming process. An innovative concept is the possibility of using multiple layer thicknesses to grow up a single part. This way we would have an optimized layer structure, having in the component different layer thickness in different sectors of it, according with the level of accuracy needed.

Increasing built rates also lead to more errors during the manufacturing process, and therefore to increased rejection rates if those errors are not detected and corrected before the part is finished. That percentage of processed parts that are rejected could be controlled by monitoring systems that help the machine to find, and even solve, its own errors, so not to compromise the system stability due to excess of speed.

Build speed will at least quadruple by 2018. The price of the materials for AM will decrease significantly in the next 10 years. With the increasing of market, volume production costs for high-quality materials will fall, and the amount of AM material consumption will reach to 9000 tons by

2023 from the current 1000 tons. Labor cost associated with AM will experiment a downward trend in the next years. This will be possible mainly because of the introduction of reliable systems which will reduce the effort on monitoring and troubleshooting, and with the introduction of systems with automated refill of material, or removal of excess powder or base support.[4]

3.3 Alterations in the product development process for additive manufacturing

The Product Development Process (PDP), as a mechanism to create new products that compete in the market by understanding the changing customers needs, may experiment some variations with the emergence of new technologies that provide new capabilities. The influence of AM in the PDP or New Product Development (NPD) can be evaluated in each of their phases.

There are plenty of models for PDP. It can be said that even one for every company involved in designing tasks. But almost all of these conceptual models for product development, designed in order to facilitate a smooth process!, are based somehow in the Booz, Allen and Hamilton (BAH) Model, published in 1982. It is one of the best known models because all of the further studies and research done over its basis, sometimes to try to improve it or either propose better solutions, ultimately end up proposing other models that are closely linked with it.

This BAH model is what is called a stage-gate model, and divides NPD into seven sequential stages or seven steps: new product strategy development, idea generation, screening and evaluation, business analysis, development, testing, and commercialization.

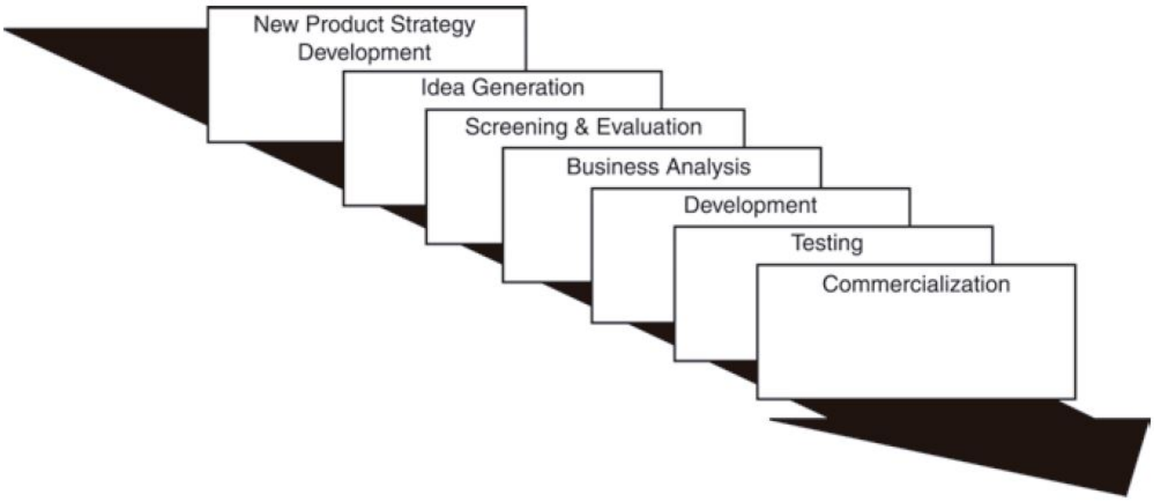

Figure 3.4: New Product Development sequential stages in BAH model.[25]

With this division, common in the development of almost all products as has been said, is possible to analyse the impact of AM in each of those stages of the product development separately.

The main phases of the Product Development Process and the impact of AM will be studied in detail in the next subsections.

3.3.1 New product strategy development

In the model of Booz, Allen and Hamilton, the PDP starts with the visualization and definition of the new trends, the missions and the associated objectives that products must have. Is like creating a point of reference or setting out the new direction, according to a generic strategy or a market trend, to follow when seeking for ideas. In this aspect, AM can be considered as one of those strategies or directions, as it is a fertile ground to create new products that were economically impossible to produce or technically complex.

3.3.2 Idea generation

Not been considered a very rigid phase, is in fact when a new product is born as an idea. This idea can be generated, or just appear, in many ways and for many reasons, coming out for example from one individual in his day-to-day life, or within a company team as a response to competitors, as a need of the market or just as a technology-push concept, mentioned above. Even if this is a process that necessarily requires creativity, some techniques can be used to help in the generation of those ideas. Brainstorming, market research, problem identification or external ideas from competitors are many times origin of this creative process. This techniques must by guided in a way that their outputs are compatible with the objectives of the previous step, strategy development. It is difficult to find a possible impact of AM in this phase of the PDP, as it is mainly a non-physical step regarding symbolical and immaterial ideas, where at the beginning all of them are welcome as a "can be done" idea.

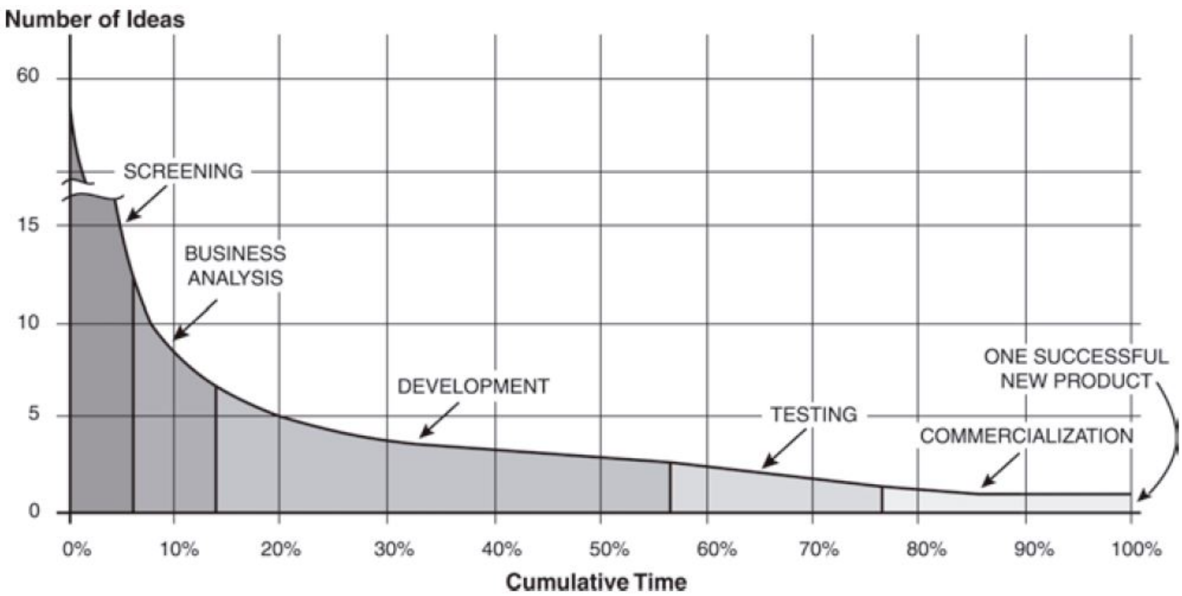

Figure 3.5: Mortality of New Product Ideas.[25]

3.3.3 Screening and evaluation

All the ideas from the previous step must be screened right after. Only promising ones move on to the next stage and are the ones that will be further investigated. Each idea must be envisioned as a product on the market where it can be evaluated on its potential contribution to given entities.[26] By checking superficially their market opportunities and profitability, the total number of possible ideas generated in previous phases is narrowed down.

During this phase of screening, AM plays a big role, but in the sense of prototyping. A quick sketch of some of the ideas in a CAD software and a 3D-printing machine can give the designing team physical objects to really feel what having that product in the hands is. This turn the idea from what they expect from it to what it really is. It can be a way to lower down that expectations of some of the ideas and reject them. Developing teams can focus in those with a bigger potential.

3.3.4 Business analysis

During the business analysis the remaining ideas are subjected to another filtering process. Business plans are made for each of the ideas, studying in detail the market and possible competence, but also defining the attributes of the product and the relation between them and the final costs, financial projection and marketing and promotion. Establishing the target specifications and refining them as a result of the economic analysis and competing products will have a big weight in the decision making of this business phase.

3.3.5 Development

During the development phase, more details are elaborated around the product idea. The main objective is to identify customer needs so, with that information, the engineering details and features that customers are willing to have can be incorporated to the product. Is a crucial step, as it is where ideas from the paper transform into a real product. In this phase, RP always have had a great impact. This is because the feasibility of the variations of the product designed with a CAD is tested by printing prototypes of them. But in the case of products that will be produced with AM the implications are much broader. Even if the part is not completely accurate, or still has not all the details of the final product, the prototype will be much similar to the final product. Instead of, for example, prototyping in plastic a new shape of an aluminium propeller helix in a prototyping machine, the different designs of that helix can be prototyped on exactly the same machine and in the same way that it will be produced if it end up being the final design. Somehow we are not talking about prototypes any more, but about different versions of final parts. However, when talking about big parts that would have high levels of consumption on time and materials during the prototyping stage, printing the whole part with all details is not efficient. Some alternatives are printing the product in low resolution with the same final machine, producing it with a faster and cheaper prototyping technology or with a lowpriced material. Also prototyping only parts of the product is a good idea for saving time and money, specially when prototyping is focused on the resolution of technical problems, or very specific parts of the final product. During this phase, a product usually suffer many alterations. In this respect, AM is the perfect weapon to see all those changes and variations in a fast prototype that has a really close look to the final product, produced in the same way, layer by layer.

This phase will be ultimately to generate several design concepts and select the best design concept to build the details. This selection process, alfa-testing, is generally done by a designing team of people from inside the company or related somehow with the product.

3.3.6 Testing

Testing is the phase of experimentation and trials. The main objective is to validate the product in the economic, commercial and functional way.

Products to be produced trough AM have great advantages in this step. From the economic point of view, as prototyping is done in the same way that production will be done, the prediction of some of the final costs of production, mentioned in 3.2, is more than accurate. The time and material consumption during the prototype manufacturing are almost the same that will be during production if finally the product reach the ramp-up and commercialization. Some of the costs predicted in the business analysis phase can be checked now. In the technical aspects of the product, laboratory testing takes also place now. As the prototypes has been made by AM, manufacturing impediments would have been shown before, and the testing now can be focused in the engineering functionality, quality and durability of each part of the product. Also because the final product will be produced with additive techniques, the output of the AM machine that creates the prototype will be almost identical or really similar to the final product. This is perfect for marketing tests with potential costumers, because what they see is exactly what they will get if this development process ends up with a successful product in the market. That feedback will be much more reliable than if costumer see a not-working prototype, with not all the features and in a different material, of a non-definitive product. There is no need to communicate the concept indirectly, because customers have in their hand not a concept but the product. With that accurate feedback of the beta-testing and after measure that customer response, is time to refine specifications with just some modifications in the CAD software, reflect the changes on the process and manufacture again some products to re-test them. The detail design can heavily change after this testing phase, and, most importantly, with no added cost of tooling.

