Prototyping of a disc golf disc

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Abstract:

The aim of the present thesis was to create a throwable, everyday use disc golf disc. The process for creating the disc would be resin casting, different from injecton moulding which is done in the industry. To be able to get into the manufacturing of a disc the theory and physics of the motion of a disc was to be explained in the first chapters. The physics of a flying disc is based on application of Bernoulli's equation, gyroscopic motion and some basic aerodynamics. The relation of these physical effects to a flying disc is also explained to some detail. There are no factual sources for why and how a disc behaves a certain way going through air so the relation was complex to understand. This present thesis also explains some basic knowledge of disc golf discs, properties, materials and design regulations. The research for the practical part will include mostly 3D-printing and work done with resin casting, these processes are also thoroughly explained in the method part. For the resin casting process a silicon mould was created for casting disc golf discs. The early trial casting was done using vinylester resin to find out if the process works for this product. The final result was obtained by using polyurethane resin for the casting. The casting was done using a prototype silicon mould because of limited time and funding. The present thesis stands on its own as a proof of concept in a way that it is possible to manufacture disc golf discs with the methods described in this thesis.

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Syftet med denna avhandling var att skapa en frisbeegolf disc för dagligt bruk. Processen för att skapa discen skulle vara hartsgjutning, som skiljer sig från formsprutning, vilket används i industrin. För att komma in i tillverkningen av en disc så måste teorin och fysiken för rörelsen av en disc förklaras i de första kapitlen. Fysiken av en flygande disc baserar sig på tillämpning av Bernoullis ekvation, gyroskopiska rörelsen och några grundläggande fenomen inom aerodynamik. Relationen av dessa fysiska effekter till en flygande disc förklaras också i viss detalj. Det finns inga faktiska källor för att förklara varför och hur en skiva beter sig på ett visst sätt, så förhållandet var komplicerat att förstå. Denna avhandling beskriver också vissa grundläggande begrepp och fakta gällande frisbeegolf discs, egenskaper, material och konstruktionsregler. Utvecklingsarbetet för den praktiska delen kommer att innehålla mestadels 3D-skrivning och arbete med hartsgjutning, dessa processer förklaras också ingående i metoddelen. För hartsgjutningsprocessen skapades en kiselform för gjutning av frisbeegolf discar. Försök på gjutning gjordes till en början med vinylesterharts, för att ta reda på om processen fungerar för denna produkt. Det slutliga resultatet erhölls genom användning av polyuretanharts för gjutning. Gjutningen skedde med hjälp av en prototyp silikonform, detta på grund av begränsad tid och finansiering. Denna avhandling står på egna fötter som en proof of concept, för att det är fullt möjligt att tillverka frisbeegolf discar med de metoder som beskrivs i denna avhandling.

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List of symbols

L	Angular momentum
I	Moment of inertia
ω	Angular velocity
δL	Change in angular momentum
F	Force
m	Mass
a	Acceleration
T	Torque
α	Angular acceleration

FOREWORD

The reason why I chose to write and research about this thesis topic was the great interest I have in the sport of disc golf. The idea of creating a disc design of my own and then producing them and having also other people using them was very exciting and fascinating. This thesis was very challenging as a whole with all the fairly difficult physics behind a flying disc and also the amount of hours spent doing practical work with 3D-printing and resin casting was very demanding. This thesis allowed me to get more insight into the behavior of disc golf discs and also how to create discs using a few new prototyping techniques.

I would like to thank Stuart Buddle and Dennis Biström for the guidance with the 3D-printing process, a lot of great insight into the world of 3D-printing was obtained during the many hours of printing. I would also like to thank Erland Nyroth for the insight in mould manufacturing regarding the creation and function of the silicon mould.

I would especially like to thank Mathew Vihtonen for the opportunity to research a topic like this, the work during this thesis was extremely interesting. I would also like to thank Mathew for all the encouraging words and guidance I received during this process.

Helsinki, April 2016

Markus Salojärvi

1 INTRODUCTION

The idea for the present thesis was to manufacture a disc golf disc for example for promotional use and recreational use. The work done in this thesis leans more towards prototyping merely because of the interest in creating a disc with different methods than in the industry. This will involve a lot of rapid prototyping work such as 3D-printing and working with resin casting.

The theory and physics behind a flying disc is complex. The physics part of this thesis is explained in the literature review chapter in a way that also the reader would be able to obtain some insight into the physics of flying discs.

The practical work that was done is explained in detail in the method part of this thesis. This chapter involves a great deal of 3D-printing, casting of silicon and working with the resin casting process. The method chapter could also be further developed with ideas for other manufacturing processes and different materials but due to the time frame and funding for this thesis the practical part will consist mostly of rapid prototyping processes.

1.1 Objectives

The main objective for this work was to try and produce a discgolf disc using rapid prototyping methods. The result of this will be discussed after approaching the five main objectives:

- Explain the motion of a disc golf disc
- Review the PDGA design regulations
- Design of a disc
- Produce a resin casting mould
- Use resin casting to produce a working disc

2 LITERATURE REVIEW

This thesis project requires a background in some specific physics theory. The literature review section will go through the physics and theory of a flying disc, some basics of disc golf and the design regulations for discs. This section will also take a look at the prototyping and manufacturing of a disc.

2.1 The Bernoulli equation

2.1.1 Bernoulli's principle

The Bernoulli equation is most commonly known for application for the flow of different fluids or gases. Simplified the principle is that the increase in velocity of a flow results in a decrease in pressure or potential energy. For example in the figure below, the fluid is flowing through a tube, which narrows in the middle, so the velocity of the fluid increases in the narrow area and as a result the pressure of the fluid decreases. [1]

This figure shows the ideal equation for Bernoulli's principle, which means that a steady flow is assumed and friction is neglected. [1]

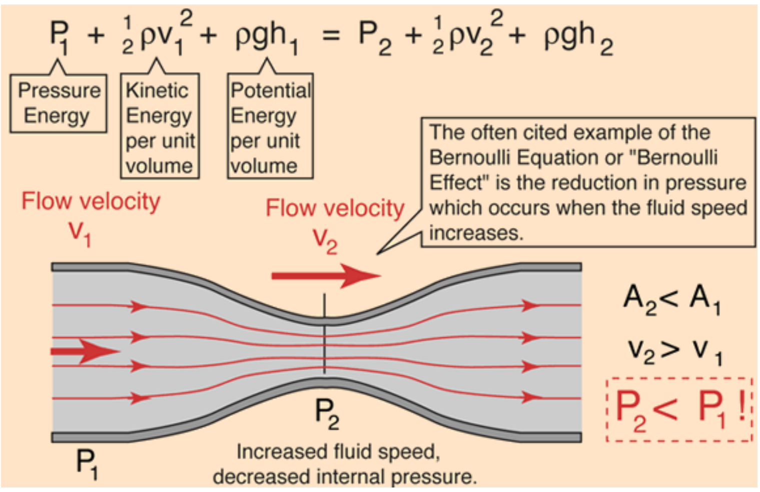

Figure 1: Bernoulli's equation [1]

2.1.2 Aerodynamics, lift and drag

One application of Bernoulli's equation is in aerodynamics, in generating lift. A good example of this is an airfoil, for example an airplane wing. [2]

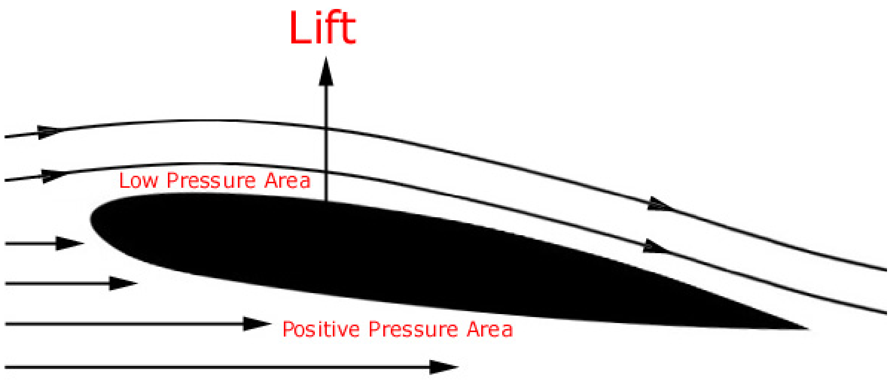

Figure 2: A typical airfoil [2]

An airfoil is designed so that it is able to generate lift when air is moving over its surface. Figure 2 shows a typical airfoil. Air moving over the airfoil has a high velocity on the top surface and a low velocity on the bottom surface, so a low pressure is generated on the top surface and a high pressure on the bottom. This combination of difference in pressures generates the lift force. [2]

There are also many discussions that Bernoulli's principle is only a small part of the lift force. Many sources discuss that the angle of attack creates the main lifting force for an airfoil. This means that because the airfoil is at an angle the air moving under the airfoil is forced to go downwards. Newton's 3rd law can be applied, which means that as a reaction to the downward force and equal upward force is created and this generates the lift force. This is depicted in figure 3. [3]

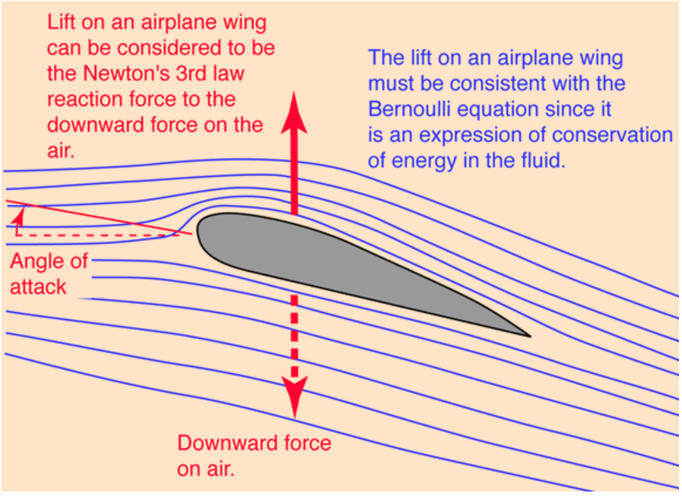

Figure 3: Newton's 3rd law as the lift force [3]

Increasing the angle of attack of an airfoil also generates drag on the back part, also called the trailing edge. When the angle of attack is too high the airfoil starts to stall because of the increased drag. [3]

2.2 Gyroscopic motion

2.2.1 Gyroscope

The definition of a gyroscope is, a wheel or disk mounted to spin rapidly about an axis but is also free to rotate about one or both of two perpendicular axes. [4]

Simplified this means a disc shaped object which spins rapidly about an axis but is free to also rotate or twist around axes perpendicular to the original spinning axis. The position of the axis of the spinning wheel or disc is not affected by any tilting or twisting movement. [4]

In general a gyroscope is depicted as a gimbal gyroscope, which is shown in figure 4. [5]

