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Requirements for Designing Moulds for Composite Components

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NINA THORVALDSEN

Requirements for designing molds for composite components
Krav til design av former for kompositt komponenter.

Composite materials are typically made in a mold giving them their geometrical shape and surface quality. Making good molds is important for the success of a composite product, however, what are the criteria for a good mold has not been investigated much. Different product will require different molds depending on the performance requirements.
This thesis shall establish a set of criteria for a good mold that should be applicable for a wide range of products. A review of current mold making techniques shall be made and the techniques shall be evaluated against the newly established criteria. Emphasis will be put on critical material properties and how these can be measured.
Finally a promising mold making method will be selected and evaluated for one specific application.

The thesis should be written as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents, etc. During preparation of the text, the candidate should make efforts to create a well arranged and well written report. To ease the evaluation of the thesis, it is important to cross-reference text, tables and figures. For evaluation of the work a thorough discussion of results is appreciated.

Three weeks after start of the thesis work, an A3 sheet illustrating the work is to be handed in. A template for this presentation is available on the IPM's web site under the menu "Undervisning". This sheet should be updated when the Master's thesis is submitted.

The thesis shall be submitted as two paper versions. One electronic version is also requested on a CD or a DVD, as a pdf-file.

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Preface

This thesis is the final report in the degree of MSc in mechanical engineering at the Norwegian University of Science and Technology.

During the summer 2011 I had a summer internship at KONGSBERG Defense Systems, at the division at Arsenalet. KONGSBERG and I were discussing the possibility for writing the master thesis in cooperation with them. We landed on the topic of moulds for composite production, which is highly relevant for Arsenalet.

Moulds for composite production are often ordered with an external company. As long as the final part turns out well, is it a good mould. To make a good laminate and a good final product, it is important to have a good tool to work with. The longer a mould lasts and the better the surface of the part gets after it, the better. KONGSBERG wants to be able to make their own moulds with high accuracy so that they fulfill the tight tolerances.

Nina Thorvaldsen, Trondheim, 8th February 2012

Front page: A 20cm wide cut of a aluminium master mould and cured Beta prepreg mould placed on top, after the composite has been released and it is possible to see the spring-in. [Photo: Nina Thorvaldsen]

Summary

The aim with this thesis was to investigate moulds for composite production. A set of requirements needs to be established for such moulds. The requirements will then be used to find the right material and production method concerning the desired result. Different production methods and materials that can be used for moulds are presented.

Two different master moulds were made using two different types of materials, ytong and aluminium. On each of these master moulds, has two types of carbon fibre prepreg been used to make moulds. After cure has the dimensional accuracy of these moulds been measured and compared with the CAD models. The accuracy has been one of KONGSBERG's main requirements. One of the two shapes of moulds was used to make parts in. These two parts have been measured after cure.

Abaqus has been used to carry out an FE-analysis with simulations of spring due to cooling after cure.

The measurements and the analysis shows the spring-in, but with some difference in the results.

The two types of mould materials indicates good results for the shape and size they were tested on. They fulfill many of their requirements.

Sammendrag

Målet med oppgaven har vært å utforske støpeformer for komposittstrukturer nærmere. Et sett med krav trengs å etableres for slike støpeverktøy. Kravene blir så brukt til å komme frem til riktig materiale og produksjonsmetode i forhold til det resultatet man ønsker å oppnå. Det er presentert forskjellige produksjonsmetoder og materialer som kan benyttes til å lage støpeformer.

Det har blitt laget to mastermodeller med forskjellig utforming og med forskjellige materialer, ytong og aluminium. På hver av disse mastermodellene har to forskjellige typer karbonfiber prepreg blitt brukt for å lage støpeverktøy. Etter herding har den dimensionelle nøyaktigheten til støpeformene blir målt og sammenlignet med CAD modellene. Nøyaktigheten har vært et av hovedkravene til KONGSBERG. Den ene verktøytypen ble brukt til å lage deler i. Delene har blitt målt etter herding.

Abaqus har blitt brukt til å utføre en FE-analyse som illustrerer krymp grunnet nedkjøling av delen etter herding.

Målingene og analysene viser spring-in, men med noe forskjeller i resultatene.

De typene av støpeformmaterialer indikerer gode resultater for de formene og størrelsene de har blitt testet for. De utfyller mange av dems krav.

Nomenclature

α	=	Coefficient of thermal expansion
BMI	=	Bismaleimid, type of resin
CFRP	=	Carbon fibre reinforced plastic
CLT	=	Classical lamination theory
CMM	=	Coordinate measuring machine
CTE	=	Coefficient of thermal expansion
Debulk	=	Apply vacuum on part during layup
Demould	=	Part release from mould
FDM	=	Fused deposition modeling
κ	=	Thermal conductivity
LTM	=	Low Temperature Moulding
M61	=	The type of HexTOOL® used in this report
Master mould	=	The mould where the mould tool is made, not for metals
Mould	=	The support structure that holds the laminate or lay-up during the laminate consolidation process [1]
NDT	=	Non-destructive test
Plug	=	Male mould
Prepreg	=	Preimpregnated fibres with a resin system
RTM	=	Resin transfer moulding
T_g	=	Glass transition temperature
Tool	=	In this report used as the same as mould
UD	=	Uni-directional
VARTM	=	Vacuum-assisted Resin Transfer Moulding

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1 Introduction

Moulds for composite are made in different materials. Metals are well known and extensively used as mould materials. The aerospace industry requires high accuracy to their products. They seek materials that have closer material properties to the product they are making.

Composite materials have many advantages over metals. The material is first of all lighter. Another advantage is that it is possible to produce a material that meets a set of specific requirements. Examples of this is high strength, low density, excellent durability and many more. However, composite materials also have disadvantages. The cost is high both due to high material and production cost. The lack of dimensional control are still one of the main challanges.

When designing a component one of the first, and most important considerations to make, is which material to use. Metals and plastics are well known to most of us. Though, composite material is a newer way to get a material with the properties specially designed for the wanted part. When designing products of composite materials are there thousands of ways to use it. One of the main benefits of composites is its possibility to make complex shapes with high strength and light weight.

When making shapes in composites a mould is needed. The mould serves as support during production of the part. Depending on how the part should look like, what kind of material is being used and how many parts are going to be produced, mould tools are made especially for the purpose. Tooling for composites is a wide field which contains many technologies [2].

1.1 Description of a mould

A mould is a tool to make a part in or on. In the composite world, this is the tool that you do the laminating on or in. This means that the laminate will have the exact look as the mould on at least one side, only mirrored. So every sign of scratches or bumps will be shown on the surface of the part. Like it is said in an article about proper mould care: "The tool surface sets the quality baseline for production-part quality, so the part shape and surface quality can be no better than that of the tool" [3]. If the mould has a perfect finish, the part will have that as well, as long as everything turns out right in the layup and curing process. Some materials has to be machined afterwards to have the perfect surface.

There is a cost aspect of what is the most effective way to make the mould. The price of the material is a big investment. To produce the mould in a cost effective manner, you need to optimize the usage of material, labour and

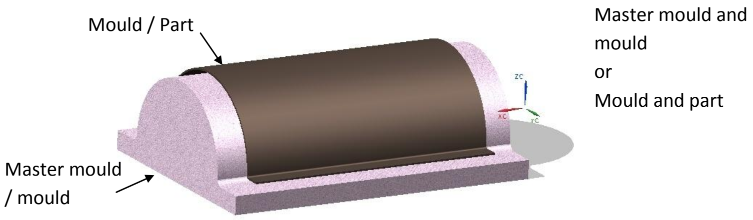
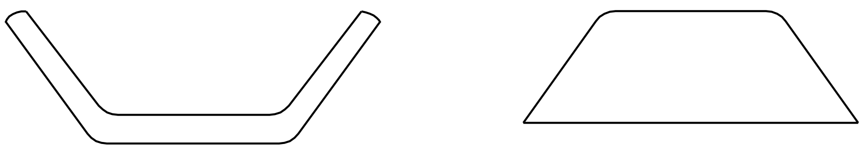


Figure 1: Mould

machining hours spent. Either if it is fully machined or built up in different steps and then maybe machined. When a lot of post work must be made on the mould before it can be used, it might lead to big additional expense.

As Taylor-Wide says in his guide to composites [4] : “Bear in mind that this is one of the few processes where we make the material at the same time as we make the component.”

The parts are either made in a female mould, which can be seen in figure 2a, or on a male mould, figure 2b(also called a plug). Depending on which side of the part that needs the right size and surface finish it is chosen either female or male mould. A male mould has the lowest layup cost. It is also possible to use a matched die mould, where both female and male moulds are used. This is a good way to control the thickness, but it has high tooling cost [2]. If the tool is correct in pressure moulding or RTM, as can be seen in figure 7 and 5, all sides will have a nice and smooth finish.



(a) Female mould tool (b) Male mould tool / plug

Figure 2: Female and male mould tool

When choosing a mould technique one of the main things to consider is how the final part should be produced. Will the part for example be exposed to high temperatures or pressure? The number of parts expected to be produced will have a big influence both on the production method and the material of the mould. For a prototype, the material can be of a less durable material than if the form should handle hundreds of part produced in it. This will contain layup, curing cycles and release. During production the part is most likely to be moved around. Therefore is it important to take in to consideration how much space that is required.

One of the biggest challenges and main considerations when choosing material for the tool is the thermal expansion. This should be as close to the coefficient of thermal expansion of the composite as possible[2]. There are different curing techniques for different materials. Some can be cured in room temperature, other in for example 60 °C and other up to 500 °C. This makes of course different requirements for the mould and its material. The curing method, as for example room temperature with vacuum or in autoclave, will also affect the chois of tool-material. More information about the different types of materials for moulds is to be found in section 4.

Some of the most common materials for moulds are listed in table 1, these will be more described in section 4.

Table 1: Materials used for moulds

- Aluminum
- Steel
- Invar®
- Titanium
- Ceramic
- Composite - high/low cure
- Graphite
- Nickel
- Carbon foam
- Concrete/Ytong/plaster
- Wood
- Tooling board
- Epoxy paste

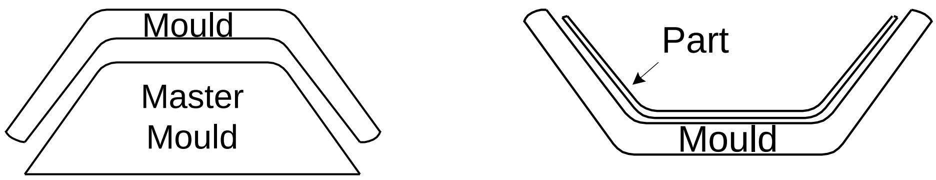
Independent of what kind of material is used, the mould needs proper care. If the mould does not get the attention it needs it will show either in shorter life time for the mould, or in increased post mould rework for the finished part. The results of insufficient mould care is first shown when it is too late, and the mould needs extensive care and renovation [3].

Composite tools are one way of producing moulds, and can be made in different ways. Airtech [5] and Composite Airframe Structures [2] divides it into three groups, but a bit differently:

Airtech	Composite Airframe Structures
◦ Hand layup	◦ Wet layup
◦ Prepreg / Autoclave processing	◦ Hot-cured prepreg
◦ Resin infusion processing	◦ Room-temperature-curing prepreg

1.2 Master moulds

The master mould is the support structure used for making a mould. The master is then a shape of the final part, see figure 3. The master mould is usually used very few times, often only once. For master moulds the materials are often different from the mould. When the master mould is designed, it is important to have the two next steps in mind, that means the mould and the final part. Both of them will somehow change, and it is then important to know that the final result will be as expected. Since it might only be used once, it can be made of a material that is not so durable, and then often at a lower cost. One of the main differences in choosing material for master mould and moulds is the temperature the curing should be carried out in. For typically low temperature components, the curing will be below 100 °C [4], but often not higher than 90 °C. This means that high temperature components are from 100 °C and above. There exist more materials for low cures than for high, and they are usually at a lower price.



(a) Master mould and mould (b) Mould with part

Figure 3: Visualization of master mould

1.3 Production methods

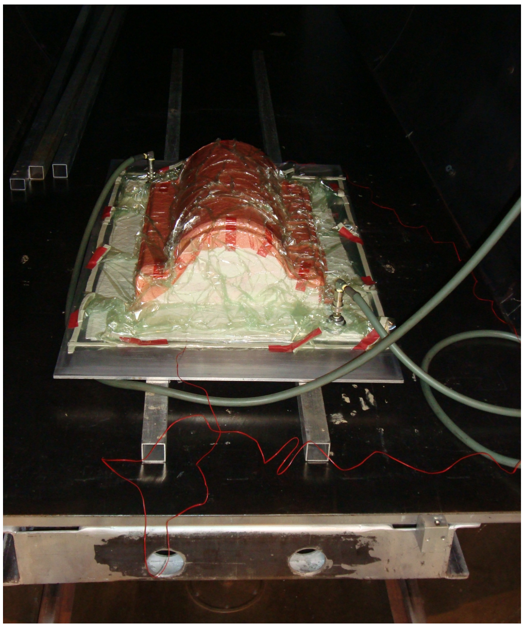
Described in the next's subsections are different ways to make composite parts. This is for the part itself, but many of the methods are also used for mould production. All moulds, that will say masters, and moulds in different materials, have to be coated with release agent before the layup can take place. For the wash out mandrel, this is not so essential.

1.4 Autoclave

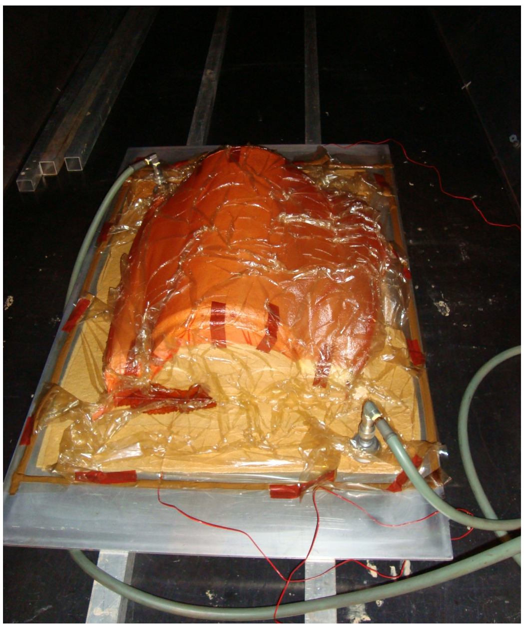
An autoclave is widely used for production of aerospace composite parts. An autoclave is an expense for the company, both the acquisition and to run the autoclave. It uses both heat and nitrogen to get the right temperature and pressure. It works like a pressure vessel, which is why it looks like a cylindrical tube with one closed end and door in the other end. The temperatures can be up to 650 °C and normal working pressure is 7 bar; max pressure is approximately 34 bar [2]. The cycle time for production in autoclave is long, normal cure can be 15 hours with heating and cooling in the right step, graph of a autoclave cure can be seen in figure 54 in appendix A. The method of layup is either hand layup by the wet layup method or by prepreg, but it is also possible with automated placement or automated tape laying [6].

The material for moulds in autoclave production has to perform properly at the temperatures and pressure the produced part needs for being cured [7].

The temperature is controlled by thermocouples T_c that are attached to the part, see figure 12. In figure 4 a part can be seen before and after cure in autoclave with attached vacuum and thermocouples.



(a) Ω of Beta prepreg before autoclave cure



(b) Ω of Beta prepreg after autoclave cure

Figure 4: Ω of Beta prepreg in autoclave in KONGSBERG
[Photo: Terje Simlenes]

1.5 Out-of-autoclave

The new thing in the aerospace industry is out-of-autoclave manufacturing. It is discussed in an article by G. Gardner, "Out-of-autoclave prepregs: Hype or revolution?" [8], if out-of-autoclave really is the new thing. When a company already has an autoclave, then they should use it. The prepregs that are made for this purpose can be cured at lower temperatures and therefore the differences of the CTE of the mould and the part will not have so big influence on the part. Many of the resin transfers methods are not for autoclave cure.

1.6 Resin Transfer moulding, RTM

Resin transfer moulding, called RTM, is a process of transferring resin into the dry reinforcement, typically a preformed form of fibres in the form of short, woven or stitched, which are placed in a closed mould. That means that the mould is sealed, resin is injected into the mould vacuum may be used. The part is cured with or without pressure. It is possible to heat both the mould and the resin for better flow and faster cure. The mould can look a bit like the mould for compression moulding, but it has an inlet for resin. It also has some of the same requirements as for compression and injection moulding. It has to withstand the pressure from the resin and the opposite force of holding the form together. There are many advantages of RTM, like class-a surface finish, short cycle times and near net shape moulded parts. The mould is expensive due to matched moulds [7, 6, 9].

A new method called Same-Qualified Resin Transfer Moulding (SQRTM) is a process where prepregs are laid up in a RTM matched mould. The same resin type as in the prepreg is drawn through the mould with vacuum, and then fills the small air holes with resin and prevents void formation [10].

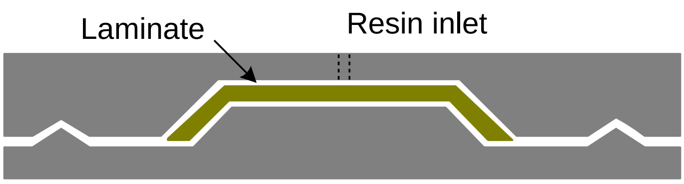


Figure 5: RTM mould with part

1.7 Vacuum-Assisted Resin Transfer Moulding

The short name is VARTM, or vacuum infusion (VI). This is similar to RTM, but the resin is pulled through the fibres by vacuum. It can either be a one sided tool with vacuum bag or two sided; figure 6 shows this with vacuum bag. The tooling cost can then be lower than for RTM process. The curing process causes heat, this have to be taken into account for big parts, where large amount of resin is needed.

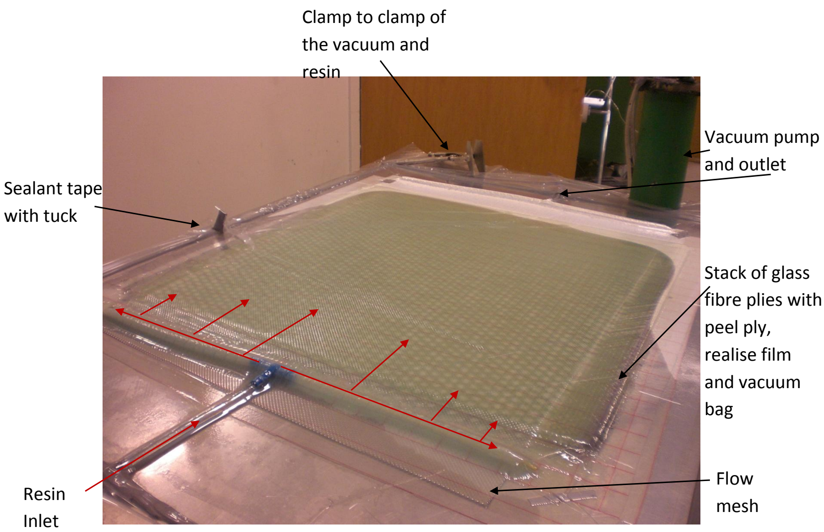


Figure 6: Vacuum infusion in the composite lab at NTNU
[Photo: Nina Thorvaldsen]

1.8 Pressure moulding

This is a low volume production process where prepregs are placed inside a mould, often by hand. These moulds are usually made of some kind of metal. The mould consists of a matched die mould see figure 7, where the part are assembled inside one of the two tools. There are as good opportunities to apply core material here as with many of the other techniques. The mould has to withstand a lot of pressure and temperature changes. One of the challenges is to know that the part inside the mould has the right temperature, and that it fills the form perfectly without edges or dry spots [11]. Compression moulding is a higher volume production method, where the material is laid lightly on top of the mould and pressed into shape by the pressure [9].

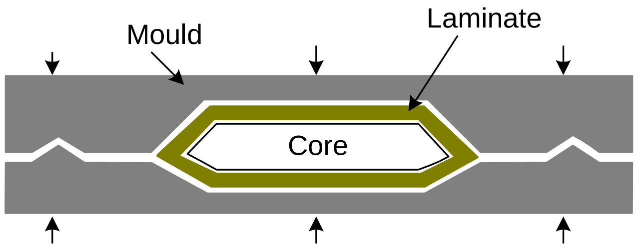


Figure 7: Pressure moulding with core material

1.9 Filament winding

It is impossible not to mention filament winding even if the focus of this report is not on that subject. The winding technique is based on winding continuous long fibre, impregnated with resin, on a rotating mandrel. The impregnating of the fibres can either be done by the manufacturer, like prepreg, or by having a resin bath during winding right before the mandrel that wets the fibres. The direction of the fibers depends on how the desired strength should be. The cure can be either in an oven or autoclave. The mould, called mandrel, can either be a part of the final structure, or a part that is removed after cure by mandrel extraction equipment, or washed out if it is a material that dissolves in water [6].

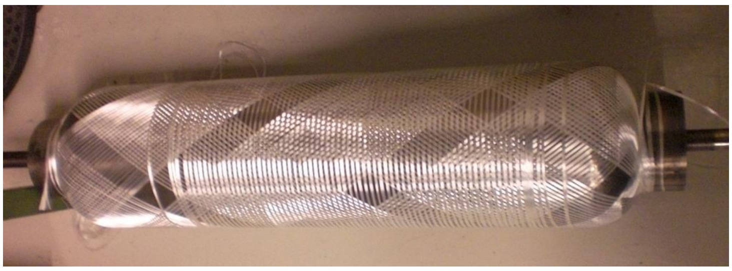


Figure 8: Filament winding test done at NTNU by the polymer and composite group

[Photo: Nina Thorvaldsen]

1.10 Injection moulding

Injection moulding is a high volume production process, especially compared with many of the other composite processes. It can contain a type of thermoplastic and some kind of reinforcement in form of short fibres. The material is injected into the mould while the mould is clamped together. It is required matched metal dies because of the high temperature and pressure. This makes the mould expensive, but it can be a cost saving process due to high production volume with good tolerances. The part will not be able to reach the same high strength and stiffness as long fibres [9].

1.11 A typical mould for building of boats

A leisure boat is usually built of glass fibre. This is a relativity large structure, and also here the more time spent on surface finish of the master mould, the more time is saved later. The master should be produced at specific dimensions and must resist styrene and heat, but it is cured at room temperature. The second step is to apply gelcoat, and let cure until it feels tacky. Then a skin coat should be applied, this gives a nice surface. Then the filled resin system is sprayed on to the desired thickness, then a roller or brush is used to remove entrapped air and get the filled resin into all small places. It is possible to apply cores to increase the stiffness. A stiffening frame can either be laid down at the wet laminate or glued onto the cured surface. The curing time is usually 24 hr. This information is taken from one specific tooling brochure from Reichhold on Polylite® Profile Tooling System [12]. Moulds for boats usually do not have those tight tolerances as for example the aerospace industry. So it is not so bad if the mould slightly changes its shape, but they also need to be assembled, so it cannot change too much. The moulds are often made of random oriented glass fibre and a resin system, but not always done by spray layup, but by hand wet layup.

