Analysis of implementing additive manufacturing for the making of casting patterns

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Sammanfattning

I den här rapporten undersöks möjligheten för att tillverka och använda gjutmodeller tillverkade genom additiv tillverkning, i folkmun kallat 3D-printing. Först görs en grundläggande analys över hur modellerna tillverkas idag och vilka krav som ställs på modellen. Detta innefattar både rena material och hållfasthetskrav, men även mer svårdefinierade krav där man enbart kan resonera kring rimliga antaganden. Sedan undersöks de tillverkningsmetoder som kan vara av intresse för den här rapporten samt vilka material som isåfall skulle vara lämpliga.

Därefter kontaktas potentiella leverantörer för att undersöka den praktiska genomförbarheten och få in jämförande prisuppgifter. Som mål var också uppställt att genomföra ett praktiskt test som skulle utmynna i att en modell i full skala testades under verkliga förhållanden som en del av företagets produktion. Av tidsskäl så var den här rapporten, tyvärr, tvungen att färdigställas innan själva testet hann slutföras, men flera viktiga steg i tillverkningen hade genomförts och prognosen såg god ut.

I rapporten så presenteras också kostnads och miljöanalyser av den tänkta tillverkningen. Där additiv tillverkning jämförs med den traditionella modelltillverkningen i trä. Slutligen sammanställs det som man har kommit fram till och rekomendationer inför framtiden ges till företaget.

Abstract

In this report the possibility for the manufacture and use of molding-patterns made through additive manufacturing methods, commonly called 3D-printing, is evaluated. First an analysis of how the patterns are currently being made and which demands that are put on them will be made. This includes more pure material and load demands, as well as more abstract and hard defined demands. After this the different possible manufacturing methods will be evaluated, as well as those materials that could be reasonable.

After this potential suppliers are contacted to evaluate the practical aspects of the project. Here comparative prices will also be gathered. The goal was set to complete a full scale test under real circumstances, as a part of the companies production line. Due to time constraints this report sadly had to be finished before those tests were completed, but several important steps had been made and everything were looking good.

In this report there are also some sections on the cost and environmental implications related to the planned production and use of a 3D-printed pattern. It will be compared to the conventional pattern-making in wood. Finally this is all compiled and recommendations for the future are made.

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1 Introduction

1.1 Background

1.1.1 Project

The company in currently using wooden patterns to produce the sand molds that the molten metal is poured into. The shapes are often quite complex and requires a skilled pattern-maker to produce new pattern as well as maintaining and repairing old ones. These patterns are then stored and used for long periods of time. Wood is a organic material and can change in size or crack due to shifting humidity levels. This puts requirements on both storing and handling the patterns that increases the storage cost compared to non-organic materials.

1.1.2 Traditional pattern making

The pattern is today made in a traditional pattern making fashion. It starts out with the pattern-maker drawing up a section in full scale on a piece of plywood. This will be used as a reference throughout the process and also used to calculate the amount of wood needed and how it should made to minimize material loss and ensure enough overlap so that the pattern remains solid. Rough-sawn pine boards are then planed flat and true. Based on the drawing and calculations done earlier the circle segments are sawed out, these circle segments are then glued up in rings on top of each other, with the joints staggered like a brick wall. Larger flat areas, like the top and bottom, of some patterns are made from thick plywood that is also sawn out and glued in place.

Planing, sawing and gluing up these segments are then made continuously, with planing and sawing of the segments for the next ring taking place while the glue dries for the previous ring. When the whole blank is assembled and the glue dried it is attached to a faceplate. This can then be attached to a lathe and turned to the finished dimensions, some light sanding might be necessary but the turned finish is often really good and will suffice. To get the proper dimensions the pattern-maker first turns all straight lines using tool slides similar to those on a metal lathe, these can be adjusted to the proper angle and then driven along a straight line. These straight segments are then connected by curves of varying radii. Here radius-patterns are made from plywood and brought into contact with the unfinished mold to see how well they fit, high spots are then removed using conventional wood turning tools and a steady hand. Large calipers are used to ensure proper tolerances.

1.1.3 Pattern usage

To understand the project, and some of the reasoning further on, it is important to understand how the pattern will be used. An attempt to explain this process will be done here.

The traditional way of sand casting is to pour a specific sand around the object that you want a imprint of, this sand is then “rammed” to make it fill the void completely and to stay in place once the object is removed. There is also another type of sand casting, called vacuum sand casting or vacuum molding[1], this is the processed used by this company. This process is described in this section with the help of figure 1.1 and 1.2.

For this process two patterns are used to create two halves of the finished mold. These are made in parallel(figure 1.1) and then combined for the pour(figure 1.2).

Figure 1.1

- 1. The patterns are fastened to a supporting plate.
- 2. A plastic film is drawn over the pattern and the support plate. Both of these have small holes in them which enables a vacuum on the other side to draw the film tightly against the pattern.
- 3. The flask is placed on top of the film, then sand is poured inside it.
- 4. A new plastic film is placed over the sand. The first vacuum is then released while a new vacuum is drawn, this time through the walls of the flask. This is what technically "hardens" the sand. No binder of any other kind is used.
- 5. With the vacuum still on it is now possible to remove the pattern and its supporting plate. The sand will hold its shape as long as the vacuum is sufficiently high. It is possible to move the shape around and turn it up side down without any major shifting of the sand.

Figure 1.2

- 6. The two mold halves are now combined and brought into contact. It is important that is is the sand that is contacting and not the two flasks, since the gap would result in a big seam-line.
- 7. The molten metal is poured in. Filling the void and burning away the plastic.
- 8. When the metal has cooled down sufficiently the vacuum can be released, resulting in the sand falling of. The sand then goes through a cooling process before it can be reused. The part that was just cast will then continue on, any sprues or risers will be removed and some surfaces will be machined. This is however beyond the limits of this project.

1.2 Project objectives

The overarching goal of the project is to evaluate and test the possibility to make the mold patterns using additive manufacturing instead of traditionally crafted wood patterns. The project involves material and process selection, together with finding a suitable supplier that can produce and deliver to the design specifications. A part of the project will involve a full scale test, meaning that all problems that should arise will also have to be solved. The project will mostly focus on manufacturing time and functionality from these patterns, but the cost aspect will not be overlooked and it is important that the new method is also cost effective. Together with this there will also be a small environmental study presented, which compares the new alternative to the current method.

1.3 Scope and Limitations

This project is limited in its scope to look at options available on the market today. No attempt will be made to in any way develop new materials or designing new manufacturing processes. As this first step only outsourcing options will be looked at, this project should not require the purchase of, or investment into, new machinery for the company.

This project is also restricted to only the part of the pattern discussed in section 1.1.2. It would be advised to look more into how the pattern is fastened to the support plate and used in conjunction with other parts of the process in the future, but to keep the comparison with how it is today as clear as possible this will not be investigated here.

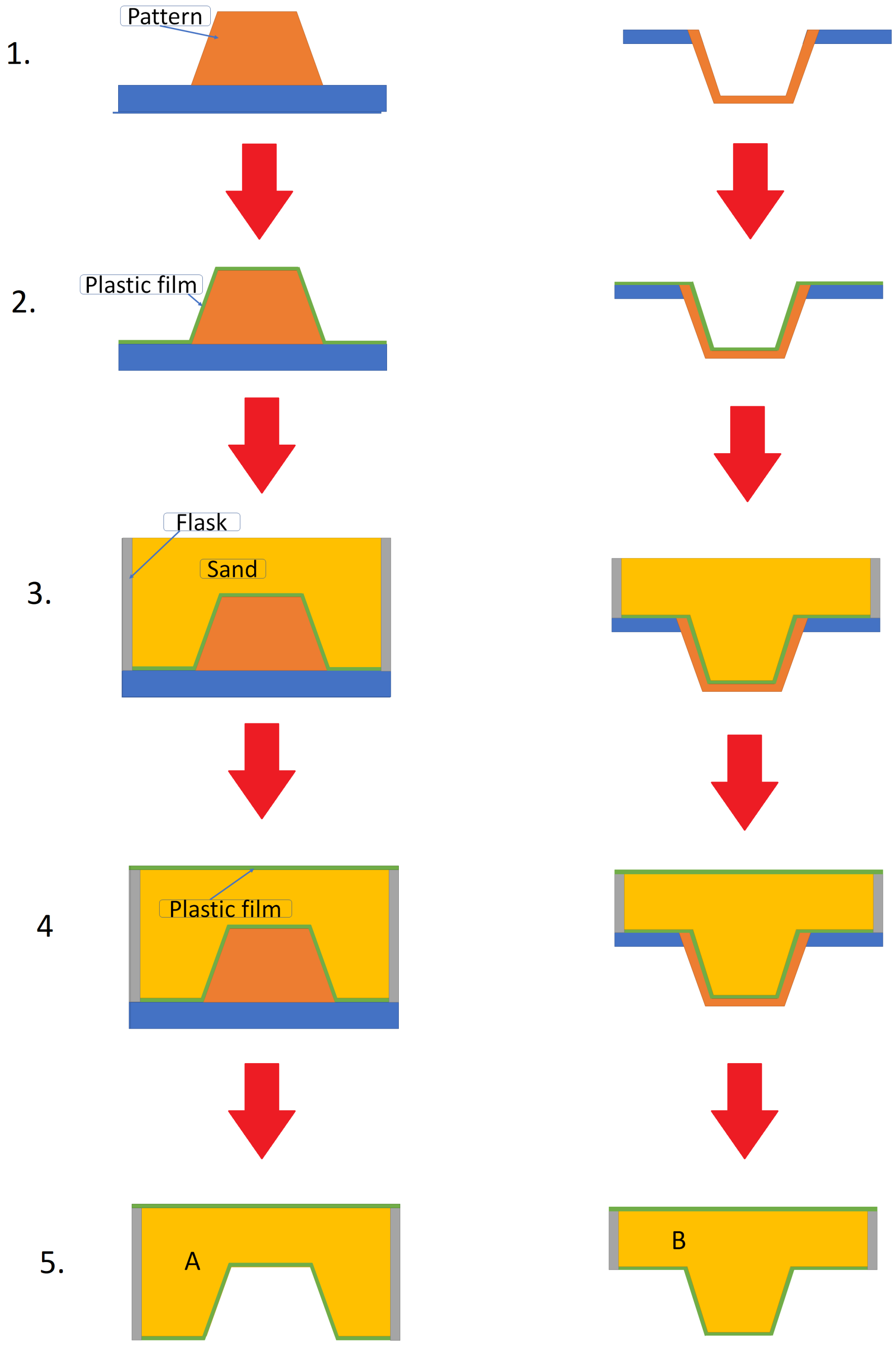


Figure 1.1: Pattern usage, step 1-5.

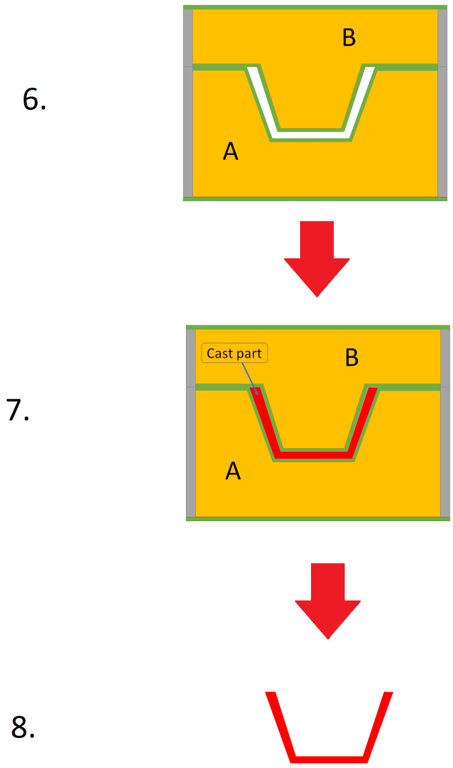


Figure 1.2: Pattern usage, step 6, 7 and 8.

2 Methodology

The project was divided into several phases, presented below. These phases helped organize the process and ensure a steady workflow. These were the main phases, but were not followed strictly and some overlap occurred.

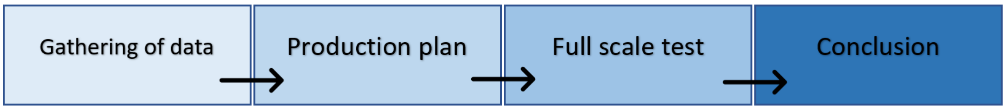


Figure 2.1: The project phases.

2.1 Phase 1: Gathering of data

The first phase focused on research and information gathering. This was done to get a clear view of the problem as well as what limitations and possibilities that exist. It would also be possible to divide this first phase into sub-phases. Where in the first phase a broader and more general research was made. The idea was to get a better understanding of the different additive manufacturing processes that exist, as well as what materials that are possible and suitable for these processes. This was done mainly through reading academic papers on the subject, together with more informal internet information from machine manufacturers websites and other websites and forums dedicated to additive manufacturing.

During this phase, and also overlapping into other phases, different types of interviews were made. On an everyday manner small 5 to 15 minutes interviews or conversations were made with the industrial supervisor. These varied from open to semi-structured[2], and involved a large variety of subjects but mainly focused on the industrial process in which the patterns would be used or how they would be handled. Generally no notes were taken during these interviews and served more to build up a general idea about the process and the company. Slightly more structured were the interviews with the factory pattern-maker, these interviews focused more on how the pattern was made and his ideas about how the structure worked. He also helped in calculating some properties needed for the cost and environmental analyses. Here it was mix between semi-structured, where there were generally specific questions asked but with open answers, and structured, where there were very specific questions such as “how thick does this part has to be?”, for example. These were not as frequent as those with the supervisor and occurred during a smaller time frame, though with longer interviewing sessions in general.

2.2 Phase 2: Production plan

Based on data from phase 1 a production plan was made. It involved more detailed conversations with sub-contractors, decisions on material and technology, and possible post-processing. In reality there were no clear division between phase 1 and phase 2, with much of the work being done in parallel. Information from phase 1 were used together with information from potential suppliers to understand what is possible and feasible, and also to create the 3D-model. The suppliers were interviewed in a semi-structured manner[2], where some clear and direct questions, and some broader questions with open answers.

2.2.1 3D-modelling

It is also during this phase that the 3D-models of the patterns were made. These were based on previous findings, like material data and shape constraints, together with input from suppliers. Since it is a complex shape with relatively complex loads simulation software were used to guide in the dimensioning of the 3D-model. SolidWorks was used for the modelling and its inbuilt simulation tool for all simulations.

2.3 Phase 3: Full scale test

Based on the findings in phase 1 and 2 a full scale test were started. The order was sent out to the selected suppliers which started production. Sadly there were no time to finish the project in time but the progress were recorded, as well as future steps.

2.4 Phase 4: Compilation and conclusion

In the final phase the previous phases were compiled and the results shown. There is a brief discussion about the results together with recommendations for the future on how to proceed with the project and things to look into in the future.

3 Phase 1: Gathering of data

3.1 Design criteria

To ensure that the final product will function properly it is important to set up clear criteria to work from. These will be both criterion that determine the physical shape and support for the pattern, as well as criteria set on the material used. With these material criterion the intention were to use a selection process based on the work of Ashby, M.F. et al. [3] to find a suitable material. Due to reasons explained further down this was not possible to execute. In any case, the mechanical data from the material choosen were then used in conjunction with the load specifications to finalize the design.

3.1.1 Load criterion

The functional geometry of the patterns is set by the company to get the desired mold shape. It is however still not decided what dimensions the support structure will need, or what shape is it should have. This will depend on the loads listed below, as well as the material properties of the pattern. The loads that the pattern will experience occur first and foremost when the plastic film is drawn tightly against the pattern using vacuum. There is at most 0.8 bar of pressure sucking the film close to the pattern, which also put great loads on the pattern itself. When talking to personnel it becomes clear that this is the main concern, and they have had times when wood-patterns have collapsed due to this load.

With this vacuum active the sand is then poured over the pattern to take its shape. The sand weighs 2 kg/l and will not be a major factor, but will still of course attribute to the total load. Since the sand is flat on top, and the pattern changes shape when moving out radially, the load will vary depending on the height of each point on the pattern.

- Vacuum: 0.8 bar
- Sand: density of 2 kg/l spread across the pattern

3.1.2 Temperature criterion

Before the sand is poured on the mold a plastic film is drawn over the mold. To get this film to follow the form closely it is heated to become more supple and then sucked to the mold, giving rise to the vacuum load mentioned in section 3.1.1. It is heated to 120°C but then quickly cools off due to heat-loss to first the air and then the pattern itself.

Another heat load comes from the sand itself. The sand is heated by the metal when it is poured into the mold, the same sand is then recirculated and reused later on. It does go through a cooling unit and should not be hotter than 30°C. But in extreme cases, due to breakdown of the cooling unit, it could get substantially hotter than that. There is no data on how hot it could get in those extreme cases, it is also unclear exactly how this heat would transfer from the sand to the pattern. One way of measuring how well a polymer resist heat is the Heat Deflection Temperature, HDT. It is a standardized test procedure where a test piece is put under a specified load, giving a stress of 0.455 or 1.82 MPa, and then increasing the temperature until the test piece deflects 0.25 mm. The temperature at which this occur is that materials HDT value[4]. If the pattern was usually put through this type of increased temperature it would make sense to have this parameter as a constraint or criterion. Otherwise the increased heat would result in unwanted deflection and imprecise castings as a result. However, since increased temperature of this kind is not something that occur regularly it might be unnecessary to have it as a criterion. What however is important is how the materials yield strength is affected by heightened temperatures, so that no plastic deformation will occur, permanently damaging the patterns. Polymers generally seem to show a progressively lower yield stress with increased temperature. The relationship follow a smooth curve until the glass transition temperature, Tg, is reached, where it sharply goes down[5]. So looking at the glass transition temperature will be a good start in knowing if the material is suitable or not. But it can not be used exclusively since the yield strength does decrease significantly even before the glass transition temperature is reached. Knowing what exact value to put it at is hard however. There is no available temperature data for the sand, it is also hard to know how fast the heat would travel from the hot sand to the pattern and then spreading through the pattern. In general the high load from the vacuum should be lifted shortly after the sand is distributed over the pattern. Meaning that even if the sand was quite hot it would not have time to spread that heat through the pattern completely, meaning that it would still remain rigid. Ultimately no final criterion can be made, but materials with higher glass transition temperatures should be favoured. One could argue that the continuous use temperature, CUT, should be used. That would, however, likely be a too strict of a parameter. There are many ways in which this temperature could be extracted, but one common approach is the relative thermal index, RTI. The RTI is the temperature at which the sample can endure 100 000 h and not lose more than half of the of the property being measured[6]. As mentioned several times, the increased temperature that the pattern might be exposed to are extreme cases and will not occur for any prolonged periods of time. Furthermore, the RTI measures several values whereas only a few are important in this application.

- Melting temperature: >120 °C
- Favour high glass transition temperature, Tg.

3.1.3 Surface criterion

To get the plastic film, discussed in section 3.1.2, to release properly from the pattern, a smooth surface finish is of great help. Exactly how smooth it has to be depends on a multitude of different factors. Such as release angles, material properties, talc or lubricants used, vacuum achieved etc. However, as a baseline the surface finish that is achieved today will be used. As a measure of surface roughness the R_a value will be used, this is a commonly used value for surface quality for most material groups, and works on wood as well[7].

In table 3.1 the surface finish values taken from a few different wood patterns are shown. It averages at roughly 2.2µm, but has a noted maximum of almost 3µm. Since even the worst of these actually works that value can be used as a baseline.

Table 3.1: Measured surface roughness of wood patterns.

Sample Nr:	Ra [µm]
1	2.019
2	2.421
3	1.506
4	2.996
Average	2.236
Max	2.996

3.1.4 Storage and repair-ability

Some of the wooden patterns that the company is using has been used continuously since the 90s, giving them a service life of over 20 years, potentially even longer. Most of them have been worn-down and reshaped or repaired continuously. It would be preferable to be able to this with the new patterns as well. Some natural wear is normal and could at least be mitigated by having a more wear resistant material. Still, accidents are bound to happen and it is not uncommon that the patterns are damaged in other ways, with cracks or broken of pieces. It is important that these kinds of damages could be repaired, in one way or another.

It is hard to set clear material criterion here, but materials that won't degrade over time, and that are possible to repair or to reshape, is necessary.

3.1.5 Wear criterion

One of the reasons that the old molds have to be repaired or reshaped is simply due to wear. It is hard to set a strong limit on what wear is acceptable, though no wear would be desirable. The only baseline that currently exist is the wood patterns, so their value will be used as a guide. This value should, however, not be seen as a hard limit, but rather as something to reference other potential materials against.

Calculating wear resistance for a certain material is not so straight forward as it might seem at first glance, and no universal wear test or unit for wear exist. It depends on a lot of factors, like temperature, pressure and speed, as well as what material it is wearing against. These factors will determine what type of abrasion that will occur. These could for example be, but are not limited to[8]:

- Battering
- Rupture
- Galling
- Erosion
- Scratching
- Gauging
- Cracking
- Scaling
- Pitting

For each case one or multiple of these factors abrasions will occur and combine to the total wear. So instead of having a set wear parameter, for each specific application a specific wear parameter should be used. Since in this case it not a case of something being dragged, and no high force impact will occur, there are no risk of things like galling or rupturing. Also, as long as the material chosen does not interact in any unforeseen way with the plastic film, no chemical degradation should occur either. With these things in mind it would seem as if the most important factor would be the material hardness. For wood hardness the Janka scale is usually used, but since it is seldom (if ever) used for other materials than wood, and is in fact a specific case of the Brinell test it will be converted to the Brinell scale instead. Todays patterns are made out of Scots Pine, but some parts, prone to higher loads and more wear, are instead made from American Hard Maple, which has a Janka value of 6450 N[9]. Since the new pattern will be made with the same material throughout it will have to be compared to the hardest component of the old pattern. The Brinell hardness is calculated as[10]:

$$BHN = 0.102 * \frac{2F}{\pi D^2 \left(1 - \sqrt{1 - \frac{d^2}{D^2}}\right)}$$

Where:

- F = Test force
- D = Diameter of the ball
- d = Diameter of indentation
- 0.102 = Conversion factor from N to kgf

For the Janka test a 11.28 mm ball is embedded to half its diameter[11], and in our case the force is the Janka value, giving:

- F = 6450 N
- D = 11.28 mm
- d = 11.28 mm

This gives a Brinell Hardness Number of:

$$BHN = 0.102 * \frac{2 * 6450}{\pi * 11.28^2 \left(1 - \sqrt{1 - \frac{11.28^2}{11.28^2}}\right)} = 3.29 kgf/mm^2$$

Comparing hardness should really only be done with the same test parameters, but this value should non the less give some guidance as to if the materials looked upon are at least close to each other, or not.

3.1.6 Machine criteria

Though it might seem trivial, it could also be considered the most important criteria. It is in any case the criteria that will be used first for the initial selection process. It is the machine criteria, simply a yes or no answer to if the machines available can use the specific material. If a material fails here it does not matter how good it would be based on other criteria. Developing new materials or testing materials not used in these applications before is outside the scope of this project, therefore sub-suppliers with knowledge about additive manufacturing will be contacted to get a good initial starting point as to what materials to look into. The primary focus will be on contacting companies with machines capable of printing the patterns in one piece, requiring a printing table with a diameter of 1200 mm, and a height of 650 mm. Though it could be possible to print it in smaller pieces and then assemble them.

3.1.7 Compilation

- Physical criteria
  - Vacuum: 0.8 bar
  - 2 kg/l spread across the pattern
  - Surface finish: $Ra \leq 3\mu m$
- Material criteria
  - Melting temp: > 120 °C
  - Favour high glass transition temperature, Tg.
  - No material degradation over time
  - Possibility to repair
  - Hardness: $BHN > 3.29 kgf/mm^2$
  - Suitable for suppliers machines

3.2 Materials

There are a lot of potential materials to choose from when it comes to additive manufacturing, some are dependant on specific printing technology but there are also some materials that will work with a multitude of different processes.

3.2.1 Ceramics

Ceramic materials have some really attractive properties. They are generally stiffer than metals or plastics, tolerate high temperatures and provide slow wear[12]. Another clear benefit is that ceramics are some of the most stable and inert materials. They exhibit low thermal expansion coefficients, good UV resistance and does not oxidize in the same way that most metals do. This combined means that they could be stored practically anywhere, which is a big benefit. From a material perspective they do however also have downsides, mainly their brittleness. These patterns will be used in an industrial process, transported with pallet trucks between buildings and then used in harsh processes. The risk of the material breaking or chipping is quite high if it gets bumped around. Apart from all of this is of course the cost, additive manufacturing with ceramic materials within the industry is still relatively new and novel, there are not many companies manufacturing machines made for ceramics, and those that exist are often limited to specific areas, such as aviation or pottery-making[12], though there are signs that this might change in the future[13].

3.2.2 Metals

Metals could, like ceramics, be considered quite novel when it comes to 3D printing, though it has undergone great development the last years and there are several companies manufacturing 3D printers capable of printing metals[14], as well as some commercial companies which offer 3D printing services in metals[15][16]. Additive manufacturing with metals is still quite high end and only mostly used for complex parts where performance, in terms of weight or size, is of high importance[17]. This is not the case with these patterns and since polymers generally cost less[18], that would be the better option.

3.2.3 Polymers

Polymers are the most common material used in additive manufacturing. This is mainly due to two reasons:

- 1. The melting point is generally lower than that of ceramics or metals, see figure 3.1.
- 2. The price is generally lower than that of ceramics[12] or metals[18].

As can be seen in figure 3.1 it is not obvious that polymers should be cheaper than metals or ceramics. But the lower melting point will result in the machines being cheaper to manufacture, since the materials do not have to hold up for such extreme temperatures, and also that less energy is used for the process itself. With a lower temperature the material will generally cool and solidify quicker as well, resulting in quicker (and therefore cheaper) printing.

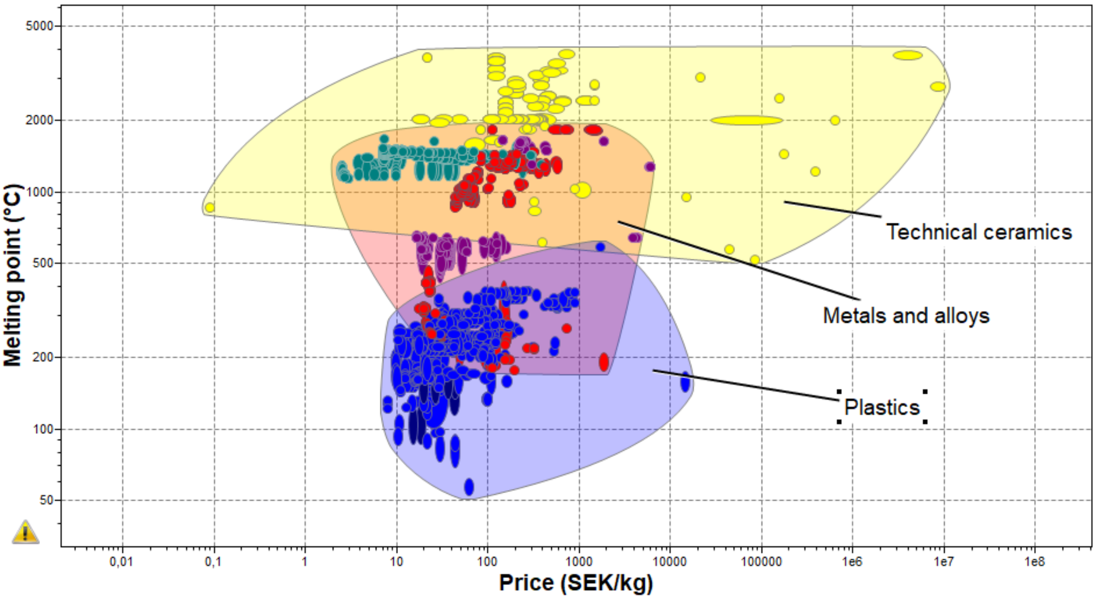


Figure 3.1: Cost versus melting point for ceramics, metals and polymers, the plot is taken from Granta EduPack.

Polymers have generally been looked down upon compared to more “natural” materials, like wood, metal and ceramics. Having a cheaper feel and generally been seen as the budget alternative. However, especially with the help of fibre reinforcements some polymers can compete with metals, especially when it comes to high performance parts where specific strength, or yield strength per density, is important. For example, carbon fibre reinforced PEEK has a yield strength between 75 and 2070 MPa with a density from 1.32 to 1.90 g/cm^3[19], giving it a specific strength in the range of 36.84 to 1568 $MPag/cm^3$. A high performance aluminium alloy, like 7075-T6 has a yield strength of 503 MPa and density of 2.81 g/cm^3[19], giving it a specific strength of 179 $MPag/cm^3$. Though these high performance materials tend to sometimes be more expensive than traditional materials, for example carbon fibre reinforced epoxi that could cost 35 USD/kg for low volumes[20])(equivalent to roughly 300 SEK as of September 2021[21]), while steel seems to be around 30 SEK/kg[22], depending on shape and alloy composition.

However, even for lower cost polymers the quality has gone up. Making plastics viable in many situations where it did not used to be. Though, in our case the material cost is not the main driving force. As explained earlier, in section 1.1.1, the patterns are today made out of wood. Wood is in this context not an expensive material, but the labour involved with manufacturing takes a lot of time and require skilled personnel. So for additive manufacturing to be a viable option in this case it is not mainly a matter of material cost, but rather the whole picture has to be taken into account. Some data for generic polymer materials can be seen in table 3.2 and figure 3.2.

Table 3.2: Mechanical data for some general polymer materials.