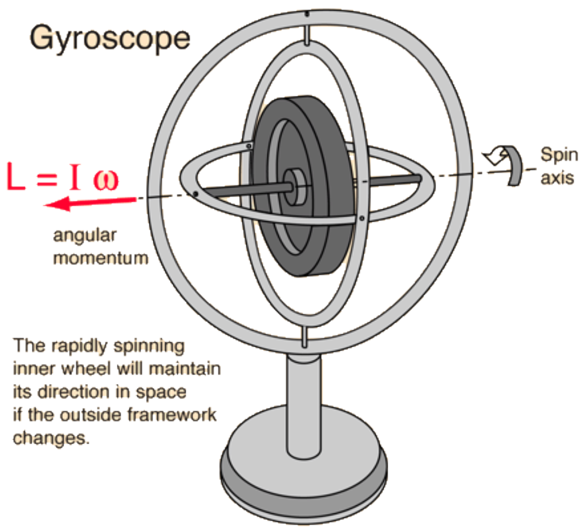

Figure 4: A gimbal gyroscope [5]

The figure shows a disc in the center which is spinning around an axis. The rings around the disc are called gimbals, their function is to isolate the central disc from outside torques. [5]

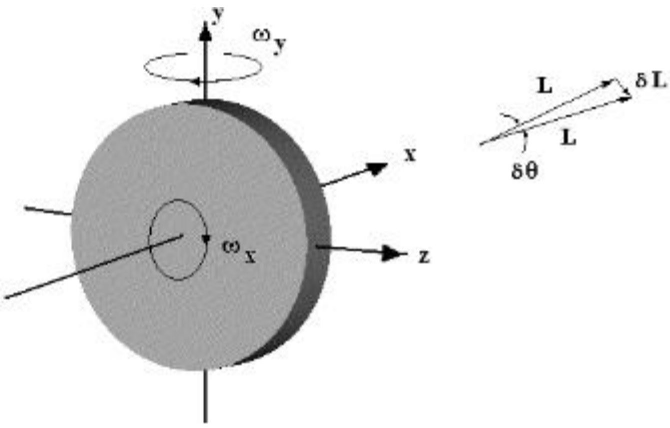

Figure 5: A free body diagram of gyroscopic motion [6]

The disc in figure 5 is spinning rapidly about an axis x. The rapidly spinning disc creates an angular momentum L on the x-axis. The angular momentum is defined as $L = I\omega$, where I is the moment of inertia and ω the angular velocity. Figure 5 shows the angular momentum drawn as a vector with a direction along the x-axis. If it is imagined that the disc is also rotating about y-axis then the vector L for angular momentum changes direction but the magnitude stays the same. The change in the vector for angular momentum is noted in the figure above as δL and is drawn as a vector perpendicular to the angular momentum vector L. [6]

By taking a look at Newton's second law of motion, $F = ma$ and applying this for rotating bodies, so it can be denoted as $T = I\alpha$, where T = torque, I = moment of inertia and α = angular acceleration, it can be observed that torque needs to be applied to create a change in momentum. When torque is applied about the z-axis it will create rotation about y-axis. This resulting behavior is called gyroscopic precession. [6]

2.2.2 Gyroscopic precession

The easiest way to understand gyroscopic precession is to take a look at a common example of this phenomenon. A wheel is mounted by a rope at one end of its center axle. If the wheel has no motion it just hangs there horizontally. When a spinning motion is applied to the wheel, when it is held up vertically just as long as to get the wheel spinning rapidly, the spinning wheel does not fall back down but instead it begins to precess. This means that the wheel starts to rotate about the mounted point of the axle in the opposite direction than the spinning movement. [7]

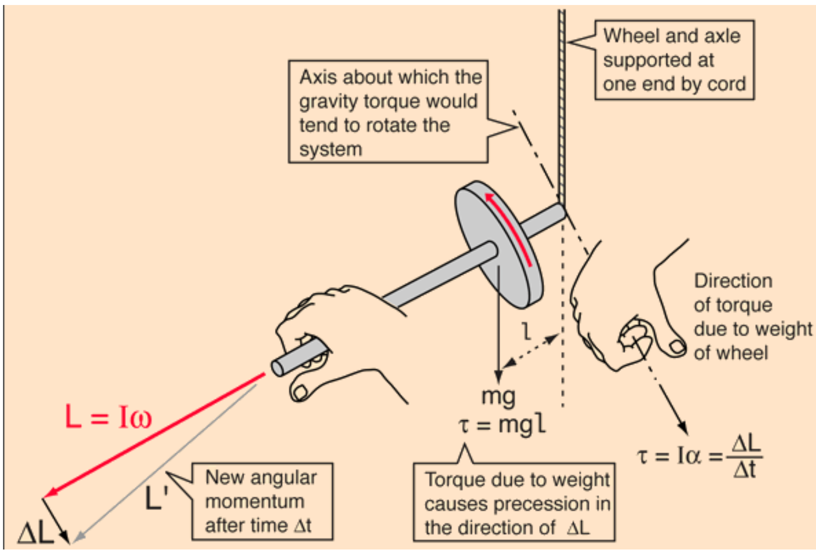

Figure 6: Gyroscopic precession [7]

2.2.3 Relation to disc golf

How the Bernoulli principle and aerodynamics relate to a disc golf disc is exactly the same as for how an airplane wing generates lift moving through air. The air moves faster over the top surface of the disc and slower under the bottom of the disc thus creating lift due to the pressure difference caused by the Bernoulli principle as explained earlier. The friction between the different plastic types and air also affect the behavior of a discs in flight properties. [8]

The gyroscopic effects on a disc are much more difficult to understand and to explain. After the release of a throw a disc has a high angular momentum and behaves much like a gyroscope. Simplified, the angular momentum on a disc means that it is rotating rapidly thus creating the gyroscopic like behavior, so the faster the disc is rotating the more stable it will behave during its flight. During the mid-flight towards the end of flight the disc behaves just as a gyroscope, when the rapid rotation starts to slow down the discs starts to fade towards the ground. The disc also fades in the opposite direction of the spin much as the behavior of gyroscopic precession. [8]

To achieve an optimal flight path of a disc, just by looking at the movement of the disc itself without considering the impact of the person throwing, the main things to consider are the release of the disc and the angle of attack. The initial release is important because the better the grip and release the more spin is generated. The angle of attack determines how far the disc is able to travel, if thrown with a too high of an angle of attack the disc will stall just as an airplane will.

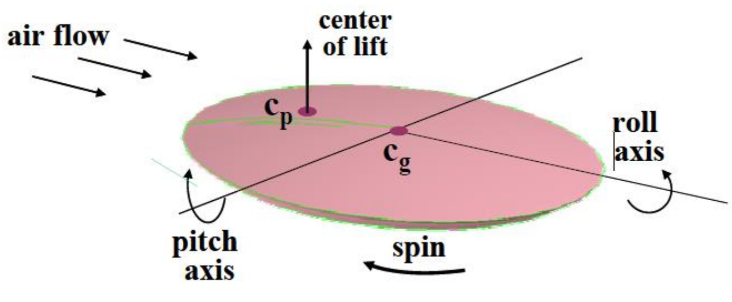

Figure 7: A free body diagram of gyroscopic elements on a disc [9]

2.3 Disc golf discs

Disc golf is a rapidly growing sport so naturally the variety of discs that are available for players is vast. There are several big companies that so to speak dominate the market at the moment, for example Innova, Discmania, Prodigy and Discraft to name a few. Because the sport is so popular, a lot of small companies are also being created to give people even more variety to choose from.

2.3.1 Profiles & disc types

There are three main types of discs, putters, mid-range and drivers. Drivers are also divided into two categories, distance drivers and fairway drivers. All these disc types have different edge profiles depending on the properties.

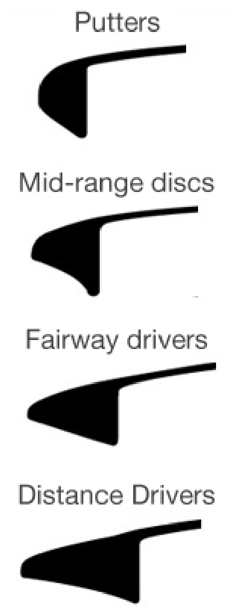

Figure 8: Disc profiles [10]

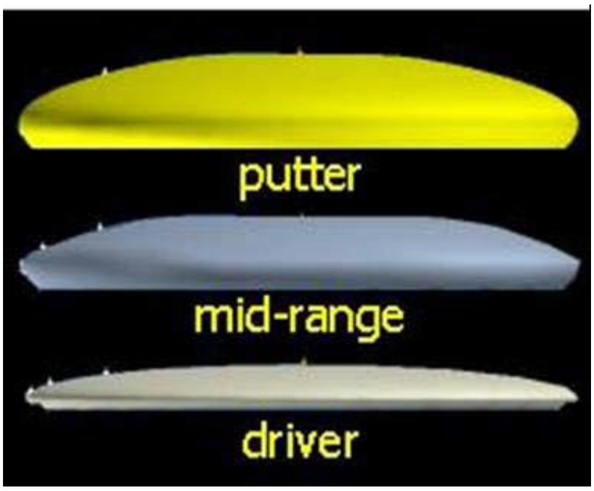

Figure 9: Generic profiles, cross-section [9]

Taking a look at figure 8 and 9 we can immediately see a difference between all the different profiles. [10]

Putters are designed to have a more round or straight high profile. This is because putters are mostly used in short distances, under 50 m, a range where a disc that travels as straight as possible is needed. There are many different types of putter profiles, rounder, straighter, lower or higher edge and so on. This enables players to choose a putter that suits their own playstyle, different players like different types of profiles merely just on the basis of how a disc feels in your hand. [10]

Mid-range discs are designed to be used in distances between 50 - 100 m, of course depending on the player and playstyle. Mid-range discs have a more flat profile and a wider rim. The same goes for mid-range discs that there are a lot of variety to choose from depending on how one likes to play, some like mid-ranges which go straight and some want other properties. [10]

Drivers are divided into two categories, fairway drivers and distance drivers. Fairway drivers are designed with a narrower rim than a distance driver, a slower driver so to speak, depending on playstyle used at various distances. Distance drivers are the main discs used, most distance and speed. The profile is very flat and the rim is very wide which makes these types of discs very fast. The distances where distance drivers are used range from 80 m and further. [10]

Disc golf discs are also available in different weights, usually classified as normal weight from 150 – 180 g and lightweight discs usually under 150 g. [10]

To define the different characteristics of discs a numbering system is used for all the different properties. [11]

Figure 10: Flightnumbers [11]

Discs are characterized with four numbers which stand for speed, glide, turn and fade. All official discs are characterized accordingly so that players can choose a disc with properties they like. [11]

Speed in discs is defined as a number between 1-14, depending on the manufacturer and the disc. This number defines the ability for the disc to cut through air. Low speeds at 1-3 are usually putters, medium speeds at 4-6 are usually mid-range discs, intermediate speeds at 6-9 are fairway drivers and high speed discs, distance drivers, are usually numbered with speed 9-14. [11]

Glide is defined with a number from 1-7, also depending on manufacturer. This is the ability for a disc to maintain its lift. [11]

Turn is characterized as a number between 1 to -5, this can also be divided into two categories of disc properties which are overstable and understable. Overstable discs are usually defined as 1 to -1 fade and understable as -1 to -5, depending on manufacturer. Some discs may have a fade marking as 0 and still feel like it is understable, so the markings are not absolute values, it also depends a lot on the feel of the disc for the individual player. What the turn number means in practice is the tendency of the disc to turn over during flight. Overstable discs resist to turn over and understable are more likely to turn over. [11]

Turning over or flipping means that for example on a backhand throw it is optimal for the disc to fly relatively straight according to the flight path of the disc and then to fade to the left. If you turn over the disc it flips over to the right instead of going straight and fading to the left. [11]

Fade is defined as a number from 0-5, this number characterizes the tendency of the disc to hook to the left or right at the end of its flight. So a low fade number means that the disc finishes more straight and a higher number means that it banks more aggressively. [11]

2.3.2 Stable / understable

When trying to study why a disc is understable or stable there was no one clear article or even source where to study this phenomenon. This subsection will contain some assumptions and experiences with this phenomenon but also ideas proposed on various discussion forums from different people with ideas and assumptions of why and how a disc is stable or understable.

