Technical University of Crete

Department of Production Engineering and Management

3D Printing: Ανάλυση Τεχνολογιών και Μεθοδολογία Εφαρμογών

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Diploma Thesis

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Chania, July 2016

"Intentionally Blank"

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3D printing: Analysis of technologies and methodology of its applications

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Στους γονείς μου.

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Abstract

Technology, due to its rapid progress, has affected recent human history significantly, probably more than any other field has achieved to. The personal computer with its vast capabilities, low price and portability has revolutionised each and every field of science, technology, communication as well as our private lives.

3D Printing (also known as additive manufacturing) is considered to be a disruptive technology, that has the vast potential to make our lives better in many ways. 3D printing is a radically different manufacturing method based on advanced technology that builds up parts, additively, in layers at the sub mm scale. This is fundamentally different from any other existing traditional manufacturing techniques.

This technology, enables us to build objects directly, encourages innovation with design freedom, gives the designers the possibility to implement their creations right away, while being a tool-less process that reduces prohibitive costs and lead times as products are sold before their real existence. Thus, is a technology that will change the way we choose, offer and produce products.

There are many benefits the 3D printing technology, such as cheap manufacturing, low pre-financing cost, quick production, little excess, less industrial waste, worldwide accessibility and creation of new business models. Each different type of 3D printers employs a different technology that processes different materials in different ways. Functional plastics, metals, ceramics and sand are, now, all routinely used for industrial prototyping and production applications. Even if at the entry level of the market currently materials are quite limited and plastic is currently the only widely used material, there are a growing number of alternatives. One of the most basic limitations of 3D printing, in terms of materials and applications, is that there is no 'one solution fits all', promoting customization greatly.

Considering the big variety of the methods and applications of the constantly growing technology of 3D printing, this thesis describes the different existing technologies of 3D printing and provides a subsequent analysis of the way each technology works, focusing on their potential, problems and benefits. The last part of the thesis concerns the production of some 3D printed prototypes, that address diverse type of objects, simple and complex, one-piece and multi-part, with the appropriate assembly techniques, which are designed and printed at the TUC TIE (Transformable Intelligent Environments) laboratory for the aim of this project.

Περίληψη

Η τεχνολογία, χάρη στη γρήγορη ανάπτυξή της έχει επηρεάσει τη σύγχρονη ιστορία όπως κανένας άλλος τομέας. Η χρήση του ηλεκτρονικού υπολογιστή, δεδομένων των ευρέων δυνατοτήτων του, χαμηλού κόστους και ευκολίας απόκτησης και μεταφοράς του, έχει επηρεάσει όλα τα πεδία της επιστήμης, τεχνολογίας και επικοινωνίας.

Η τρισδιάστατη εκτύπωση (γνωστή και ως μέθοδος προσθετικής παραγωγής), θεωρείται ότι διαθέτει τη δυναμική να καλυτερεύσει την ποιότητα ζωής μας προς πολλές κατευθύνσεις. Πρόκειται για μια άκρως διαφορετική μέθοδο κατασκευής και παραγωγής αντικειμένων συγκριτικά με τις παραδοσιακές, που βασίζεται στην τεχνολογία της δημιουργίας υλικού προσθετικά, χτίζοντας επίπεδα, σε κλίμακα χιλιοστών. Δίνει η δυνατότητα δημιουργίας πολύπλοκων αντικειμένων άμεσα και ενθαρρύνει την καινοτομία. Δεν απαιτεί πολλά εργαλεία και μηχανήματα, που μειώνει το κόστος παραγωγής, αποθήκευσης, διανομής προϊόντων και δίνει τη δυνατότητα της πώλησης των προϊόντων προ της πραγματικής τους ύπαρξης. Πρόκειται λοιπόν, για μια μέθοδο που θα αλλάξει τον τρόπο που διαλέγουμε, διαθέτουμε και παράγουμε προϊόντα.

Υπάρχουν πολλά πλεονεκτήματα που προσφέρει η τεχνολογία της τρισδιάστατης εκτύπωσης, όπως για παράδειγμα το φθηνό κόστος κατασκευής και χρηματοδότησης για την ανάπτυξη της ιδέας ενός προϊόντος, η γρήγορη παραγωγή, η αποφυγή των βιομηχανικών αποβλήτων, η παγκόσμια εμβέλεια και προσβασιμότητα της τεχνολογίας, η δυνατότητα δημιουργία νέων επιχειρηματικών μοντέλων. Οι διαφορετικοί τύποι τριδιάστατων εκτυπωτών χρησιμοποιούν ποικίλες τεχνολογίες για να επεξεργαστούν το κάθε υλικό με διαφορετικό τρόπο, κάτι που λειτουργεί ως περιορισμός αφού δεν υπάρχει "μια λύση για όλα". Αν και η χρήση των υλικών για την κατασκευή πρωτοτύπων στην αγορά επικεντρώνεται κυρίως στην επιλογή του πλαστικού, υπάρχουν συνεχώς αναδυόμενες εναλλακτικές, όπως μεταλλικά, κεραμικά και άμμος.

Λαμβάνοντας υπόψη τη μεγάλη ποικιλία μεθόδων και εφαρμογών της εν λόγω συνεχώς αναπτυσσόμενης μεθόδου, στη διπλωματική αυτή περιγράφονται οι τεχνολογίες της και παρέχεται περαιτέρω ανάλυση των εφαρμογών τους, επικεντρώνοντας το ενδιαφέρον στη δυναμική, τα προβλήματα και πλεονεκτήματά τους. Το τελευταίο κομμάτι της εργασίας αναφέρεται στην παραγωγή κάποιων τρισδιάστατα εκτυπωμένων δειγμάτων, που αντιπροσωπεύουν βασικά είδη αντικειμένων, απλών και πολύπλοκων, μονοκόμματων ή σε κομμάτια που απαιτούν συγκεκριμένη συναρμολόγηση, και σχεδιάστηκαν και εκτυπώθηκαν στο εργαστήριο TUC TIE για τις ανάγκες της διπλωματικής, όσο αναφορά το τεχνικό της κομμάτι.

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Also, I would like to thank Mr. Sotiris Ntzoufras, TIE Lab assistant, for his help and advice during the period of our collaboration for the conduction of the experiments.

At this point, I would like to thank Dr. Aristomenis Antoniadis and Dr. Bilalis Nikolaos, professors of Production Engineering and Management Department for their presence and help.

I could not forget to thank my friends for the fun, the unforgettable moments that we spent together and all the lifetime experience we shared.

Last and most important, none of this would have been possible without the support, patience and love of my beloved family, which have constantly been by my side all these years. Thank you for everything.

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Chapter 1
Introduction

1.1 Definition and History of Additive Manufacturing

Additive Manufacturing (AM) is the family of manufacturing technologies that includes 3D printing. AM is the current terminology established by ASTM International (American Society for Testing and Materials). Throughout its history, AM in general has gone by various names: Stereolithography, 3D layering and 3D printing. This thesis uses the term "*3D Printing*" because it seems to be the most common term used to describe AM products.

3D Printing is the process of making three dimensional solid objects from a digital file. The creation of a 3D printed object is achieved using additive processes. In an additive process an object is created by laying down successive layers of material until the entire object is created. Each of these layers can be seen as a thinly sliced horizontal cross-section of the eventual object. [1] During the print process, the 3D printer starts at the bottom of the design and builds up successive layers of material until the object is finished.

The earliest 3D printing technologies first appeared in the market in the late 1980's, at which time they were called Rapid Prototyping (RP) technologies. This is because the processes were originally conceived as a fast and more cost-effective method for creating prototypes for product development within industry.

The origins of 3D printing can be traced back to 1986, when the first patent was issued for stereolithography apparatus (SLA) by Charles Hull, who first invented his SLA machine in 1983. Hull's contribution is the design of the STL (STereoLithography) file format widely accepted by 3D printing software as well as the digital slicing and infill strategies common to many processes today. [2]

In 1989, Scott Crump patented the Fused Deposition Modeling (FDM) process, a special application of plastic extrusion, which is the technology that is used by most 3D printers to date, forming the Stratasys Company.

Throughout the 1990's and early 2000's a host of new technologies continued to be introduced, still focused wholly on industrial applications and while they were still largely processes for prototyping applications, R&D was also being conducted by the more advanced technology providers for specific tooling, casting and direct manufacturing applications. This saw the emergence of new terminology, namely Rapid Tooling (RT), Rapid Casting and Rapid Manufacturing (RM) respectively. [3]

1.2 Applications of 3D Printing

AM overcomes the limits imposed by conventional production techniques. Thanks to its advantages it is already benefiting companies in a wide range of sectors such as aerospace, oil and gas, marine, automobile, manufacturing tools, medical applications and lifestyle products.

Functional components with complex geometries and defined aerodynamic properties can be manufactured quickly and cost-effectively. It can also produce lattice structures with low density, high strength, good energy absorption and good thermal properties which can be used for light weighting and better heat dissipation in applications like heat exchangers in aerospace, automobile and computer industries. AM also means manufacturers can increase the efficiency of their R&D processes, enabling them to get their products on the market more quickly and obviating the need for storage.

The figure 1.2 shows a conventional and an optimized object manufactured by AM where internal 'bamboo' structure is used for lightweighting. In the original structure, the item weights 530 gr, is made out of 3 different materials and 7 components, whereas the optimised one weights 392 gr (reduced weight by 26%), it's made only out of 1 material and 2 components. Conventionally manufactured part may require a number of different manufacturing processes like casting, rolling, forging, machining, drilling, and welding etc. whereas, same part can be produced by using AM which eliminates required tooling, energy and raw material, as it produces part in single processing step. [4], [5]

Original structure   Design volume   Optimised structure
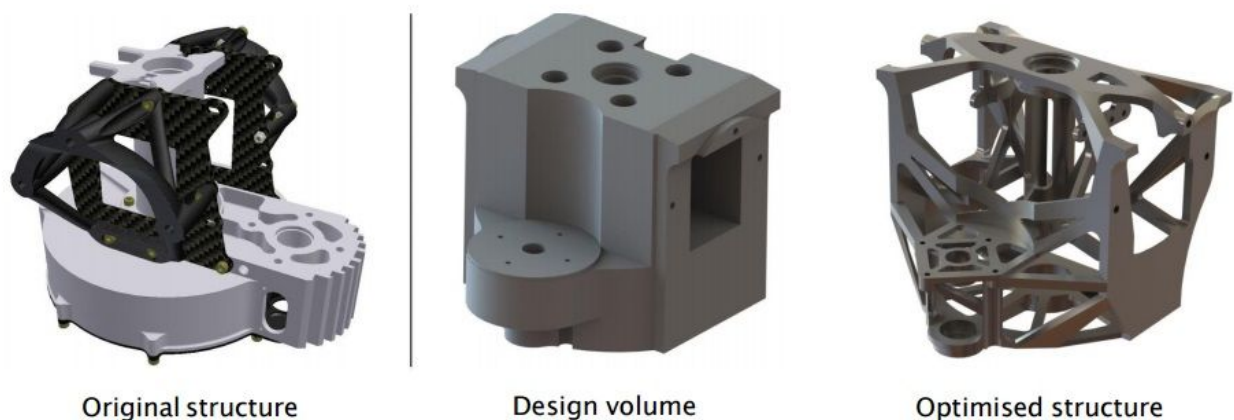
Figure 1.2: Conventional vs Optimised design

1.3 Limitations of 3D printing

Despite the revolutionizing effects of 3D printing, it is still an evolving technology and has its limits, which are mostly related to issues of feedstock materials, intellectual property protection, cost, speed, energy consumption and limitations of the printers. [7]

At present, 3D printers can work with approximately 100 different raw materials. This is insignificant when compared with the enormous range of raw materials used in traditional manufacturing. [8] Most 3D printers can only print objects using a specific type of material - a serious limitation that prevents 3D printers from creating complex objects. [9]

Another issue, is the limitations of a 3D printer. The cost of 3D printers is high, making its purchase still not feasible by the average householder. Different 3D printers are required in order to print different types of objects. Also, printers that can manufacture in color are costlier than those that print monochrome objects. There are also limitations of size, as printed objects are limited by printer size, with larger objects needing larger printers. [8] Large industrial printers have their own constraints. They are not cost-effective except for small-scale uses. They are too slow to be used in mass production. [7] The procedure can be speeded up by making the layers thicker, but in this way, the surface finish quality is lost. One solution for individuals and professionals alike, is the utilisation of specialised 3D printing bureaus where under some service cost, print on demand is provided.

Another parameter is the one of the cost, which is based on material used, so big things are expensive, and small things are cheap. In many cases cost is not related to complexity neither to the number of parts. So, producing anything in bulk is not to be worth it. [10]

The ease with which replicas can be created using 3D technology raises issues over intellectual property rights. It is undeniable the ility to easily share digital blueprints online and print out the objects at home. Security experts worry about 3D printing's ability to magnify the effects of digital piracy and the sharing of knowledge that could prove dangerous in the wrong hands. [7], [9] 3D printing will also give rise to copyright infringement increasing the amount of counterfeit products that will damage the authenticity and demand for many brands. As a result, many businesses producing a unique product may suffer from the growth of 3D printing. Also, as any desired object can be printed, an owner of a 3D printer can print objects that are protected by copyrights. By cutting off the availability of 3D printer design of the protected work can help to protect the copyrights. However, it is nearly impossible to remove the availability of all the existing design files on the internet. [11] One looming problem with 3D printing is how to protect designs and materials. Perhaps, as in today's music business, people

will pay a one-time fee for a design download. Or a designer could supply basic models for free, but charge for customization. [7]

Last and most complicated parameter, is this of the usability of the 3D Printing technology. There are many challenges in the procedure, as in order to 3D print something, one has to design it first and then check for mistakes. Learning CAD programs takes time, patience, and need to acknowledge things like tolerances. Another issue is the 3D scanning. The idea of scanning a broken part and 3D printing it is a massive over-engineered approach to replacing a part but in only works for scanning the outer surface of a part, not the inside of it. Last concern regarding the usability of the technology, is the downloading of the 3D files. Even if there are many 3D model libraries on the internet, they are not guaranteed to be 3D printable. [10]

The 3D printing boom could eventually prove disruptive in both a positive and negative sense. The economics of 3D printing now and for the foreseeable future make it an unfeasible way to mass produce the vast majority of parts manufactured today. So instead of looking at it as a substitute for existing manufacturing, we should look to new areas where it can exploit its unique capabilities to complement traditional manufacturing processes.

Chapter 2
Processes and Technologies

There are a number of different types of 3D printing technologies, which process different materials in different ways to create the final object. Functional plastics, metals, ceramics and sand are, now, all routinely used for industrial prototyping and production applications. Generally speaking though, at the entry level of the market, materials are much more limited. Plastic is currently the only widely used material - usually ABS or PLA, but there are a growing number of alternatives. [3] Not all 3D printers use the same technology. There are several ways to print and all those available are additive, differing mainly in the way layers are build to create the final object. Some methods use melting or softening material to produce the layers.

Since 2010, the American Society for Testing and Materials (ASTM) group "ASTM F42 – Additive Manufacturing", developed a set of standards that classify the Additive Manufacturing processes into 7 categories according to Standard Terminology for Additive Manufacturing Technologies. These seven processes are:

1. Material Extrusion
2. Material Jetting
3. Binder Jetting
4. Vat Photopolymerisation
5. Powder Bed Fusion
6. Sheet Lamination and
7. Directed Energy Deposition. [1]

Each method has its own advantages and drawbacks, which is why some companies consequently offer a choice between powder and polymer for the material used to build the object. Other companies sometimes use standard, off-the-shelf business paper as the build material to produce a durable prototype.

The main considerations in choosing a machine are generally speed, cost of the 3D printer, cost of the printed prototype, cost and choice of materials, and color capabilities. [2]

2.1 Material Extrusion

2.1.1 Fused Deposition Modeling

Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF) was invented by Scott Crump in the late 80's and is trademarked by Stratasys, Inc. [1] It is a common additive manufacturing and rapid prototyping technique, probably the most popular printing process due to the number of printers available on the market.