3.3.7 Commercialization

The commercialization involves the production ramp-up and specific distribution for the introduction of the product into the market. For product manufactured with AM, there are again many advantages in this stage. As there are no specific and expensive tools needed to produce the product, is still possible to quickly change any aspect of the design. This may happen if the customer expectation is not enough satisfied or competitors introduce improvements to their products that can not be found in the new product in the market as a reaction.

Following any of the PDP models is crucial to minimize the risk of failure of commercializing a new product. Nevertheless, adopting a systematic procedure for the product design does not guarantee success. Even if the assertion that the product failure rate is around 80% is common, and failure rates as high as 90% or higher are sometimes cited, actually the new product failure rates are around 40% depending on the industry. Research studies between 1945 and 2004 find failure rates in the range of 30-49% [27]

In the table 3.1, appear detailed most of the reasons for this new product failure rates.

Causes of New Product Failure
1. Market/marketing failure
Small size of the potential market
No clear product differentiation
Poor positioning
Misunderstanding of customers needs
Lack of channel support
Competitive response
2. Financial failure
Low return on investment
3. Timing failure
Late in the market
Too-early market not yet developed
4. Technical failure
Product did not work
Bad design
5. Organizational failure
Poor fit with the organization culture
Lack of organization support
6. Environmental failure
Government regulations
Macroeconomic factors

Table 3.1: Common reasons behind new product failure.[28]

Products manufactured with AM are very agile when moving through these failure causes. The small size of the market is not so important as they do not need specific tooling to be produce. This make costs much more linear with the number of units produced, without the necessity of amortising moulds, dies or roll forms. As said before, there is also a minimization of the misunderstanding of customer needs as they get more accurate prototypes during trial phase, and the response to competition can be done by changing some designs without the necessity of making big changes in the production line. This last reason make also easier to adapt and design an unlimited number of times if necessary, until customers see that level of ”good design” that they are seeking for.

On the whole, AM give to the product, and therefore also to the product development process, a degree of freedom and adaptability much higher than what common products have in traditional manufacturing processes. A model of the PDP that is mainly designed to avoid risks and costly product failures can be softened and development teams can go through it in a faster way, as some of the decision taken during the process are not rigid or fixed from that moment on, like they are with traditional manufacturing methods.

In this sense, much more intellectual and economic resources can be destined to research people desires. This is really interesting for many companies because to attain purchaser needs has become over the years something increasingly difficult. Customers quickly change preferences and each day increases the heterogeneity of their demands. Thus, forecasting these desires and the exact specifications that customers are looking for, even when sometimes not even them know what that specifications are, have a much bigger weight in that new-adapted product development process than other more technical aspects that can be slightly solved afterwards. The main culprit has been a faulty understanding of customer needs. That is, many new products fail not because of technical shortcomings but because they simply have no market. [29]

4

Satisfaction of all product specifications with additive manufacturing.

Contents

4.1 Size, shape and positioning

4.1.1 Size limitations

The limitation in the size of the parts that can be made by AM processes is a target for all the companies present nowadays in this market.

Is true that increasing the dimensions of the available build volume is likely to result in lower average cost as certain fixed process elements, for example warm-up or cool down, can be amortised over a larger build volume [14], but the major problems are not so much in the machine's chamber volume, which are currently not perceived as a limiting factor, but in the process reliability to fully occupy bigger chambers with satisfactory results.

In big parts, specially in slender shapes, warping may occur due to the temperature gradient during the cooling down. The inhomogeneous heat dissipation, with a more significant effect in massive objects, cause high internal tensions in the materials induced due to changes in the material density, as the material is transformed from a melting state to a solid state.[30]

Although, warping is not an exclusive drawback of AM as it must be also taken into account when components are produced by many other manufacturing techniques, like welding or casting. Lowering printing temperature or, as will be seen in future chapters, applying heat treatment can partially avoid this issue.

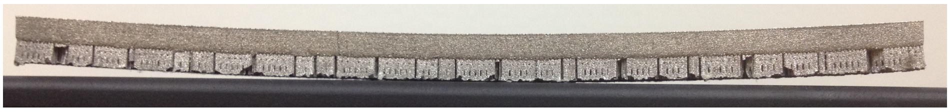

Figure 4.1: Warping of a DMLS part without thermal treatment. Source: Center for AM, NC State Univ.

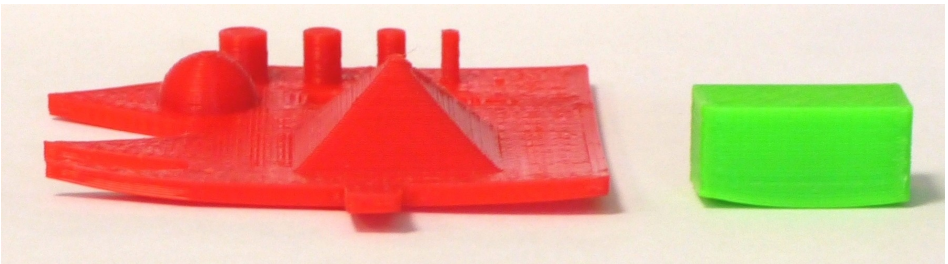

Figure 4.2: Warping of FDM parts. Source: Magazin 3d druck

In big parts with large surface layers another problem related with the temperature is found, specially for FDM. Printing at a lower temperature, even if it is good for avoiding or, at least, minimizing drawback, is not always an option. Because the printer will take a long time to complete the printing path of that layers, the lowest temperature required for allowing a good interlayer adhesion is not maintained.

Completely closed and well insulated chambers are key to prevent variations in temperature and so minimize these problems, both interlayer adhesion and warping.

This effect of curling and warping is more visible, as has been said, in slender shapes. During the design phase all these details must be taken into account, trying to reduce the number of that kind of wall in the model or minimizing their effects. For example, it is possible to partially avoid warping by adding in the design discs (mouse ears), as seen in figure 4.3, or little square boxes in the corners. These tiny one-layer disks or boxes keep warm the zone they are attach with for a longer period of time, and also contribute to generate an extra structure preventing the warping, and they can be easily trimmed after cooling. These surfaces sometimes are also expanded to a big platform that fix the hole part as can be seen in figure 4.4

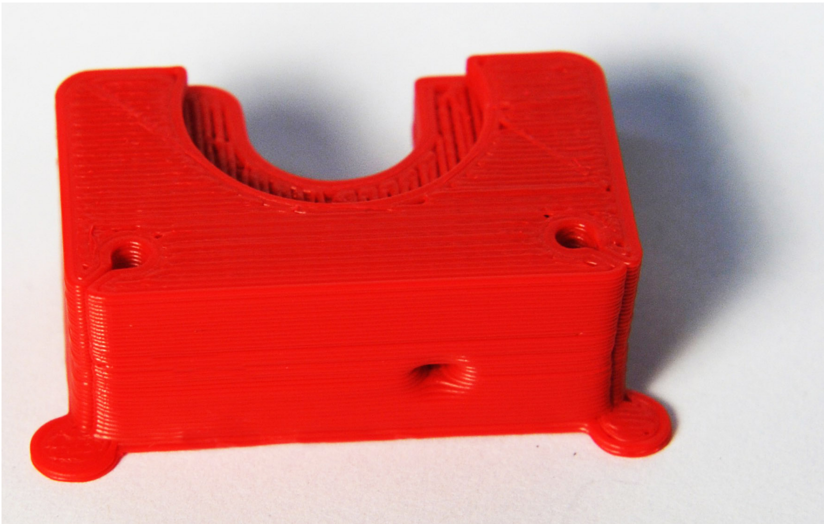

Figure 4.3: One-layer disks to prevent warping. Source: Makerbot industries,LLC

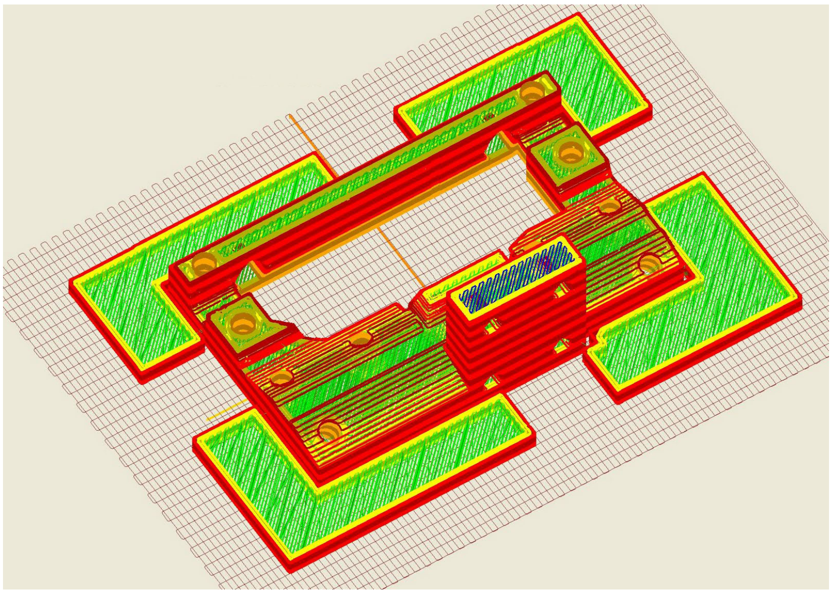

Figure 4.4: Added platform to keep assembly flat. Source: Makerbot industries,LLC

As the main reason for this curling is the internal stress of the product generated as massive material cools down, another solution involves reducing the infill. By printing a part not completely solid but with some percentage of hollowness, there will be a reduction in the amount of internal tension as the part cools down.

So controlling infill ratio is key for keeping the desired shape, while avoiding warping. In figure 4.5 the internal structure of a printed part with a reduced infill percentage can be seen.