1.12 Electically heated ceramic composite tooling

Brádaigh, Doyle and Feerick [13] discussed ceramic composite tooling that is electrically heated. These moulds are good for large composite structures such as wind turbine blades and components for the aerospace industry. This has an advantage since the parts can be cured out-of-autoclave and then saves investments and energy. The ceramic can be heated up to 1000 °C, but the mould itself can be used at up to 300 °C. The result of this study was promising, and from the tests done at 12.6 metre wind turbine blade and an aerospace part successfully manufactured [13].

1.13 Fused deposition modeling, FDM

As discussed in [14], one new way to produce master moulds and moulds is by fused deposition modelling (FDM). The wanted result was to reduce cost and cycle time, with the same or better result. FDM has for many years been used for prototyping. By using this method is it possible to produce a tool without a series of negative and positive splash moulds. This reduces cycle time and saves the environment from cure and deposit of extra parts. The material that is used for this type are various types of thermoplastics [14].

1.14 Nickel deposition

The electro-deposition nickel mould production is a process that has many steps, which is one of the reasons why it is a costly method. First a master model has to be created. Then a splash is made on the master for then making a plating mandrel in the splash. The plating mandrel is sunken into an electroforming nickel solution to make the layer of nickel. The nickel part is then attached to a tool support structure, and the plated mandrel is removed. It has several advantages like a durable mould, easy release of part, damage resistance and the possibility to repair with soldering or welding. But the CTE is quite high, close to the one for steel, which is higher than composites. Also here a correction factor must be included, since the electroformed tool expands during cure, or shrink [2]. Nickel Vapour Deposition (NVD) is another and faster way to make a nickel mould. The method creates a more uniform wall thickness than electro-deposited and is a much faster method. A shell of nickel is created with nickel powder and carbon monoxide gas in a chamber, and applied on a CNC machined aluminium master. The method gives a virtually stress free mould with low CTE and fast heating and cooling of the mould [10].

2 Objectives

One of the aims with this project was to establish a set of requirements for moulds for making composite parts. Another aim was to find a good mould technique for some of the models for KONGSBERG. To be able to reach this, it was important to know what they where looking for. What are actually the requirements for the moulds they are making? There exist a various ways to make moulds, so some different methods will briefly be described. The requirements will be different for different types of parts. This depend much among others on the size and shape of the part. To know if the mould reaches its dimensional requirements, the mould and part will be measured.

KONGSBERG have the interest of knowing more about shapes that are formed as the Ω and the C-shape.

There was chosen two rather small parts, see among others figure 11 and 14. On each of these shapes will there be tested two promising materials for moulds, to find the positive and negative about them. Within each of them, there will be different ways to make them. These two materials was choosen mainly because KONGSBERG wanted to investigate them further.

Since KONGSBERG is using most epoxy based carbon fibre prepreg with long fibre, that is the main focus area in the report.

The procedure of the document and work are listed in table 2;

Table 2: Method used for finding a result

- Description of different mould techniques
- Requirements for moulds
- Different materials available for mould production
- How to get from requirements to the selection
- Make two of the promising solutions
- Measurements and analyses
- Was this as wanted?

3 Requirements

The need to establish requirements for mould can be compared with the importance of identifying costumers need in product design. To be able to know what the final result should look like, the product specification must be known. The spesifications are often revised more than once due to lack of information on the constraints to the product technology. Tool design and fabrication is the foundation for a good part. There is just as important to spend engineering time and money on the mould design as for the part [15, 9].

As mentioned earlier, there exists a number of mould techniques and ways to make composites. Many of the requirements for these techniques are often the same, but many are different. There are different ways to make the parts, different materials, thickness, stability, surface finish, look and so on. One of the most common requirements is that the part turns out the way it was supposed to, that the size fits in with the assembly it should fit into. With a good surface finish on the mould, the part will have a good surface quality, but never better than the mould. Not all moulds have to withstand the same temperatures and pressure during manufacturing and that will make different requirements and specifications. Some parts are meant to have the perfect finish while others are meant to be done something with afterwards. Is it desired to make the mould in house or outsource it? Some of the techniques require a lot of equipment, so if the company only wants to have a very few number of moulds in that technique, it should be considered to let somebody else do the making.

Many of the requirements for making a tool for metallic structures or injection moulding are the same for lamination tools for composites as well. Many of the requirements are so naturally given, that it sounds strange to mention, and might be easy to forget to mention. Others are so matter of course that they are always mentioned but not necessarily easy to maintain. In addition for the mould design it is important that the tool extend at least 5cm beyond the part to make room for sealant tape. It is also important to have the vacuum attachment in mind.

For KONGSBERG it is important to have a mould with the right shape and to know what they are working with. This is more important than to reduce cost and time. Of course these are important aspects as well, but they don't have the highest priority. Since parts they produce are assembled with many other parts, it is important to have them as accurate as possible. The requirements for accuracy in the aerospace industry are stricter than in many other industries. The less time used on unnecessary adjustments on each part, the more time and money is saved and it is possible to achieve a

Table 3: Requirements for moulds, more described in the next sections

1	Release part
2	Coefficient of thermal expansion
3	Dimensional accuracy and stability
4	Hold vacuum
5	Finish
6	Durability
7	Environment, health and safety
8	Weight
9	Costs
10	Machinability
11	Repair and modify
12	Heat and pressure
13	Materials lifetime
14	Maintenance
15	Adaptive work on part
16	Curing conditions
17	Lead time

higher production rate. There are quite tight tolerances, so it calls for more accurate mould. Many of the products KONGSBERG are making are meant to be flying, and small changes in the symmetry or wrong size of shapes can make big difference to the performance and the fuel consumption. It is important to have a mould they can use many times, since much time and effort is used on one mould. One of the reasons for that is of course that they don't have to make a new one all the time, there are expenses of making a mould in labour and material costs, but also environmental concerns of the use and disposal of parts. If they have to make a new one every 10th time instead of every 100ed time, it will lead to a lot of waste. For other applications as one of the first prototype it is best to for example make a low cost mould for one time use.

A summary of some requirements compared with different material types can be found in table 6.

3.1 Release part

It is desired that it should be as easy as possible to release the part from the mould. Release agent must always be applied on the mould before layup. The material in the mould and part must not react with this agent. In some cases it is not possible to make the part without having an assembled mould.

That means that the mould is taken apart when the part should be released. This leads to extra concerns about where it is possible to have edges and where the part can be sanded afterwards. There is also a challenge to get it vacuum tight. The sealing of the part must withstand the same heat and pressure, but must be able to release again. For filament winding a segment mandrel is required where the part are not to be slided off after cure, a wash out mandrel or is a part of the structure.

3.2 Coefficient of thermal expansion

Coefficient of thermal expansion, CTE (α), is especially an issue for parts that are undergoing high temperature changes during cure. If the CTE is similar to the produced part, the spring will be smaller and likely make crack in the ply or delamination [9, 16].

In the mould making industry for composites this is one of the main considerations. The CTE for composites is low, and it is an advantage to have the coefficients for the mould and the part as close to each other as possible. The coefficient tells how much the material expands with temperature changes. Some carbon fibre epoxies have negative CTE.

There are different standards for measuring the CTE. A typical method is to measure the change in length of a specimen when constant heat is applied. ASTM E228-11 describes it for rigid solid materials with a Push-Rod Dilatometer. In ISO 11359-2 the method of testing the coefficient of linear thermal expansion and glass transition temperature by Thermomechanical analysis (TMA) is given. This is by using thermodilatometry where TMA is one type [17]. In Structural Analysis of Polyneric Composite Materials says it that a normal method to find the in plane thermal expansion is to use resistance foil strain gages [18].

3.3 Dimensional accuracy and stability

As mentioned in the book Advanced Composites Manufacturing [7], the production method for all advanced composites needs the tooling to be hard if the structure should be supported during layup and cure. As discussed later in this chapter, the spring-in phenomena is a well known problem in composite production, meaning both the mould and part making.

Some moulds need support structure, either for holding the mould stable during layup or to stabilise the structure during cure. If autoclave is used, the mould has to withstand a certain pressure, usually 7 bar, and it then most likely has to be solid. If not, you might risk to having the mould collapse during cure, and the part will then be totally different from what you wanted [4].

Thermal conductivity (κ), also called heat conductivity, is the conduction of heat transfer and is affected by temperature and pressure. This is often evaluated when mould material are selected. A high thermal conductivity means a high heat up and cool down rate. A test method would be to calculate the heat by applying two different temperatures in each end of a specimen. Typical test method that are more described in ISO/TR 22007-1 are: hot-wire method, line-source method, transparent plane source method, temperature wave analysis method, laser flash method [19, 20].

T_g is the point of where a polymeric material changes from "a rigid glossy solid into a softer, semi-flexible material" [9]. This means that T_g is the maximum temperature in which the material can be used, and still have the same mechanical properties. The actual operating temperature should always be at least 10 °C lower than T_g [9]. This value is often provided by the material manufacturer.

For compression moulding, injection moulding and transfer moulding the ASTM standard D 6289-08 [21], "Standard Test Method for Measuring Shrinkage from Mold Dimensions of Molded Thermosetting Plastics", gives one interpretation of the results of the mould shrinkage (MS), given in equation (1).

$$MS = \frac{L_0 - L_1}{L_0} \cdot 100\% \tag{1}$$

This is in percentage where:

L_0	=	length of the dimension of the mould, specified in mm
L_1	=	length of the corresponding dimension measured on the test specimen, mm
L_2	=	length of the same dimension of the test specimen, measured after heat treatment at 48h or 168h, mm.

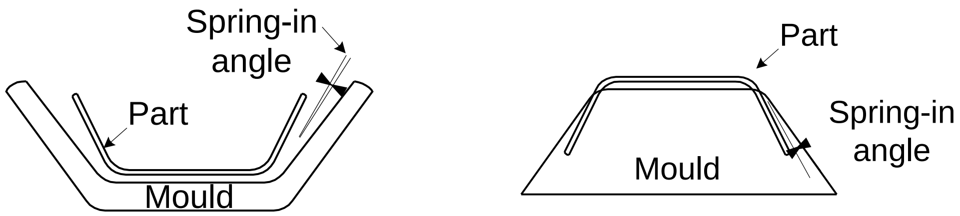
All measurements of dimensions should measure the length of the cavities to the nearest 0.02mm at a temperature of 23 ± 2 °C.

The post shrinkage (PS) is given in equation (2)

$$PS_{48h} or PS_{168h} = \frac{L_1 - L_2}{L_1} \cdot 100\% \tag{2}$$

3.3.1 Spring-in

Spring-in, also called spring back, is a common phenomenon for most kind of materials and especially moulded parts. The behaviour is different from material to material, thickness, shape, temperatures etc. For metal for example the spring can occur when sheet metal is bent, and it then bends slightly back. For composite materials the spring often happens after or during curing, then opposite of metals, so the final shape might be smaller than the mould. It is normal to make the mould with an angle of 2° bigger than how the final part should be, see figure 9, [9].



(a) Female mould with spring-in (b) Male mould with spring-in

Figure 9: Visulaization of spring-in

There are three main reasons for why spring-in occurs, these can be seen in table 4.

Table 4: 3 reasons for why spring-in occurs, taken from [22]

- Chemical shrinkage (the volume changes/shrink due to resin hardening)
- Thermal shrinkage (the volume changes due to CTE)
- Mismatch between coefficient of thermal expansion (CTE) for resin and carbon fiber

Chemical shrinkage happens when the resin is crossed linked in the curing process. Thermal shrinkage is caused by the CTE. The mismatch CTE of resin and fibre is one of the main reasons for the spring-in on curved parts. This because of the strain difference in x and z direction [23, 24, 22].

An equation for predicting spring-in for laminates with angle are found in equation (3). The equation considers temperature difference during cure, thermal expansion, cure shrinkage and the angle of the part. This is more discussed in [25], it is also used by people at KONGSBERG.

$$\Delta\theta = \Delta\theta_{CTE} + \Delta\theta_{CS} = \theta\left(\frac{(\alpha_l - \alpha_t)\Delta T}{1 + \alpha_t\Delta T}\right) + \theta\left(\frac{\phi_l - \phi_t}{1 + \phi_t}\right) \tag{3}$$

One way to measure the spring is using different measuring machines, either with laser or coordinate measuring machine. Another way to measure

Where:

$\Delta\theta$	=	Spring in angle
$\Delta\theta_{CTE}$	=	Thermal component of the spring-in angle
$\Delta\theta_{CS}$	=	Cure shrinkage component of the spring-in angle
θ	=	Part angle
α_l	=	longitudinal coefficient of thermal expansion
α_t	=	Through thickness coefficient of thermal expansion
ΔT	=	difference between cure temperature and ambient temperature
ϕ_l	=	longitudinal cure shrinkage
ϕ_t	=	through-thickness cure shrinkage

it might be to embed optical fibres in the laminate, and measure the changes during cure and post curing of the mould. This has been considered, but a solution to measure during cure with optical fibres in autoclave has not been found. Then another solution can be to glue the fibres on after curing. It is also possible to apply a grid on the master mould and then inside the mould, take pictures of it after cure, compare the pictures and see what the differences are.

3.4 Hold vacuum

If the part is exposed to vacuum and pressure it must withstand it. This is very obvious, and it will be a very bad mould if it does not. If the moulds are to be used many times it must hold the vacuum during its whole life. Composite mould tools are often sealed with some kind of resin, both for sealing pinholes and to get rid of potential vacuum leaks. For smaller mould an envelope bag can be used, then the vacuum tightness is not so critical. Methods for which this is important are VARTM, RTM and autoclave moulding. Pressure moulds for example must not handle vacuum, but the pressure from the press [4].

In the most of composite production is it important to avoid voids. This is also important for a mould made of composite. This is on of the resons for using vacuum. One way to find out if there are voids in a laminate are to use non-destructive testing (NDT). Normal methods for this is ultrasonic inspection and x-ray [9].

3.5 Finish

Since the part will have the same finish as the mould, this is an important aspect. If it is desired to have a shiny finish of the part, the mould has to be absolutely perfect and highly polished. It must be considered which side to be tooled. If there is desired to have a nice and smooth outer surface or are parts to be assembled inside, so it need dimensional control on the inside [20, 9]. See figure 2 for male and female moulds.

The mould should ideally have center points and a type of line that locate where the part are to be trimmed. The points will help on the location of the layup.

If the part is a loadbearing structure during use, the production method may be different from a non structural element. The part receives better material properties by curing in autoclave than with for example pressure moulding. This is due to the combination of vacuum and pressure in the autoclave that eliminates voids. Pressure moulding usually have only pressure and heat [9].

It is possible to measure the surface with a surface roughness tool. These measurements should be taken of the master mould first to be sure that is good enough. The master mould will be coated with release agent before the mould layup is done, this will seal small pores and smoothen the surface more. One of the main reasons for this is of course to be able to release the mould from the master. How good finish does the material gives us? Is it a perfect mirrored picture of the master?

3.6 Durability

Some moulds are used only once, other hundreds or thousands. The materials durability has to be chosen so it fits to the number of cycles it is supposed to last. This is often one of the overriding factors in the material selection process. It is one way to make moulds that fits for one type of production method but not others. Some moulds are better for RTM production and some are better for autoclave. Steel is a typical material for processes that requires many cycles, 1000-100 000. Composite moulds have various lifetime, from 1 to 1000 cure cycles [9].

3.7 Environment, health and safety

The concern of health and safety are always different from company to company. How much health and safety equipment that must be used often depends on how often a mould will be made and how volatile the material is during the whole life cycle. Either way it is desired to use materials that are best both for the people who are going to work with them and of course for the environment before, during and after use. Things that are often not mentioned in the data sheets, are the volatiles and odoures that might affect some people more than others. Some materials and liquids are more allergies inciting than others and some people are more sensitive to chemicals than others. If the mould will only be used or produced a few number of times, it can be more justifiable to use more personal protective equipment then if it is for everyday use.

Machining of composites is not good for the health, the dust is light and the particles are very small. Fibres might penetrate the skin; the carbon fibres are often thinner and stiffer than glass fibres, so it is even worse and care must be taken. If possible, the machining should be done in a closed room. Dust should be prevented, dust extract fan and masks should be used. Some health and safety issues that are normal for composite production [26, 27] are:

- Irritating to eyes
- Irritation to skin
- Risk of serious damage to skin
- May cause sensitization by skin contact
- Must be considered as having carcinogenic effects on human beings

For the environment, the toxicity of the material is important. When the material are selected, the disposal must be considered. If the material is very toxic, it will be bad for the health as well. Other aspects of the environmental are the amount of produced and deposed parts. Which means that a material that can take many cure cycles before it need replacement is better for the environment. An other aspect is how much energy that are used for heat-up and cool-down. A material with high thermal mass will need more energy for this.

3.8 Weight

This is not always the main criteria, but it must be taken into account. It is especially important for the worker who transports the mould in different areas of the production hall. It should be possible to move during layup as well. This is also a health criterion for the workers who move the moulds around. If the part is too heavy to move, this might lead to strain injury since the mould has to be moved at some point. For small parts it might be interesting to be able to use an envelope bag for vacuum. It is sometimes easier to get an envelope bag sealed than one that is sealed around the edges. Then it must be possible to move the mould into the bag. In many companies where big parts is produced, the movement of the mould are often done with machines, and then the machine must be able to handle the weight. If the part and mould are big and heavy it might lead to challenges.

Weight is also an issue for the production rate and energy for heat-up.

"Lover weight means lower thermal mass, enabling faster heat-up/cool-down cycles." [16]

3.9 Costs

One way to make perfect surface finish on a composite mould is to make the master mould perfect, and then have the right material that can be used directly from the master to create the mould. Or the master can be rather roughly machined, and then the mould machined to the right tolerance. It must be considered if it is more expensive to make a perfect master mould or to machine the mould tool afterwards. The cost can be measured in different ways. One way is to only look at the real cost of the materials, but that is not accurate enough. Everything in the process that leads to more people involved and more hours spent on the part is a disadvantage. If the material cost is low, but it leads to high labour costs because of maintenance and complementary work, it might not be the best solution after all.

Considering for example the master mould; machining the master mould perfectly in metal compared with a rougher material with not so tight requirements. It costs less to machine a soft material to a rough finish than to machine it to a fine surface or machine metals.

Small cost example

- Cost of ytong pr kg
- Cost of machining ytong pr m^2
- Cost of materials to strengthen the ytong surface
- Cost of machining the mould

versus

- Cost of aluminum pr kg
- Cost of machining aluminum pr m^2

3.10 Machinability

If the material is easy to machine it will lead to reduced production costs. Some materials are better for machining than others, and some might change stability during or after machining. Stiff materials are easy to machine, but soft materials are better to shape by forming than machine. If it is machined in blocks and put together after machining it might lead to challenges if the machined parts have deformed.

3.11 Repair and modify

Often when a full assembly is to be done, the different parts in the assembly don't fit like they were supposed to, or there is an assembly detail that has not been considered. It might be things that people haven't thought about, like that hands should be able to reach into small places, and put the different parts together. It might also be that parts change during curing and then are slightly different from the requirements that are set. These are things that lead to changes of the part, and then it must be possible to change the tool. Also as discussed in chapter 3.3.1, the spring-in, is one of the things that might lead to changes of the mould, if it is not calculated right. The spring is often applied to the tool by trial and error to find the right shape, and then changes must be possible to make. Changes can be done either by applying material to the master mould, the mould, or if it is too big, machine it down.

3.12 Heat and pressure

The material has to handle the temperatures it is exposed for. Most of the epoxies that has been post cured, is cured so that changes are not supposed to occur. Maximum cure-, post-cure- and service temperatures are easy to find in the manufactures papers. High temperatures strain gauges can be used on specimens to find for example T_g. Solid materials will most likely be able to withstand autoclave pressure. In moulding methods where a press is used, metal moulds are the most common in use. The materials thermal mass have something to say of how fast the material can be heated up and cooled down. For all cures except for room temperature, has this a role. It can affect the curing process if this is slow.

3.13 Materials lifetime

As known, prepregs has a limited life time, metals of course don't have the same issue. The material must handle the out-time[1] it takes to make the part. All materials that contain resin have a certain time it can be held at room temperature before the curing process gets too far. The out of store life is described by hours, days or months. The storage is usually maximum -18 °C. These data are provided by the manufacturer and may wary for different materials. It might take days to make a mould in composites, so it

[1]Prepregs has a certain time it can be exposed to other temperatures than the storage temperature

must be known roughly how long time it will take to make the part and how long time it is left for the material.

3.14 Maintenance

All moulds have to be taken care of and perfectly cleaned and released after each use. The less time this takes, the better. If the mould has low durability it either can be used only a few times or it need extended maintenance or coating. The hardest material is not always the best. After the material is cured it has to be demoulded, and if the mould is not perfectly cleaned and/or treated with release agent, it might be difficult to loosen. If the mould then is made by soft material, it might stick to the part, and the mould needs repair.

3.15 Adaptive work on part

For metals moulds that are perfectly machined, the adaptive work is only release agent, if the part tolerate spring and thermal issues are taken into consideration. If the mould is being made of a composite material, the way to proceed from the production is different. Either the master mould has to have a perfect surface or the mould has to be machined to a perfect finish. Often a combination is used. If one machining is saved, time is saved.

3.16 Curing conditions

If the part is going to be cured in an autoclave it is preferred that all parts that have been laid up in a mould can be cured together. It is always desired to fill the autoclave with as many parts as possible. Some materials can influence differently on the temperature and curing process. It is recommended to cure parts made on metal moulds together and parts made on composite moulds together, and not to mix, according to expertise in autoclave curing at KONGSBERG. This due to different thermal mass, and difference in the heat up rate. If a small mould with short heat up rate are cured together with a massive metal mould with slow heat up rate, can the curing be wrong. The autoclave temperature is controlled by the thermocouple with the highest and lowes temperature. The thermocouples on the two parts will then display a higher temperature on the part for the fast heat up rate.

3.17 Lead time

For example different tooling materials in carbon fibre are not produced in an infinite amount, and there are not many that produces it. This means that it might take a while to order it and the price can be high. Materials like wood, steel and aluminium might be easier to get on short notice, but it might also here be challenges like finding a place that has machining capasity.

4 Materials for moulds

Material selection for moulds is often based on experience, which can be either one in the company, recommendations from others in the industry or suppliers. It is not always possible to say which material is best for the specific mould [20]. In the subsections below are brief summaries of some typical materials for mould production, what kind of production is typical for them and benefits and negative aspects of using that material. In table 6 is there a summary of the materials with different properties.

When mould material is selected with a greater expands rate than the composite produced on it, this must be taken into account when dimensioning the tool. The tool will then expand more during heat-up, and contract more during cure than the produced part. Both can cause cracks in the part in incorrect method is used [9].

4.1 Aluminium

Aluminium is a well known material for moulds in composite production. It is possible to achieve a perfect surface and it can be used in relatively high temperature curing processes. The CTE is higher than for composites. The material is quite expensive and the machining cost is high, and higher with better surface finishes [16, 2] . CERTAL® is one aluminium type in the 7000-series. This is used and recommended as a mould material due to good shape stability, corrosion resistance and good machinability [28].