FDM begins with a software process which processes an STL file, mathematically slicing and orienting the model for the build process. [12] The model or part is produced by extruding small flattened strings of molten material to form layers as the material hardens immediately after extrusion from the nozzle. A plastic filament or metal wire is unwound from a coil and supplies material to an extrusion nozzle which can turn the flow on and off. There is typically a worm-drive that pushes the filament into the nozzle at a controlled rate. The nozzle is heated to melt the material. The thermoplastics are heated past their glass transition temperature and are then deposited by an extrusion head. The nozzle can be moved in both horizontal and vertical directions by a numerically controlled mechanism. The nozzle follows a tool-path controlled by a CAM software package, and the part is built from the bottom up, one layer at a time. [13], [14]

Orientation of the part can significantly impact a part's aesthetics or functionality. Various orientations can maximize build time, strength or surface finish. The best orientation depends on the part's intended use and purpose. If aesthetics are critical to the final use of the part, reducing stepping and build layer lines will dictate the orientation. If functionality and strength are critical, reducing supports and space between layers will dictate orientation. [15]

The 3D printer may dispense multiple materials to achieve different goals: Some FDM 3D printers can have two or more print heads that can print in multiple different colors [12]. Also, one print head may use one material to build up the model and use another as a soluble support structure, or one could use multiple colors of the same type of thermoplastic on the same model. FDM generally has some restrictions on the slope of the overhang, and cannot produce unsupported stalactites. [14] Considering that, special support material must be extruded below any overhang such as a window, cutout, horizontal undercut, blind holes, etc. to act as "scaffolding" until the plastic model material cures. Support material will automatically be provided during the build process, but it increases the amount of material used and also the build time. The exception to this rule is building in the form a self-supporting angle, which varies depending on the material, is usually around 45 degrees and its design reduces material usage and build

time. [15] There are water-soluble material, which allows support structures to be relatively easily washed away, once the print is complete. Alternatively, breakaway support materials are also possible, which can be removed by hand once the part comes off the machine ,and the part or prototype can then be finished and polished to the final requirement [16]. Support structures, or lack thereof, have generally been a limitation of the entry level FDM 3D printers. However, as the systems have evolved and improved to incorporate dual extrusion heads, it has become less of an issue. [17]

Many materials are available, such as ABS (Acrylonitrile Butadiene Styrene), PLA (Polylactic acid), PC (Polycarbonate), PA (Polyamide), PS (Polystyrene), lignin, rubber, among many others, with different trade-offs between strength and temperature properties. [14] It varies between the industrial versus the consumer version. The most common however are ABS, PLA and PC. Unlike ABS, PLA is biodegradable and is popular due to it being non-toxic. There is also dissolvable materials such as PVA which are used for support. [13]
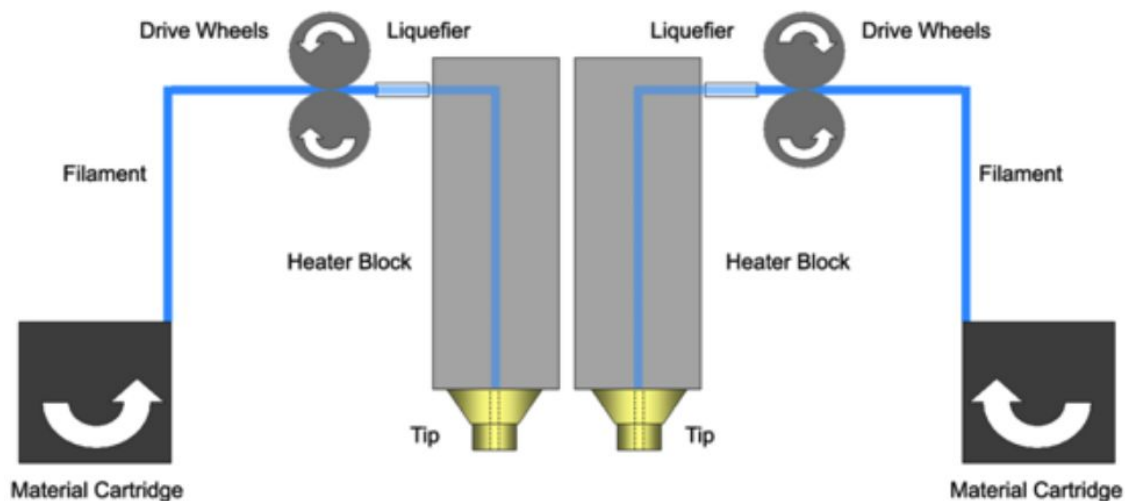
Figure 2.1.1: Fused Deposition Modeling Process

2.2. Material Jetting

Material jetting is a 3DP process whereby the actual build materials (in liquid or molten state) are selectively jetted through multiple jet heads (with others simultaneously jetting support materials). In this process, wax material is applied in droplets through a small diameter nozzle, similar to the way a common inkjet paper printer works, but it is applied layer-by-layer. These layers build up one at a time in an additive process to create a 3D model. Fully cured models can be handled and used immediately without additional post-curing. Along with the selected model materials, a gel-like support material facilitates successful printing of complicated geometries. Support material can be removed by hand or by a high-powered water jet station. The nature of this product allows for the simultaneous deposition of a range of materials, which means that a single part can be produced from multiple materials with different characteristics and properties. [19]

Material jetting is the only AM technology that can combine different print materials within the same 3D printed model in the same print job. Additionally, the multi-material printing process is capable of constructing functional assemblies, which reduces the need for multiple builds.It can also achieve very good accuracy and surface finishes. However the technology only works with wax-like materials, and there is only a limited number of wax-like materials available for material jetting. In addition, due to the type of material, parts are rather fragile and the build process is rather slow. [20]

Figure 2.2: *Material Jetting Process*

2.3. Binder Jetting

Binder Jetting, also known as full color 3D printing or Inkjet Powder Printing is an AM process that is popular since it can produce detailed 3D prints with color. [13] Inkjet print heads apply a liquid bonding agent onto thin layers of powder. By gluing the particles together, the part is built up layer by layer. A binder jetting machine will distribute a layer of powder onto a build platform. A liquid bonding agent is applied through inkjet print heads bonding the particles together. The build platform will be lowered and the next layer of powder will be laid out on top. By repeating the process of laying out powder and bonding, the parts are built up in the powder bed.

Binder Jetting does not require any support structures, since the powder is self supporting. It also works with almost any material that is available in powder form. [21] It is capable of printing a variety of materials including metals, sands and ceramics. Some materials, like sand, require no additional processing. Other materials are typically cured and sintered and sometimes infiltrated with another material, depending on the application. [22] Compared to FDM, this process requires further post processing techniques such as vacuuming of the excess powder or depowdering the object using compressed air. [13]. If not further processed, the particles may result fragil, with limited mechanical properties. Binder Jetting is unique in that it does not employ heat during the build process. Other additive techniques utilize a heat source which can create residual stresses in the parts. These stresses must be relieved in a secondary post-processing operation. [22]

Figure 2.3: *Binder Jetting Process*

2.4. Vat Polymerisation

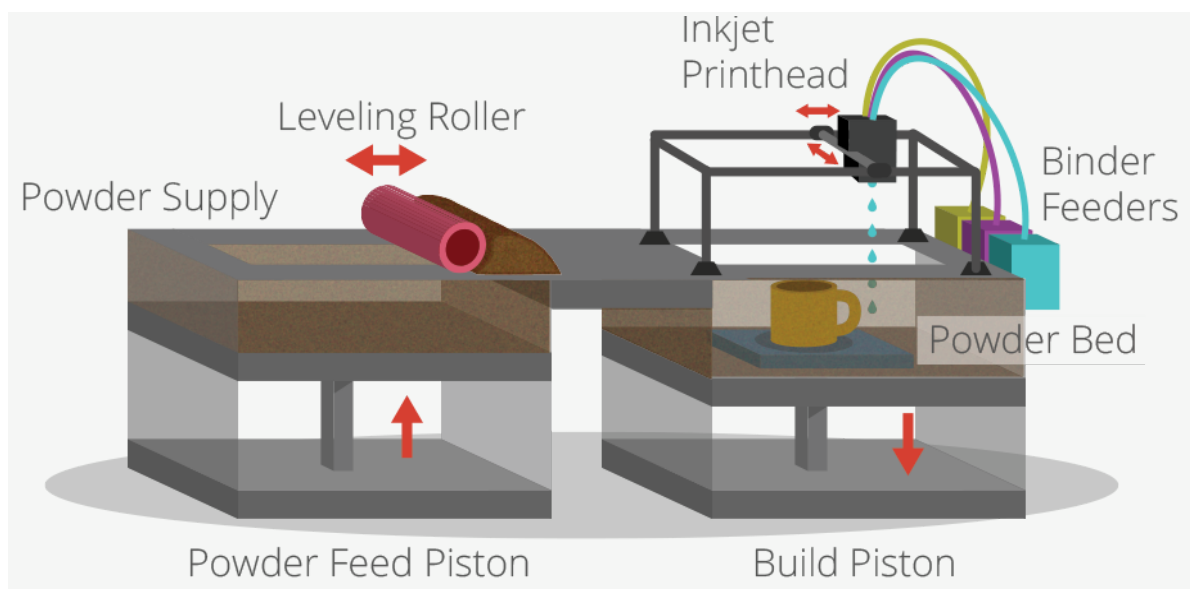Vat Photopolymerisation describes a group of different AM technologies. The term comes from the roots photo - meaning light- and polymer, which describes the chemical composition of the solid plastic. The different Vat Photopolymerisation technologies use different light sources and technical setups to emit and the resins surface selectively. [17]

In photo-polymerization, a vat of liquid polymer is exposed to controlled lighting under safelight conditions. The exposed liquid polymer hardens. The build plate then moves down in small increments and the liquid polymer is again exposed to light. The process repeats until the model has been built. The liquid polymer is then drained from the vat, leaving the solid model. Inkjet printer system spray photopolymer materials onto a build tray in ultra-thin layers until the part is completed.   Each photopolymer layer is cured with UV light after it is jetted, producing fully cured models that can be handled and used immediately, without post-curing. The gel-like support material, which is designed to support complicated geometries, is removed by hand and water jetting. It is also suitable for elastomers. Ultra-small features can be made with the 3D micro-fabrication technique used in multi photon photopolymerisation. This approach uses a focused laser to trace the desired 3D object into a block of gel. Due to the nonlinear nature of photo excitation, the gel is cured to a solid only in the places where the laser was focused while the remaining gel is then washed away. Feature sizes of very small scales are easily produced, as well as complex structures with moving and interlocked parts. [2]

The most commonly used technology in this processes is Stereolithography (SLA). Other technologies using Vat Photopolymerisation are the new ultrafast Continuous Liquid Interface Production or CLIP and marginally used older Film Transfer Imaging and Solid Ground Curing. [1]

2.4.1. Stereolithography

SLA is often considered the pioneer of the AM processes, with the first production systems introduced in 1988 and patented by 3D systems founder Charles Hull. [24] SLA is a laser-based process that works with photopolymer resins, that react with the laser and cure to form a solid in a very precise way to produce very accurate parts. It is a complex process, but simply put, the photopolymer resin is held in a vat with a movable platform inside. A laser beam is directed in the X-Y axes across the surface of the resin according to the .STL file, whereby the resin hardens precisely where the laser hits the surface. Once the layer is completed, the platform within the vat drops down by a fraction (in the Z axis) and the subsequent layer is traced out by the laser. This continues until the entire object is completed and the platform can be raised out of the vat for removal. [1]

This technology requires the use of supporting structures which serve to attach the part to the elevator platform, prevent deflection due to gravity and hold the cross sections in place so that they resist lateral pressure from the re-coater blade. Supports are generated automatically during the preparation of 3D CAD models for use on the SLA machine, although they may be manipulated manually. Supports must be removed from the finished product manually, unlike in other, less costly, rapid prototyping technologies. [25]

SLA is generally accepted as being one of the most accurate 3D printing processes with excellent surface finish. However limiting factors include the post-processing steps required and the stability of the materials over time, which can become more brittle. [1] These photopolymer parts do not have the strength of SLS or FDM parts, but can typically achieve much higher levels of detail and cosmetically superior finish, unlike SLS prototypes, which are typically powdery and granular. As the photopolymer is UV sensitive, these products are susceptible to deforming and changing colors in sunlight, that's why this technology is commonly used to generate highly detailed artwork, non-functional prototypes, and can be used to make molds in investment casting applications. Also, SLA is well suited for small-batch or small-lot manufacturing of prototype or end-use parts. [13], [25]

2.4.2. Continuous Liquid Interface Production

CLIP is a chemical process that carefully balances light and oxygen to eliminate the mechanical steps and the layers. It works by projecting light through an oxygen-permeable window into a reservoir of UV curable resin. The build platform lifts continuously as the object is grown. The heart of the CLIP process is a special window that is transparent to light and permeable to oxygen, much like a contact lens. By controlling the oxygen flux through the window, CLIP creates a "dead zone" - a thin layer of uncured resin between the window and the object. This makes it possible to grow without stopping. As a continuous sequence of UV images are projected, the object is drawn from the resin bath. Sophisticated software manages the entire process by controlling the variables.

This process makes it possible to exploit a huge range of materials desired for production-quality parts. It is possible to draw from the whole polymer family to meet highly specific application requirements. Parts printed with CLIP are much more like injection-molded parts. CLIP produces consistent and predictable mechanical properties, creating parts that are smooth on the outside and solid on the inside, unlike the traditionally made 3D printed parts that are notoriously inconsistent. In addition, while speed is dependent on various factors, traditional 3DP takes hours to finish. CLIP is 25 to 100 times faster than currently available commercial PolyJet or SLA machines. [26]
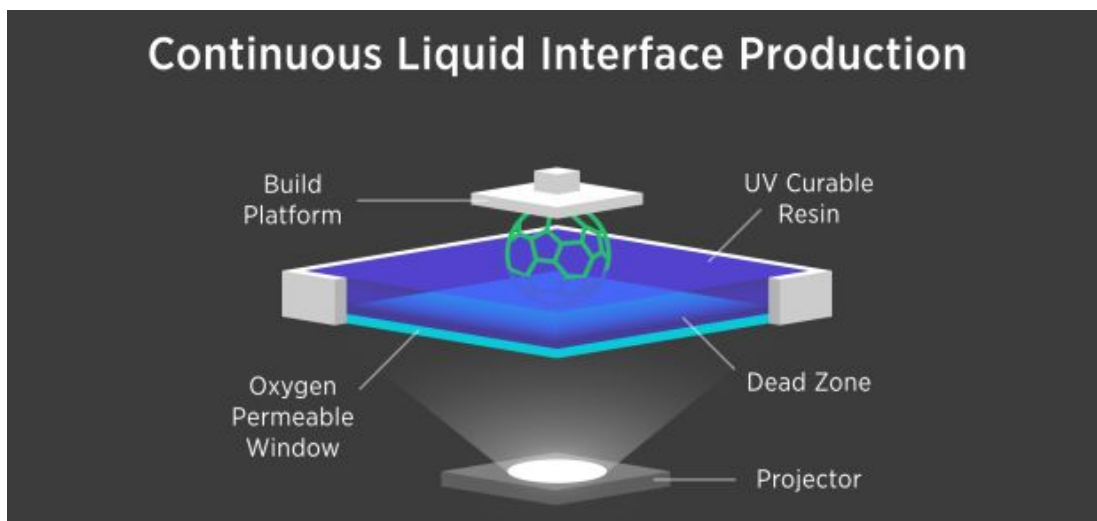

Figure 2.4.2: *Continuous Liquid Interface Process*

2.4.3. Digital Light Processing

Digital Light Processing is a 3D printing process where a projector is used to cure photopolymer resin. The major difference with SLA is the light source. DLP uses a more conventional light source, such as an arc lamp, with a liquid crystal display panel or a Deformable Mirror Device (DMD), which is applied to the entire surface of the vat of photopolymer resin in a single pass, generally making it faster than SLA.

Objects that are printed with DLP have less visible layers versus other processes such as FDM. Compared with SLA, DLP can have faster build speeds due to a single layer being created in one singular digital image whereas with SLA, the UV laser has to scan the vat with a single point (trace out the object layer). Also like SLA, DLP produces highly accurate parts with excellent resolution, but its similarities also include the same requirements for support structures and post-curing. However, one advantage of DLP over SLA is that only a shallow vat of resin is required to facilitate the process, which generally results in less waste and lower running costs.