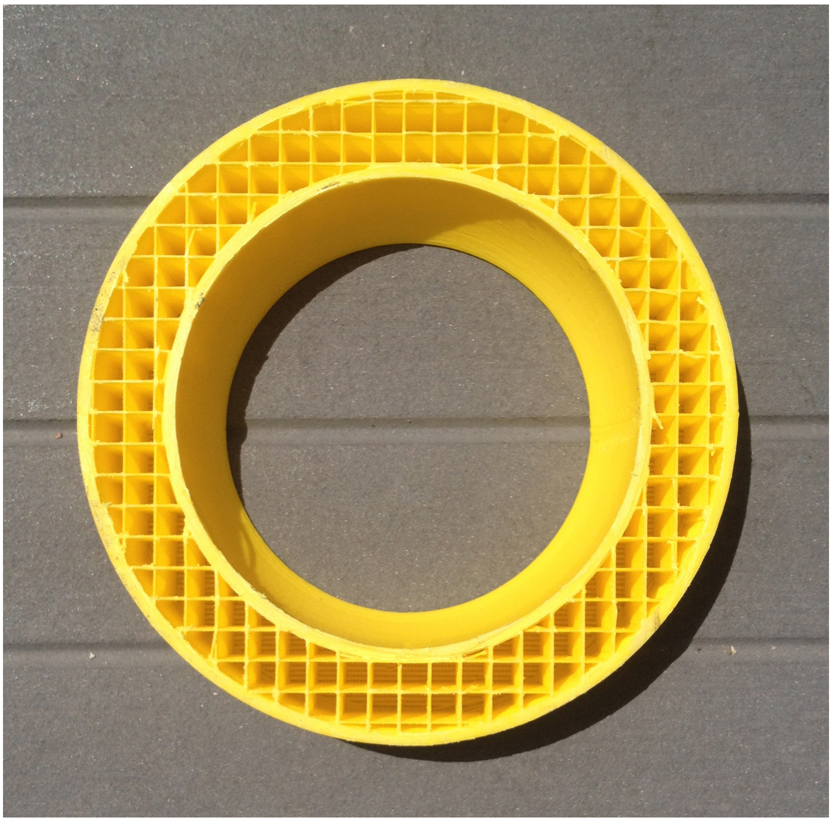

Figure 4.5: Sectioned part with a reduced infill percentage

4.1.2 Object orientation, path configuration and structure

The influence of the orientation of an object while printed is one of the most significant factors and thereby has a strong impact on the strength of 3D printed parts. The anisotropy of the procedure make some directions specially week under tension. Adhesive strength between layers or across filaments (traction test in build direction) is appreciably less than the strength of continuous filaments or longitudinal strength, where the traction force is applied in the specimen perpendicular to the build direction.[31] (See figure 4.6)

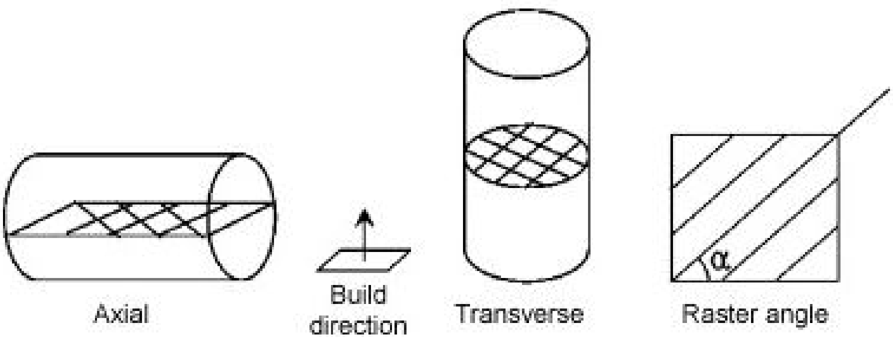

Figure 4.6: Build direction and layers in FDM specimens related to traction test.[31]

This conclusion can be ratified by tensile tests realized with test specimens according to ASTM standard. In an article by A.Silva and M. Fontul [32], specimens were tested at 0 and 90 degrees with respect to the build direction while printing. As a result, test specimens with traction perpendicular to build direction can withstand loads that were around 70% higher than in traction tests in build direction, preserving also a long plastic strain before fracture.

Parts need to be durable enough to withstand repeated use in functional end-use applications. Build orientation impacts strength, so if durability is crucial, it is best to choose an orientation that increases the number of layers that connect features like tabs or hinges to the body of a part. Connecting these components with multiple layers decreases the risk of them breaking off. [33]

Not only build direction, but also parameters like the cord height or the raster angle are very important for FDM processes.
When printing each layer, the FDM machine builds that layer by depositing down tracks of the extruded material. These tracks are usually called "roads" and they form the path. This path can follow an automatized pattern to fulfil the shape of the slice. Usually this automatic path is made by the contour of the slice formed by one or two cords, and then filled with a continuous cord in a 45° raster angle orientation.
If special characteristics are needed, some attributes can be assigned to those "roads" for each slice. Most of the basic AM machines do not have a way to easily control the general layer path, so final results rely on the position of the object in the printing chamber. The newest and most advanced machines are able to create a specific path for the "roads" of materials in each layer.

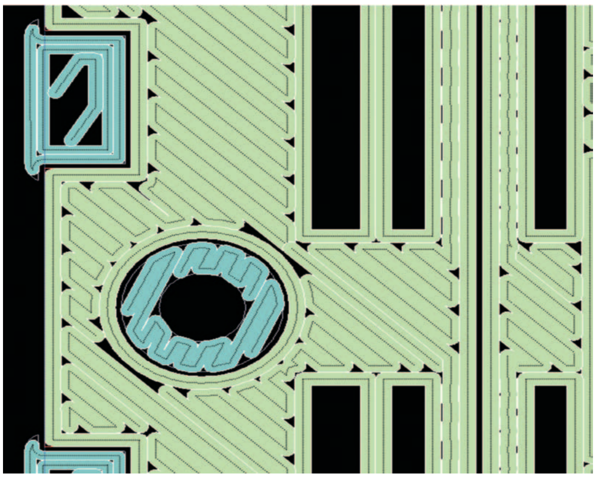

Figure 4.7: Complex path in FDM layer.[34]

For some products it can be particularly important to control where the heads (initial part of the path) and tails will begin and end at each layer of material, to avoid weaker less dense areas. Unfilled areas are likewise found in almost each layer as well as among particular layers in products produced by FDM [34]. See, for example, figures 4.7 and 4.8

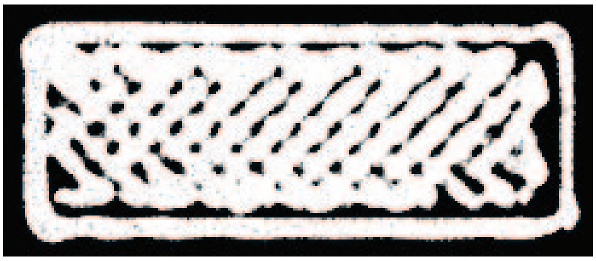

Figure 4.8: Non-filled area in a FDM cross-section.[34]

Printing conditions influence the structure homogeneity. Processing temperature has an important role when trying to minimize the non-filled area. In the figure4.9 a graph shows the effect of increasing from 280°C to 290°C the temperature of the end part of the liquefier that converts the stock material to a fluid state, for both 70°C and 75°C temperature in the chamber.

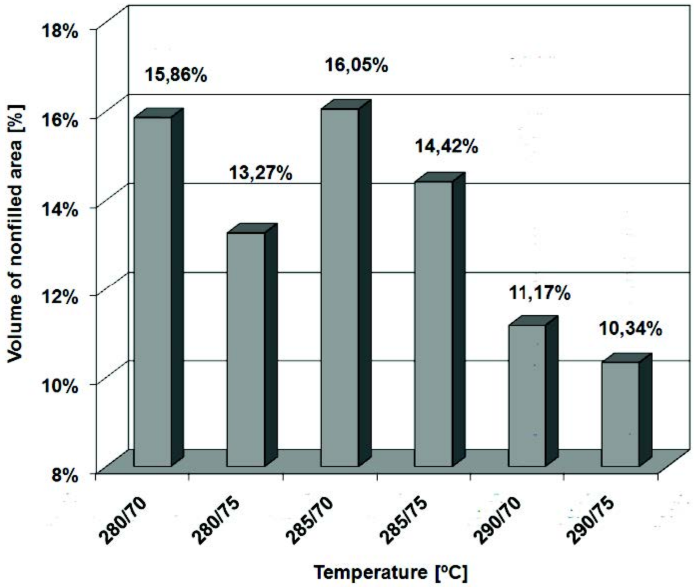

Figure 4.9: Non-filled area in FDM cross-sections depending on temperature.[34]

For parts printed with a higher chamber temperature, the non-filed volume is reduced between 1% to 3%, but the biggest difference appear when heating up the liquefier, where this reduction is around 5%.

It is important to note that volume of non-filled area is also affected by the shape of the fabricated part. The influence of processing temperatures is less significant in the parts with circular cross-section (figure4.10) than in the parts with rectangular cross-section. [34]. Material distribution is not uniform in the whole volume, and higher density can be observed in the area of layer building closer to the start point.
To fulfil wide and curved shape slices is much easier for FDM technology so if we want to reach parts with maximum infill percentages we must avoid as much rectangular shapes as possible.

Orientation and build angle has a significant influence in the surface quality, an aspect that must be taken into account when manufacturing final products with a minimum quality required. This point is discussed in section 4.3

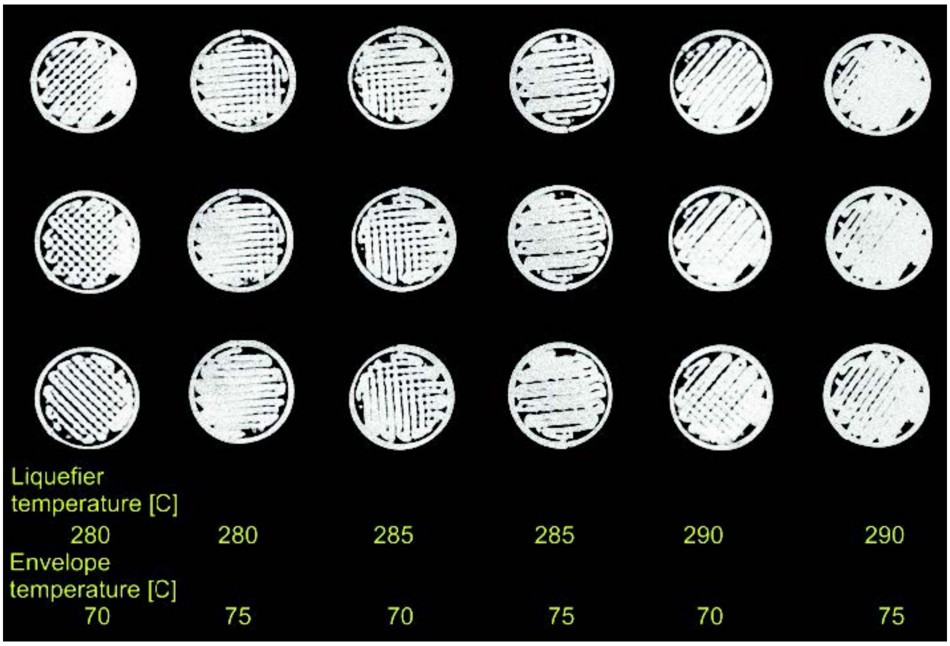

Figure 4.10: Non-filled area in a FDM cross-section.[34]

4.1.3 Structure

The infill percentage, discussed in a previous section, is closely related to the structure of the part. An object can be printed with different macro-structures and, at the same time, with a different infill percentage for that same structure. These parameters together will lead to a final global density, apparent density and real density, depending on the amount of open and closed pores or holes that part and material has in a macro and micro scale (See appendix A for further details).