Nr	Name	Tens.Str.[MPa]	Brinell[kgf/mm^2]	Tg[°C]	Source
1	ABS	28.3	9.51	108	[23][19]
2	HDPE	27.6	4.77	-110	[23][19]
3	LDPE	9.6	1.99	-110	[23][24]
4	Nylon	85.5	10.61	111	[23][19]
5	PC	65.5	11.63	150	[23][19]
6	PEEK	96.5	19.38	145	[23][19]
7	PET	79.3	8.39	77	[23][19]
8	PTFE	10.3	3.06	-103	[23][25]
9	PVC	51.7	11.12	60	[23][19]

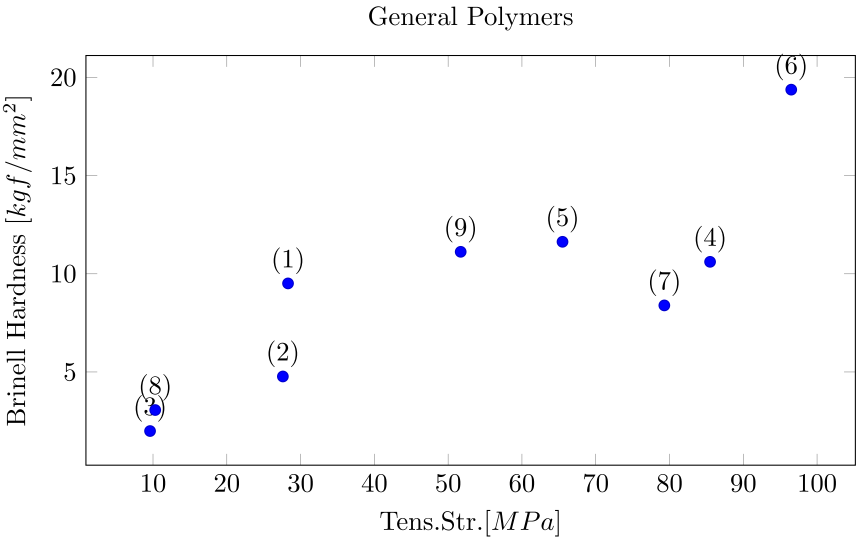


Figure 3.2: Plot based on data from table 3.2.

3.2.4 Reinforcements

To improve the mechanical properties of polymer materials several kinds of reinforcements can be used (it is also possible to reinforce metallic and ceramic materials in similar manners, but that will not be discussed here), this is especially useful and necessary for 3D printed structures since

Table 3.3: Mechanical data for some polymers suitable for Fused Deposition Modeling, FDM.

Nr	Name	Dens.[g/cm^3]	Tens.Str.[MPa]	HDT[°C]	Source
1	410MF07	1.16	30.7	70	[26]
2	ABS-CF10	1.1	21.3	99	[26]
3	ABS-M30	1.05	27.5	99.9	[26]
4	Antero800NA	1.28	59.7	147.23	[26]
5	Antero840CN03	1.27	52.6	150.8	[26]
6	Nylon12	1.01	41.8	84.3	[26]
7	Nylon12CF	1.01	32.7	153.7	[26]
8	PC	1.2	35.5	142.2	[26]
9	PC-ABS	1.1	25.9	102.9	[26]
10	PC-ISO	1.2	57	126	[26]
11	PLA	1.26	26	51	[26]
12	PPSF	1.28	55	189	[26]
13	Ultem1010	1.29	28.2	212.2	[26]
14	Ultem9085	1.27	39.4	172.9	[26]

Table 3.4: Mechanical data for some SLA resins.

Nr	Name	Dens.[g/cm^3]	Tens.Str.[MPa]	HDT[°C]	Source
1	48HTR	1.23	64	110	[27]
2	FLHTAM01	1.2	51.1	130	[28]
3	HTM140	1.2	56	140	[29]
4	PERFORM	1.61	80	119	[27]
5	Poly1500	1.20	30	52	[30]
6	Somos12120	1.15	77	110.7	[27]
7	Taurus	1.13	46.9	50	[30]
8	Xtreme	1.18	38	54	[30]

they tend to have worse mechanical properties than when conventional processes are used[31]. Two quite common methods of reinforcing polymers are fiber reinforcements and particle reinforcements[32]. They both have capabilities of improving properties such as tensile modulus and tensile strength, while also lessening the amount of distortions and shrinking in the final part. These effects are generally greater in fiber-reinforced parts, but also generally comes with higher cost than particle-reinforced parts. The particles used can be added directly to the filament and then printed practically as normal[32].

Introducing fibers can sometimes be more difficult but great advances have been made and there are today many Fused Deposition Modeling, see section 3.3.1, printers available that are capable of printing with continuous fiber reinforcement. This is especially useful since the improvements from fiber reinforcements depend heavily on fiber orientation, which can be controlled with an FDM process[32].

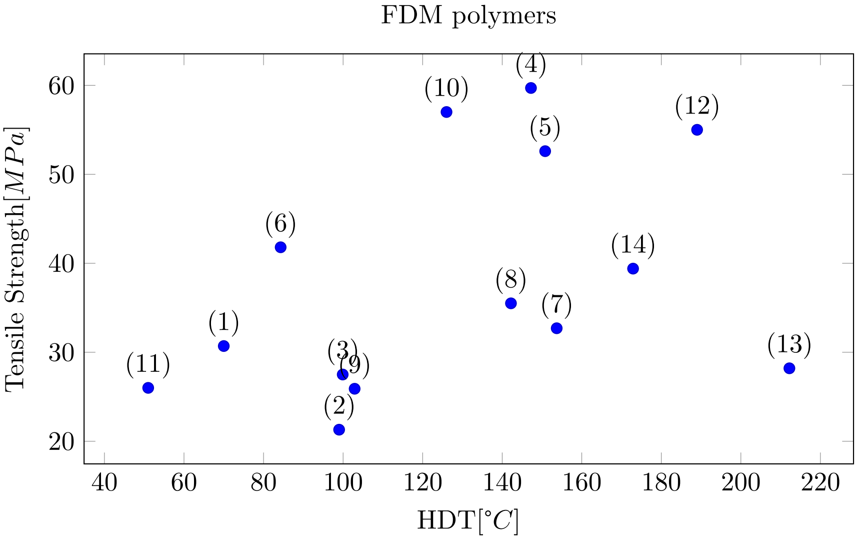


Figure 3.3: Plot based on data from table 3.3.

3.3 Printing technologies

Most 3D-printing technologies today works a layer technique. Where the model is “sliced” horizontally in a software to create 2D-layers. These slices, or layers, are then printed via different processes, one atop the other, to build up the 3D structure. There are processes which does not go this route, called “Additive Non-layer Manufacturing” [33], though these seem to mostly be experimental and not ready for commercial use.

3.3.1 FDM - Fused Deposition Modeling

The FDM method works via an extrusion process. The material is heated to an almost molten state, whereafter it is extruded through a nozzle that routed along a specified path to build up the model. Since the method is relatively simple and generally has the lowest investment-cost it has become one of the most common additive manufacturing processes for home and amateur use, but also for large scale industrial use. It is limited in material selection to those with relatively low melting point, such as thermoplastics, which could limit the strength and applications of the final product. Though the easy implementation of reinforcements could in some ways mitigate this shortcoming[32]. Another downside to this method is the need for support structure during the printing of overhanging features. This structure needs to be removed afterwards and recycled.

FDM can also be referred to as FFF - Fused Filament Fabrication. These two terms are interchangeable[34]. Data for some materials suitable for FDM-printing can be seen in table 3.3 and figure 3.3.

3.3.2 SLA - Stereolithography

Stereolithography uses UV light to cure a photosensitive resin, kept in a tank. A UV laser moves along the surface to create the 2D feature, which is then moved away one layer height from the laser and the next layer can be printed. Depending on if a “top-down” or “bottom-up” process is used the need for support structure could be less compared to FDM, and the surface finish is

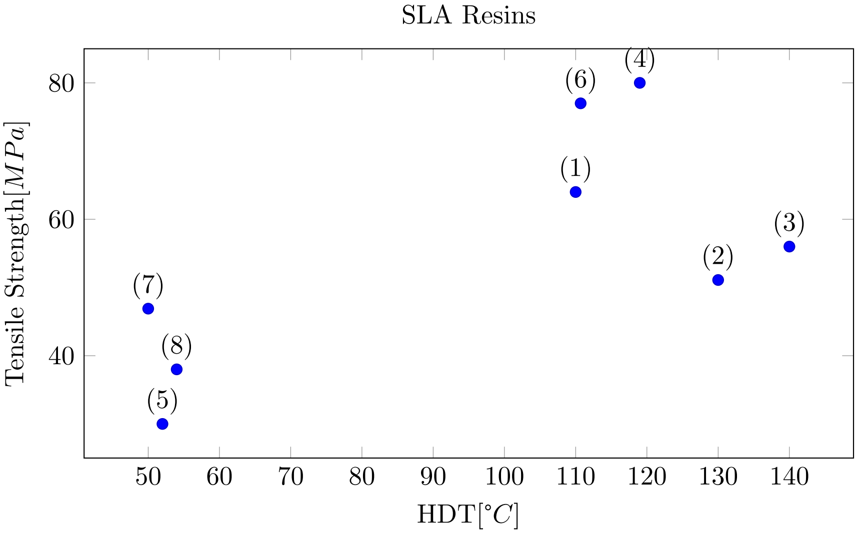


Figure 3.4: Plot based on data from table 3.4.

generally high. The process is generally slower though, not generally making it very suitable for larger objects. It also often requires post-process-curing[32].

The resins used can vary widely, so a proper material for the occasion should be possible to find, and it is even possible to include additives to improve properties[35]. However, the resins are cured using UV-light, and will usually remain light sensitive even after curing, meaning that the material will degrade quite quick of kept outside, and a bit slower if kept inside. This could be mitigated by painting or metal-plating, but SLA prints are not generally good for long term usage[36]. Data for some materials suitable for SLA-printing can be seen in table 3.4 and figure 3.4.

3.3.3 SLS - Selective Laser Sintering

As the name suggest, selective laser sintering is a process which selectively sinter together powder, using a laser. A thin layer is spread evenly across a surface, whereafter the laser goes over and sinter together a 2D-shape. A new layer is spread across out again and the process is repeated. When all layers are done the finished model can be lifted out and excess powder removed, this powder has not been affected by the laser and can be reused. The powder can be ceramic, metallic or a polymer, and depending on the process might need post-processing to finalize the sintering process[32]. Because of the powder supporting the build structure no extra structure is needed. The sintering also leads to better layer adhesion compared to other additive manufacturing methods, giving the resulting product a more isotropic structure[37].

3.3.4 InkJet Printing

The 3D InkJet printing functions similarly to a normal 2D printer, that you might have at home or in the office. Small droplets are disposed through a nozzle, and then immediately cured with an UV light. These droplets contain a slurry based on powder from the desired material. There can often be several printer heads next to each other, which gives one of the main advantages of this technique. Namely that these different nozzles could use different materials, and therefore create a part containing different materials with different characteristics. Another possibly use is to have on nozzle print the regular material and a separate nozzle for the support structure. If a uniform material is desired all printer heads could use the same material to decrease the printing time. Due to the use of powders virtually any polymer, and many other materials, could be used for this process[34][32][38]. PolyJet printing is a similar technology used by Stratasys, where no powder is used. Instead it prints in a photosensitive resin. It is capable of really thin layer sizes, but since the technology is relatively new the selection of resins is quite limited [34]. The sizes of machines available also seem to be relatively low and limited.

3.3.5 LOM - Laminated Object Manufacturing

In laminated object manufacturing a thin sheet of material is rolled of a drum, onto the working surface. It is heated and/or pressed to adhere to the layer beneath. After this a laser moves over the object and cuts the outer profile, as well as crosshatching the waste material for ease of removal afterwards[32].

It is a fast and cheap process, making it suitable for rapid prototyping. It is, however, not suitable for finished products or mass manufacturing. This is since the quality of prints are generally poor, requiring post-processing, and that removing waste material is an arduous process[39].

3.4 Material and technology selection

As shown in the two previous sections about materials and printing technologies, it is not a straight forward task to decide upon a material and suitable printing technology. Though some materials and technologies could probably be discarded right away for either not fulfilling the requirements or being too novel, and therefore too costly for our purposes. But this would still leave a large number of options without a clear way forward. Another main issue is that especially not all technology systems are readily available from potential sub-suppliers, and not all suppliers have a familiarity with all materials. To select a technology that is not available or a material that no one has any familiarity with would just be dumb, and of no use for this project. So to get a better idea of what is available and viable several swedish and european companies providing printing services for large objects were contacted. The outcome of this was however quite poor, with only two companies responding at first, whereof one later withdrew. This left only one company, which at least made the decision making quite easy. This company is based in Värnamo, Sweden and produces large FDM-printers, capable of printing parts measuring 1200x1200x1500mm. Their main business is selling these printers, but they also provide a printing service where you send in your CAD-models and they print them. They focus on large scale printing with high material throughput to decrease printing times. Their nozzle sizes vary from 2 mm to 8 mm, whereas the standard for at home printers seem to be 0.4 mm, though it is possible to print with upwards of 1 mm[40]. The result of printing with such a large nozzle will be a very crude print, not fit for direct use. Instead the idea is to print the pattern really fast and slightly oversize, and then machine the pattern to its final size.

In discussions about material selection they recommended an ABS plastic called SICOFLEX MZ341 S25000. Its material properties can be seen in table 3.5[41]. Since no hardness mentioned in the data sheet the generic value for ABS was taken from table 3.2.

There were also no indication of the glass transition temperature, so the general value of 108 °C for ABS was used[19]. As mentioned among the criteria, see section 3.1.2, the glass transition temperature will not give the full picture. Instead it is important to look at how the material

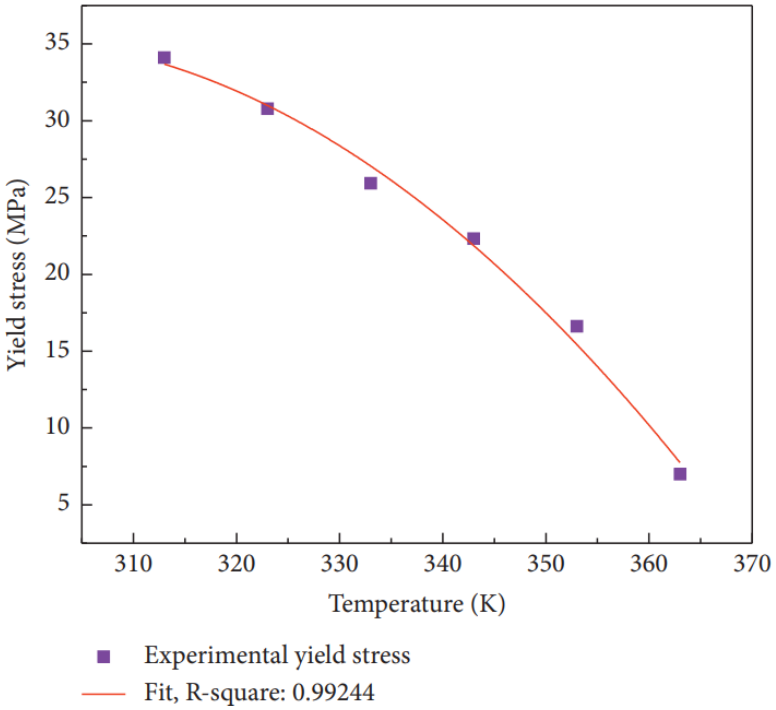


Figure 3.5: Yield stress at different temperatures for ABS XR-401 [42].

behaves at elevated temperatures below the glass transition temperature as well. The yield strength of ABS XR-401 decreases rapidly with increased temperature and with 90 °C it is down to roughly 7 MPa[42], see figure 3.5. It is assumed that our material, SICOFLEX MZ341 S25000, will behave in a similar manner. That means that this has to be taken into account and that the stresses are not allowed to be above 7 MPa. The increased heat will of course also soften the material and effect the displacement, but as a worst case scenario this could be accepted.

Table 3.5: Data for SICOFLEX MZ341 S25000[41].

	Value	Unit
Density	1060	kg/m^3
Tensile modulus	2200	MPa
Yield strength	40	MPa
HDT	91	°C
Melt temperature	210	°C
Glass transition temperature	108	°C
Brinell hardness	9.51	kgf/mm^2

3.4.1 Health concerns

With manufacturing there always comes a risk of exposure to things like chemicals, fumes or particles. By choosing the right material and process these risks can at least somewhat be mitigated. If it is deemed necessary to have processes or materials deemed to be dangerous necessary precautions should be taken. These could be things like proper ventilation, personal respiratory protection, eye protection and so on.

3.4.1.1 3D-Printing

The additive manufacturing method of FDM, fused deposition modeling, can be likened to a CNC-controlled extrusion process. Where the polymer is heated to a semi-liquid state at which it can be disposed in a controlled manner onto a platform, layer by layer to create a 3D-structure. It is primarily this heating that could cause issues. This increased temperature primarily result in volatile organic compounds, VOCs, and ultrafine particles, UFPs [43][44][45].

The health implications from both VOCs and UFPs depend heavily on concentration and exposure time. In small amounts VOCs can produce eye and nose irritations, as well as nausea and headaches [46]. Longer term exposure can cause real harm to the central nervous system as well as other organs [46][47]. Cancer is also suspected as a long term effect of some VOCs [46]. It should however be noted that not all VOCs seem to be show any health concerns, and that the long term effects of low level exposure is still being investigated[46]. Ultrafine particles enters the body through inhalation. They are then small enough to pass through the lung organ and subsequently travel to other organs. Since the lungs are the first line of defense respiratory conditions are also the most common, but cardiovascular diseases, diabetes and cancer have also been linked to UFPs, but more research is needed in the area [48]. It should also be noted that there are many sources for UFPs commonly around us everyday, and increased amounts are not unusual. In a 2 and a half year project the particle concentrations in five european cities were measured. In Stockholm it varied from 2781 to 37 279 $particles/cm^3$, while it reached over 175 000 $particles/cm^3$ in Barcelona[49]. These particles can come from a variety of sources, like cigarettes and cars, but of course also from industrial plants and in small part also from 3D-printers[44].

3.4.1.2 Usage

With use comes wear, and it is not unlikely that the pattern will be damaged in some ways. It could get bumped into by a pallet truck or accidentally dropped and damaged that way. In these instances there is usually a crack or a void that will be filled and sanded down. To glue ABS together, or fill cracks and dents, a slurry made from ABS granulates and acetone could be used [50]. This is also what the 3D-printing supplier recommended, and how they glue together larger pieces. Acetone is frequently used in several applications. It is commonly used as a solvent or paint thinner, nail polish remover or degreaser[51]. The risk level of acetone is quite low, with low levels of acute or chronic consequences. Intermittent or occasional use was not considered adverse[52]. This does not mean that it is completely safe either. If no breathing protection is used, or the ventilation is insufficient, the fumes can irritate eyes, skin and throat together with risk of headaches or dizziness. It may also cause damage to the nervous system if large amounts are inhaled, but no clear conclusion on this topic has been drawn[53]. To avoid these risks long armed garments together with protective gloves and glasses should be used[54]. The main risk with acetone is the fire hazard. The liquid as well as the fumes are highly flammable and should be kept away from any open flames or risk of electric discharges[53].

Sanding always create dust, this is true for wood as well as for polymers. It is an easy thing to assume that wood dust is not very dangerous since it is such a natural material that humans have worked for a very long time. This is, sadly, not the case. When woods are sanded they can break down into fibers that when inhaled can lead to everything from coughing to cancer[55]. How dangerous the wood dust is depends on different factors, like species and sanding grit[56][57]. Dust from plastics is also harmful, and can not be ruled out as a safety concern. Apart form the more obvious concerns with inhaling dust and the short term effect most people have experienced, like irritation and coughing, polymer dust can also lead to more advanced effects, like pneumoconiosis also called “miners lung”[58]. A further worry with sanding or grinding polymers is the risk of unreacted plasticizers, stabilizers and hardeners that the polymer may contain[58]. Another large concern is from thermal decomposition. When heated several polymer variant may start do decompose, loosing mechanical properties and releasing potentially toxic and flammable fumes as a consequence. The temperature at which this occur, however, seem to be far above both normal and maximum temperatures that may occur during operation[59][60], this concern can therefore be dismissed.

3.5 Cost analysis

A part from the strictly functional view on this problem (that is: is it possible to make functional patterns with additive manufacturing?) it is also important to look at the economical aspect. Most things are possible to achieve if enough money and resources are available, but it has to make economical sense for any company or single person to see it as a viable solution. In this section the manufacturing and storage cost of the two alternative manufacturing methods will be evaluated and compared. However, as stated in the project formulation (see section 1.2), the main focus of this project is not the economical side and patterns made through 3D-printing could still be seen as a viable option even if their cost is somewhat higher than those made in the conventional way.

To simplify the comparison only the outer patterns will be compared. Since the inner and outer parts are made quite similar these results can then be viewed as representative for the whole.

3.5.1 Polymer based additive manufacturing

Though making a pattern using additive manufacturing might seem simpler than the conventional method described in section 3.5.2, and it might very well be, but it is still a process with several steps and things to consider. The first production step is of course the printing itself, where the material, together with any support structure is printed. Afterward comes the post processing, this can have a few different forms depending on which additive method is used, but generally the support structure will be removed and in some cases tempering (or curing) will be performed to enhance material properties[28].

Depending on what surface finish that is required it might then be necessary either do some milling or sanding, or milling followed by sanding to make the surface smoother. Since it is currently not possible to print the parts on site the finished part will also have to be transported, some transportation between manufacturing sites might also be necessary if one supplier can not do all processes.

Table 3.6: Summation of cost for the manufacturing of 3D-printed patterns.

Operation	Cost[SEK]	Percentage[%]
Material	3 150	12.12
Printing time	5 585	21.49
Milling	17 000	65.41
Transportation	255	0.98
Total	25 990	100

3.5.2 Traditional wood pattern manufacturing

As mentioned earlier, making the wood patterns is not a straightforward operation. There are many separate jobs that all have to be carried out in a good way to make the final object come out in the desired way. The wood is purchased milled and dried, but still has to be planed flat and square. From these pieces circle segments can be cut out in preparation for gluing up the large turning blanks. These are glued and clamped up in overlapping layers, oversized compared to the finished part, more about this process can be read in section 1.1.2. The cost of wood and plywood varies over time and has recently increased substantially. The purchase price for the company has increased from a normal level around 6000 SEK/m^3 to a current price of 10 400 SEK/m^3. Where it will go from here is unclear, though it is possible that it will return down to normal levels, it is impossible to know for certain and the current price will still be used.

Table 3.7: Breakdown of material cost for making the wood patterns.

Material	Amount	Unit	Cost per unit	Cost[SEK]
Wood(pine)	0.33	m^3	10 400	3 432
Plywood	1.488	m^2	672	1 000
Total	-	-	-	4 432

Table 3.8: Breakdown of manual labour times for making the wood patterns.

Operation	Time[hours]	Cost per hour[SEK/hour]	Cost[SEK]
Planing+Sawing+Gluing	24	480	11 520
Lathe-work+Finishing	8	480	3 840
Total	32	480	15 360

Table 3.9: Summation of cost for the manufacturing of wood patterns.

Operation	Cost[SEK]	Percentage[%]
Material	4 432	22.39
Manual labour	15 360	77.61
Total	19 792	100

3.5.3 Storage cost

When it comes to storage there are several things to consider. First there is the cost associated to having space allotted to storage. This is space that could otherwise have been used for other things, such as production. There are then maintenance cost for the building itself, making sure that it stay in shape and will not deteriorate. This cost will depend on what type of building it is for how much maintenance that will have to be done. Also depending on the building, as well as what things are stored there, some climate control system will also be needed. This could for example be keeping the space cold if you were to store food. In this case the main concern is to keep the moisture level constant to minimize wood movement. It would also be possible to look at the cost for repairing patterns due to wear over time, and incidental damages, but since these can be assumed to be similar for both parts this cost will not be taken into consideration here.

There are some costs associated with storing plastic parts as well. With some plastics it could be possible to store them outside, meaning that the only cost would come from land use, but in general they have to be stored inside since most plastics are UV-sensitive, see section 3.2.3. This means that they will also have the costs associated with allotted space and building maintenance. However, climate control in the way that was used for the wooden patterns should not be necessary. Polymers are not at all effected by differing moisture content, and the expansion and contraction that occur due to temperature shifting is negligible. If we say that the temperature might shift 10 °C, with a coefficient of thermal expansion, CTE, of 80 µm/m°C (which is the average value for ABS[19]), that would mean that the pattern, having a height of roughly 0.6 m, would grow 480 µm, or 0.48 mm. This could be contrasted with pine-wood that would swell between 1.14 and 1.92 mm (depending of wood orientation) for every percentage of moisture increase[61]. Considering that the moisture level in wood can vary from 2-6% during winter to 7-12% in the summer, though in a heated house with no extra climate control[62], really shows how large these dimensional fluctuations could be. To combat these fluctuations a dehumidifier is in use in the pattern storage facilities. It has a rated power consumption of 12.66 kW and runs all year around. With 8760 hours in a year that gives a total energy usage of 110 901kWh per year. The energy cost differs throughout the year, but a conservative estimate could be around 1 SEK/kWh, which would result in roughly 110 000 SEK per year. This is, however, for the entire storage area. There are approximately 225 pattern sets (complete sets of inner and outer) of varying sizes in the storage facility. The pattern looked at in this project is amongst the smaller ones, and if all patterns were of its size at least there would be room for at least 300 pattern sets. If the energy cost were divided equally between these patterns currently in the room that would mean a yearly cost of:

$$\frac{110901SEK}{225} = 492.89SEK \tag{1}$$

If instead the estimated number of 300 is used the yearly cost comes out as:

$$\frac{110901SEK}{300} = 369.67SEK \tag{2}$$

So roughly speaking between 350 and 500 SEK/year for the pattern set, or 175 to 250 SEK/year if cost is distributed equally within the set. If the lifespan of a pattern is estimated to 30 years that would add up to roughly 6500 SEK.

3.5.4 Conclusion

As can be seen in table 3.6 and table 3.9 the cost for manufacturing of the 3D-printed option comes out as 25 990 SEK and the one made in wood comes out as 19 792 SEK. So there is definitely a difference in favour of the wood variant, then there is also the running storage cost that has to be taken into consideration. This adds another 6 500 SEK over a lifespan of 30 years, bringing the total for wood up to 26 292 SEK. This makes the two options more equal. The lifespan of 30 is used since, as mentioned in section 3.1.4, some of todays patterns are already over 20 years and are still in good condition and are far from worn enough to warrant being replaced.

3.6 Environmental analysis

When looking at a new manufacturing method or changing component materials, it is not only the production cost that will change. The environmental impact will also differ. This could be for the better or for the worse, it could also be that the new method or material could be better in some instances and worse in others. In this section there will first be a general discussion of potential environmental aspects and differences between the traditionally made patterns and the prototype made with additive manufacturing. This will be followed by a small data based comparison. Carbon dioxide equivalents, CO_2e, will be used as the comparing unit. CO_2e is the main driving force behind the greenhouse effect and is commonly used as a comparison between different alternatives in life cycle analyses[63].

For this evaluation, just as for the cost comparison in section 3.5, only the outer pattern will be looked at.

3.6.1 Discussion

3.6.1.1 Material and recycling The most obvious difference is of course the materials. Most polymers are petroleum based, meaning that they are in one way or form made from a fossil resource. Though the question about how and when to best use the forest have been raised, wood is still a renewable resource[64][65][66]. When the tree grows it captures carbon from the atmosphere, which is then stored in the wood. As long as the wood is then kept in use, be that housing, furniture or in our case, casting patterns, it will still hold this carbon. Thus having a negative impact on the carbon dioxide level in the atmosphere, which is a good thing. This carbon is then released once the wood is decomposed naturally or burned, but it will only release the same amount of carbon that it captured during its lifetime. Making it a net zero game, not considering the energy used for harvesting, transportation and machining of the wood. If that is taken into consideration the CO_2 footprint is still less than 0.4 kg/kg of wood[67], and an energy consumption of less than 10 MJ. The same can not be said for fossil resources, like polymers. Just from the creation of the material ten times more CO_2 will be released when compared to wood(between 3.6 and 4kg/kg, and 90-99 MJ/kg for ABS[67]). After their lifetime, if they are burned, carbon that they are built up from is released, this can be seen both as a way of regaining some of the energy put into making the material, but it will also release large amounts of carbon dioxide. Burning of plastic waste is quite common, especially in Sweden. This is called energy recycling. The energy generated from burning waste is usually used for a combination of district heating and electricity generation, and is a way of decreasing the necessity of pumping up new raw oil[68]. If this energy recycling was not conducted, and they were just left at landfills. The carbon would in a way still be captured withing the parts, and only be released slowly since polymer based materials generally decompose much slower than wood. However, this is also a problem. The plastics will degrade to microplastics which can have severe influences on soil quality and from leaking into ground water also having an effect on animals drinking that water. A positive aspect of parts made from plastic is that they could sometimes be almost fully recycled. The material can be ground down into granulates, this granulate can then, in the case of thermoplastics like ABS, PLA and polycarbonate, be melted down and reused to make new parts. This is not a perfect process, and the material properties tend to degrade over time. To overcome this and ensure good properties it is common to add some virgin material[68]. The percentage of virgin material that has to be added depends on how contaminated the recycling material is. Industrial waste is generally seen as cleaner and requires less new material, while consumer waste if often contaminated by food remnants, paper and other plastics. Recycling wood in the same way is of course not possible. The only type of recycling of wood that is commonly practiced is the energy recycling talked about earlier.