Similar to SLA, DLP is commonly used to generate highly detailed artwork, non-functional prototypes, and can be used to make molds in investment casting applications. [13]
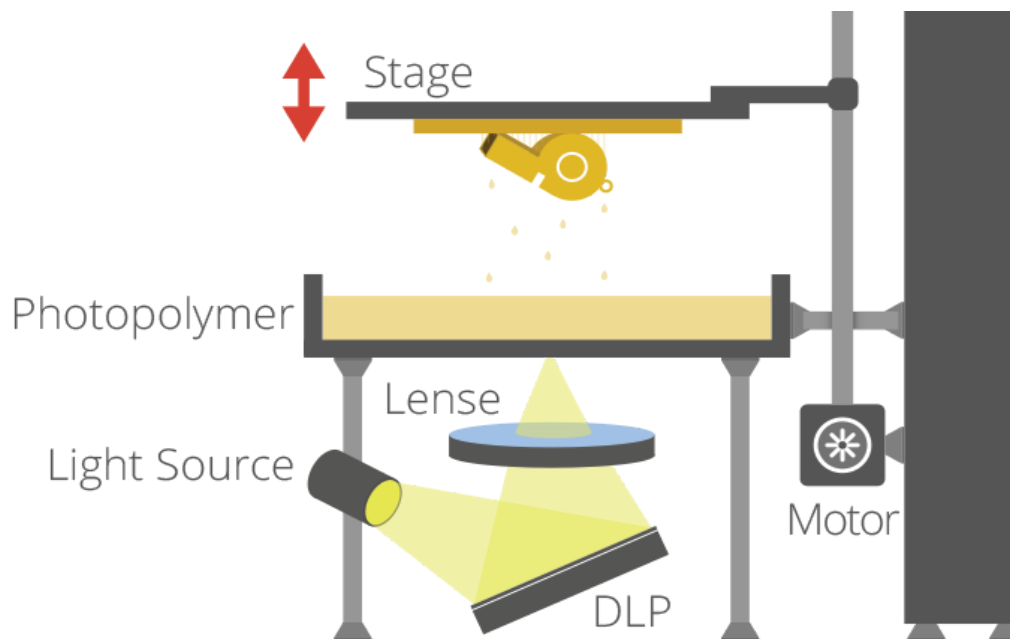

Figure 2.4.3: Digital Light Processing

2.5. Powder Bed Fusion

The Powder Bed Fusion (PBF) process includes the following commonly used printing techniques:
1. Selective Laser Sintering
2. Selective Laser Melting
3. Direct Metal Laser Sintering
4. Electron Beam Melting and
5. Selective Heat Sintering.

PBF methods use either a laser or electron beam to melt and fuse material powder together. [27] The powder bed is in inert atmosphere or partial vacuum to provide shielding of the molten metal. An energy source (Laser or electron beam) is used to scan each layer of the already spread powder to selectively melt the material according to the part cross section obtained from the digital part model. When one layer has been scanned, the piston of building chamber goes downward and the piston of the powder chamber goes upward by defined layer thickness. Coating mechanism or roller deposits powder across build chamber which is again scanned by the energy source. This cycle is repeated layer by layer, until the complete part is formed. The end result of this process is powder cake and the part is not visible until excess powder is removed.

Build time required to complete a part in PBF based processes is more as compared to DED (Directed Energy Deposition) technologies but, higher complexity and better surface finish can be achieved which requires minimum post-processing. Several parts can be built together so that build chamber can be fully utilized.

These processes inherently require support to avoid collapse of molten materials in case of overhanging surfaces, dissipate heat and prevent distortions. Supports can be generated and modified as per part requirement during pre-processing phase and the same has to be removed by mechanical treatment during post-processing phase. After support removal, part may undergo post-processing treatments like shot peening, polishing, machining and heat treatment depending on the requirement. [5]

2.5.1. Selective Laser Sintering

Selective Laser Sintering (SLS) uses high power CO_2 lasers to fuse plastic, metal or ceramic particles. The laser is traced across a powder bed of tightly compacted powdered material, according to the 3D data fed to the machine, in the X-Y axes. As the laser interacts with the surface of the powdered material it sinters, or fuses, the particles to each other forming a solid. As each layer is completed the powder bed drops incrementally and a roller smoothes the powder over the surface of the bed prior to the next pass of the laser for the subsequent layer to be formed and fused with the previous layer. Once finished, the entire powder bed is removed from the machine and the excess powder can be removed to leave the printed parts.

One of the key advantages of this process is that the powder bed serves as an in-process support structure for overhangs and undercuts. Complete mechanical assemblies can be made mechanically functional simply by removing the un-sintered powder. Compared with other methods of AM, SLS can produce parts from a relatively wide range of commercially available powder materials like polymers, metals, composites and green sand. [28] Also, it requires very little additional tooling once an object is printed. [30] SLS is unique in that this rapid technology permits multiple parts to be stacked in the Z height and nested inside other parts in the build to optimize the build production efficiency. [31]

On the downside, because of the high temperatures required, cooling times can be considerable. Furthermore, porosity has been an issue with this process and trapped volumes may occur. [19]
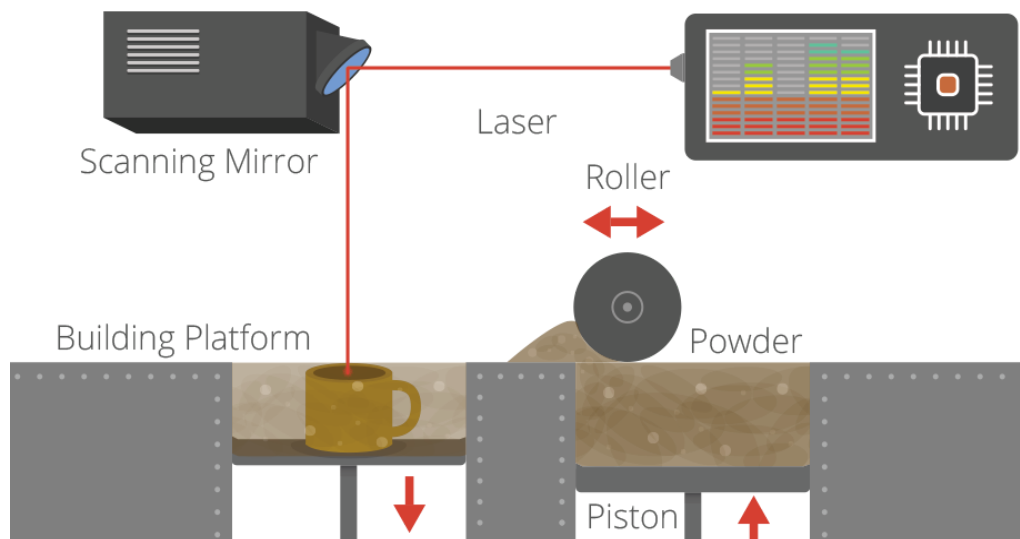

Figure 2.5.1: Selective Laser Sintering Process

2.5.2. Selective Laser Melting

SLM is an advanced form of the SLS process where, full melting of the powder bed particles takes place by using one or more lasers. [5] SLM enables the production of nearly unlimited complex geometries without the need of part-specific tooling or preproduction costs. First, the 3D-CAD volume model is broken down into layers and transferred to the SLSM machine. Subsequently, the powder material (grain fraction 10–45μm) is deposited as a defined thin layer on a substrate. The geometric information of the individual layers is transmitted by laser beam to the powder bed wherein the regions to contain solid material are scanned under an inert atmosphere, leaving a solid layer of the piece to be produced. After lowering the substrate by one layer thickness, the process steps are repeated until the part is finished. Since standard metallic powders are used, which melt completely, the part has a density of approximately 100%, thus assuring mechanical properties that match or even beat those of conventionally manufactured parts (cutting, casting). [32]

This 3D printing process holds a unique position in modern day product development. It combines the design flexibility of 3D printing with the mechanical properties of metal. From tooling inserts with cooling channels to lightweight structures for aerospace, any application that involves complex metal parts potentially benefits from the Laser Melting technology. [33]

In SLM, part manufacturing takes place under argon gas environment for reactive materials to avoid contamination and oxidation whereas non-reactive materials can be processed under nitrogen environment. So it can be expected that the manufactured parts have quite high oxygen content. [5]

2.5.3 Direct Metal Laser Sintering

Direct Metal Laser Sintering (DMLS) is an AM technique for metal 3D printing that was developed by EOS. It uses a laser as a power source in order to sinter metal powder by aiming a laser and tracing a cross section of the object layer by layer. The build changer has a material dispensing platform and a build platform along with a re-coater blade which is used to move new powder over the build platform. The process fuses metal powder into a solid part by melting it locally using the focused laser beam where it traces the cross section of the object layer by layer.

DMLS has many benefits over traditional manufacturing techniques. Its ability to quickly produce a unique part is the most obvious because no special tooling is required so it is convenient for short production runs. Also, can use most alloys and prototypes can be functional hardware made out of the same material as production parts. [13] DMLS is also one of the few AM technologies being used in production. Since the components are built layer by layer, it is possible to design internal features and passages that could not be cast or otherwise machined. Complex geometries and assemblies with multiple components can be simplified to fewer parts with a more cost effective assembly. Also, the parts produced using DMLS can easily be machined, processed, polished, etched and textured, as well as parts can be produced using a variety of material types. They are also temperature -resistant pieces.

It is though the technology that typically costs much more than other rapid metal prototyping techniques and depending on part geometry, DMLS printing presents size limitations.
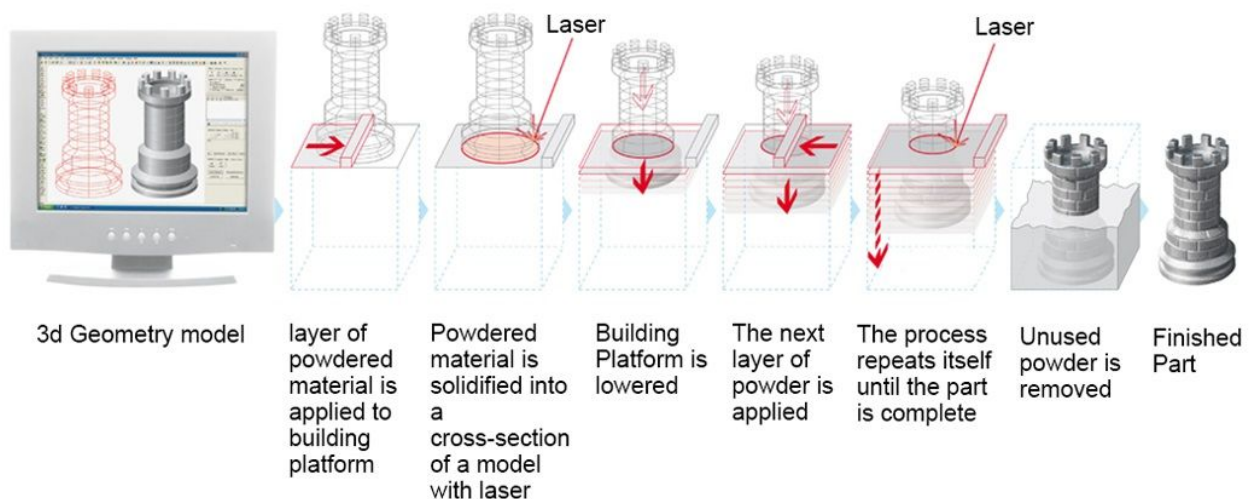

Figure 2.5.3: Direct Metal Laser Sintering Process

2.5.4. Electron Beam Melting

During the process, a heated tungsten filament emits electrons at high speed which are then controlled by two magnetic fields, focus coil and deflection coil. Focus coil acts as a magnetic lens and focuses the beam into desired diameter whereas deflection coil deflects the focused beam at required point to scan the layer of powder bed. When high speed electrons hit the powder bed, their kinetic energy gets converted into thermal energy which melts the powder. Each powder bed layer is scanned in two stages, the preheating stage and the melting stage. In preheating stage, a high current beam with a high scanning speed is used to preheat the powder layer in multiple passes. In melting stage, a low current beam with a low scanning speed is used to melt the powder. When scanning of one layer is completed, table is lowered, another powder layer is spread and the process repeats till required component is formed.
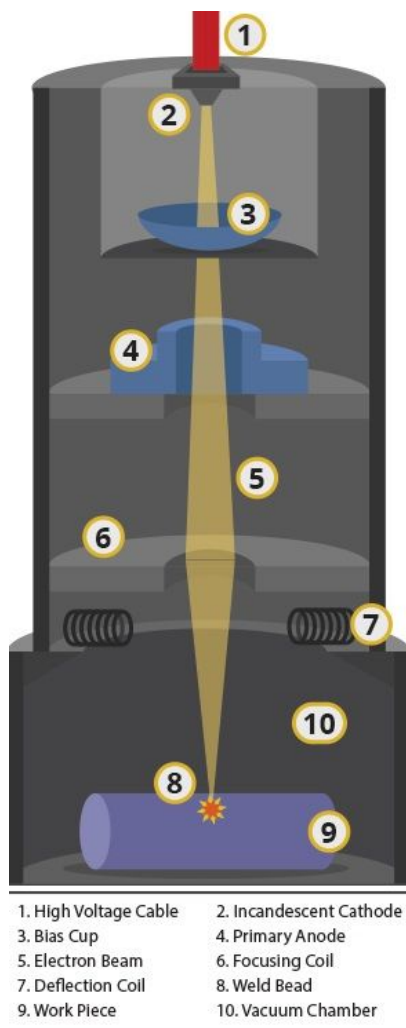
The helium gas supply during the melting further reduces the vacuum pressure which allows part cooling and provides beam stability. This method can produce fully dense metal parts and can retain the characteristics of the material. Also, it has good mechanical properties compared to traditional production technologies. Some of the materials used with this technology are titanium alloys which make it an excellent choice for medical implant market. [5], [13]

Because of rapid heating and cooling of the powder layer, residual stresses are developed. High build chamber temperature is maintained by preheating the powder bed layer. This preheating reduces the thermal gradient in the powder bed and the scanned layer which reduces residual stresses in the part and eliminates post heat treatment required. Preheating also holds powder particles together which can acts as supports for overhanging structural members. So, supports required in the EBM are only for heat conduction and not for structural support. This reduces the number of supports required and allows manufacturing of more complex geometries.

1. High Voltage Cable   2. Incandescent Cathode
3. Bias Cup   4. Primary Anode
5. Electron Beam   6. Focusing Coil
7. Deflection Coil   8. Weld Bead
9. Work Piece   10. Vacuum Chamber

Figure 2.5.4: Electron Beam Melting Process

2.6 Sheet Lamination

Sheet lamination, or Selective Deposition Lamination (SDL). The name of the process describes the process itself: This word 'Selective' refers to the selective method that the printer uses in depositing the adhesive to bond the sheets of paper. A much higher density of adhesive drops are deposited in the area that will become the part, and a much lower density of adhesive is applied in drops in the surrounding area that will serve as the support. Deposition refers to the method of applying the adhesive in droplets onto a sheet of ordinary paper following the cutting of the profile of the part in that sheet (this process is repeated for each sheet of paper that will be used to create the part). Lamination describes the process of building up successive layers of a substance and bonding them to form a durable finished product.

SDL is one of the very few 3D printing processes that can produce full colour 3D printed parts, using a CMYK colour palette. Since the parts are standard paper, which can be further processed using some wood finishing techniques post-processing, they are safe and eco-friendly and the whole process can be characterised as low cost one. Also, the prototypes result to be incredibly durable. They can be drilled, threaded, tapped or made water resistant with a quick dip in a sealant. Also, they don't need to go under post-processing. [34]

Where the process is not able to compete favourably with other 3D printing processes, is in the production of complex geometries and the build size is limited to the size of the feedstock. [1], [13]
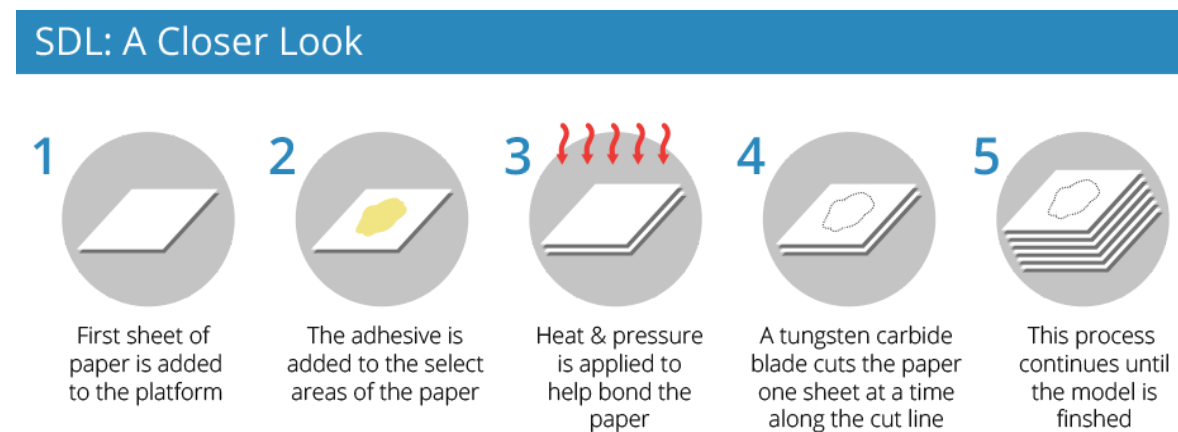

Figure 2.6: Selective Deposition Lamination Process

2.7 Directed Energy Deposition

Directed energy Deposition (DED) processes enable the creation of parts by melting material as it is being deposited. Although this basic approach can work for polymers, ceramics, and metal matrix composites, it is predominantly used for metal powders. Thus, this technology is often referred to as "metal deposition| technology.