FDM is especially characterized by its structure inhomogeneity, as a result of the basic principles in which the technique is based. The parameters selected while printing highly affect the structure of the parts that are produced, changing layer shapes, perfection of filament or the portion of unfilled volume of the specimen. This volume of non-filled area is also affected by the shape of the fabricated part. At the same time, as technology is more able to control this inhomogeneity, it becomes an important feature for fused deposition, for its potential to fabricate parts with locally controlled properties like density and porosity.[34]

It is known that process parameters such as the air gap between adjacent tracks, raster angle, raster width and thickness of deposited layers influence the performance of parts produced on an FDM machine. [35]

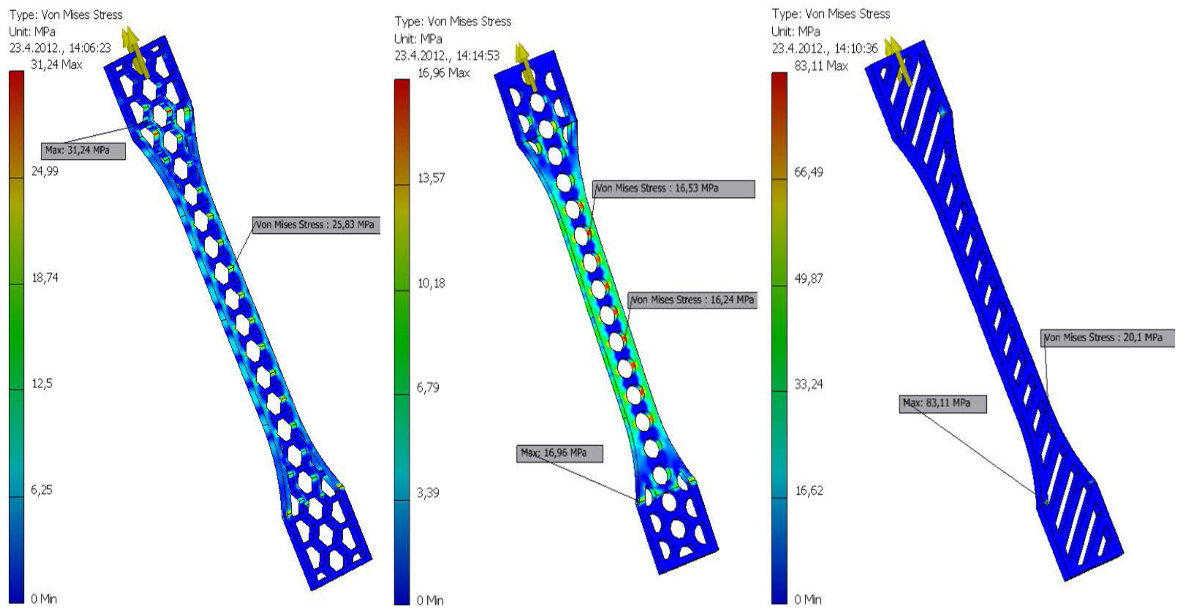

Figure 4.11: Distribution of stress in different structures.[36]

When comparing special structure samples with full-bodied ones, it is appreciable a significant impact of that structure and the orientation of the sample. When designing light weight structures, for example, the sufficient strength is key for not to compromise the whole integrity of the structure, which will lead to a fatal fracture.

In tests by T. Galeta, P. Raos and M. Somolanji, the tensile strength at break was measured for honeycomb, drilled and striped structures, shown in figure4.11, and compared with its minimum cross-section area.

When comparing the type of structure as an influencing factor, the honeycomb-structured samples show the highest strength.[36] Worst results in the stress tests were achieved by the samples with striped structure, with an average of half of the tensile strength at break compared with the honeycomb. Drilled parts find their place between honeycomb and striped specimens.

The samples with a lattice structure show bigger strengths than compact material samples even if the compact ones can withstand highest forces before breaking. Even if compact structures are stronger, the specific strength of special structure samples is higher, this is, they provide a higher strength per kilogram of material. Special structures provide sufficient strength with reduced mass.

It is also very important to consider the savings of using these structures, not only savings in printing time, but also in printing costs, energy and materials. Considering these structures in the design of products manufactured with AM is for sure an excellent idea when possible, specially for large parts or when talking about long-run productions of an object.

4.2 Materials

Many of the products that can be seen in the shops, the consumer products, are made by some kind of thermoplastic. Thermoplastic in AM is closely linked to Fused Deposition Modeling, as many of the machines for FDM are compatible with plenty of these materials. Prototyping with the same material in which the final part is going to be made of is important, but being able to produce final parts with additive techniques with the most commonly used material for consumer and commercial products and components is a big step forward for the AM market.

The processes in all Additive Manufacturing techniques influence the quality of the material when the product is created. In FDM, the properties of the processed material in any part are slightly different from the properties of the primitive raw material, and these differences depend on the temperature and speed parameters when printing.

There are many materials that can be used in AM. Even putting only the focus on FDM it is possible to find plenty of them.

Probably one of the most used is Acrylonitrile Butadiene Styrene ABS. This is a family of thermoplastic very common in industrial and domestic uses. One of their main features is the resistance to impacts, but one of the main problems for its use in AM is that, as it is amorphous, it has not a defined melting point. Anyway, its glass transition temperature is approximately 105°C, in which it turns from a hard state to a molten-rubber state.

There are in the market different variations of the traditional ABS. For example it is easy to find ABS with reformulations to improve the properties after FDM processes, or translucent ABS or ABS with electrostatic dissipative properties that prevent damages in products with static electricity incompatibilities, like electronic enclosures. There are also ABS's that meet the ISO standards in the regulation for consumers safety to prevent ilness and disease and that can be sterilized, specially formulated for medical uses or products in contact with food for human consumption.

Policarbonate is also a very common thermoplastic for manufacturing, because of the easy way in which it can be moulded and thermoformed. It has a very good heat resistance and one of the highest tensile strengths between the FDM materials. Some variations include also a biocompatible version of PC or a combination of PC and ABS, which put the stronger mechanical properties and resistance to high temperature of the PC together with the flexural strength and surface appeal of the ABS.

As materials with less use, but still important, can be considered for example the Polyetherimide (PEI) resin, the PPSF or the nylon. The PEI resin is a high performance thermoplastic used in the aerospace industry because it meets high requirements related with fire, oxidation and toxicity. It has one of the highest tensile and flexural strength, durability and resistance to heat and chemicals. The PPSF is also perfect for chemicals resistance, gasoline and acids. It has also the highest heat resistance, reaching heat deflection temperatures around 190°C, which make it perfect for advanced applications. The nylon material is indicated for high-fatigue applications. Chemical resistance is also a characteristic feature of this material. [37].

In spite of all mentioned materials, there is a main drawback, and not just in FDM but in any AM process, and this big drawback for the industry is the amount or variety of raw materials available.

There are plenty of materials used each day for many components all over the world that still nowadays can not be used in AM. It will be really desirable to have the hole palette of materials and many universities, research labs and chemistry or AM companies are working on this problem, and developing new materials, but is still seen as one of the deficiencies for adopting this new way of manufacturing as a competitive way to substitute subtractive technologies for some specific parts.

The development of titanium, tungsten carbide, silicones is a reality in AM, but important steps forward must be done in this chapter to finally reach the desired situation in which one single machine can produce a product using different materials at the same time.

Because of the mentioned variation of properties after the additive manufacturing process, and because of the importance of the material that is being transformed for setting the correct parameters in the machines, each commercial material in the market shall include a compilation of the main properties and the most affected ones. (See table 4.1 with P400 ABS properties after extrusion) Anyway, is true that the material properties are also modified when these same materials are used in other manufacturing processes, like injection molding.

ABS-P400 Properties

Mechanical Properties[1]

Tensile Strength (Type 1, 0.125", 0.2"/min)	ASTM D638	22 MPa
Tensile Modulus (Type 1, 0.125", 0.2"/min)	ASTM D638	1,627 MPa
Tensile Elongation (Type 1, 0.125", 0.2"/min)	ASTM D638	6%
Flexural Delamination	ASTM D790	14 MPa
Flexural Strength (Method 1, 0.05"/min)	ASTM D790	41 MPa
Flexural Modulus (Method 1, 0.05"/min)	ASTM D790	1,834 MPa
IZOD Impact, notched (Method A, 20°C)	ASTM D256	106 J/m

Thermal Properties

Heat Deflection (HDT) @ 66 psi	ASTM D648	90°C
Heat Deflection (HDT) @ 264 psi	ASTM D648	76°C
Glass Transition Temperature (Tg)	DMA (SSYS)	104°C
Melt Point	(NA)[2]	(NA)[2]
Coefficient of Thermal Expansion	ASTM E831	5.60 E-05 in/in°F

Other

Specific Gravity	ASTM D792	1.04
Vertical Burn	UL94	HB
Dielectric Strength	IEC 60112	32.0 kV/mm

[1] Build orientation is on side edge except for flexural delamination which is upright.

[2] Not applicable (NA) due to amorphous nature. Material does not display a melting point.

Table 4.1: Example of a material properties table for the ABS-P400. Source: Stratasys, Inc.

When talking about raw materials, there is an important consideration to have in mind, not only for additive processes, but in any material selection for any product and production process. This important parameter is the compactness/porosity of the material. It is so important because the strength of a part decrease when the porosity level increase. With high porosity, the material will also be in general less resistant to chemical attack, and some properties related with thermal conductivity and resistance to thermal shock will be also diminished.

Some empirical relation laws are found between the Young's modulus and the density or porosity of a material, for example this one by Phani and Niyogi

$$E = E_0 \left(1 - \frac{P}{P_c}\right)^f \tag{4.1}$$

where E is the effective Young's modulus of the porous material with porosity P, E_0 is the Young's modulus of the solid material, P_c is the porosity at which the effective Young's modulus become zero and f is a parameter dependant on the morphology and pore geometry of the porous material, usually considering $f = 1$ for a linearized model[38]. Plotting this equation for any material will result in a descendent curve as porosity increase.

This porosity is a factor depending on the material, but as explained in the subsection 4.1.2, many times the porosity or amount of holes is dramatically increased by the manufacturing method used when producing the part. Porosity of the material and porosity of the final product is thus key to guarantee the final strength of the structure.

When talking about the materials and, of course immediately after, about their tensile strength, some ideas come to mind about including structures inside a printed part. This will lead to a redistribution of forces inside the structure, so the additive manufactured product could be lighter and could be made in a cheaper material with inferior mechanical properties.

4.3 Appearance and surface

The value of aesthetics and the attention to quality and cosmetic appearance of the surface is mandatory in final products production. Even though a smooth surface and soft finish is usually also a requirement for rapid prototyping, it has much more bearing for products that reach customers.

An issue with FDM is surface quality which is dependent on layer thickness and build angle. [34].

In FDM, with a layer by layer approach based on a deposition of extruded thermoplastic, the surface aspect when the part goes out of the printer does not reach the usual minimum requirements of the products that are currently on the market.

The multiple layers are visible many times on the surface as lines and roughness, or even worst, as rungs of stairs. This is related with the orientation of surfaces with respect to the building orientation or direction. Products with walls or surfaces completely vertical, so perpendicular to the base growing in the z-axis, or completely horizontal, parallel to the base, do not present these problems, showing a smooth surface even for not so high resolutions (tinny layer thickness, see figure 4.12).