3.6.1.2 Manufacturing Here there are also some pros and cons. The first thing that will be discussed is sourcing and shipping. The majority of the wood used comes from swedish forests (some high wear parts are made from american maple). The wood is dried at the and packaged at the lumberyard before it is shipped to the company where the rest of the manufacturing takes place. The exact route for the polymers depends on what supplier, sub-supplier and so on. But the material will most definitely have travelled a longer route before it reaches the foundry site.

The material utilization at least has a great potential of being much better for for the plastic pattern. With additive manufacturing the material can be added right where it is needed. There is often some support material that will be removed, and some post processing machining might be necessary to achieve a good surface finish, but this is usually much less than for the conventional method described in section 1.1.2. Though the manufacturing processes differ very much from each other it is hard to say that one would have a much larger environmental impact than the other. The additive manufacturing process likely requires much higher power, and the same goes for CNC-milling, but making the wood pattern is a much longer process, with constant human involvement. It is especially this last part, the human part, that makes the two methods hard to compare. For the additive manufacturing it is slightly easier.

Polymer We first have to start with the $C0_2$ footprint of the primary production. Polymers are a global commercial product that will have to be imported, the emission equivalent of making 1 kg of ABS is between 3.6 and 4 kg of CO_2[67]. If we see the additive process as an extrusion process, which is at least true for an FDM-process, then the energy consumption is 5.8-6.4 MJ/kg[67]. With production in Sweden, with swedish electricity production, that is equivalent to 76-84 g of CO_2e per kg of extruded plastic. Swedish electricity produces 13.1 gCO_2e/MJ as of 2013[69]. After this there will likely be some machining, but since plastics are generally softer than metals the required energy will also be lower, possibly around 0.8 MJ per kg of removed material[67], which would result in 10 g of CO_2e per kg of removed material. This is in of it self lower than the main material production, but the amount of material is also much less. According to data from the supplier approximately 75 kg of material will be used during the printing process. This includes the actual part, any machining allowance, as well as the support structure previously mentioned. The base material it self would account for emissions of:

$$75kgABS * 3.8kgCO_2/kgABS = 285kgCO_2 \tag{3}$$

The printing of this material would then account for an energy consumption of:

$$75kg * 6.1MJ/kg = 457.5MJ \tag{4}$$

Which would be responsible for CO_2 emissions of 6000 g = 6 kg. The finished weight is estimated at 56 kg, meaning that there is 19kg that will be removed. This would result in 15.2 MJ. Equivalent to 190 g = 0.19 kg of CO_2.

Wood The wood is sourced relatively local, from swedish forests, so here specific values for swedish production can be used. For sawn coniferous lumber in Sweden the carbon emissions varies between 24-37 kg/m^3[70]. The estimated use is 0.33 m^3 for the outer pattern. If the average carbon emission is used, then the emissions are roughly 10 kg, of CO_2.

$$0.33m^3 * 30.5kg/m^3 = 10.06kgCO_2 \tag{5}$$

Then there is the plywood used. Half a sheet, originally having the dimensions 2440x1220x15 mm, is used. Three circles are cut out on it and then glued together to make a 45 mm high cylinder. It becomes a part of pattern and sits quite close to the top. Anyway, its volume is 0.0223 m^3, and with a density of 460 kg/m^3[71] that gives it a weight of 10.27 kg. The conservative value given by *Boverket* is emissions of 0.4475 $kgCO_2e/kg$[71], which gives the emissions in this case as:

$$10.27kg * 0.4475kgCO_2e/kg = 4.60kgCO_2 \tag{6}$$

The description of the machining process is described in more detail in section 1.1.2, but can roughly be broken down to planing, sawing and turning. Getting a good estimate for the energy consumption per kg of waste material here is hard. Consider for example when the circle segments are sawn out. Cutting the kerf will require the same amount of energy no matter how large the waste side is. In an attempt to overestimate, rather than underestimate, the energy usage the same value as for machining plastics will be used, that is 0.8 MJ per kg of removed material. The next hard question is how much material is removed? Or possibly, how much of the initial material is left in the pattern? The best way of doing this would probably be to base the calculations on full scale drawings that the pattern-maker has prepared.

Figure 3.6: The full scale drawing used to make the patterns.

The drawing is made in full scale and shows the layers built up from the circle segments. The drawing shows internal and outer surface of the patterns, as well as the layers to create both the inner and outer pattern. Based on this drawing and the surface used throughout the project, a 3D-model having the dimensions of the finished wood pattern was made. This can be seen in figure 3.7. Within SolidWorks it is then possible to get the models volume, which in this case was 0.1019 m^3. This means that the waste wood is:

$$0.33m^3 - 0.1019m^3 = 0.2281m^3 \tag{7}$$

With an average density for pine being 440 kg/m^3[70], that gives the weight of the waste material as:

$$0.2281m^3 * 440kg/m^3 = 100.36kg \tag{8}$$

And thus the energy consumption and subsequent CO_2e as:

$$100.36kg * 0.8MJ/kg = 80.29MJ$$

$$80.29MJ * 13.1gCO_2e/MJ = 1051.80gCO_2e = 1.05kgCO_2e$$

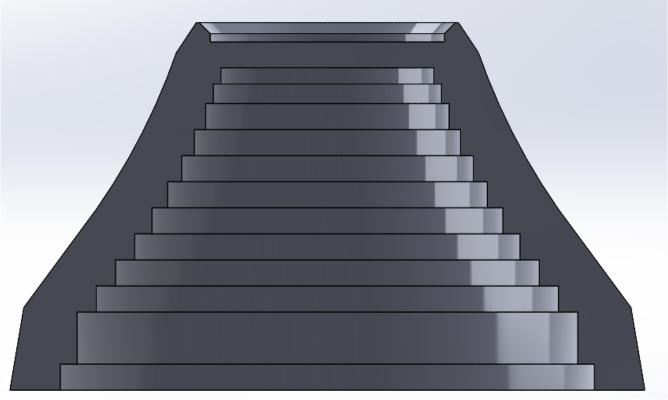


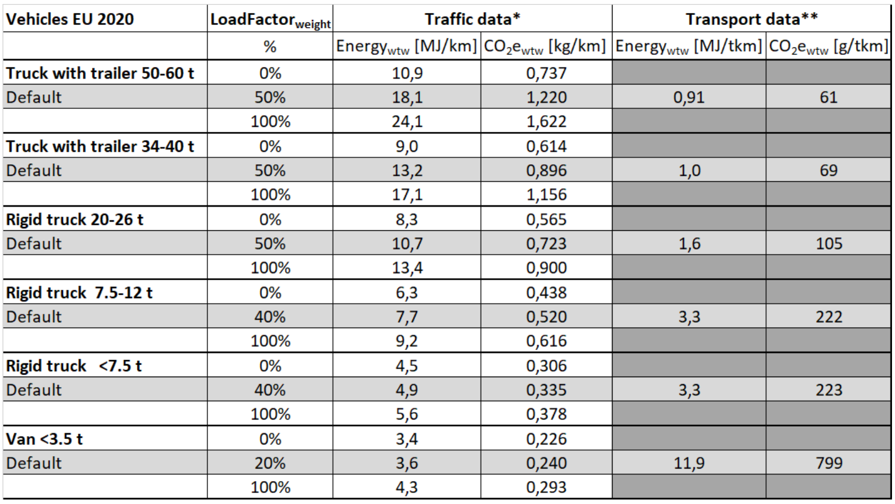
Figure 3.7: 3D-model of the wood pattern.

3.6.1.3 Transportation The 3D-printed pattern is shipped in its finished form. It is first printed at one location and then shipped to another location for milling. That is a 47 km distance. After that the finished part is sent to the factory plant, adding another 197 km. Making the total 244 km. The traditional wood patterns are made on site and therefore does not require any further transportation, but the material to make the patterns still has to be shipped. The lumber that the company buys is shipped only 25 km from the supplier. This is not a sawmill and only works as a retailer in this regard, but the wood is from Sweden. One could argue that it is the total distance from the sawmill to the factory that should be used, but then the transportation route from the polymer factory to the 3D-printing location should also be used. It was decided that in this case it would be better, and more feasible to only look at the last transportation step. As can be seen in figure 3.8 it is not only the distance that determines emissions from shipping. The weight of the cargo of course also has an impact, as well as what type of vehicle is used. We are dealing with two different types of transport in this case. The transportation of the wood for the traditional pattern will be shipped on a full truck, though it is likely that it will be of relatively small size. When ordering you do not order for just one pattern, rather a larger amount is ordered and then stored until needed. So here transport data values are used, assuming that the truck is fully loaded. For type of vehicle the rigid truck < 7.5 t will be used. The 3D-printed pattern will be delivered on a dedicated truck, the same size of vehicle will be used, but the traffic data will be used instead of the transport data. The load factor is the factor of how much you are transporting over how much that could be transported, when the vehicle gets closer to the maximum load its fuel consumption will also increase. In this case with the two pattern halves weighing approximately 100 kg each, making the pay weight 200 kg. This makes the load factor:

$$L_f = \frac{200}{7500} = 0.02667 \tag{9}$$

Or just over 2.5%, so for our intents it is reasonable to set it to 0%.
Since the truck will be shared between the two patterns the emission will also be split into two.

- Polymer
  - Distance = $D_p = 244$ km
  - Emission per km = $E_p = \frac{0.335}{2} = 0.1675\ kgCO_2e/km$



Vehicles EU 2020	LoadFactor$_{weight}$	Traffic data*		Transport data**	
	%	Energy$_{wtw}$ [MJ/km]	CO$_2$e$_{wtw}$ [kg/km]	Energy$_{wtw}$ [MJ/tkm]	CO$_2$e$_{wtw}$ [g/tkm]
Truck with trailer 50-60 t	0%	10,9	0,737		
Default	50%	18,1	1,220	0,91	61
	100%	24,1	1,622		
Truck with trailer 34-40 t	0%	9,0	0,614		
Default	50%	13,2	0,896	1,0	69
	100%	17,1	1,156		
Rigid truck 20-26 t	0%	8,3	0,565		
Default	50%	10,7	0,723	1,6	105
	100%	13,4	0,900		
Rigid truck 7.5-12 t	0%	6,3	0,438		
Default	40%	7,7	0,520	3,3	222
	100%	9,2	0,616		
Rigid truck <7.5 t	0%	4,5	0,306		
Default	40%	4,9	0,335	3,3	223
	100%	5,6	0,378		
Van <3.5 t	0%	3,4	0,226		
Default	20%	3,6	0,240	11,9	799
	100%	4,3	0,293		

Figure 3.8: Energy and emission data for road transportation in the EU[72].

  - Emissions total = $E_{ptot} = D_p * E_p = 244 * 0.335 = 40.87kgCO_2e$

- Wood
  - Distance = $D_w = 25$ km
  - Weight = $W_w = 0.33m^3 * 440kg/m^3 = 145.2kg = 0.1452t$
  - Emission per km = $E_w = 0.223\ kgCO_2e/tkm$
  - Emissions total = $E_{wtot} = D_w * W_W * E_w = 25 * 0.1452 * 0.223 = 0.809kgCO_2e$

Giving a factor of 50 between the two alternatives.

3.6.1.4 Usage

For the foundry work it self there will be no major difference, especially not from an energy of environmental perspective. The only difference during the usage phase will be the storage. The wood patterns need a proper storage facility, with climate control, especially in the sense of humidity control. Polymers, on the other hand, are not affected by humidity levels in the same way at all and could theoretically be stored outside, as long as they had some protection against UV-light, though it would make sense to have them inside as well since even polymers will expand and contract depending on temperature. So only looking at energy and emissions from the humidity control, assuming heating is the same, which is around 110 000kWh(see section 3.5.3) for the entire storage room, and 470 kWh of that could be attributed to the single pattern set. That is equivalent of 1692 MJ. As discussed is section 3.6.1.2, each MJ is responsible for 13.1 gCO_2e. This gives the yearly emissions from humidity control to:

$$1692MJ * 13.1gCO_2e/MJ = 22165gCO_2e = 22.2kgCO_2e \tag{10}$$

As all other comparisons in this section has been done with outer pattern alone it would be suitable to do so here as well. We therefore split this emission in half to distribute it between the two pattern halves equally, resulting in yearly emissions of $\underline{11.1\ kgCO_2e}$.

3.6.2 Results

Table 3.10: Emissions from making the pattern with additive manufacturing.

	CO_2e Emissions[kg]	Percentage[%]
Material	285	85.82
Extrusion	6	1.81
Machining	0.19	0.06
Transportation	40.9	12.32
Total	332.09	100

Table 3.11: Emissions from making the pattern out of wood.

	CO_2e Emissions[kg]	Percentage [%]
Pine Wood	10.1	60.99
Plywood	4.6	27.78
Machining	1.05	6.34
Transportation	0.81	4.89
Total	16.56	100

3.6.2.1 Conclusion Wood is a “green” and renewable material with low environmental impact, its main downside is that it is a “one time use” material, though this “one time” can be very long depending on the service life of the pattern.

Polymers, on the other hand, have a much higher environmental impact but is recyclable to a certain extent. Recycling the material would decrease the carbon footprint of manufacturing quite dramatically, though still being above that of wood. However, the emissions from keeping the humidity stable enough for the wood results in emissions in the same magnitude yearly as can be attributed to their manufacture. As it stands right now it would take around 30 years for the pattern to “save” as much emissions, from not being effected by the humidity, as it have in deficit from its manufacture compared to wood. This time could however be shortened quite extensively if the main material was recycled, or at least contained a large amount of recycled material.

4 Phase 2: Production plan

4.1 Supplier contact

In conjunction with the 3D-modelling, contacts was taken with companies offering 3D-printing services. A sample part meant to show the size and complexity required was sent to potential suppliers. The main focus was on companies with production in Sweden, to reduce transportation times and cost as well as making the overall communication easier, but a number of European companies were also contacted. In spite of repeated attempts to establish contacts the response rates were disappointingly low, with one company ending up being the only alternative. Throughout the remainder of the design process there were several contacts with this company, both with regards to the material selection, see section 3.4, and with the design it self to ensure that it would be possible to produce. Our contact at the 3D-printing company then recommended another company that they have worked together with in the past that could do the milling.

4.2 3D-modelling

Additive manufacturing differs from regular manufacturing in that it is much more reliant on the 3D-model for its creation than conventional manufacturing. Generally no drawings are needed. Instead the software only looks at the model and tries to recreate it the best it can. This somewhat resembles CNC-manufacturing, where the path is created using CAM software, but this generally requires some person oversight who looks over the code and makes adjustments. A CNC-program could also be created solely based on 2D-drawings. Something that, though it should be theoretically possible, does not happen with 3D-printing. Because of this it is critical that the 3D-model looks the way that the print should be performed, not how the final product should look. Often the user have to scale to model to account for shrinkage[73], or make the model overly large to have room for post-processing like sanding, grinding or milling.

This differ much from the current process, described in section 1.1.2. Here a lot is left to the pattern-maker. The designer usually only specify the shape of the actual pattern surface, the surface that will determine the imprint in the sand. The rest is left to the pattern-maker that decides on wall thicknesses, support structure, hole placement for vacuum and so on. With the pattern production being outsourced, and with it being a more automated process all of these decisions have to be made and specified by the designer. This will result in an increase of the workload for the designer, but also increased control of the finished product.

4.2.1 Interface with support plate

The two pattern halves are fastened to their respective support plates in slightly different ways, though they both use wood screws as the main way of fastening. If this project has a positive outcome, and if it is decided to continue using 3D-printed patterns, it could be worth looking into other ways of solving this interface. There are lots of potential ways of doing it, but that would be outside the scope of this project, and it would be unwise to have it involve more problems which could lead to failure. It is safer to test one aspect at a time, and if that succeeds then try to improve on it further in the future. This would of course be different if there was a big need to change this, if for example the material was changed to something much harder or softer that would not work with the fastenings used today. This is, however, not the case and though there exist specific thread forming screws for plastics, normal wood screws will work fine[74].

4.2.1.1 Outer pattern The outer pattern, see figure 4.3a, is fastened directly to a flat plywood board. Beam compasses are used to find the center and marking a big centered cross on the board. With this it is then possible to measure and mark where the outer edges of the pattern will land and center it using these marks. It is then screwed in place from underneath. Attempts have been made to use location pins instead. This would theoretically allow for higher accuracy and also allowing the pattern to be removed and replaced for adjustments or repair. However, at least for wood this proved to be a worse alternative. If the pattern got dropped or bumped it would dislocate the pins, resulting in an offset pattern. This could of course happen with only wood screws as well, but with them it would be easy to fix, while it is practically impossible with the location pins.

4.2.1.2 Inner pattern The inner pattern is fastened in a slightly more difficult way. It is made upside down in relation to how it is showed in figure 4.3b. The pattern has a rebate which makes the whole pattern fit inside a hole in the support plate and rest against the recess. This can be seen in figure 4.1. The hole in the plate is made slightly oversize to allow for some adjustment, this gap is then filled with epoxy. Wood screws are then used to hold the pattern steady against the support plate. Because of the glue used to fill the joint it is not possible to adjust this part of the pattern if it were to move, but the glue joint also makes it more stable, so it is less likely to move in the first place. Also, since it is not actually critical that they sit exactly in the middle, what matters is that the two patterns are coaxial, it will always be possible to move the outer patterns so that it aligns with the the this one. Another difference, visibly in figure 4.1, is the bottom support plate, this also gives extra stability to the pattern when in use. The two support plates are connected with the flask, and must have a set distance between them for the flask to hold them correctly.

4.2.2 Modelling

The base model provided by the company had the desired shape of the void left by the two sand-molds. Meaning that it was slightly larger than the final product since you also in casting have to take shrinking and post-processing into account. This model can be seen in figure 4.2. From this model the inner and outer surface was taken to use as the basis for the two patterns that will be used. These can be seen in figure 4.3.

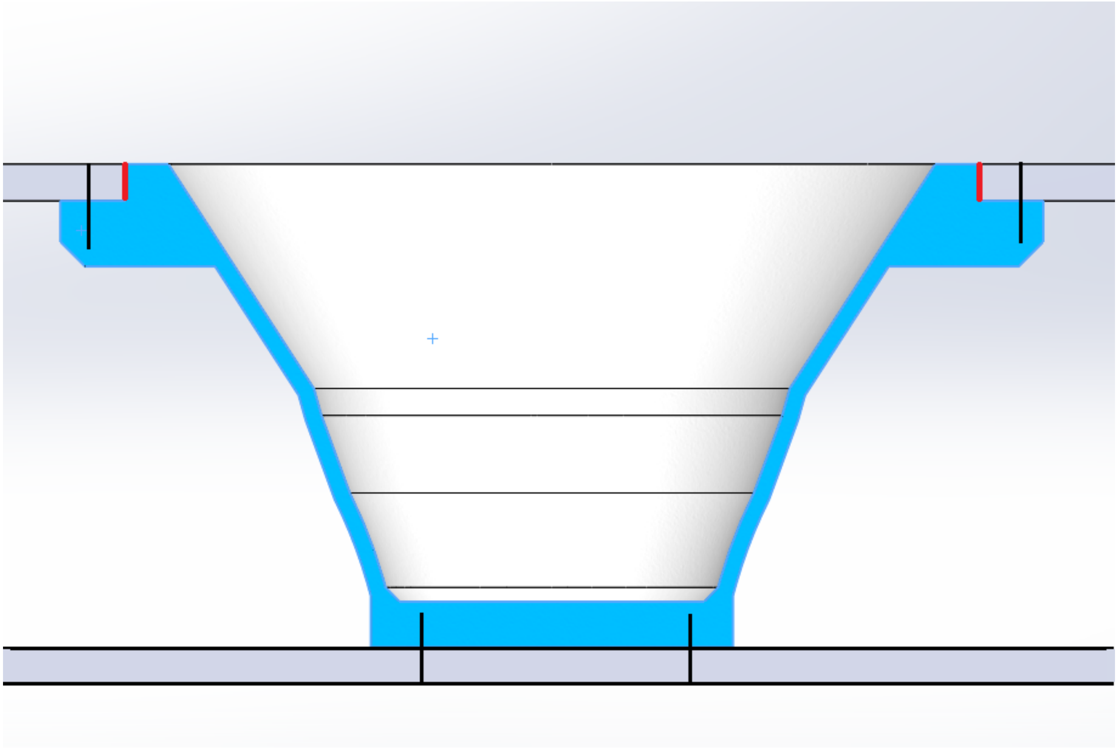


Figure 4.1: Image of inner pattern (blue), its support plates (grey), glue joint (red) and screws (black).

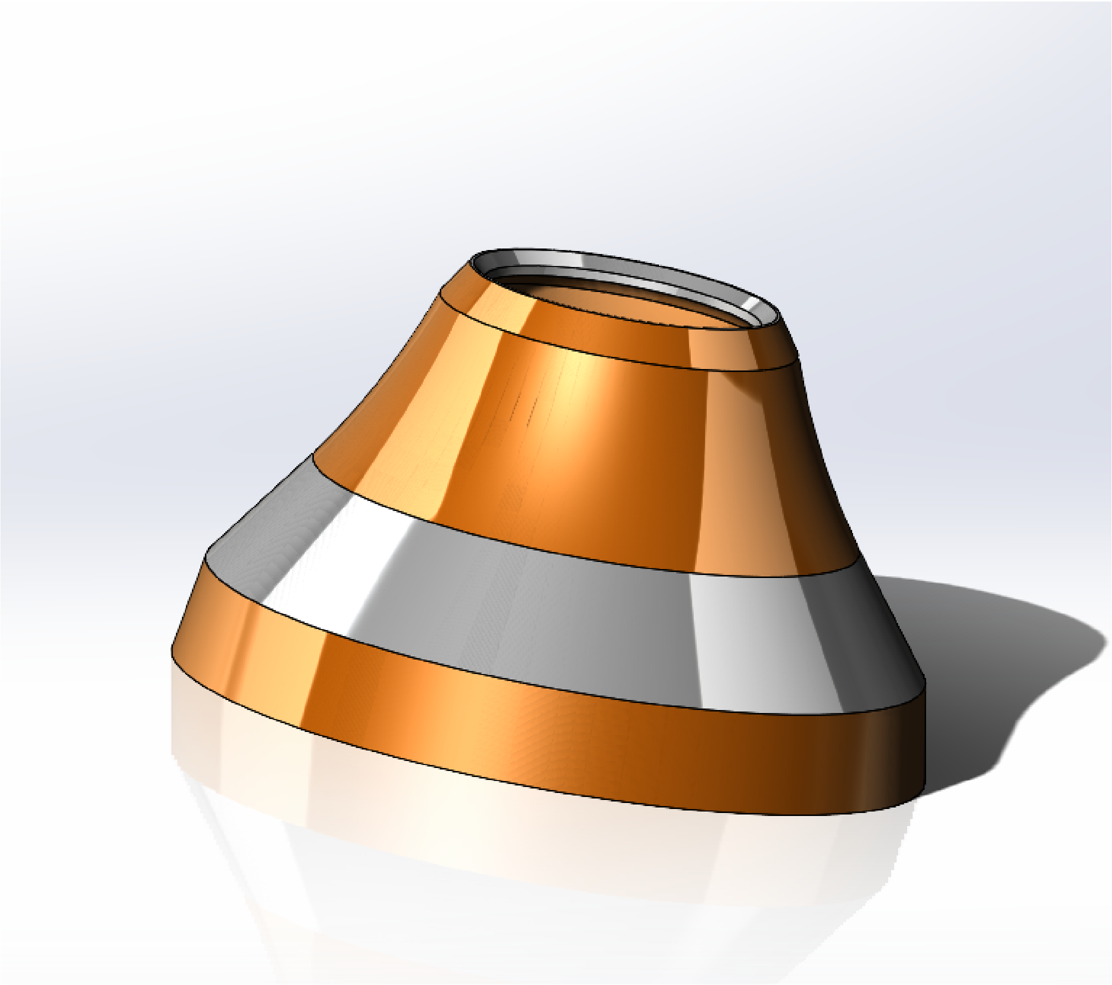
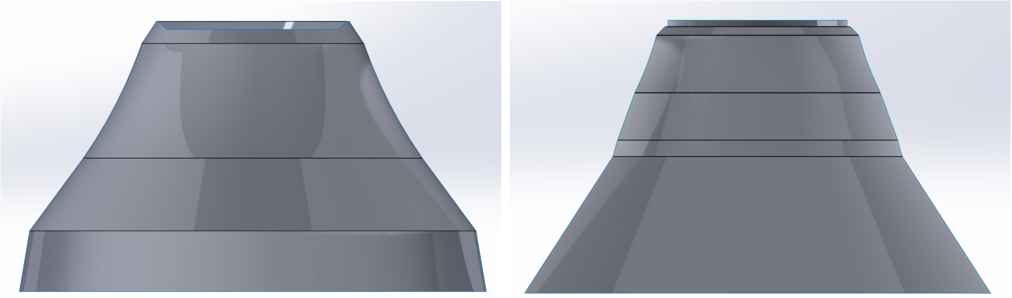


Figure 4.2: The original model.



(a) Outer surface

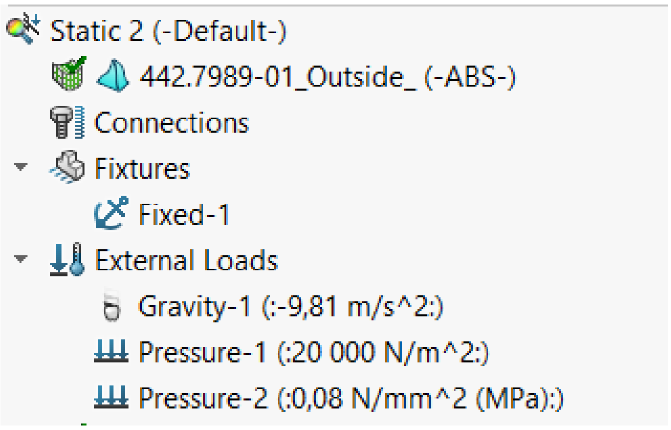
(b) Inner surface

Figure 4.3: Contour of surfaces extracted from the original model 4.2.

4.2.2.1 Outer pattern To begin with most energy was put into the pattern for the outer surface. This was mainly done for two reasons:

- It was deemed to have an easier fastening and loadcase since it is simply bolted down and all forces go through the bottom of it.
- It has a higher potential for optimization, this is also due to how the loads interact with the shape.

Based on the surface mentioned earlier a model was created. Several types of shapes were created and tested against each other using the built in simulation software of SolidWorks. All tested geometries together with their simulation results can be seen in appendix A. To ensure that the pattern will hold up to the load specified in section 3.1.1, it is important to perform some simulations. This will be done both to see that the material strain limit is not exceeded, and that the displacements are reasonable. No data exist on how great the displacements are on the current patterns, so personal judgement, together with discussions with technical staff and operators, will be used based on the results that to find a suitable compromise.



Static 2 (-Default-)
  442.7989-01_Outside_ (-ABS-)
  Connections
  Fixtures
    Fixed-1
  External Loads
    Gravity-1 (:-9,81 m/s^2:)
    Pressure-1 (:20 000 N/m^2:)
    Pressure-2 (:0,08 N/mm^2 (MPa):)

Figure 4.4: Set-up for simulations.

The forces acting on the part was directly taken from the load criteria, plus that gravity was added. All "outer" surfaces were used for the pressure load and the load coming from the weight of the sand. Since the sand has an even top layer, but height varying depending on the pattern height, the forces will vary, with it decreasing going outward. To support the part the base was seen as fully fixed. Neither of these forces are that exact, and having the bottom fully fixed is not an accurate way of simulating the real load. However, the maximum stresses are in all cases far from the maximum allowed, and these simulations should be seen more as comparisons between different alternatives. For this applications this crude setup will suffice. As an improvement these things could be changed, for example the support plate should be seen as flexible but for that to help it is important to know *how* flexible. It could also be worth investigating how element size effects the results.

To begin with several different wall thicknesses and support structures were tested. In table 4.1 the extracted data from the simulations in appendix A can be seen.
The weight is not important in of itself, but it shows how much material will be used and the material cost is major part of the total production cost, see section 3.5. It is because of this that

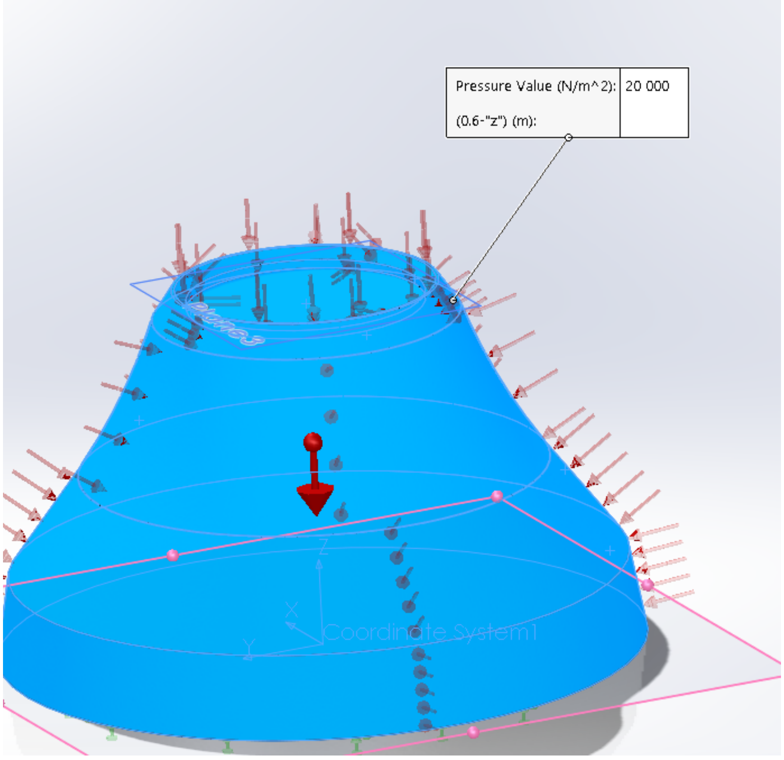


Figure 4.5: Load from the sand.

the weight should be minimized.
The stresses are in all instances far below the maximum stress of any potential material, see tables 3.2, 3.3 and 3.4, and is therefore not of any major concern
What more important, however, is the maximum displacement. It shows how much the pattern will deviate from its original form with all the loads applied. Depending on how the pattern deviates it might mean that the casting will become thicker, requiring more material than necessary, slimmer, making it weaker than expected, or simply the wrong shape, meaning that it will not behave in the way it was intended to. There is no data for how much deviation that might be allowed, so the goal will be to find a good compromise between mass and displacement. The data shown in table 4.1 should therefore not be seen as definitive, but rather as a guide as to which designs to continue with.