There are a number of different factors that affect the stability of a disc golf disc, the weight, size, shape and the speed at which the disc is thrown.

The general weight of the disc does not determine how a disc behaves, but the weight distribution has some role in the behavior. One idea is that when most of the weight of the disc is on the outer rim it behaves more stable than if the weight would be more evenly distributed. When most of the mass of a disc is on the outer rim the rpm generated from the release after a throw would presumably be a lot higher thus creating a more stable and straight flight path than with lower rpm.

Another idea that has been proposed quite often is that flatter discs are more stable in flight than “domey” discs, although this is not a fact, this is just based on experiences people have had when throwing discs.

Some articles and forums discuss quite a lot of something called the parting line height. The parting line is a result of the injection moulding process, the line is from the plane where the mould is parted when it opens and closes. This line is usually visible on discs on the outer edge of the rim. What this represents as a base for an idea has to do with the fact that when plastics cools down it usually shrinks, how much depends on the plastic grade. So it has been quite clearly stated that when using for example one type of disc and the same mould but different plastic grades, high and low grade, significant differences in behavior in flight can be observed. This is because of how the plastic shrinks after injection. Lower grade plastics usually shrinks more and higher grade plastics less, this means that when the plastic starts to shrink the parting line height changes. So it is assumed that when moulding with the same mould but different grades of plastics a difference in parting line height will be visible. The general idea is that a higher parting line height means a more stable disc and a lower parting line a more understable disc. One observation about this is also that when the plastic cools down and shrinks a lot it will look a lot more “domey” than flat.

Then there is the manufacturing process, injection moulding. Although injection moulding is a good way to produce discs it is also a hard process to control. There can be a lot of variation between discs even from the same mould and the same production run. Sometimes the discs behave just as the flight numbers describe and other times completely differently than they should. This all comes down to so many different variables, environment where the moulding machines are, type of plastic, storage of plastic material, dry or moist plastic or just as simple as an worn mould produces completely different discs than a new one.

Concluding from these ideas and observations for creating a more stable disc the design should have the weight distributed mostly on the rim and the plastics used should be of a higher grade and the cooling of the injection moulding process should be planned carefully so that the shrinkage is kept under control.

To create a more understable disc the weight should be more evenly distributed with a more “domey” design.

2.4 PDGA technical standards

The professional disc golf association, PDGA, has their own technical standards committee which is responsible for testing and measuring all new discs. They inspect all discs according to their standard rules of design for an official disc golf disc. These design rules are to be followed if a company wants the approval for the disc to be used for example in competitions and official events. [12]

This section will go through the requirements for PDGA approval to some detail. [12]

According to the PDGA regulations, an official competition disc should have a circular, saucer-like design with a uniform flight plate without any perforations and also an inner rim depth that is between 5 to 12 percent of the outside diameter of the disc. The PDGA defines the flight plate as the upper section of the disc delineated by the points where the inner rim depth is measured.

Secondly the PDGA states that the disc should be made of solid, non-magnetic plastic material without any inflatable components but electronical components may be embedded if none of its metal components are externally exposed.

The third statement in the requirements is that a disc should not be less than 21 cm in outside diameter and not exceed 30 cm. The PDGA further states that the disc should not exceed the outside disc diameter weight of 8.3 g/cm and a maximum weight of 200 g. The sixth point in the requirements state that a disc should not have a thicker flight plate than 0.5 cm including any raised features. The regulations further state that a disc should have a smooth surface on the bottom part of the rim; a surface without any irregularities or protrusions. The rim area should be beyond the top of the flight plate which does not include a surface elevation greater than 3 mm above the outer edge of the flight plate. Rim width should be no greater than 2.6 cm and the inner diameter of the rim should not be less than 15.8 cm and the rim configuration rating should be 26 or higher. Rim configuration is shown in figure 12.

The PDGA regulations also state that the discs should pass the leading edge radius test with a 1.6 mm radius gauge and have a flexibility rating of 12.25 kg at most. These measurements are explained in figure 13.

Final points for requirements for a disc are that the discs should be of production-type and available for the public commercially and be as produced without any post-production modifications.

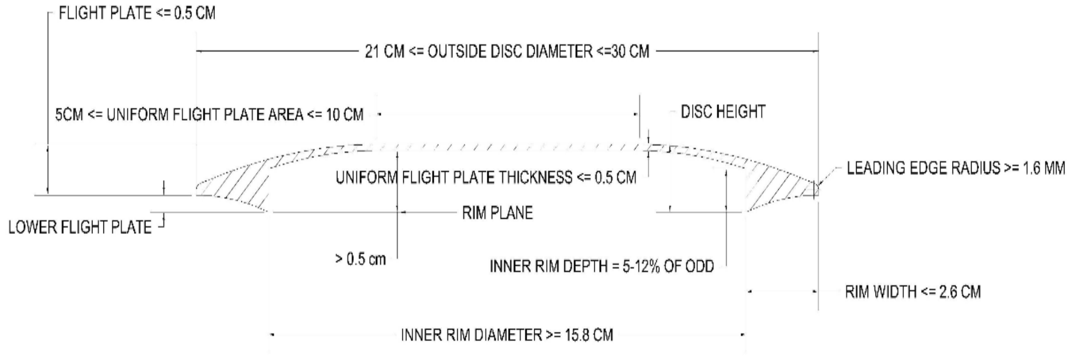

Figure 11: Diagram of design requirements [12]

(6) Rim Configuration - The rim of the disc is held perpendicular to a contour gauge having 13 probes per cm (such as the Valued ST142). The rim of the disc is then pressed gradually into the gauge to a depth of 5 mm. The resulting movement of each affected probe is measured to the nearest 0.25 mm, and then totaled to produce the rim configuration rating. The ratings of three samples are determined, and the median score is used as the final rating (see drawing).

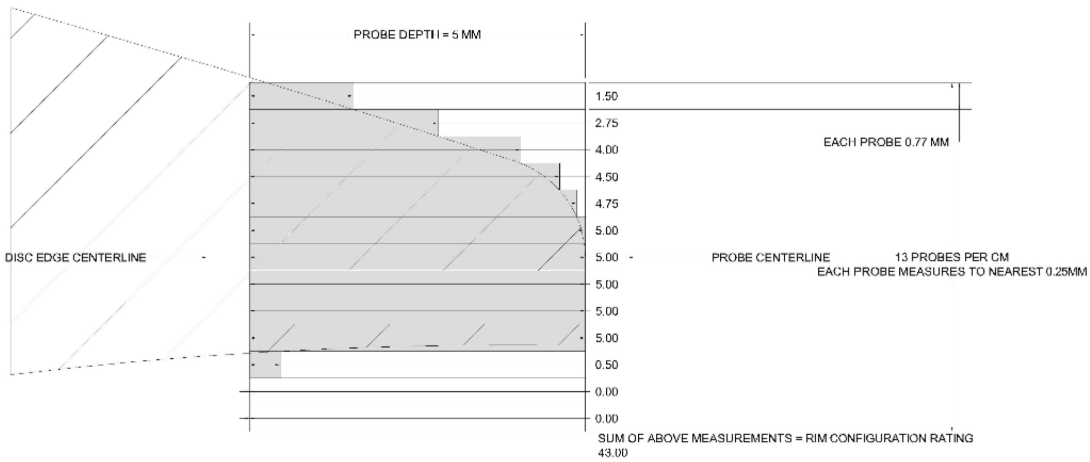

Figure 12: PDGA regulations rim configuration measurement [12]

(7) Leading Edge Radius - This attribute is evaluated using a 1/16-inch (1.6 mm) radius gauge. To pass this test, the leading edge of the disc must not come in contact with the gauge.

(8) Flexibility - The disc is held on its edge in a vertical position perpendicular to a scale with a precision of at least 2 oz. (56.7 g). The upper rim of the disc is then gradually pressed down within 5 seconds. The flexibility rating is determined at one of two points, depending on how the disc reacts to applied pressure.

Figure 13: PDGA regulations for measurement of discs [12]

The PDGA also regulate the classification of other types of discs which are 150 class, super class, vintage class and mini markers. These classes are not really relevant for this thesis because the focus is on a normal regulation disc golf disc. [12]

2.5 Rapid prototyping

The definition of rapid prototyping is to create a full scale model of a desired part rather quickly using some sort of 3D-technology. Data from computer aided design is most commonly used with the different 3D-technologies available. This type of prototyping is called rapid because the manufacturing techniques available enable companies to create a model or prototype in a matter of hours instead of several weeks with normal manufacturing processes. [13]

The advantages of rapid prototyping are that the designer can instantly see the product and compare it with the design parameters. Rapid prototyping is effective for designers to make sure that the product functions and looks as it should before it goes to the client or a manufacturer. The technology is also very useful for different mould tooling processes such as injection mould tooling or for example creating a 3D-print of the part and then creating a silicone mould. [13]

The term rapid prototyping includes a lot of different processes used for creating full scale models and prototypes of different types of parts. There are two main types of processes, subtractive and additive. In a subtractive process the desired part or model is cut out from the raw material where as in the additive process the model or design is created by adding layer by layer of material. Subtractive processes usually utilize some sort of computer aided manufacturing software to control the operating machine, a few examples for subtractive processes are:

- Laser cutting
- Water jet cutting
- Plasma cutting
- Milling
- Hot-wire cutting [13]

Additive processes usually utilize the designers 3D computer aided design data in the machine software to create the parts, a few examples of additive processes are:

- Stereolithography apparatus (SLA)
- Selective laser sintering (SLS)
- Three-dimensional printing (3D-printing)
- Fused deposition modelling (FDM) [13]

In the practical part of this thesis some of these additive processes will be utilized for possibly creating the disc golf disc prototype to then be further used as a core for a resin casting mould. A brief explanation of a few additive processes that could be used for manufacturing the core part for the mould in the following segment.