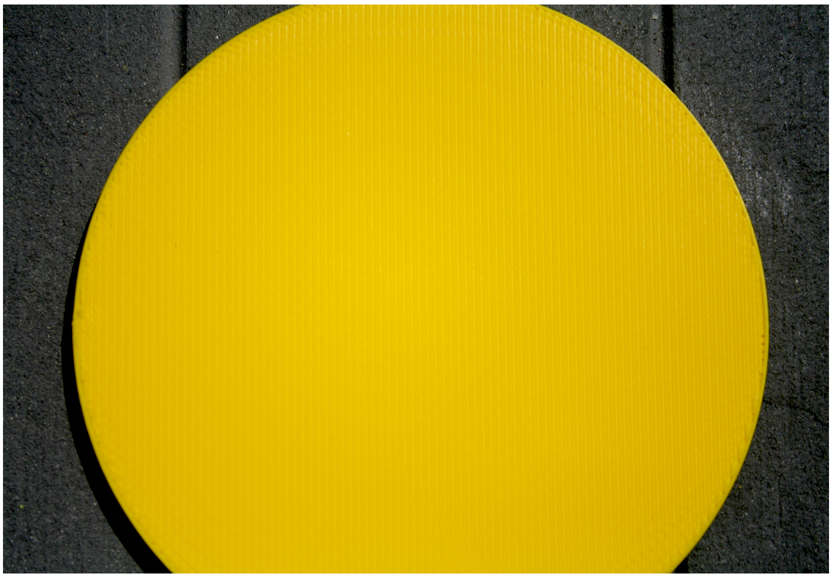

Figure 4.12: Smooth horizontal FDM surface with 254μm resolution

In the other hand, the appearance of these lines and stair rungs increase for sloping surfaces, as the inclined planes can be approximated only by the indentation of the consecutive next layers, as can be seen in figure 4.13. With the same resolution, it is clearly observable a better outcome with building directions in which the sloped surfaces are more vertical, so with a bigger angle with respect to the base when printing (See figure 4.14). This drawback can be minimized also by reducing the layer thickness, but in exchange of increasing the manufacturing time.

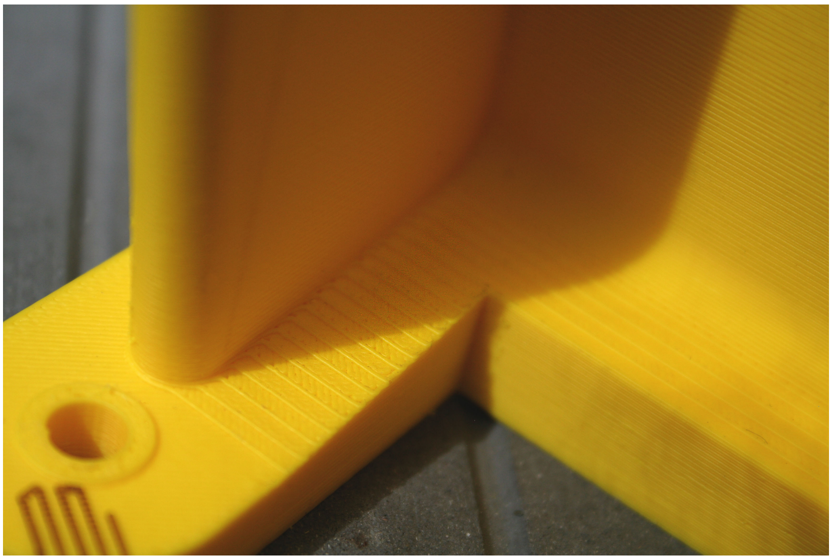

Figure 4.13: Visible rungs on a real FDM part with 254μm layer thickness

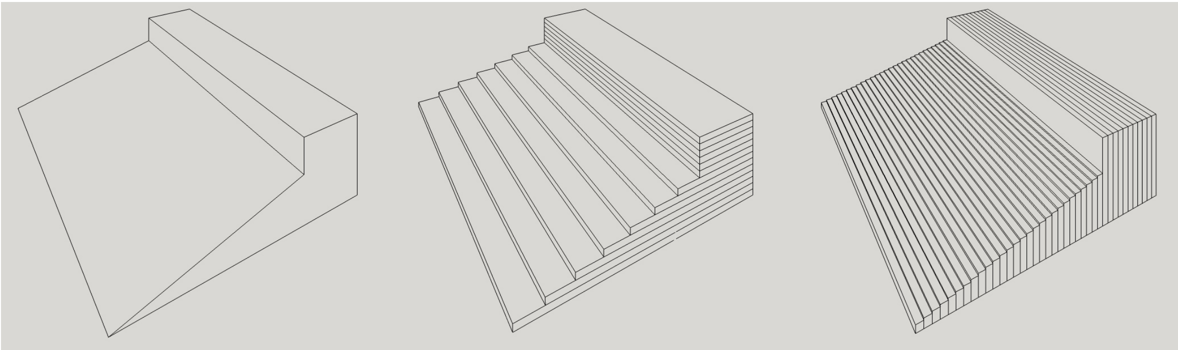

Figure 4.14: Schematic approximation of a 14° slope surface in different building directions (layers thickness 254μm)

With other AM methods, like polyJet printing or StereoLithography the effect of this rough surfaces is less noticeable. Reaching a layer thickness of less than 50μm, so less than one twentieth of a millimetre, this fine resolution technologies have to deal with other drawbacks, but not with rough surfaces. (See figure 4.15)

Figure 4.15: Soft surface in 25 μm resolution with SL technology.

Additionally to these basic considerations, there are in the market solutions for providing the FDM parts a better surface finish. They are secondary operations made to grant parts the appearance needed to definitely be a final product, and not just a prototype.

FDM manufactured products can be painted, glued or drilled as any other plastic component in the industry, but is true that the porosity of the parts is a downside of the technology for many of the finishing processes. To solve this problem there are infiltration products to seal the FDM parts by penetrating the pores in the surfaces and filling them with epoxy resin, which guarantee a durable seal for air and liquids, as required for many market applications, withstanding also hight temperatures and soft-chemical attack.

Bead blasting, a subtype of abrasive blasting, is another finishing process used in the plastic moulding manufacturing industry, but can be perfectly applicable also to FDM parts. The usual fine glass abrasive is substituted by a plastic blast made of fine thermoplastic, and by firing it at high speed to the surface of printed parts, is possible to remove any remaining support structures and achieve a surface with the desired quality result, always covering first the parts that are not suppose to be treated. There is a range of different blasts available, from soft to harsh in the Mohs hardness scale, and also different sizes for different applications and speeds.

As an alternative to bead blasting, and specially indicated for large scale productions, whether in additive or any other manufacturing process, mass finishing improve the surface aspect of many parts at the same time by introducing them in vibratory machines or centrifugal barrels. It works perfect with fragile parts or tiny details of the products, as the product inside the vibratory or centrifugal machines is non-abrasive or has a soft abrasive specification. Parts end up with a polished and glossy surface.

Electroplating can make a big difference in the final aspect of a product manufactured layer by layer. Creating a thin coating of almost any metal, a high resistance, hard and durable material is achieved. With this finishing process there is also a spectacular increment of the tensile and flexural strength of the parts, specially if they are thin and the ratio surface-volume is big. This is evident as the thin layer of metal has much higher strength properties, that combined with the printed material create a composite material with optimal properties. Is important to note that the product or part must be able to resist temperatures over 40 or 60 °C that are easily reached in a coating treatment. A correct sealing process is also necessary for an adequate electroplating.

Painting is, for sure, one of the finishing processes that help a part to make a big step forward for meeting the cosmetic requirements of a final product. Talking about products produced by AM, complexity and intricate geometries come to our mind, but unfortunately, internal zones will not be easy to paint, although is also true that this internal zones will also be much more difficult to be spotted, so reaching this nooks and crannies is much more important in previous steps to printing, i.e., blasting and sealing. The application of a thin layer of primmer before starting the painting process is more than recommendable. Air spray painting, hydro dipping (see figure 4.16) or any other surface painting method can be used.

Figure 4.16: Car dashboard printed in ABS, smoothed, sealed and hydro dipped. Source: Stratasys Ltd.

There are also processes to bond FDM parts together if necessary, specially interesting for producing large products or, regarding to the quality, to produce some specific parts of a design with a very good resolution and with high detail features, without penalizing in time the production of the hole part.

These alternatives range form epoxy and cyanoacrylate adhesives to mechanical fasteners to hot air welding, ultrasonic welding or solvent bonding. All these solutions are commonly used for many other manufacturing processes, and they are not necessarily only for AM, but they are perfectly adaptable to this new way of manufacturing final products.

Multimaterial printers are a reality nowadays but their prices are high, and they are targeted mainly for rapid prototyping. This is because there is a problem related with the quality of the creation of the layers in different materials that would require, for an optimum product, of different technologies. As is very often said, he who focuses upon everything has, in fact, no focus. Is evident that reliable multiple material AM machines would be a revolution, not only in the aesthetic aspect, but specially in the manufacturing versatility and increase complexity of the final products able to be produce by this technology. What has no technical inconvenience nowadays is printing with the same material in different colours, which take out the necessity of painting to achieve an aesthetic level, that can be reached just by blasting and polishing the parts that form the final product.

For all finishing processes, final tolerances must be taken into account. The final tolerance is intimately related with the layer thickness capability of each machine, but as many finishing processes increase or decrease the exterior surface of the products, some adjustments must be done on the CAD file to offset the external surfaces to allow them after to increase the thickness of coating material, or just the opposite, the subtraction of some μm due to a removing process. The most critical dimensions for each component or part must be checked during the coating or removing phases, to maintain them until the final product is realised.

5

Production tests

Contents

5.1 Introduction

During this chapter an analysis of some additive manufactured parts will be done.

It will start with the creation from the ground up of an specific component with AM, in particular with a professional FDM prototyping machine. The design of that part for an AM process and the usual design it has for more conventional production methods will be compared and the main differences between both designs will be highlighted.

Parts were designed in CatiaV5 and converted to a $.stl$ (STereoLithography) file format. Some variations were introduced between the four replications of the same component, in order to compare the tolerances and precision of the machine.

Section 5.4 will go trough a starting visual examination of the printed parts to check if they are functional or have remarkable printing errors. After this first examination, the four specimens will be measured with the help of micrometers to check the main dimensions of the parts and compare them and their average with the design dimensions from de CAD.

To finish, results will be detailed, and the difference between nominal and real measures will be compared with the tolerance grades of the ISO normative.

5.2 Equipment used

For printing the parts a FDM printer will be used. This machine is a Dimension SST-768, from Stratasys Ltd., and in fact is considered as a 3D prototyping printer. It uses ABS plastic filament to build parts and assemblies, with the help of a soluble support material when necessary. General opinion of experts consider this FDM printer as accurately representing the CAD designs and specially useful for concept modeling and functional testing.

The Dimension SST-768 is also able to build complex functional parts with mobile components with a reasonable range of precision, but is true that is more reliable for especially not mobile or stationary parts.

Figure 5.1: Dimension SST-768 FDM printer. [39]

The usable building chamber in the Dimension SST-768 is a 203 x 203 x 305 mm cubicle. This size is moderately big for many applications. As parts will be printed all at the same time, the original component will be designed in size and form to fit in the chamber with 3 other variations.