To make the data more easily visualized a plot was made, this can be seen in figure 4.8. There are several candidates which quite closely follow the same line, marked in red. Most of these could be considered good options with perhaps 12 and 13 being the best. The decision to continue with option 12, called triangular hollow support, was done mostly from a production stand-point since it seemed as though it would be easier to make. Images of all the alternative can be seen in appendix A.

To improve on these results a design study was made where a comparison was made with varying outer wall thickness, as well as two different thicknesses for the triangular support itself. This was also compared with having no support, or a wall thickness of 0 mm, as a baseline. The reason for only testing 8 mm and 16 mm is that the nozzle used by the 3D-printing company will be 8mm, see section 3.4, therefore the wall thickness will have to be a multiple of 8. This

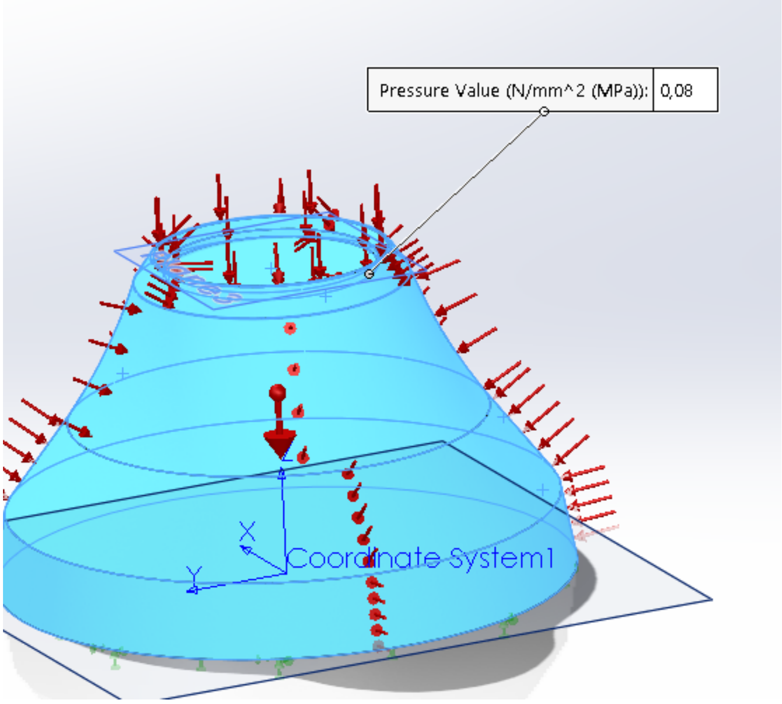


Figure 4.6: Load from the vacuum

would in a way apply to the outer wall as well, but here it will be printed oversize anyway and then machined down to the proper dimensions, which the support structure will not, meaning that any thickness can be chosen. The results from this can be seen in figure 4.9, 4.10 and 4.11.

The weight varies almost linearly with the wall thickness, which is unsurprising. The maximum stress and maximum displacement follows the same general pattern with a gentle slope in both cases. The maximum stress is, as noted previously, always far below the maximum allowed stress of 40 MPa, see table 3.5. It can however be noted that for larger wall thicknesses, the effects of the support on the maximum displacement shrank quite much, while there were still a major difference to having no support at all. So since no major gains were achieved from having the support thicker it was decided to have it be only 8 mm thick. Deciding the outer wall thickness was harder. No clear distinctive transition point can be be found along the curve, it was only a question about compromise between stiffness and cost. In conjunction with the industrial supervisor the decision was made to have the wall thickness be 30 mm, which would give a theoretical displacement at maximum load at 0.23 mm.

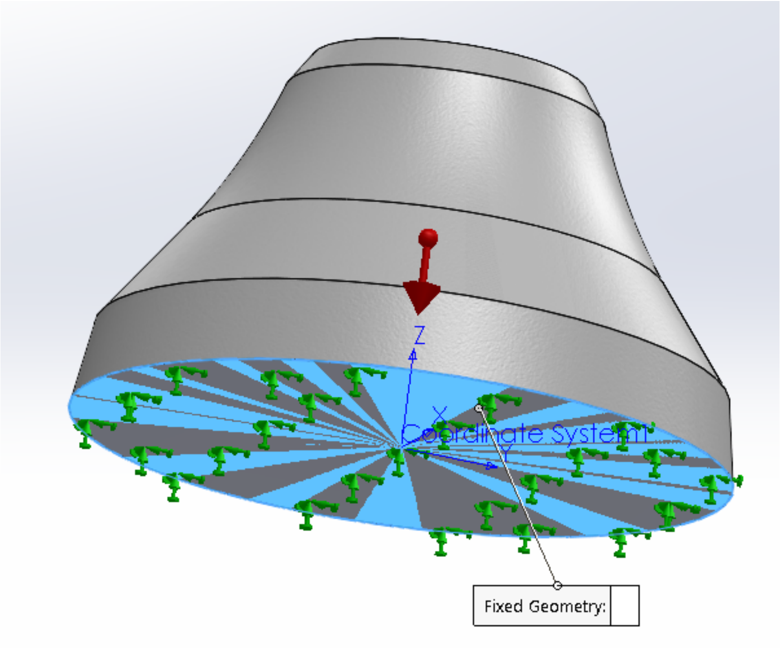


Figure 4.7: The fixed base.

Table 4.1: Data from simulations.

Nr:	Name	Weight[kg]	Max.Stress[MPa]	Max.Disp.[mm]
1	Completely filled	242.97	0.0956	0.0066
2	10mm shell	17.92	5.91	3.16
3	20mm shell	31.6	4.08	1.52
4	40mm shell	58.74	1.38	0.309
5	60mm shell	83.82	0.741	0.108
6	20mm shell w. hex beam	34.49	2.07	0.433
7	20mm shell w. honeycomb	94.27	0.577	0.0413
8	= w. hex beam & gussets	52.89	3.29	0.523
9	= w. circular beam	35.54	2.04	0.430
10	= w. thin wall support	40.25	3.14	0.511
11	= w. triangular support	53.2	2.23	0.339
12	= w. triang. hollow support	35.61	3.84	0.386
13	= w. trusses	43.42	3.98	0.340

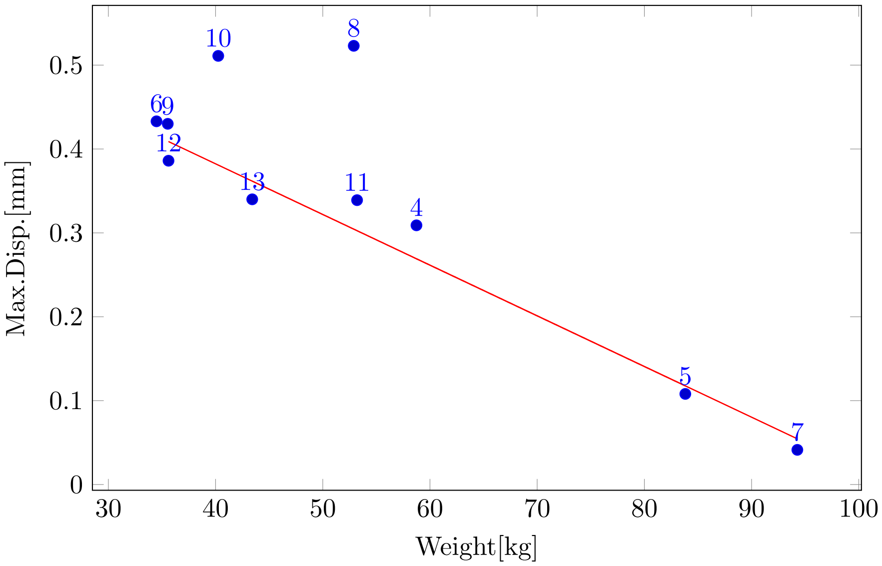


Figure 4.8: Plot based on table 4.1, with large values excluded for clarity.

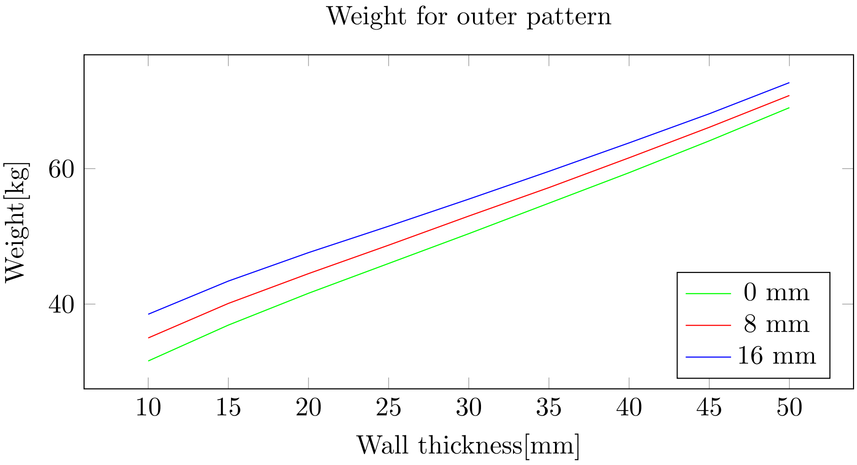


Figure 4.9: Weight depending on wall thickness for three different thicknesses of the triangular support.

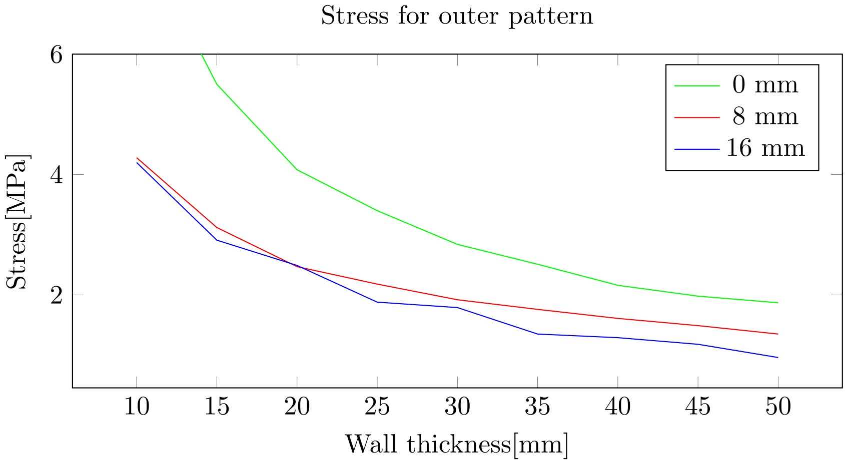


Figure 4.10: Maximum stress depending on wall thickness for three different thicknesses of the triangular support.

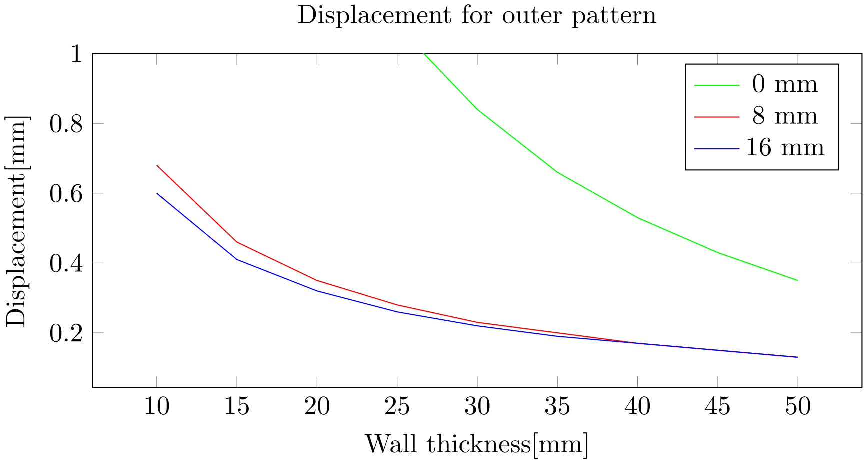


Figure 4.11: Maximum displacement depending on wall thickness for three different thicknesses of the triangular support.

4.2.2.2 Inner pattern The essential shape of the inner pattern can be seen in figure 4.1 together with how it is fastened to its support plates. With the intent of keeping this fastening interface no major changes to its overall shape can be made. Instead the focus was to find the optimal wall thickness. This was done via a design study, the process for which is described more in depth in section 4.2.2.1.

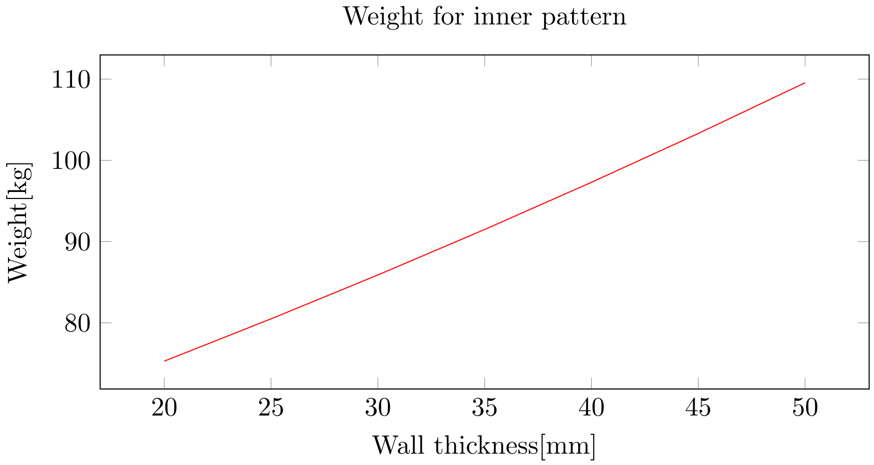


Figure 4.12: Weight depending on wall thickness for the inside pattern.

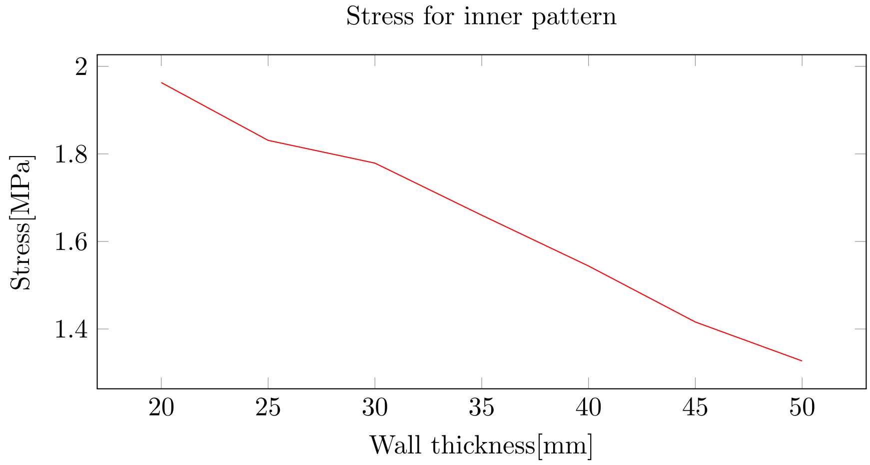


Figure 4.13: Maximum stress depending on wall thickness for the inside pattern.

Unsurprisingly, the plots shown in figure 4.12, 4.13 and 4.14 appear in roughly the same way as those in section 4.2.2.1. Weight is a linear function of wall thickness and the displacement is a gentle curve. Once again with no clear transition point.

The plot for stress does however appear a bit out of place, it is always far below the allowed maximum of 40 MPa for the specific material that can be seen in table 3.5, but it is not a smooth downward curve. It appears a bit jagged, see figure 4.13. When looking at the model, small localized stress concentrations can be found on the rim of the model, see figure 4.15. The

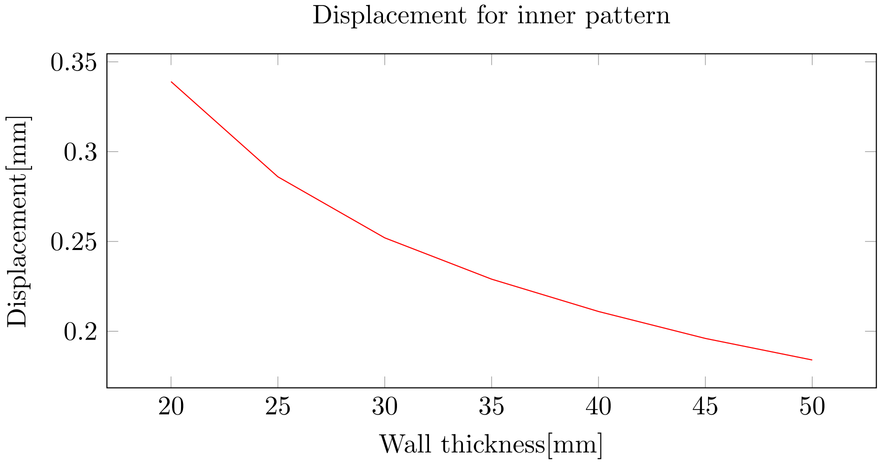


Figure 4.14: Maximum displacement depending on wall thickness for the inside pattern.

reasons for this is unclear but they are most likely a consequence of the simulation set up and will not occur in reality. It would however still be of no concern since they are, as previously stated, far below the allowed maximum. Anyhow, just as for the outer pattern, it is the total displacement that will decide the wall thickness. With the same requirement as for the outer pattern a displacement of 0.23 mm was used, this would give the wall thickness as 35 mm.

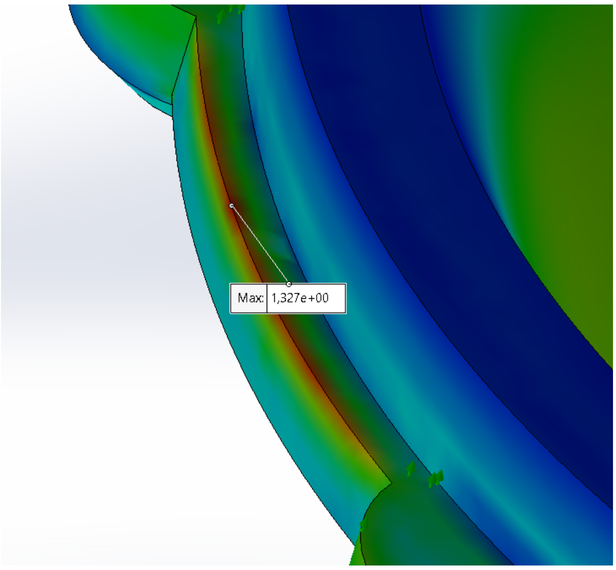


Figure 4.15: Local stress concentration on inner pattern.

5 Phase 3: Full scale test

The finished CAD-model was sent to The Industry, our chosen 3D-printing supplier, for a last check and final quote. Some small changes were made to fit their machine and then they could start printing. The machine to print 1200x1200x1500mm was not yet ready, the largest they had at the moment could only had a base area of 1000x1500mm, meaning that the inner pattern had to be printed in two halves and then glued together before milling, the printing of one of these halves can be seen in figure 5.1 and the finished part in figure 5.2.

There were also problems with the outer patterns triangular support.The supporting triangular wall collapsed during printing, see figure 5.3. To replace this a cylinder was printed and put in the center as a support. As can be seen in table 4.1(20mm shell with circular beam) this will likely result in slightly larger displacements, but the maximum stress will decrease, the other alternative would have been to alter the design again and try to reprint it, but in the interest of saving time and resources this approach was not chosen.When all of these parts where finished printing they were sent of to do the milling. After that they would be sent to the factory where the pattern-maker will attach it all to the support plate.

5.1 Early end

This is unfortunately only how far the project had gone when the project had to be terminated. There had been delays with administration and manufacturing which meant that the patterns where not finished in time and no full size tests of the molding process could be made. It is however the wish of the author that the company still proceeds as planned and try the pattern as a part of the production set-up. There are, as of now, no reason to believe that it will fail to deliver what is expected, and is one plausible alternative to the traditional pattern making practice.

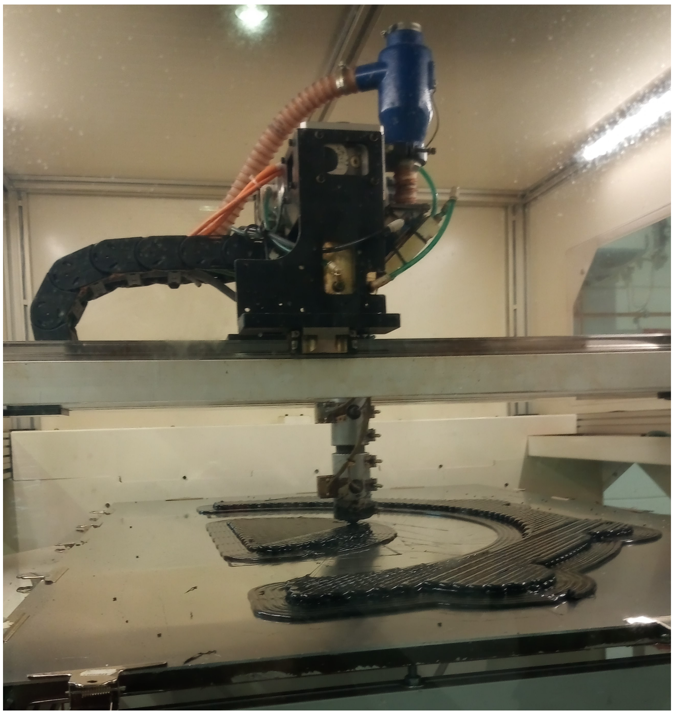


Figure 5.1: Printing in process.

Figure 5.2: Finished printing.

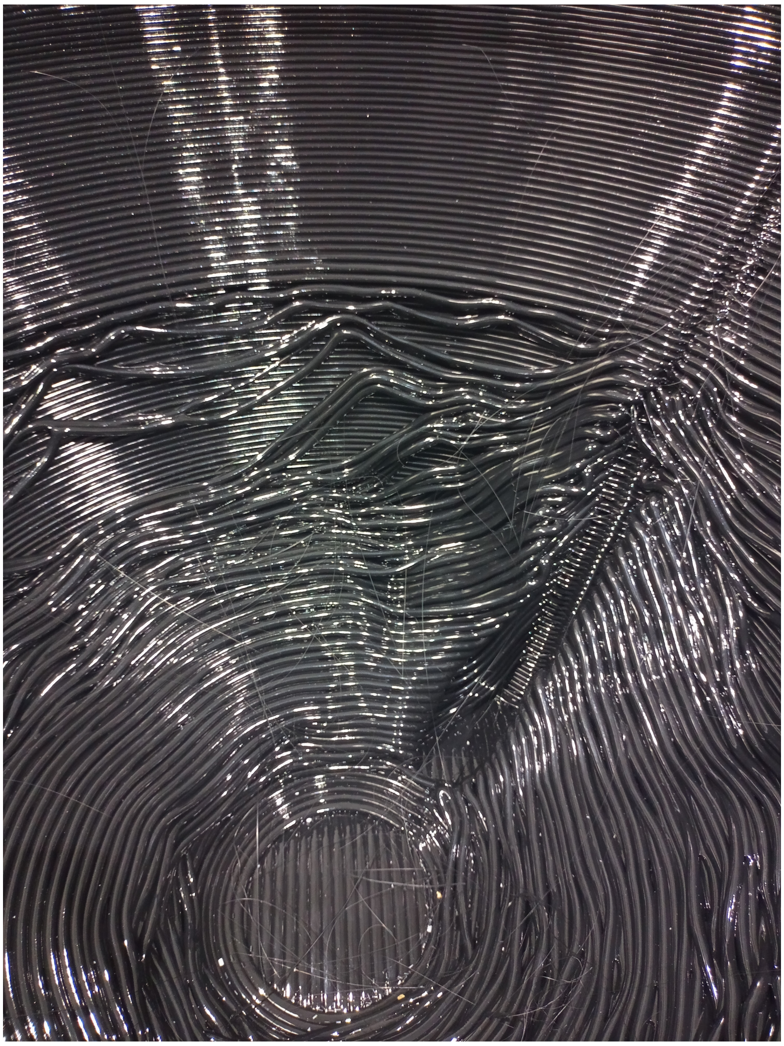


Figure 5.3: Picture of the collapsed support-wall.

6 Phase 4: Compilation and conclusion

6.1 Manufacturing decisions

The process decided upon was FDM, Fused Deposition Modeling, and the material chosen was an ABS-polymer with the name SICOFLEX MZ341 S25000.

6.2 Results in numbers

All the numbers below, if not stated otherwise, is for the outer pattern.

Added to this manufacturing cost should also be the yearly cost of storage, which was estimated as around 200 SEK per year for one pattern.

Table 6.1: Cost for manufacturing patterns.

Material	Cost[SEK]
Polymer	25 990
Wood	19 792

Table 6.2: Emissions from pattern manufacturing.

Material	CO_2e Emissions[kg]
Polymer	332.09
Wood	16.56

Just as for the cost there are also emissions linked with storage, in this case the storage emissions are calculated to 11.1 $kgCO_2e/year$

6.3 Discussion

As stated in the Project objectives section, see 1.2, the main objective was to test the possibility of using additive manufacturing for the manufacture of mold patterns. Due to a lack of time it was not possible to complete this test, but the results so far seem promising.

The other two things that have been evaluated is the cost and environmental impact of a 3D-printed pattern compared to a conventional pattern made out of wood. As for the cost, the results are quite inconclusive. They show the traditional pattern making is cheaper, but not by any extreme amount. Especially when the storage cost is also considered.

As for the emissions the difference might seem large at first, with the 3D-printed version made out of a polymer creating 20 times more CO_2e than the traditional pattern made out of wood. But the magnitude of these emissions are quite small when put into a context. An average newly registered car for 2020 emits 93.47 gCO_2e/km[75], meaning that it only has to drive 10 km per day for a single year to create as much emissions as a polymer pattern.

$$93.47gCO_2e/km * 10km * 365days = 341165.5gCO_2e = 341kgCO_2e \tag{11}$$

You could also compare it with a single trip by airplane from Sweden to Thailand, for a single person, which would result in emissions of 3 800 $kgCO_2$[76]. In these contexts neither the wood nor the polymer pattern have any large emissions.

6.4 Further recommendations

The project seems to fall out well in the sense that it is possible to make and use a pattern made with additive manufacturing. However, just because it is possible does not mean that it is the best option. As can be seen in the results above the polymer pattern is not better from a cost or environmental perspective. It could potentially win in the long run due to lower storage cost and environmental impact, but the numbers used here are quite uncertain at their best, and are bound to change during the lifetime of the pattern.

The other main objection is that it will not solve the main objective, namely to reduce the lead time. At least not as long as the production is outsourced to sub-suppliers, and having the production in house also does not seem practical with the low volumes expected.

It should also be noted that since this was the first test it was decided that it should be on a relatively simple part. While this did make the production, and likely the testing, easier. It did not utilize the full potential of additive manufacturing. Additive manufacturing is generally best utilized for complex parts where conventional production methods struggles. Therefore, if it is decided to continue testing with other parts, it could be beneficial to test at some of the parts that are today most time consuming and costly for the pattern-maker. When building and making the patterns traditionally the time increases by a large amount for every increase in complexity. Whereas the cost for additive manufacturing is more or less set by the material usage and time in the machine, and this machine time is not as much dependent on complexity as it is on part volume. But it should also be noted that the majority of the cost for polymer pattern is not due to printing, but rather from the milling operations, see table 3.6. This will increase with complexity, but once again not by very much, and likely mostly due to set-up time and CAM-programming. Another way of perhaps minimizing this cost would be if it were possible to do this machining in house. There are machines that are likely to be able to perform this task available. It is not certain that this would be beneficial from an economic perspective, though it is likely. What is more likely is that it could shorten lead times, at least if there are some machines available without disrupting the normal operation of the factory.

If, in the future, it is decided that additive manufacturing will be the method used for making of the patterns, it could also be important to notice that some responsibilities will shift. Right now only the "active" surface, the surface that will have contact with the sand, is sent to the pattern-maker. It is then up to him to decide how thick the walls should be, if any support structure is needed and where to put the holes for the vacuum. If the patterns are to be made using additive manufacturing these things will have to be decided beforehand. To help with this it would be advised to have a routine for how to carry out the simulations so that they are done consistently over time. It could also be of interest to look into other materials than the ABS used for this project. As stated in the section about material selection, see section 3.4, this decision was based mostly on the fact that it was what the supplier was most accustomed to. With a deeper material selection project there are likely room for improvements, either to cost or performance, or both.

A final note should be said about the 3D-printing process itself. It is not certain that the process selected here is the one that will always be the most advantageous. There are processes that are likely to produce a surface finish that will not require any post-printing milling, just a light sanding if even that. As can be seen in the cost analysis section, see section 3.5. Milling stands for a large proportion of the total cost (65%, see table 3.6). So even if these other 3D-printing processes are more expensive than the current there are still a possibility for them to be cheaper overall.