DED processed direct energy into a narrow, focused region to heat a substrate, melting the substrate and simultaneously melting material that is being deposited into the substrate melt pool. Unlike powder bed fusion techniques, DED processes are not used to melt a material that is pre-laid in a powder bed but are used to melt materials as they are being deposited.

DED processes use a focused heat source (typically a laser or electron beam) to melt the feedstock material and build up three-dimensional objects in a manner similar to the extrusion-based processed. Each pass of the DED head creates a track of solidified material, and adjacent lines of material make up layers. Complex three-dimensional geometry requires either support material or a multiaxis deposition head. A schematic representation of a DED process using powder feedstock material and lasser is shown in figure 2.7.

Commercial DED processes include using a laser or electron beam to melt powders or wires. In many ways, DED techniques can be used in an identical manner to laser cladding and plasma welding machines.
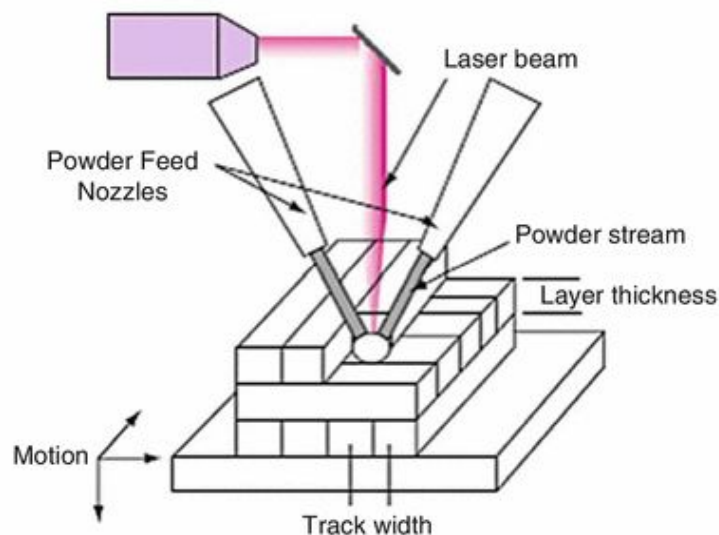

Figure 2.7: *Direct Energy Deposition Process*

Chapter 3
Design of the parts

3.1. Introduction

The experimental part concerns the production of some 3D printed prototypes, that address three diverse type of objects.

First type of object is a multi-part one, which aims to demonstrate the complexity of printing different parts that have to be mounted into a single one and how this can be achieved in the best way so that the object is functional. In particular, the designed object is a phone case that is decorated with gears in its back part, that serve as decoration and are moving at the same time.

The second type concerns an object that is meant to be decorative, so its surfaces should be of good quality. Since the direction of the printing is an important parameter that affects the quality of the surface, the purpose of this test print is to see which printing direction serves better our purpose. The designed object is a a double sliding ring.

The third type concerns an object that is functional, so it has to be of strong structure. Since the direction of the printing affects the mechanical properties of the object and other parameters as it's consistency, density, durability, flexibility etc, the purpose of this test print is to see which printing direction can offer more of these quality parameters to the printed object. The designed object is a clothespin.

The purpose of the diversity of these objects is to show the difficulties of designing and printing in each category, and the problems that may occur in each situation.

3.2. Limitations in Design

All the three objects were designed in Pro/Engineer program. Some parameters are necessary to be taken into account before and while designing, in order to create an object that is feasible to be printed. Such parameters are:

1. Size the model to fit the printer. The dimensions of the designed object should be compatible with the dimensions that the printer can print. The build volume of our printer is 28.5* 15.3 *15.5 cm, so the objects should be up to this size.

2. The minimum thickness of the walls of the objects should be at least 2mm. Thickness less than 2mm plays the pre quality under risk, as the filament driven from the spool might stick to the nozzle because of getting overheated and not being able to

be extruded properly. Also thin walls make small parts of the model unable to be printed or be very fragile and break off easily. In other cases, walls that are too thick generate too much internal stress and could cause the item to crack or even break.
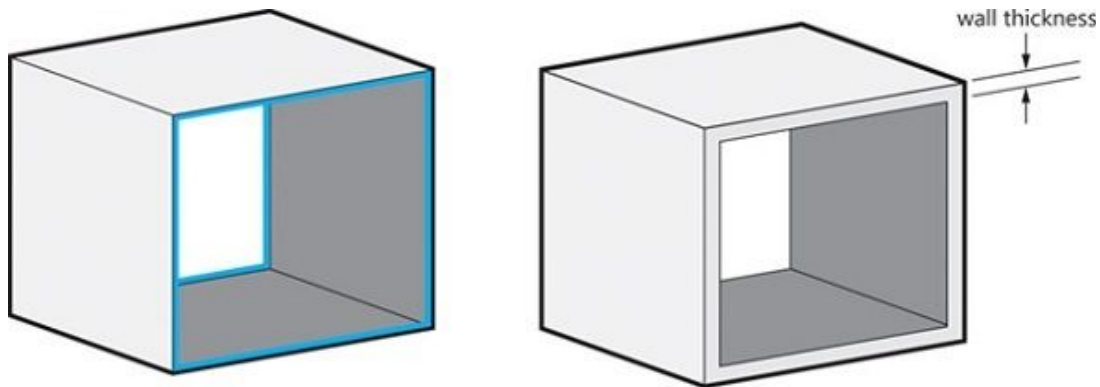

Figure 3.2.a: Proper adjustment of the wall thickness

3. Mind the weight distribution of the model. If the model should stand by itself and not topple over, the bottom of the model should have a strong grounding. Maybe the model needs a base, thicker legs or multiple points of contact on the ground to hold it up, or even use of support material. It's important also to take into account the direction of the printing.

4. Mind the creation of openings/holes that can be printed without support during printing, the creation of inclined surfaces, avoidance of corners, smoothness of the edges and the thickness of the vulnerable areas

5. Properly adjust the file resolution. The most common file format is STL (which stands for standard triangle language), which means that the model will be translated into triangles in a 3D space. Choosing the right resolution for the file is important to ensure a good quality print. Exporting in low resolution, results in making the model looking faceted, since the triangles in the STL file are big and the surface of your print will not be smooth. On the other hand, exporting in too high resolution, will make the file too big and sometimes impossible to handle. It might also contain an extreme level of details that the 3D printer cannot print. [35], [36].
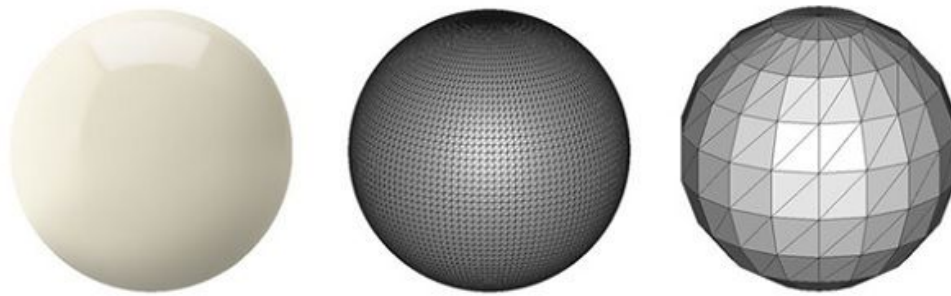
Figure 3.2.b: Visual representation of different file resolutions from extremely high (left) to quite low (right)

3.3. Design part

The following paragraphs describe with details each object and its parts, that were designed according to the notes of the paragraph 3.2..

3.3.1. Design of the phone case

The following images show the designs of the phone case - designed for LG L65- of dimensions 7*13*1.1 cm and its parts include:
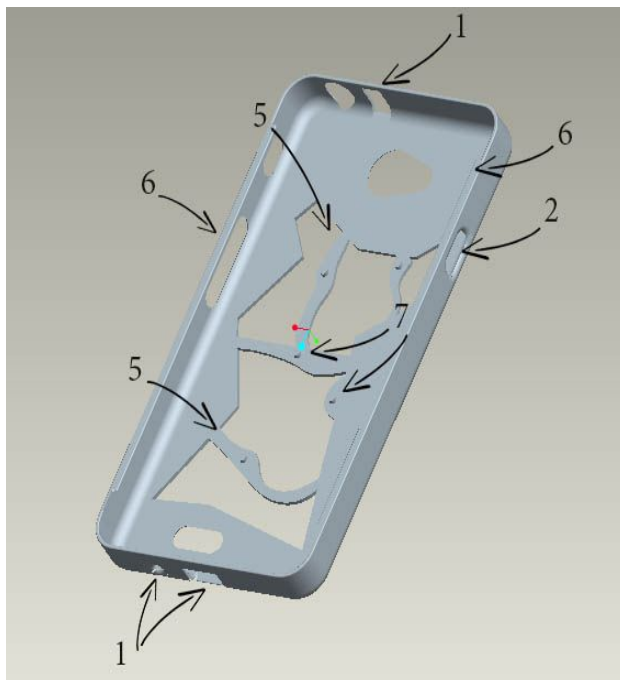
1. Openings in the sides of the case, for insertion of the charging cable and the earphones.

2. Openings in the sides of the case, for the volume button and the turn off button.
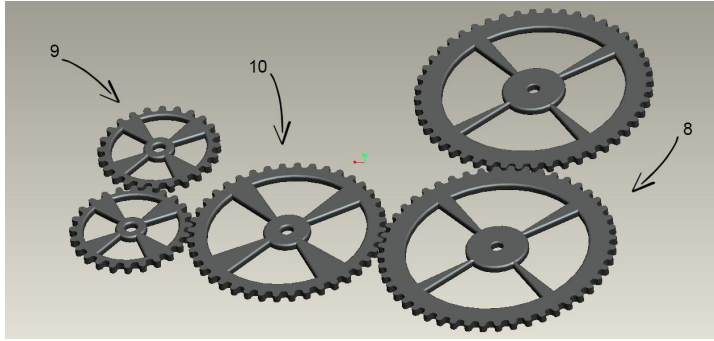
3. Opening in the back part of the case. for the camera and the flash light.

4. Openings in the back part of the case, for decorative purposes.

5. Bridges where the gears are hold with small knobs.

6. Two knobs, one along each side of the case, for holding the phone inside the case.

Figure 3.3.1.a: Preview of the front part of the phone case in ProEngineer

7. Five small knobs where the five gears are inserted, placed in the inner back part of the case.

8. Two gears of 48 teeth.

9. Two gears of 24 teeth.

10. One gear of 40 teeth.

Figure 3.3.1.b: *Preview of the gears in ProEngineer*

The figure *3.3.1.d* is a preview of the insertion of the gears inside the case and the complete assembly of the case. Next step was to adjust the settings of STL format. The settings of the STL format are the same in all the three designed models that will follow.

These settings are:

● Selection of Binary instead of ASCII type, for reducing the file size, which is better for saving and sharing.

● Setting of the Chord Height as 0.01 mm, for better precision of the STL file. The smaller the chord height, the less deviation from the actual part surface, but the bigger the file.

● Setting of the Angle Control as 0.05 mm, for better precision of the STL file. Unless a higher setting is necessary, to achieve smoother surfaces, setting close to 0 is recommended. [37]

Figure 3.3.1.c: *Preview of the assembly of the phone case with the gears in ProEngineer*

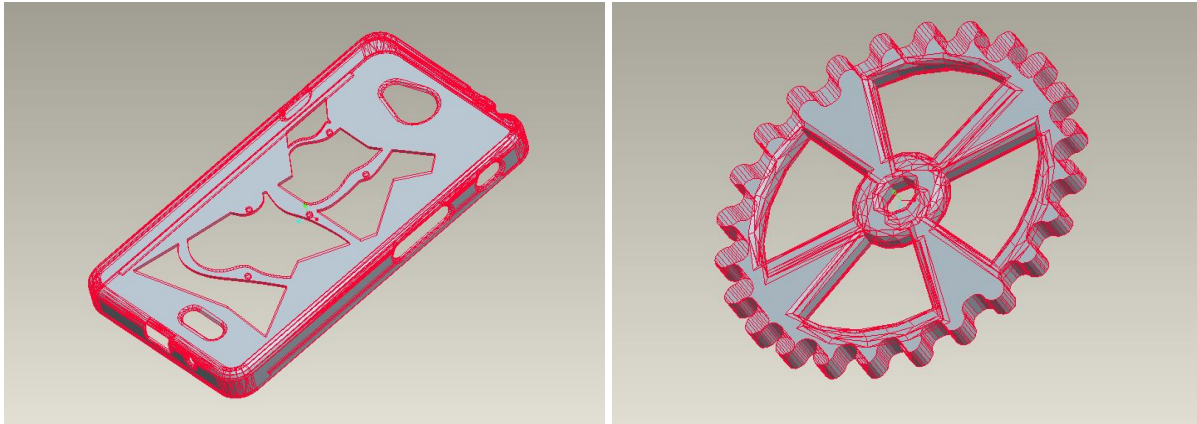The following images are previews of some of the STL files:

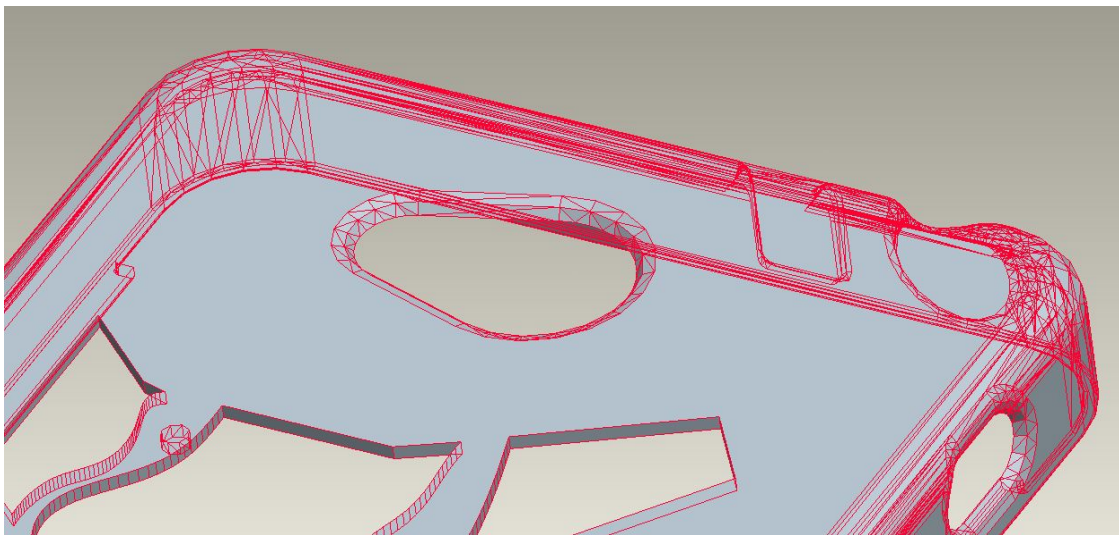*Figure 3.3.1.d: Preview of the STL file of the phone case and the gear*

Figure 3.3.1.e: Detail of the preview of the STL file of the phone case

3.3.2. Design of the double sliding ring

In the following image is shown the design of the ring. It consists of 2 rings, one sliding into the other. More detailed:
1. The inner ring has a small storage place with depth 3.5 mm.
2. The thickness of the walls of the storage place is 2 mm, which is the minimum thickness that can be printed without problem.
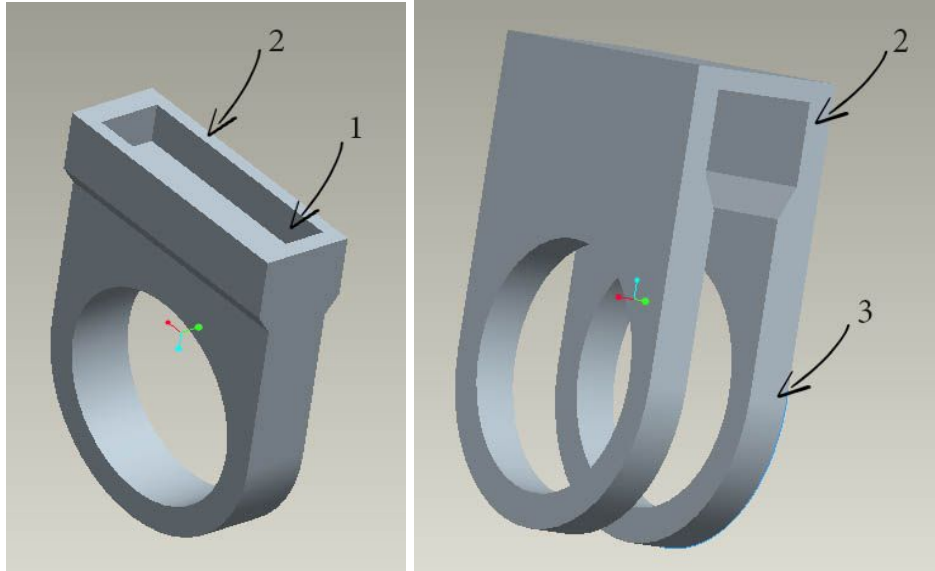
Figure 3.3.2.a: Preview of the inner and outer rings in ProEngineer

3. The thickness of the ring is 5 mm, which is slightly large, so that it ensures durability.
4. The outer ring has bigger outer surface, so that includes the inner one, and its dimensions are 3.4*2.3*1.2 cm.