Regarding the material, as has been said, Dimension SST-768 uses an ABS plastic filament. The Stratasys commercial denomination for this ABS is ABS-P400, and for this printer is available in several different colors (white, black, red, blue, green, yellow and steel gray). Anyway, parts are typically built in a single color with this printer, since the operator must change the filament cartridge to change build color, and this process may increase costs and total time of build. [39]

One of the primary advantages in the use of ABS plastic material is that the fused plastic is both strong and durable. It can take a lot of handling and most features do not shear under moderate pressure.

The main machine's limitations are its inability to reproduce very small curves and the long length of time which is required for each build. Although the stated minimum solid feature is 1.016mm, a wall this thin will tend to crack from shrinkage while cooling after removing from the machine. Other features built at this thickness tend to break during model post-processing and support material removal. [40]

5.3 Product to be produced

A ball joint or ball-and-socket joint is a mechanical joint in which a ball moves within a socket so as to allow rotary motion. The rotary motion permits angular rotation about a central point, usually within a specified angular limit based on the bearing or socket geometry. They consists of an outer ring or socket and an inner ball with a locking feature that makes the ball captive within the outer ring. The outer surface of the ball and the inner surface of the socket are spherical and are collectively considered the surface raceway, sliding against each other. They work similar to the ball and socket design of the human hip joint.

To produce a working ball joint with functional movement and a high angular rotation there are multiple options. Probably the mostly used designs are the ones shown on the figures 5.2 and 5.3. In 5.2, the ball is locked in the socket by a retaining ring as showed, while in 5.3 the retention is done by a group of 3 parts forming the complex component of the socket that requires mounting, grouping them together with a small screw through a side screw hole.

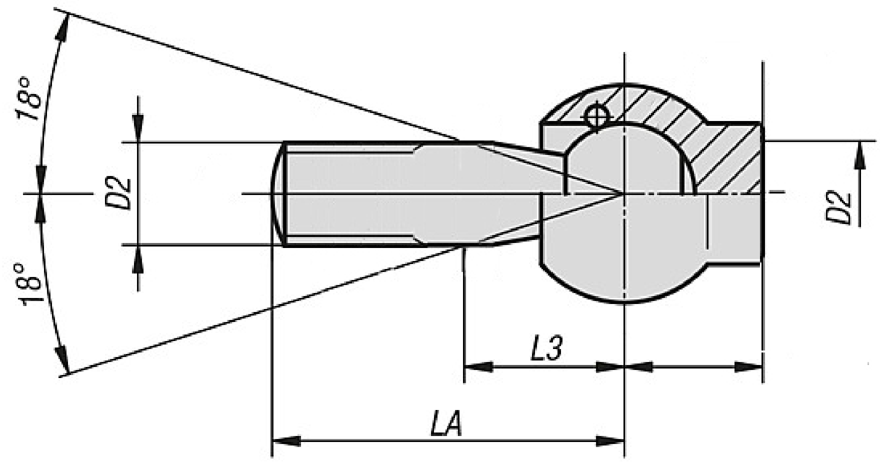

Figure 5.2: Ball-and-socket joint with retaining ring.

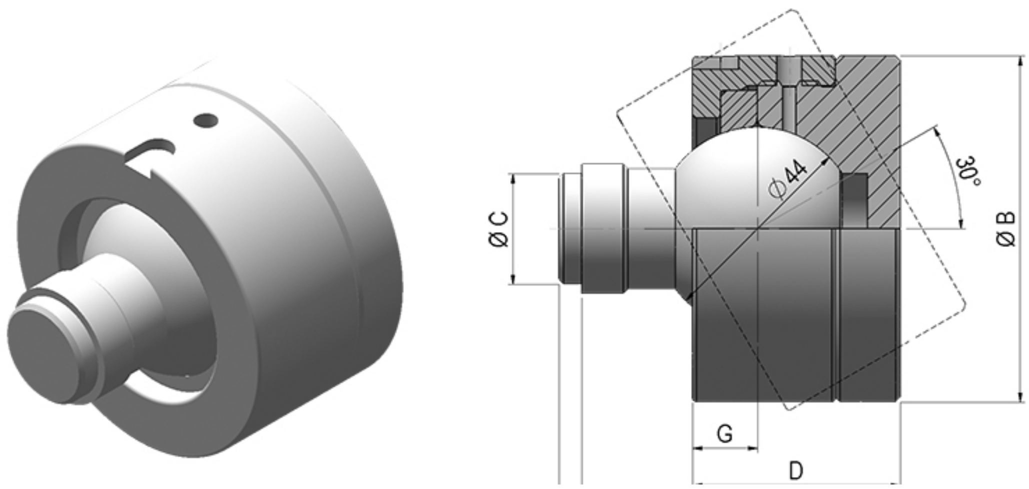

Figure 5.3: Ball-and-socket joint with assembled socket.

The main idea beneath 3d printing allow us to make a much easier and assemble-free design of a ball-and-socket joint. With a one piece socket and without needing to retain the ball with any extra element, the component can be printed all at once, with the only worry of the tolerance between the contact faces and the surface finish to guarantee the soft movement of the joint.

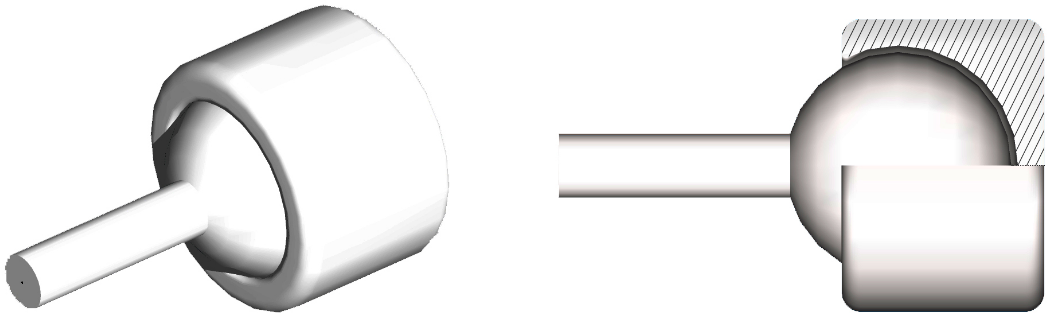

Figure 5.4: Ball-and-socket joint model for 3d-printing.

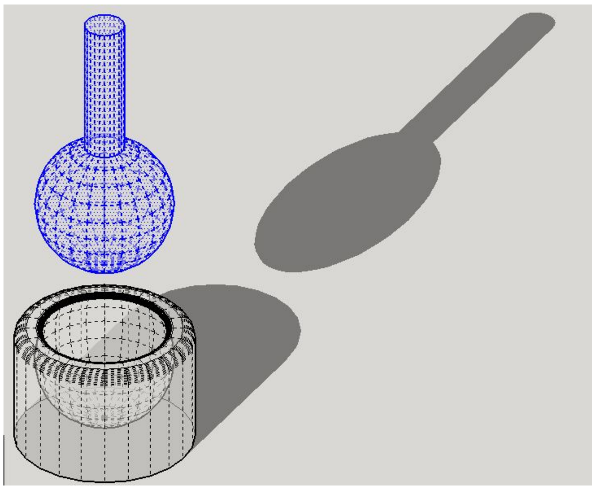

Figure 5.5: Final Ball and socket.

Even if in the figure 5.5 ball and socket are represented separately in a exploded graph, it must be consider only as a explanatory sketch, and there will be no way of taking out the ball from the inside of the socket without breaking the printed part.

There will be 4 different replications with variations of the part. Keeping the ball with exactly the same dimensions for all the tests, the socket will be manufactured in 4 different sizes based on the same model. This 4 will have respectively the dimensions showed in figure 5.6. The set of engineering tolerances for the 4 variations of the ball and socket are designed considering the limitations showed in the Dimension SST-768 user guide, from which the printer is said to be able to print features with 0.010 inches, this is 254 μm, but in such special conditions that is highly recommended to print in at least 4 times that minimum value. This minimum value obviously correspond to the best resolution value of the printer, with a 0,254 mm layer thickness, although is also able to print with a 0,013 inches layer thickness (330 μm)

Figure 5.6: Ball and socket gap.

So part number 4 has a set of 0,254 mm between ball and socket (matching exactly the layer thickness for the finer resolution, the one selected for the tests). It is not expected to work properly as it has a high chance of ball and socket merging in a single not-mobile part. Even if a soluble support material is added in the gap, according to the recommendation in its users manual and to the advise of the Engeneering Technical Support Services of the University of South Florida [40],the machine will probably not be able to meet the strict tolerances set.

As explained beforehand, the design size of the manufactured products is limited to the size of the chamber. For the distribution of the 4 parts in the 203x203 mm tray of the chamber, a high surface load factor of 0,625 is reached, covering more than the 62% of the available surface.

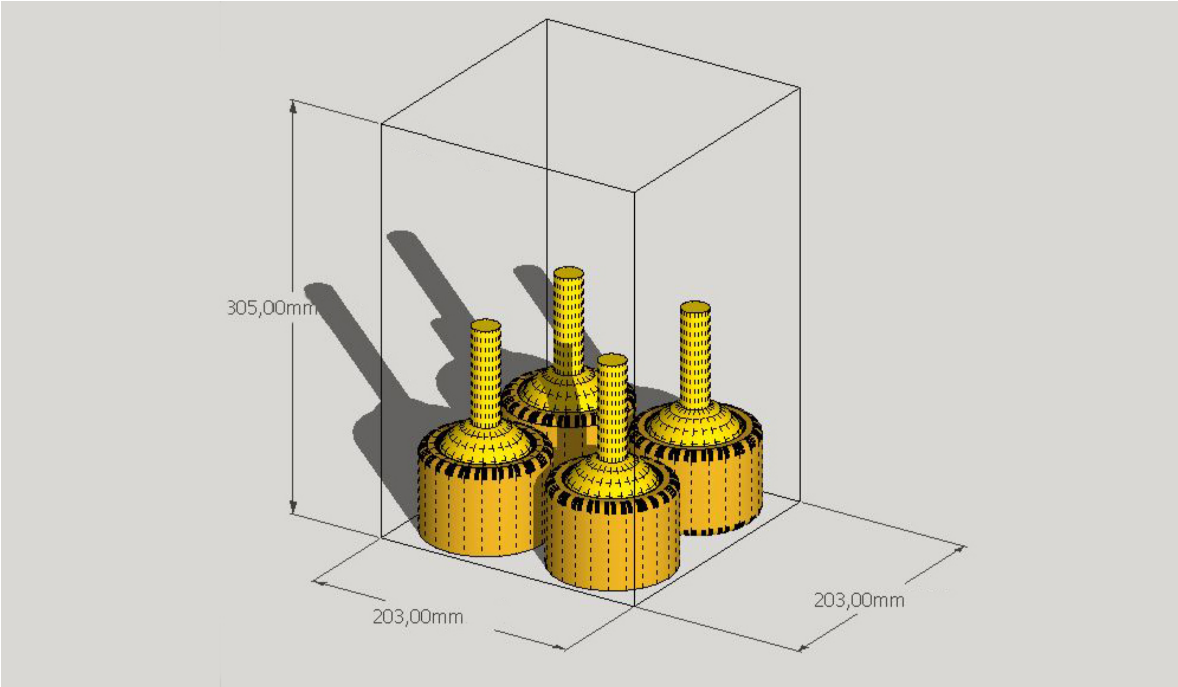

Figure 5.7: Parts distribution in SST-768 chamber.