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A Simulation results

Filled

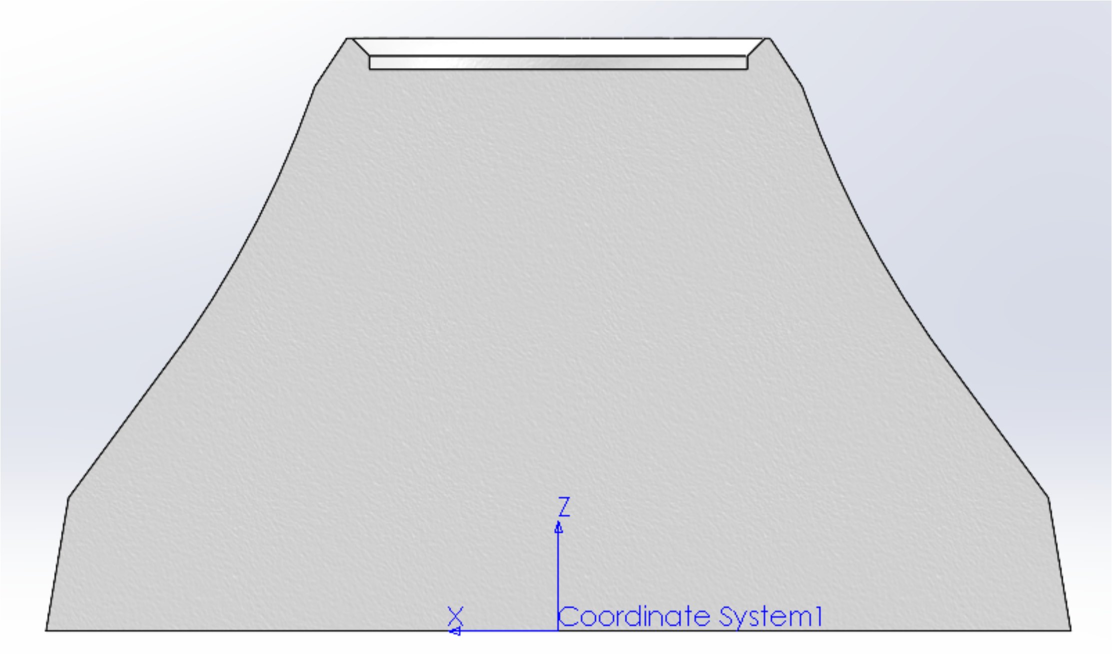

Figure A.1: Filled.

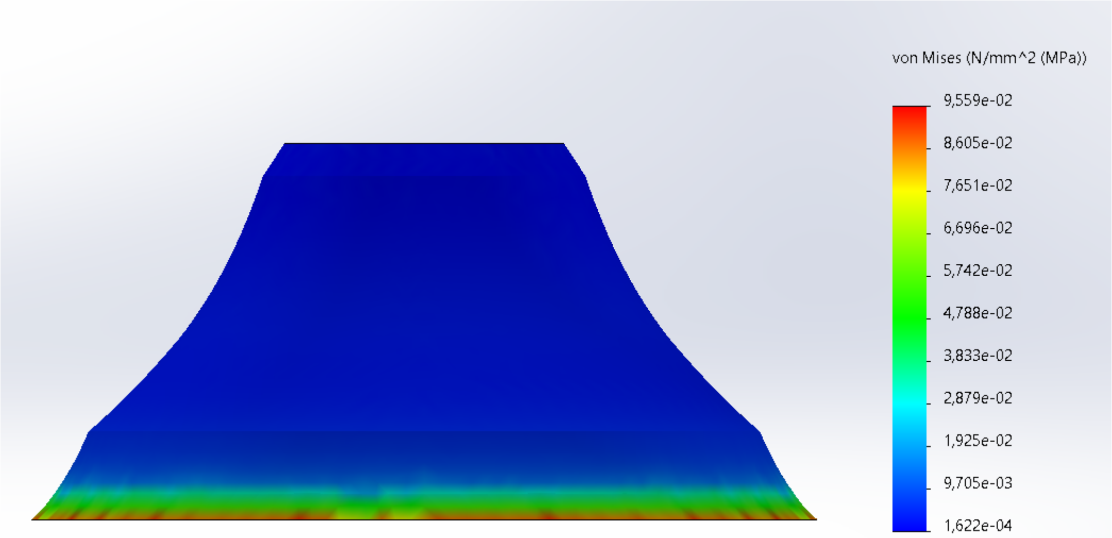

Figure A.2: Filled: Stress.

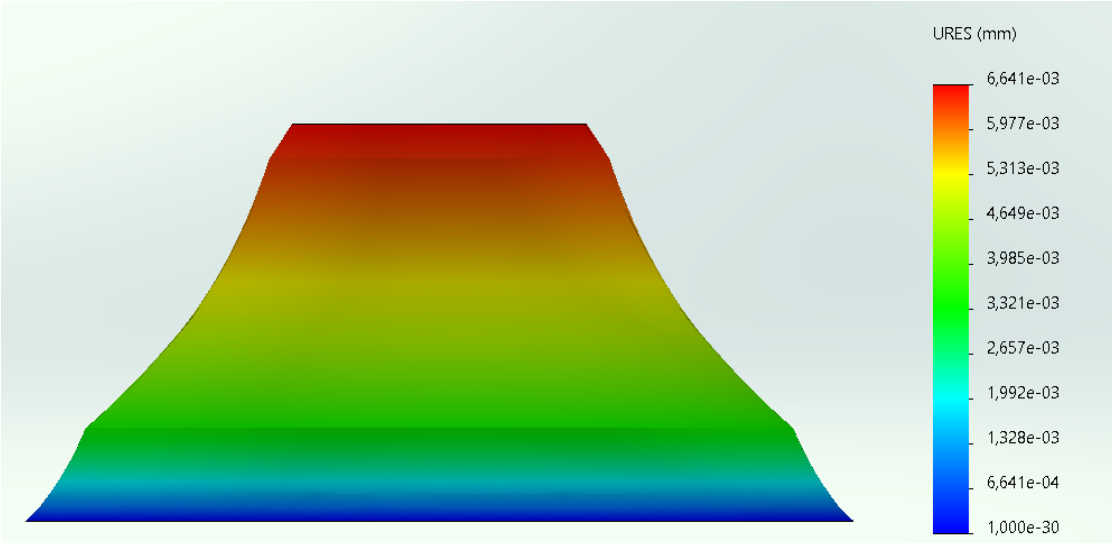

Figure A.3: Filled: Displacement.

10mm shell

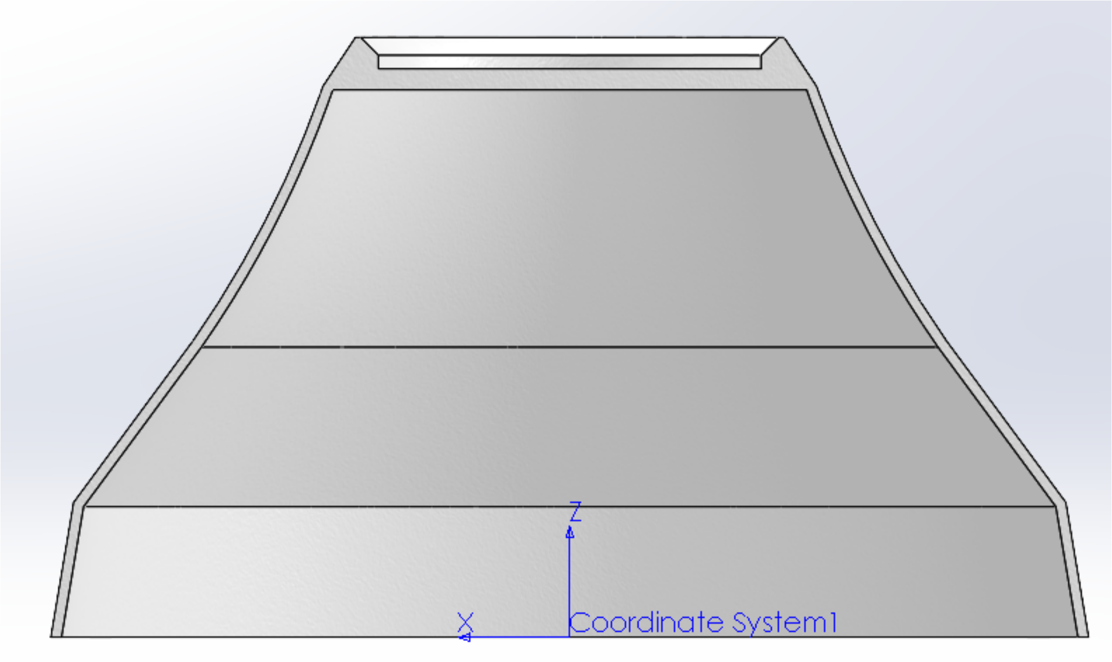

Figure A.4: 10mm shell.

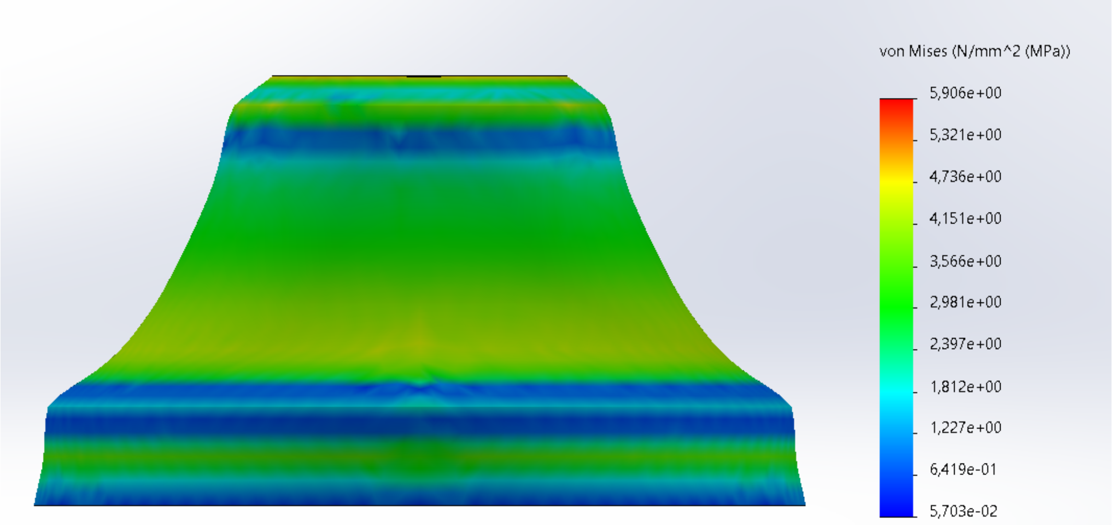

Figure A.5: 10mm shell: Stress.

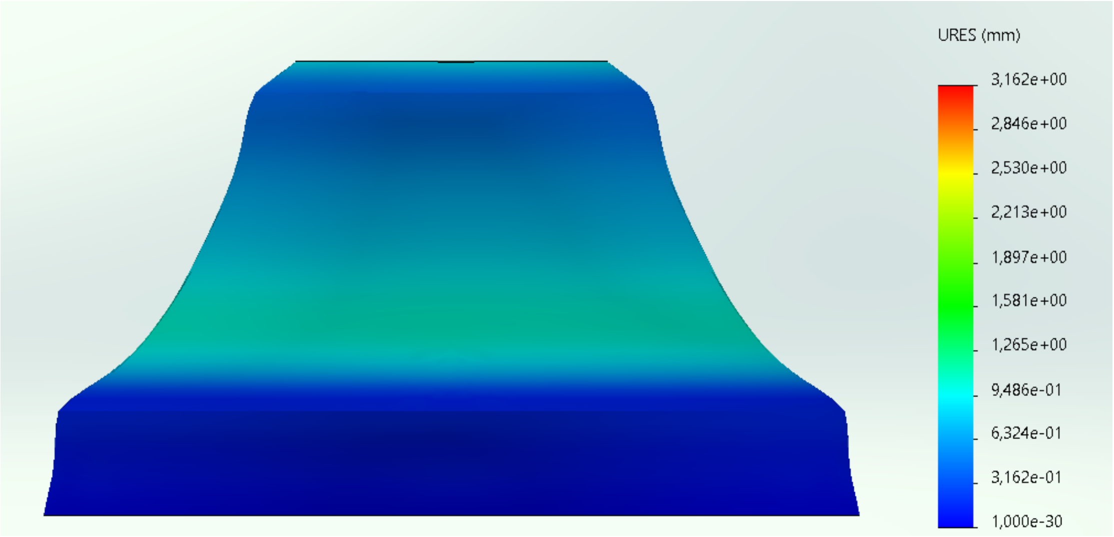

Figure A.6: 10mm shell: Displacement.

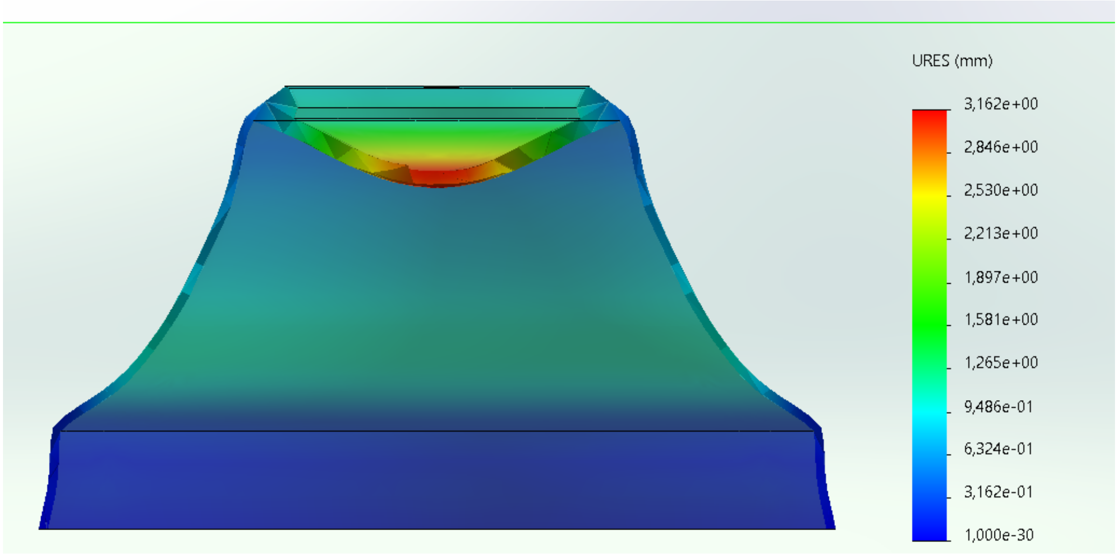

Figure A.7: 10mm shell: Section of displacement.

20mm shell

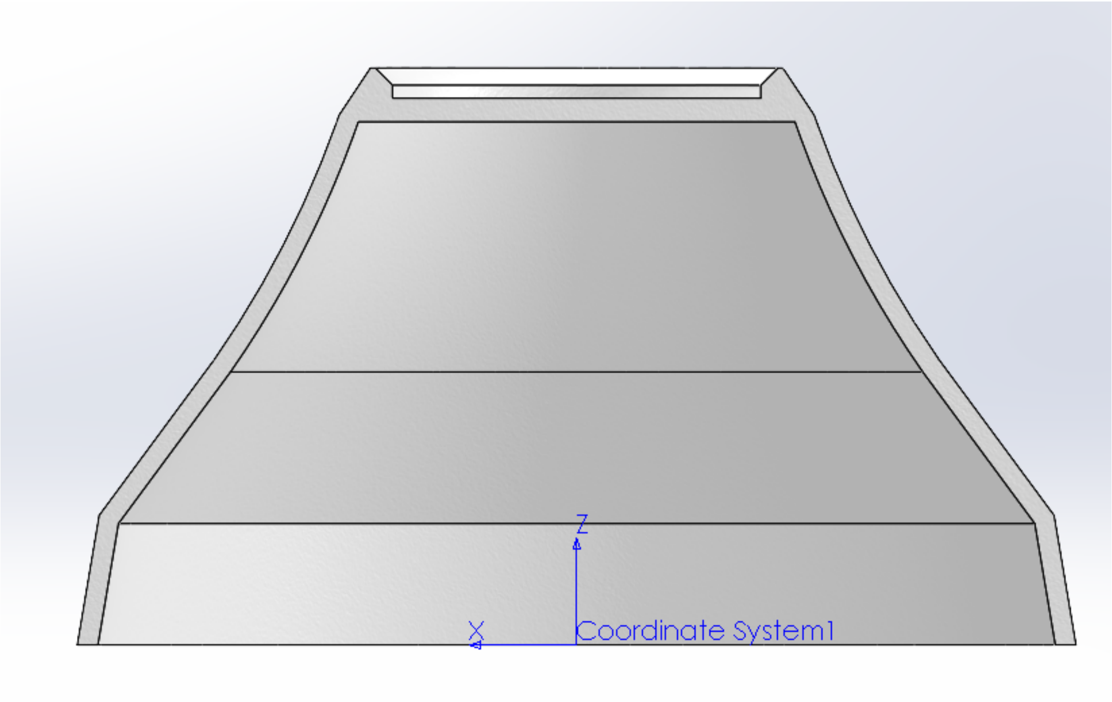

Figure A.8: 20mm shell.

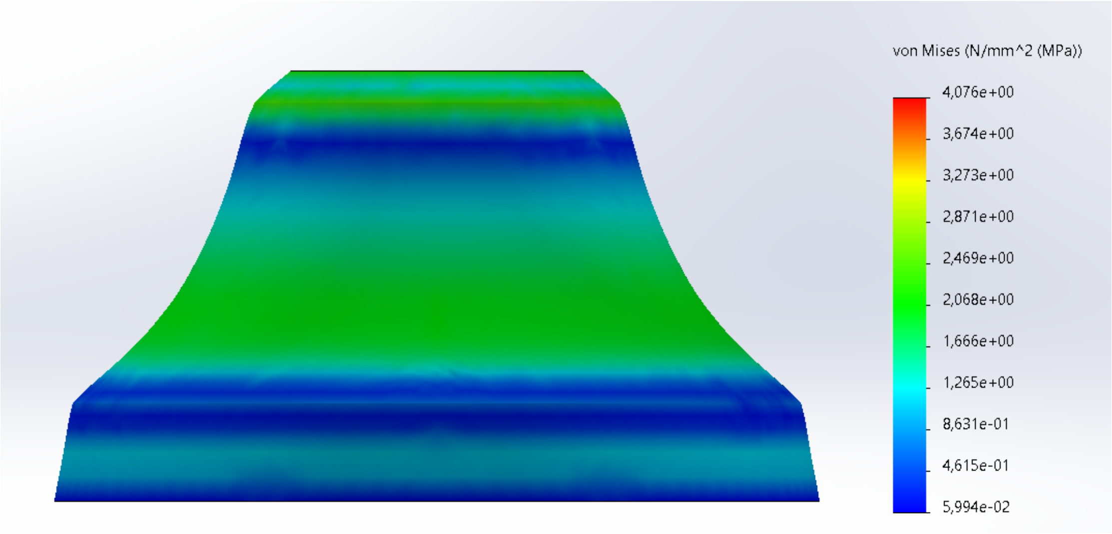

Figure A.9: 20mm shell: Stress.

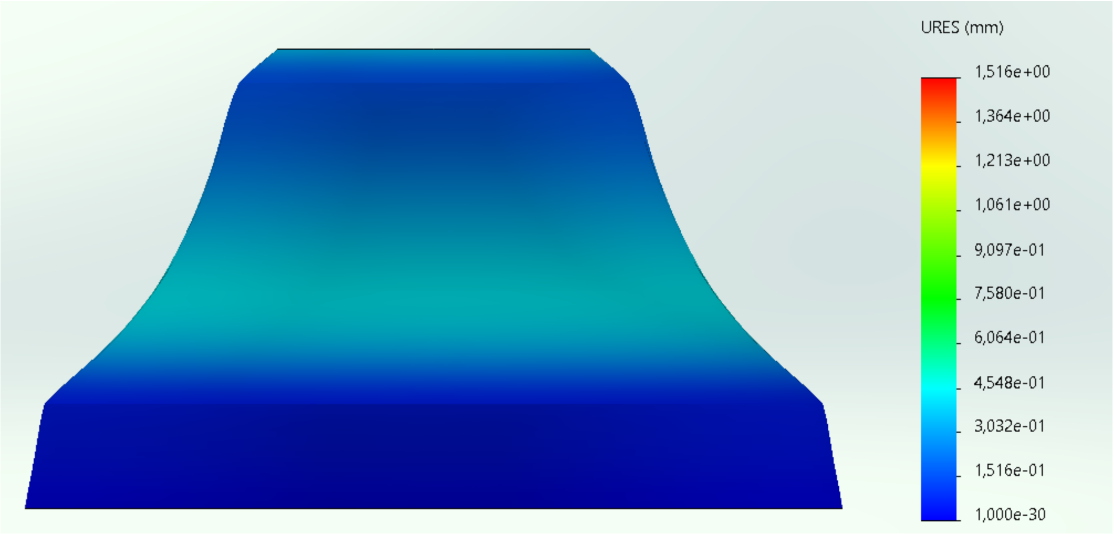

Figure A.10: 20mm shell: Displacement.

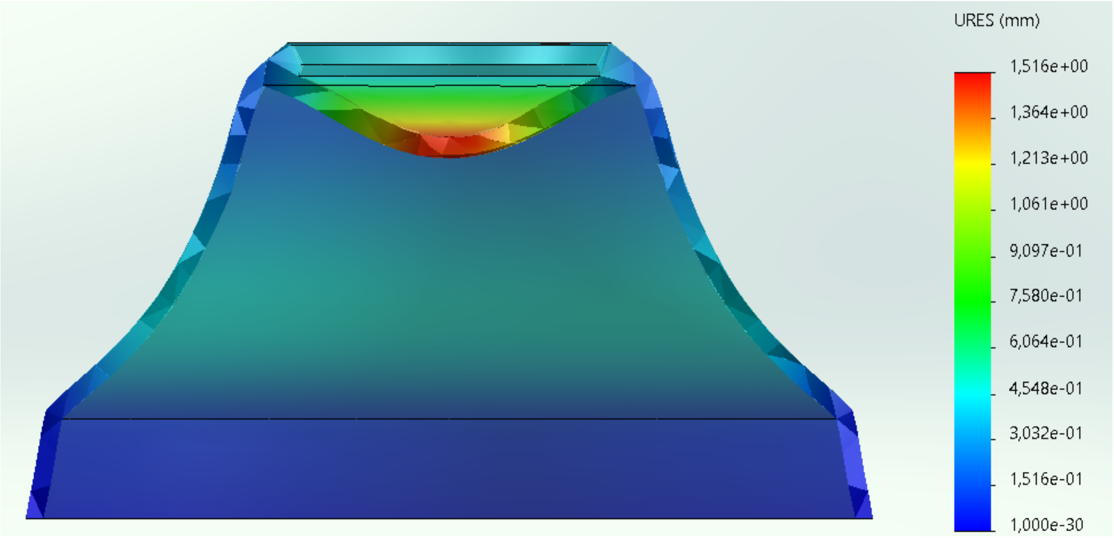

Figure A.11: 20mm shell: Section of displacement.

40mm shell

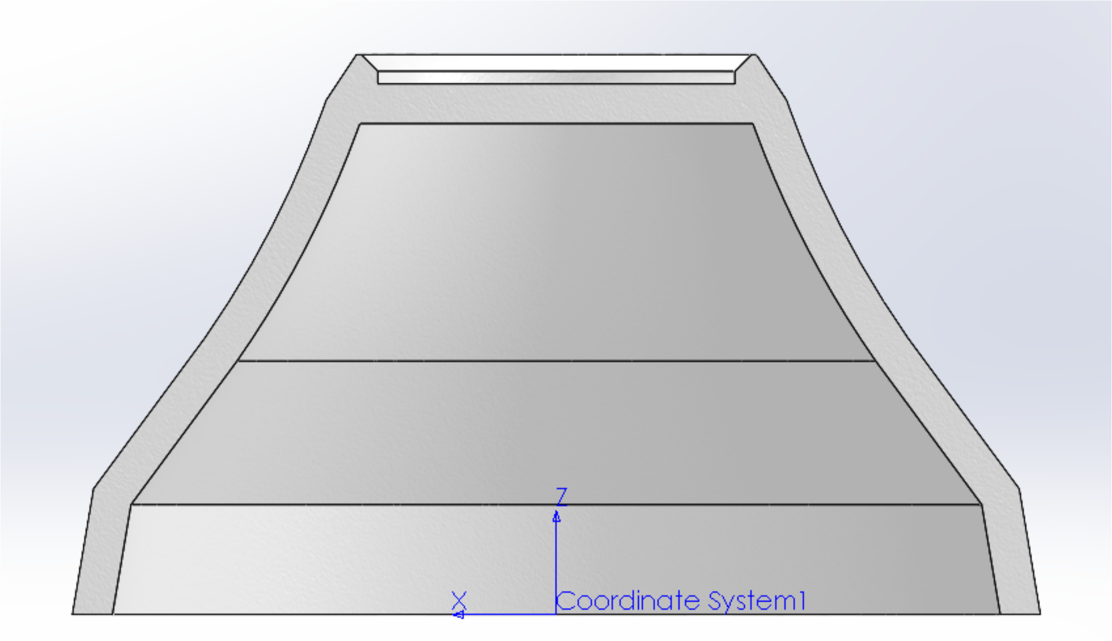

Figure A.12: 40mm shell.

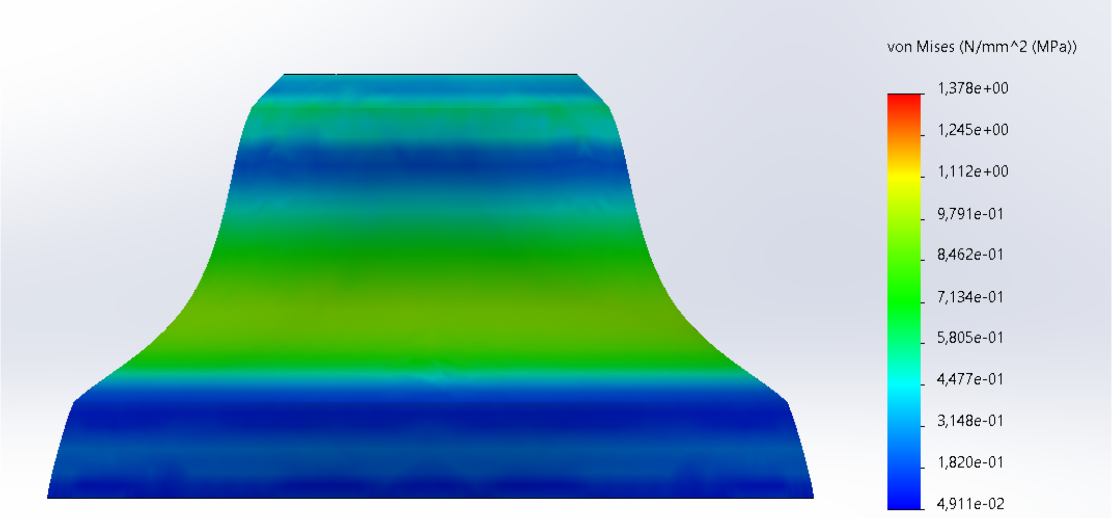

Figure A.13: 40mm shell: Stress.

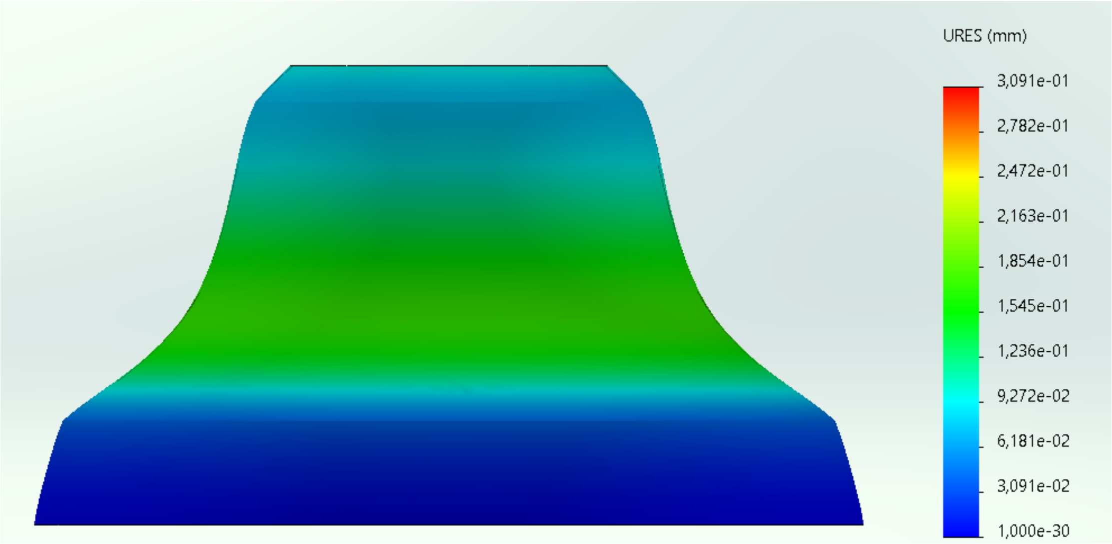

Figure A.14: 40mm shell: Displacement.