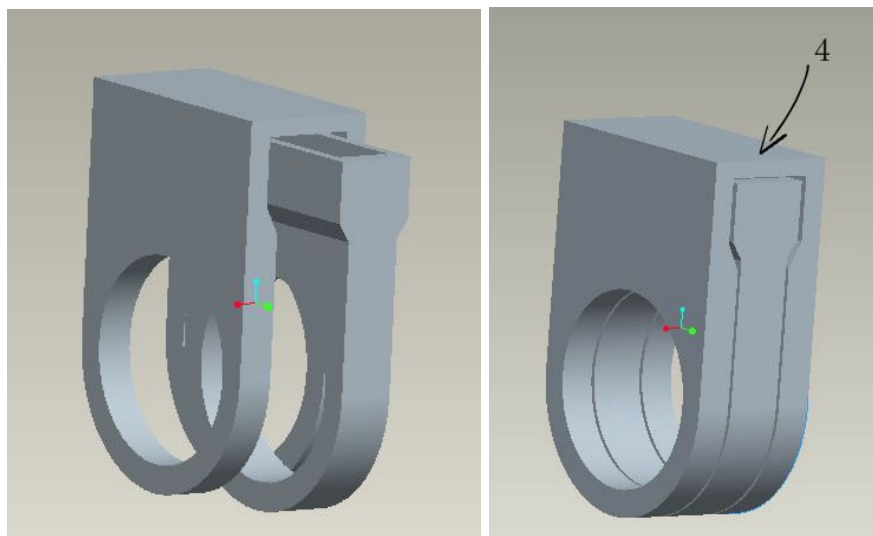In the following image we can see the assembly of both rings.

Figure 3.3.2.b: Preview of of the assembly of the outer and inner ring in ProEngineer
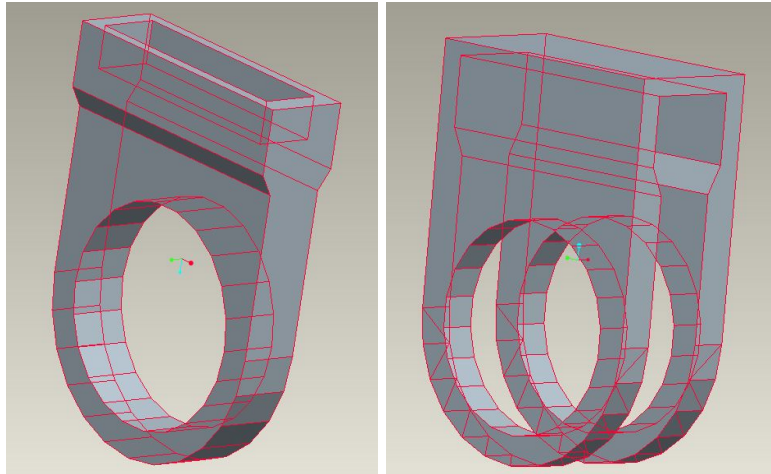
The following image is a preview of the STL files:

Figure 3.3.2.c: Preview of the STL file of the inner and outer ring

3.3.3. Design of the clothespin

The clothespin consists of two parts- which is the same part duplicated and its dimensions are 8*1.25*1.1 cm, as it is shown in the following picture. It consists of:

1. Two insertions - curves where the spring is placed.

2. Teeth for grabbing.

3. Two insertions - curves for grabbing.

4. Grooves that make the structure lightweight and of less volume.

Figure 3.3.3.a: Preview of the part of the clothespin in ProEngineer

The figure 3.3.3.c is a preview of the STL file of the single part of the clothespin:
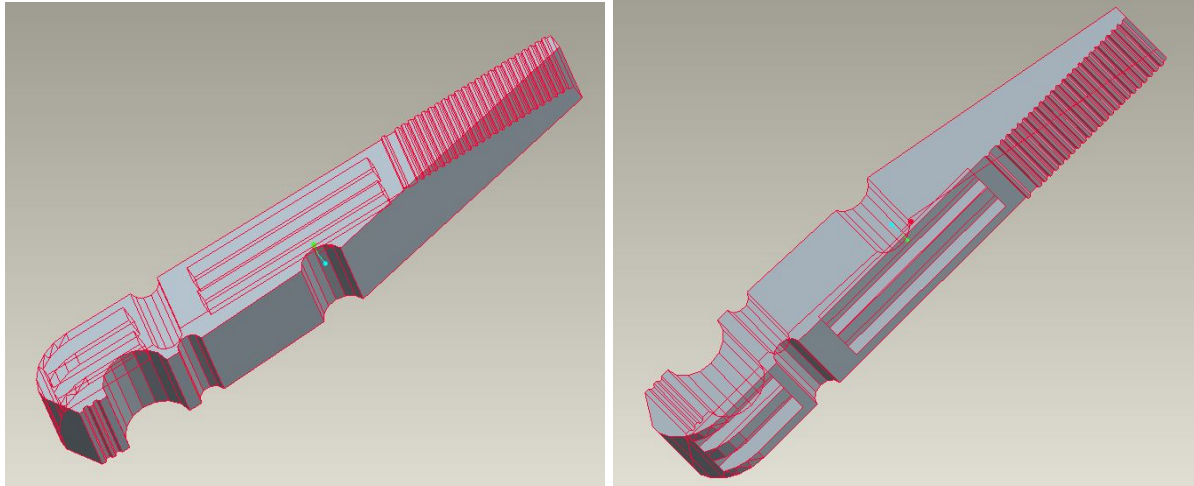
Figure 3.3.3.b: Preview of the STL file of the clothespin

3.4. Methodology of test prints

The realization of the test prints requires a series of stages of preparation.
These are the adjustment of the settings of the prototype before each printing, the printing itself, the post - processing of the object after its printing (if required) and finally the cleaning of the printer.

3.5. Adjustment of the settings

The performance of a 3D printer and the quality of the 3D prints it makes are only partially a result of the hardware specifications. The other part is the software that's used to prepare the 3D files and convert them to the gcode instructions that instruct the printer what to do – a process called slicing.
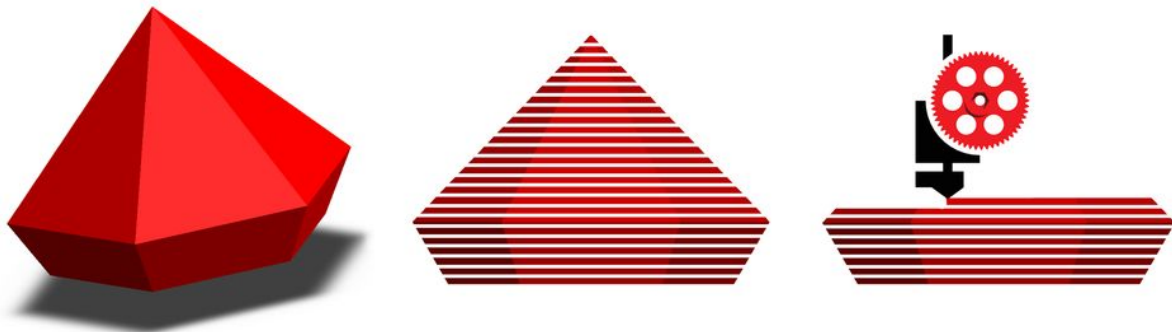

Figure 3.5: Process of creation, slicing and printing of an object

Makerbot desktop Software 3.9.1. is the tool used to convert a 3D model into printing instructions for the 3D printer. Slicer draws a path that the nozzle which lays down the plastic will take. It does the same for every layer, until it reaches the top of the objects. It is very important to set the right adjustments before each printing, as it generates toolpaths to fill the objects, calculates the amount of material to be extruded, affects the surface quality, strength and weight of the printed object, as well as the time needed for the printing time. [38], [39].

The main print settings that affect the most the final result and that I was customising during the test prints are:

-The raft: The raft is a removable base which helps the prints to adhere well to the build plate. Examples of its adjustments will be demonstrated later on.

-The support: The support material is removable scaffolding like structure, that is used to support parts of the object that cannot support themselves (like openings, holes, etc.).

-The layer height: The layer height is the thickness of each layer in the prints. In all the test prints, I kept it at 0.2 mm, which is recommended in general and offers good surface quality.

-The infill: The infill is the internal structure of the object. The more infill, the more solid the object. For example, 0% infill means hollow object while 100% infill means totally solid object.

-The shells: The shells are the outlines that make up the walls of the object. The shells can increase the strength of the model, and usually two to five shells are enough to create a strong object.

Before each printing, I adjusted the settings of slicing of each object to fit better the needs of the test prints as following:

3.5.1. Adjustments for the phone case

After inserting the STL file, I placed the phone case in the middle of the build plate with the larger and more solid surface attached to the build plate.

Apart from the default settings, I changed the adjustments of some of them. The most noteworthy ones are: the layer height is set to 0.2mm (in all the relevant settings as support in the bridging, in the model properties and the infill), which is satisfying wide for a big object as this phone case. The number of shells in the model properties is set to be 3 because we want the case to result durable, so it needs a strong cover around it. Last, I set the extrusion speeds to 70mm/s (such as floor surface fills, infill speed, raft

speed, sparse roof surface fills speed). The printing was set as high, for more precise results and since there was no hurry for the printing time.

With these settings, the printing time resulted to be 2:44 hours and the weight of the case 43.15 gr, as indicated by the makerbot.

Then, I adjusted the settings of the gears. After inserting all the five gears to the build plate, I moved them so that they are not very attached to each other, and they get printed in separate rafts. If they get printed in one raft, the raft may get overheat because of big size and curved, so it is probable that it doesn't stick to the build plate.

The most important settings of the gears are the following: the resolution and the layer height is set to 0.1 mm instead of 0.2 mm, as the gears are much smaller in size than the case, and this resolutions provides more detailed result. Also, the infill density is set to 5% instead of 10% that was used in the phone case. The number of shells is kept to 3 as we want the gears to be strong as well. Last, most of the extrusion speeds are set to 50 mm/s because the gears are quite small and with details, so the nozzle needs to go a bit slower so as to catch all the detailed edges. The printing was set as high, because we want to ensure a good print result, as the design of the gears is quite detailed and the adjustments of settings are not enough to cover its edgy points. Also, there is no much difference in the print time between standard and high mode.

With these settings, the printing time resulted to be 30 minutes and the weight of all the five gears 7.2 gr, as indicated by the makerbot.

3.5.2. Adjustment for the double sliding ring

A. First test print

In this first test print I printed only the outer ring in horizontal print. Its most important settings are: the layer height is 0.2 mm, the number of shells is 3- since the ring is quite delicate and may break easily if doesn't have strong cover, the infill density is 5% since it has already quite strong shell and doesn't need to be fully solid in the inside. In addition, the extrusion speeds are set to 50 mm/s because the volume of the ring is small and in low speed will be printed in better quality. Also, the support density is set to 40% and the the bridging is on, so as to ensure good support. In the standard mode and according to these settings, the printing time is estimated to be 38 minutes and the material used to be 6.33 gr. The simulation of the procedure is shown in the following preview:
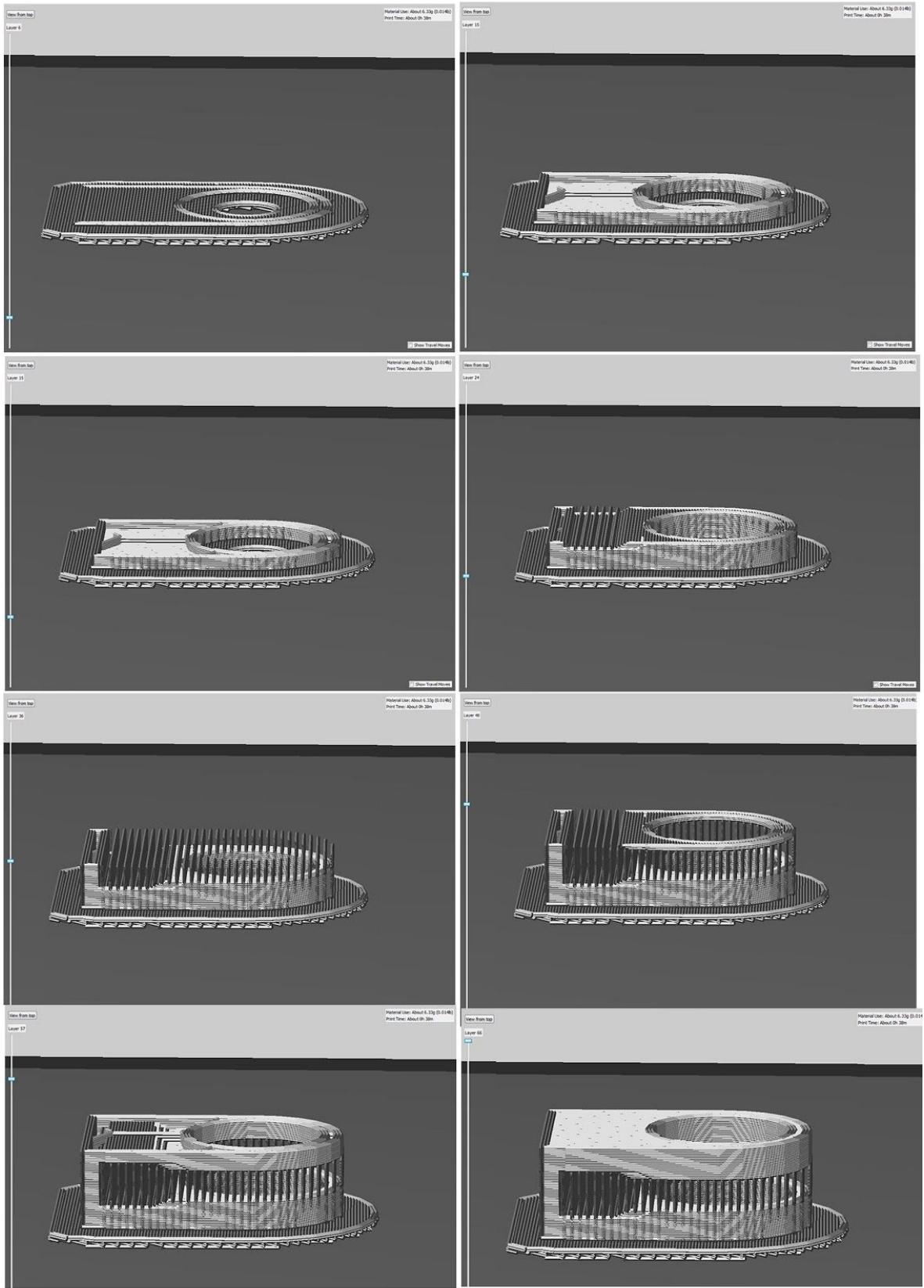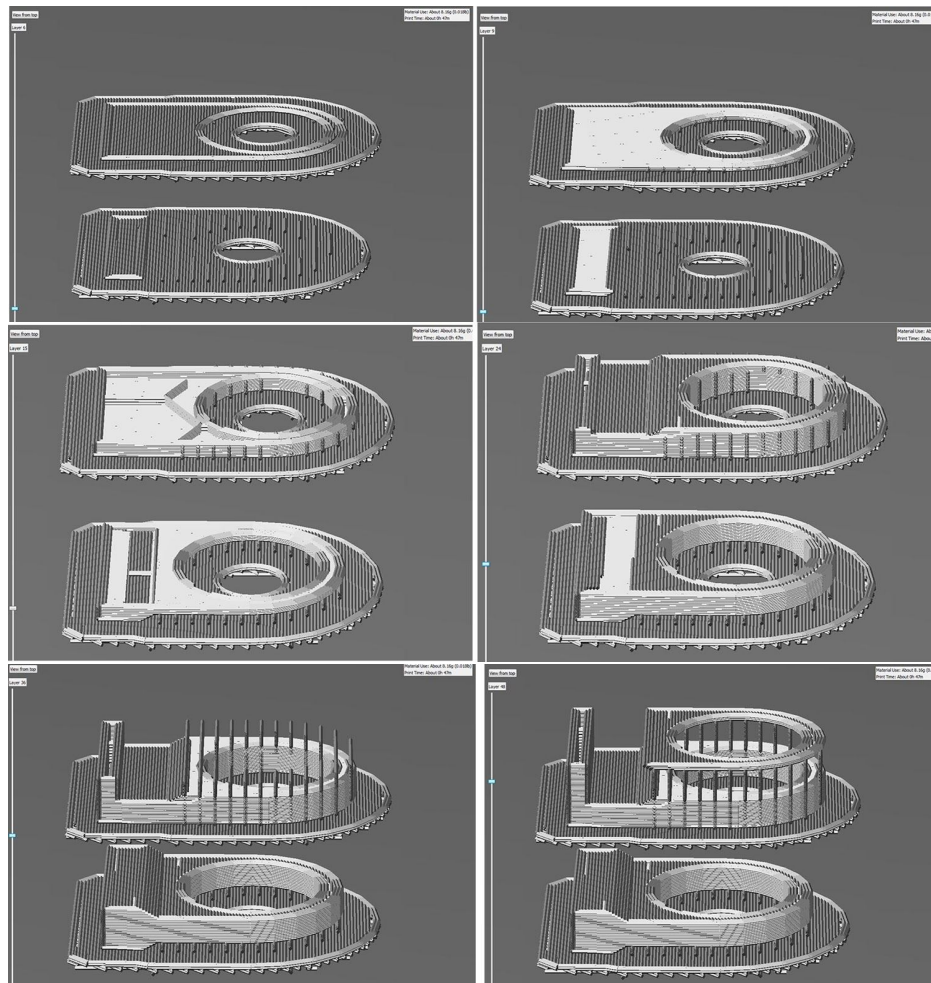
Figure 3.5.2A: *Simulation of printing progress of the outer ring in horizontal print*

B. Second test print

In the second test print, both the rings (the inner and the outer one) were printed horizontally, as shown in the figure 3.5.2B.b. I repeated the settings of the first test print with the only difference being the reduction of the support density. In this case it was 20%. With these settings, the printing time resulted to be 47 minutes and the weight of both the rings 8.16 gr, as indicated by the MakerBot.