Stereolithography apparatus, or shortened SLA, was first introduced in 1986 and the first machine produced in 1987. SLA was the first commercially available rapid prototyping process. [13]

How the SLA process functions can be observed from figure 14. The main idea of the process is that the part is built up layer by layer. This process starts with a container filled with liquid UV-curable resin. A horizontal platform is lowered into the resin only as much as the first layer thickness. The resin is then cured by using an UV-laser to build up the part by layers. The horizontal platform in the liquid resin is lowered every time the UV-laser has cured one outline layer. After the outline of the part is ready, the desired part is placed in an UV-oven for the resin to be fully cured. [13]

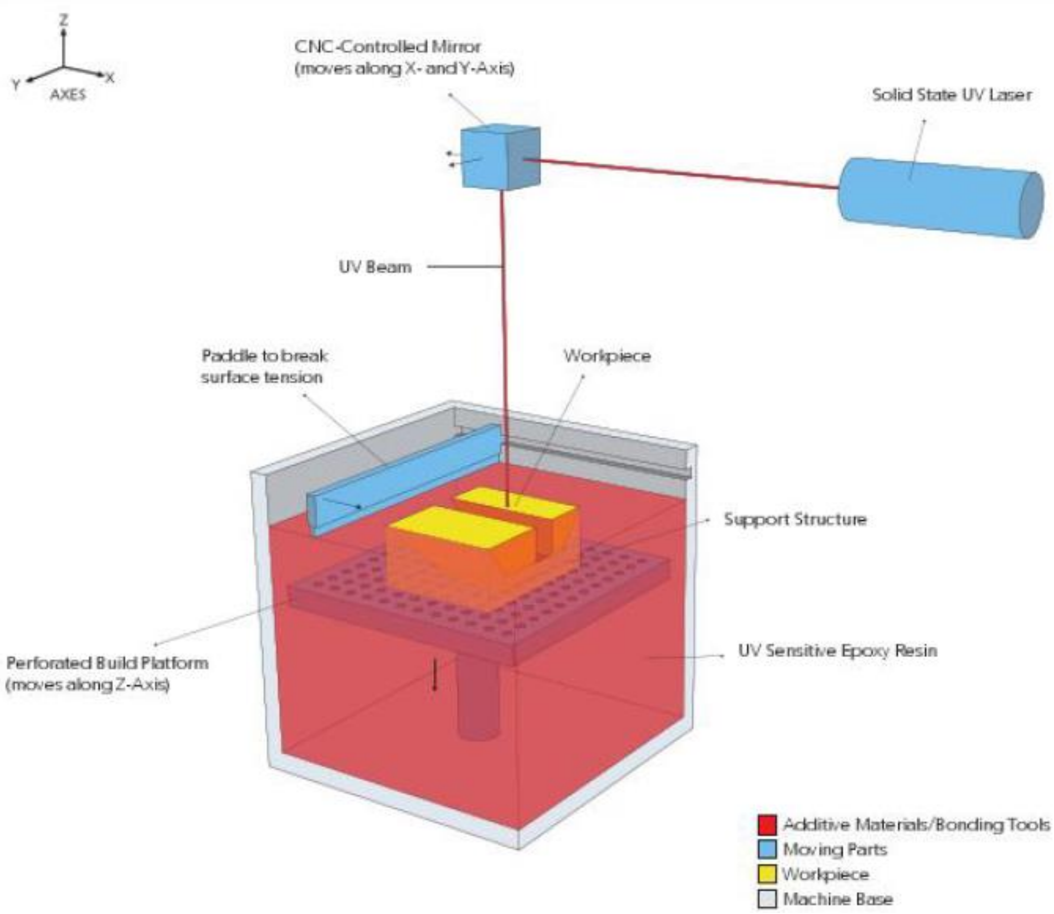

Figure 14: SLA printer [13]

Fused deposition modelling, or more commonly known as FDM, was developed and commercialized during late 1980 to early 90s. In an FDM process a thermoplastic material is heated and extruded through a nozzle. This process also builds up the part layer by layer by extruding the heated thin plastic filament through a small nozzle onto the work platform. The building of layers can be mechanically done in different ways depending on the FDM machine but as a simple example the layers are built up by lowering the platform by the layer thickness so the platform moves up and down and the nozzle moves in the x and y directions. The FDM software utilizes CAD data to create the part which means that the layers are built up as cross-sectional slices of the CAD model of the desired part. Depending on the design of the part it may be necessary to extrude supporting material through another nozzle simultaneously, this is needed if the part has a lot of overhanging areas. The support material is usually broken off after the part is ready. The quality of the finished part again depends on the machine used, because there are a lot of differences in nozzles and plastic filaments that are used in the industry by different FDM machine manufacturers. Some FDM printers have better end result quality than others. [13]

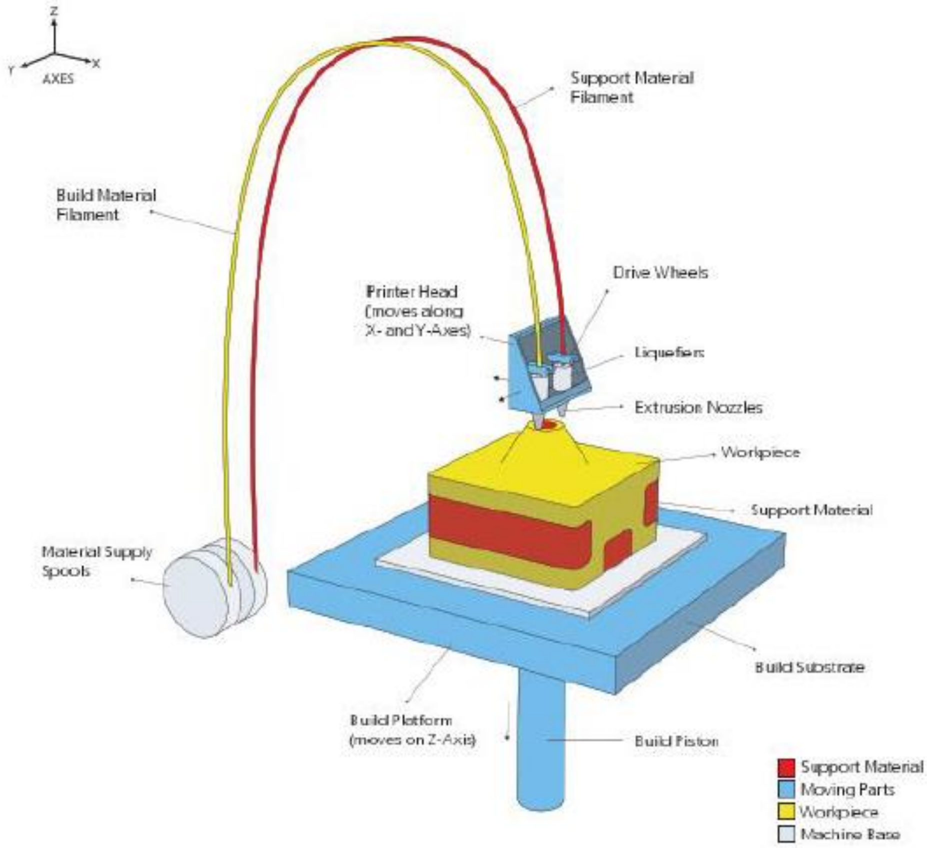

Figure 15: Fused deposition modelling printer (FDM) [13]

These two 3D-printing processes are best suited and most easily accessible for this thesis project for creating the disc golf disc core which will then be used for creating the mould for the resin casting process.

2.5.1 Resin casting

The common manufacturing process for producing disc golf discs is injection moulding. The industry uses this because injection moulding allows relatively cheap mass production of discs. For this thesis, the idea is to try and manufacture working discs using the resin casting process.

The resin casting process is in general a very simple process involving three main steps. The first step is to create a master or core of the part, in this case a disc golf disc. The core part itself has to be as precise and smooth as possible because it is used to create the cavity for the resin casting silicone mould. So the second step is creating the silicone mould, in this case it will be a split mould with two mould halves, one top and one bottom. The split line of the mould will depend a lot on the design of the part and the placement inside the mould. The last step is the materials, there are a lot of different resins that can be used for this process depending on what properties are desired of the finished product. [14]

2.5.2 Materials

The materials used in this thesis project for the resin casting process can be categorized on a shoreness scale for polyurethane rubbers and plastics.

There are two main types of material definitions for polyurethanes on this scale, shore A and shore D. When talking about a material characterized as shore A the properties lie in a range that can be defined as more a rubber like material. The shore A range can be observed from figure 16, so shore A 20 up to shore A 80 is characterized as rubber but at shore A 90-95 an overlap with shore D can be observed. This is the cross-over point where shore A also starts to have more plastic like properties. The shore D scale then represents materials in different hardness stages for plastics.

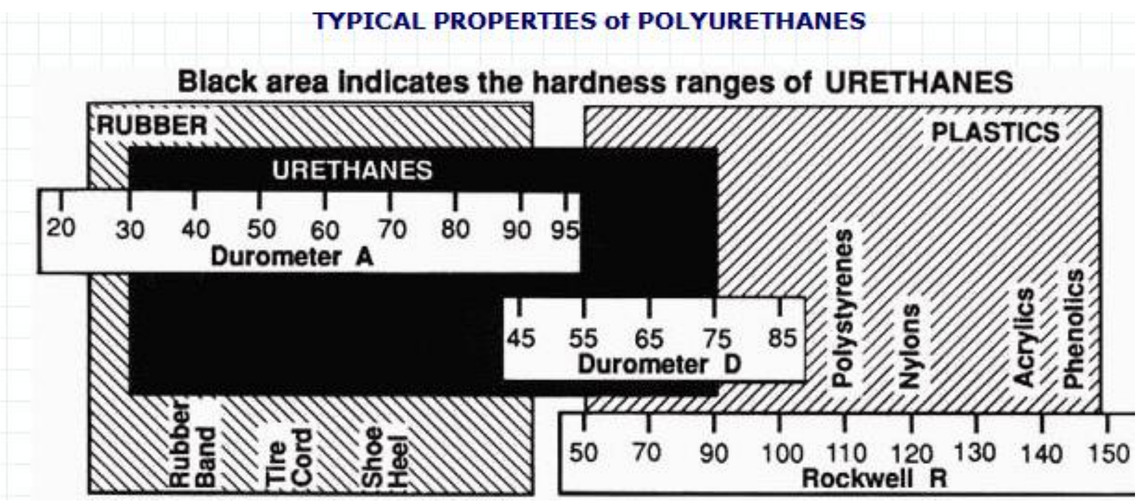

Figure 16: Polyurethane shorescale [15]

All materials used for this project:

Creating the silicon mould:

- Spare wood planks
- Screws
- Play-doh
- Straws
- Superglue
- Silicon shore A 40, from Kevra Oy – Andvanced Composite Technology [16]
- Water with 10% soap solution
- Latex gloves

Trial casting:

- Wooden frame for clamping
- 4 or 5 screw clamps
- 100 ml syringes
- Vinylester resin
- Latex gloves
- Plastic dogbone tensile test piece cut into insert pieces

Polyurethane casting:

- Polyurethane resins from FormX webshop [17]
    - Smooth-Cast 45D
    - Smooth-On Task 3 (80D)
    - Smooth-On Task 14 (50D)

3 METHOD

The idea when starting the practical part for this thesis was to begin with finding out if the resin casting process will work for this product. This was good to find out before deciding to create a master part for a casting mould. So the appropriate next step was to create a prototype silicon mould for resin casting using a regular production disc golf disc as the master part.