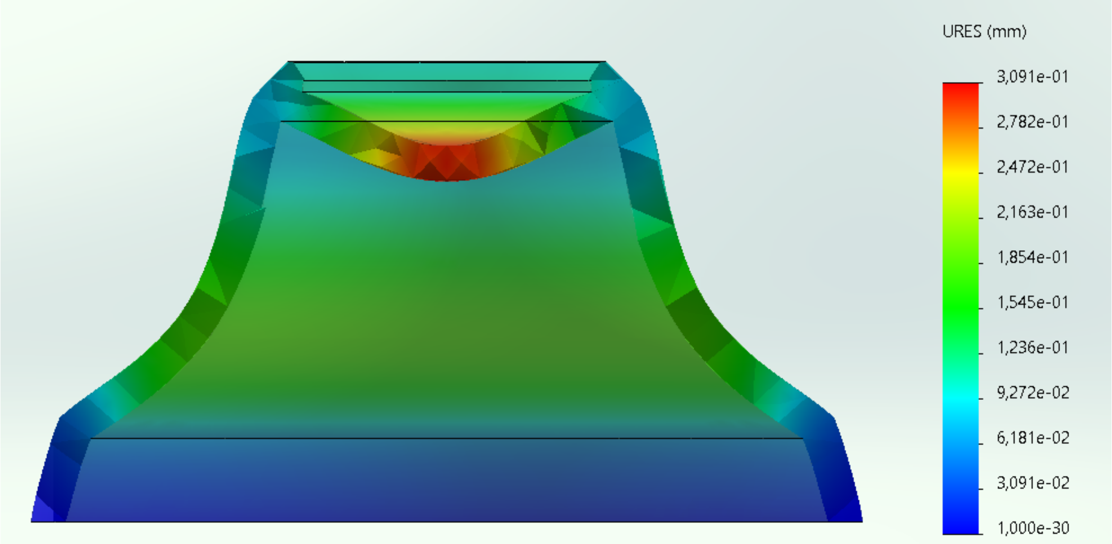

Figure A.15: 40mm shell: Section of displacement.

60mm shell

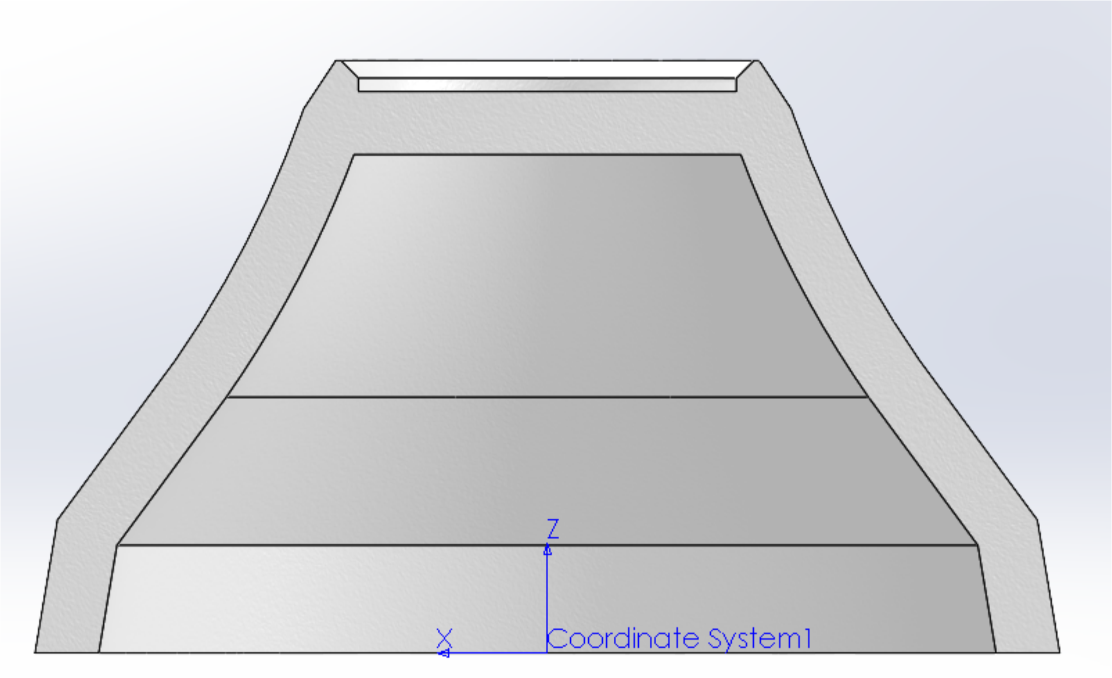

Figure A.16: 60mm shell.

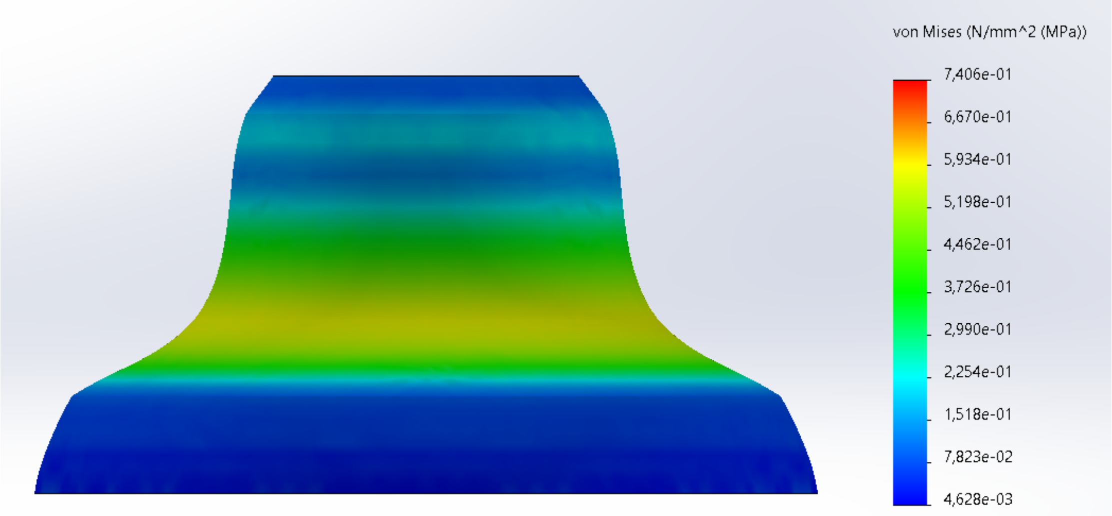

Figure A.17: 60mm shell: Stress.

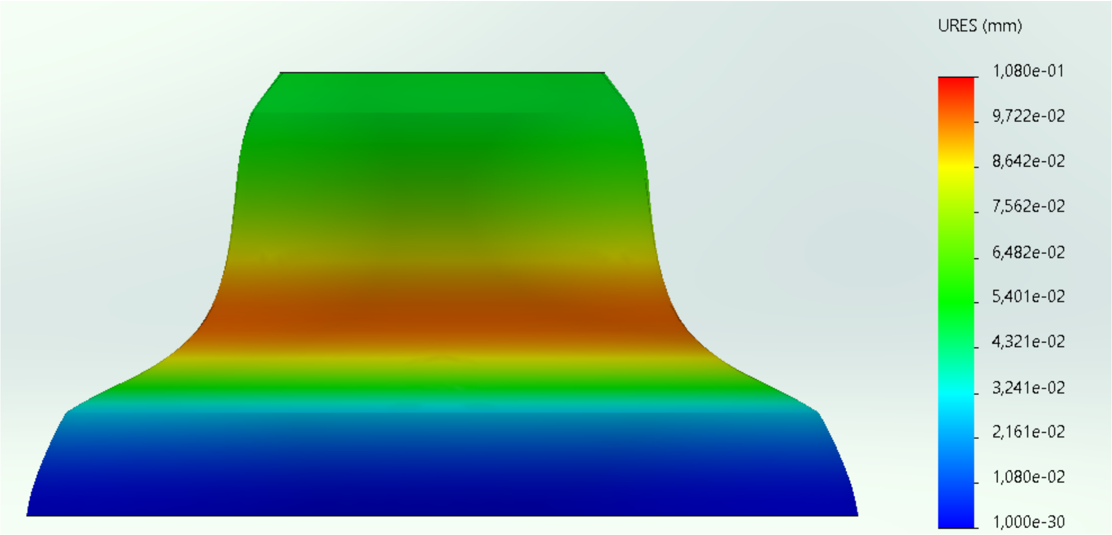

Figure A.18: 60mm shell: Displacement.

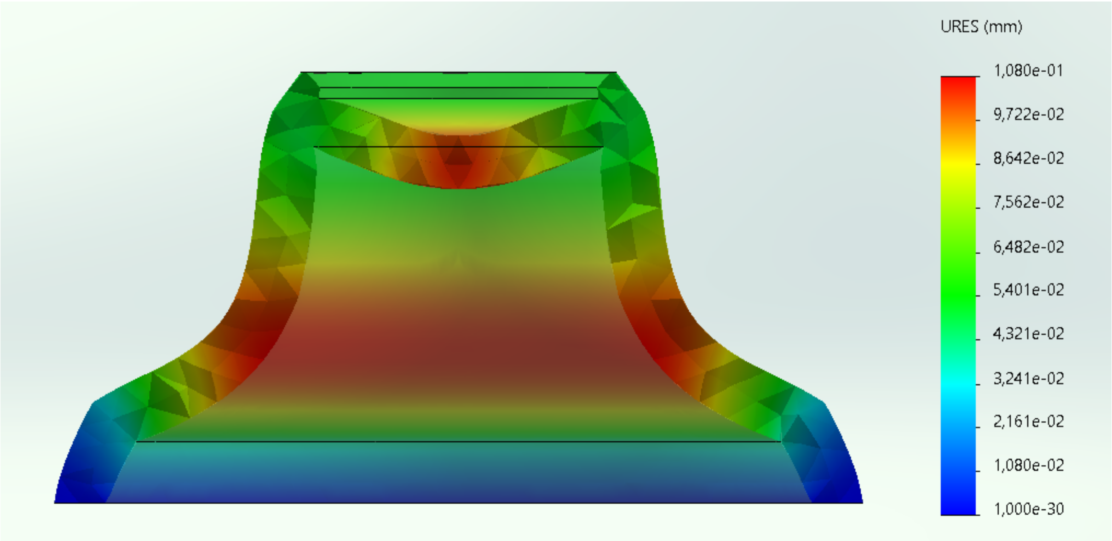

Figure A.19: 60mm shell: Section of displacement.

20mm shell with hex beam

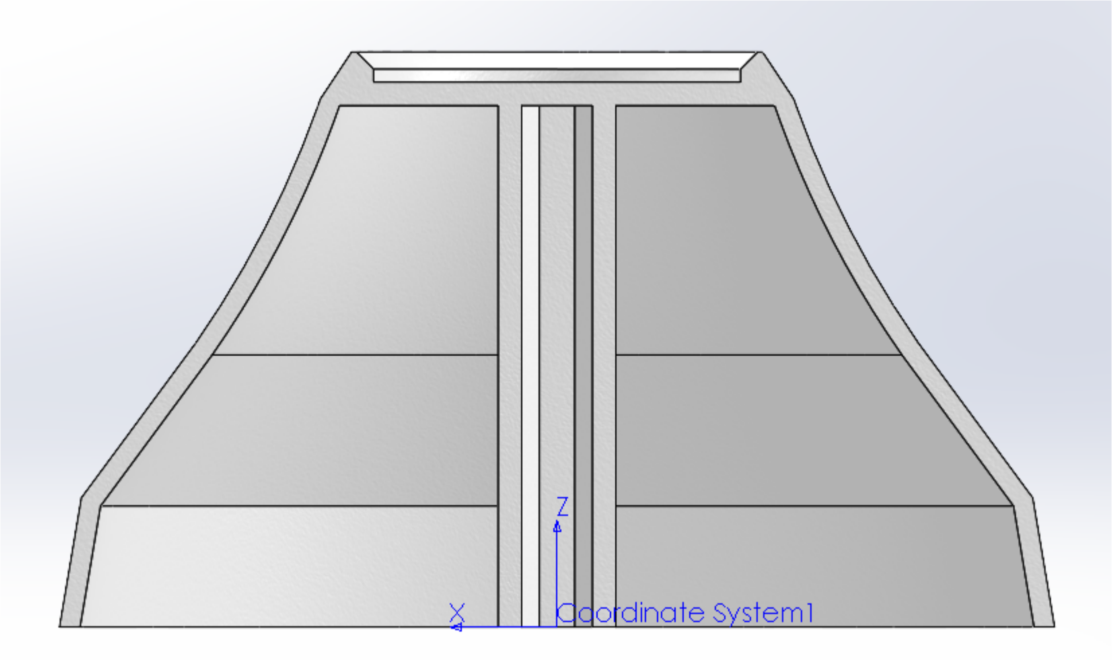

Figure A.20: 20mm shell with hex beam.

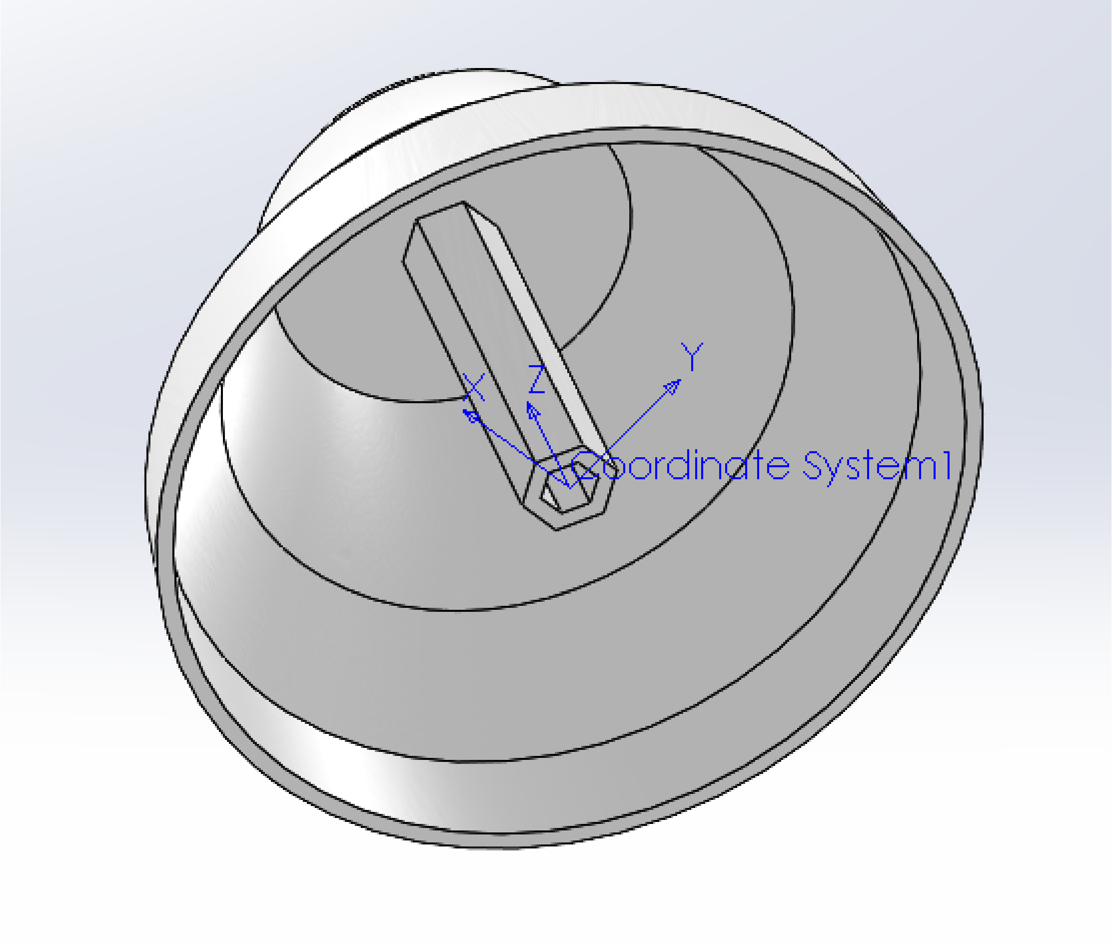

Figure A.21: 20mm shell with hex beam, underside.

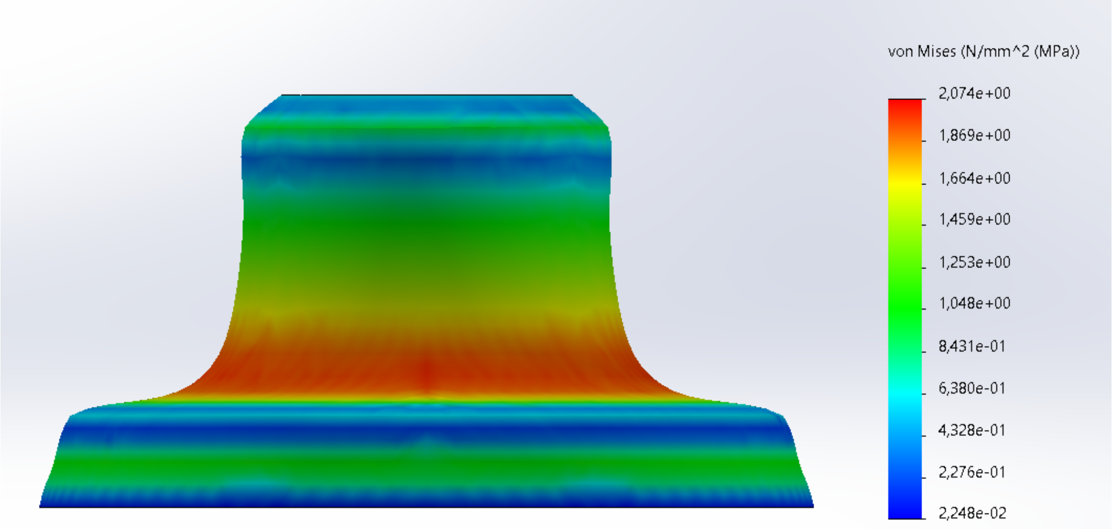

Figure A.22: 20mm shell with hex beam: Stress.

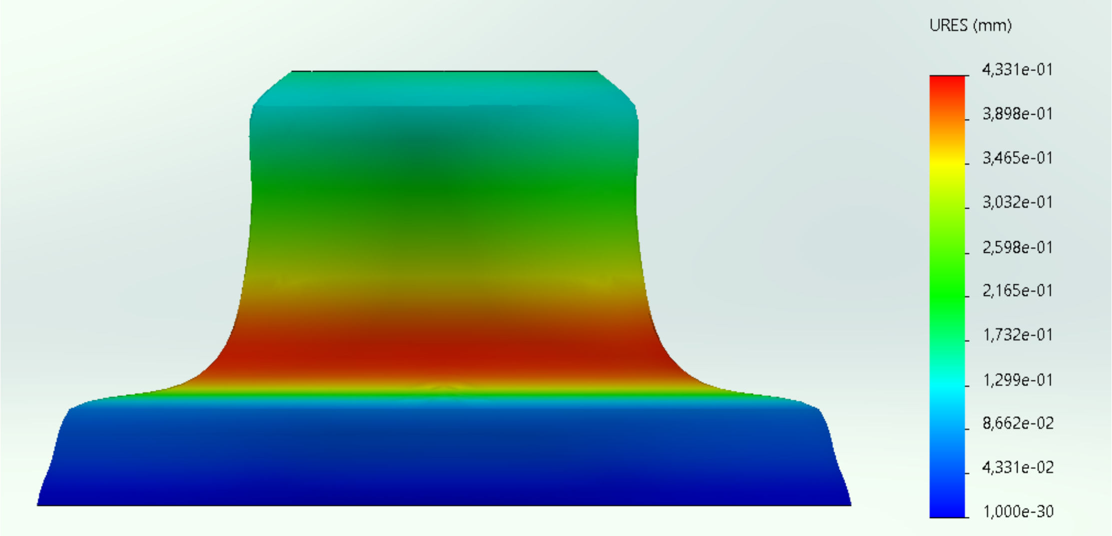

Figure A.23: 20mm shell with hex beam: Displacement.

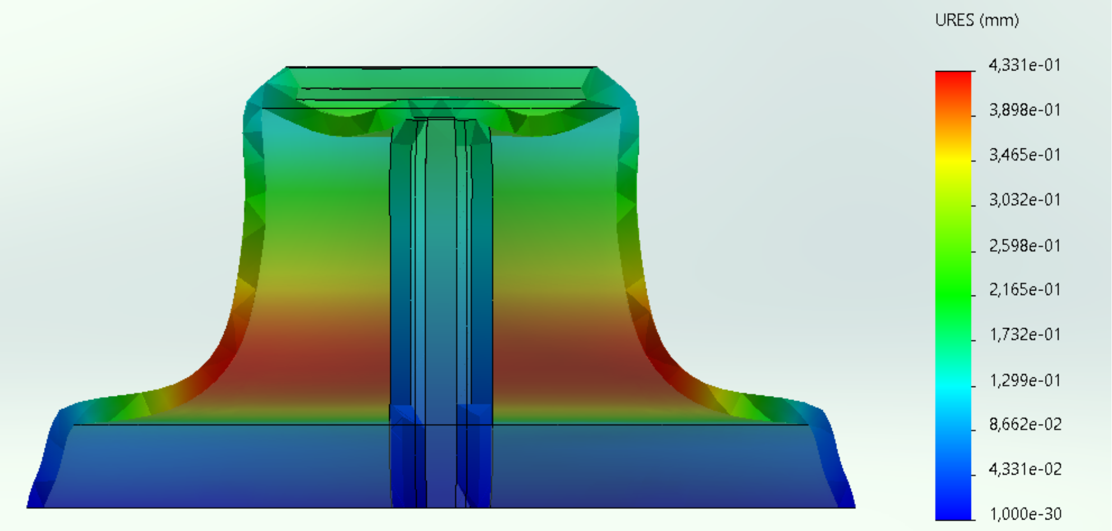

Figure A.24: 20mm shell with hex beam: Section of displacement.

20mm shell with honeycomb pattern

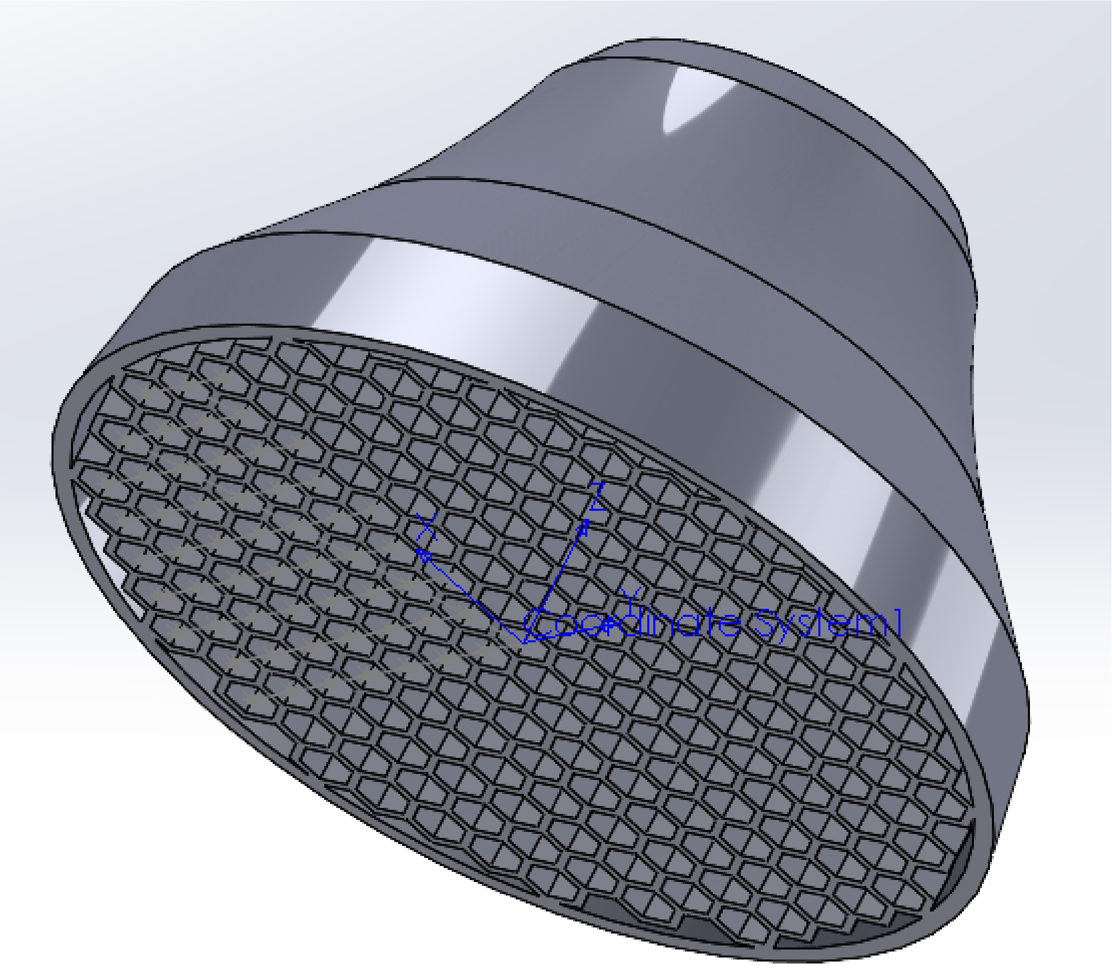

Figure A.25: 20mm shell with honeycomb pattern.

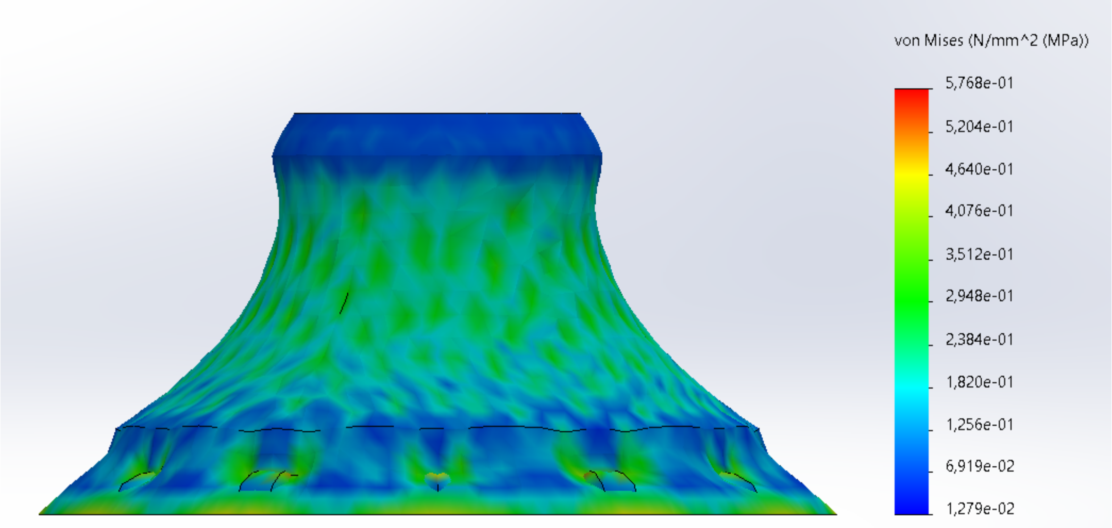

Figure A.26: 20mm shell with honeycomb pattern: Stress.

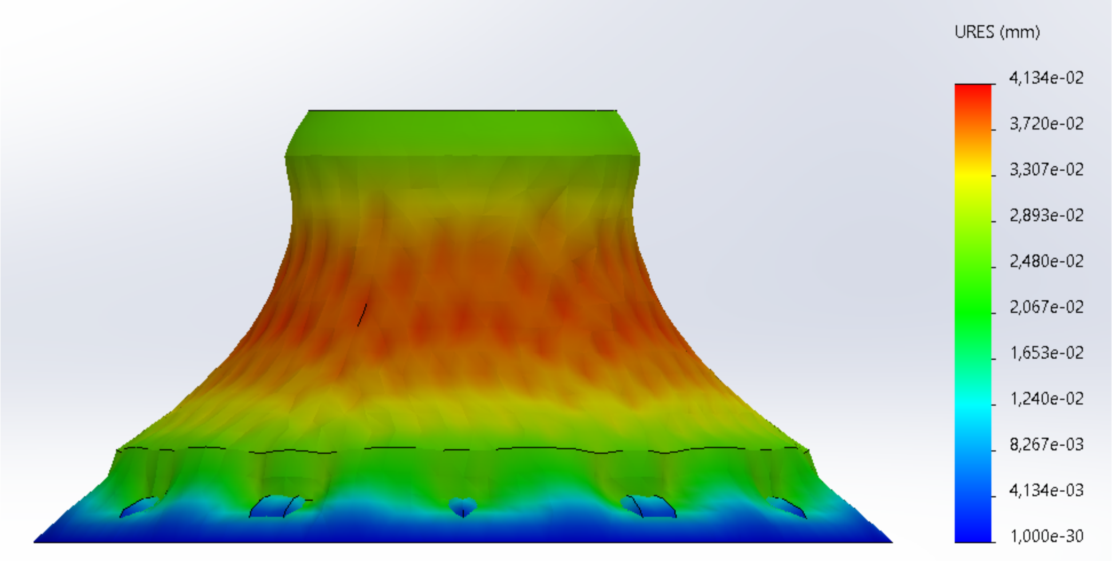

Figure A.27: 20mm shell with honeycomb pattern: Displacement.