Some of the steps of the simulation of the printing as captured in the MakerBot program are illustrated in the following pictures:
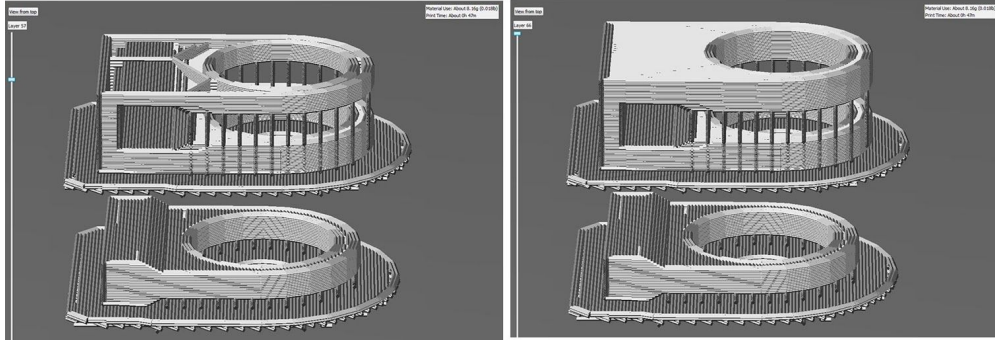
Figure 3.5.2B: *Simulation of printing progress of the inner and outer ring in horizontal print*

C. Third test print

In the third test print, I printed both the rings vertically, as shown in the figure 3.5.2C.b. The setting remained the same as in the second test print. With these settings, the printing time resulted to be 52 minutes and the weight of both the rings is 6.56 gr.

Some of the steps of the simulation of the printing as captured in the MakerBot software are illustrated in the following pictures:

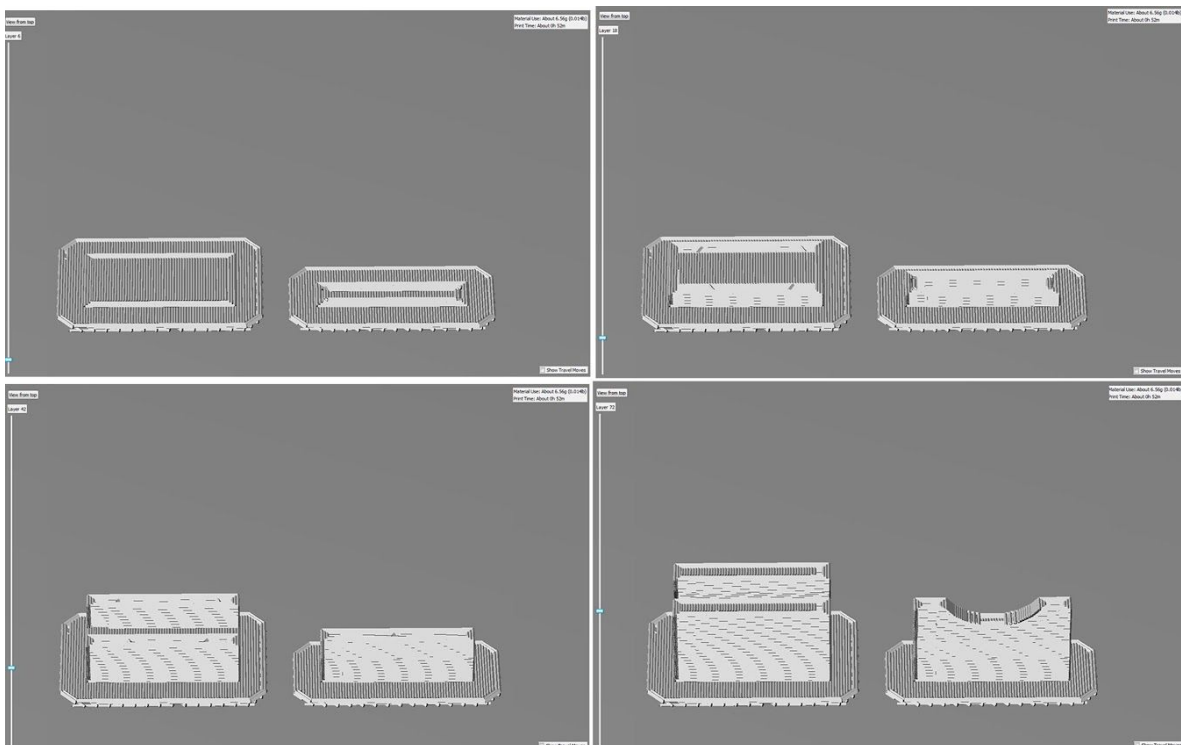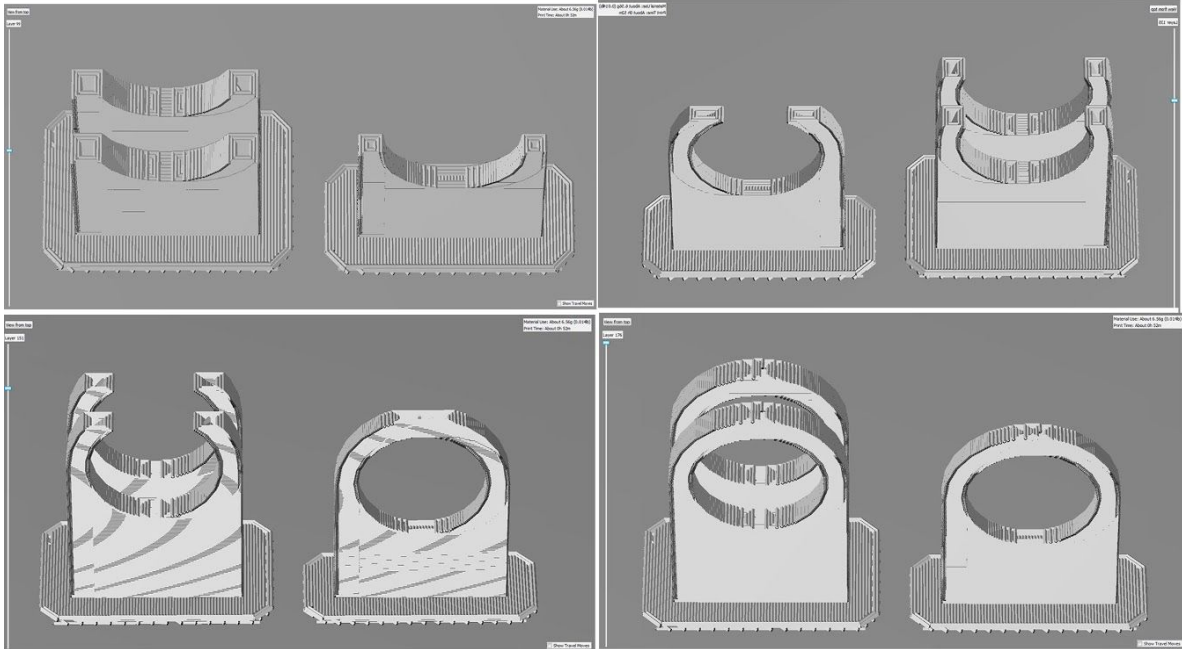*Figure 3.5.2C: Simulation of printing progress of the inner and outer ring in vertical print*

3.5.3. Adjustment of the clothespin

A. First test print

In the first test print, both parts of the clothespin were printed horizontally (as shown in figure 3.5.3.a), and for both parts were used the same settings. Apart from the default settings, the ones I adjusted are: the layer height is set to 0.2mm (in all the relevant settings as in the model properties and the infill). The number of shells in the model properties is set to be 3 because I want the result of the print to be durable as a clothespin should not break easily. Finally I set the extrusion speeds to 50mm/s (such as floor surface fills, infill speed, raft speed, sparse roof surface fills speed) and the infill density to 5%. The printing was set as standard, since the low one would not result in good quality of the print, and the high one would be an exaggeration.

With these settings, the printing time resulted to be 1 hour and 18 minutes and the weight of both the parts of the clothespin is 12.7 gr. Some of the pictures during the simulation of the printing at the MakerBot are the following:
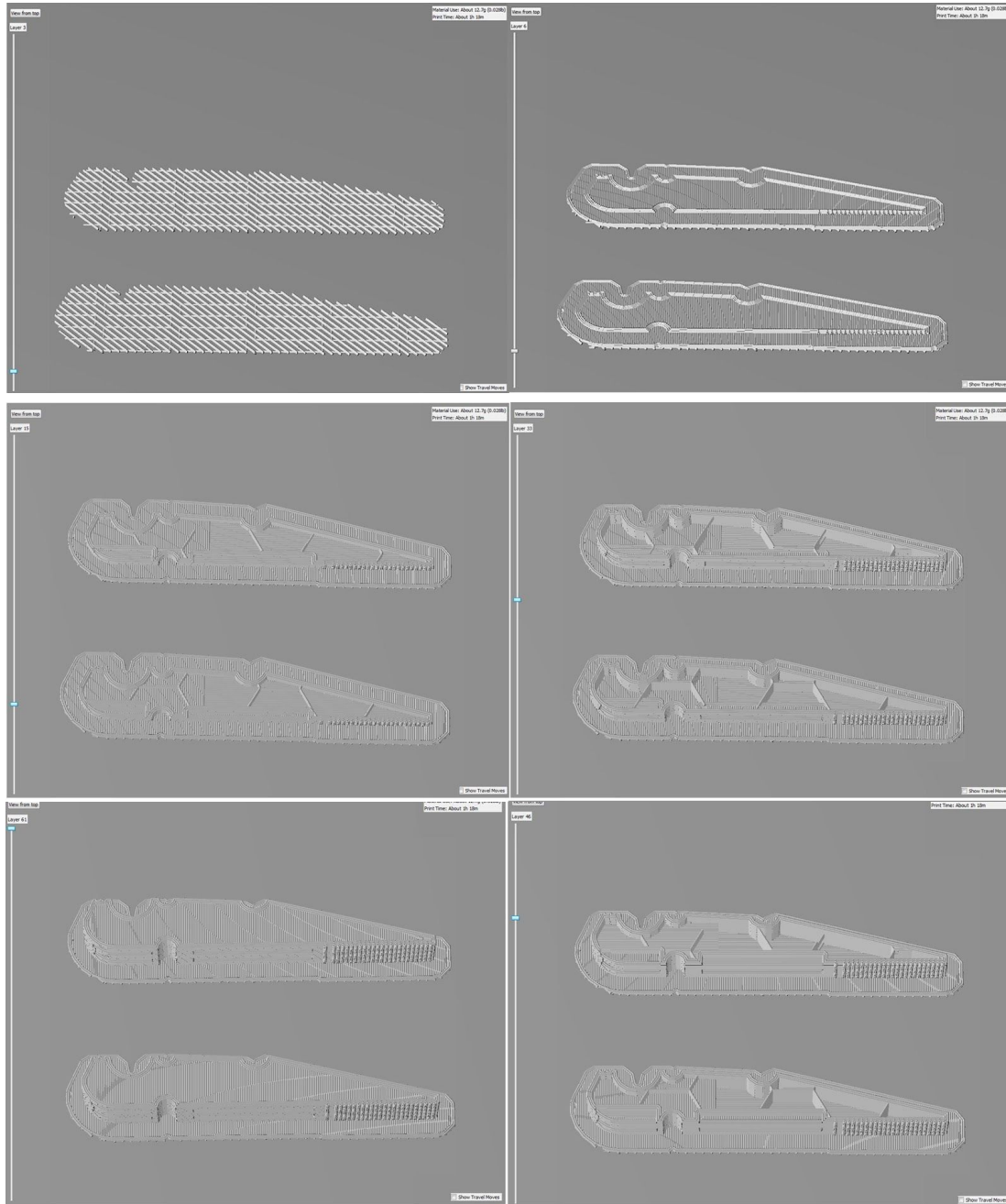
Figure 3.5.3A: Simulation of printing progress of both parts of the clothespin in horizontal print

B. Second test print

In this test print, I printed vertically only one part of the clothespin. I repeated the settings what were used in the first test print, so as to see how the print would result by using the same adjustments but different printing directions. With these settings, the

printing time resulted to be 50 minutes and the weight of this part is 5.03 gr, as indicated by the MakerBot.

Some of the pictures during the simulation of the printing at the MakerBot are the following:

Figure 3.5.3B: *Simulation of printing progress of the clothespin in vertical print*

C. Third test print

In the last test print, I printed the other part of the clothespin, as well vertically. The difference in the settings of the second test print, is that I printed it in low mode

instead of standard. In addition, in the model properties I used only one shell instead of 3 that is the recommended level to provide a good result, and kept the infill density to 5%. With these settings, the printing time resulted to be 43 minutes and the weight of this part is 2.63 gr.