The second important fact to find out was where and how to create a 3D-printed master for the final mould. This could also be possible to do at Arcada, there are three FDM printers and one SLA printer and the idea was to try these out and see how it will turn out.

Also a third point to consider was that if the silicon resin casting mould would not work properly then the next step would be to use CAM and mill a mould out of polywood or aluminium using a CNC machine.

3.1 Prototype work

3.1.1 3D-printing

The 3D-printing of several smaller prototype discs and a few larger full scale prints were carried out at Arcada. Most of them failed due to properties of the 3D-printing machines and the print settings and also the design of the smaller discs. The designs were not based on any measurements rather just merely free-hand ideas for designs for what geometries could be accomplished with 3D-printing. From the start of the printing at Arcada there were already a few restrictions due to the sizes of the printbeds and the sizes of the machines available.

The machines that were used for these trial 3D-prints were two MakerBot Replicators 5th generation for the FDM printing and a Formlabs SLA 3D-printer. A third FDM printer was also used, a Minifactory 3D-printer, but even with several different designs the Minifactory printer was not able to create any good 3D-printed discs. [18] [19] [20]

Four fairly successful small scale prints were created, two with FDM and two with SLA. The first one can be seen in figures 17 and 18. This was printed on one of the MakerBot replicators. The design for this first one was not in any way in realistic dimensions, the idea was merely just to test the MakerBot 3D-printers.

Figure 17: First print, FDM, material PLA, 114 mm diameter

Figure 18: First print, FDM, bottom, material PLA, 114 mm diameter

The second print was done simultaneously as the first one with the same design sent to the Formlabs SLA printer software, this can be seen in the following figures 19 and 20. This one was not very successful in means of looking as designed. The size of the rim height was so small that it barely created an edge on the inside. Also the software of the SLA machine creates a base before it starts printing the part itself so because the top of the disc design was so flat and the area quite large there was a clear edge on the top layer which should instead have been a smooth radius.

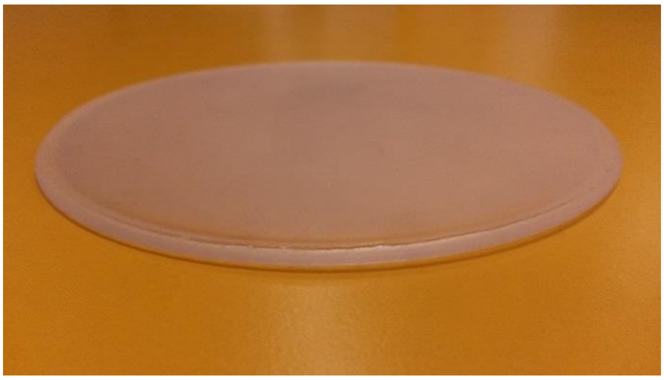

Figure 19: Second print, SLA, top, photopolymer resin, 114 mm diameter

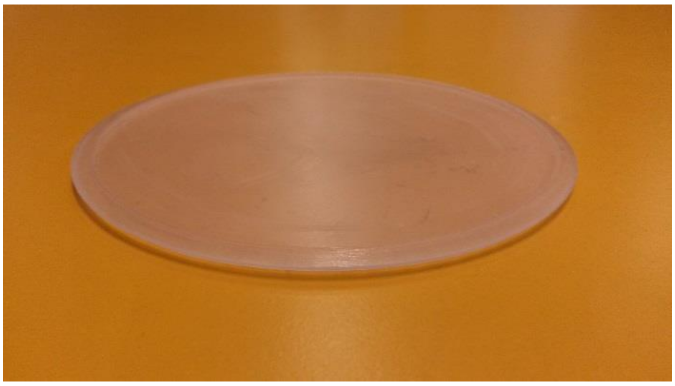

Figure 20: Second print, SLA, bottom, photopolymer resin, 114 mm diameter

The third successful print can be seen in figures 21 and 22, this was also done with the MakerBot Replicator. Several attempts with fairly similar design was done before this one and most of them failed quite early in the printing process. For some reason the MakerBot software placed this at a two degree angle in the object placement before starting the print all the previous tries the object was placed flat in the software. This change in angle allowed the printer to be able to create the full design. The only problem in the finished part was that the support material was not really optimal because it would have to be sanded or grinded down and the idea is to try and get as smooth surface finish as possible.

Figure 21: Third print, second FDM, top side, material PLA, 113 mm diameter

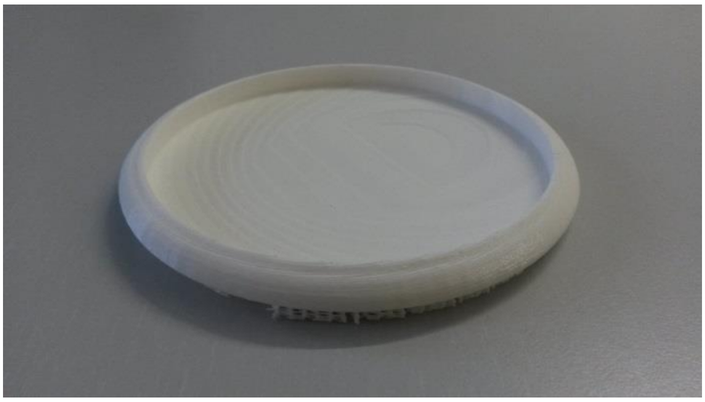

Figure 22: Third print, second FDM, bottom side, material PLA, 113 mm diameter

The fourth print was again done with the Formlabs SLA 3D-printer and the SolidWorks design was the same as for the previous third print. This can be seen in figures 23 and 24. The first try at printing this design with the SLA actually resulted in jamming the machine, the center part of the disc created a vacuum in the resin bath because the design was again placed flat in the printer software before printing, so the print bed jammed in the lower position. A second run at this print was made with the design placed in the software at an angle of 20 degrees. This way the result was very encouraging. The SLA is accurate enough to create a good surface quality and detail. The only problem was that because it was printing it at an angle one end on the top side of the disc is slightly slanting lower than it should compared to the original design.

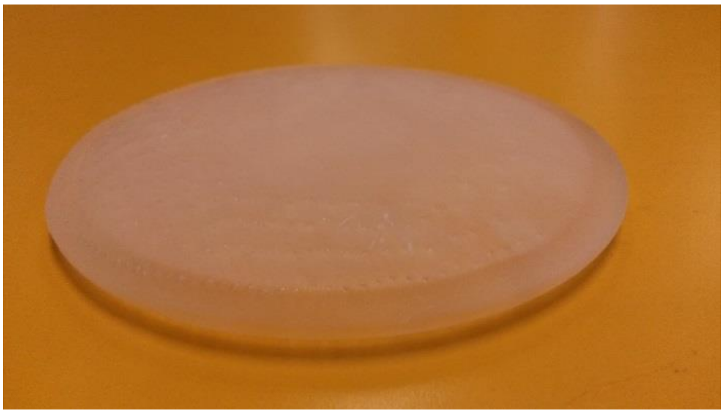

Figure 23: Fourth print, SLA, top, photopolymer resin, 113 mm diameter

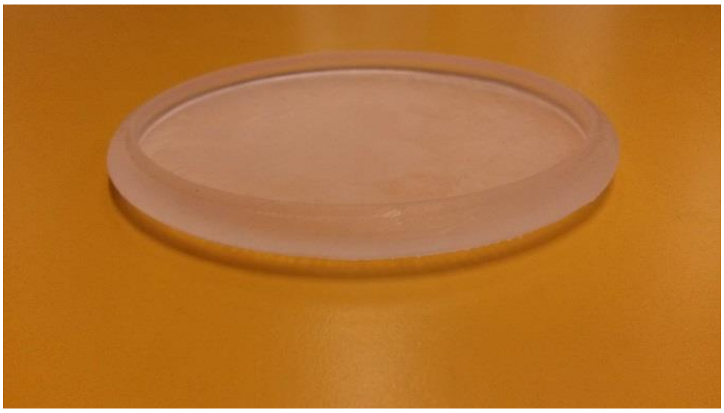

Figure 24: Fourth print, SLA, bottom, photopolymer resin, 113 mm diameter

A number of 3D-prints were also made with the design being a bit scaled down from original size and also a few full size discs.

A few tries were made with the disc scaled down from 201 cm to 140 cm on the second MakerBot printer, which has been mounted with a heated bed that goes up to 60 °C.

Figure 25: Scaled down disc, FDM print on heated bed, 140 mm in diameter, PLA

Figure 26: Scaled down disc, FDM on heated bed, 140 mm in diameter, PLA

One successful 3D-print was created of the design being scaled down to 140 mm on the printer with the heated bed, this result can be seen in figures 25 and 26. The print came out with a fairly good quality, but when printing with FDM and PLA as the material the surface finish will not be that good so quite a bit of sanding and polishing would have to be done to make the surface quality as good as an SLA for example.

A few tries to 3D print a disc at 190 mm diameter on the same MakerBot FDM printers were also attempted but without a heated bed. The surface area of the disc was so large that when the filament started to cool down it also began to shrink so the print started to come apart from the edges because of the rather large thickness on the bottom cooling down and shrinking.

The next idea to try in this stage was to only print a half of a full size disc and then glue the two halves together. This time the disc was placed vertically in the upright position in the MakerBot software, this can be seen from figure 27.