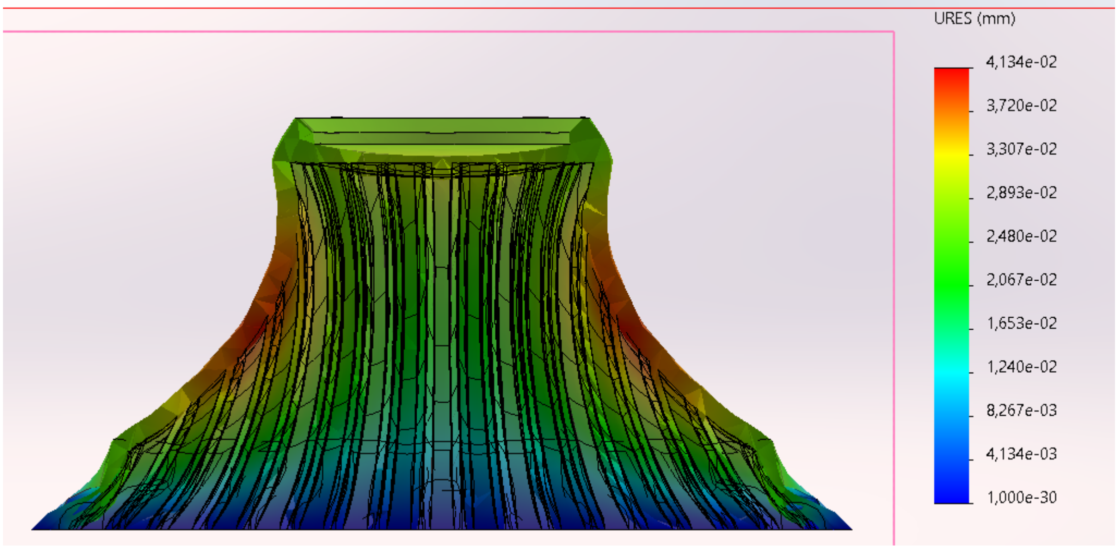

Figure A.28: 20mm shell with honeycomb pattern: Section of displacement.

20mm shell with hex beam and gussets

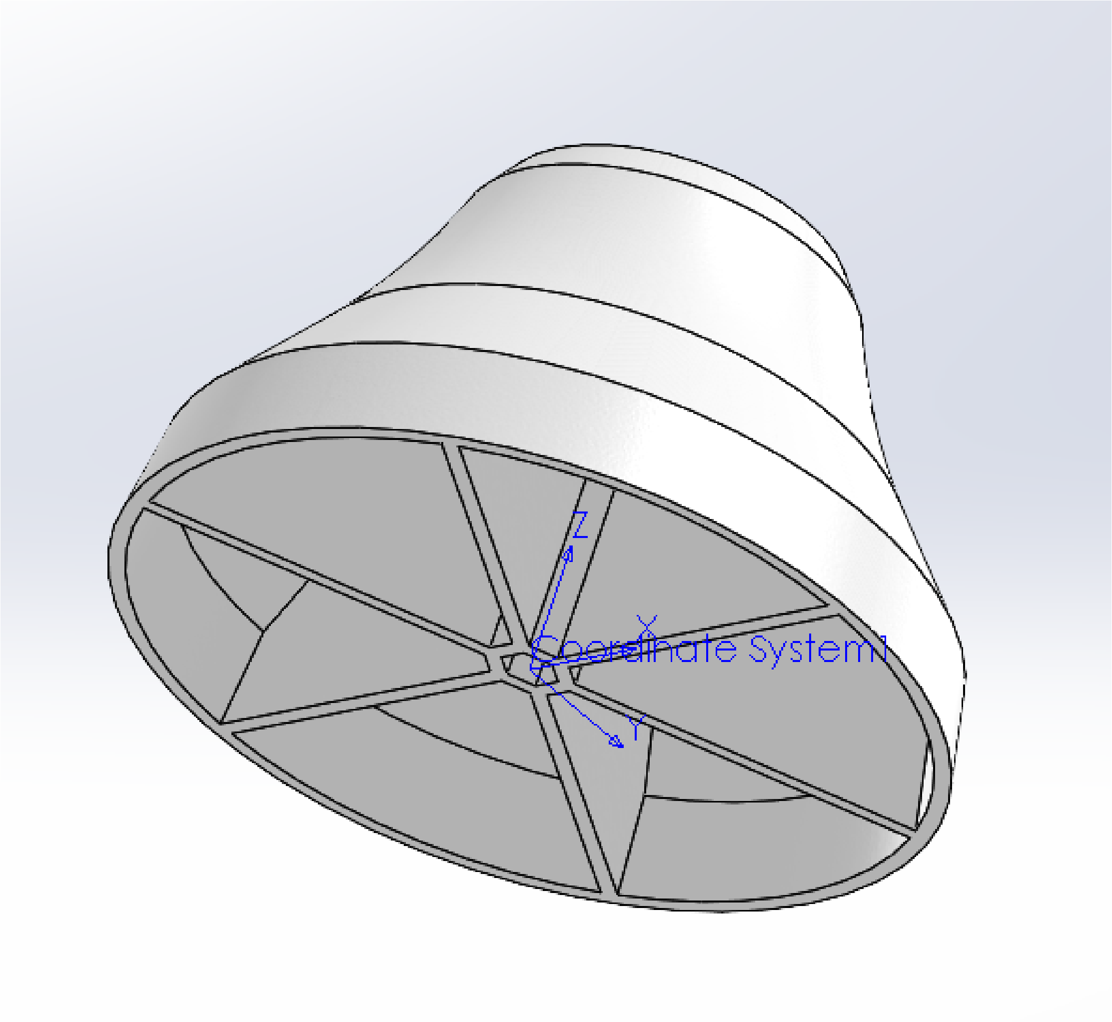

Figure A.29: 20mm shell with hex beam and gussets.

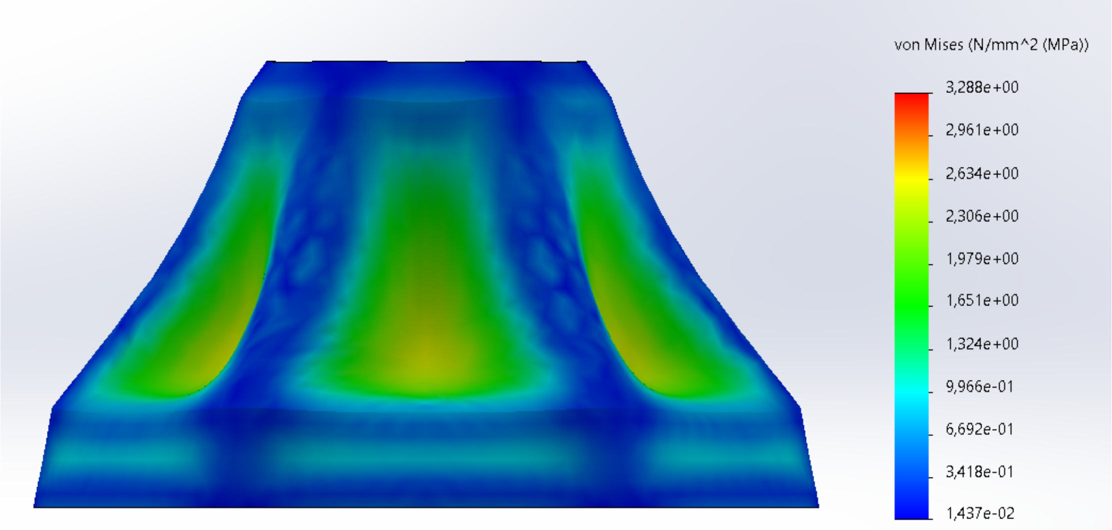

Figure A.30: 20mm shell with hex beam and gussets: Stress.

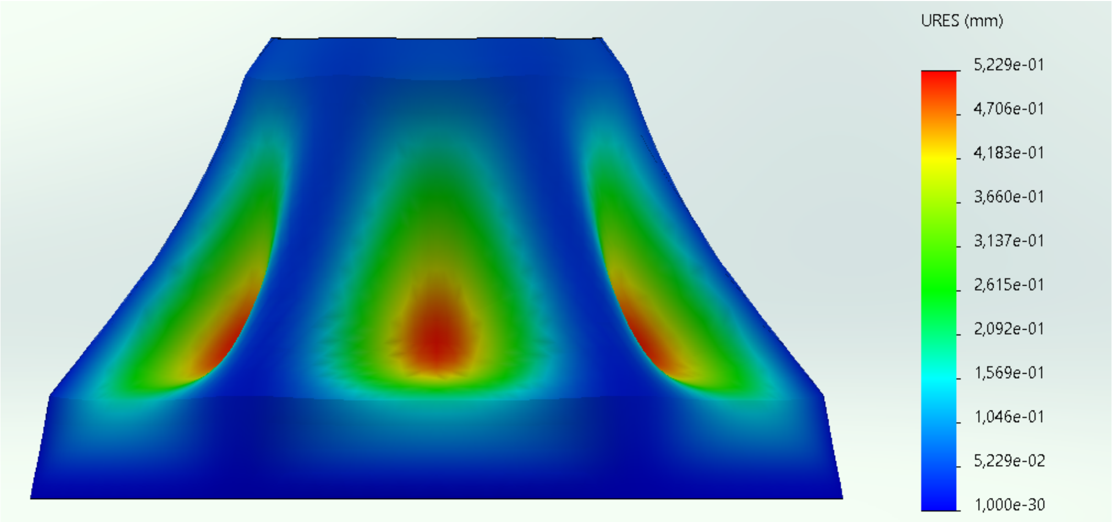

Figure A.31: 20mm shell with hex beam and gussets: Displacement.

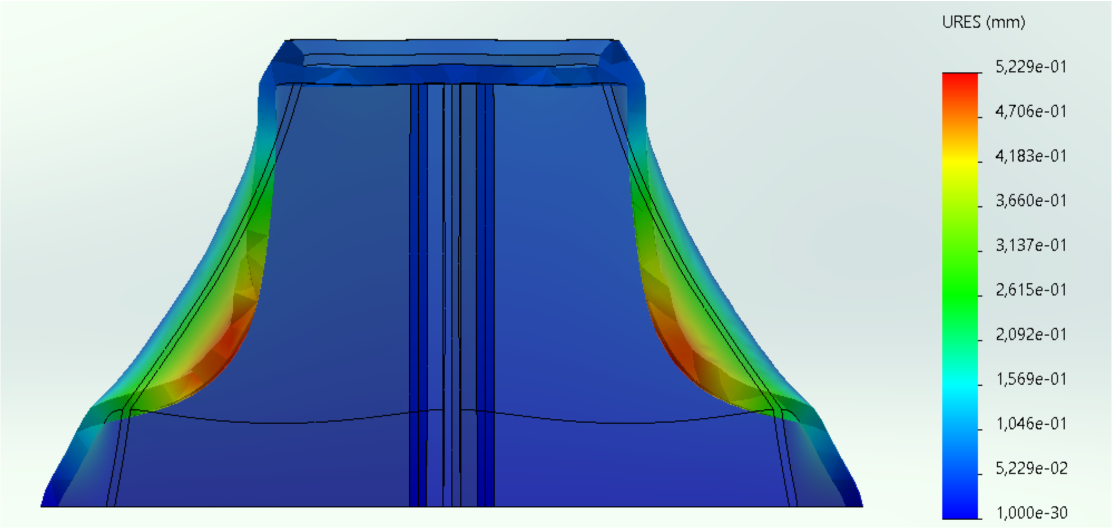

Figure A.32: 20mm shell with hex beam and gussets: Section of displacement.

20mm shell with circular beam

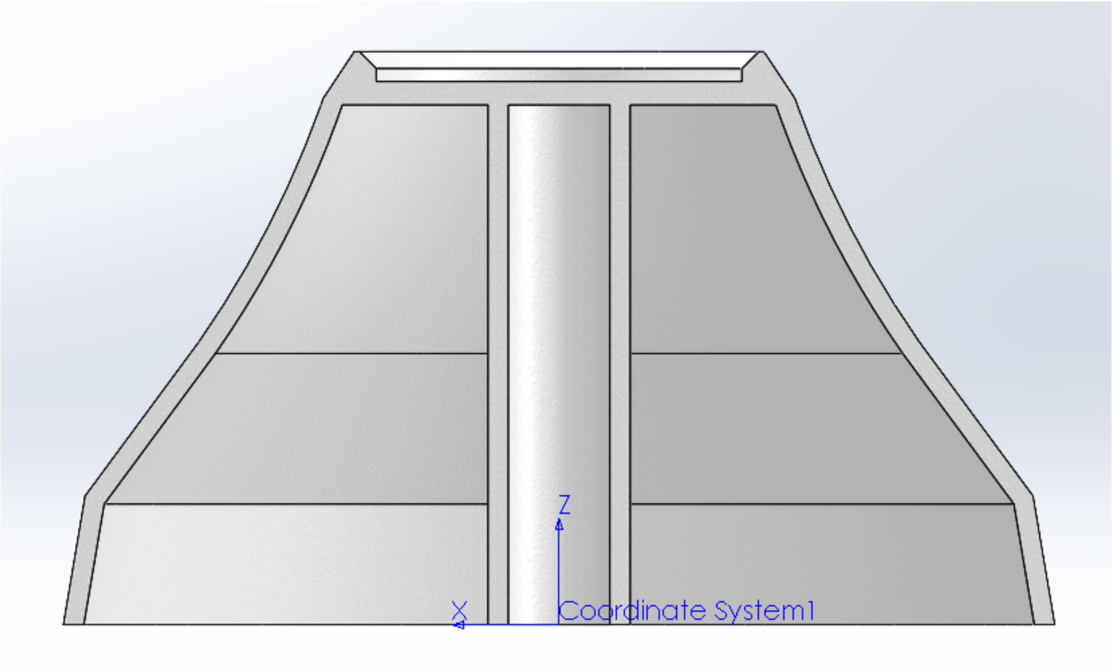

Figure A.33: 20mm shell with circular beam.

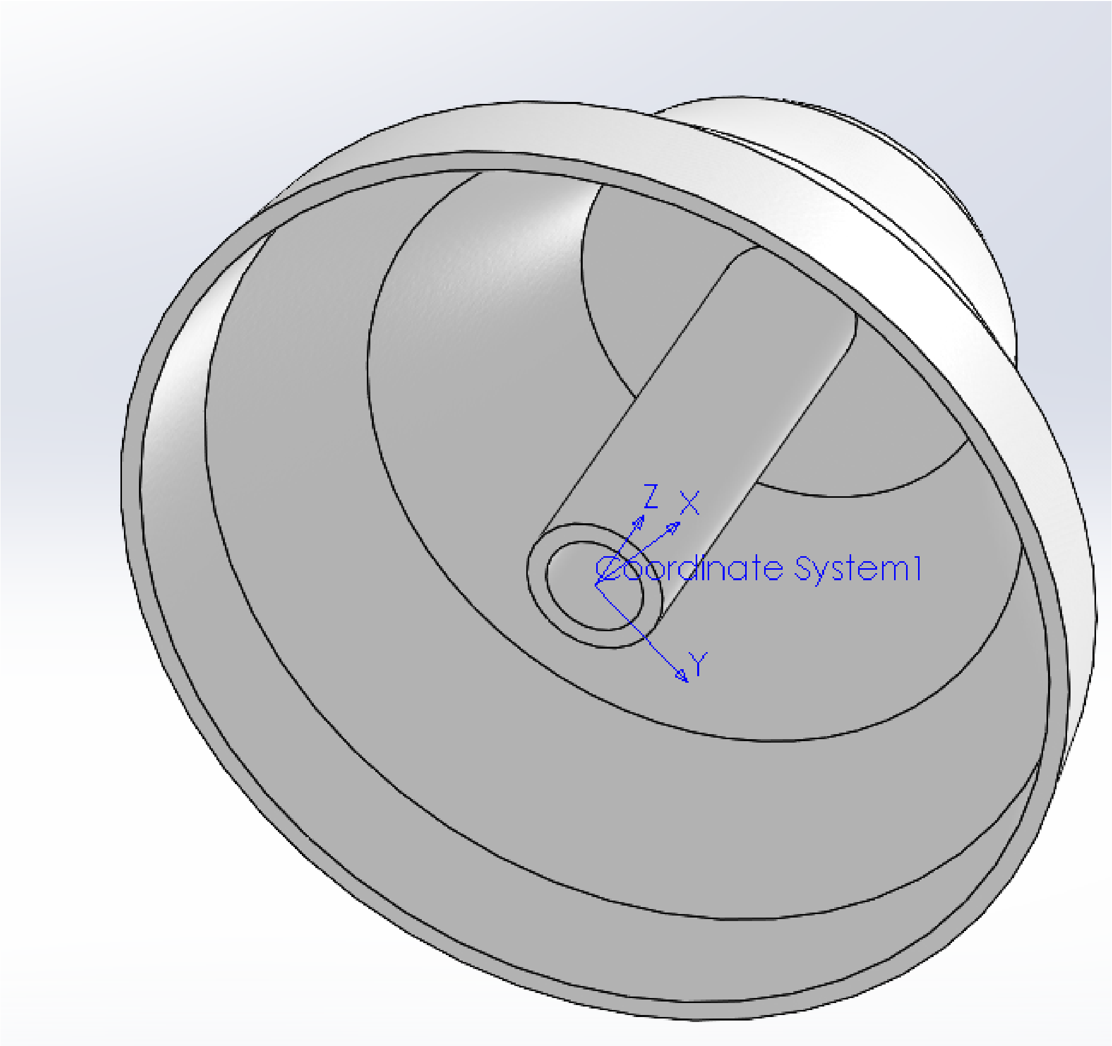

Figure A.34: 20mm shell with circular beam, underside.

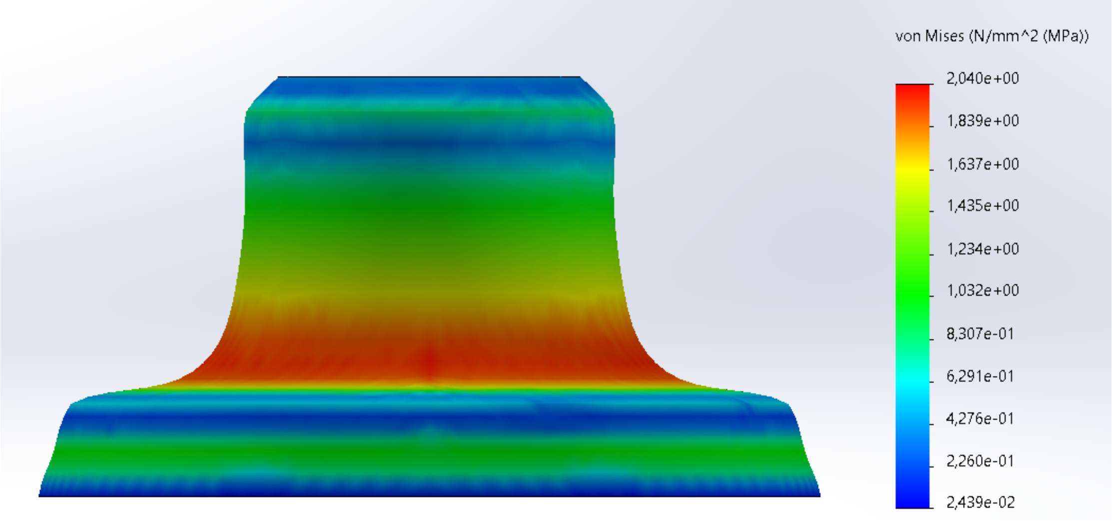

Figure A.35: 20mm shell with circular beam: Stress.

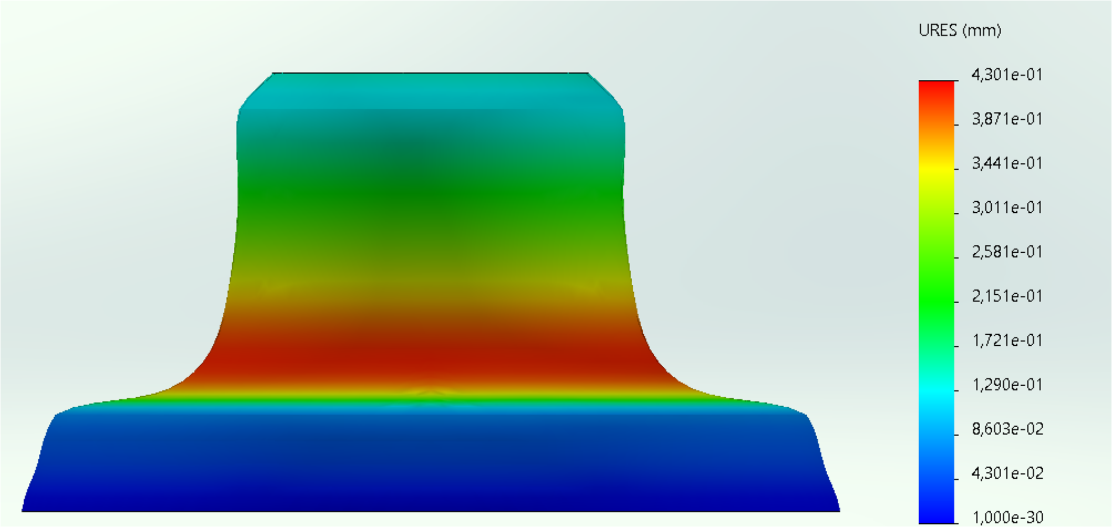

Figure A.36: 20mm shell with circular beam: Displacement.

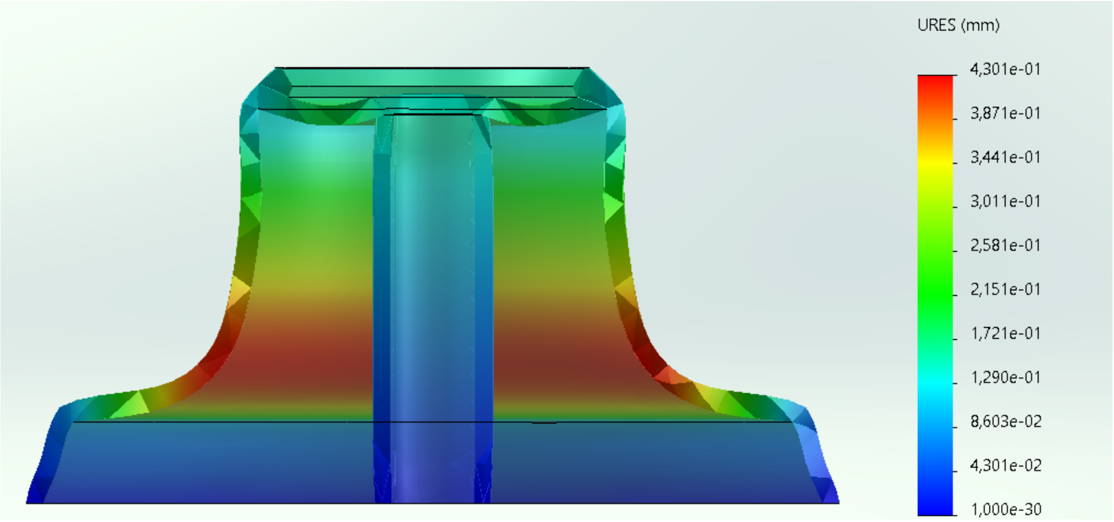

Figure A.37: 20mm shell with circular beam: Section of displacement.

20mm shell with thin wall supports

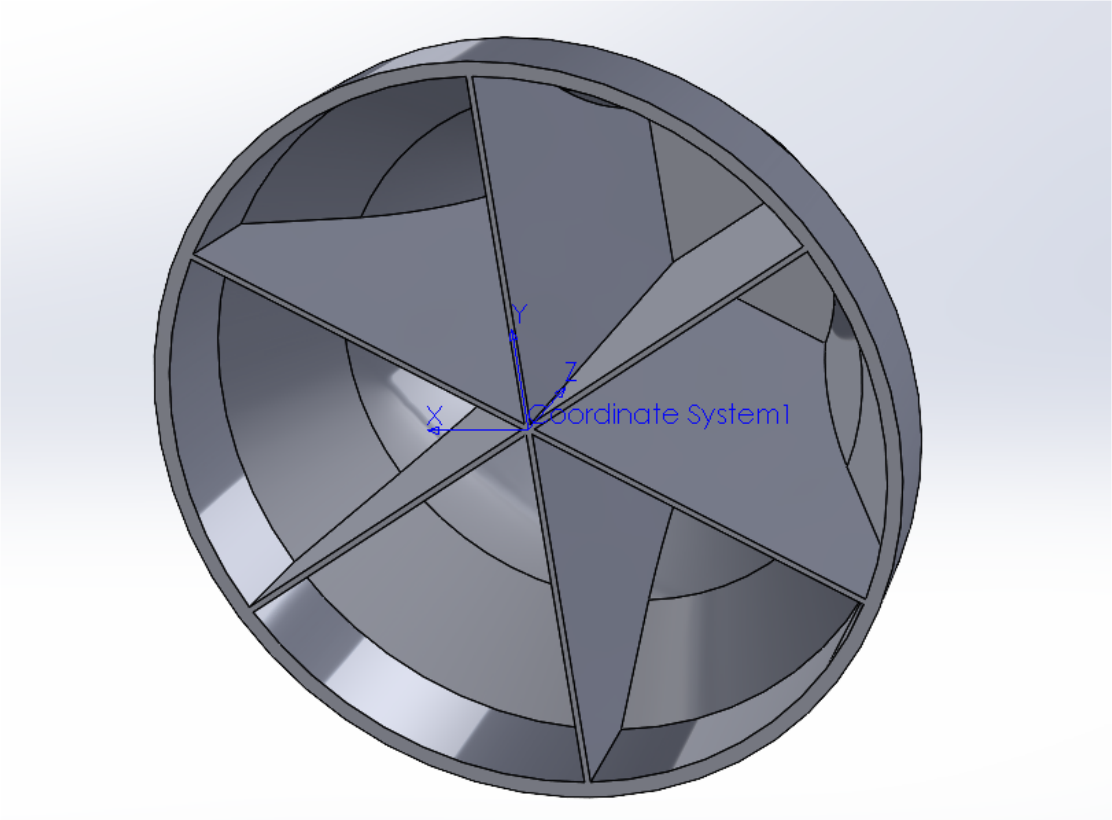

Figure A.38: 20mm shell with thin wall supports.

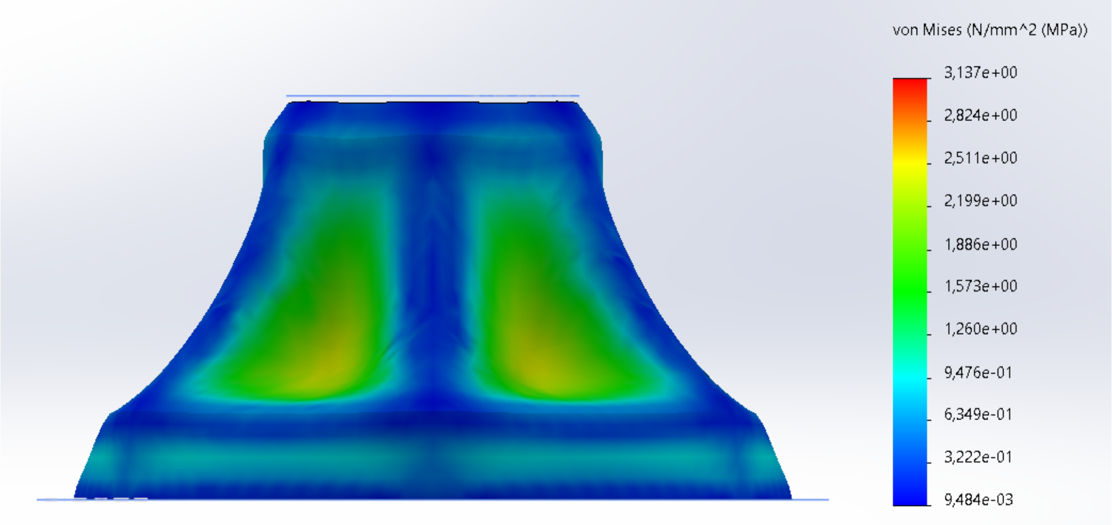

Figure A.39: 20mm shell with thin wall supports: Stress.

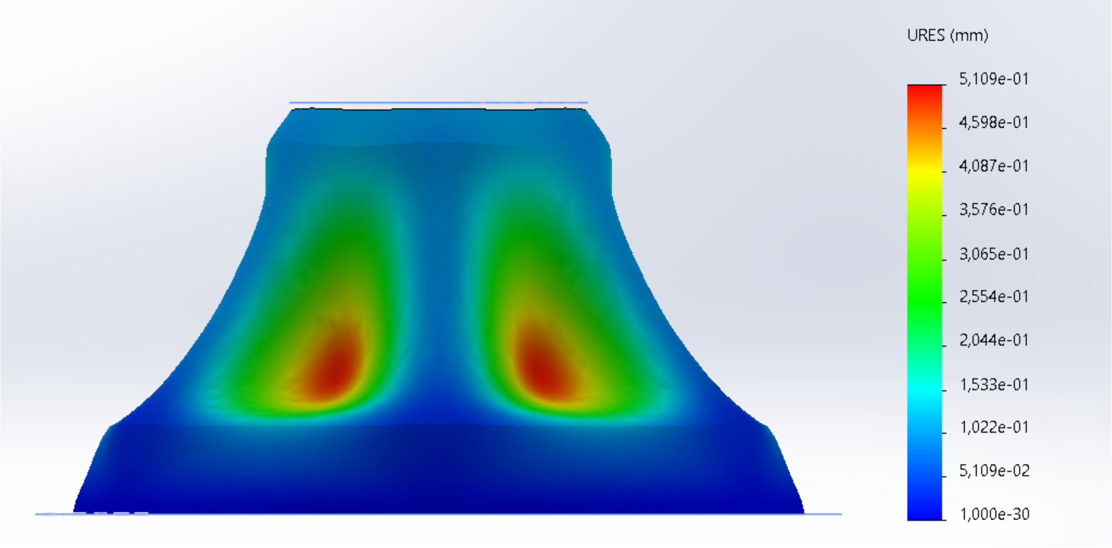

Figure A.40: 20mm shell with thin wall supports: Displacement.