4.2 Steel

Some of the main advantages of steel are the low material cost. Other positive thins for moulds are steels ability for readily cast and welding. It is also durable and can stand 1500 autoclave cures [9]. It has good availability and better CTE compared with aluminium; $10.2 - 14.5 \cdot 10^{-6}$ / °C for mould steel vs. $23 \cdot 10^{-6}$ / °C for CERTAL® [29, 28], but yet again higher than carbon/epoxy. One of the main disadvantage is high manufacturing costs, which applies for all metals, difficulties of forming into complex shapes, but maybe most important its high weight [9, 2].

4.3 Invar®

Invar® is an alloy of iron and nickel. The material is expensive and heavy, but performs very well. Invar® is a well known mould material especially in the aerospace industry, where the tolerances are higher than in other industries [16]. CTE is from $0.63 \cdot 10^{-6}$ / °C for temperatures $(-55) - 95$ °C, $2.5 \cdot 10^{-6}$ / °C for higher temperatures like $20 - 200$ °C [29].

4.4 Titanium

Titanium is normally only used as coating in form of titanium nitride TiN for injection moulding tools. This is if it is desired to have a harder surface on a metal mould and better flow. It has excellent chemical resistance. Advantages are better abrasion and corrosion resistance and better lubricant. Application temperatures are 425 °C and higher. There are more types of coating for moulds with more or less the same purpose [30, 29].

4.5 Ceramic

Ceramic is a group of materials, they are known as brittle material. In general can they withstand heat very well, up to 1000 °C and can be shaped into several contours and complex shapes. They have low CTE at $0.9 - 8.1 \cdot 10^{-6}$, close to carbon fiber composites. The dimensional control is very good. It is suitable for high temperature cure like of polyamides and thermoplastic. Disadvantages are low machinability, difficult to repair, long heat-up and cool-down rates [2, 13]. Is often used with electric heat embedded in the tool, which ceramics are perfect for, see more in chapter 1.12.

4.6 Composite - high/low cure

One of the biggest benefits of composite moulds is its possibility to match CTE to the carbon fibre part. It exist a high number of various compositions of fibre and resin types. All of the composite moulds need a master mould or mandrel. They also have a weight that is much lighter than metals. There has been challenges with cracking of the mould after some cures, which results in leakages. The materials on the marked now are better developed, so it there are less changes of matrix cracking [9, 31]

Glass fibres and epoxy are good for low temperature moulding. Depending on the postcure temperature, can they take temperatures up to 180 °C, but in general they are for low temperature cures than carbon fibre. One of the reasons for this might be that they can not match carbon fibres on fatigue properties and modulus. For high performance composite applications carbon fibre is preferred. But in commercial use glass fibres are extensively used. They have advantages like low cost, good impact, chemical and tensile strength [9].

It is of course advantages and disadvantages with composite mould tools, and some of the positive ones that are mentioned in Composite Airframe Structures [2] are listed below:

- Since the mould is not machined from a block, but built up, it contains less materials than others.
- Low cost can be achieved since the master model can be of a lower cost than the mould.
- Low CTE and more similar to the produced part can be achieved.
- Low density makes it easier to handle in production.

One of the main weak points of composite mould tools is the matrix. It is tough for the matrix to withstand the number of cycles of the curing of parts if this is many without cracking.

A list of different types of suppliers with some of their composite materials for moulds, taken from [31], is found in table 5. Most of them have more types than listed.

4.7 Graphite

The monolithic graphite method is to create a near net size by bonding blocks together and machine them down. The surface is coated either with a film, resin or resin and laminate. Advantages are easily machining, low fabrication and material cost, low CTE and dimensional stability up to 2000 °C. It is easy to repair and modify, but might be brittle and soft, so it can easily be destroyed as well. This depends on the quality, there exist many different qualities. The cross section cannot be too small to maintain the structural integrity. When machining the material a lot of dust is created, this can be injurious to the health [2].

4.8 Nickel

Nickel is most used as electro-deposited, or as Nickel Vapour Deposition (NVD), this is more discussed in section 1.14. Both methods make good moulds, that requires less metal than with steel and aluminium. Since it is not machined but deposited, this also leads to lighter moulds. They often need a backing structure for layup and cure.

Table 5: Suppliers and material for mould in composite

Supplier	Prod. method	Name	Material	Use °C	Comment
Hexcel	Autoclave	HexTOOL® M61	BMI/Carbon prepreg	190	Postcure
Hexcel	Autoclave	HexTOOL® M81	Epoxy/Carbon prepreg	125	Postcure
Cytec Engineered Materials	Autoclave	DURATOOL 450	BMI/Carbon prepreg	High	Postcure
Cytec Engineered Materials	Autoclave	DURATOOL 7620	Epoxy/Carbon prepreg	Mid	Postcure
Advanced Composites Group		HTM® 556 & 515-1	BMI/prepreg	200/250	
Amber Composites		HX42	Epoxy/prepreg	200	
Amber Composites		HX90N	Epoxy/prepreg	High	
Graftech International	Machined	GRAFOAM®	Carbon foam	High	Core material
Advanced Composites Group	Machined	CB1100	Ceramic block		Laminated with carbon
Touchstone Res. Laboratory	Machined	CFOAM®	Coal	High	To be coated
BBC Products	Machined	MB5000	Polyurethane foam		For master's
Nord Composites	Spray and hand lay-up	RM2000	Polyester	Low	Zero Shrink™
Nord Composites	Spray and hand lay-up	RM3000	Vinylester	Low	Zero Shrink™
Cook Composites and Polymers	Spray and hand lay-up	OptiPLUS™	Resin	High	Vacuum infusion
Airtech Adv. Materials Group	Infusion	Toolfusion®	Epoxy		
Airtech Adv. Materials Group	Autoclave	Beta prepreg	Benzoxazine	185	Postcure
Remmele Engineering	ConnexSys	Invalite™	Invar and composite	High	hybrid tool

4.9 Carbon foam

CFOAM is a rather new technology. The material is non-combustible, and is made from coal, has a CTE close to composite and is then good for mould production. The material contains pores. A way to seal them and make a good surface is to apply HexTOOL® material and cure. It will then need to be machined, but the first part does then not has to be perfectly machined [16]. Anette Sæter tested in her master thesis [32] two different types of carbon foam, CFOAM and GRAFOAM, and it seemed promising to use as mould materials. KONGSBERG have after that investigated a bit more, and it performs well, but it absorbs too much moisture, Fred Simonsen told. It was the intension to use GRAFOAM together with HexTOOL®, but the technical support in HexTOOL® will not support any use of these two materials together, since the foam can fail during cure of the HexTOOL® material, or during use later [Email from Hexcel® forward by Tor Sigurd Breivik].

4.10 Concrete/ Ytong / Siporex

Ytong is actually a building material, but can be machined and used as master moulds with low material cost. Before use it needs many hours of drying. It is some kind of porous concrete material, contains a lot of air, so it is lighter than in the normal form of concrete. It needs different layers of coating after machining, before use. It is quite brittle so it is not unlikely that it is not reusable after cure [33],[KONGSBERG].

4.11 Wood

Wood is a quite known in one form for all of us, and usually has a low cost. It can be used for mould tools, but then usually for master moulds due to it's softness. One of the most expensive sorts is one of the easiest types to work with due to its stable and close grained timber, Mahogany. It might distort during heat up and cool down [33, 4].

4.12 Tooling board

Ebaboard is one of many good tooling board products; they are usually used for master moulds and for other applications for the tool making industries. It is a resin based material that is perfect for being machined to the right shape. The weight is high, it is quite expensive as well as high CTE. There is many different products for different use, finish and purpose [34, 33].

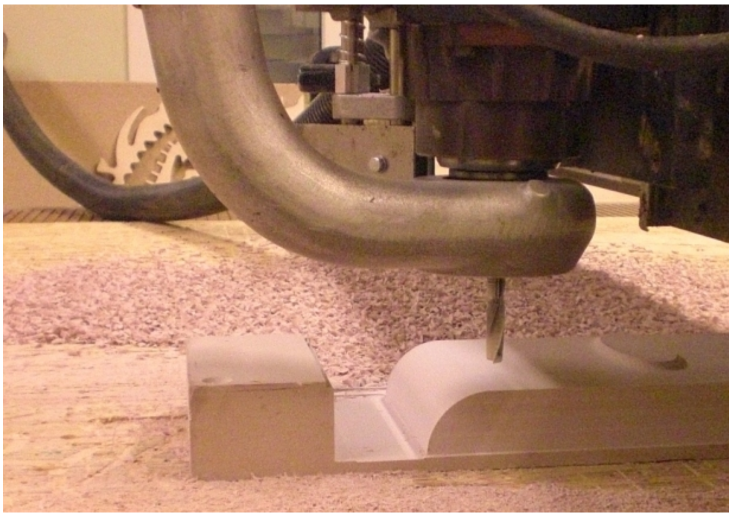


Figure 10: Machining of Ebaboard block at NTNU
[Photo: Nina Thorvaldsen]

4.13 Epoxy paste

Epoxy paste exists in many different resin types and application methods. One of the methods is to make dough with hand layup of glass fibre and resin on both sides. Often used together with some kind of fibre for better strength. Curing is done in room temperature. There are types both for low and high cure temperatures. Hysol is one of Henkels series of epoxy paste [35].

Table 6: Material selection

Material	Thermal		Density	Cost			Comment
	α [$\cdot 10^{-6}$/ °C]	κ [W/m °C]	ρ [kg/m^3]	Material	Production	Cure	
Aluminium	23	173	2810	High	High	High	Fair durability [29]
Steel	10.2-14.5	14.4-42.4	7640-7890	Low	Med-high	High	durable [29] mould steel
Invar®	0.63-2.5	10.15	8140	High	High	High	[2, 29]
Titanium	9.4	19	5220	High	High	High	Durable, as coating [29] TiN
Ceramic	0.9-8.1	1.44-11.5	1600-3900	Low	High	High	Tight dimensional control [2, 29]
Carbon fibre / resin	0-9	3.46-6.63	1500	High	High	Low-high	Need master mould [9, 2]
Graphite	2.2-3.6	57.6-125	1730	Low	Medium	High	Low therm mass [2, 29]
Glass fibre / epoxy	12.6-23.4	3.17-4.33	1900	Low	Low-med	Low-med	Need master mould
Nickel	11.9-13.3	72.6-77.8	8900	Med	High	High	Durable, size limitations [2, 9]
Carbon foam	4.86	0.25-25	272	High	Mid	High	Absorbs moisture, [29]
Concrete / Ytong / Plaster	10	0.045-0.138	115-535	Low	Low	Low-high	Absorbs moisture, fragile, for master's [36]
Wood	3.6-21.6	0.052	90-600	Low	Low	Low-med	As master, [29] Plywood, balsa, Mahogany
Tooling board	35-109	Not found	450-1760	Med-high	Med	Low	Not durable material [34]
Epoxy pasta	93	Not found	1100	Low	Low-med	Low-med	Time consuming [35]

5 From requirements to design

The mould design is in close relation with the part design. The material used in the part has big influence on the material in the mould and the same applies for production method. It is not possible to consider only one requirement individually. To select the right material, and how it should be produced are in close relation. The master mould and the mould are as important as the part itself.

Often are the parts shape and number of produced parts overriding requirements in the design process [9].

KONGSBERG has, as mentioned earlier high requirements towards tolerances, so the stability of the mould is important. They want to control most of the processes, so making the mould is one thing they want to do them self. They want the mould to be light, easy to handle, possible to cure in the autoclave together with other moulds made out of composites. This means that to make the mould out of metal is maybe not the best solution. Listed below are KONGSBERG's requirements for the Ω- and C-shape together with how materials from section 4 can fulfill these.

Release part

The shape of the Ω and the C are so they can be made by a one piece mould. In this case the Ω is actually a half circle with flanges. If it had been a proper Ω with opening smaller than the biggest width, a two piece mould must have been considered, this if the part could not have been slided out. All materials in table 6 are applicable.

Coefficient of thermal expansion

KONGSBERG wants this to be matched with the CTE of the produced part. The part will be made with a typical woven carbon fibre prepreg. The CTE for these are low, the mould material should be the one with the best matching. Since they want a light material with CTE close to the part, it is wise to first consider a composite mould. Materials that are closest in CTE is carbon fibre/resin, carbon foam, graphite, ceramic, Invar® and some types of wood, but Invar® is not light.

Dimensional accuracy and stability

Dimensional accuracy and stability is one of KONGSBERG's main criteria. The mould will need some kind of support structure for layup, which can be used as stabilizing tool during cure as well. For all of the materials mentioned in section 4 this is a challenge, some more than others, like wood. Some, like graphite is stable with thick cross sections, but might be unstable if the thickness of the mould is too small. For resin types, the temperature must be kept under T_g for being stable. The materials with low CTE are more stable than with high. Ceramic for example have very good dimentional stability.

Hold vacuum

The part must hold vacuum. On these two parts may a envelope bag be used. The because of small size. For larger structures, it can not be based on that. All of the materials can achieve vacuum tightness with help form for example resin.

Finish

KONGSBERG want to have a good surface finish on the part. They want the outside of the part to have the best surface. Which leads to female mould, and male master if that is needed. Trim lines and center points are applicable for the best location of the part in the mould. These criteria can be complied by any material.

Durability

The cycles are desired to be as many as possible, at least 200. The only materials that don't fulfill this is wood, ytong, tooling board and epoxy paste. Metals, especially steel can take many curing cycles.

Environment, health and safety

High priority are on the health and safety for the workers. It is desired to be able to do the layup without gas masks. For many prepreg types this can be done. Concerning the machining must the dust have to be evaluated. For the environment is it desired to have a mould with fast heat-up and cool-down rate that can take many cure cycles. For resin types these things has to be looked up for each type. The materials without resin are sufficient.

Weight

KONGSBERG among others want a light mould. It will be transported, and the heat-up rate is desired to be as short as possible. These two moulds are quite small so the weight have a natural limit, but for bigger parts this is a real issue. Here all the metal moulds falls out.

Costs

Low cost is desireble, but not the most important requirement. Due to this, it might be a good idea of using a known durable and stable method and material, even if it has a higher cost. There are not that many materials with both low material and production cost. Ytong, wood, epoxy paste and glass fibre can have a low cost, the most of these materials have already been excluded by other requirements.

Machinability

If the master is rough, the mahchinability of the mould material is important. The machinability to a material depends much on the quality, it usually exist more than one type. One of the material with poorest machinability is ceramic.

Repair and modify
KONGSBERG want to be able to modify their moulds. Metals can easily be machined down. There is possible to welded parts on, but it might lead to pores. Ceramics are difficult to repair and modify. The rest of the materials are possible to machine and add parts by adhesion. The adhered surface might be waker then the rest of the part, depending on the material, the adhesion might behave different to heat. There are individual differences of how machinable they are. With for example laminates with long fibres, machining can cause unsymmetrical stresses, but also vacuum leakage along the fibres.
Heat and pressure
The mould will be used in autoclave with temperatures up to 180 °C. Wood, tooling boards and epoxy pasta can have problems with the temperature, some resin types as well.
Materials lifetime
If the mould is made out of composite, the layup and bagging of these parts will take from 3 to 5 days before they are cured. For these small parts, the material life time will not going to be a problem. But for bigger parts, where the layup may take more than a working week, it can cause difficulties for some prepregs. Resin for infusion are mixed after the plies are layed up, so that is not a problem.
Maintenance
KONGSBERG have good routines for mould care, and want to use the same methods that is used today. It is desired to use as little time as possible on each part. For any material to use, mold care have to be executed.
Adaptive work on part
The adaptive work on a mould are today a time consuming process. KONGSBERG want to use less time on this. The material have to be either master mould that can be fine machined or a mould material that can be fine machined.
Curing conditions
The curing are to be done in autoclave with other composite moulds. This leads to a preference for composite moulds.
Lead time
KONGSBERG must know that it is possible to receive enough material when they need it. This is can be difficult for some carbon fibres types. For all materials this depends on the supplier and how big amount.

KONGSBERG already have experience with HexTOOL® M61 and want to compare it with another material. Beta prepreg was as mentioned demonstrated from Airtech, with good result. A decision of make another mould with these two materials was taken. Looking at the different requirements, each are fulfilled in a sufficient way. To see material properties for the materials, look in section 6.1.1 and 6.2.1. They have many of the same qualities like low CTE, light, can be cured with composite moulds and ability to be repaired and modified, with their individual differences. Beta can for example be stored in room temperature for long time, while this is not the case for the M61 material.

The weight of the Beta are 36% lighter than the M61 type.

One thing that are not mentioned in Betas data sheets [37] are the materials odour of degasification. The safety data sheet [37] have the same requirements for protective equipment as for other prepregs, and are not rated as more injurious to the health, but people have reacted on it.

In the two materials data sheets they are rated as machinable. HexTOOL® are in general a more tested product, and the surface after machining turns out good. The shape have shown tendency of change after machining.

6 Mould production

From the results of the different requirements, KONGSBERG's needs and experience, was it decided to make tests for moulds with two different, but still quite similar materials. There has been made two different types of moulds. One is shaped as a half circle with flanges, after this referred to as Omega (Ω), made of ytong, see figure 11. The other mould is a part that will for the rest of the document be called C-shape, see figure 12 to 15. This is made on an aluminium master mould. They have both been made of the same two different materials, and the same production method has been used. One of the materials is a known product for composites moulds, this is called HexTOOL® M61, and is produced by Hexcel®. The other type is called Beta Prepreg, produced by Airtech and contains a different resin type called benzoxazine. For material data for these two materials see table 8 to 11.

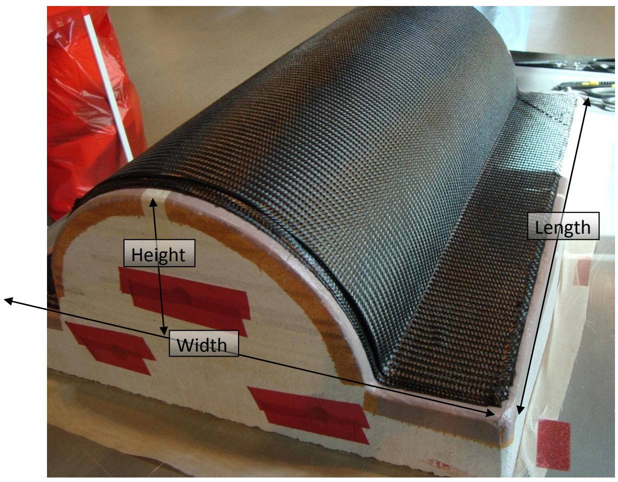


Figure 11: Width, height and length of a Ω mould during layup at KONGSBERG

[Photo: Nina Thorvaldsen]

Table 7: Approximate sizes of moulds given in mm

Shape	Material	Width	Hight	Length
Ω	HexTOOL®	200	140	450
	Beta	200	140	550
C	HexTOOL®	400	250	300
	Beta	400	250	300

6.1 HexTOOL®

HexTOOL® M61 is a prepreg type that contains a bismaleimid (BMI) resin. The ply contains random oriented strips of chopped unidirectional carbon fiber. It has extensively been used for producing composites moulds. The thickness of a ply is approximately 1.27mm, but this varies quite a lot over the ply. Some places has holes and other places, thick parts that are up to 2mm. If a thick mould should be made, it does not require that many layers to achieve the wanted thickness. The material is quite hard to work with in normal room temperature, especially to cut. It is stiff, and needs to be heated with a heating gun to be able to shape it correctly around edges and corners. When the ply is heated it becomes very ductile and flexible. It then forms well by using hands or forming equipment to guide the ply into the right places.

HexTOOL® is the material KONGSBERG is using today for mould production. This has given various results and satisfaction. One of the difficulties has been the lack of knowing how it deforms.

6.1.1 Material data for HexTOOL®

All of the material data are collected from [33], and are listed in table 8 and 9.

Table 8: Uncured and cured material data for HexTOOL® M61 [33]

Property, uncured	Value
Fibre	Carbon
Resin	Bismaleimid
Nominal resin Content	38 %
Nominal bundle size (prepreg strip size)	8.0mm x 50mm bundle, quasi isotropic orientation
Nominal ply areal weight	2000 g/mm^2
Storage life, (-18) °C or below	12 months
Property, cured	**Value**
Cured ply thickness, based on nominal prepreg properties	1.27mm (big individual variations)
Out of autoclave post cure	220 °C
Coefficient of linear thermal expansion	$4 \cdot 10^{-6}$/ °C
Minimum initial cure temperature	190 °C
T_g Glass transition temperature (Dry / wet)	275/230 °C
Maximum service temperature	220 °C

Table 9: Mechanical Properties for HexTOOL® M61, for dry material [33]

Property	Temp.[°C]	Method	Value	Unit
Tensile Strength	23 / 180	EN2561	260 / 210	MPa
Tensile Modulus	23 / 180	EN2561	41 / 40	GPa
Compression Strength	23 / 180	EN2850B	300 / 270	MPa
Compression Modulus	23 / 180	EN2850B	32 / 30	GPa
Flexural Strength	23	EN2562	380	MPa
Flexural Modulus	23	EN2562	38	GPa
Short Beam Shear Strength	23 / 180	EN2563	50 /43	MPa

6.2 Beta Prepreg

Beta prepreg is a new composite tooling material on the marked. KONGSBERG had some material for testing to see if this a suitable material for their production of composite tooling. This is a woven material, which makes it easy to predict the final laminate thickness. One of the big advantage of the Beta prepreg is it's tack. It is easy to apply the different plies to another and it stays there. This may be a disadvantage as well since it sticks to everything. The plies are fair to cut with a laminate scissor.

6.2.1 Material data Beta Prepreg

All the material data on Beta Prepreg BG-6 are collected form [37], and are listed in table 10 and 11.

6.3 Layup of prepregs for autoclave cure

To achive the best possible result of the final product, both the recommendations from the manufacture and experience are important. The time it takes to lay up a part depends a lot on the complexity of the part, how many plies, the specified accuracy, the fitting of the plies and the experience.

First step: The mould has to be perfectly cleaned and inserted with the necessary number of release agent, and dried. Some of the prepregs are easier to form into the right shape if the mould is a bit warm, so this is sometimes done before the first ply.

Second step: It is extremely important to get the first ply perfectly aligned and into all corners of the mould. This among other reasons to avoid bridging and collection of resin. A debulk is always required after the first ply. Here it is normal to use a release film, breather and vacuum bag.