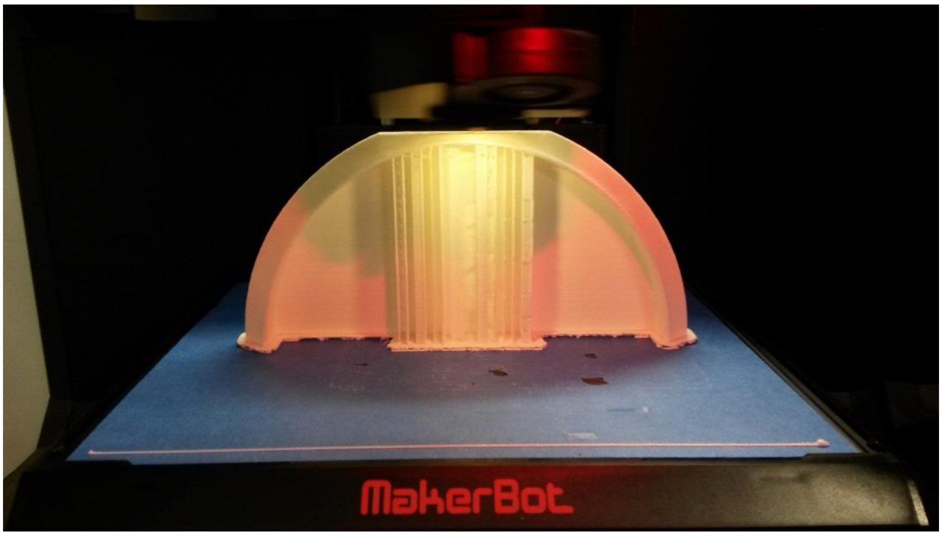

Figure 27: Makerbot Replicator printing half of a disc

The 3D-printing of the two halves of a full size disc was successful, the result can be seen from figure 28, figure 29. The profile of the disc came out fairly good, with respect to the design, with the FDM printer, this can be observed from figure 30.

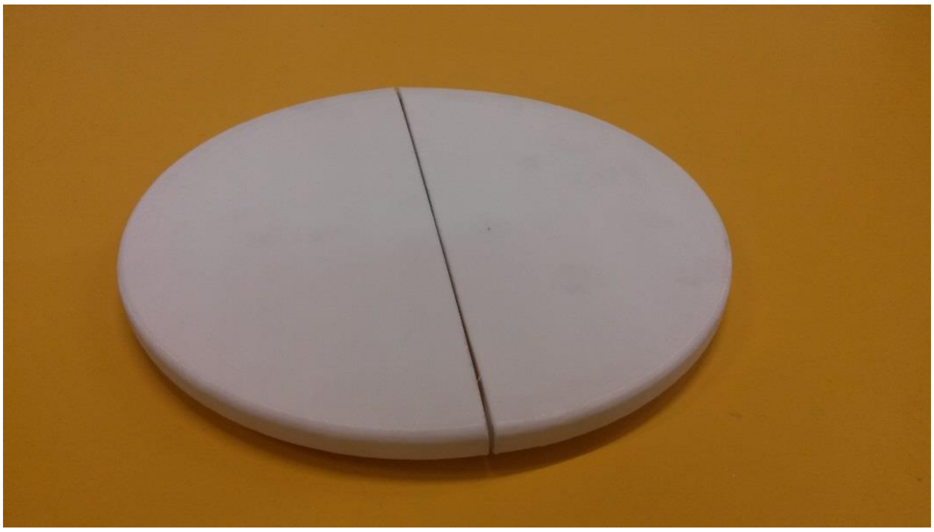

Figure 28: Two 3D-printed disc halves, PLA, 190 mm diameter

Figure 29: 3D-printed disc halves, bottom, PLA, 190 mm diameter

Figure 30: 3D-printed disc half profile, PLA

The two disc halves had the surface quality that was expected from an FDM 3D-printer so a bit of sanding and polishing would have to be done to get a smooth surface. The edge of the disc that was on the print bed would also have to be sanded down quite a lot before being able to glue them together. This is because the ends of both of the halves have warped inwards because of the shrinkage of the PLA filament, the shrinkage was fairly small considering that the print time was a tad over 5 hours with both halves.

3.1.2 Prototype mould

For the casting process it was necessary to create a prototype mould from one production quality disc to find out if the process would be functional and then be able to proceed to creating the 3D-printed master part.

The casting process of a silicon mould is rather simple, the following paragraph will explain the procedure to some detail.

The first step is to figure out what kind of mould should be created, an open mould or a split mould or something else. For this product a split mould was the option, that is a mould with two halves, one top half and one bottom half. The next step was to decide how to have the master part placed in the mould, for this mould the part would be horizontally and in the middle of the mould with the split line accordingly with the parting line of the production disc. After this, a rectangular frame was made out of wooden spare planks, for containing the silicon when casting the mould halves, this frame can be seen in figure 31.

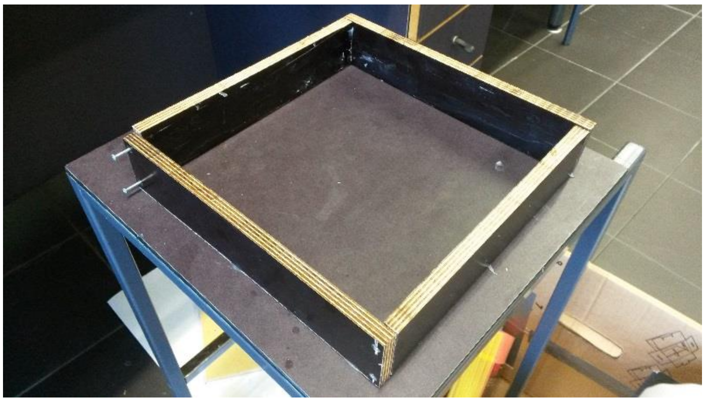

Figure 31: Wooden frame for silicon casting, roughly 25 cm x 25 cm

Now the master part was placed horizontally on a straight sheet of wood, which acted as a reference plane for the mould halves, and at this stage play-doh was placed around the disc under the rim up to the parting line. Play-doh was used here to keep the silicon from filling up the whole shape of the disc to get the parting line for the mould accordingly with the parting line of the disc, the idea for the bottom half was to fill up the wooden frame from the bottom sheet up to the edge. When all this was done all that remained was to clamp the frame down with four screw clamps and mixing and pouring the silicon on top of the disc. The silicon used for this cast was obtained from Kevra and the brand of silicon was RTV1540 A with a shore A stiffness of 40. This silicon was a two component silicon with A and B components with a mixing ratio of 1:1 and with a cure time of 8 hours but both mould halves were left for 24 hours to cure and harden. The amount of silicon used for the bottom mould half was approximately 600 g of each component so a total of 1.2 kg. The casting of the bottom half can be seen from figure 32.

Figure 32: Casting of bottom mould half

When the bottom half was cured the top mould half could be cast. This procedure was as simple as for the bottom half. First the frame was opened carefully and the first half was turned over and the play-doh carefully removed around the disc. The next step was to glue an inlet and an outlet straw, the inlet for the injection of resin and the outlet for air, this was done using superglue. At this stage the bottom half of the mould was placed back into the wooden frame the other way with the bottom of the disc now facing upwards. The bottom mould half was then treated with a solution containing water and 10 % of a cleaning solution called fairy, this would ease the splitting and opening of the mould when the top half was fully cured. Now all that remained was mixing the silicon again with the 1:1 ratio and pouring it on top of the bottom mould half. A total of 1.8 kg of silicon was used for the casting of the top half. The casting of the top half can be observed from figure 33.

Figure 33: Casting of top mould half

Two moulds were cast, the first one failed a bit after the casting process. The casting of the bottom half for the first mould was very successful no mentionable problems. After letting the bottom half cure and then casting the second half on top of that the silicon that was used ran out so the top most layer became very thin. When trying to later pry the mould open the two halves were completely stuck together, most likely because of using the wrong type of release agent and to some extent the lack of design on how the mould will open easily. The only solution then was to just cut it open and at least have a look at the quality. The positive thing about the first mould even though it was not successful is that the surface quality the silicon is able to create is rather good.

The second silicon mould was more successful, the only problem with the second casting was that the amount of silicon needed to cast the top half was estimated too low. So when forced to add more silicon after already casting 1.2 kg it was a lot harder to control the amount of air bubbles, which led to that the top mould has a lot more air bubbles than was intended. The result of the second casting can be seen in the following figures 34 and 35.

Figure 34: Bottom mould half

Figure 35: Top mould half

3.1.3 Trial casting

This section will go through a number of test castings which were done with the successful silicon mould of a production disc. The material used for these tests was a vinylester resin, because of its viscosity this was a good choice for getting an understanding of how the polyurethane resin will flow through and fill the mould.

The first issue that had to be addressed with the mould was how to get the material to flow in. A trial run was conducted by trying to pour material in through the middle inlet hole but that did not work at all. The middle part of the mould is just heavy enough to press down on the middle of the bottom half so that there is no space for the material to flow. This issue was solved by testing to inject some water into the mould with a syringe. The water flowed through the mould cavity really well when injected with a 20 ml syringe so it was realized that the injection of resin could be accomplished by using 100 ml syringes.

After the problem with the method for injection of the resin was resolved the mould function was tested with the mould being in different positions, that is placing it flat horizontally or placing it upright vertically. Different injection positions were also tested to see which positioning would give the best result.

The first casting test was done with the setup being the following, the mould flat horizontally and one injection hole in the middle and one air outlet on the rim. The mould was clamped down with four screw clamps on the edges of the mould. The vinylester resin was injected with a 100 ml syringe from the middle. The result of the first casting can be seen in the following figure 36.

The result of the first test was encouraging although there were a lot of faults in the part. The outer rim is not completely filled which means that there was an air pocket because there only was one air outlet. The second issue was that the middle part did not completely fill up.

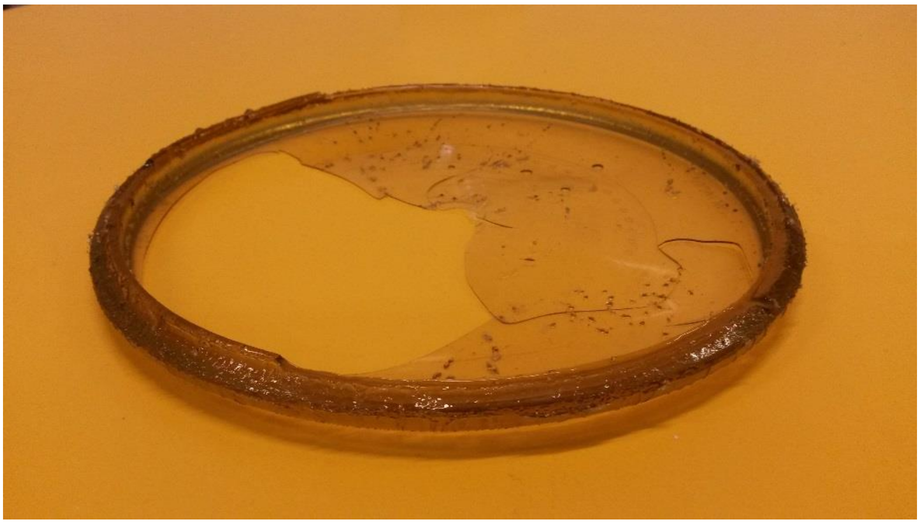

Figure 36: First vinylester casting

A number of tests were done in a similar manner with the difference of having two air outlets on the rim of the disc. The results were almost similar with the difference that the rim of the disc was filling up fairly nicely but the middle part still was not filling up at all.

To be able to get the middle part to fill up the casting process was tested a few times with having the mould vertically in the upright direction and injecting from the middle and from the edge of the mould. The result of this can be observed from figures 37 and 38.