Figure 5.8: Parts already manufactured in ABS with the SST-768 in a 254 μm resolution.

5.4 Examination and measure of the parts

In a quick visual examination of the printed test specimens, it can be easily spotted a big error that occur during the manufacturing process. Clearly visible at midway of the socket in figure 5.9, there is a translation at 45° in x and y axes for all consecutive top half layers in all the parts produced.

Figure 5.9: Sample number 3.

There is also a bumped line along the cylindrical surface of the sockets. This is caused by the accumulation in the same (x, y) coordinates of all the heads and tails of each path, where each layer begin and end to be printed. This surface imperfection is also present in the balls and their rods.

For the measure of the parts a 150mm calliper and a set of 3 micrometers, ranging 0-25mm, 50-75mm and 75-100mm, was used.

• Measures of external diameter of the sockets (table 5.1):

4 measures on each specimen, 2 near the top of the socket ($D1$,$D2$), with an approximated angular distance of 90° and another 2 in the bottom part, next to the base($D3$,$D4$), keeping also that approximated angular distance of 90°.

By measuring the external cylindrical surface diameters expressly over the bump lines and comparing with the average diameters for the socket, the bump previously mentioned has an average of a 100 μm high, which is a 0,11% of the diameter dimension.

Specimen	D1	D2	D3	D4	Average	Design	Difference
1	90,45	90,48	90,50	90,51	90,485	90,50	-0,015
2	90,52	90,48	90,54	90,42	90,49	90,50	-0,01
3	90,51	90,50	90,46	90,49	90,49	90,50	-0,01
4	90,42	90,46	90,45	90,52	90,4625	90,50	-0.0375
							-0,0181

Table 5.1: Diameters for the socket.(All values in mm)

• Measures of the diameter of the rod (table 5.2):

4 measures on each specimen, 2 near the top ($D1$,$D2$), with an approximated angular distance of 90° and another 2 in the bottom part, near the union with the sphere($D3$,$D4$), keeping also that approximated angular distance of 90°.

Specimen	D1	D2	D3	D4	Average	Design	Difference
1	14,90	14,96	14,95	14,92	14,9325	15,00	-0.0675
2	14,92	14,95	14,98	15,00	14,955	15,00	-0,05
3	14,92	14,94	14,95	14,97	14,945	15,00	-0,055
4	14,95	14,99	14,98	14,92	14,975	15,00	-0,025
							-0,0493

Table 5.2: Diameters for the rod.(All values in mm)

• Measures of the heights of the socket (table 5.3):

4 measures on each specimen ($H1$,$H2$,$H3$,$H4$), with an approximated angular distance of 90° between them.

Specimen	H1	H2	H3	H4	Average	Design	Difference
1	62,70	62,65	62,68	62,67	62,675	62,50	+0,175
2	62,66	62,68	62,69	62,70	62,6825	62,5	+0,1825
3	62,65	62,65	62,68	62,69	62,6675	62,5	+0,1675
4	62,68	62,65	62,66	62,68	62,6675	62,5	+0,1675
							+0,1731

Table 5.3: Heights for the socket.(All values in mm)

After detailed examination and external measuring, the parts were cut with an automatized saw blade N°0, which has a 0,20 mm saw thickness. When setting the line for the cutting, this line was corrected by displacing it this distance (200 μm), as it is the width of material removed by the saw while cutting.

Test specimens 4 and 2 can be seen in figures 5.10 and 5.11 respectively.

Sample 4 was the one with a 0,254mm gap between ball and socket. This is the equivalent to the minimum 0.010 inches size recommended in the Dimension SST-768 user guide for features printed with the best resolution. As was mentioned in section 5.3, some sources explain the impossibility of the machine in reaching that detail level, so both mobile parts of the product were merged in a single not-mobile part. The gap is almost inappreciable all around the sphere, and high temperatures while printing melt ABS from the ball and the socket together in much of the contact surface (see figure 5.10).

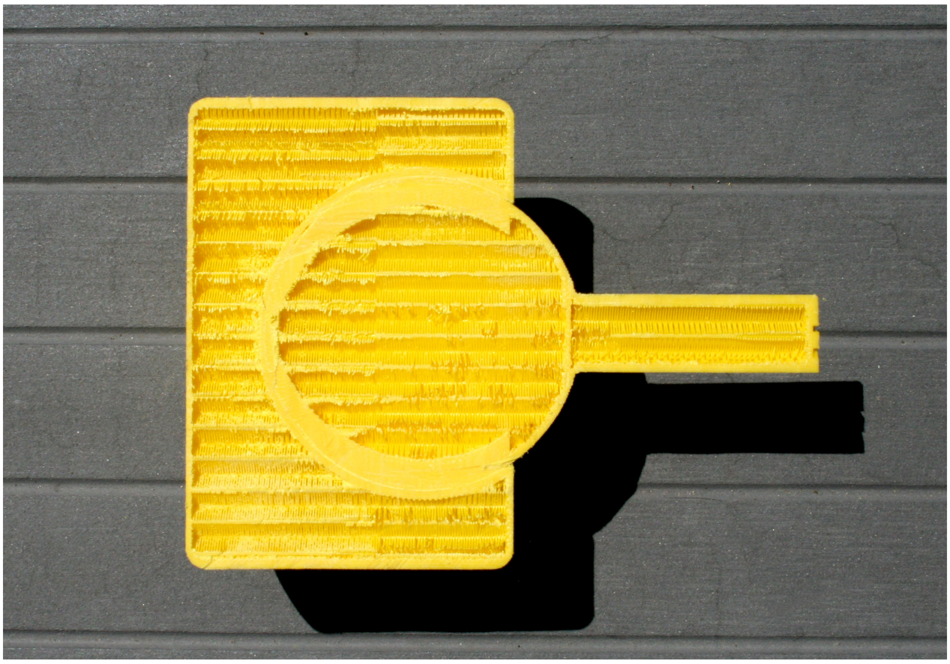

Figure 5.10: Sample number 4.

Sample 2, was cut in half through the origin point of the spheric surfaces. This allow to calculate the gap between ball and socket without the need of realizing spheric corrections of the measures. So the sphere of the ball and the interior spheric surface of the socket will be measured to calculate this gap in both cases.

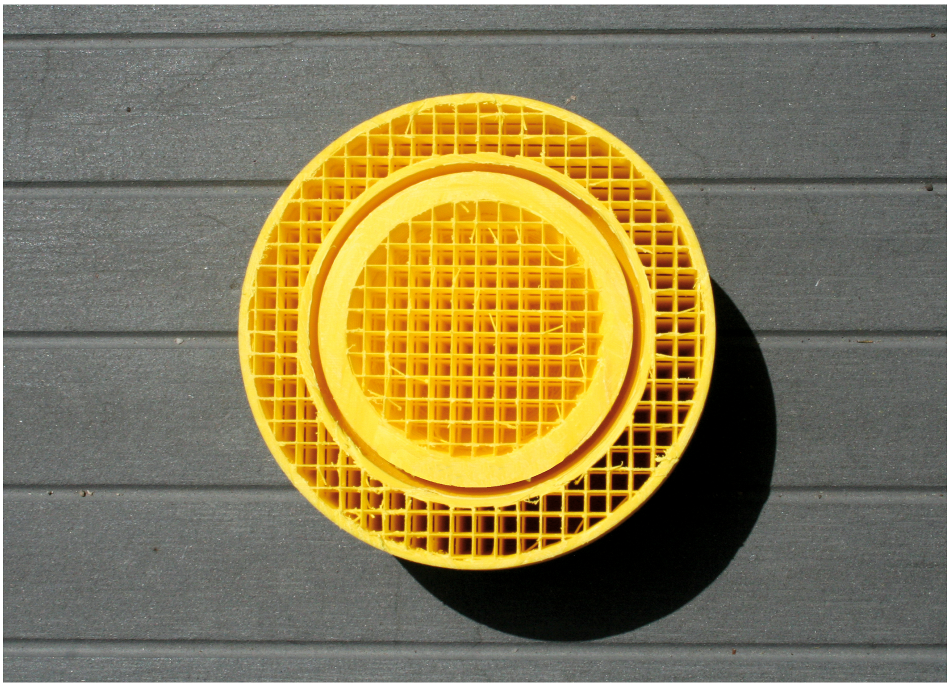

Figure 5.11: Sample number 2.

• Measures of the diameters of the sphere (table 5.4):

Before cutting completely the test specimens 1 and 2, it was only cut the socket all around, so living free the balls to make possible their diameter measure. This cut was also made this way because of the difficulty of cutting both mobile parts (ball and socket) with precision, as there was a gap between them in which the ball can oscillate and freely move. 2 measures were taken on each specimen ($d1$,$d2$), with an approximated angular distance of 90° between them.

Specimen	d1	d2	Average	Design	Difference
1	59,94	59,96	59,97	60,00	-0,03
2	59,93	59,96	59,945	60,00	-0,055
					-0,0425

Table 5.4: Diameters of the ball (just two specimens)(All values in mm)

• Measures of the interior diameters of the sockets (table 5.5):

It will be measured in the test specimens number 1 and 2, the ones completely cut in half trough the origin point of the spheric surfaces. 2 measures on each specimen ($D1$,$D2$), with an approximated angular distance of 90° between them.

Specimen	D1	D2	Average	Design	Difference
1	65,01	65,04	65,025	65,08	-0,055
2	63,99	64,02	64,005	64,064	-0,059

Table 5.5: Diameter of the interior surface of the socket (just two specimens)(All values in mm)

◇ Gap calculation (table 5.6):

Specimen	D	d	Gap	Design	Difference
1	65,025	59,97	5,055	5,08	-0,025
2	64,005	59,945	4,06	4,064	-0,004

Table 5.6: Gap calculation (just two specimens)(All values in mm)

5.5 Results

The parts were produced with an internal quadrangular structure. This was not for any structural reason but to save material and printing time. Despite this, with that internal structure that guarantee a 50% infill ratio, they take 34 hours and 20 minutes to be printed.

During that printing time, as mentioned in section 5.4, a bumped line appeared along the cylindrical socket surface. All measures were taken avoiding that defect. If not, measures with at least 0,1mm will reduce considerable the level of tolerance reached in the part.

Measures from section 5.4 are compared with the IT grades provided in table B.1 from the European normative EN 286-1:2010 (See appendix B), with values in millimetres and micrometres.

For the diameter of the socket, the average difference with respect to the designed diameter value is -0,0181mm. The designed dimension was 90,50mm, so the real dimension value is a 0,02% smaller than the projected dimension. This tolerance is acceptable in standard tolerance grade IT6 and above, as can be checked with table B.1.

The diameter of the rod is, in average, 0,0493mm smaller with respect to designed dimension. With an original dimension of 15,00mm, this is 0,33% smaller than the projected dimension value, and is accepted in grade IT10 and higher.