Some of the pictures during the simulation of the printing at the MakerBot are the following:

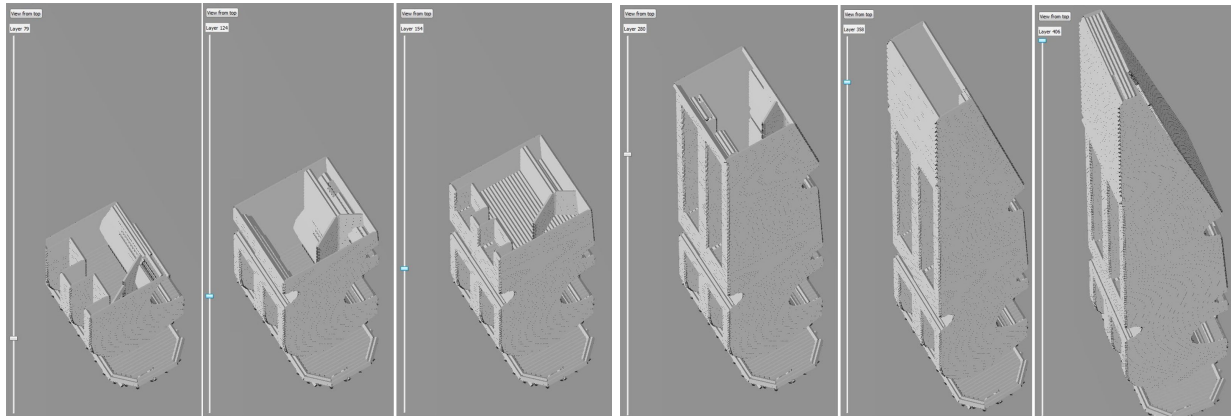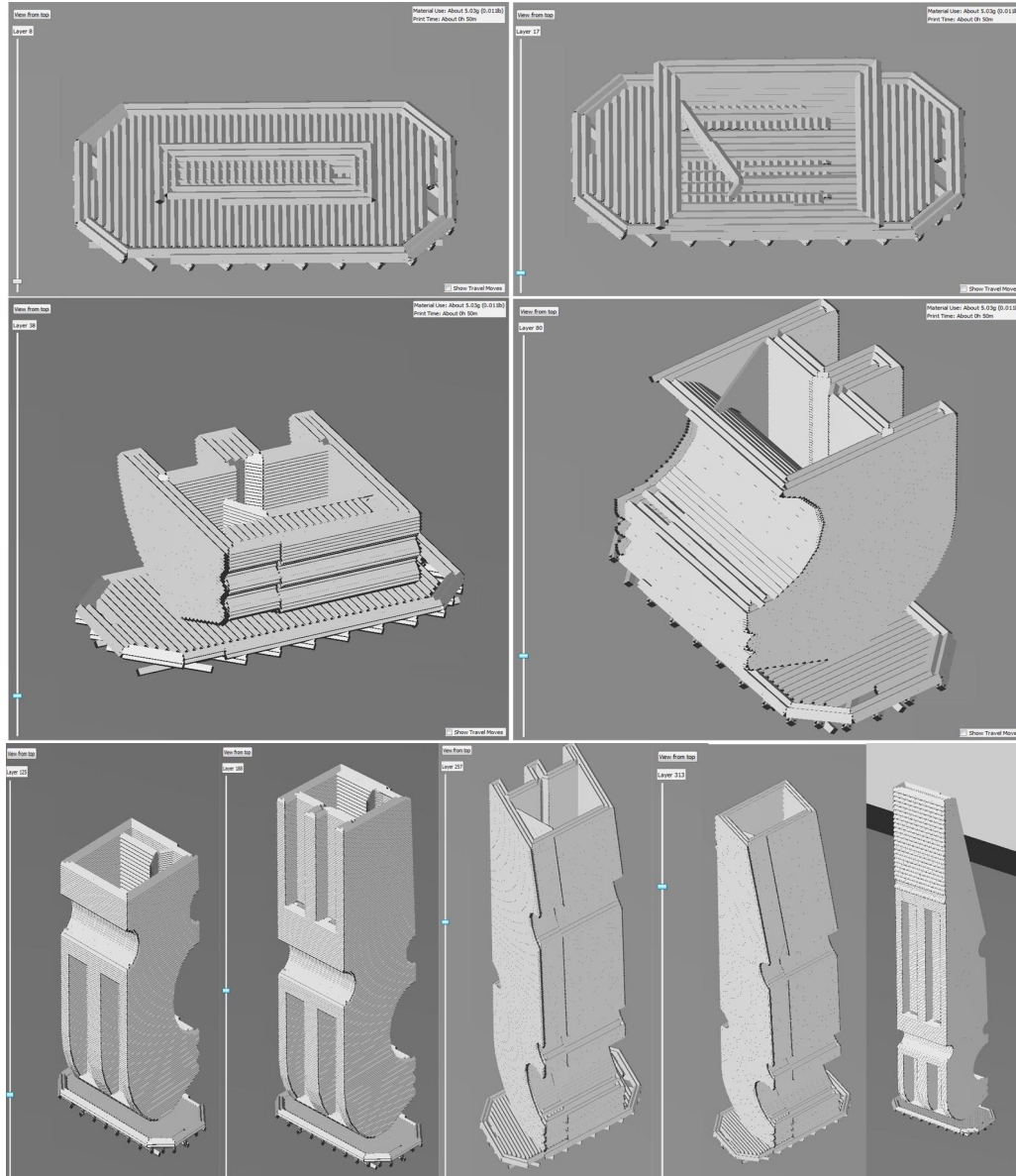*Figure 3.5.3C: Simulation of printing progress of the clothespin in vertical print*

Chapter 4
Experimental part (Test prints)

4.1.The 3D printer

All the test prints took place at the Transformable Intelligent Environments Laboratory at Technical University of Crete (TIE Lab). The printer used was the MakerBot Replicator 2 Desktop 3D Printer (Figure. 4.1), which makes solid, three-dimensional object out of melted PLA (Polylactic) filament. The printing method that supports is Fused Filament Fabrication (FFF). Some additional important specifications about the printer are that has build volume 28.5 * 15.3 * 15.5 cm, the nozzle diameter is 0.4 mm, and the diameter of the filament should be 1.75 mm.

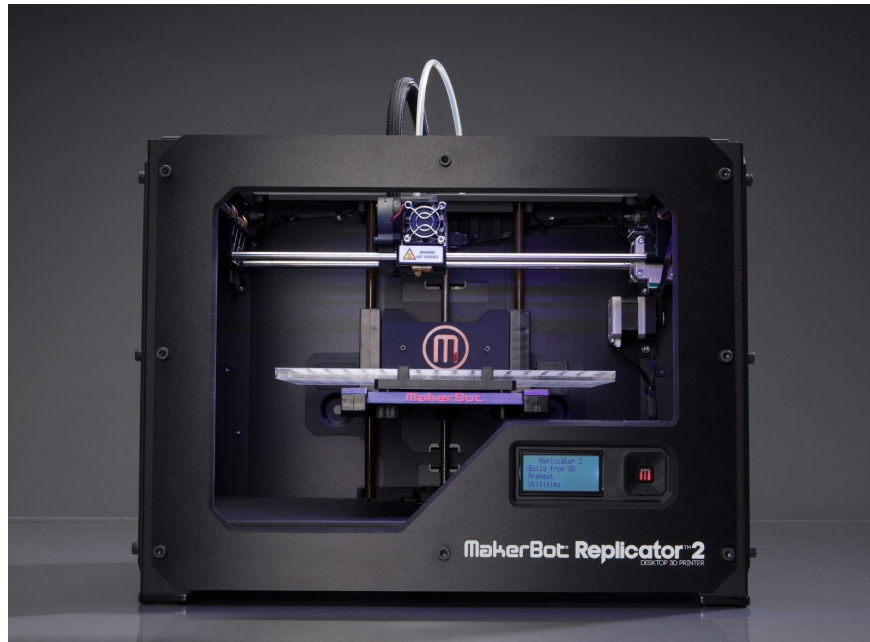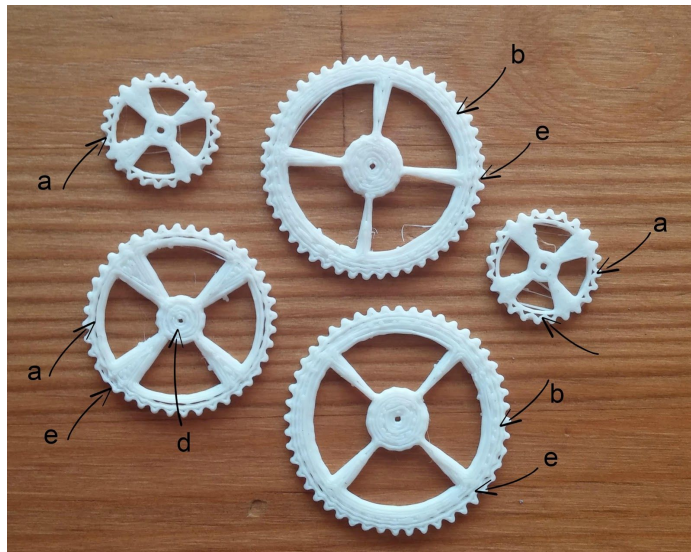
Figure 4.1: MakerBot Replicator 2 Desktop 3D Printer

4.2. Printing the objects

4.2.1. Printing the phone case

Firstly, I printed the gears of the phone case, all the five together, but each gear on different raft.

It is obvious that the big gear is quite compact (b), while the medium and two small gears have very loose layers with gaps (a). This happened because the outer part of the gear is very thin and even if the resolution was set to 0.1 mm- which is the minimum possible, failed to make it solid.

The teeth of the gears- besides their small thickness- in general resulted to be quite detailed and sharp, with only a few exceptions (e).

Figure 4.2.1.a: *Print result of the gears*

This problem could have been avoided in the designing part, by increasing the thickness of that part of the gear.

There are also a few plastic remainings (c), but this is a minor flaw as they are few and they can be easily cut with a pair of pliers or scissors.

The main flaw in these printings, is the very small diameter of the hole in the middle of the gears (d). Instead of 1.5mm that were designed, they resulted to be only 0.5 mm. Sequently, they don't fit in the knobs of the phone case, unless they go under further processing, like opening them with a pointy tool. The same discrepancy between dimensions in design and printing is noticeable also in the small gears, that were designed with outer diameter 1.55 mm, but resulted to be 1.5 mm.

Figure 4.2.1.b: *Print result of the phone case*

Since the phone case is a sensitive object that should be durable and resist breaking, instead of the normal PLA, was used another PLA filament material of better

quality. It is obvious that its surfaces are more shiny and seem of better quality. The sense of durability and very detailed finishes is also result of the adjustment of 3 shells small distance between the layers. Though, there are a few remaining fibers of filament, that can be easily removed with a sandpaper or cut them with scissors (figure 4.2.1.c).

Figure 4.2.1.c: Detail the inner part of the phone case
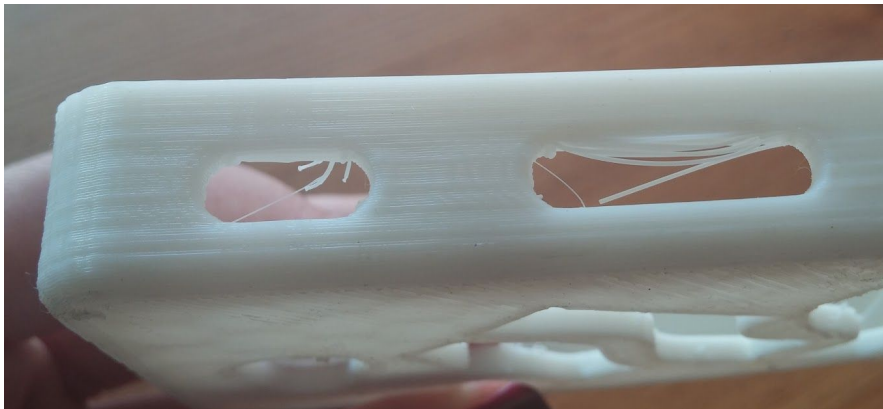
One flaw that is very obvious is that are quite some serious plastic hangings under the side holes and under the two knobs, one along each side of the case. Figure 4.2.1.d shows the first case of flaws.

Figure 4.2.1.d: Detail of overhangs of the phone case

This happened because this hole was created without support. It is also a long opening, which means that the nozzle has to drive longer distance to cover this length, which makes it more challenging. Without support material underneath, the upper side of the hole hangs because of the weight of the hot filament that is constantly adding new one. Other holes that are smaller and not so long, as in the following pictures, resulted to be printed perfectly (figure 4.2.1.e).

Figure 4.2.1.e: Detail of the phone case

The plastic hanging underneath the knobs along each side of the case is shown in the following picture:

Figure 4.2.1.f: Detail of flaws of the phone case

This flaw happened because there was no support material under the knobs. I didn't use support material because it would be difficult to remove it by hand later.

Also, since the knob should be protruding only 2.5 mm from the side according to the design and with the slight rounding support under the protrusion, it should have been printed well without adjustment for extra support. Though, the protrusion resulted to be 4 mm instead of 2.5 as we can measure and see in the following images (figure 4.2.1.h).

Figure 4.2.1.g: Detail of flaws of the phone case

Last but not least, we can notice that the upper surface of the case has some small gaps between the first layers, as shown in the image below:

Figure 4.2.1.h: Detail of flaws of the phone case

4.2.1.2. Results

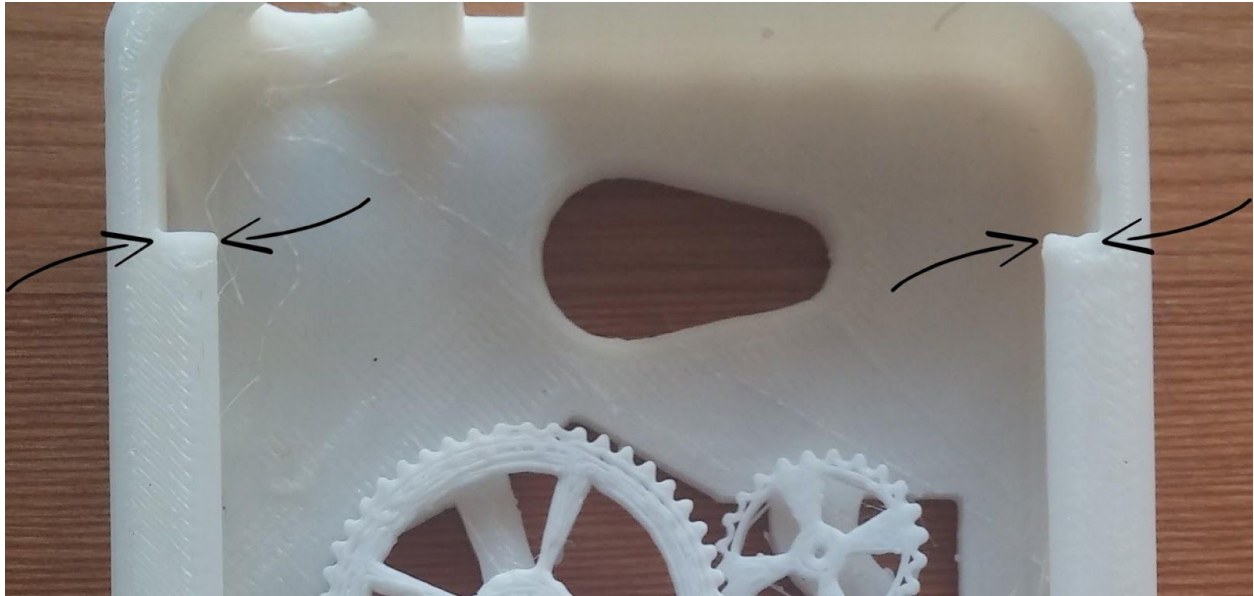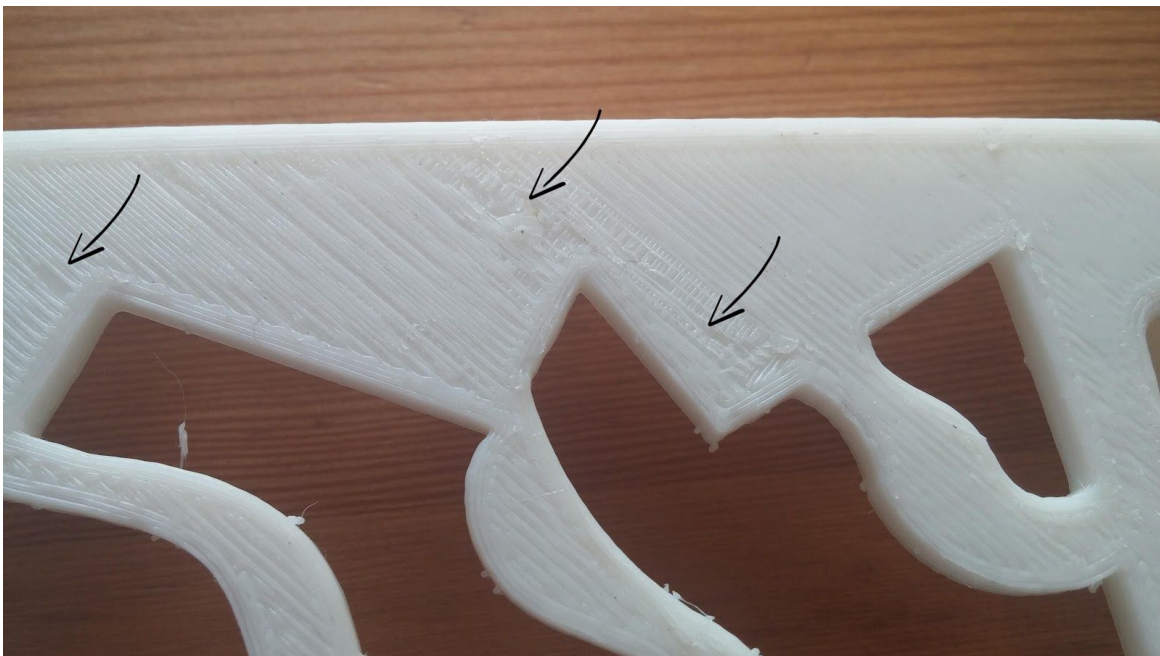The purpose of the procedure of printing the phone case with the gears, is to show the difficulty of printing individually some parts that have to be assembled later. Considering that, the procedure didn't work, as the gears don't fit in the knobs, so the case cannot be considered complete without them. This leads us to the conclusion, that even if in the design part the tolerances seemed perfect, in reality there is always some divergence and this should be taken into account when designing, especially in small scales.