Figure 37: Casting test with mould upright vertically

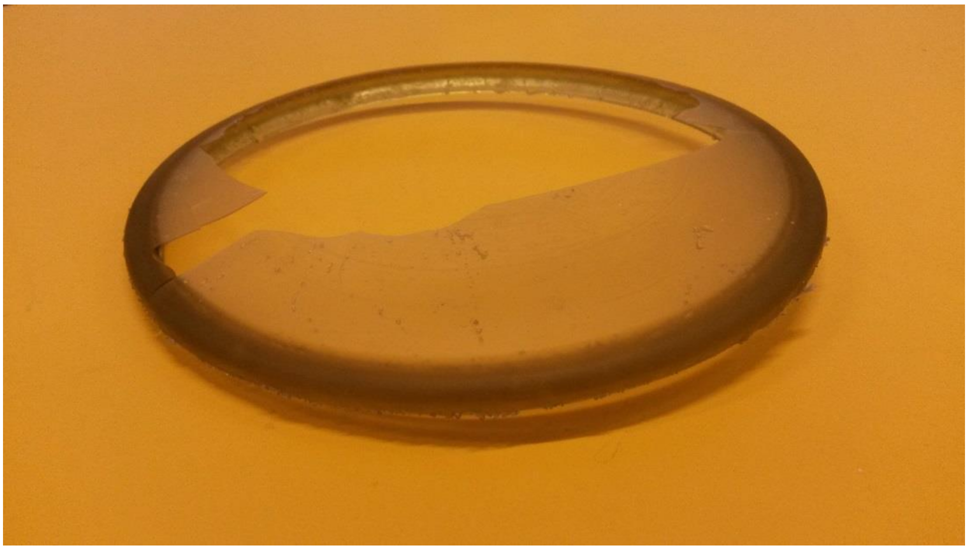

Figure 38: Casting test with mould upright vertically, top view

The result of the casting did not change at all despite changing the placement of the mould. The problem with having the mould placed upright is that the halves have to be clamped together a lot harder than when having the mould horizontally, so the clamping force will also push in the middle of the mould which means that the top half would be touching the surface of the bottom half in the middle. This was a big problem, because the thickness in the middle of the master disc that was used was around 1.8 mm and the thickness of the resin castings that were obtained from the mould were only around 0.2 mm to 0.4 mm in thickness.

A few different ideas were tossed around of how to attack this issue. One idea was to screw two plates of metal going diagonally over the top of the top mould half. This was a good idea in theory, but when trying to screw a few screws into silicon it just would not stick. When applying force to try and tighten the metal plates, so that they would "draw" the center of the mould upwards, the screws would just spin around and not go any deeper because the silicon chosen for the mould would just give out and not hold.

Another idea was to place some small plastic pieces in the mould cavity between the two mould halves to support the heavier top half so that it would not sag down. The first try was with placing three circular roughly 2 mm thick pieces of cured vinylester resin in the mould cavity. This can be observed in the following figure 39.

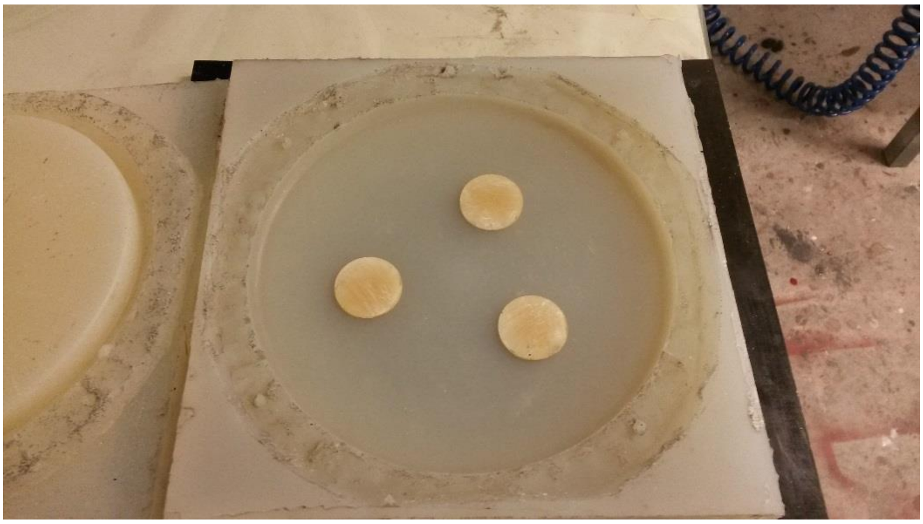

Figure 39: Circular pieces of resin as support for top mould half

The result from this was fairly successful, the middle part had a tad more resin with the mould setup with the supports in the cavity. The next attempt was with placing small pieces cut off of a plastic dog bone tensile testing piece. The pieces which were cut off were also roughly 2 mm thick and were placed inside the mould cavity in a manner which can be observed from figure 40.

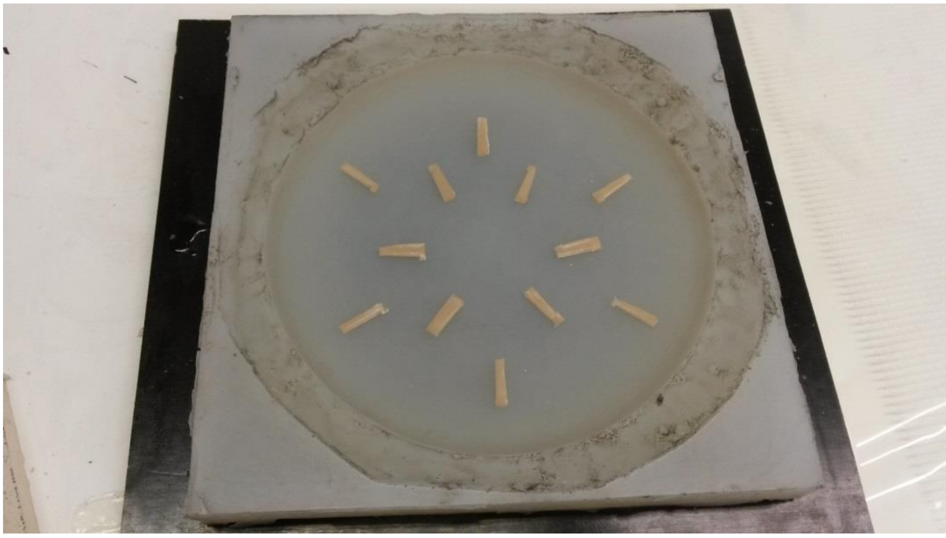

Figure 40: Plastic dog bone insert pieces

The result of casting vinylester resin into the mould, with the setup of having the dog bone insert pieces in the cavity, was a success after a few tries. The result is obviously not perfect because inserts of some sort had to be used for being able to get the mould working properly. The result can be seen from the following figures 41 and 42.

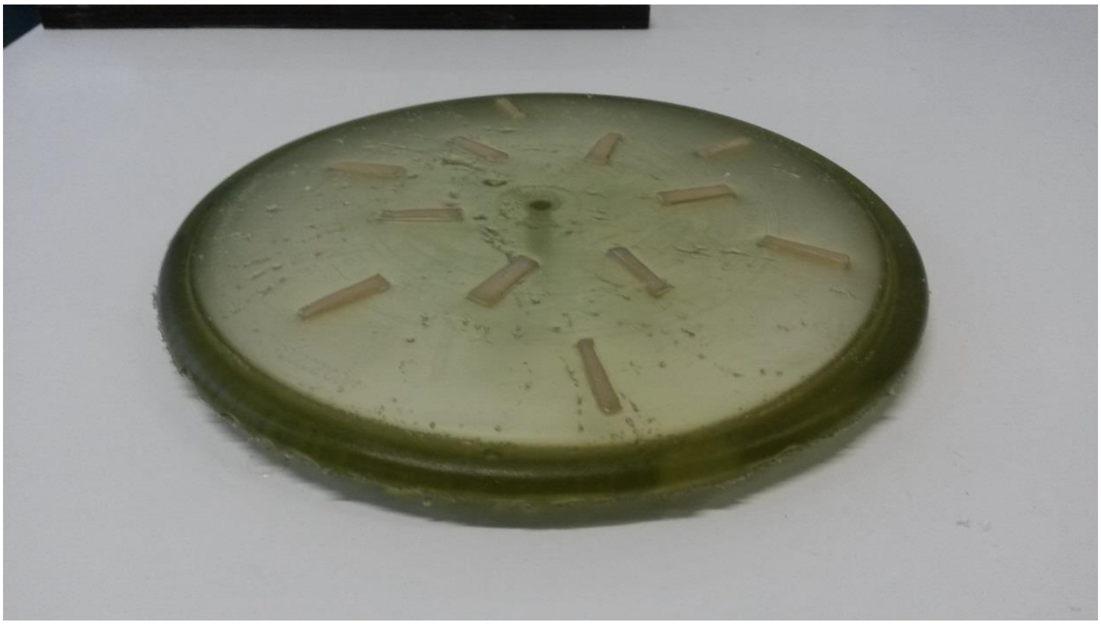

Figure 41: Vinylester disc with plastic inserts, top view

Figure 42: Vinylester disc with plastic inserts, bottom view

3.1.4 Casting procedure

The casting procedure will be explained in detail in this subsection.

1. First thing to consider when starting the casting was to clean both mould halves using acetone to remove any dirt and excess resin from previous casting.
2. The second step was that both mould halves were treated with a substance called chemlease, this creates a wax like surface on the mould so that the part is easier to remove after curing.
3. Now the plastic inserts can be placed onto the bottom mould half. This is optional because in this case the plastic inserts are necessary but this may not be a necessary step for other products or moulds.
4. Now the top mould can be placed ontop of the bottom half and the mould can be clamped together by using screw clamps or something similar. This is shown in the following figure 43.

Figure 43: Clamping of the mould

5. The next step is mixing the resin that is used, for this example an amount of 200 ml of resin was used and an appropriate percentage of hardener was added.
6. When the mixture of resin and hardener is completely mixed and the amount of air bubbles is low the resin can be injected into the mould using a 100 ml syringe. This can be observed in figure 44.