Table 10: Uncured and cured material data for Beta Prepreg [37]

Property, uncured	Value
Fiber	Carbon
Resin	Benzoxazine
Nominal resin content	37 ±3 %
Weaving style	6K 2x2 twill, 0/90° orientation
Nominal ply areal weight	365 g/mm^2
Storage life, 25 °C or below	6 months
Storage life, (−17) °C or below	12 months
Property, cured	**Value**
Cured ply thickness	0.36mm
Coefficient of linear thermal expansion	$2.7 \cdot 10^{-6}$/ °C
Minimum initial cure temperature	185 °C
Out of autoclave post cure	218 °C
T_g Glass transition temperature	251 °C
Maximum service temperature	218 °C

Table 11: Mechanical Properties Beta Prepreg BG-6 [37]

Property	Temp.[°C]	Method	Value	Unit
Tensile Strength	22 / 185	ASTM D 3039-08	800 / 740	MPa
Tensile Modulus	22 / 185	ASTM D 3039-08	64.3 / 62.3	GPa
Compression Strength	22 / 185	SASMA 94-1R	720 / 430	MPa
Compression Modulus	22 / 185	SASMA 94-1R	59.9 / 60.6	GPa
Flexural Strength	22 / 185	ASTM D 790-03	1900 / 610	MPa
Flexural Modulus	22 / 185	ASTM D 790-03	58.8 / 56.0	GPa

Third step: The rest of the layup is done with the specified ply direction, and debulk as often as needed.

Fourth step: Then it is time for the final bagging. Here some materials require a resin trap to keep the resin in the part and not all over the inside of the bag. Resin leak might also lead to bag burst. If there is made a resin trap, it also need an inner bag. This should not be airtight, so small strings of glass fibres are applied around the edge, see figure 12. In this case the inner bag was the realise film, see figure 15. Thermocouples are applied to know the temperature of the part. Vacuum valves are applied through the bag. For smaller parts like this, two is sufficent.

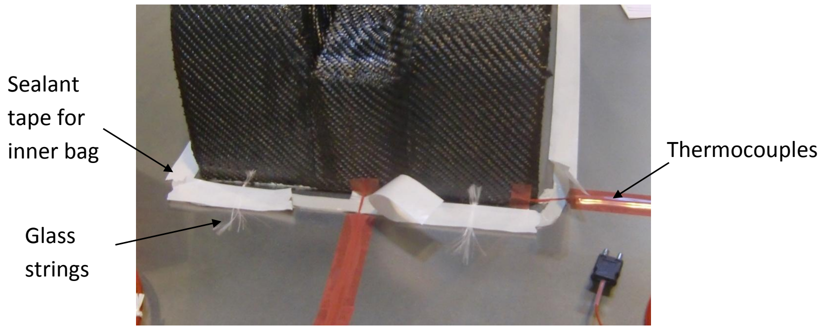


Figure 12: Thermocouples (T_c), glass fiber strings and sealant tape for inner bag on the C-shape mould

[Photo: Nina Thorvaldsen]

6.4 Ω shape

The master material of the Ω shaped mould was ytong which was coated with different layers to protect the ytong, making it possible to remove mould from the master mould and obtaining a slightly better surface finish. Both materials, HexTOOL® and Beta Prepreg was laid up on this type of plug. The approximate size is given in table 7. The thickness of the mould was approximately 10mm, they where choosen to be that thick for the ability to machine them after cure.

The layup of the mould in HexTOOL® material was done by people in KONGSBERG. The manufacturer's user guide [33] was used as assistance to get a good result. It was used 8 plies for the layup. The final thickness was 10mm ±2mm.

The lay up of the Beta prepreg was mostly done by people from Airtech, as a part of promoting the new material. It was done with help and observation of a team from KONGSBERG and the writer. Pictures of the layup and curing can bee seen in figure 11, 4a and 4b. This was also done following the manufacturer's user guide [38] and are more described in part 6.3. It was used 28 plies, which gave a thichness of 10mm ±0.5mm. There were used two thermocouples to maintain the right temperature during cure, and two vacuum valves to maintain the vacuum. This is recommended for parts at this size.

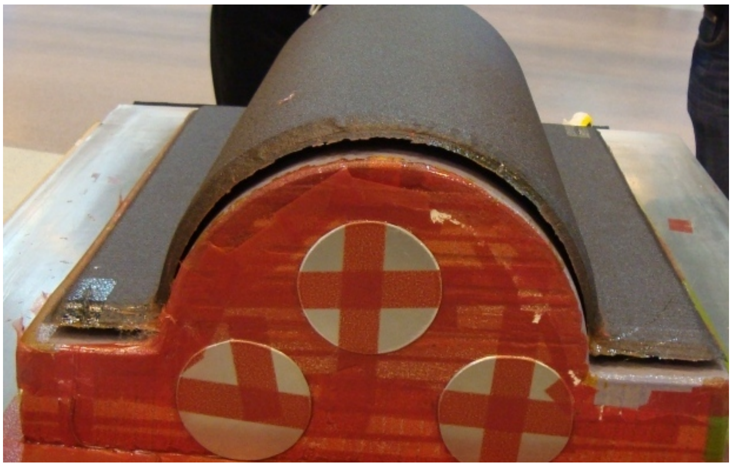


Figure 13: Ω mould and master mould after cure
[Photo: Nina Thorvaldsen]

6.5 C-shape

For the C-shaped mould the machining of the master mould was outsourced. The material was CERTAL® aluminium, which is more described in the part about aluminium, section 4.1. This is an aluminuim type that is thermally stable, and often used for moulds. This is an advantage when the material is being machined and heated and cooled. When the master mould had arrived KONGSBERG, it was released with frekote B-15 and 44 by the instructions given in their respective technical data sheets [39, 40].

Figure 14: Layup of C-shaped M61
[Photo: Nina Thorvaldsen]

The layup of the mould in HexTOOL® material was done by the author with assistance from people at KONGSBERG. The plies of the HexTOOL® are approximately 4 times thicker than the Beta prepreg, so to achieve the most similar final thickness there where used 5 plies. HexTOOL® was done in 2 days, and half a day with bagging. Figure 14 is during layup, the rear part shoves a uneven surface after demoulding. In front the stiffness of the ply before heating is showed. Three thermocouples was used, one was in the place where the aluminium mould was thicker than the rest, and the two others located where the mould had a more average thickness, picture of this on the Beta perepreg can be seen in figure 12. After a free standing post cure, the mould was sanded. Nothing was used for sealing the pores, to figure out how it works without. It was coated with release agents.

The layup of Beta prepreg was done mainly by the author, with good assistance of KONGSBERG employees. The layup was 15 plies of 0/90° of woven layers. The manufacturer's specification [38] was followed during the production and curing. The lay up took 4 days including bagging. The curing was done in an autoclave. After demoulding, the mould was postcured free-standing. Then a layer of pore sealing was applied. This works good on small pinholes and small irregularities, it gives a good surface and makes it easier to release the part form the mould after cure.

The two moulds were then sanded to a finish of 2000 grit paper. The moulds were coated with frekote, as the aluminium master mould was.

Figure 15: Inner bag, during bagging of the C-shape
[Photo: Nina Thorvaldsen]

6.6 Parts made in C-shape mould

The layup of this part was done by the same materials as if it should have been a proper part. Woven carbon fibre fabric with 0/90° and ±45°

Table 12: Number of plies, final thickness and weight of the C-shape

Material	Plies	Thickness [mm]	Weight [g]
HexTOOL	5	4.50-8.70	1942.55
Beta	15	5.12-5.44	1656.45

was used. There was made one part in the HexTOOL® mould and one in the Beta prepreg. Most of the layup was done by people in the layup team at KONGSBERG, but also some of it by the author. Some of the shapes on the mould are hard to follow by one ply, since it is double bent and with 90° bends on each side. So to be able to get the ply into the mould, there had to be made some cuts in the laminate. This was filled with small pieces of fabric in the same directions. All types of cutting fibres in a layup will weakened the strength.

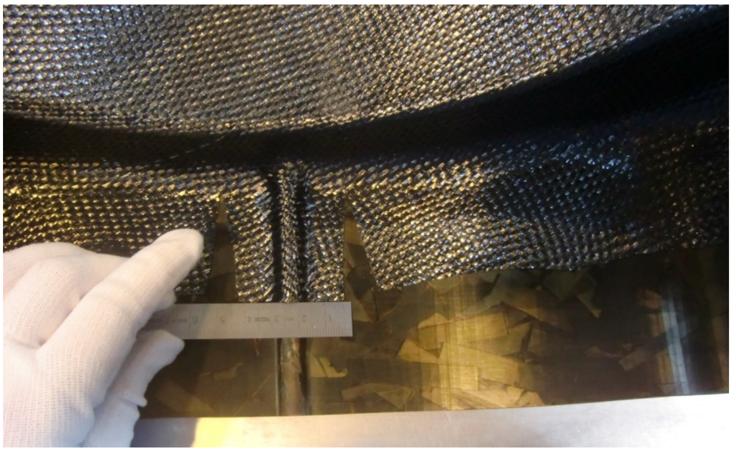


Figure 16: Layup of part in M61 C-shaped mould at KONGSBERG
[Photo: Nina Thorvaldsen]

7 FE analysis

Finite element analysis is a tool used to evaluate the strength of the structure. The program used for the analysis is Abaqus/CAE-6.10-2, which is a software application for finite element analysis and computer aided engineering. The CAE version was used, which is a Complete Abaqus Environment. This provides a simple but consistent interface for creating, monitoring and evaluate results from Abaqus Standard and explicit simulations. The program is divided into different modulus where values like geometry and material properties, generating of mesh of the part are applied to get the desired simulation[41].

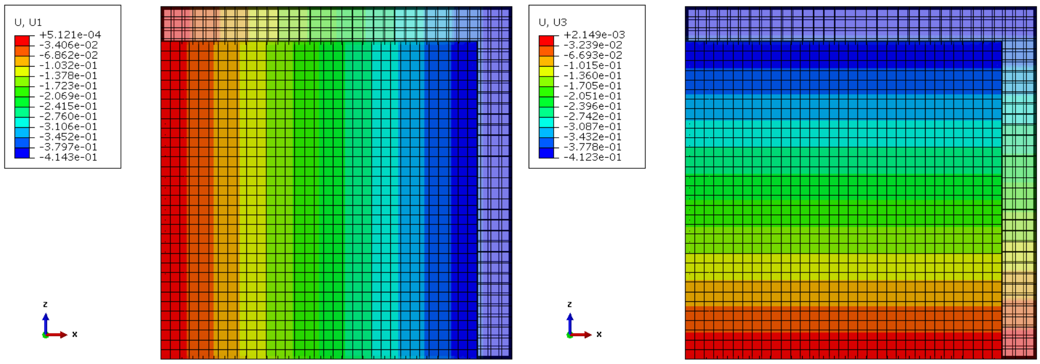
One of the main challenges in mould making is, as mentioned earlier, the spring-in phenomenon that appears during cure. In this finite element analysis the spring-in has been analyzed. The main focus has been on the mould, but also master mould and part has been applied.

From [25] it is expected that a part made on an aluminium mould, which have higher CTE, will spring more than if it were made in a carbon fibre mould. It also concludes that a C-shaped part spring more than a L-shaped. It is normal to calculate with a draft angle of $1 - 2°$, to be able to remove part from mould [9, 4].

7.1 The process

To be able to make the analysis for curved shapes, it is a good idea to make a simple plate model of the laminate before making a more advanced shape. With a plate is it easy to see if the boundary conditions are correct. In figure 17 and 18 one of these tests is shown. In x and z directions the displacements are the same, and in y it is different. The plate test was done with BMI and CFRP materials in table 13, shown here is CFRP. The smallest, solid part is after cure and shrink, the bigger, shaded part is the basis.

The thought is if only one element is considered locally as a block in x-y-z directions, the fibres have strength in one direction and are weaker in the two resin direction. The laminate has the same thermal properties in the resin directions and a different along the fibre. Since the laminates are either 0/90°, ±45° or chopped bundles in all directions, they will have the same properties in the two fibre directions, and then it will only be one direction for the resin. The resin usually has a much higher coefficient of thermal expansion than the fibre. Many of the carbon fibre have a negative value, see table 13, while the resin has a positive. This is one of the main reasons for the spring [18].



(a) U1, x-direction (b) U3, z-direction

Figure 17: Analysis of a plate

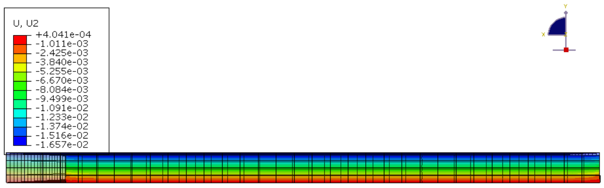


Figure 18: Analysis of plate U2, y-direction

If it is only the thermal expansion factor that is different in two directions, the plate has the same geometries and material properties in the two directions. The temperature difference was applied over the whole plate, which leads to the uniform shrink of the plate. The corners was fasten, all four in y-direction, two in x-direction and two in z-direction, for figure 17a to 18.

In figure 20a and 20b it can be seen how a laminate with various orientations are connected to coordinates. This is how it is applied in Abaqus. They are inspired by figures in [18].

Material data that have been used in these analysis are listed in table 13. The material data for CFRP is for unidirectional fibres which can be seen in figure 20a. To orient the firbers in the right direction, in this case 0/90° as in figure 19, the different directions have to be applied when the composite laminate is created. Composites are often oriented in different directions, so to be able to calculate different properties, the angle θ are used in the calculations.

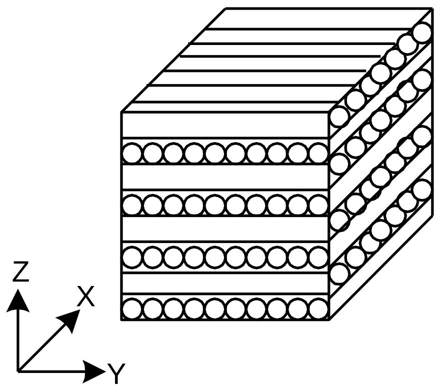
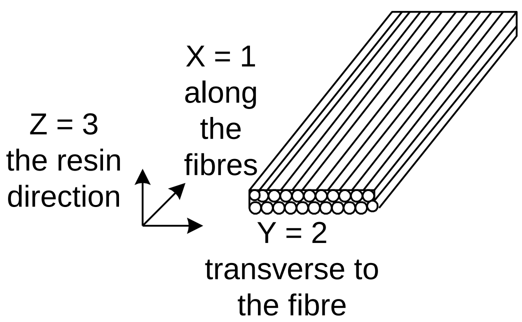
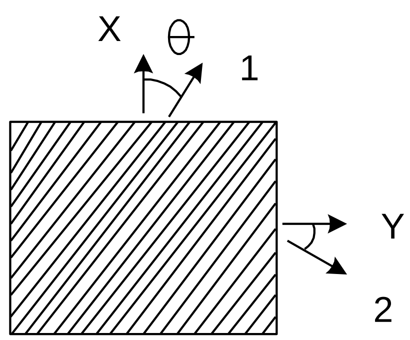


Figure 19: Illustration of a 0/90° laminate in Abaqus



(a) UD laminate



(b) UD with θ orientation of fibres

Figure 20: Fibre orientations

Table 13: Material properties used in the analysis

Material	Symbol	Value	Unit	Ref
CFRP	E_{11}	150.76	GPa	[23]
	$E_{22} = E_{33}$	7.93	GPa	for
	$\nu_{12} = \nu_{23}$	0.2525		all
	ν_{31}	0.3		except
	$G_{12} = G_{13}$	3.7	GPa	ρ
	G_{23}	2.5	GPa	
	ρ	1300	kg/m^3	[29]
	α_{11}	$-0.8 \cdot 10^{-6}$	/ °C	
	$\alpha_{22} = \alpha_{33}$	$27.62 \cdot 10^{-6}$	/ °C	
BMI	$E_{11} = E_{22} = E_{33}$	2.0	GPa	Per Olav
	$\nu_{12} = \nu_{23} = \nu_{31}$	0.49000		Kristiansen
	$G_{12} = G_{13} = G_{23}$	0.8	GPa	from
	ρ	800	kg/m^3	KONGSBERG
	$\alpha_{11} = \alpha_{33}$	$4.9 \cdot 10^{-6}$	/ °C	
	α_{22}	$4.9 \cdot 10^{-5}$	/ °C	
Aluminium	E	72	GPa	[28]
	ν	0.33		and
	ρ	2810	kg/m^3	[29]
	α	$23 \cdot 10^{-6}$	/ °C	
Ytong	E	2	GPa	[36]
	ν	0.3		and
	ρ	115	kg/m^3	[29]
	α	$10 \cdot 10^{-6}$	/ °C	

7.2 Analysis of the Ω mould

There has been performed a temperature analysis, with temperature difference as load. With one of the methods for thermal analysis, like coupled temperature displacement, some things are not permitted within Abaqus. The temperature for example can not be predefined, but must be applied as an boundary condition. While by using static/general analysis, the temperature have to be used as predefined [41].

With help from KONGSBERG, one solution for the analysis has been made. The theory is to only apply thermal load, and then the part will spring since it has different thermal expansion in the different directions. This was tested out on the BMI material listen in table 13 and worked well.

It is absolutely desired to use the through thickness expansion. It was then chosen to build the model as a solid and not a shell, though it is recommended for composite parts to use a shell method unless the through thickness is of interest[41].

Predefined fields was here used as temperature. It will lead to thermal strains in a stress/displacement analysis when there is a temperature difference between a predefined temperature field and any initial temperatures, this if the CTE is given [41].

There are basically two different methods of modeling that have been investigated, if not considering shell vs solid. The shell method was tested, but results are not included since the through thickness deformation is desired. The first method is to use coupled temperature displacement with different temperatures as boundary conditions. The structured mesh is then C3D20RT, which is a 20-node thermally coupled brick, triqadratic displacement, trilinear temperature and with reduced integration.

The other method is a more normal static/general analysis with predefined temperatures. The start temperature is applied in initial and the difference in temperature is applied in step, which is ΔT. This gave the most promising results with the plate test, so this method was chosen for the rest of the analysis.

The material orientation have been applied so the normal are turning outwards the whole part. This will give the desired sets of squared elements with the stacking of the plies in the right order. See figure 22.

It has been made composite layup with four plies, in 0/90°, this means two in 0° and two in 90°, see figure 19. When a laminate of woven fabric are made in Abaqus it has to be made as two plies. Four plies was created. These where made symmetric, which is the same as 8 plies. The mesh has been divided in four elements in the hight, so each element contains 8 plys, which in total give 32 plies. The mesh of the Ω can bee seen in figure 22.

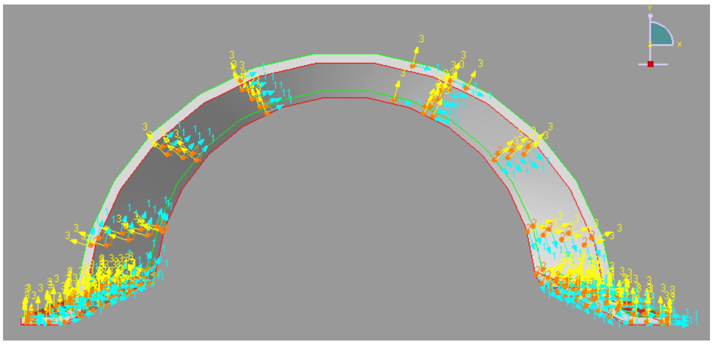


Figure 21: Material orientation of the Ω part

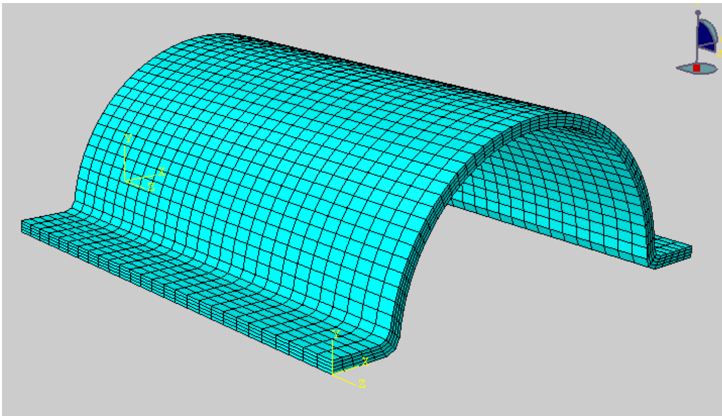


Figure 22: Meshed part, four elements in the thickness direction

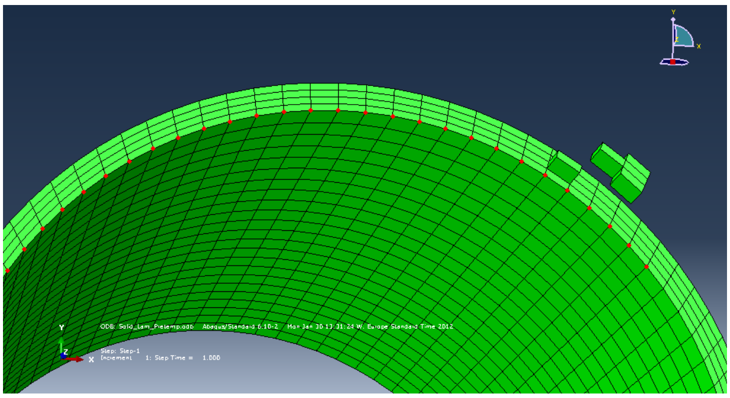


Figure 23: Selecting of nodes on the Ω

In figure 24, 25 and 26 it is possible to see how the shape crimps after cure. This is from 180 °C and cooled down to room temperature. The smallest, inner part is the coled one, the outer shaded one is before cooling. The material used in the analysis is CFRP in table 13. In table 14 can the different values across the shape be seen. To see where the different points are, see figure 36, note here y and z have changed places. The table and figures shows a significant displacement in the x-direction. The z-direction has a change, but less. The maximum displacement is in x-direction, and are 4.946mm, which is 3.5%, or 1.03°.

In table 14 results from two analysis have been assembled. The two column to the left are for the first analysis, this is only the mould. Figure 24 to 26 displays these. The four column to the right is for the second analysis. This is of a mould with a part inside. This can be seen in figure 27, where only the deformed shape is shown. The mould and part was assembled, and the analysis was done with both parts. The maximum displacement on the moud was 5.394mm, which is 3.8%, or 1.13°. The maximum displacement of the part was 4.054mm, which is 2.8%, or 0.84°.