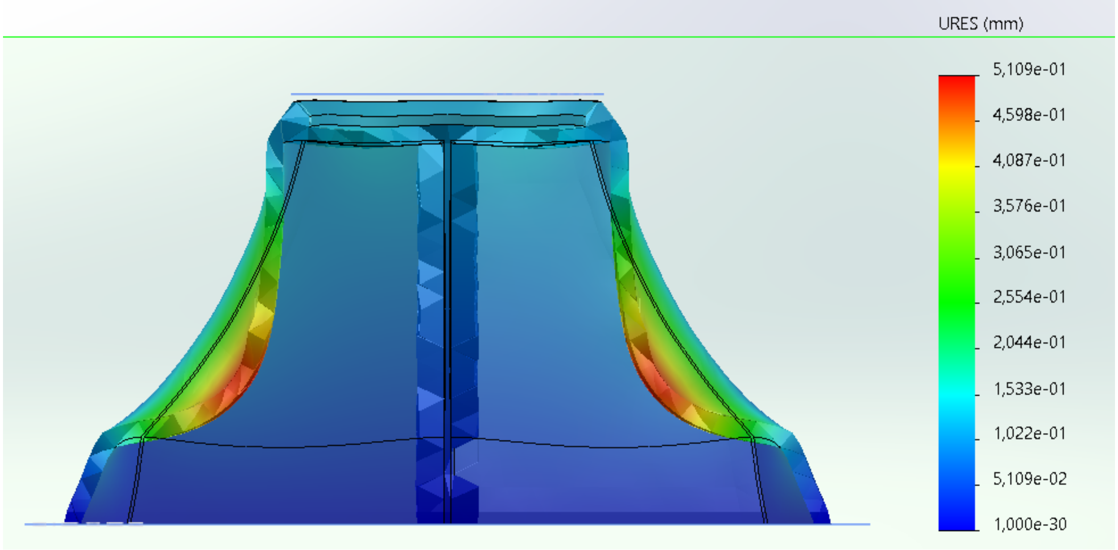

Figure A.41: 20mm shell with thin wall supports: Section of displacement.

20mm shell with triangular support

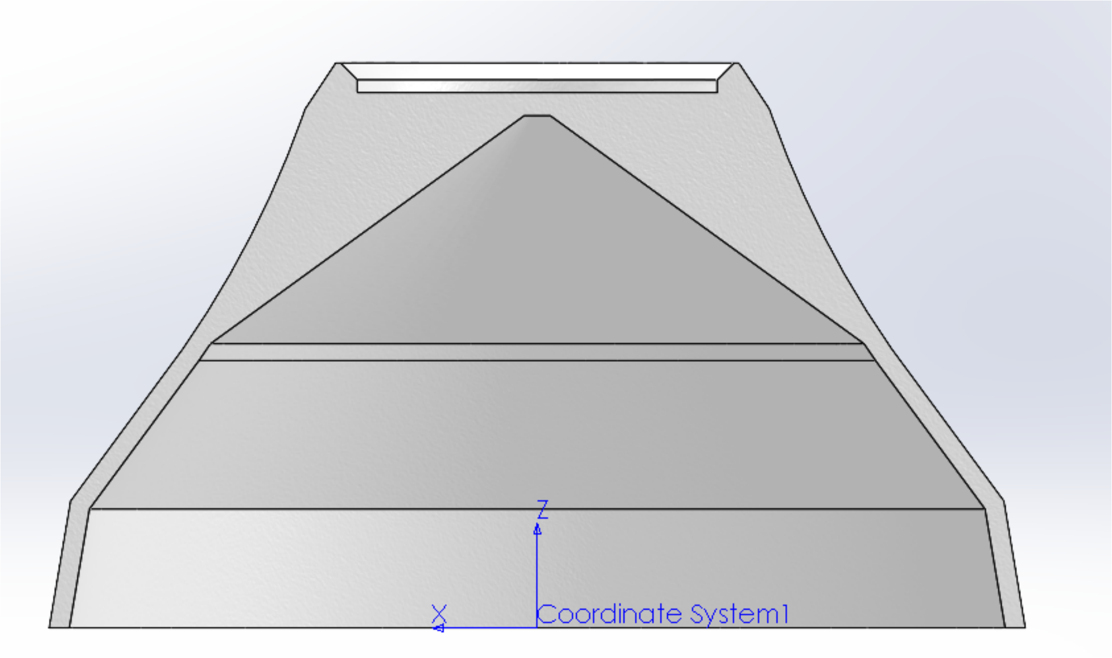

Figure A.42: 20mm shell with triangular support.

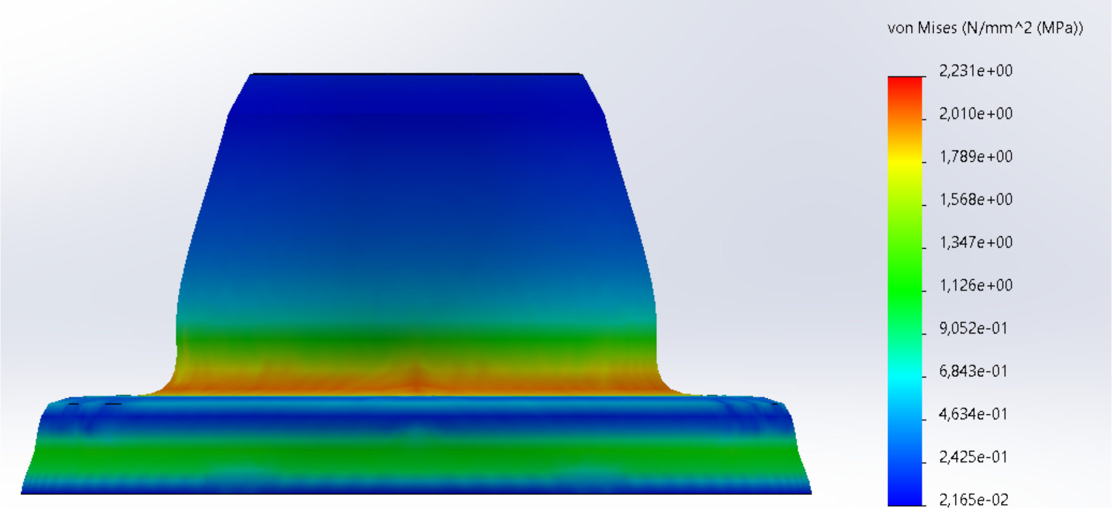

Figure A.43: 20mm shell with triangular support: Stress.

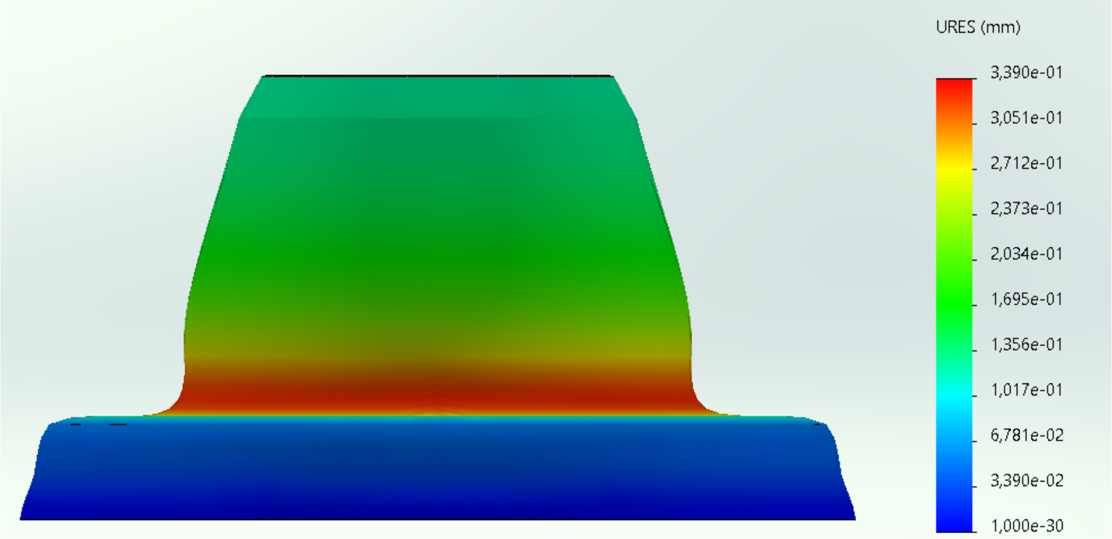

Figure A.44: 20mm shell with triangular support: Displacement.

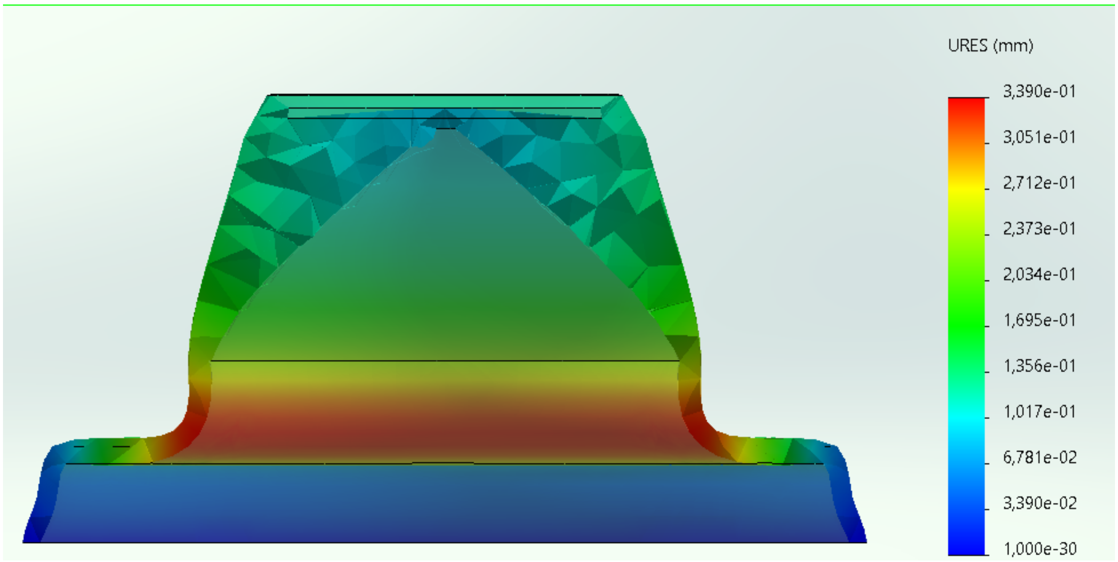

Figure A.45: 20mm shell with triangular support: Section of displacement.

20mm shell with triangular hollow support

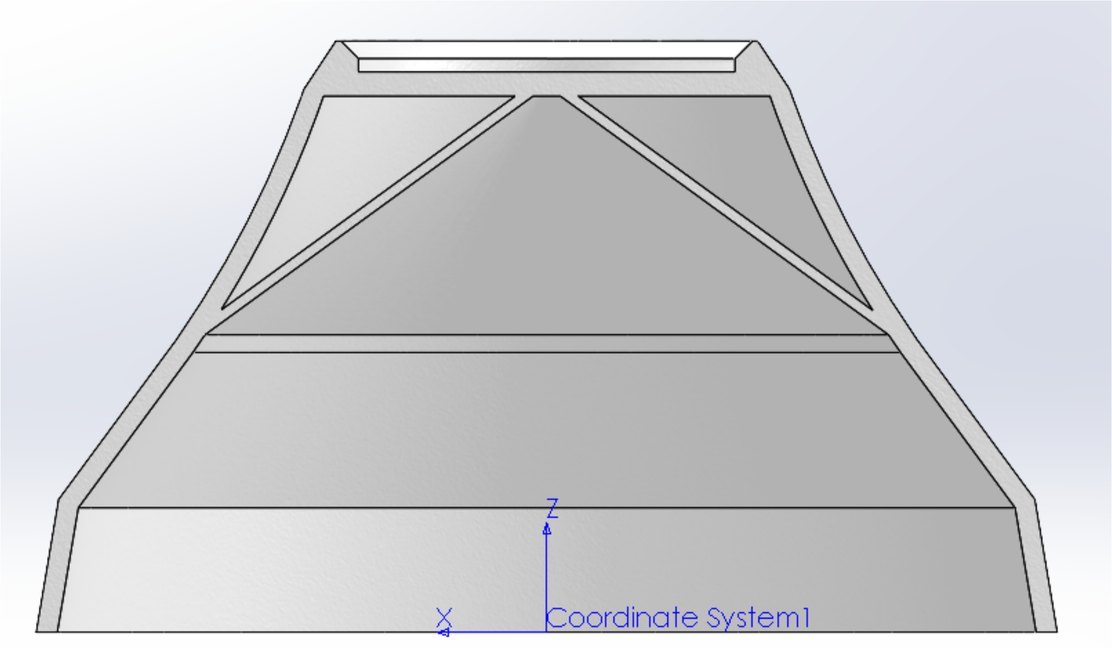

Figure A.46: 20mm shell with triangular hollow support.

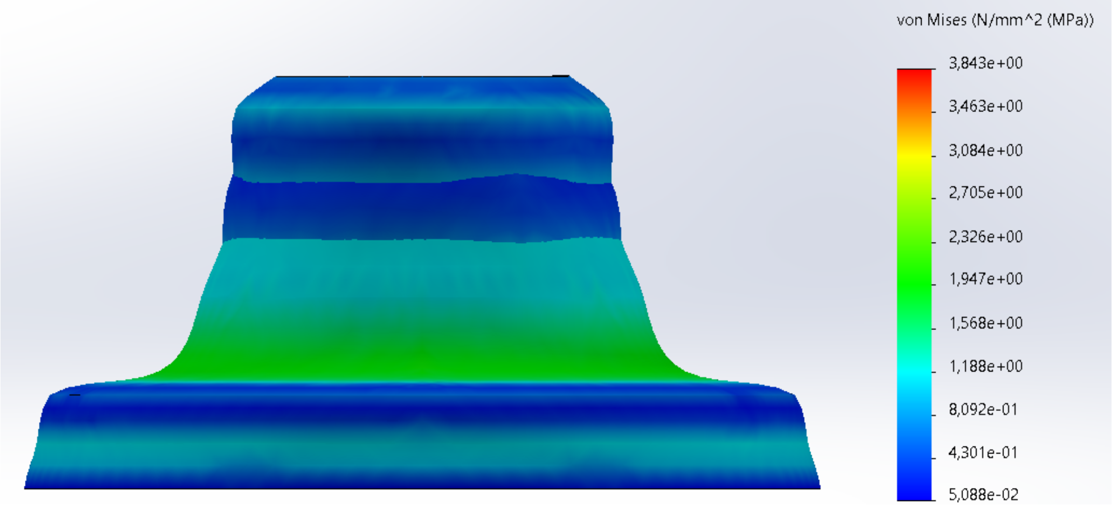

Figure A.47: 20mm shell with triangular hollow support: Stress.

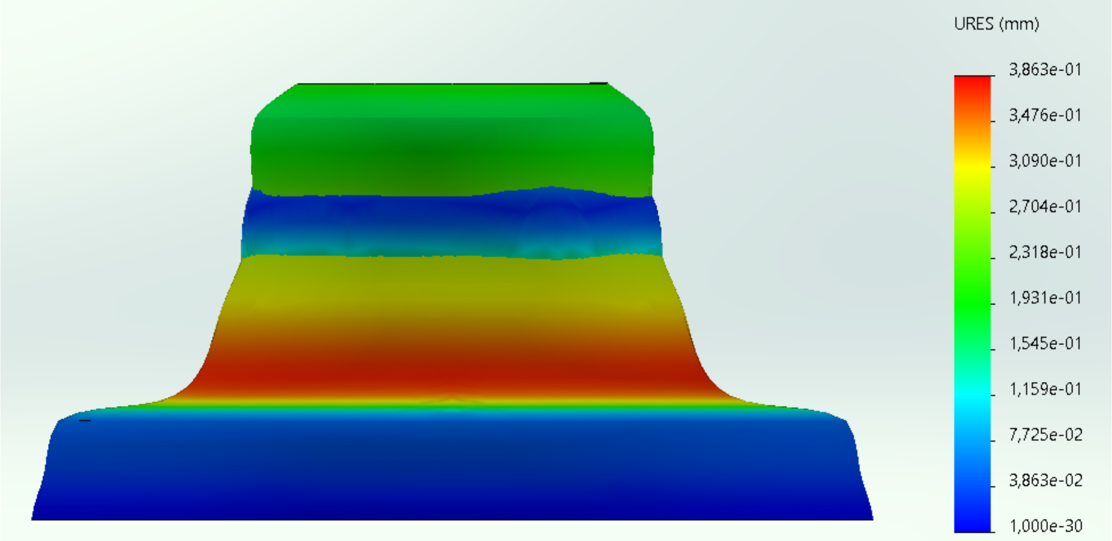

Figure A.48: 20mm shell with triangular hollow support: Displacement.

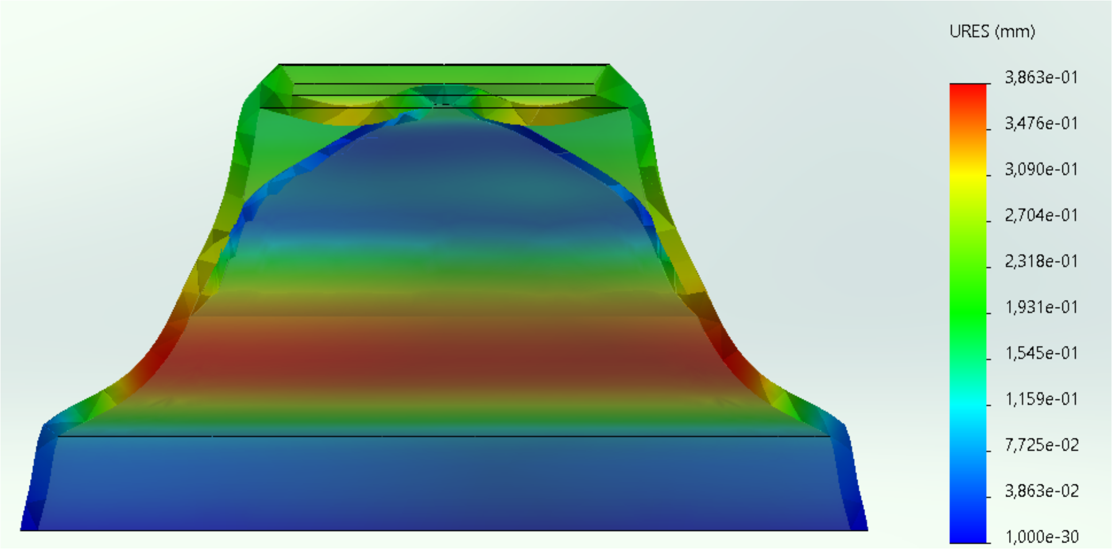

Figure A.49: 20mm shell with triangular hollow support: Section of displacement.

20mm shell with trusses

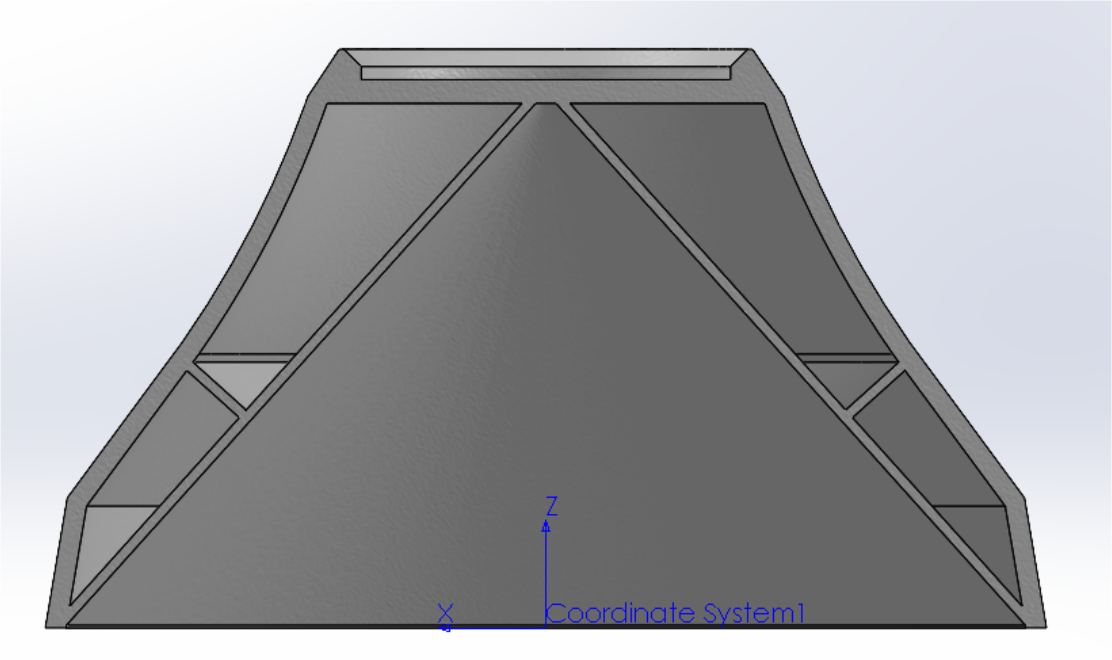

Figure A.50: 20mm shell with trusses.

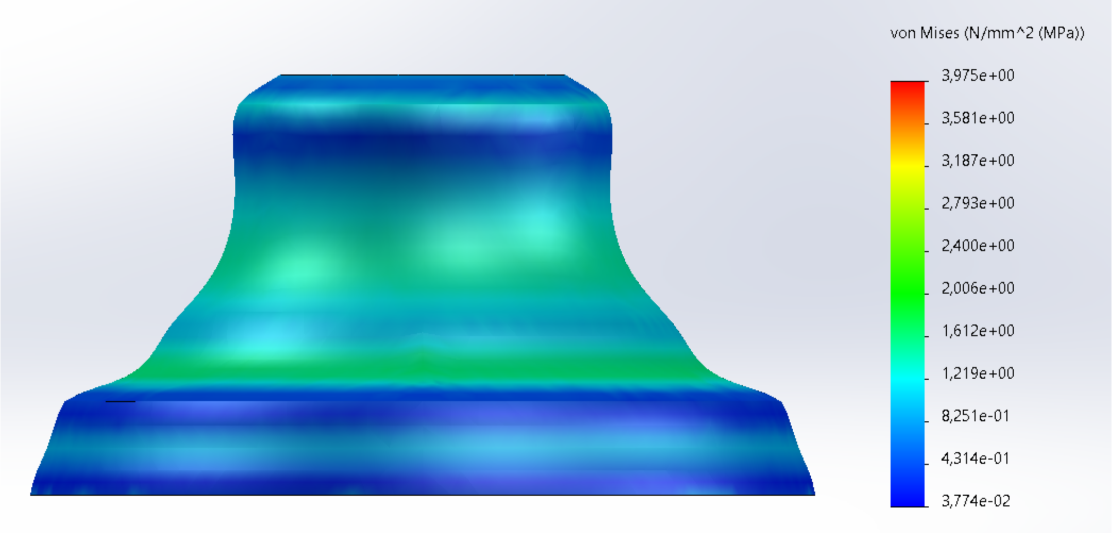

Figure A.51: 20mm shell with trusses: Stress.

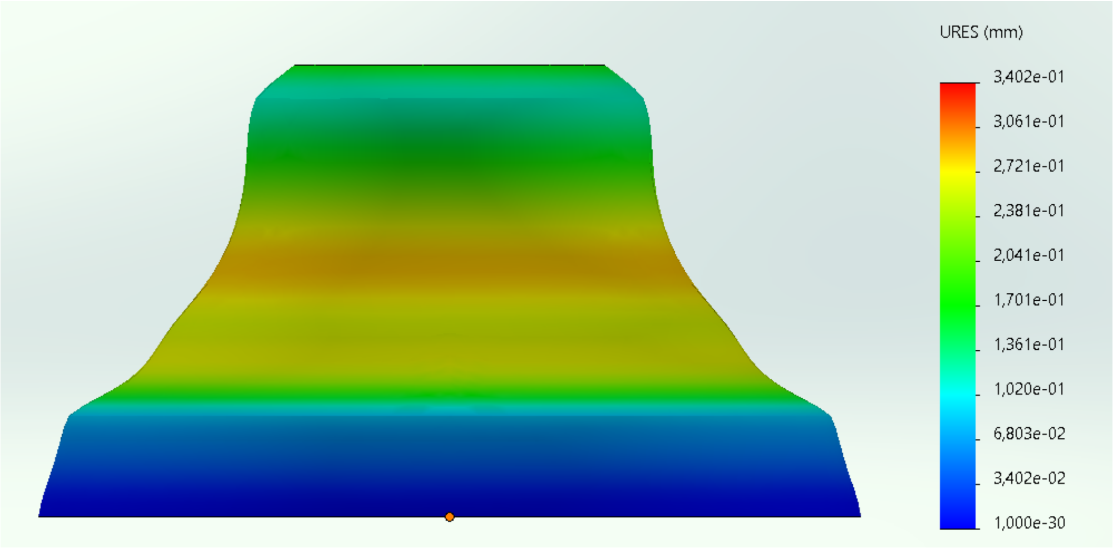

Figure A.52: 20mm shell with trusses: Displacement.

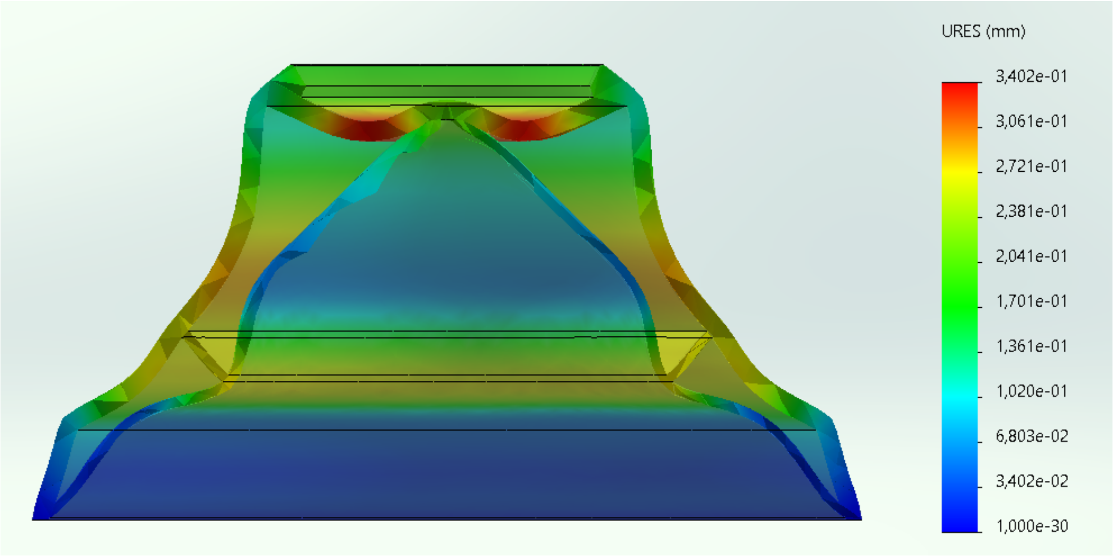

Figure A.53: 20mm shell with triangular hollow support: Section of displacement.

3D-printing large foundry patterns

3D-printing is a hot topic with new uses and possibilities popping up practically every day, but is it really the "be-all, end-all" solution to industries demands? Sometimes going back to a more conventional process might be the right decision.

For a long time the pattern making process has been more or less standardized, with a pattern-maker making the pattern out of wood, often with traditional methods such as turning. Though this produces good results it is really dependent on the pattern-makers personal skills and precision, and though the turning itself does not take that long, building up large blanks before the turning even starts does. To work around these issues the idea of making the patterns with 3D-printing arose, what in the industry is called additive manufacturing.

With 3D-printing you don't start with a solid object and then machine it down. Instead the machine build up the part layer by layer to achieve the desired three-dimensional shape. 3D-printing is today quite common, both in some industries but perhaps more noticeably as a hobby product. The prizes for 3D-printers have gone down drastically in the last ten years and as a result a lot of people find it both fun and useful to print their own parts from time to time. This could be either just for fun sakes or for printing more useful parts such as spare parts that are otherwise not available.

The problem for this project was then the size. Most hobby 3D-printers are quite small, few being able to print anything larger than a 300mm cube. For this project the base has to be at least 1.2m and the height is around 600mm. This leaves few options, which in turn sets limits to what techniques that are available. For this project it narrowed it down so that the only option was FDM, Fused Deposition Modeling. If you have ever seen a 3D-printer, it is likely that it was an FDM-printer. It is by far the most common printer and can be likened to a computer controlled hot glue gun that works its way up, layer by layer. It is a fast and cheap method, but comes with a crude surface finish.

The foundry patterns require a smooth surface to avoid the sand getting stuck to it when the pattern is removed, since this was unachievable with the 3D-printing alone the part will then also have to be machined down with a CNC-mill. One could say that this was the downfall of the project, adding another machine operation adds another level to the cost calculations, as well as delaying the finished product substantially. The cost difference to the conventional patternmaking was not that large and could have been outweighed by a shorter delivery time, but this was not the case. The project was definitely not complete failure, it showed that it is possible to make these patterns with 3D-printing and it might just be that the technology is not ready yet. There are other 3D-printing techniques that offer better surface quality that might be available in the right size in the future, only time will tell, but at the moment it might be best to stick with what is tried and true, gluing up large pieces of wood and spinning them around a central axis while you slowly remove the wood by bringing a sharp metal piece in contact with the spinning surface.

Author: Simon Håkansson
Full report:
Håkansson, Analysis of implementing additive manufacturing for the making of casting patterns, 2022