From the rest of the procedure, we can conclude that if we want a strong object, 3 shells is the proper adjustment, and if we want shiny and good surface quality, the roof surface extrusion speed should be quite low, so as to avoid gaps between the passes of the nozzle. In addition, we can understand that the bridging is essential when there are unsupported structures, otherwise there is always the risk of failure.

From the printing of the gears we can conclude that is better to avoid printing in low mode, even if it is faster. The result when printing in standard - if not high mode - is much more worth it than saving 20 minutes in printing.

4.2.2. Printing the double sliding ring

The sliding ring will be printed in two different directions, once vertically, and once horizontally, so as to show that the direction of the printing affects the quality of the surface, which is important for a decorative object.

4.2.2.A. First test print

In this test print the ring is printed horizontally. It is obvious that the quality of the surfaces is very bad and rough, which is a result of the use of dense support material (support density 50%) and the extra bridging. Instead of good support that was supposed to offer so big density percentage, resulted to be too much support material left, and cannot be removed, as we can see in the following picture.

Figure 4.2.2.A: Print result of the outer ring

4.2.2.B. Second test print

In this test print I repeated the first test print settings, with the difference of reducing the support material and removing the bridging, which was the main flaw of the first test print. The object resulted of better quality than in the first case as we can see in the figure 4.2.2B. In general though, we can notice that the surfaces of both the inner and outer ring are a bit rough, thus I smoothed them with a sandpaper, but still didn't make much difference. In addition, there is some remaining support in the storage place of the inner ring, which cannot be cleaned as the gap is very narrow, so practically it ended up to be useless.

Figure 4.2.2B: Print result of the outer and inner ring

4.2.2.C. Third Experiment

In this case, both the inner and outer rings are printed vertically and the result is shown in the figure 4.2.2.C. It is obvious that the surfaces are of excellent quality, very smooth and shiny, without any gaps between the layer.

I didn't use any support material during the printing, which was very helpful as it didn't leave any rough points, didn't need further processing or cleaning.

Figure 4.2.2C: Print result of the outer and inner ring

Since the storage gap in the second test print resulted to be very narrow, I slightly altered the dimensions of the inner ring by enlarging its width and reducing the thickness of the walls of both the outer and the inner rings. Also, from the last picture we can notice that the inner part of the ring is not very smooth. This happened because of the high layer height (0.2 mm). In order to achieve a better surface quality we should have used lower layer height (0.1 mm).

4.2.2.3. Results

The purpose of the procedure of printing the double sliding ring is to prove that the direction in which we print affects the quality of the surface of a decorative object. Indeed, by comparing the results of the second and third experiment, it is obvious that the ring that was printed vertically is of much better quality and more shiny in its surfaces. Also, it is easier to slide the inner ring into the outer one, without friction. In addition, the use of support material makes big difference in the final result, as well as

the use of sandpaper or any other post-processing. If the use of support material cannot be avoided, it is better to use as less bridging as possible, so that can be easily removed later.

4.2.3. Printing the clothespin

The clothespin will be printed in two different directions, once vertically, and once horizontally so as to show that the direction of the printing affects the mechanical properties of the object as well as the quality of the surfaces of the object, which is important for a usable object.

4.2.3.A. First test print

In this test print, both the parts of the clothespin are printed horizontally.
The result of each side can be seen in the following pictures:

Figure 4.2.3.A.a: *Detail of flaws of both parts of the clothespin*

It is obvious that this surface is not very solid, meaning that there are some gaps between the passing of the nozzle that have created this effect. Apart from that flaw, all the other surfaces are of very good quality, smooth as well, and the parts of the clothespin are very strong and resistant.

Figure 4.2.3.A.b: Print result of both parts of the clothespin

4.2.3.B. Second test print

In this test print, one part of the clothespin was printed vertically. The result is shown in the following picture:

Figure 4.2.3.B.a: Print result of part of the clothespin

Figure 4.2.3.B.b: Detail of flaws of part of the clothespin

There are some curved edges created at the upper part of the openings as indicated by the arrows, due to the weight of the hot new filament that was constantly that was getting added layer by layer. Apart from that flaw, the clothespin is of very good quality and all its surfaces are very smooth and seems pretty strong as we can see in the following picture.
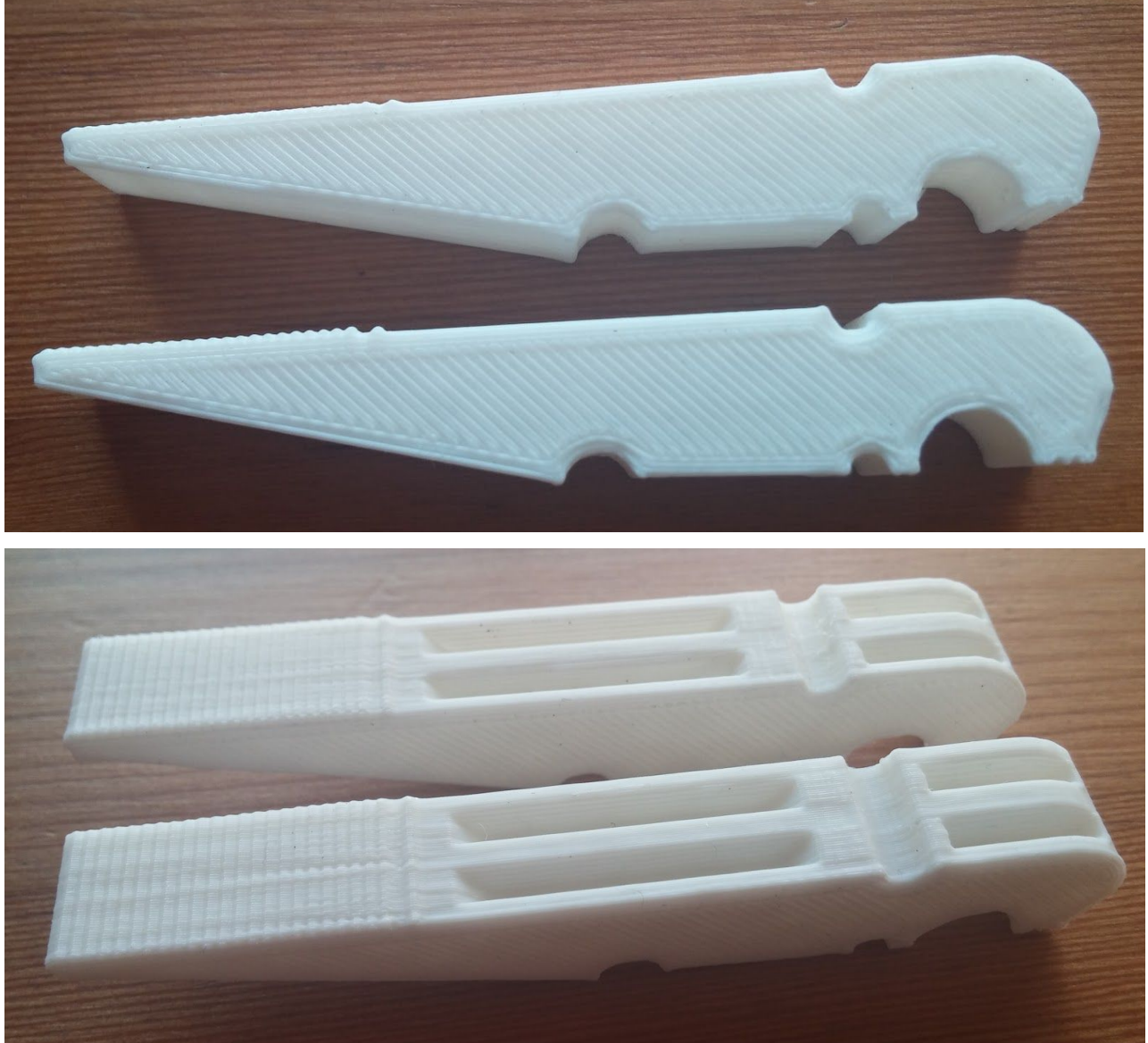

Figure 4.2.3.B.c: Print result of part of the clothespin

4.2.3.C. Third test print

In this test print, one part of the clothespin was printed vertically. The difference with the second test print is that in this case, I used only one level of skin and set the velocity to low, so that the printing is faster. The result of this test print can be seen in the following pictures:

Figure 4.2.3.C.a: Detail of flaws of part of the clothespin

As we can see, the quality of all the surfaces is very bad especially because of the low skin level. It is obvious that the the parts that have overhanging structures, are very loose, and this happened because there was no support underneath them, so the upper part of the hole formed a curved surface.

Figure 4.2.3.C.b: Print result of part of the clothespin

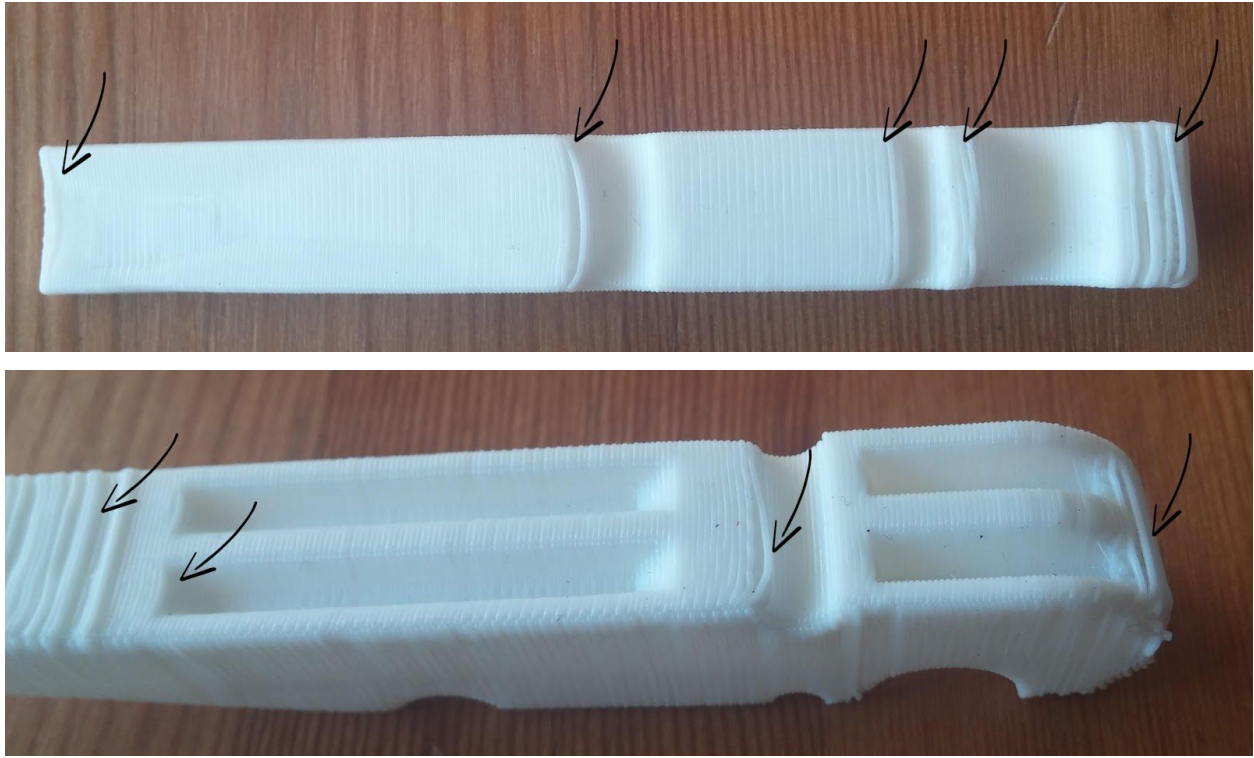The worst part of this object is its lower part, where are the first layers that were. printed. The distance between the layers is quite loose, the surface is rough and there is created a big hang of the melted filament (figure 4.2.3.C.b).

4.2.3.4. Results

The purpose of the procedure of printing the clothespin is to show that the direction in which we print affects the usability and other parameters of an object that is meant to be for use. As we can see from the parts of clothespin that we printed, there is big difference in the final result of the part that was printed vertically and the one that was printed horizontally, as the first one has less flaws. This happens because when printing the clothespin vertically, the footprint is smaller, and at the end of the printing the large gaps between the passings of the nozzle are avoided. Among the first and second test print, the result of the first one is more solid, more consistent and stronger than the second one.

In addition, from the third experiment we conclude that even if the vertical printing is prefered over the horizontal one, the adjustment of the settings matters. It is important to provide a good structure of the object with strong shell and good infill pattern and density, as well as set the printing to standard or high mode.

4.3 Collection of the printed objects

After each printing was finished, I removed the build plate from the build platform, and with a pointy tool I peeled of the object with its raft. Then, I peeled off the object by its raft carefully by hand. Later, I removed the support material with a pair of pliers, which left this part of the surface quite rough, so I smoothed it with a sandpaper. This procedure of cleansing was needed only to for the rings where support material was used, and for some parts of the phone case that didn't result very smooth.

4.4. Cleaning of the printer

With a pointy tool I removed the excess material out of the build plate, and then I placed it back to the build platform. After the extruded PLA was cooled down, I pulled the string of filament that comes out of the nozzle so as to discard the extra filament. This is a very important procedure that has to be repeated after each printing, because leaving plastic clinging to the extruder nozzle may cause new extruded plastic to stick to the nozzle instead of the the build plate.

Chapter 5
Conclusions

5.1. General conclusions

The purpose of this thesis is to investigate the possibilities of 3D printing, its potential and its limitations. After the theoretical exploration on the existing technologies of 3D printing in the first chapters, we proceeded to the experimental part. For this aim, I designed and printed some prototypes to get familiar with the printing procedure.

During the first chapters of the thesis, an investigation of the processes and technologies is provided. By analysing each method and comparing to the others, we conclude that there is a variety of technologies and materials offered in the market, and there is potential for big improvement of the existing ones. In addition, depending on the demands of the design and the usability of the project, there will always be a technology that fits our needs.

In the second part of the thesis, I designed three types of objects, each one addresses to a different purpose - a multi-part one, a decorative one and one of everyday use - which aim to focus on the difficulties in printing in each category. Generally, we concluded that while designing it is important to keep in mind the tolerances and the limitations of our printer, since this will affect the dimensions of the part, the printing quality and the accuracy of the prototype. In addition, we noted that the printing orientations affects not only the quality of the surface, but also the strength and functionality of the part. Also, the printing orientation defines the material used, the need of support material -which also affects the surface quality and strength, and the time that it takes to be built. We also came into conclusions related to the adjustment of the settings and realised that its proper adjustments are essential for a good print result and they depend on the object we want to achieve.

Concluding the thesis, I can say that the investigation met its purpose, the objects that were designed and printed gave me a good understanding on how the printing technology of our university's printer works (FDM). I also gained valuable knowledge and understanding on how to adjust the settings of each printing, depending on what result I want to achieve. Most importantly, I gained overall knowledge about the 3D printing technologies, what each can offer, how to target the design and what to do in order to achieve a successful print result.

5.2. Suggestions for future research

There are a lot of interesting topics to approach for future research related to 3D printing.

It would be interesting to see what result we get from different filaments in FDM process. For example, ASA filament provides high quality surface functional prototypes. Nylon 12 provides good isotropic mechanical performance- letting the prototypes to bend and to resist friction. ULTEM 9085 provides significant strength and can print complex geometries without support. So, a possible experiment could be to design prototypes that are made of different materials and experiment with a printing in each case.

Another idea is to experiment with functional 3D printed parts. For example, by submitting them to bending, compressive or stretching experiments, we can test their tolerances and their mechanical properties and see how the adjustment of the settings before printing affect their break bounds and which are the best combinations to provide a functional and strong prototype.

In addition, 3D printing could be combined with 3D scanning. After scanning some parts and digitally process them, experiment to print them. It would be challenging to check how this procedure works, which are its problematics and dynamics.

Other possible research could be on how 3D printing affects the economy and the supply chain, by comparing the cost of an item produced by a traditional production line with another one that is 3D printed. Also research could be conducted on how to eliminate the industrial costs by integrating AM in the production lines and how this would benefit the industry in general.

Chapter 6
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