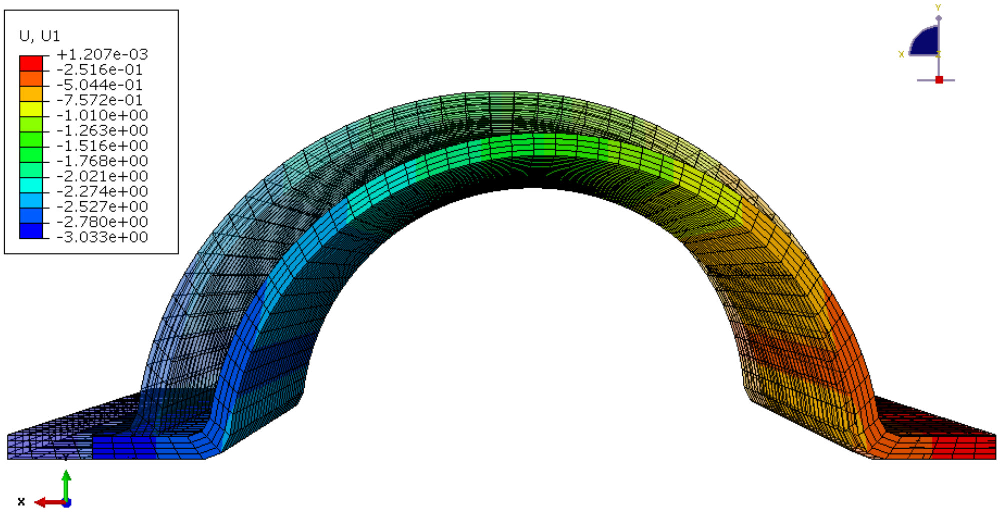


Figure 24: Analysis of the Ω in U1, x-direction

The analysis in figure 27 is done by the same method as for the mould in figure 24- 26. The more detailed numbers are presented in table 14. The numbers shows a similar displacement of these tree shapes. The part with master mould and mould has 3D elements, C3D20R: a 20-node quadratic brick, reduced integration. Initial temperature at 180 °C was applied with

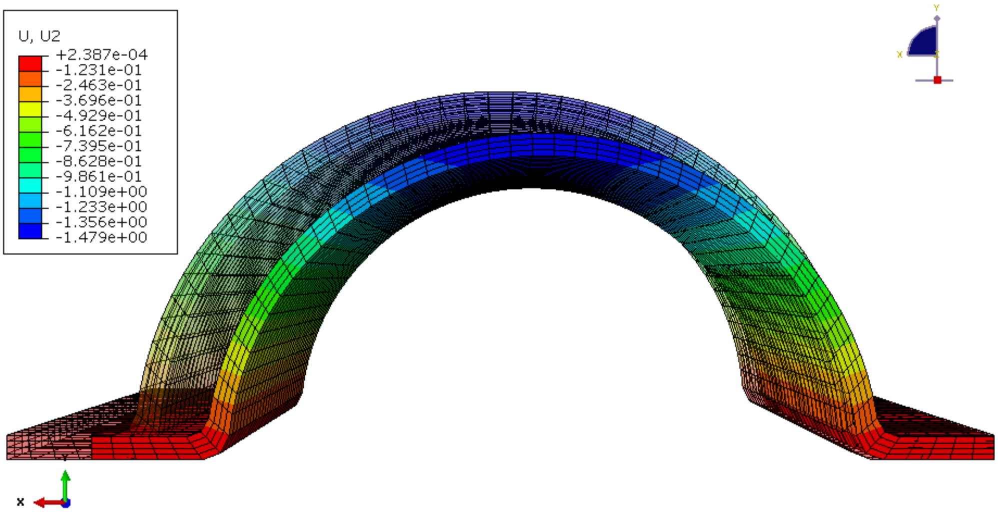


Figure 25: Analysis of the Ω in U2, y-direction

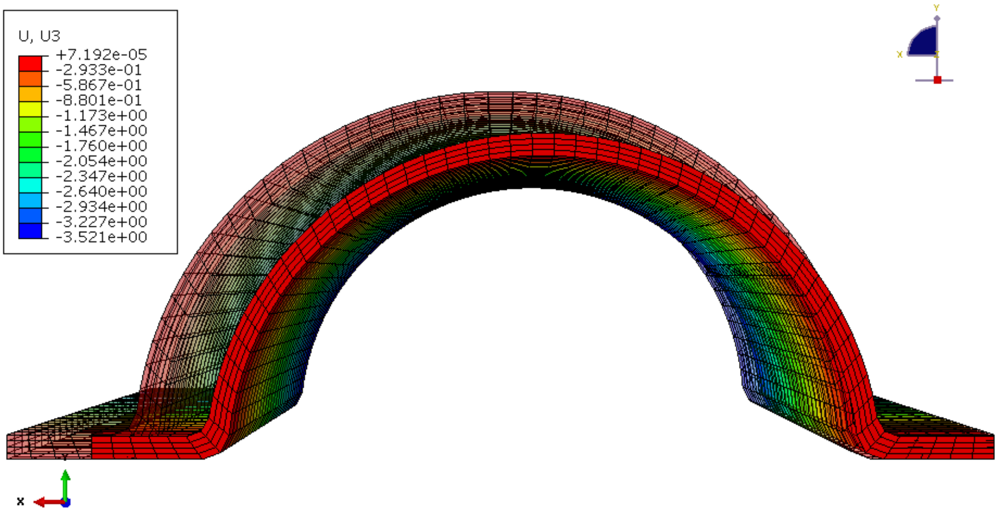


Figure 26: Analysis of the Ω in U3, z-direction

Table 14: Displacement of the Ω, FE analysis

Point in arc	Displacement, [mm]					
	Mould alone		Mould with part		Part in mould	
Nr	X	Y	X	Y	X	Y
A.1	-0.004	0.006	-3.145	0.001	-3.099	-0.035
A.2	-3.143	0.006	-3.136	0.007	-2.522	0.120
A.3	-3.102	0.104	-0.355	0.144	-2.157	0.263
A.4	-0.700	0.255	-0.834	0.285	-1.889	0.440
A.5	-1.040	0.412	-1.183	0.486	-1.687	0.650
A.6	-1.285	0.592	-1.455	0.761	-1.591	0.813
A.7	-1.527	0.905	-1.552	0.935	-1.560	0.895
A.8	-1.562	0.991	-1.578	0.997	-1.548	0.878
A.9	-1.574	1.012	-1.609	0.917	-1.501	0.766
A.10	-1.641	0.857	-1.719	0.733	-1.401	0.616
A.11	-1.803	0.643	-1.967	0.490	-1.224	0.438
A.12	-2.019	0.401	-2.249	0.260	-0.955	0.261
Piont	Displacement, wings, [mm]					
Nr	X	Y	X	Y	X	Y
W.1	-0.122	0.140	-3.137	0.003	-0.010	-0.036
W.2	-0.001	0.001	-3.026	0.124	-3.098	-0.032
W.3	-3.156	-0.000	-0.013	0.000	-0.129	0.041
W.4	-3.139	0.0317	-0.124	0.120	-0.007	-0.040
W.5	-3.035	0.127	-3.139	0.002	-3.101	0.029
W.6	-2.215	0.344	-2.705	0.165	-0.670	0.142
W.7	-2.329	0.290	-2.885	0.134	-0.504	0.096
W.8	-2.454	0.242	-0.003	-0.000	-0.324	0.061
W.9	-2.589	0.201	-0.006	-0.001	-0.068	0.026
W.10	-2.893	0.140	-0.009	-0.001	-0.014	-0.024

−160 °C in step1. 20-nodes is with quadratic elements, without is a 8-node element.

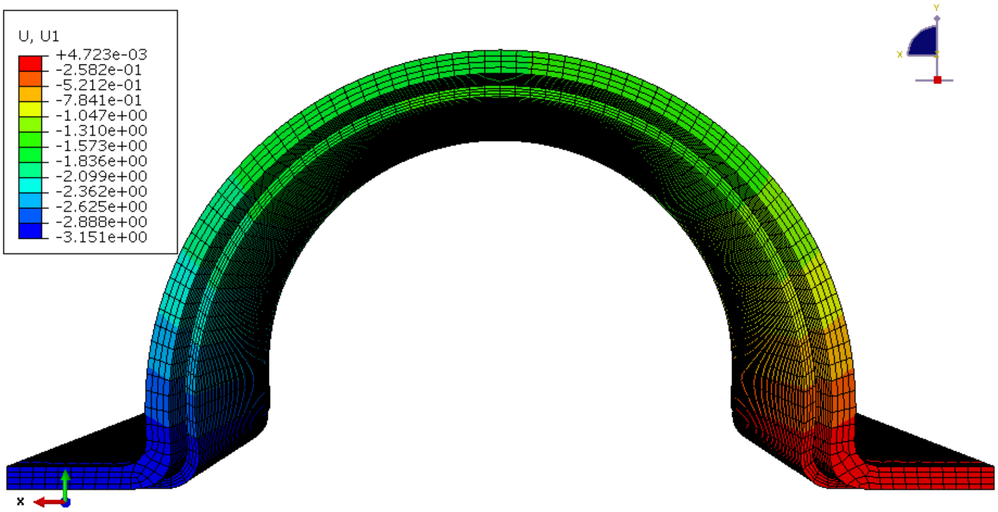


Figure 27: Analysis of the Ω with a part, U1 x-direction

The two analysis of master mould and part showed in figure 28 and 29 was carried out by the same method as the mould with part in figure 27.

Table 18 in appendix B presents the results from figure 28 and 29. The displacement on the aluminium master are bigger than for the ytong master. The displacement of the two mould on top are to be considered as the same, there can have been small individual differences in the selection of nodes. It was expected that the part cured on the aluminium master would had a lager displacement than the one at the ytong master. This means that the distribution of temperature and expansion between the master and the mould most likely not are done correctly. Due to time consuming process of analysis and processing data, there were not found a better solution. It indicates the reason for equal numbers for the different parts in table 14.

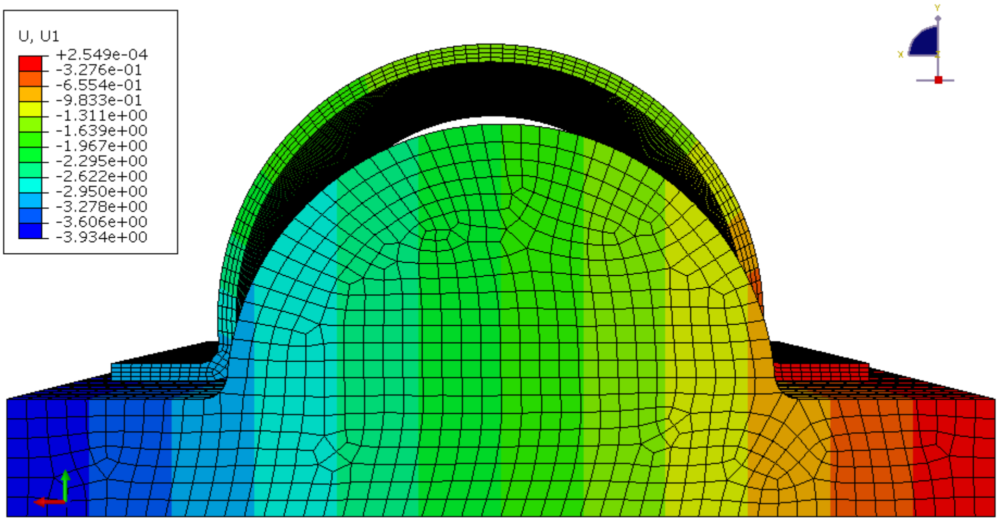


Figure 28: Analysis of the Ω part made on a aluminum master mould, U1 x-direction

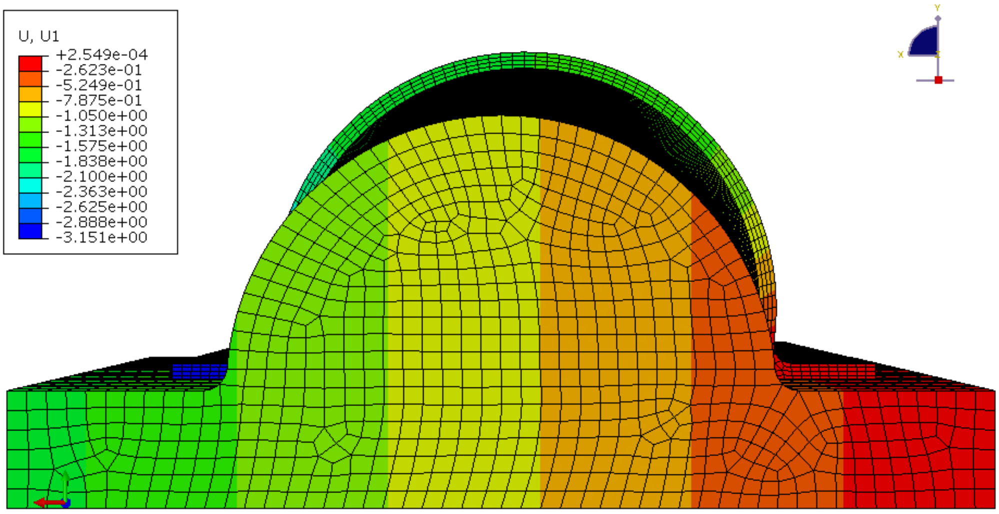


Figure 29: Analysis of the Ω part made on a ytong master mould, U1 x-direction

8 Measurements

Eight parts have been made in total. Two master moulds, four moulds, and two are parts made in two of the moulds. As described in section 6, two different types of materials have been used for the moulds. These two materials have been made on two different shapes. In this section the results will be presented from the measurements of these parts. The intension was to find out which one of these two materials has the lowest spring-in, and how much the final parts in these mould deforms. The number of produced part is not enough to give a final conclusion, but it will give some ideas. All measurements that are reported is done in an ZEISS CMM machine (coordinate measure machine) at KONGSBERG, see figure 30. It has to operated by qualified people with a certificate of apprenticeship in measurement. This machine has a big working load. This is the reason for why new measurements have not been carried out when it was discovered something with the measurements that could have been done differently.

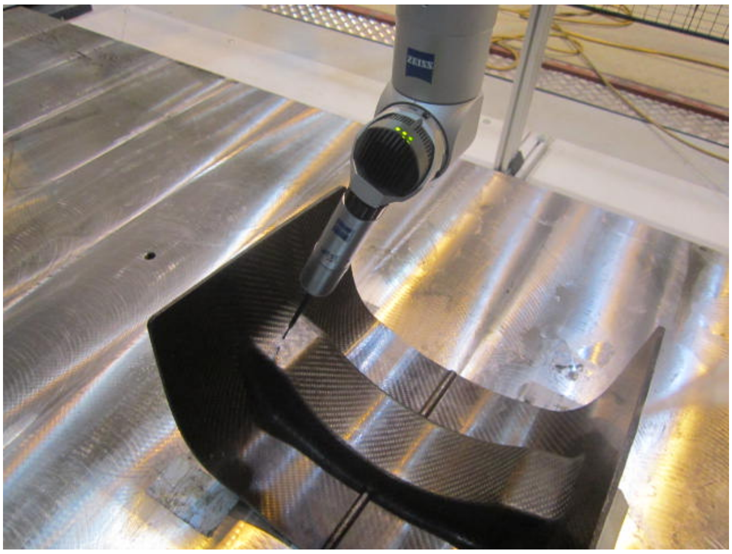
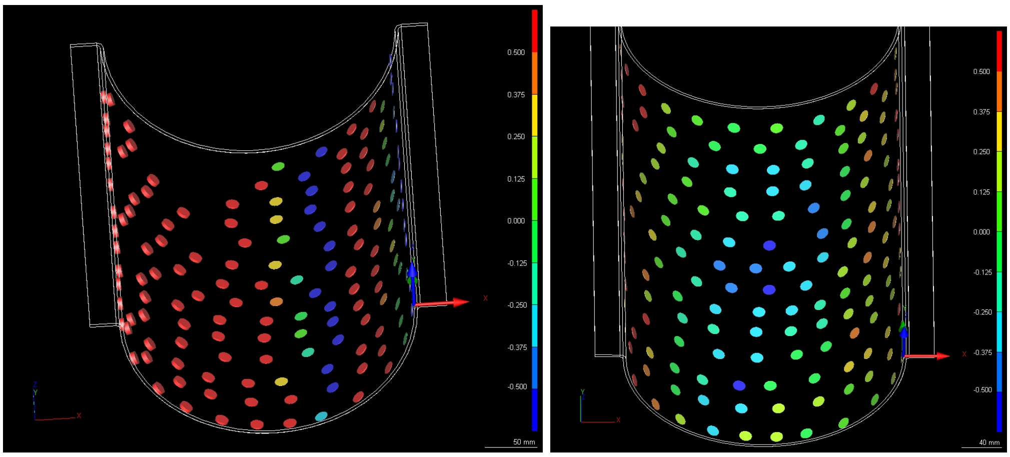


Figure 30: The C-shaped mould with Beta prepreg during measuring
[Photo: Eirin Holmstrøm]

8.1 Measurements of the two Ω moulds

The outer surface of the two materials in the two Ω moulds are different. This is one of the reasons why it is expected to have different results. The Beta prepreg has an even thickness over the whole part, while the

HexTOOL® has rather big individual differences of up to $\pm 2mm$ on a 6mm thick part. Both moulds have been made on ytong. The inside of the two moulds has approximately the same roughness, of $\pm 0.5mm$. A first rough measurement was done using a slide caliper. This showed a result of approxmetly 4mm spring-in in total, which means 2mm on each side. This was for the mould made of Beta prepreg. The mould made with HexTOOL® had a spring-in of 7mm, this is 3.5mm on each side. The spring was measured more accurately with the ZEISS CM machine. The interest is to find out how much spring-in there has been. To see if the spring is constant over the whole curvature, and if there is that big a difference for the two materials. This will be compared to the CAD-model of the ytong master mould.



(a) Ω made of Betaprepreg (b) Ω made of HexTOOL®

Figure 31: Plot of the measured Ω shapes

The measurements were done with 10-12 points in the arc and 4-5 points on each of the "wings". Figure 31 illustrate with colours which points are inside the tolerance and whats outside. Green is zero, red is outside in the negative direction, and blue in the positive. By looking at the plots in picture 31 it can be seen that one of them is more out of tolerances than the other. It also illustrates the tendency of smaller parts. This plot is from the measurements done without the "wings". One measurement was done after this, where the "wings" on the part were measured as well. The numbers used in the report is from the last measurement, can be seen in table 15. To look closer at where the different points were measured, see appendix C.

In figure 32 to 34 two different results of the measuring of the Ω part can be seen. This is a shape of cut number 3, 8 and 13 in y-direction. The black line with small dots illustrates the CAD shape of the Ω mould. The blue line with circles is the mould made of HexTOOL®. The red line with a cross is the mould made of Beta prepreg. The values of the HexTOOL® mould showed a offset in the z-direction of 5mm. This can happen when part is placed in the measuring machine. The curve of HexTOOL® has been shifted 5mm lower in the z-direction. This has been done with all of the Ω shaped HexTOOL® mould. This applies also for the results presented in table 15. A cut of the six points on the top left hand side from cut 8, can be seen in figure 35.

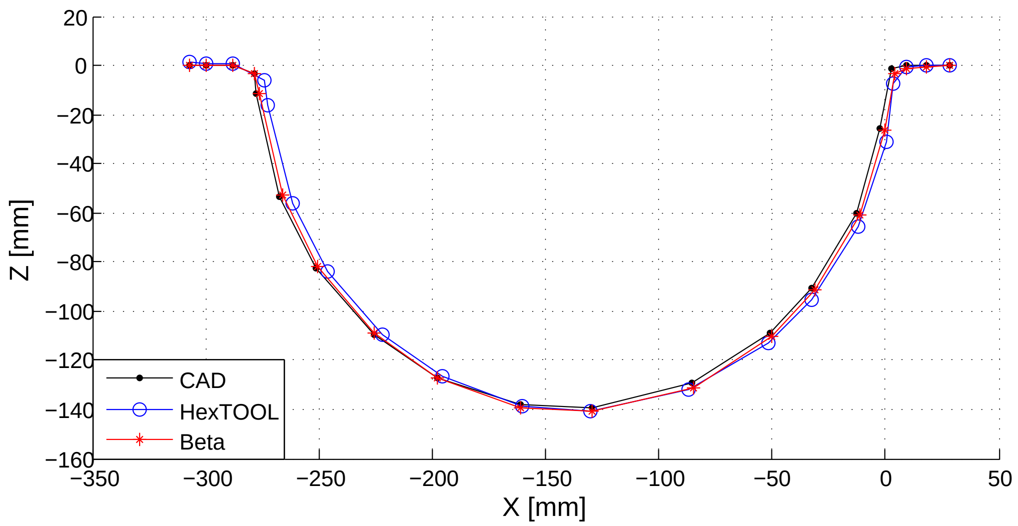


Figure 32: Cut 3 of the two Ω moulds. Maximum displacement for HexTOOL® was 3.099mm, which is 1.14%, or 0.68°. For Beta was the displacement 1.889mm, which is 0.69%, or 0.02°

Out of what is known about the spring-in phenomenon is that the change depends on the material and the fibre orientation. A part will decrease its various angles during cure. This means for the Ω shape, the arc will be smaller. This will push the edge of the "wings" downwards, when the model is seen with the arc on top and the vings on the bottom. The spring in the angle between wings and arc, will bend them slightly upwards again. From the FE analysis, see figure 59, it should cross the original arc by having a small part on the outside at one side and a bigger part on the inside at the other end.