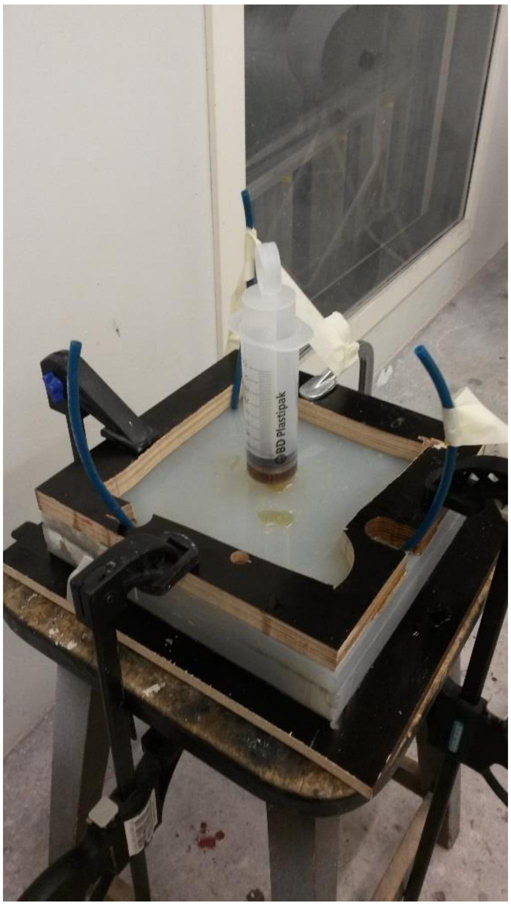

Figure 44: Injection of resin into the mould

In this case the injection of resin was done in two steps. First an amount of 30 ml was injected, to ensure that the complete volume can be achieved as good as possible, and then the syringe was filled up to a full 100 ml and the mould was injected with resin until some excess resin began to flow out of the air outlets.

3.2 SolidWorks design

All design work in this thesis was done with the SolidWorks 2015 - 2016 edition. SolidWorks is a 3D computer aided design software and used for creating parts, assemblies and 2D drawings. [21]

3.2.1 3D-Model

The design for this disc was to try and create a profile that would work as a mid-range type of disc. As can be seen from the 3D printed disc half profile earlier in figure 30 the properties for a mid-range profile was accomplished fairly well with the design. The idea was to also try and keep the dimensions of the disc inside the PDGA disc design regulations. The design can be seen in the following figure 45.

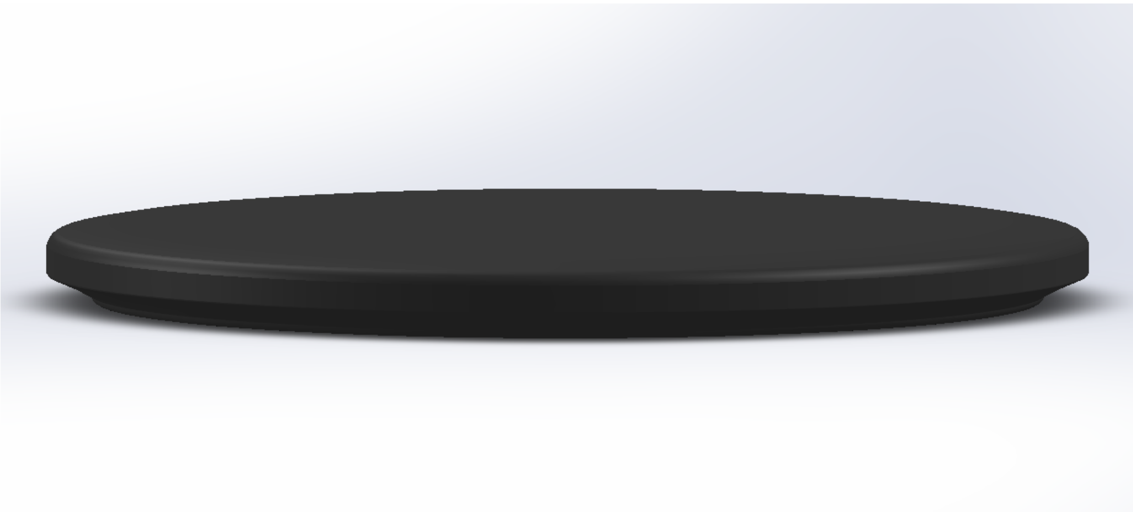

Figure 45: Disc design [21]

The material properties for this disc was selected as polyurethane in the SolidWorks software and this generated with this design a theoretical mass of 175.8 g which is well inside the requirements. The dimensions of the disc can be seen from figure 46, the dimensions are in mm.

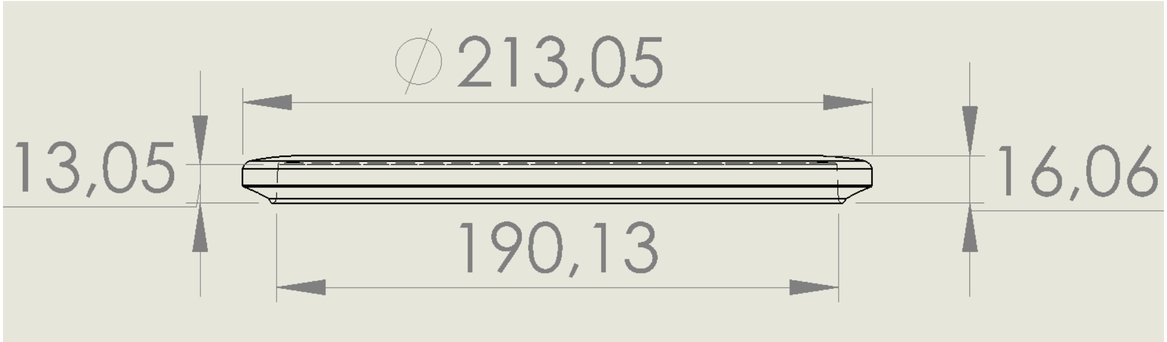

Figure 46: Disc dimensions [21]

4 RESULTS

The result for this thesis was the final resin casting with the polyurethane materials and the silicon mould. The result was fairly as expected because the trial casting with vinylester resin was quite extensive. The casting procedure was the same for all three examples presented in this section, that is, polyurethane resin was injected from the middle with the mould horizontally on a straight surface with three air outlets for letting excess air out. The weight of the master part used for creating the mould cavity was around 171 g as a reference for these tests.

The result of the first casting with polyurethane resin, Smooth-Cast 45D, can be observed from figure 47.

Figure 47: Polyurethane resin cast disc, Smooth-Cast 45D

There are some faults in the casting result which are visible, for example a big air pocket left a hole on one side. Although there are faults the result is still fairly good, the mould continuously reproduces the shape of the original master disc even though it has been quite extensively used. The first material was not as rigid as was expected so the disc is not firm in any way so this material is not really optimal for creating a durable disc golf disc. The shore hardness of this material was 45D, semi-rigid polyurethane resin. The weight of this example came out to 110 g.

The second casting was done using the polyurethane resin Smooth-On Task 3. The result can be observed from the following figures 48 and 49.

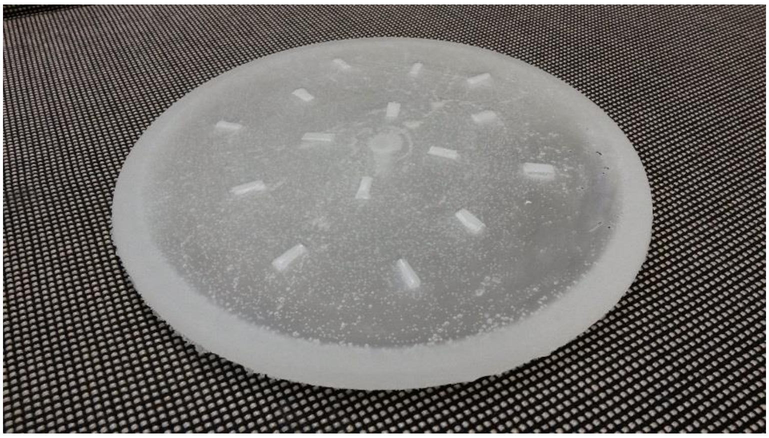

Figure 48: Second polyurethane casting, Smooth-On Task 3

Figure 49: Second polyurethane casting, Task 3, bottom view

The result of the second casting was really encouraging with the hardest material, shore hardness of 80D. The disc feels really durable and firm, the result is fairly close to actual disc golf disc quality. There are faults again in the disc but that is to be expected as the mould itself is not perfect. The weight of the disc with this material came out to 122 g.

The third casting was done using the Smooth-On Task 14 polyurethane resin. The result of this casting can be seen in figure 50.

Figure 50: Third casting, Smooth-On Task 14

The result for the third casting was almost identical to the first one with the Smooth-Cast 45D. This was expected because the material shore hardness property for the Task 14 was 50D. This time the air pocket problem was fixed by placing the plastic inserts in a way to allow the resin to flow to the problem area. This material was also really flexible and not at all firm so also not suitable for production of high quality durable discs. The weight of this example came out to 116 g.

5 DISCUSSION

The result of this thesis was not as expected, the aim was to create a working everyday use disc golf disc and this was successful to a certain extent. There were a lot of problems along the process. The first issues which emerged were with the silicon mould. Although silicon is a really good material for reproducing even difficult designs to a great detail a few material specific aspects have to be taken into account before creating a mould. For this case the mould was designed too light, the amount of silicon needed for each half was estimated too low, so the top part of the mould became a fair amount heavier than the bottom half. If the top part would have been made even thicker and bigger then the silicon could have probably been able to keep the middle part from sagging downwards. There could also have been done more research on the silicon material, for example obtaining a silicon with a greater shoreness value than 40A to get a more rigid mould. The mould design could also have been further developed to find out which ways would have been the most optimal for injecting the resin and to relieve the air out from the mould. Another issue using silicon as the mould material is that silicon tends to get tired the more you use it so it will eventually start to lose its shape.

The trial resin casting, which was done with vinylester, was crucial for this thesis. The testing of the mould took a lot more time than expected and the mould did not function as good from the beginning as it should have. This led to that the master 3D-printed disc would not be ordered and a third and final silicon mould was not created because it would have cost a lot more and would have required more time than this project had left. The result of the trial casting was a success in the end after a good number of casting attempts.

The success of the trial casting allowed the project to go further and order in some polyurethane casting resins to try and cast the final discs, although this was to be done using the prototype mould instead of having a mould created based on the design which was drawn. The problem in the final result was that the shore hardness of the different materials, which were ordered, was estimated wrong. Two of the materials were way too soft for creating disc golf discs of good quality, these were the Smooth-Cast 45D and Task 14 at 50D. The description of the materials when ordering was semi-rigid so based on that it was fairly difficult to estimate the final behavior of the material when casted and cured.

6 CONCLUSION

This thesis required a lot more practical work than was expected and with the time frame given and the limited funding it was not possible to study all aspects to the fullest capacity. There could be done more work with mould research and mould material development. The resin casting process could be further developed with different injection methods and also by adding pressure to the mould while the resin is curing. There could also be more work done in material research for the final disc material, because there are a vast number of different casting resins available and there was no idea in spending more time or funding for this thesis to try more materials. In general this thesis was succesful in a way that this work done here functions very well at the least as a proof of concept, because it is completely possible to create a 3D-printed disc and create a mould based on that disc and then use the resin casting process to manufacture several discs.

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APPENDICES

Table 1. Materials

Table of materials	Material	Supplier	Image
1	Smooth-Cast 45D	FormX	
2	Smooth-On Task 3	FormX	
3	Smooth-On Task 14	FormX	
4	Silicon shore A 40	Kevra