The height of the socket, with a designed dimension in the CAD of 62,50mm, is in average 0,1731mm longer in the manufactured parts. This dimension would be rejected in a product with a tolerance grade exigence lower than IT11 according to table B.1.

The diameter of the ball, with an original dimension of 60,00mm in the design, is in average a 0,07% shorter than projected (-0,0425mm). This variation is accepted in grade IT8, thus of course in higher grades.

Note that the statistical sample for this dimension is only four measures, instead of the sixteen measures taken in the previous cases.

The measure of the interior diameter of the socket must be analysed more carefully, since the measures of this dimension are the only ones taken over a cut surface, even if all the necessary precautions to ensure a good precision measure were adopted. This dimension also change in each test specimen, so the statistical sample is even more reduced, having only two measures for each dimension, instead of sixteen.

For specimen number 1, there is an average difference of -0,055mm with respect to the 65,025mm of the designed dimension. For specimen number 2, this difference increase to -0,059mm with respect to the 64,005mm of the designed dimension.

Both measures are accepted for IT9 and higher standard tolerance grades.

As a result of all this variations, the final gap, which is the most critical dimension for the proper and smooth functioning of the ball and socket joint, will pass a test for tolerance IT9. This is because even if there has been variations in the dimension of both ball and socket diameters, this variations are both a reduction of length, in almost the same amount of millimetres, so there is a compensation that result in a net displacement of the gap.

5.6 Conclusion of results

As a conclusion, evidence suggests that there is a big difference between the tolerance control in z vertical dimensions and the ones in horizontal dimensions (this is, along the plane xy).

While all dimensions checked in parallel direction to the building surface were accepted in the more restrictive levels of tolerances, the measures for dimensions along the building direction show much poorer results. Not just the average dimension of vertical measures would be rejected from tolerance level IT10, but also some of the single dimensions will not even reach the next less restrictive level IT11 from table B.1, jumping to the grades reserved for large manufacturing tolerances (IT12-IT18). (See table 5.12)

	For Measurig Tools								For Material									
IT Grades	01	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
							For Fits							For Large Manufacturing Tolerances				

Figure 5.12: General use of International Tolerance (IT) Grades.[41]

This is probably because precision in the movement of the printing head along x and y axes is much better than the precision on the control of the thickness of the layers, to finally end the part with the software estimation number of slices required for that dimension. As stated earlier in a previous section, the thickness of the layer is influenced by many factors. The temperature of the previous layer, for example, is key for the thickness of the path that has just been deposited above it, and the compactness between layers is difficult to check or estimate. The total weight of the part and factors like warping and curling also affect more to vertical than horizontal dimensions.

Warping and curling can be assessed with geometric tolerances and automated coordinate machines that were, unfortunately, not available.

6

Conclusions and Future Work

Contents

6.1 Conclusions and Future Work

Additive manufacturing is a revolutionary way to produce objects, which does not mean that it will be the only way to manufacture products and components in the future, as many times is said. All these additive processes will probably end up having just a share of the manufacturing machinery market in the years ahead. They will be very efficient in some specific operations or producing very particular parts, either on their own or combined with other traditional methods in an integrated machine.

The real revolution of the AM technology is not so much in the substitution of other manufacturing methods already existing, but in the way they are able to produce complex parts and mobile components, changing radically the way in which the industry has to look to many products, specially regarding their design limitations and production methods.

Product design must change in the sense that all the benefits that AM can contribute with must be taken into account to get the one hundred percent of the technology.

Adopting additive processes, not just for prototyping phases but for final production of the parts, implies a more versatile production, with reduced costs in tooling and with a not so static design in time. This means somehow that preliminary design phases have for AM less weight in the design process compare with their usual impact in PDP for goods produced with other technologies, technologies that have bigger fixed costs that must be amortized in time by producing long runs of exactly the same component. This is mainly because the risk of designing a product that is not sold as much as expected or, for example, realizing in the last pre-production stages, or even after product launch, that some modifications must be done, are not so serious inconveniences.

AM contributes to the technical development of the products, as it removes significant costs that arise when there are modifications in some components, or costs associated with the introduction of new products. In this way, additive technologies promote product innovation and evolution of the goods that are consumed.

The surface quality and materials aspect in components produced through AM are vitally important. There are already AM technologies enough to manufacture products in many materials, and many finishing processes, some of them rescued from other manufacturing techniques already existing in the industry and others designed just to solve some of the problems of each technology related with this surface aspect, quality and resistance. This necessity of bringing good quality products into the market will boost the finishing processes market, developing or adapting new technologies that will become much more important in future years.

The implementation of this new technology by large manufacturers is a barrier that AM must overcome. The effects of the implantation of this technology in the industry still remain as an open question. They will have to rethink their strategies and redesign their processes, to decide whether or not to make an investment in additive technologies, and to structure a plan to have a high return of that investment.

There is only one way to understand all the unknowns and to break through all the barriers that still exist for AM to be integrated in a profitable productive model, and is the investment for the development and study of the technology. In this respect, as a continuation of this thesis, it would be interesting to manufacture another series of parts with a complex design and to check their geometric tolerances with the help of automated coordinate machines. Typical defects present on additive manufactured products, like warping and curling, would be detected.

Estimations of time expenditure and costs for the production of some components can also be done following the Booz, Allen and Hamilton Model or any variation. After manufacturing the real products in an AM machine while measuring the printing time, materials and electricity consumption, the theoretical and real cost per part can be calculated and compared, to check the validation of the model and the process. Comparing them also with -already existing- really accurate estimations for well known manufacturing processes used in the industry to produce similar parts can be very useful for understanding the real possibilities of these technologies to end up replacing some of the other manufacturing techniques and tools in large consumer goods manufacturers companies with a production based on an economy of scale.

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A

Real, apparent and global densities in an object

As seen in subsection 4.1.2, the structure and infill percentage of an object printed will lead to different global densities, apparent densities and real densities.

Density in a material is defined as mass divided by the volume,

$$\rho = \frac{M}{V} \tag{A.1}$$

where M and V are respectively the mass and the volume of the test specimen in that specific material.

Mass is therefore the value of the dry weight of the test specimen, this is

$$M = M_{solid} + M_{air} \tag{A.2}$$

For the volume we have to take into account some considerations. Any material is composed of an specific amount of material and an amount of holes or pores (porosity). This way, is possible to distinguish between three types of volumes inside a material sample:

- V_m is the mass volume, the volume occupied by the mass of the material.
- V_{cp} is the volume occupied by closed pores or hollows, free space not connected to the outside.
- V_{op} is the volume occupied by open pores or hollows, so connected to the walls and accessible from the outside.

Total volume is therefore defined as:

$$V_T = V_m + V_{cp} + V_{op} \tag{A.3}$$

and the apparent volume as:

$$V_A = V_m + V_{cp} \tag{A.4}$$

With all this in mind is possible to specify 3 different kind of densities for the material, as follow:

- Global density

$$\rho_g = \frac{M}{V_T} \tag{A.5}$$

- Apparent density

$$\rho_A = \frac{M}{V_A} \tag{A.6}$$

- Real density

$$\rho = \frac{M}{V_m} \tag{A.7}$$

B

European normative EN286-1 International Tolerances

The European normative EN 286-1:2010 consider geometrical product specifications and the code system for International Tolerances (IT) on linear sizes, basis of tolerances, deviations and fits. This mechanical tolerance grades specifies tolerances with associated manufacturing processes for a given dimension.

Basic size mm		Standard tolerance grades																	
		IT1[2)]	IT2[2)]	IT3[2)]	IT4[2)]	IT5[2)]	IT6	IT7	IT8	IT9	IT10	IT11	IT12	IT13	IT14[3)]	IT15[3)]	IT16[3)]	IT17[3)]	IT18[3)]
Above	Up to and including	Tolerances																	
		µm											mm						
–	3[3)]	0,8	1,2	2	3	4	6	10	14	25	40	60	0,1	0,14	0,25	0,4	0,6	1	1,4
3	6	1	1,5	2,5	4	5	8	12	18	30	48	75	0,12	0,18	0,3	0,48	0,75	1,2	1,8
6	10	1	1,5	2,5	4	6	9	15	22	36	58	90	0,15	0,22	0,36	0,58	0,9	1,5	2,2
10	18	1,2	2	3	5	8	11	18	27	43	70	110	0,18	0,27	0,43	0,7	1,1	1,8	2,7
18	30	1,5	2,5	4	6	9	13	21	33	52	84	130	0,21	0,33	0,52	0,84	1,3	2,1	3,3
30	50	1,5	2,5	4	7	11	16	25	39	62	100	160	0,25	0,39	0,62	1	1,6	2,5	3,9
50	80	2	3	5	8	13	19	30	46	74	120	190	0,3	0,46	0,74	1,2	1,9	3	4,6
80	120	2,5	4	6	10	15	22	35	54	87	140	220	0,35	0,54	0,87	1,4	2,2	3,5	5,4
120	180	3,5	5	8	12	18	25	40	63	100	160	250	0,4	0,63	1	1,6	2,5	4	6,3
180	250	4,5	7	10	14	20	29	46	72	115	185	290	0,46	0,72	1,15	1,85	2,9	4,6	7,2
250	315	6	8	12	16	23	32	52	81	130	210	320	0,52	0,81	1,3	2,1	3,2	5,2	8,1
315	400	7	9	13	18	25	36	57	89	140	230	360	0,57	0,89	1,4	2,3	3,6	5,7	8,9
400	500	8	10	15	20	27	40	63	97	155	250	400	0,63	0,97	1,55	2,5	4	6,3	9,7
500	630[2)]	9	11	16	22	32	44	70	110	175	280	440	0,7	1,1	1,75	2,8	4,4	7	11
630	800[2)]	10	13	18	25	36	50	80	125	200	320	500	0,8	1,25	2	3,2	5	8	12,5
800	1000[2)]	11	15	21	28	40	56	90	140	230	360	560	0,9	1,4	2,3	3,6	5,6	9	14
1000	1250[2)]	13	18	24	33	47	66	105	165	260	420	660	1,05	1,65	2,6	4,2	6,6	10,5	16,5
1250	1600[2)]	15	21	29	39	55	78	125	195	310	500	780	1,25	1,95	3,1	5	7,8	12,5	19,5
1600	2000[2)]	18	25	35	46	65	92	150	230	370	600	920	1,5	2,3	3,7	6	9,2	15	23
2000	2500[2)]	22	30	41	55	78	110	175	280	440	700	1100	1,75	2,8	4,4	7	11	17,5	28
2500	3150[2)]	26	36	50	68	96	135	210	330	540	860	1350	2,1	3,3	5,4	8,6	13,5	21	33

1) Values for standard tolerance grades IT01 and IT0 for basic sizes less than or equal to 500 mm are given in IS0 286-1, annex A, table 5.

2) Values for standard tolerance grades IT1 to IT5 (incl.) for basic sizes over 500 mm are included for experimental use.

3) Standard tolerance grades IT14 to IT18 (incl.) shall not be used for basic sizes less than or equal to 1 mm.

Figure B.1: International Tolerance (IT) Grades.[41]