In table 15 are the maximum, minimum and average differences from the CAD part presented. These values are taken on 14 places along the y-axis, see figure 36 and appendix C for a better understanding of where the points were taken. As the table shows, the mould made from HexTOOL®

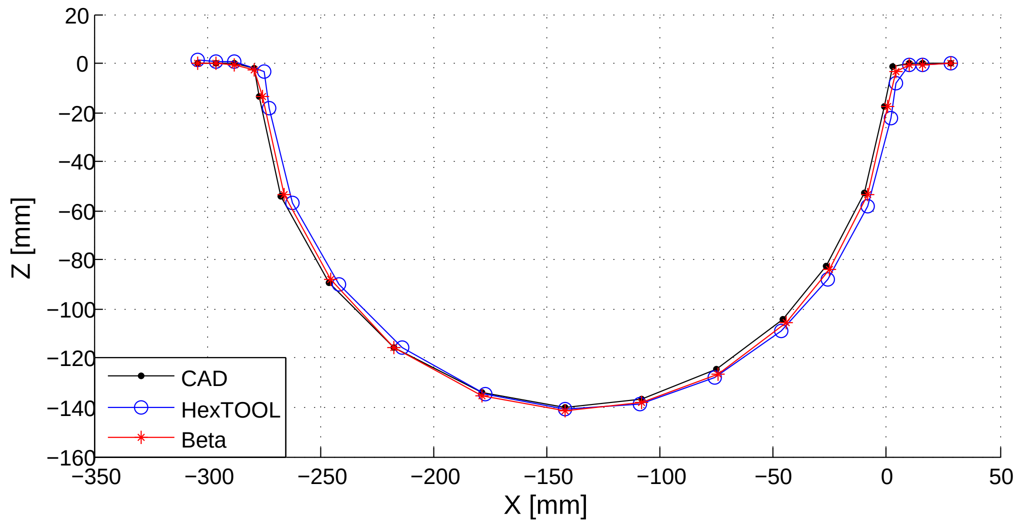


Figure 33: Cut 8 of the two Ω moulds. Maximum displacement for HexTOOL® was 2.624mm, which is 0.96%, or 0.28°. For Beta was the displacement 1.935mm, which is 0.70%, or 0.20°

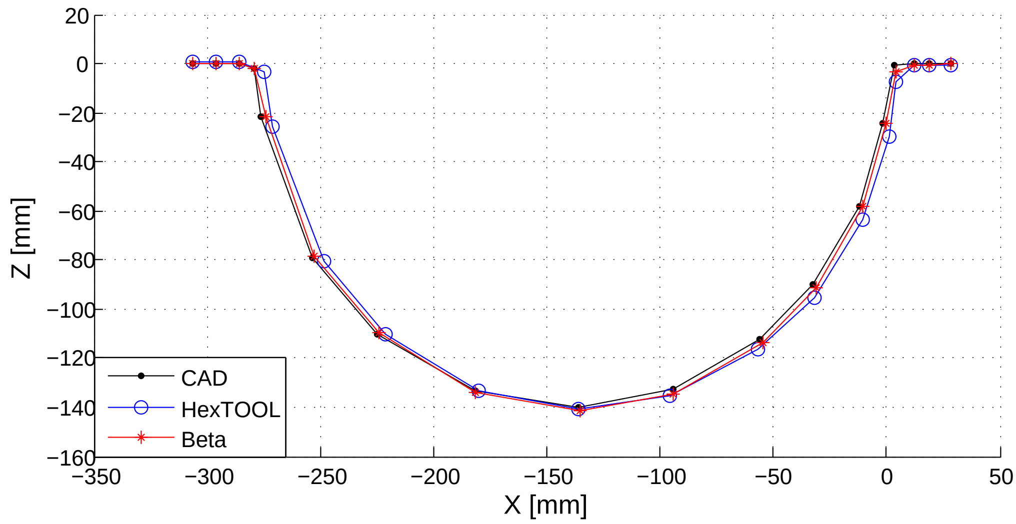


Figure 34: Cut 13 of the two Ω moulds. Maximum displacement for HexTOOL® was 3.168mm, which is 1.17%, or 0.34°. For Beta was the displacement 1.223mm, which is 0.49%, or 0.13°

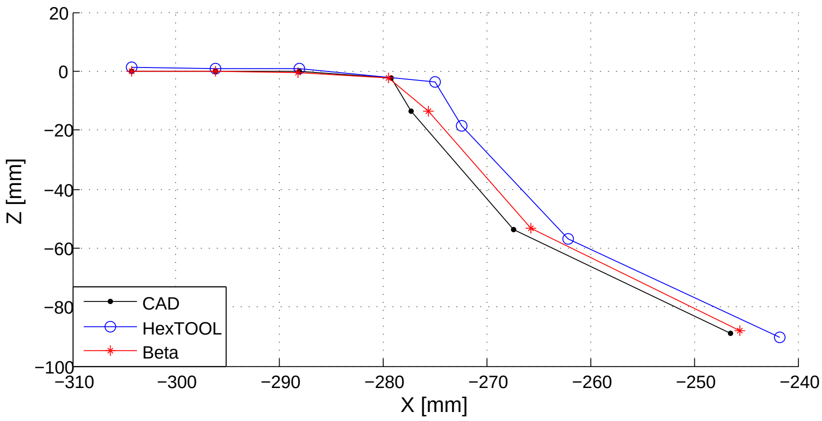


Figure 35: A section of cut 8 of the two Ω moulds

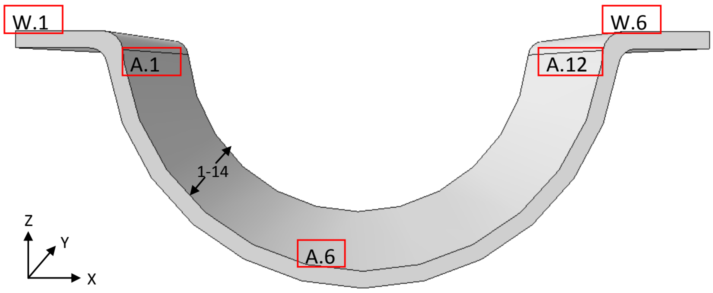


Figure 36: A schematic drawing of where the different measurements point on the Ω have been taken

has a bigger spring than the Beta prepreg. The maximum of the average x-displacement in the arc is 3.8194mm and 0.1671mm respectively for them. It also shows that the spring in x-direction are highest, as expected, closest to the wings. The graph of the average displacement can be seen in figure 37. In these numbers as well the mould of HexTOOL® is shifted 5mm lower in the z-direction. It can also be seen that the Beta mould has more even displacement.

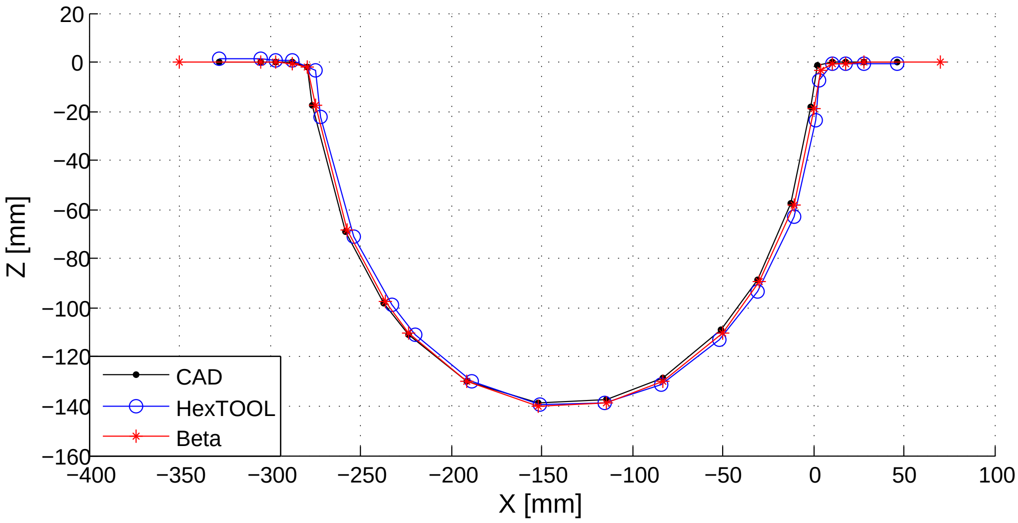


Figure 37: The average form of the two Ω mouls together with the CAD part, displacement for HexTOOL® is 3.8194mm and 0.1671mm for Beta

In z-direction of A.5,A.6,A.7 and A.8 there are increased height, see table 15. In these points as well as in the different graphs, is the HexTOOL® shifted 5 mm lower as the graph in figure 34. A graph of the average displacements is found in figure 37.

8.2 Measurements of the C shape

The C-shaped aluminum master mould was measured against the CAD file. The two moulds made on it was also measured. One of them was made of HexTOOL® M61 and the other of Beta prepreg. The production and materials are more described in section 6 about mould production. Two carbon fiber parts were also made in the two different moulds. These have also been measured. Here also the layup is more described in section 6.6 and the measurements in section 8.3.

Table 15: Maximum, minimum and average displacement of the Ω mould in the whole y-direction, all measurements are in mm

Point in arc Nr	Displacement, x-direction, arc, [mm]					
	HexTOOL®			Beta		
	Max	Min	Average	Max	Min	Average
A.1	5.514	4.729	5.172	2.184	0.703	1.631
A.2	5.786	4.451	5.201	1.636	0.724	1.252
A.3	5.101	3.256	4.264	1.078	0.066	0.614
A.4	4.208	2.900	3.604	0.534	0.014	0.263
A.5	2.654	1.385	2.026	-0.374	-0.065	-0.198
A.6	0.836	0.001	0.436	-0.208	-0.005	-0.092
A.7	-0.889	-0.381	-0.580	0.663	0.092	0.317
A.8	-1.129	-0.717	-0.890	1.012	0.627	0.796
A.9	-0.839	-0.369	-0.625	1.367	0.991	1.223
A.10	-0.369	-0.007	-0.004	1.558	1.054	1.346
A.11	1.906	0.467	1.381	1.642	1.193	1.419
A.12	2.789	0.059	2.154	1.998	1.159	1.684
	Displacement, z-direction, arc					
A.5	-0.273	-0.004	0.006	-1.160	-0.160	-0.538
A.6	-1.266	-0.062	-0.541	-1.401	-0.685	-1.143
A.7	-2.564	-0.512	-1.527	1.970	-1.260	-1.650
A.8	-3.438	-1.945	-2.894	-2.058	-1.626	-1.829
Point on wings Nr	Displacement, z-direction, wings, [mm]					
	HexTOOL®			Beta		
	Max	Min	Average	Max	Min	Average
W.1	1.401	0.944	1.114	-0.152	0.008	0.031
W.2	1.242	0.903	1.085	-0.412	-0.015	-0.141
W.3	1.283	0.881	1.041	-0.631	-0.078	-0.194
W.4	1.018	0.630	0.714	-0.669	-0.165	-0.367
W.5	-2.865	-0.586	-1.281	-0.755	0.014	-0.237
W.6	-6.937	-4.986	-6.178	-2.329	0.016	-1.878
W.7	-1.376	-0.459	-0.908	1.432	-0.039	-0.632
W.8	-0.906	-0.003	-0.359	-0.878	0.036	-0.406
W.9	-0.769	-0.003	-0.303	-0.556	0.009	-0.130
W.10	-0.744	-0.160	-0.401	0.417	0.116	0.224

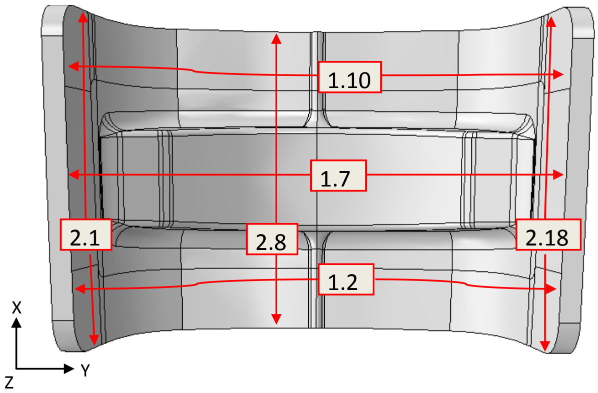


Figure 38: A schematic drawing of where the different measurements point on the C-shape have been taken

8.2.1 Aluminium master mould

The machining of the master mould was done by another company as mentioned earlier. It was not delivered with a measurement report. The surface was not as the specified requirements. That two tings is why it was decided to measure it. These values show that there are differences from the CAD, see figure 39 and 40, as also seen by only looking at the part. The comparison of the two moulds made on the aluminium plug are mostly compared with the CAD part.

The values of aluminium master shows that there is a difference of up to 2.3mm from the CAD part in the y-direction. The measurements was taken mostly on the top of the mould and not all the way down, this means that it might only be the corners that are smaller. One possibility is also that it might have been a dislocation from its axises. It can be seen in figure 40 that the top cure follows perfectly, so this is most likely not the case.

8.2.2 Moulds made in C-shape

The points where the HexTOOL® mould and the Beta prepreg mould are taken at the same places. The intention was to match these with the points taken of the aluminum master mould, but as it can be seen, they are not at exactly the same places. This can be seen from comparing figure 39 with 42 and 43. From the various numbers there is a bigger depart on the numbers in the x-direction, than in the two other directions. This difference is between 2 and 0,3mm, see table 16 and figure 42 to 47.

In figure 43 the difference from CAD part and Beta mould can be seen. The red points has number from +0.4mm and higher, the green points are

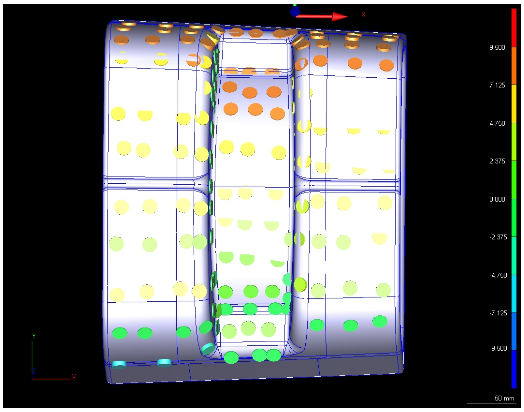


Figure 39: Plot of the various values of the Aluminium master mould

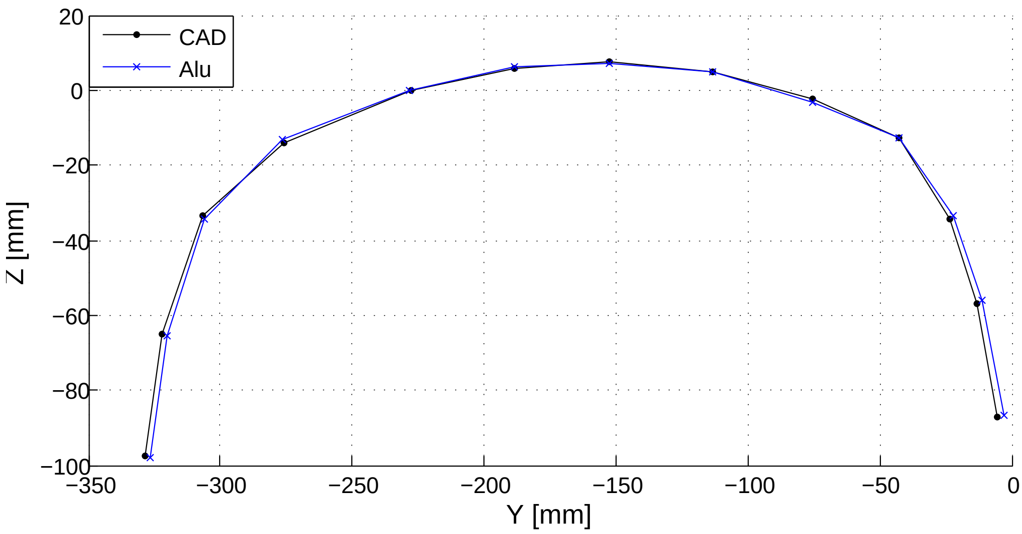


Figure 40: Cut 1.10 on the C-shaded aluminium master mould, the total displacement in y-direction is 0.2mm, which is 0.06%

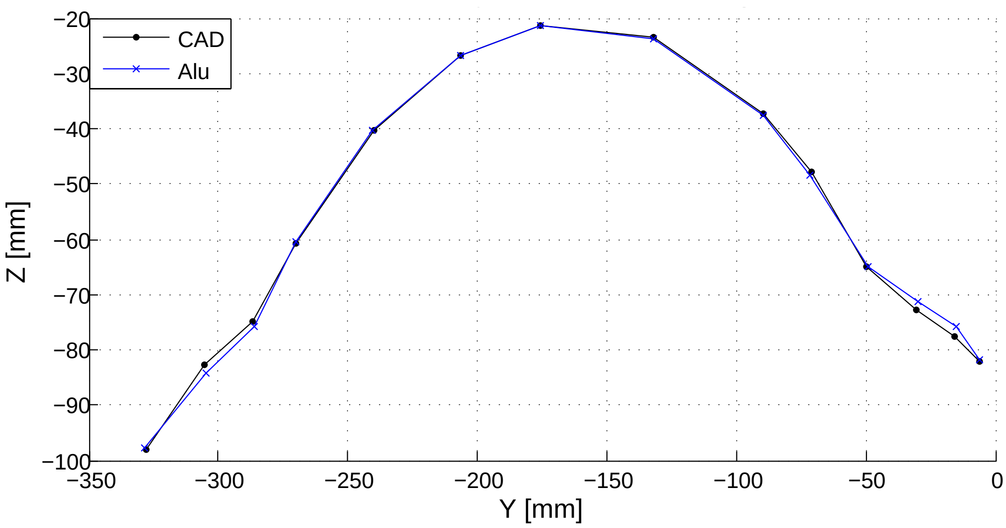
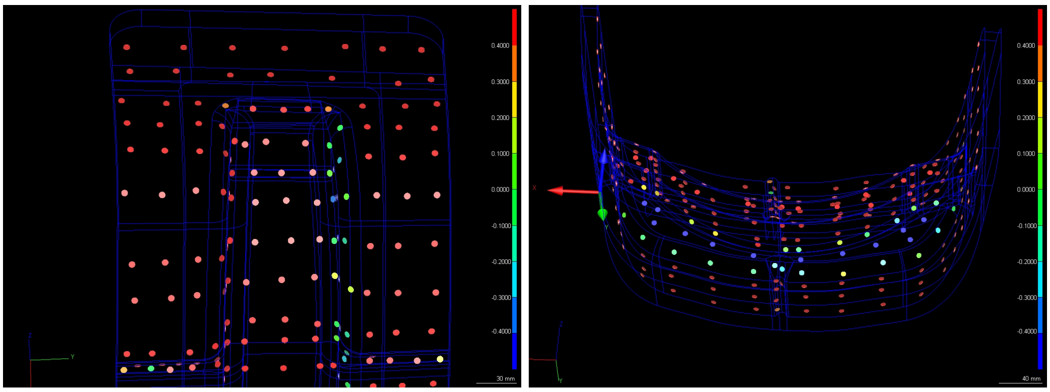


Figure 41: Cut 1.7 on the C-shaded aluminium master mould, the total displacement in y-direction is 0.2mm, which is 0.06%

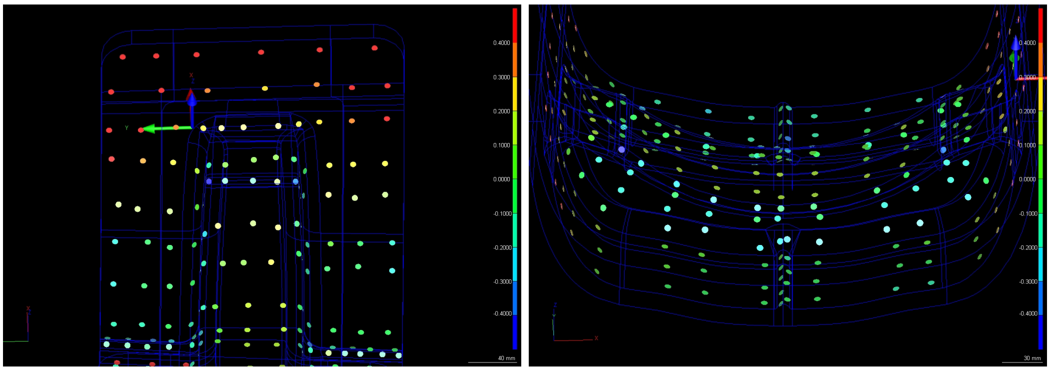


(a) C-shape made of HexTOOL® X-direction

(b) C-shape made of HexTOOL® Y-direction

Figure 42: Plot of the measured depart from CAD part, C-shape, HexTool

around 0, and blue -0.4mm and lower. This is most meant as an illustration of where the poins of biggest deposits are.



(a) C-shape made of Beta prepreg X-direction

(b) C-shape made of Beta prepreg Y-direction

Figure 43: Plot of the measured depart from CAD part, C-shape, Beta

In table 16 is the displacement in the y-direction of the C-shape shown. Number 2.7-2.11 are not of interest in this direction. From numbers 2.3, 2.4, 2.5, 2.14, 2.15 and 2,16 is the difference less in the middle of the part than in the edges. This means that the curve in the middle is helping the part to be held in the right shape. This can also be seen from the graphs in the opposite direction, figure 47, where it is as close as zero displacement.

8.3 Measurement of parts made in C-shape mould

Two parts were made in each of the C-shaped moulds, as explained in section 6.6. One part was made in the HexTOOL® mould and the other in the Beta prepreg mould. This was to see if they turned out with the same deformation or not. The shape has a slightly different height at one side compared to the other. They were measured with a 180° angle difference. This was solved by shifting places for the z-direction on the Beta part, and this gave correct results.

The part made in the Beta mould is measured 180° different to the CAD part around the z-axis. Which means that the displacements in table 17 is showing a higher value than what is really the case. The maximum displacement is bigger, and the minimum is most likely smaller than the actual. Lack of time is the reason for why this have not been done once more. The capacity in the measuring machine is pushed to the limit.

Table 16: Displacements in y-direction for C-shaped moulds, given in mm

	Displacement, y-direction, [mm]					
	HexTOOL®			Beta		
Nr	Max	Min	Average	Max	Min	Average
2.1	0.717	0.131	0.443	0.608	0.203	0.408
2.2	1.215	0.589	0.929	1.083	0.554	0.853
2.3	1.424	0.654	1.037	1.245	0.406	0.838
2.4	1.362	0.007	0.640	1.153	0.008	0.536
2.5	0.933	0.011	0.426	0.864	0.003	0.363
2.6	0.456	0.005	0.157	0.360	0.002	0.113
2.12	0.398	0.000	0.106	0.337	0.002	0.066
2.13	0.658	0.013	0.441	0.554	0.001	0.331
2.14	1.821	0.013	0.834	1.548	0.000	0.645
2.15	2.259	0.045	1.167	1.957	0.006	0.927
2.16	2.571	1.220	1.905	2.221	0.960	1.551
2.17	2.637	2.067	2.333	2.196	1.575	1.794
2.18	2.831	2.350	2.558	2.274	1.677	1.889

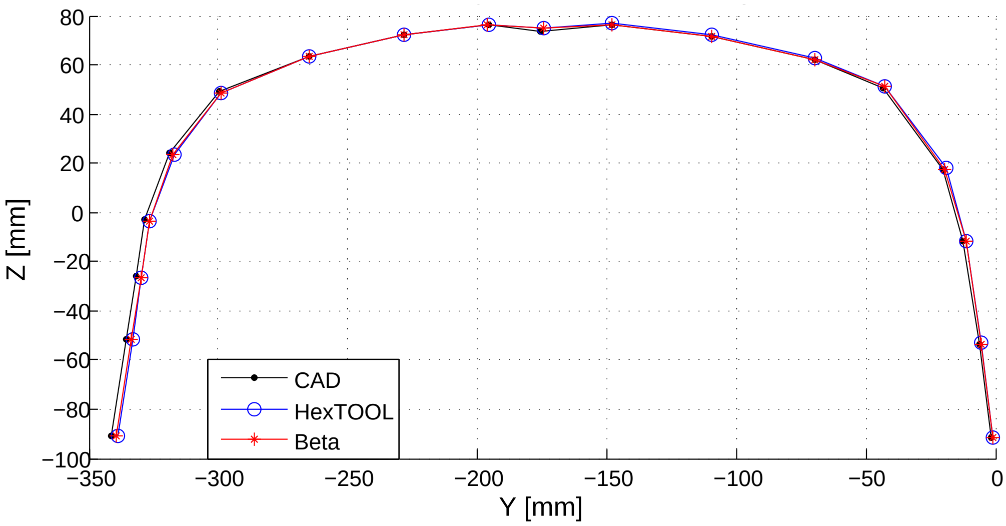


Figure 44: Cut 1.2 on the C-shaped moulds, maximum displacement for HexTOOL® was 2.311mm, 0.69% and for Beta 1.7064mm, 0.50% this is where the opening is biggest, y-direction. At point 4 from the bottom it was 0.787mm and 0.683mm

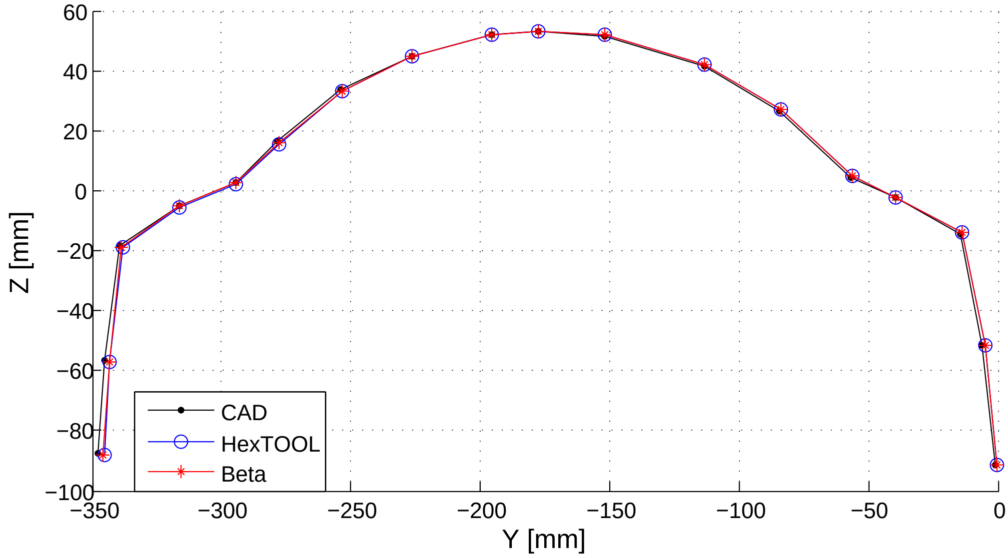


Figure 45: Cut 1.7 on the C-shaped moulds, maximum displacement for HexTOOL® was 1.617mm, 0.46% and for Beta 1.124mm, 0.33% this is where the opening is biggest, y-direction. At point 3 from the bottom it was 0.5mm for both moulds

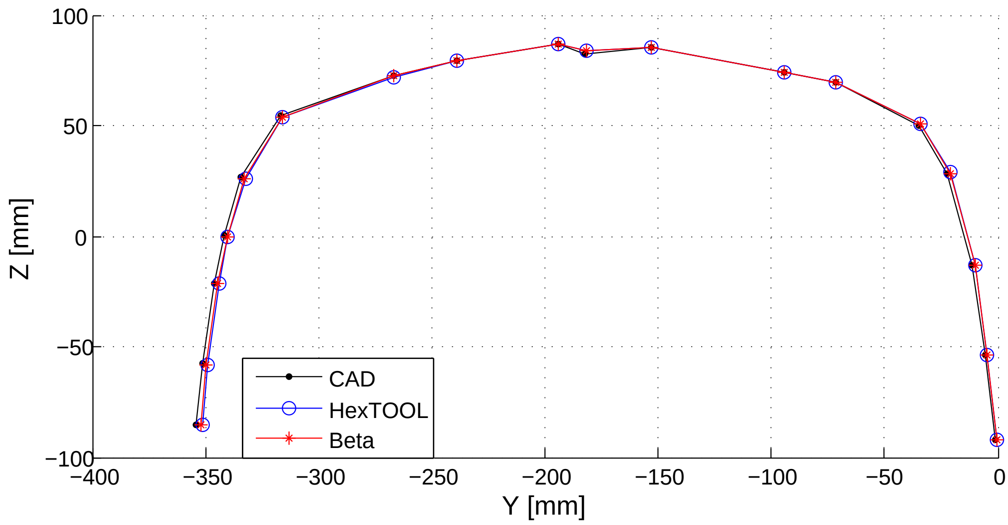


Figure 46: Cut 1.10 on the C-shaped moulds, maximum displacement for HexTOOL® was 1.913mm, 0.53% and for Beta 1.206mm, 0.34% this is where the opening is biggest, y-direction. At point 5/4 from the bottom it was 0.296mm and 0.197mm

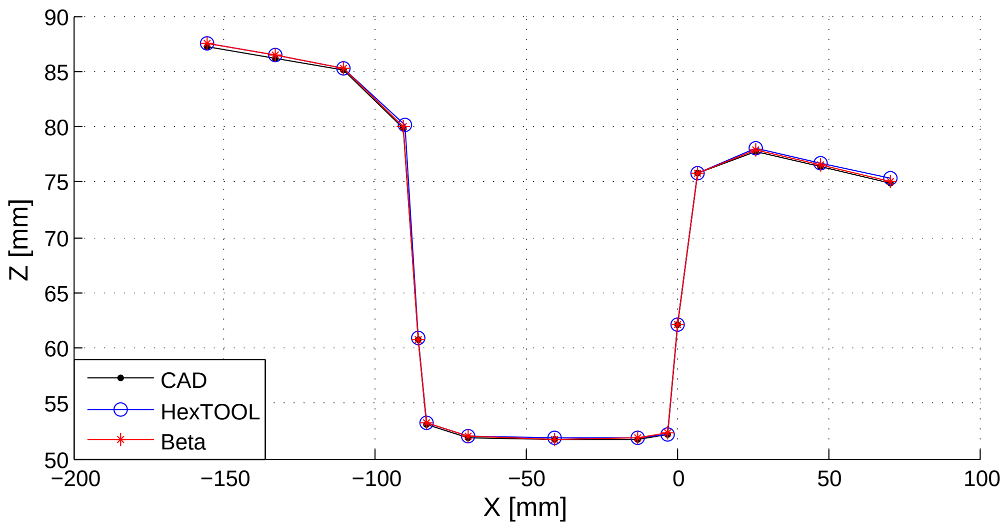
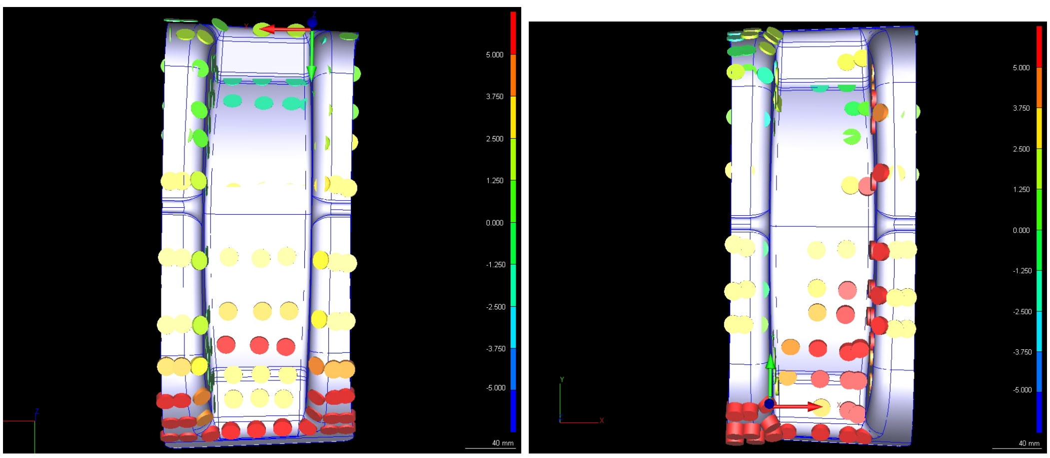


Figure 47: Cut 2.8 on the C-shaped moulds, maximum displacement for HexTOOL® was 0.428mm and for Beta 0.254mm, z-direction



(a) Part made in C-shape mould of HexTOOL®

(b) Part made in C-shape mould of Beta prepreg

Figure 48: Plot of the measured parts made in composite C-shape mould

Table 17: Displacements in y-direction for C-shaped parts, given in mm

	Displacement, y-direction					
	made in HexTOOL®			made in Beta		
Nr	Max	Min	Average	Max	Min	Average
2.1	-0.711	0.006	-0.0503	-9.740	0.057	3.451
2.2	1.878	0.200	1.095	-9.292	0.008	2.167
2.3	2.019	0.000	1.010	-7.442	-0.001	-1.814
2.4	2.312	0.001	0.731	-2.480	-0.008	-0.552
2.10	1.164	-0.002	0.494	-2.949	0.006	-0.901
2.11	1.928	-0.001	1.072	-3.456	-0.002	-0.882
2.12	2.590	-0.505	1.446	-4.738	-0.113	-1.172
2.13	3.078	1.893	2.588	5,805	0.001	-2,617

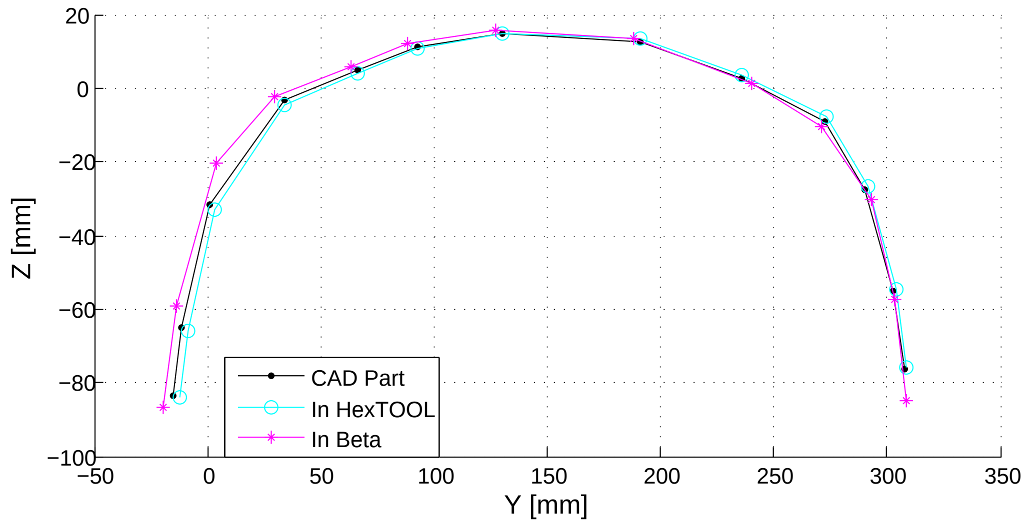


Figure 49: Cut 1.2 on the C-shaped parts, maximum displacement for part made in HexTOOL® was 1.504mm, 0.48% and in Beta 5.741mm, 1.182%

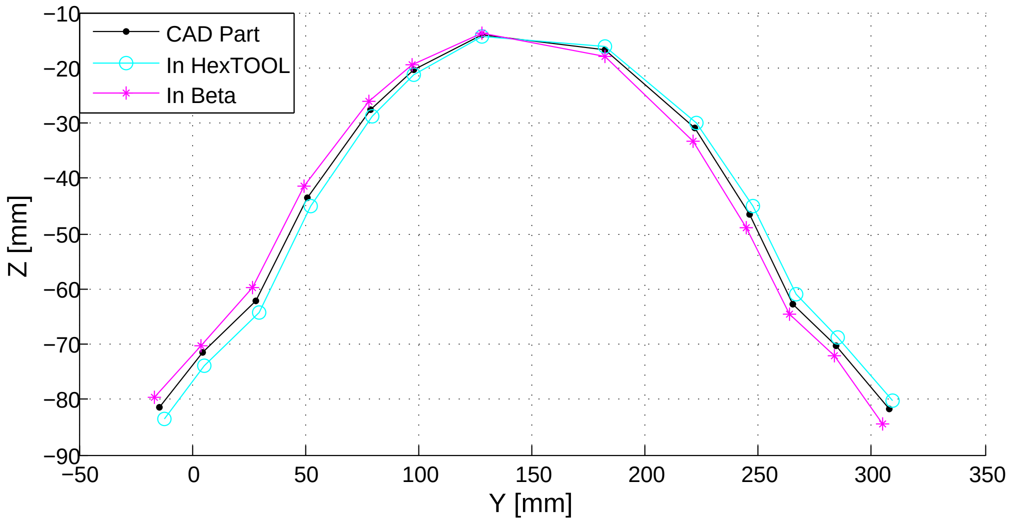


Figure 50: Cut 1.7 on the C-shaped parts, maximum displacement for part made in HexTOOL® was 0.746mm, 0.23% and in Beta 0.634mm, 0.2%

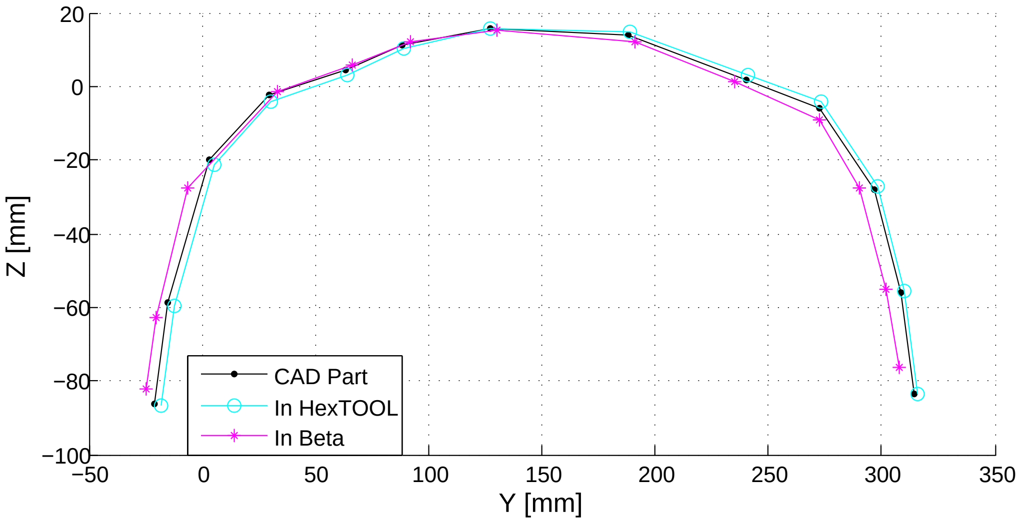


Figure 51: Cut 1.10 on the C-shaped parts, maximum displacement for part made in HexTOOL® was 1.643mm, 0.57% and in Beta 3.403mm, 1.18%

8.3.1 All three C-shapes together

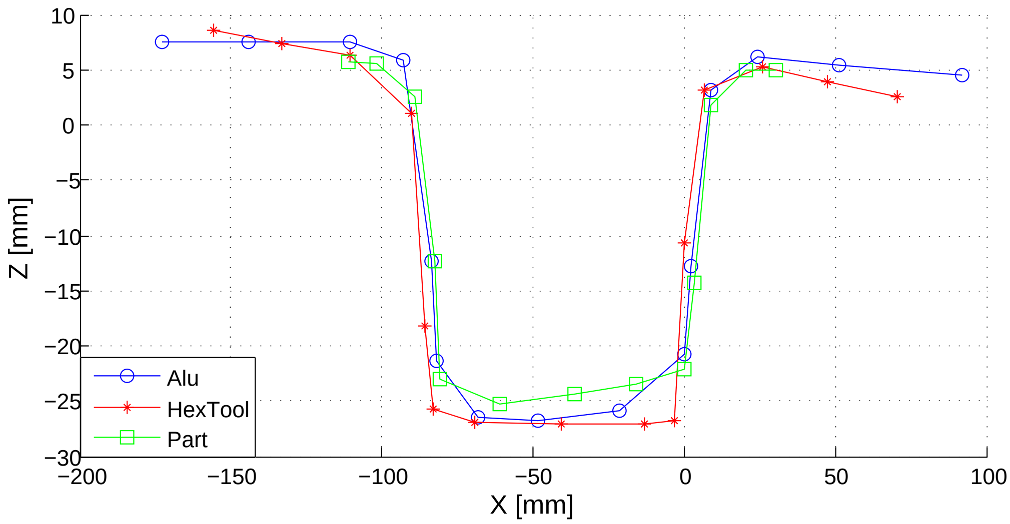


Figure 52: Cut 2.7 of the aluminium mould, HexTOOL mould, and part

In figure 52 is the graphs of the aluminim master mould, M61 mould and and the part made in the M61 mould showed. Here it looks like they are all out of tolerances. By looking at figure 53, where the same graphs are put together with each of the different CAD models, can it be seen that there are only small displacements. The difference in figure 52 is due to measurements on different places of the mould, and is the reason for why the results are not presented this way.

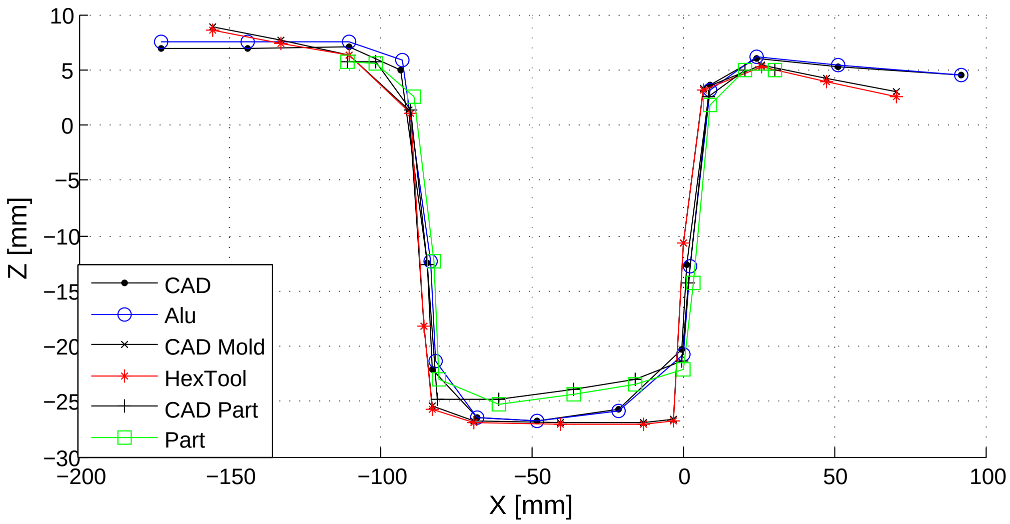


Figure 53: Cut 2.7 of the aluminium mould, HexTOOL mould, and part with their CAD part

9 Results

It was choosen to make the two moulds with composite materials. Advanced composite materials are thermally stable which makes it easier to achieve dimensional control.

The maximum displacements in x-direction of the Ω moulds are 4.670mm for HexTOOL® and 1.206mm for the Beta, see table 15.

The moulds made on a ytong plug received a rough surface, which must be machined before it can be used as a mould. Since it anyways needs machining, the spring is not too big problem as long as the cross section is thick enough. The moulds are approxmetly 10mm in thickness. The strength will still be sufficient if half of the measured displacement is removed on each side. It was not available machining time to see if the dimensional accuracy was maintained if this was done.

9.1 FE analysis and real part

The Ω shape has been evaluated both using FE analysis and as a real mould. They both shows the same tendency of a smaller arc after cure. The FE analysis shows a more pessimistic trend than the real part. This means 3.5% for the FE-analysis and 1.17% for the measured part.

For both the FE-analysis and the measurements shows a tendency of when the arc is decreasing, it naturally receive a smaller radius. Which pushes the arc of the deformed shape to cross the original shape.

9.2 Measurements, C-shape

The C-shaped master mould were made using a fine machined aluminium plug. This gave the moulds a finer surface which only needed sanding and pore sealing to achieve a sufficient mould surface. The thickness of the moulds were not made for machining. It was choosen to not have a machinable thickness because the master mould would give it a good enough surface, which it did.

The C-shape has been made with the whole mould process. That means master mould, mouls and part.

The mould of HexTOOL® had difference from the CAD model of maximum 3.55mm, average 3.0mm and minimum of 2.481mm. The mould in Beta had difference in y-direction of maximum 2.882mm, average 2.29mm and minimum 1.88mm.

The final part produced in the HexTOOL® mould has a difference from the CAD file of 3.789mm. The average is 2.638mm and the smallest were

1.887mm. The part made in Beta had a difference of maximum 15.54mm, average 6.07mm, and minimum 0.06mm.

9.3 HexTOOL® and Beta prepreg

HexTOOL® and Beta prepreg will be compared with consideration of KONGSERG's needs and use. The number of made parts are not sufficient to give a real statement of what is best, but it will give some ideas. It will be compared both what the numbers actually say and experience in working with the different materials.

In table 8 to 11 the values for the two tooling materials, cured and uncured, and mechanical property are listed. As seen, the temperature values are similar. The plies are different both in thickness and fibre orientation. The random orientation of the fibres in the HexTOOL® material is both an advantage and disadvantage. It makes it easier to form into places since it allows a certain deformation of the plies. The randomness also leads to random thickness before and after cure. This gives a more varying deformation. The woven plies of Beta prepreg are easier to cut and predict thickness, but uses much more time with layup due to smaller thickness of plies than for the HexTOOL®.

Beta prepreg have a natural tack that makes it easier for the layup because the plies stick to each other. This has showed itself as nearly too good, but it can be decreased with cooling of the material. In the same way that the M61 material gets soft and easy to shape with heat.

The main disadvantage of the Beta prepreg is how some people have reacted on its volatiles.

When comparing the two moulds made as C-shape in figure 42 and 43, it can be seen that the overall difference from the CAD file is bigger for the HexTOOL® than the Beta prepreg mould. This is also given by the numbers in table 16. The difference is not big, the maximum between them is about 0.5mm. They have the same tendency of where this difference is biggest, at the biggest gap in the y-direction.

Both of the materials advertise themselves as being stable after and during machining.

10 Discussion

One method for using requirements is to rate them with values and always be sure that the highest rated is followed. This might give a different final result than to look at all of them, not equally, but more evenly. As mentioned earlier, mould selection is often in the end based on what is known and tried out.

10.1 The selection

There has been used two types of master moulds. One of them was Ytong, this gave a rough surface on the produced mould. This leads to supplementary work on the mould in form of machining in addition to normal pore sealing and release agent.

Was it best to use; ytong or aluminium master? The cost of ytong is much lower than for aluminium, both in raw material and machining. The ytong master require adaptive work before it can be used. It is often assembled from blocks. It also need layers on the outside so it is possible to release the mould. The cured mould need to be machined. For each part this must be compared.

It was chosen to make two moulds in two quite similar materials. Both of them are light, and easy to maneuver. One disadvantage of having a small mould in a light material, is that it might move too easily. A solution for this is to make a support structure that can be fastened to a table. It should be possible to move for better layup.

It may have given a wider idea of different materials for moulds if only one shape was tested, but with more than two types of materials.

NDT of the mould to see if the composite have received any cracks from the aluminium plug.

10.2 FE analysis

In table 14, displacements for the cured mould are listed together with those of a mould cured with a part inside. The number for the different parts showers similar results of 4 $\pm$0.5mm displacement in x-direction.

In the FE analysis a finer mesh could have been used. This might have given a more accurate result. The mash on the part was equally distributed without to sharp angles in the corners of the elements.

It was used material data for one type of carbon fibre prepreg for the analysis. It was not applied the resin cure shrinkage in the analysis. This could have been done for each of the two produced parts, this might have given results closer to each of them. It was not the intention for this thesis to find the material properties for the used materials in the produced parts. If this had been carried out and used in the analysis it would have given more accurate results for each of the material type.

It was tested out to apply pressure that should have illustrated the autoclave pressure, but a good solution for this was not found.

10.3 The measurements

There are uncertainties in the measurement results. One of them is that the Ω shape had a rough surface. The ytong material gives a roughness on the surface. It was thought of straightening out the biggest peak, but that might have caused the shape to change. The ytong is brittle and crumble easily, which means that it might have lost some material at some places. It has also been covered with a thin sheet of release film, which built 3/10mm. It was not possible to do accurate measurements of the ytong part, so results of how the final shape looked like do not exist. Instead the parts were measured against the 3D drawing.

The two parts were made out of two different ytong master moulds, which also might have contained small individual differences. The first master mould broke after cure. This may happen with ytong moulds, so if it is desired to make more than one part on the mould, it should be considered another material.

The measurements of the C-shape could have been done with more points to achieve a more accurate result. It was not possible to measure the mould up against the master mould, or part against the measured mould. If it was found a solution for connecting the measured aluminium master mould to the made mould, and then the made mould to the made part, a more clear result would have been presented. Since the points are taken on slightly different places, it can not be directly compared, but it indicates a trend. The measured parts was in this report measured with the CAD part as point of departure, this give a result if the final part are alike the designed shaped. But if the mould has changed during production, this is not taken into consideration.

10.4 Future work

Suggestions for future work:

◦ Find a way to link the measured mould to the new measurements of the part produced in the mould.

◦ One way to get a strong but light material with low CTE could be to attach cores in the laminate. This can be an advantage for lower spring, and then can be possible to use in moulds. One of the challenges with core material is to expose them to many temperature changes.

◦ Make for example the same C-shape mould in materials at lower cost. It could have been for example glass fibres with high cure resin or epoxy paste method. It would hopefully give a answer if the materials at higher cost performs better or not.

◦ HexTOOL® are now also made with long fibres, as woven plies. This might be an interesting material to investigate more. This will give a more even thickness, but the advantages of the easy forming of the ply due to the short random fibres are gone.

◦ Machine the two Ω moulds after cure to see if they change during or after machining. In composite parts that is always a possibility.

11 Conclusion

This report has considered different techniques for mould making. This is a phase under continuous development and improvement. There are many materials that can be used for each production method. There are many factors that play a role in the selection. Depending on size, shape, cure temperature a method is selected. What kind of material to use and which method varies for different parts.

A set of requirements for composite moulds have been establiched. The most important requirement are different for different parts. Things that divides the most important aspects are among others shape, size, accuracy of part, and material for part.

For big moulds one of the biggest challenges is to be able to maneuver the mould. The weight of the mould itself might be a challenge to the structure holding it. To reduce the thermal mass is important. For small parts the dimensional accuracy are often a bigger challenge.

One of the main challenges in mould production is to know how much the material changes during cure. This has been investigated in form of FE-analysis and measurements of real parts. The real part showed a smaller spring-in than the FE-analysis, 1.17% versus 3.5%.

Two mould materials were choosen to investigate. From the produced moulds, both materials gives a good final mould for the given part. From the measurements shoves the HexTOOL® 0.7 $\pm$0.5mm larger spring than Beta.

Parts made with double bended mould, have here a tendency of less spring-in in the area of two curves.

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A Appendix, thermologger

The thermo log of the curing of the C-shaped Beta prepreg in autoclave. The temperature and pressure was sufficient during the whole cure.

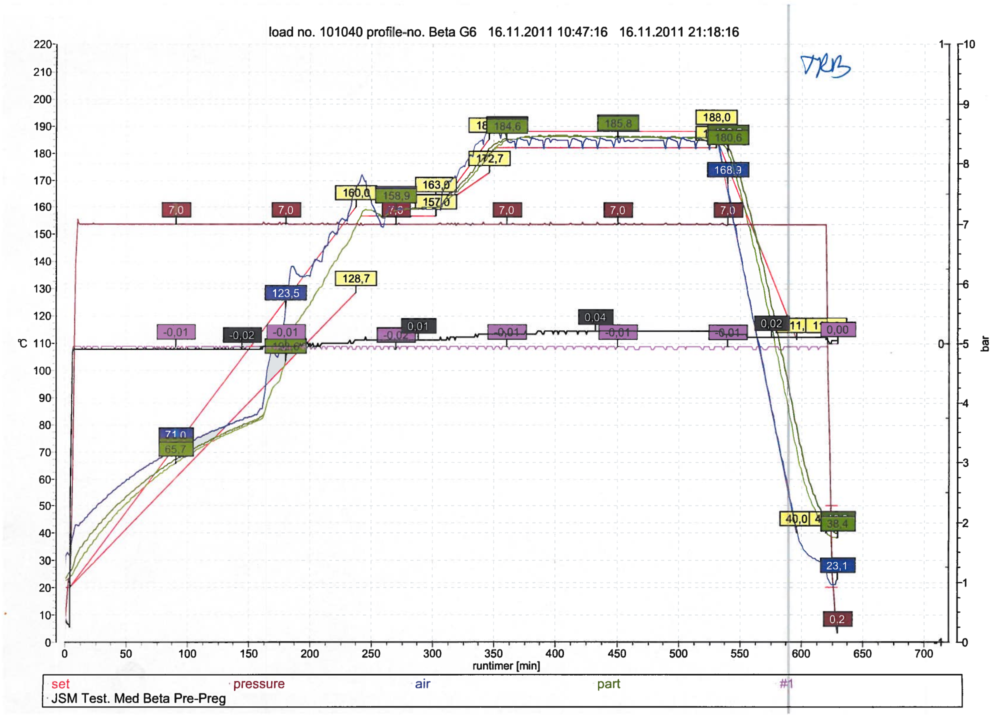


Figure 54: Thermo log of Beta cure, C-shape

B Appendix, FE analysis

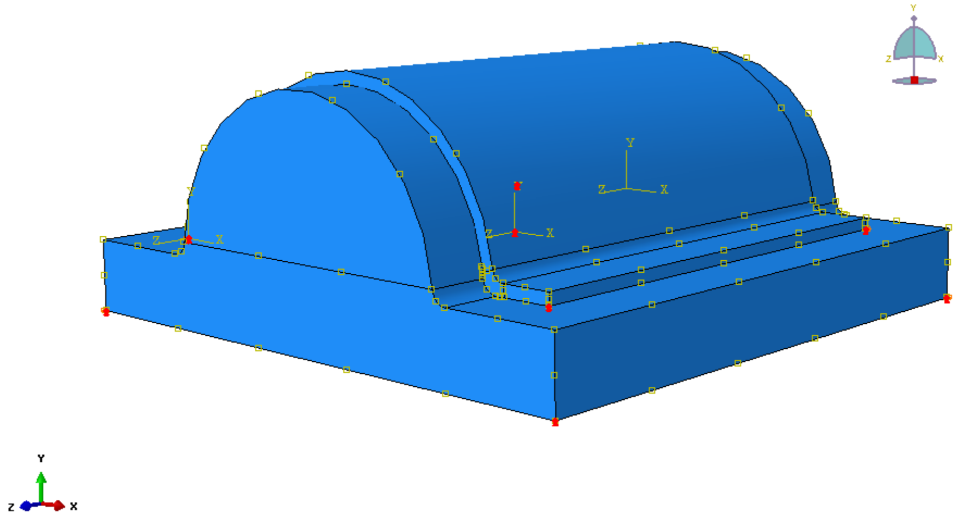
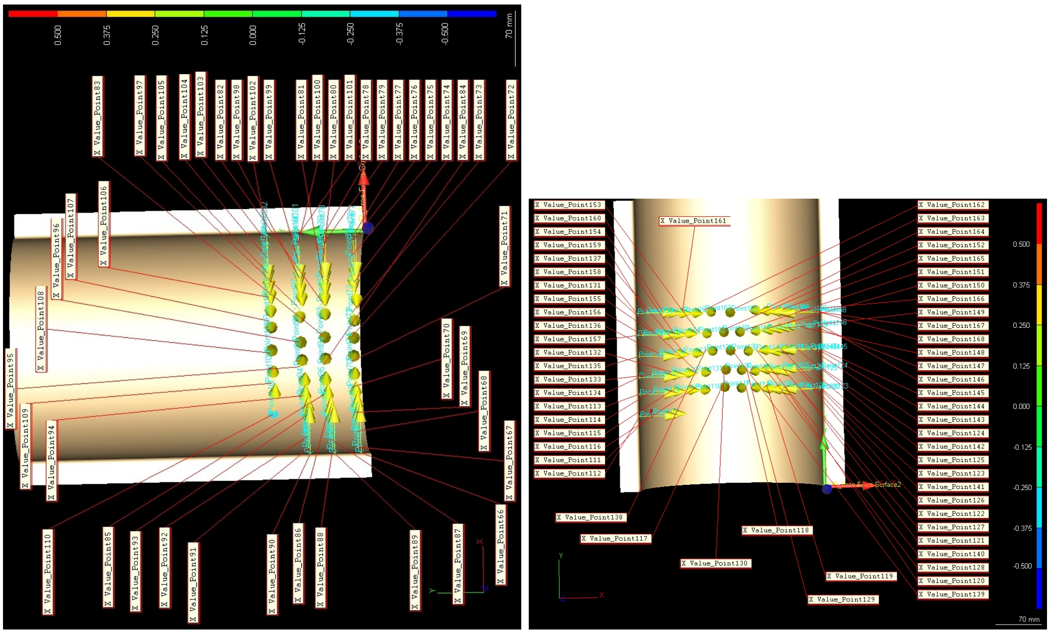


Figure 55: Boundary conditions on the Ω mould and master mould

Table 18: Displacements of master moulds of aluminium and ytong, with their respective moulds

Point	Displacement, [mm]							
in arc	Aluminium master		Mould, on alu		Ytong master		Mould, on ytong	
Nr	X	Y	X	Y	X	Y	X	Y
A.1	-2,885	-1,066	-3,146	0,001	-0,456	-0,463	-3,142	0,001
A.2	-2,620	-1,348	-3,136	0,007	-0,571	-0,586	-3,098	0,097
A.3	-2,274	-1,520	-0,029	0,061	-0,722	-0,661	-2,792	0,148
A.4	-1,967	-1,564	-2,619	0,186	-0,855	-0,680	-2,386	0,260
A.5	-1,735	-1,539	-2,248	0,320	-0,956	-0,669	-2,016	0,455
A.6	-1,514	-1,466	-1,922	0,526	-1,082	-0,622	-1,745	0,700
A.7	-1,253	-1,299	-1,774	0,666	-1,165	-0,565	-1,642	0,849
A.8	-0,943	-0,858	-1,658	0,822	-1,234	-0,491	-1,590	0,966
A.9	-0,845	-0,494	-1,574	0,997	-1,300	-0,373	-1,574	0,997
A.10	-0,547	-0,469	-1,544	0,916	-1,342	-0,215	-1,563	0,965
A.11	-0,312	-0,469	-1,345	0,629	-1,472	-0,203	-1,345	0,629
A.12	-0,078	-0,469	-0,834	0,285	-1,574	-0,204	-0,763	0,256
Piont	Displacement, wings, [mm]							
Nr	X	Y	X	Y	X	Y	X	Y
W.1	-3,058	-0,555	-3,137	0,003	-0,381	-0,242	-3,131	0,031
W.2	0.000	-0,469	-3,132	0,031	-1,710	-0,204	-2,977	0,124
W.3	-3,049	-0,469	-2,977	0,124	-0,340	-0,204	-0,019	0,026
W.4	-3,015	-0,709	-0,124	0,120	-0,391	-0,308	0.000	0.000
W.5	-2,990	-0,858	-0,014	0.000	-0,410	-0,373	-3,147	0,001
W.6	-3,699	-0,469	-0,263	0,130	-0,443	0,161	-0,443	0,161
W.7	-3,542	-0,469	-0,011	-0,001	-0,012	-0,001	-0,012	-0,001
W.8	-3,386	-0,469	-0,008	-0,001	-0,009	-0,001	-0,009	-0,001
W.9	-3,230	-0,469	-0,004	-0,000	-0,006	-0,000	-0,005	-0,000
W.10	-2,680	-1,202	-0,002	-0,000	-0,003	-0,000	-0,003	-0,000

C Appendix, Measurements



(a) Measurements points 1

(b) Measurements points 2

Figure 56: Plot with the measurement points in the arc of the Ω

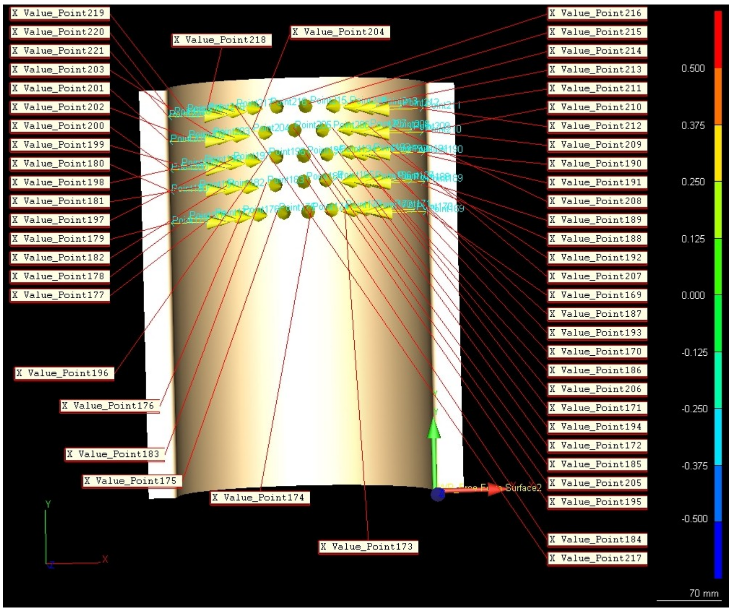
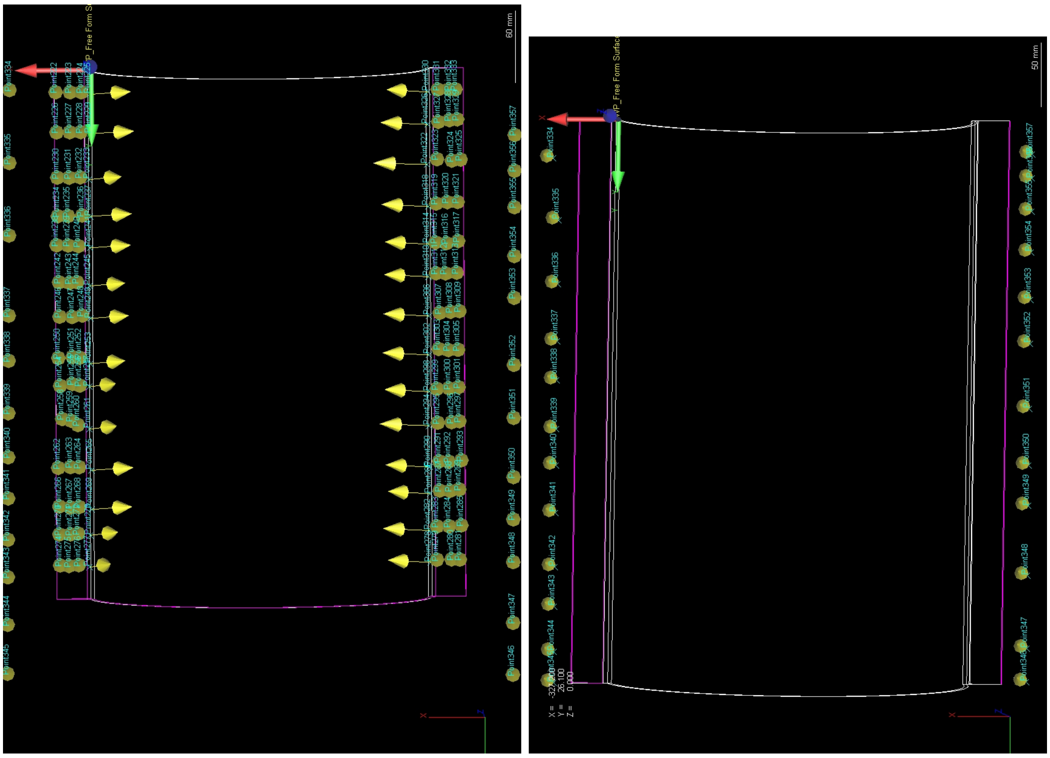
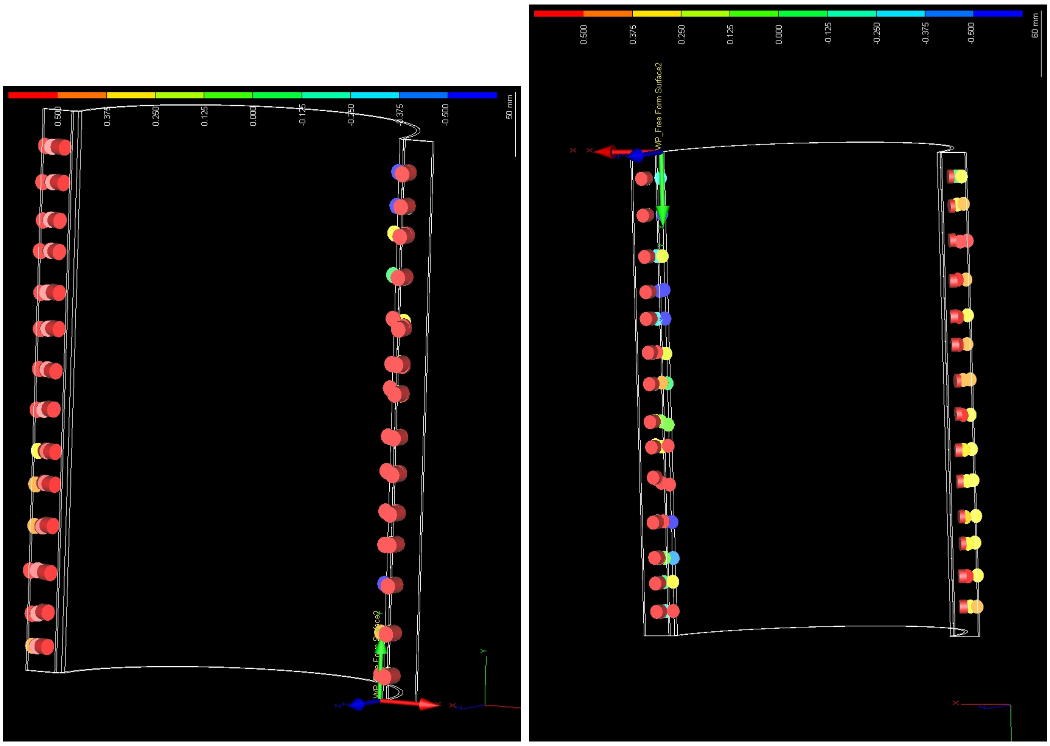


Figure 57: Measurements points 3



(a) Measurements points 4 (b) Measurements points 5

Figure 58: Plot with the measurement points on the wings of the Ω



(a) Plot of depart of the wings on Hex-TOOL

(b) Plot of depart of the wings on Beta

Figure 59: Analysis of the Ω, wings

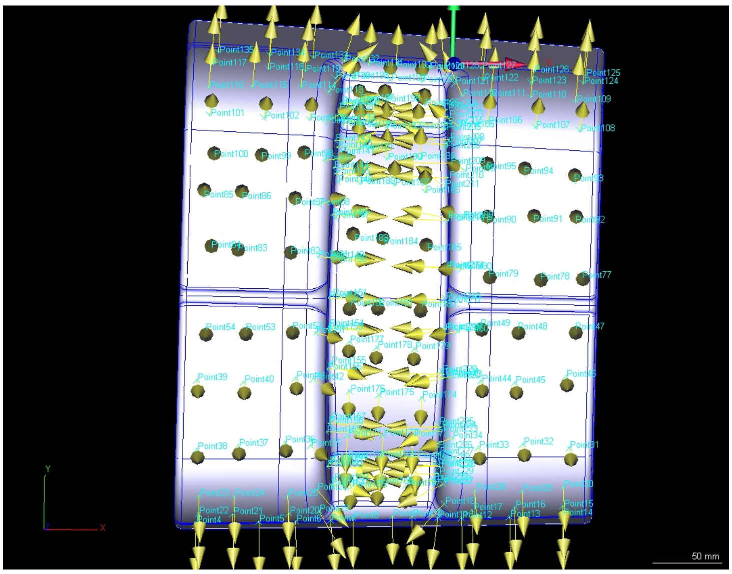


Figure 60: Aluminium master mould with measuring points

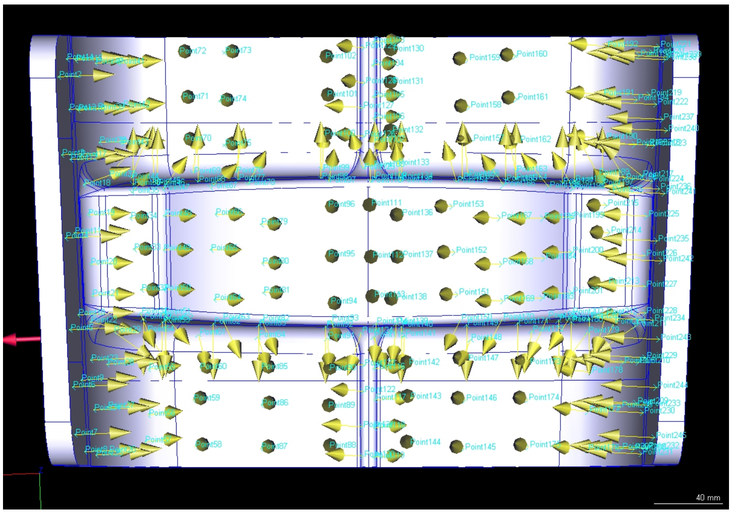


Figure 61: Carbon mould with measuring points

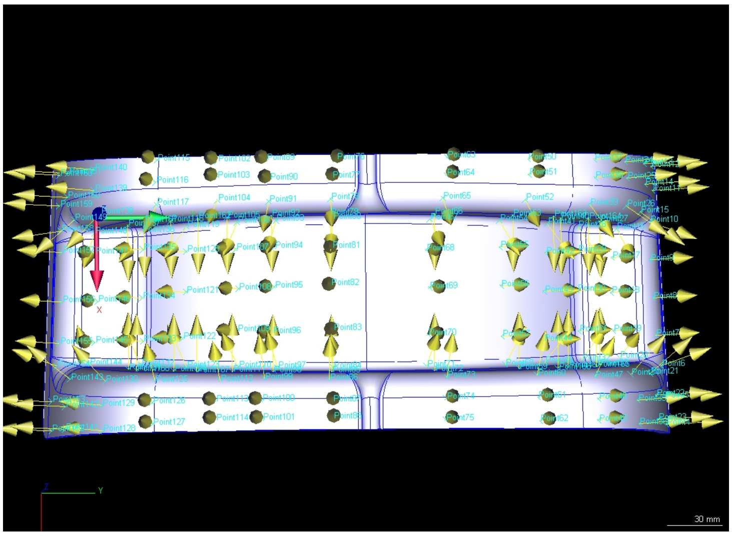


Figure 62: Carbon part with measuring points